Kent Academic Repository

Marsden, Ben (1992) *Engineering science in Glasgow: W.J.M. Rankine and the motive power of air.* Doctor of Philosophy (PhD) thesis, University of Kent.

Downloaded from
https://kar.kent.ac.uk/86115/ The University of Kent's Academic Repository KAR

The version of record is available from
https://doi.org/10.22024/UniKent/01.02.86115

This document version
UNSPECIFIED

DOI for this version

Licence for this version
CC BY-NC-ND (Attribution-NonCommercial-NoDerivatives)

Additional information
This thesis has been digitised by EThOS, the British Library digitisation service, for purposes of preservation and dissemination. It was uploaded to KAR on 09 February 2021 in order to hold its content and record within University of Kent systems. It is available Open Access using a Creative Commons Attribution, Non-commercial, No Derivatives (https://creativecommons.org/licenses/by-nc-nd/4.0/) licence so that the thesis and its author, can benefit from opportunities for increased readership and citation. This was done in line with University of Kent policies (https://www.kent.ac.uk/is/strategy/docs/Kent%20Open%20Access%20policy.pdf). If y...

Versions of research works

Versions of Record
If this version is the version of record, it is the same as the published version available on the publisher's web site. Cite as the published version.

Author Accepted Manuscripts
If this document is identified as the Author Accepted Manuscript it is the version after peer review but before type setting, copy editing or publisher branding. Cite as Surname, Initial. (Year) 'Title of article'. To be published in *Title of Journal* , Volume and issue numbers [peer-reviewed accepted version]. Available at: DOI or URL (Accessed: date).

Enquiries
If you have questions about this document contact ResearchSupport@kent.ac.uk. Please include the URL of the record in KAR. If you believe that your, or a third party's rights have been compromised through this document please see our Take Down policy (available from https://www.kent.ac.uk/guides/kar-the-kent-academic-repository#policies).

ENGINEERING SCIENCE IN GLASGOW

W.J.M. RANKINE AND THE MOTIVE POWER OF AIR

by

Ben Marsden

A thesis submitted for the degree of
Doctor of Philosophy

Unit for the History, Philosophy and Social Relations of Science
University of Kent at Canterbury

June 1992

ABSTRACT

This thesis analyses the construction of academic engineering education in Glasgow University during the tenure of the first two professors of civil engineering and mechanics, concentrating on the second, William John Macquorn Rankine (1820-72). His education, engineering activities, and involvement in societies (engineering, scientific, local or peripatetic) both enabled the establishment of supportive social networks and made available resources for the creation of an "engineering science" which was perceived as academically acceptable and practically beneficial. University allies furthered academic integration. Societies and journals provided extensive opportunities to promote, publicize and legitimate academic engineering.

Chapter one demonstrates the diversity of academic engineering, with content contingent upon social pressures, personal inclinations of incumbent professors, and local justificatory frameworks. Chapters two and three analyse Rankine's interactions within educational, scientific and practical engineering contexts in Scotland and Ireland during the 1830s and 1840s as active publishing participant.

Chapters four and five present a study of the "air-engine" which aroused phenomenal public interest in the late 1840s and early to mid 1850s. An example of a "failed technology" often neglected by historians, its contemporary significance saw it annexed to the cause of energy physics; "realized" in an "improved" form by Rankine and James Robert Napier(1821-79) as the embodiment of a harmony between theory and practice; paraded as a new source of motive power usurping the steam-engine; adduced as evidence for the supremacy of dynamical theories of heat; and manipulated as propaganda for the re-vitalization of the Glasgow chair of civil engineering and mechanics.

Chapter six charts the career of Lewis Gordon, first professor of civil engineering and mechanics, demonstrating the manifold difficulties faced in establishing academic engineering in Glasgow in the 1840s. Chapter seven exhibits the intense campaign accompanying Rankine's re-establishment of engineering in the University, with the air-engine playing a major role.

Finally, chapter eight examines the synthesis of concepts central to scientific and engineering practice (measurement and economy) through efficiency to construct a coherent directive for academic engineering with "engineering science" central.

To the air-engine enthusiasts of the world

FABLES

THE CAT AND FIDDLE

A FIDDLE was boasting of the sweetness of its voice. "Vain instrument!" exclaimed a cat who stood by, "your notes are but a feeble attempt to imitate mine."

MORAL.-*Art strives in vain to vie with nature.*

[W.J.M. Rankine, *Songs and Fables*, V.]

The chameleon's dish: I eat the air, promise-crammed.

[Shakespeare, *Hamlet*, III, ii.]

Our revels now are ended. These our actors,
As I foretold you, were all spirits and
Are melted into air, into thin air:
And, like the baseless fabric of this vision,
The cloud-capp'd towers, the gorgeous palaces,
The solemn temples, the great globe itself,
Yea, all which it inherit, shall dissolve
And, like this insubstantial pageant faded,
Leave not a rack behind. We are such stuff
As dreams are made on, and our little life
Is rounded with a sleep.

[Shakespeare, *The Tempest*, IV, i.]

ACKNOWLEDGEMENTS

I wish to thank the following for their advice and support during the writing of this thesis.

The Science and Engineering Research Council for funding this project.

My supervisor, Crosbie Smith, for the unlimited energy he expended in improving this thesis, allowing it to progress rapidly and economically to completion. He assisted me in ways which are too numerous to mention and will only be appreciated with the benefit of (contextual) history.

Professor M.P. Crosland for his constant support and encouragement, and for providing me with a shelf on which to store my music.

Alex Dolby for showing me the advantage of giving free range to my thoughts.

Jon Agar for offering me numerous cups of tea and copious insights (not necessarily in that order), William Ashworth, Yakup Bektas, John Brooke, Ana Carneiro, Irene and Gordon Crowe for showing sanity in a mad world, Billy Ginn, Graeme Gooday for arguing that I avoid the allure of alliteration, Helen Harrison for suggesting I write less meaningfully, Ian Higginson, Arthur Page, Elizabeth Pidoux for being D.H. Lawrence, and Phil Shore.

The archivists and librarians (either in person or through correspondence) of:

University of Kent at Canterbury, in helping me track down numerous items of Rankine memorabilia.

Glasgow University Archives, in particular, Michael Moss and Iain Russell.

Adam Smith Business Record Centre; British Museum Library; Cambridge University Library; Edinburgh University Library; Glasgow University Library; Institution of Civil Engineers; Mitchell Library, Glasgow; National Library of Scotland; Queens University Belfast; Royal Society of Arts, London; Royal Society of London; Science Museum Library, London; Scottish Record Office, Edinburgh; Strathclyde Regional Council Archives; St Andrews University Library; Wellcome Institute for the History of Medicine.

My parents for keeping me continually entertained in the last two and three quarter years and for putting things in perspective. Daniel, Sarah, Carole, Daisy, Rosie and Milly of course.

Amalia Hatjievgeniadu for being there, even when I wasn't.

And finally Hamish at the Mitchell Library, Glasgow, who advised me sagely "if in doubt, make something up"...

CONTENTS

Chapter 7 - The harmony of theory and practice: constructing engineering science

Chapter 8 - Conclusion

CHAPTER ONE

Academic engineering and engineering science

In what follows I use the term "academic engineering" to signify the teaching of engineering within a university or college of higher education: specifically, this differentiates an institutional teaching framework from that broader assimilation of engineering working practices in nineteenth-century Britain by the then standard method of apprenticeship or pupillage, and from the practice of engineering as a profession.[1] The growth of academic engineering, both in terms of student numbers and the variety of courses offered, profoundly influenced the structure of what we might call, by way of distinction, "practical engineering"; the status of engineering as a profession searching for recognition within society;[2] and the corporate relationship between engineers and places of higher education.[3]

Developing a complementary view, I make the basic observation that the discipline of academic engineering was by no means uniform and unvarying across the wide range of institutions and teachers in higher

---

[1] I do not deal with mechanics institutes. For a study of the development of engineering education see George S. Emmerson, *Engineering education: a social history* (David & Charles: Newton Newton, 1973). The first chair of engineering in Britain was established in 1840 at the University of Glasgow. See *The education and status of civil engineers, in the United Kingdom and in foreign countries* (Institution of Civil Engineers: London, 1870), for details of ten courses of academic engineering in Great Britain and Ireland at the time of publication. See also Eric Ashby, *Technology and the academics* (Macmillan: London, 1966); W.H.G. Armytage, *A social history of engineering* (Faber and Faber: London, 1961).

[2] See R.A. Buchanan, *The engineers: a history of the engineering profession in Britain 1750-1914* (Jessica Kingsley: London, 1989), particularly Chapter Nine, "Engineering Education and Training", pp.161-79.

[3] See Michael Sanderson, *The universities and British industry 1850-1970* (Routledge: London, 1972). Sanderson chooses 1850 as the lower end-point of his study, ten years after the establishment of the Glasgow chair.

education.[4] There was no single obvious form assumed by civil engineering in order to penetrate the walls of the universities of nineteenth century Britain; neither was there merely a linear process by which "craft engineering" became by stages "scientific".[5] At least partially, context dictated content: different courses were created to meet the contingent demands of local communities and academic colleagues.[6] In turn, a lasting and successful course might ameliorate its academic environment from within. Yet an insensitive response to the demands of internal and external communities could erode vital local support for academic engineering. Furthermore, the social, intellectual, or financial rewards offered to a university professor might simply prove insufficient in comparison to those of, say, the consulting engineer or the aspiring gentlemanly specialist working within a diverse network of Victorian

---

[4] For a recent broad survey of *national* and *international* styles of engineering pedagogy and professionalization see Peter Lundgreen, "Engineering Education in Europe and the U.S.A., 1750-1930: The Rise to Dominance of School Culture and the Engineering Professions", *Annals of Science*, 47(1990), 33-75. Lundgreen does not consider the Scottish chairs of engineering which will be of particular concern in this thesis.

[5] However useful as a first approximation, it is certainly insufficient, in the context of this thesis, to follow a historiography which attempts "to establish the stages by which engineering was transformed from a craft into a science". See R.A. Buchanan, "The rise of scientific engineering in Britain", *British Journal for the History of Science*, 18(1985), 218-33, on p.218.

[6] For a recent collection of essays highlighting the benefits of a study of technology viewed as integral to its "sociocultural surroundings" see Stephen H. Cutcliffe and Robert C. Post (eds.), *In Context: History and the History of Technology. Essays in Honor of Melvin Kransberg* (Lehigh University Press: Bethlehem, 1989). "Common to all the essays...is a sense of the importance of a contextual approach, both historical and historiographical"(p.13). Brock's interesting analysis of the foundation of the Imperial College of Engineering in Tokyo emphasizes the process of experimentation by which many culturally induced elements of, for example, Scottish and Irish engineering courses (e.g. the sandwich course), were tried out in a newly-established institutional environment, with generous resources available, and great curricular freedom. Such relatively unconstrained situations were of course rare. See W.H. Brock, "The Japanese connexion: engineering in Tokyo, London, and Glasgow at the end of the nineteenth century", *British Journal for the History of Science*, 14(1981), 227-43. For a parallel study treating similar processes of subject negotiation and construction see Graeme Gooday, "Teaching Telegraphy and Electrotechnics in the Physics Laboratory: William Ayrton and the Creation of an Academic Space for Electrical Engineering in Britain 1873-1884", *History of Technology*, 13(1991), 73-111.

scientific elites.[7]

The pattern of short-lived and abandoned chairs in the 1840s is unmistakeable. John Benjamin Macneill, appointed to the new professorship of engineering at Trinity College Dublin in 1842, found himself unable to fulfil academic and professional duties simultaneously: he chose to withdraw from the College in 1846 (chapter 3).[8] Similarly, the railway engineer Charles Blacker Vignoles, first to hold the chair of engineering at University College London (established in 1841), gave up teaching in 1845 due to the increasing pressure of business.[9] Ironically, the economic revival led by the railway mania of the second half of the decade which created a demand for engineers simultaneously acted to deprive the universities of their engineering professors. Lewis Gordon, first professor of civil engineering and mechanics at Glasgow, provides one further example of this phenomenon (chapter 6).

At a time when existing academic engineering classes were, in their day-to-day activities if not in their actual creation, the work of individuals rather than larger departments, and there were few direct teaching precedents to follow, either the establishment of a new chair, or the passing of an existing professorship to a new occupant, was often viewed as the opportunity for a thorough re-examination of the nature of institution-based engineering pedagogy. Thus on election to the Glasgow professorship Lewis Gordon published a preliminary manifesto for academic engineering: *A Syllabus of a Course of Lectures on Civil Engineering and Mechanics* (1841); and in 1868, nearly three decades after the founding of the first British chair, Fleeming Jenkin asserted to his Edinburgh audience that "a Professor of Engineering in this country...has still to

---

[7] For an analysis of one such network centred on the study of geology see Martin J.S. Rudwick, *The Great Devonian Controversy. The Shaping of Scientific Knowledge among Gentlemanly Specialists* (University of Chicago Press: Chicago and London, 1985), and in particular pp.17-18 for his justification of the term "gentlemanly specialist".

[8] Armytage, *Social history of engineering*, p.129; Buchanan, *Engineers*, p.167.

[9] Buchanan, *Engineers*, p.165.

create that system of instruction which in other Faculties needs only to be developed and improved."[10] In Jenkin's case an attempt was made to integrate elements borrowed from continental models. Often, however, local context, convenient division of academic labour within an institution, or even the specific demands of influential individuals could prove decisive in moulding the final structure and emphasis of a course.

Three examples serve to illustrate this essential divergence. The long-established Jacksonian chair of experimental philosophy in Cambridge had originally been intended for the teaching of chemistry. Successive professors had modified the terms of the chair, largely according to their particular interests: with attendance at such non-examinable scientific courses both voluntary and free there were no particular strictures dictating content.[11] From his election in 1837 the high Cambridge wrangler Robert Willis unashamedly concentrated his teaching on a *kinematic* classification of machines, illustrating his well-attended lectures with a system of mechanical models constructed from individual components as his audience enthusiastically looked on.[12] Since this geometry of motion excluded reference to causal forces, ideas of work and value were subsidiary to his conception of academic engineering. Willis's *Principles of mechanism* (1841) was complemented by William Whewell's *Mechanics of engineering* published the same year, indicating both cooperation in syllabus formation and the mutual negotiation of subject division. Together they attempted to make engineering a subject for advanced reading within a Cambridge liberal education.[13] Particularly

---

[10] Fleeming Jenkin, *A lecture on the education of civil and mechanical engineers in Great Britain and abroad* (Edmonston & Douglas: Edinburgh, 1868), p.5. My emphasis.

[11] Harvey W. Becher, "Voluntary Science in Nineteenth Century Cambridge University to the 1850's", *British Journal for the History of Science*, 19(1986), 57-87.

[12] T.J.N. Hilken, *Engineering at Cambridge University 1783-1965* (Cambridge University Press: Cambridge, 1967), pp.50-7; Robert Willis (1800-75), *D.S.B.* ; Robert Willis, *A System of apparatus for the use of lecturers and experimenters in mechanical philosophy, especially in those branches which are connected with mechanism* (London, 1851).

[13] Becher, "Voluntary Science", p.68.

following Whewell's reaction in the 1830s against the unbridled use of continental analysis,[14] Willis's emphasis upon synthetic geometry, embodied and exemplified in his carefully-fashioned mechanical models, yet facilitated by the flexible terms of the Jacksonian chair, was a particularly appropriate response to the personal, social and intellectual context of mid-nineteenth century Cambridge.[15]

In marked contrast, Fleeming Jenkin, professor of civil engineering at Edinburgh University from 1868 to 1885, emphasized the centrality of *economy* to academic engineering:

> Above all, it is possible to inculcate the true principles of economy upon the mind of the student...[The] object of the engineer is...to use his judgment and invention so as continually to endeavour to increase production at a diminished cost.[16]

Jenkin's election to the new professorship had largely been dictated by the Dundee industrialist Sir David Baxter. Since Baxter had offered the considerable sum of £5000 towards the endowment of the Edinburgh chair the Government was understandably willing to sanction the appointment of his favoured candidate. But Baxter had further stipulated that the professor bring students into direct contact with manufacturing industry: they should be taught surveying "in the field" and given extensive visits to industrial workshops. Jenkin's success, in the face of strong competition from such distinguished candidates as W.J.M. Rankine, resulted from the expectation that he would follow Baxter's wishes more closely. Thus at least initially, the content and structure of the course were contingent

---

[14] Harvey W. Becher, "William Whewell and Cambridge mathematics", *Historical Studies in the Physical Sciences* , 11(1980), 1-48, on pp.25-6.

[15] The suggested establishment of a professorship of engineering in 1850 led to nothing. Hilken comments that Willis showed no enthusiasm for giving up the freedom of the Jacksonian chair to build up a more rigid school of engineering. See Hilken, *Engineering at Cambridge University* , p.54.

[16] Jenkin, *Lecture on education* , p.18. For a biographical memoir by R.L. Stevenson (no less) see Sidney Colvin and J.A. Ewing (eds.), *Papers Literary, Scientific, etc. by the Late Fleeming Jenkin...* (2 vols., Longmans & Co.: London, 1887), i, pp.xi-cliv; and also C.A. Hempstead, "An Appraisal of Fleeming Jenkin (1833-1885), Electrical Engineer", *History of Technology* , 13(1991), 119-44.

upon the desires of one powerful individual.[17]

In the event, Jenkin drew upon his extensive experience of continental teaching methods, a predilection for political economy, and the increasingly cogent discourse of engineering *professionalism* to synthesize his own unique brand of academic engineering and to justify its place within an ancient Scottish university. Thus, for example, introducing restrictive entry examinations, traditionally alien to the initial stages of a democratic Scottish education, he stressed the analogy between medicine, law and engineering as exclusive professional specialisms.[18] At University College London, where as professor Jenkin relied solely on student fees, there had been no such examination: classes had been larger and of a lower overall mathematical standard.[19] Clearly institutional structure and private remuneration partially dictated the nature of academic engineering in London and Edinburgh.[20]

The strength of the incumbent professoriate, either individually or in consort, might be decisive in determining the degree to which a prospective professor could hope to gain academic autonomy. In 1855 George Wilson, first regius professor of technology in the University of Edinburgh and Director of the new Industrial Museum of Scotland, gave an inaugural address, disarmingly entitled "What is Technology?". His speech candidly acknowledged the very real problems faced in creating intellectual space within an existing academic environment. With resignation Wilson conceded the long and sometimes arbitrary processes of negotiation and persuasion by which new disciplines were created:

> How shall I limit myself to selected arts, and not encroach upon the subjects taught from the existing University Chairs?...How shall I faithfully fulfil my commission...and yet faithfully respect the rights of my brother professors?...[They] have

---

[17] Ronald M. Birse, *Engineering at Edinburgh University: a short history 1673-1983* (University of Edinburgh: Edinburgh, 1983), pp.94-5.

[18] Jenkin, *Lecture on education* , p.35.

[19] See Jenkin's evidence in *Minutes of the Select Committee on Scientific Instruction (Samuelson Commission)* , given on 14 May 1868, in particular questions 2425 and 2568.

[20] Jenkin held this post in London for only one year, from 1867. See Buchanan, *Engineers* , p.165.

> nearly all commissions nominally as wide as my own, and these have been restricted in meaning only by common consent, by traditional custom, or conventional use and wont.[21]

It is not hard to discover the stimulus for this straightforward concession to internal academic pressure. In the late 1840s James David Forbes, professor of natural philosophy at Edinburgh University, had kept a keen and authoritarian eye on Lewis Gordon's attempts to expand the boundaries of "civil engineering and mechanics" in Glasgow (chapter 6). With the establishment of a similarly ill-defined chair in his own university Forbes wrote directly to the Principal, expressing concern over the avoidable tendency to "withdraw amateur students, & the public generally, from the classes of Natural Philosophy & Chemistry":

> [The Crown] could not have chosen a person more likely to be acceptable to his colleagues than Dr. G. Wilson. *And I am very sure that he will exercise such rights as his commission may give him in a way which will interfere as little as may be with the other courses of the University*. Looking however to the interests of my successors...it is impossible not to see that "Technology" may be made to embrace nearly all the most interesting applications of Natural Philosophy, as Mechanics, Hydrostatics, Heat, and Electricity, not to mention by far the greater part of Chemical Application...*the department of the Lectures on Technology should be in some manner defined* ...I believe that Dr Wilson would himself be well disposed to concur in any reasonable plan for defining the subjects of his course...[22]

Two months later Wilson was ready with a sufficiently explicit disciplinary definition of "technology", designed to retain sufficient content for a viable course, whilst respecting the territorial claims of

---

[21] George Wilson, *What is technology? An inaugural lecture delivered in the University of Edinburgh on November 7, 1855* (Sutherland and Knox: Edinburgh, 1855), pp.16-17. For Wilson's brief academic career see Birse, *Engineering at Edinburgh University*, pp.66-8. Robert Anderson has discussed the relationship between Wilson's chair and his Directorship of the Industrial Museum of Scotland in Edinburgh. See Anderson's Presidential Address entitled "'What is Technology?': Education through Museums in the Mid-nineteenth Century" delivered at the joint British Society for the History of Science/London Centre for the History of Science, Medicine and Technology conference "Getting the Big Picture" on 8 May 1991.

[22] Forbes to Principal Lee of Edinburgh University, 10 September 1855, f.37R-39V, MS 3448, National Library of Scotland. Emphasis added. Forbes was opposed the suggestion of the Town Council (who exercised administrative power over the university) that Wilson's students alone pay a reduced matriculation fee "to favour the Popularity of the new chair".

his colleague. The result, appropriately subdivided into animal, vegetable, and mineral technologies was a miscellany running from hat-making to telegraphy which proved overwhelmingly popular with the Edinburgh public.[23] Wilson had chosen to avoid conflict with the professors of natural philosophy and chemistry, instead successfully exploiting the diverse treasures of the Industrial Museum to attract an appreciative audience.[24]

In this thesis I shall concentrate on one such example of local variation in the style and content of academic engineering, showing directly how the structure of a course, and its legitimation, reflected pressures of a social, political and financial kind. In particular, I argue that for William John Macquorn Rankine, regius professor of civil engineering and mechanics at the University of Glasgow from 1855 to 1872, the *core* of academic engineering (for which Rankine later adopted the term "engineering science") was essentially science regulated by economy: that is, a union of academically accepted scientific pursuits - mathematics, natural philosophy, inorganic chemistry, geology and mineralogy - supplemented and modified in a manner specifically designed to treat quantitatively the economic and financial constraints placed upon

---

[23] For a summary of Wilson's syllabus of 1858-9 see Birse, *Engineering at Edinburgh University*, pp.67-8.
[24] Ibid., p.68.

the practical engineer in the commercial environment.[25]

Many of the products of Rankine's extensive activities, including a wide-ranging output of research papers,[26] and a comprehensive and much-praised series of engineering textbooks,[27] can be seen as directed towards that "self-aggrandizement" which was positively encouraged in an atmosphere of Glasgow "improvement".[28] However, I will show that this *core* of engineering science, though an immediate response to the academic and industrial communities of Glasgow, was also excellent propaganda for academic engineering in general. By centralizing a quantitative, mathematical approach which purported to provide optimal "solutions" to engineering "problems", Rankine's engineering science broadly satisfied both academic *and* industrial criteria; by explicitly delimiting engineering science and exercising diplomatic and propagandistic skill to

---

[25] Rankine's engineering science has received attention from David F. Channell. I give a deeper analysis of the context surrounding Rankine's personal construction of engineering science, examining the ambient culture according to which it was fashioned and within which it held rhetorical coherence. See, however, Channell's *A unitary technology: the engineering science of W.J.M. Rankine* (unpublished PhD thesis, Case Western Reserve University, 1975); "The harmony of theory and practice: the engineering science of W.J.M. Rankine", *Technology and Culture*, 23(1982), 39-52; "Engineering science as theory and practice", *Technology and Culture*, 29(1988), 98-103; and "The role of Thomas Reid's philosophy in science and technology: the case of W.J.M. Rankine", in M. Dalgarno and E. Matthews (eds.), *The Philosophy of Thomas Reid* (Kluwer Academic: Dordrecht, 1989), pp.447-55. This last article has been republished in modified form as "W.J.M. Rankine and the Scottish Roots of Engineering Science", in Elizabeth Gerber (ed.), *Beyond History of Science. Essays in Honor of Robert E. Schofield* (Lehigh University Press: Bethlehem, 1990), pp.194-203. Channell has also produced *The history of engineering science: an annotated bibliography* (Garland: New York and London, 1989).

[26] See the second section of my bibliography.

[27] See bibliography. Jenkin described Rankine's textbooks as "combining originality and sound practice more admirably than any I am acquainted with in any language". Jenkin, *Lecture on education of engineers*, p.5. By 1873 they were widely known as used in many colleges in the United States of America. See, for example, [American Academy of Sciences], "[Obituary of W.J.M. Rankine]", *Proceedings of the American Academy of Arts and Sciences*, 9(1874), 276-8, on p.277.

[28] See, for example, J.R. McCulloch, *The Principles of Political Economy* (Edinburgh, 1825), p.129: "as a society is nothing more than an aggregate collection of individuals, it is plain that each, in steadily pursuing his own aggrandizement, is following that precise line of conduct which is most for the public advantage." Quoted in M. Norton Wise, with the collaboration of Crosbie Smith, "Work and waste: political economy and natural philosophy in nineteenth century Britain (I)", *History of Science*, 27(1989), 263-301, on p.288.

create for it a conceptual niche *between* "practical" engineering and "theoretical" science, Rankine not only avoided conflict but also presented academic engineering as *necessary*, the vital key to that *harmony of theory and practice* for which he consistently argued throughout his life.

Clarifying Rankine's formulation of academic engineering I highlight particular forces exerted by the engineering community of Glasgow and by academic colleagues; and I show how the ideas of *economy*, *efficiency*, and *measurement* were synthesized to provide the basis for a university discipline capable of bringing those forces into equilibrium.

By examining extensive archival material I have analysed the processes by which Rankine and his friend James Robert Napier, a prominent member of the Clyde shipbuilding family, attempted to "realize the advantages" of an improved form of air-engine (a heat-engine using air rather than steam as working substance). During the late 1840s and early 1850s such engines were quite seriously expected by many to supersede the steam-engine. I examine the arguments presented for the engine by Rankine; conversely I show that the promise of air, displayed as a revolutionary "application" of the new "science" of the mechanical action of heat to "practice", was in itself a cogent argument for Rankine's construction of engineering science as a valuable and distinct study worthy of a place within the University of Glasgow. I suggest further that the air-engine of James and Robert Stirling in particular was a valuable resource for those, such as William Thomson, Lewis Gordon, James Thomson and Rankine, wishing to present and justify the new theories of the mechanical action of heat.

Thus Rankine's engineering activities, his work on heat as "man of science", and his academic ventures were inextricably interlinked, fertilizing, enriching, and shaping each other. All such activities relied heavily upon the skilful exploitation and, eventually, the creation of societies (in particular the Institution of Civil Engineers, the

Glasgow Philosophical Society and the British Association for the Advancement of the Science), both as a means of establishing supportive social networks and as avenues of publication. The rhetoric of engineering science and of the *harmony of theory and practice* reflected the demands of Rankine's diverse audiences; but equally such coherent and palatable models of academic engineering were formed by specific elements of Rankine's experience. Engineering practice and first-hand knowledge of the demands of industrial communities shaped the conviction that to be acceptable and valuable, practical data must necessarily be derived from large-scale observation within an economy of practice. Complementing this, theories of the mechanical action of heat, and the construction of the concept of energy, allowed Rankine to define what he pointedly chose to call "perfect" heat-engines, ideal representatives of the wasteless economy of nature. "Actual" engines, such as his own "improved" air-engine, could be compared directly and numerically to these ideal goals. Remaining ever conscious of the need for economy, the sacred duty of the scientific engineer was to pursue this ultimate yet unattainable perfection.

CHAPTER TWO

Academic apprenticeship

Introduction

In this chapter and the next I sketch Rankine's early life and career until the early 1850s. I analyse the motivation and pattern of his activities, charting the changing direction in his professional attitudes, and fleshing out specific trends in his intellectual growth. Locating Rankine in a social and cultural context dominated by the "railway mania" of the 1830s and 1840s, and examining the influences of a distinctive Edinburgh University education, I will investigate the growth of a methodology of engineering science which synthesized educational experience with a traditional grounding in engineering practice.

It has been suggested that Rankine underwent an abrupt metamorphosis from practising civil engineer in the 1840s into "man of science" in the 1850s and beyond. Thus, for example, Archibald Barr has asserted that from "1848 till 1855 [Rankine] appears to have devoted himself entirely to researches on Molecular Physics";[1] whereas for Oakley it is clear that by the time he took up the Glasgow chair of engineering in 1855 "Macquorn Rankine, a mathematical physicist, was essentially an academic".[2] This change, we are led to believe, was catalyzed through the agency of Rankine's first published papers on the mechanical theory of heat.[3]

I examine this suggestion and conclude that, on the contrary, Rankine

---

[1] Archibald Barr, "W.J. Macquorn Rankine, a Centenary Address", *Proceedings of the Royal Philosophical Society of Glasgow*, 51(1920-2), 167-87, on p.173.

[2] C.A. Oakley, *A history of a faculty: engineering at Glasgow University* (University of Glasgow: Glasgow, 1973), p.8.

[3] "On an equation between the temperature and the maximum elasticity of steam and other vapours", *Edinburgh New Philosophical Journal*, 47(July 1849), 28-42; "On a formula for calculating the expansion of liquids by heat", *Edinburgh New Philosophical Journal*, 47(October 1849), 235-9; and the series of papers published in the *Proceedings* and the *Transactions of the Royal Society of Edinburgh* subsequently. For an exhaustive study of Rankine's thermodynamics from a predominantly internalist viewpoint see the works of Keith R. Hutchison listed in my bibliography, in particular, for an extensive but accessible summary, "W.J.M. Rankine and the rise of thermodynamics", *British Journal for the History of Science*, 14(1981), 1-26.

acted efficiently, effectively and with considerable assistance from a broad network of influential friends, relatives, colleagues and former teachers to locate himself with comfortable security in both "practical" and "theoretical" camps. Thus in 1852, for example, Rankine could promote an ambitious new scheme for the provision of Glasgow with water from Loch Katrine whilst almost simultaneously engaging at the level of national scientific elites in cosmological debate over the dissipation (and, for Rankine, the subsequent reconcentration) of the energy of the universe. Typically, Rankine *published* on both issues.[4] Perhaps the most striking instance of practical, theoretical and pedagogical symbiosis from 1853 onwards was the Napier and Rankine air-engine (chapters 4,5 and 7).

The variety and utility of this diverse network of acquaintances has not been stressed before. Chameleon-like, Rankine created an ideology of engineering science, both personally determined and publicly serviceable, which provided equal intellectual buoyancy in the elite scientific societies of London, Glasgow and Edinburgh, the peripatetic British Association, and the communities of practical engineers supposedly resistent to such scientific influence.[5]

This chapter deals with Rankine's upbringing, education in Glasgow and Edinburgh, and earliest existing publication of 1840. As such it begins to provide the context for his success in obtaining the Glasgow chair. Although simply stated, that success has not been adequately explained, or directly addressed in the existing literature. Information

---

[4] See W.J.M. Rankine and John Thomson, *On the Means of Improving the Water Supply of Glasgow* (George Richardson: Glasgow, 1852); and *On the Means of Improving the Water Supply of Glasgow. Second Letter* (George Richardson: Glasgow, 1852), also published in the *Reformers' Gazette* for March and June 1852 (which backs up the most plausible hypothesis that Rankine was politically liberal or whig); and "On the Reconcentration of the Mechanical Energy of the Universe", *Philosophical Magazine* , fourth series, 4(November 1852), 358-60.

[5] For Rankine's involvement in the BAAS and the Glasgow Philosophical Society see chapter 7; for his formation of the Institution of Engineers in Scotland see chapter 8. This extensive institutional representation finds its most obvious manifestation through office-bearing and publication.

on this first period of Rankine's career is largely secondary and circumstantial. However, publications of the 1840s, which will be analysed in chapter 3, provide a surprisingly rich chart of activity. Using these and other sources to identify the networks which Rankine had by 1850 successfully established, and which were to be expanded considerably by 1855, we can speculate intelligently upon the reasons for his eventual acceptance within the somewhat rigid, complex, and essentially closed structure of Glasgow University. The three decades prior to the Edinburgh Royal Society publications certainly merit consideration. Examining this period provides the obvious perspective, and the only adequate one, from which to view his papers on the mechanical theory of heat, so often taken as the starting point of his intellectual career, and his appointment to the Glasgow chair.

The early years: making the natural philosopher

In this section I wish to begin to place Rankine within his local social and cultural context. Such a context had implications for the nature of his education, his subsequent employment, and his acceptance within a broad range of social, academic, and professional elite groups. Indeed, we shall see how success within one such group might provide sufficient intellectual impetus and opportunity for the penetration of other elites displaced within society.

William John Macquorn Rankine was born in Edinburgh on 5 July 1820.[6] It has often been stated that the major influence upon Macquorn's early life was his father: David Rankine, engineer and, by 1820, retired lieutenant of the Rifle Brigade[7] or 21st Regiment.[8] David was the younger son of Captain Macorne (or Macquorn) Rankine of Drumdow in Ayrshire and

---

[6] Lewis D.B. Gordon, "Obituary Notice of Professor Rankine", *Proceedings of the Royal Society of Edinburgh* , 8(1872-5), 296-306, on p.296.

[7] John Mayer, "The Late Professor W.J. Macquorn Rankine", *Nature* , 7(1872-3), 204-5, on p.205.

[8] P.G. Tait, "Memoir [of Rankine]", in W.J. Millar (ed.), *Miscellaneous Scientific Papers* (Charles Griffin & Co.: London, 1881), pp.xix-xxxvi, on p.xx.

thus of ancient Scottish family.[9] This unusual name originated with the McQuorns of Ballyreoch in County Antrim,[10] so Rankine had Irish blood, though probably of Scottish settler variety, rather than "native" Irish. On his father's side he was descended from the Rankines of Carrick and the Cochranes of Dundonald.[11] Indeed, his ancestry had been successfully traced back to Robert the Bruce.[12] With this pedigree, he could well be acclaimed by Tait as "a Scot of Scots".[13] As David Rankine achieved success within the ill-defined profession of engineering, Macquorn inherited from his father a position in the lower regions of that nebulous category of the middling classes.[14]

In addition to the direct paternal connection with the ethos of engineering, Macquorn later followed in his father's military footsteps when he became closely and enthusiastically involved with the organization and administration of the Glasgow University Volunteer Rifle Corps from 1859 (chapter 7).[15] Again, characteristically, he took the opportunity to publish.[16] Rankine's father also had a brother, John, who had become a citizen of the United States of America and by 1853 was living comfortably, if not in affluence, in Canadaigua, New York.[17] This

---

[9] Gordon, "Rankine", p.296.

[10] Barr, "Centenary Address", pp.169-170. Barr was the first student to enrol with Rankine's successor at Glasgow, James Thomson.

[11] Tait, "Memoir", p.xx. A song entitled "The Carrick Hills" written in 1872 is republished in Rankine's *Songs and Fables with illustrations by J.B.* (2nd edition, Maclehose: Glasgow and London, 1874).

[12] Tait, "Memoir", p.xx. See, for details Barr, "Centenary Address", p.169. The connection with Robert the Bruce appears to have been through his mother's family, the Grahams.

[13] Tait, "Memoir", p.xx.

[14] See, for example, J.F.C. Harrison, *The early Victorians 1832-51* (Panther/Granada: St Albans, 1973), p.130. For the social *aspirations* of the professionalizing class of engineers see R.A. Buchanan, "Gentlemen engineers", *Victorian Studies*, 26(1983), 407-29.

[15] Crosbie Smith and M. Norton Wise, *Energy and Empire. A biographical study of Lord Kelvin* (Cambridge University Press: Cambridge, 1989), p.356; S.P. Thompson, *The Life of William Thomson, Baron Kelvin of Largs* (2 vols., Macmillan: London), 1, pp.405-6.

[16] *Table of distances for rifle-firing at targets* (Lithographed on a card. Glasgow, 1860); *Miniature Targets for Position and Aiming Drill within doors* (Maclure and Macdonald: Glasgow, 1860).

[17] See letters from John Rankine to W.J.M. Rankine, 1853, in Acc. 8660, National Library of Scotland.

transatlantic family connection was to prove both convenient and useful to Rankine in the early 1850s as he endeavoured to coordinate simultaneous British and American patenting of the "improved air-engine" with James Robert Napier (chapter 5).

Rather different in nature but certainly of equal importance was his maternal ancestry. Macquorn's mother Barbara was the elder daughter of the distinguished Glasgow banker Archibald Grahame of Drumquhassel, a founder of the Chamber of Commerce and the Glasgow Royal Infirmary.[18] Archibald originally hailed from Dalmarnock,[19] and was a descendant of the Grahames of Dougalston.[20] Strong links persisted with this socially integrated and commercially prominent branch of the family throughout Rankine's life: there is more than an indication of business links with the railway companies by which he was later employed (chapter 3). When he died in 1872, unmarried and childless, he had chosen as legal heir to his estate a cousin: Jane Hannah Grahame, daughter of the London Parliamentary Solicitor Alexander Grahame.[21]

Rankine, then, came from a middle class family that was particularly well-connected on his mother's side: as the daughter of an affluent banker, Barbara would clearly have occupied a somewhat higher social position by birth than her husband.[22] In an early Victorian "age of patronage", it is likely that links with the Grahams weighed in Macquorn Rankine's favour, particularly in his successful application for the Glasgow chair.

One further member of this family who deserves attention was the Scottish chemist Thomas Graham (1805-69),[23] son of a Glasgow merchant and

---

[18] Barr, "Centenary Address", pp.169-70. The name is frequently but inconsistently given the altenative spelling "Graham".

[19] [Royal Society of London], "Obituary of W.J.M. Rankine", *Proceedings of the Royal Society of London* , 21(1873), i-iv, on p.i.

[20] Tait, "Memoir", p.xx.

[21] See Rankine's Inventory (a full list of his possessions and assets at death, as required by Scottish law) and Testament, SC 36/48/70 and SC 36/65/171 respectively, Scottish Record Office.

[22] See, for example, Harrison, *Early Victorians* p.128.

[23] Biographical details in *DNB* and *DSB* . Thomas Graham is chiefly remembered for his work on the diffusion of gases.

manufacturer who was in turn the cousin of Rankine's grandfather, Archibald Grahame.[24] Like Rankine he attended the Glasgow High School. After graduating as M.A. from Glasgow University in 1824, having attended the lectures of Thomas Thomson,[25] he taught in Edinburgh and Glasgow, finally in 1830 succeeding Ure[26] as professor of chemistry at Anderson's College. There Graham was in direct competition with Thomson for students and for their fees (chapter 6). From 1837 Graham acted as professor of chemistry at the recently established University College London until in 1855 (the year of Rankine's Glasgow appointment) he was appointed by Palmerston's administration to the prestigious office of Master of the Mint, once occupied by Newton. Graham succeeded no less a contemporary scientific luminary than Sir John Herschel. He remained at the Mint until his death on 11 September 1869. Rankine then rapidly took steps to obtain the post for himself: his application was well supported by friends and colleagues but the campaign came to nothing when it transpired that the position was to be abolished.[27]

The significance and ubiquity of such family connections in academic and administrative circles in Scotland during this period can hardly be overestimated. In the University of Edinburgh, for example, there were ten appointments to medical chairs between 1786 and 1807: in eight of these the son of an Edinburgh medical professor was elected.[28] Murray's reminiscences of Glagow College in the middle of the nineteenth century outline an astoundingly rich family network of Scottish university professors, radiating from Allen Thomson, professor of anatomy at Glasgow

---

[24] See Tait, "Memoir", p.xxiii.
[25] See *DNB* and also J.B. Morrell, "Thomas Thomson: Professor of Chemistry and university reformer", *British Journal for the History of Science*, 4(1969), 245-65.
[26] Alexander Ure (1778-1857), *DNB*.
[27] Tait, "Memoir", p.xxiii-xxiv; *Nature*, 1(1869), p.193.
[28] D.B. Horn, *A Short History of the University of Edinburgh 1556-1889* (Edinburgh University Press: Edinburgh, 1967), p.108.

College from 1848.[29] A small section of this network demonstrates a genetic link between the first two regius professors of civil engineering and mechanics at the university: Lewis Gordon[30] and Macquorn Rankine. The first wife of Allen Thomson's father was Margaret Gordon, who had family connections with Lewis Gordon; Allen and his half brother Dr William Thomson, Professor of Medicine at Glasgow from 1841,[31] married the sisters Nina and Eliza Hill, who were related to Rankine himself. There were professional connections too: both Gordon's father and the Hill sisters' father, Ninian Hill, were Writers to the Signet, members of an ancient and revered legal society centred upon Edinburgh. Rankine's own partner in the profession of engineering in the early 1850s was John Thomson, the son of this same Dr William Thomson.

These links had a very tangible utility, first when Gordon became professor in Glasgow (chapter 6) and once again when Rankine succeeded him (chapter 7). Both Allen and Dr William Thomson figured as representatives of an increasingly powerful reforming whig faction in the University to which both Gordon and Rankine were, at different times, allied. The half-brothers therefore appear prominently in my analysis of the roles played by Gordon and Rankine as they attempted to gain acceptance for themselves and for their disipline within Glasgow College. Although such family connections were not of course preconditions for acceptance and induction into the University elite, these and similar patterns show that they were certainly not disadvantageous. At the very least they provide one more factor to explain the choice of successful candidates for the Glasgow engineering chair.

The tale of Rankine's early life reflects in many respects a familiar narrative for this time. The only other child in the family, a son David,

---

[29] David Murray, *Memories of the old College of Glasgow: some chapters in the history of the University* (Jackson, Wylie and Co.: Glasgow, 1927), p.247; Allen Thomson (1809-1884), *DNB*.

[30] For biographical details see Thomas Constable, *Memoir of Lewis D.B. Gordon, F.R.S.E.* (T. and A. Constable: Edinburgh, 1877).

[31] William Thomson (1802-52), *DNB*.

died young;[32] Macquorn's own health was feeble for several years in his early youth;[33] and he was given early instruction in religion by his parents.[34] In the absence of any decisive evidence, Rankine was probably unremarkable in maintaining a Scottish presbyterian faith throughout his life.[35] The technical questions of religious orthodoxy could assume great importance within the context of Glasgow University and provided suitable vents for the animosity directed towards Gordon as professor there in the early 1840s (chapter 6).

Early instruction in arithmetic, elementary mathematics and mechanics and physics came mainly from his father.[36] David Rankine was certainly well-qualified to teach such subjects: his own *Popular exposition of the effect of forces applied to draught*, which was written during Macquorn's early childhood, rested upon an extensive knowledge of British and French physical texts (chapter 3). Those details of early education outside the home give a pattern of brief attendances interrupted by bouts of unspecified illness. He attended the Ayr Academy (the Burgh Academy of Ayr) in the west of Scotland from 1828 until 1829;[37] for only a few months at the end of 1830 he studied at the intensive Glasgow High School with a Mr Rowblatt[38] and then, in Edinburgh again, he was taught geometry by a certain George Lees who as a writer of textbooks must have

---

[32] Barr, "Centenary Address", p.170.
[33] Gordon, "Rankine", pp.305-6.
[34] Ibid., p.296.
[35] On taking up the professorship in 1855 Rankine signed the standard declaration, required by statute, testifying that he would not in any way use his position to subvert the teachings, doctrines or privileges of the Church of Scotland. See Glasgow University Minutes of Senate, 90(10 December 1855), p.278. Beyond this statement of convenient implied passive religious conformity I have found no indication of the detail of Rankine's religious belief. Tait's description of Rankine as a "Scot of Scots" (quoted ealier) implies almost certainly that he was presbyterian.
[36] Gordon, "Rankine", p.296.
[37] Tait, "Memoir", p.xx.
[38] See Class Book for Glasgow Grammar School from October 1829, Mitchell Library, Glasgow. Rankine was in attendance between 11 October 1830 and 25 November 1830, but was absent on 14 January 1831 and thereafter. Smith and Wise, *Energy and Empire*, p.318 is in (minor factual) error.

been of some standing within the Edinburgh community.[39] But throughout much of this period Rankine was unable or unwilling to attend a public school because of the state of his health.[40] Though the exact nature of his illness remains mysterious it seems clear that for some time he was effectively confined in his parents' house in Edinburgh, due to what one obituarist described enigmatically and uninformatively as a "surgical ailment under which he laboured for a considerable length of time".[41] By necessity then, his knowledge of more advanced mathematics was obtained chiefly by private study.[42] It is of course unlikely that any elementary school would have been in a position to guide him in the more recent products of contintental mathematics.

In typical mythologizing fashion, the major event in Rankine's early intellectual development was described by him in later life. In December 1834, at the age of fourteen, he recorded for posterity how

> My uncle Archibald Grahame gave me a copy of 'Newton's Principia' which I read carefully; this was the foundation of my knowledge of the higher mathematics and dynamics and physics.[43]

The magnitude of this achievement is surely compounded by Lewis Gordon's comment that Rankine read the book in the original Latin. (By way of comparison, in the early 1840s William Whewell recommended Cambridge undergraduate students to read at least the elementary sections of the *Principia* in Latin as a standard component of the "permanent" sciences.[44]) Beyond its value as educational illustration, this event helps to reinforce our impression of the status of Rankine's family located within the literate and bibliophilic Scottish middle classes, interested in self-promotion through education, and in the education of

---

[39] Gordon, "Rankine", p.296. Lees published *Elements of Arithmetic, Algebra, and Geometry, for Use of the Students in the Edinburgh School of Arts* (Adam Black & William Tait: Edinburgh, 1826).

[40] Tait, "Memoir", p.xx.

[41] [Engineering], "W.J. Macquorn Rankine", *Engineering*, 15(1873), 13-15, on p.13.

[42] Gordon, "Rankine", p.296.

[43] Ibid., pp.296-7; Tait, "Memoir", p.xx.

[44] Harvey W. Becher, "William Whewell and Cambridge mathematics", *Historical Studies in the Physical Sciences*, 11(1980), 1-48, on p.32.

others through the dissemination of information. Later, Rankine recommended the *Principia*

> for modern science has added no new principle to the dynamics of Newton; what it has done is to extend the application of dynamical principles to phenomena to which they had not been previously applied; in fact, to the correlation of the physical sciences - or, in other words, what is denoted by the convertibility of energy.[45]

Newton was conveniently available for retrospective attribution. From the 1850s onwards Rankine was to be intimately associated with a faction of the scientific community with an interest in the promotion of the concept of energy as a unifying principle within physics.[46] Since it was at just this time that he was endeavouring to prepare his entry into the University of Glasgow, energy also occupied from the first a major position within the curriculum of Rankine's academic engineers (chapters 5 and 7).

Mathematics, then, was a major preoccupation in Rankine's youth. Perhaps with some irony, P.G. Tait[47] remarked that during this early period of Rankine's teens he felt that

> he "wasted" a great deal of time in the fascinating but too often delusive pursuit of "Theory of Numbers".[48]

This rather odd reference was perhaps an oblique reference to the rhetoric of "waste" which formed such an essential part of Rankine's (and others') ideology of "useful" and "useless" ("wasted") work with its overwhelming moral overtones. But it also raises issues regarding Rankine's attitude towards and fascination with mathematics. Differing reports from diverse groups and individuals suggest a conflict between Rankine's chosen style of mathematical presentation and the audience for which that style was

---

[45] Undated quotation in Gordon, "Rankine", p.297.

[46] W.J.M. Rankine, "On the General Law of the Transformation of Energy", *Proceedings of the Glasgow Philosophical Society*, 3(1848-55), 276-30 (read 5 January 1853); "Outlines of the Science of Energetics", *Proceedings of the Glasgow Philosophical Society*, 381 (read 2 May 1855).

[47] See C.G. Knott, *Life and scientific work of Peter Guthrie Tait* (3 vols., Cambridge University Press: Cambridge, 1911). Tait's "Memoir" is particularly interesting as one of the few substantial accounts of Rankine's life.

[48] Tait, "Memoir", p.xxi.

tailored or even created. Maxwell, for example, was dryly critical of the mathematical expression of parts of Rankine's work on the mechanical action of heat.[49] In the next section I will describe some of the early resources he drew upon in his mathematical and scientific education.

Academic traditions and the University of Edinburgh

By 1814 a regular course of study had been laid down for those students at the University of Edinburgh proposing to graduate in arts. Since the rules were flexible and, increasingly, individual professors offered distinct courses in an intellectual division of labour, it was very common for students to matriculate without then going on to graduate. For arts at least, though not of course in medicine or law, payment of the matriculation fee (compulsory from 1810) left them free to pick and choose as many or as few courses as they wished.[50] In Edinburgh, where students were youthful, basic salaries were small and professors collected fees according to the number of students they taught, there were strong incentives to make classes "elementary, spectacular and popular".[51] Equally, there were powerful reasons for existing professors to resist the creation of new chairs, or curricular encroachment by colleagues.[52]

For two sessions, Rankine studied at the University, entering at the not unusually early age of sixteen in November 1836 and leaving in May 1838.[53] There he matriculated in arts, as was most common at this time, and chose to attend courses in chemistry, botany, natural history and natural philosophy but not mathematics. I shall discuss this particular

---

[49] See J.C. Maxwell, "[Review of] Tait's Thermodynamics", *Nature*, 17(1878), 257-9 and 278-80. From a less relevant twentieth century viewpoint Hutchison has rather dismissively characterized Rankine as one who was "ever willing to blur fine distinctions". See "Rise of thermodynamics", p.11.

[50] Horn, *University of Edinburgh*, pp.30, 44, 68, 100, and 102.

[51] J.B. Morrell, "Practical chemistry in the University of Edinburgh, 1799-1843", *Ambix*, 16(1969), 66-80, on p.68.

[52] Horn, *University of Edinburgh*, p.58.

[53] William Thomson matriculated at Glasgow College at the tender age of ten. See Smith and Wise, *Energy and Empire*, p.49.

omission later. There is no record of Rankine attending any of the other courses offered.[54]

In 1836 he studied chemistry under the Edinburgh educated David Boswell Reid, who was not strictly speaking connected with the University.[55] After two years spent teaching practical chemistry privately in his own laboratory, Reid was appointed in 1828 as assistant to Thomas Charles Hope, professor of chemistry and medicine from 1799 to 1843. Hope was an immensely popular lecturer, drawing audiences of over 500, but he had little enthusiasm for practical teaching: this he regarded as purely optional, delegating it to a series of assistants such as Reid who took responsibility for practical classes given at their own risk.[56] The situation was an uneasy one. Reid, whose status was that of "permitted independent teacher", rented a room from the University, paid all the expenses, and performed all the teaching duties for this practical course; yet he gave a high percentage of his earnings from fees directly to Hope who, in return, used his acknowledged influence to obtain students, particularly in medicine, for Reid's lectures.[57]

Reid's resignation and provocative reduction (by half) of the traditional fee for his combined course of "practical and theoretical chemistry" precipitated what can best be described as a price war amongst Edinburgh's substantial group of extramural chemistry teachers. This and

---

[54] Gordon, "Rankine", p.297; matriculation albums for 1836-7 and 1837-8; transcipts of arts and law matriculation signatures for 1836-7 and 1837-8 sessions; matriculation indexes; natural philosophy class lists 1836-7 and 1837-8; botany class lists for 1836-7 (summer session); Edinburgh University Library. These demonstrate that 1836-7 was indeed Rankine's first University session. His matriculation numbers were 398 and 271 respectively in the two sessions, which makes it possible to distinguish him from other Rankines in the Univesity contemporaneously. The existing class lists indicate that these were probably the only classes Rankine attended. I am grateful to the archivists of Edinburgh Univesity Library for carrying out this search.

[55] Mayer, "Rankine", p.205. David Boswell Reid (1805-63), *DNB*. He was the son of the Edinburgh educational reformer Peter Reid (1777-1838), who advocated a reduction of the time spent on Latin and Greek and an increased emphasis on modern languages, geography, history and mathematics.

[56] Morrell, "Practical chemistry", pp.66-71.

[57] Ibid., p.72. Reid had 201 students in 1832.

subsequent disputes in 1833 and 1834 succeeded in both discrediting the University's official practical course and Hope's once prestigious chair.[58] Rankine's failure to attend Hope's class is understandable. In 1835 there were at least four separate courses outside the University in practical chemistry, including Reid's: his was an intensive course, concerned mainly with the basic skills of manipulation such as filtration and analysis with the blow-pipe.

These issues are illuminating in many respects within the context of this thesis. Here was one clear instance of the intense competition engendered by the Scottish academic system of fee-paying: in some respects Edinburgh was jealously regarded as an educational marketplace. Unprepared to teach practical courses himself, Hope had attempted to exploit those taking place and had successfully blocked the establishment of a chair of practical chemistry independent of his own. Reid, on the other hand, was prepared to link his efforts for the introduction of such a chair (ideally to be occupied by himself) to the discourses of an age of reform: the entrenched privileges of Hope were, as much as those of any exclusive group, to be examined and brushed aside. Taking this line, Reid received strong support from the whig Edinburgh newspaper *The Scotsman* . Thus presentation and publication of academic issues shaped and were shaped by political and social context. Finally, the emphasis placed upon a valid distinction between "theoretical" and "practical" chemistry by Reid's supporters was made possible by Hope's marked indifference to active, practical, laboratory-based chemistry.[59] Rhetorical or literary presentations of a distinction between "theory" and "practice" drew upon such contingent local resources (chapter 6 and 7).

In the summer of 1837, running from the beginning of May to the end of July, Rankine studied botany under Robert Graham and natural history

---

[58] Ibid., pp.73-7.
[59] Ibid., pp.77-8.

under Robert Jameson.[60] The botanist Robert Graham (1786-1845)[61] originally studied and practised medicine at Edinburgh and Glasgow. He held the chair of botany at Glasgow University from its creation in 1818, then moved to the corresponding regius professorship at Edinburgh in 1820. Graham's three month course centred upon the Royal Botanic Garden at Inverleith to which students were granted unlimited access. Rankine manifested little direct interest in botany beyond this University tuition, though in the 1850s he did recommend it as a useful study for the academic engineer "with special reference to timber trees".[62]

Studies undertaken with Jameson, a naturalist of international reputation, seem to have been more immediately significant.[63] Although, like Graham, originally trained in medicine, Robert Jameson (1774-1854)[64] quickly became interested in mineralogy and natural history. In 1800 he had studied for two years with Werner at Freiburg. Returning to Edinburgh after a period of continental travel he was in 1804 appointed regius professor of natural history and keeper of the university museum.

His university teaching, like Hope's, attracted large numbers of pupils. The scope of his course was very broad, dealing with meteorology (which included a no doubt useful section on "Prognostics of the weather"), hydrology, mineralogy, geology, botany and zoology. In hydrology stress was laid upon "the importance of Water in the economy of Nature": as a geological "Neptunist" Jameson regarded water as the primary agent of geological change.[65] Later in the course he treated the "uses of Minerals in Medicine, Agriculture, the Arts, and in the economy of Nature"; rocks too had their uses to man and within this great natural

---

[60] Tait, "Memoir", p.xxi; botany class lists 1836-7 (summer session), Edinburgh University Library; *The Edinburgh University Almanack MDCCCXXXIII* (MacLachlan & Stewart: Edinburgh, 1833), p.13.

[61] See *DNB* for biographical details.

[62] *Introductory lecture on the science of the engineer* (Richard Griffin: London, 1857), p.14; *Edinburgh Almanack*, pp.85-7.

[63] Mayer, "Rankine", p.205.

[64] For biographical details see *DNB*.

[65] See Robert Jameson, *DSB*.

economy; animals both vertebrate and invertebrate had their "Uses in the economy of Nature". The course ended with a majestic assertion of "The mutual relations that exist amongst all the objects in Nature, and those general laws that appear to be common to the whole."[66] Clearly for Jameson the animal, vegetable and mineral kingdoms demonstrated nothing less than a great unified "economical" system, self-regulating in its action. Through his eminent teacher of natural history, and by other means, Rankine absorbed this publicly available and convincing vision of a perfectly-ordered world, to be repeated in modified form when the time came to justify his course of academic engineering to the British Association in Glasgow (chapter 7).

It is likely that Robert Jameson assisted Rankine in a rather more direct fashion. With David Brewster, Jameson founded the *Edinburgh Philosophical Journal* in 1819, which he edited from its tenth volume until his death in 1854. Two of Rankine's earliest papers appeared in this journal in 1849.[67] As an ex-student of Jameson, his access to what had by then become the *Edinburgh New Philosophical Journal* may well have been facilitated: publication was an important asset in building a scientific career. Rankine's very first paper, which will be discussed later, addressed geological (or more accurately geothermal) problems of the day which had almost certainly been introduced to him during Jameson's lessons. Lewis Gordon had also studied with Jameson in the early 1830s, and, like Jameson, went on to study at the Freiburg School of Mines in 1838 (chapter 6).[68]

G.E. Davie has described the broad, humanist scope of Scottish University education during this period.[69] In the light of this study it is surprising to see no mention made of non-scientific subjects in the list of classes attended by Rankine. Although this may be a consequence

---

[66] *Edinburgh Almanack*, pp.87-94.
[67] See bibliography.
[68] Constable, *Gordon*, p.8.
[69] G.E. Davie, *The democratic intellect* (2nd edition, Edinburgh University Press: Edinburgh, 1964).

of the predispositions of his biographers and obituarists, the particular omission of any reference to formal study in mathematics requires further explanation: the class lists show that Rankine did not attend the mathematics course.[70]

William Wallace (1768-43) succeeded John Leslie as professor of mathematics at Edinburgh in 1819.[71] His style of mathematics fell broadly within a well-established geometrical tradition tenaciously adhered to within Scotland.[72] In his University teaching he offered three separate classes for students of varying standards. The most advanced class did not always meet, though Wallace maintained apologetically in 1833 that "an attempt is always made to form one". When enough students were gathered together the subjects chosen differed from year to year and might include astronomy, navigation or gunnery; in one year amongst many "the Doctrine of Fluxions, otherwise called the Differential and Integral Calculus" was expounded.[73] But in general Wallace showed some disdain for the modern algebraic mathematics of post-Analytical Society Cambridge and had gone so far as to suggest in 1823 that a course on the calculus should be substituted by one on astronomy.[74]

He remained at the University until in the late 1830s poor health made it necessary, and a comfortable civil list pension of £300 made it possible, for him to relinquish his duties. By the time of Rankine's attendance at Edinburgh, then, Wallace was ailing and his retirement in 1838 left the way open for a newcomer: there followed the controversial election to the chair of mathematics of the high Cambridge wrangler Philip

---

[70] Mathematics class lists, Edinburgh University Library.

[71] For biographical details see *DNB*.

[72] See, for example, William Wallace, *A geometrical treatise on the conic sections; with an appendix, containing formulae for their quadrature* (Edinburgh, 1837); and Richard Olson, "Scottish philosophy and mathematics 1750-1830", *Journal of the History of Ideas*, 32(1971), 29-44.

[73] See *Edinburgh Almanack*, pp.25-6 for Wallace's course in 1833.

[74] Horn, *University of Edinburgh*, p.97. The courses in the Scottish universities were in many instances extremely malleable: Wallace's predecessor had taught astronomy, geography, navigation, gunnery and fortifications in addition to mathematics. Ibid.

Kelland, an outcome engineered by James David Forbes, Edinburgh University professor of natural philosophy.[75]

It is clear that Rankine was not taught by the Cambridge reformer, who only took up his position after Rankine had left the University to begin an engineering apprenticeship. But neither did he attend Wallace's mathematics class. It remains uncertain whether he had much to gain from the traditional geometry-based course of Wallace, given the mathematical sophistication he had achieved before coming to the University. Rankine may well have shared the impatience shown by James David Forbes for Wallace's teaching procedures.[76]

We may assume that, in this subject at least, Rankine was largely an autodidact. Self-tuition might explain the somewhat idiosyncratic nature of Rankine's mathematical language. It is impossible to discover the resources for the development of his "mathematical style" with such certainty as we might do for William Thomson, or George Gabriel Stokes, regarded by contemporaries as mathematicians of the first rank with whom Rankine later corresponded and was to some extent in intellectual competition. Unlike Thomson, Stokes, Tait and Maxwell, Rankine had not been exposed directly to the rigours of the Cambridge Mathematical Tripos; but his work was often to be refereed and judged by those who had gone through this arduous training.[77] This omission may well have contributed to any resistance he met with in penetrating the Oxbridge-dominated mid-nineteenth century scientific elite. But in a curious fashion, Rankine was subjected to the influence of Cambridge, mediated through the teaching

---

[75] J.C. Shairp, P.G. Tait, and A. Adams-Reilly, *Life and letters of James David Forbes* (Macmillan: London, 1873); Philip Kelland (1808-79), *DNB*.

[76] See Davie, *Democratic intellect*, pp.105-26, particularly pp.117-8.

[77] See for example letters 77-8, 80, 145, 228, 239, 242, 266-7 in David B. Wilson (ed.), *The correspondence between Sir George Gabriel Stokes and Sir William Thomson, Baron Kelvin of Largs* (2 vols., Cambridge University Press: Cambridge, 1990) for examples of Stokes and William Thomson as referees for Rankine's papers on elasticity and other topics; and the rather critical report by Philip Kelland of Rankine's papers on heat presented to the Royal Society of Edinburgh, 14 March 1855, Acc. 10000/357, Royal Society of Edinburgh Archives, National Library of Scotland.

of Forbes whose natural philosophy class he attended during the sessions 1836-7 and 1837-8.[78]

Forbes was happy to regard himself as the disciple of the Cambridge polymath William Whewell, accepting and courting the support of a "Cambridge network" of intellectuals.[79] An extended tour of London, Cambridge and Oxford in the spring of 1831 had provided the opportunity for the initiation of friendships with Somerville, John Herschel, Babbage, Whewell , Lyell, Airy and Buckland, important scientific figures all, and closely connected with the establishment and success of the British Association for the Advancement of Science. Beyond these friendships, Forbes's early experimental work on heat and meteorology was closely influenced by members of this group. Measuring solar radiation with Herschel's "actinometer", for example, was only one instance of that "Humboldtian" science promulgated by the Oxbridge-dominated BAAS from the early 1830s.[80] Forbes's great enthusiasm during this period for the

---

[78] Tait, "Memoir", p.xxi; Rankine's admission certificate, Institution of Civil Engineers; and natural philosophy class lists, Edinburgh University Library. There has understandably been confusion between W.J.M. Rankine and another of Forbes's pupils, John Rankine, who published the "Results of observations made with Whewell's Anemometer", *Transactions of the Royal Society of Edinburgh* , 14(1840), 359-7. This paper has frequently been attributed to W.J.M. Rankine, an error which appears to stem from a citation in the Royal Society catalogue of scientific papers and is repeated, for example, in American Academy of Arts and Sciences obituary (see bibliography). The 1836-7 session was John Rankine's fifth as an arts student. He can clearly be distinguished from Macquorn Rankine by his matriculation number (475). The class books show that John did indeed attend Forbes's class in 1836-7.

[79] For a discussion of the patterns of the teaching of natural philosophy and "physics" in the early nineteenth century in Cambridge, London, and Edinburgh see Crosbie Smith, "'Mechanical Philosophy' and the Emergence of Physics in Britain: 1800-1850", *Annals of Science* , 33(1976), 3-29, in particular, for the influence of Whewell on Forbes, pp.25-8. Susan Cannon developed the idea of a "Cambridge network" in *Science in Culture: the Early Victorian period* (Science History Publications: New York, 1978), pp.29-71. For Forbes see especially pp.42-3.

[80] For the idea of "Humboldtian" science see Cannon, *Science in Culture* , pp.73-110. For Cannon, Herschel's worldwide correlation of meteorological observations (p.82) mark him out as a Humboldtian. The early years of the British Association are discussed authoritatively in Jack Morrell and Arnold Thackray, *Gentlemen of science. Early years of the British Association for the Advancement of Science* (Oxford University Press: Oxford, 1981).

British Association for the Advancement of Science almost certainly influenced Rankine's move towards involvement with the organization in the 1850s (chapters 5 and 7).

On election to the Edinburgh chair of natural philosophy in 1833, having competed successfully but acrimoniously against his former mentor David Brewster, Forbes aimed to establish a new centre of studies in the Cambridge style, very much in contrast to the prevailing Scottish tradition of popular, qualitative education. He hoped to "foster a spirit for sound physico-mathematical attainment at present nearly unknown in Scotland": working well within the University's administrative structure he was made Dean of the Faculty of Arts in 1837, despite his junior position.[81] From this position of strength and wishing further to consolidate a reforming position, Forbes manoeuvred for the appointment of Philip Kelland to the Edinburgh chair of mathematics in 1838 in preference to D.F. Gregory, one-time pupil of Wallace (although later Cambridge-educated) and youngest son of James Gregory (1753-1821), professor of medicine at Edinburgh university.[82] Gregory was likely to continue teaching in a manner consistent with Scottish traditions. Kelland, on the other hand, was the first Englishman with an exclusively English education to occupy a chair in the University of Edinburgh: he was also divorced from the spirit of Scottish university teaching.[83]

For the natural philosophy class Forbes initially relied heavily upon the guidance of Whewell, who recommended him to study, amongst other writers, Poisson (on mechanics, hydrostatics and heat), Lacroix (on calculus), and Fourier (on heat).[84] But however much Forbes may have

---

[81] "Forbes", *DNB*, p.398.

[82] Duncan Farquharson Gregory (1813-44), *DNB* ; see also R.L. Ellis, "Memoir of the late D.F. Gregory", *Cambridge Mathematical Journal*, 4(1845), 145-52. Gregory's links with Cambridge, at least, were strong. He was the founding editor of the *Cambridge Mathematical Journal*.

[83] Morrell and Thackray, *Gentlemen of science*, p.480; "Kelland", *DNB*, p.1228.

[84] Smith, "Mechanical Philosophy", p.26.

regarded himself as a protégé of Whewell and an importer of the Cambridge mathematical and physical style to the alien culture of the University of Edinburgh, he could not aspire, and nor did he wish, to reproduce the mathematical education offered there for his own students. Rather, he fused the Scottish tradition of conceptual unity through "mechanical philosophy" with an emphasis on Cambridge-style "mathematical physics" or "mixed mathematics", with its peculiar receptivity to continental-style developments. With the passing of the Copyright Act of 1837 the Edinburgh University Library lost its right to a free copy of books published in Britain, but compensation meant that the library was able and, under Forbes, particularly willing to purchase foreign books.[85]

A paper by Wilson offers material for a detailed assessment of Forbes's course in comparison with the natural philosophy course at Glasgow College, and the Mathematical Tripos in Cambridge.[86] Reservations must be made regarding Wilson's approach, however, since he does not fully consider the differing contexts of Edinburgh, Glasgow, and Cambridge. Most importantly, in comparing Forbes's Edinburgh course with the Cambridge Tripos, Wilson omits the professorial side of the Cambridge curriculum, represented by such men as William Whewell and Robert Willis. Stokes, for example, attended Willis's lectures on engineering as an undergraduate (chapter 1). The varied and changing nature of this Cambridge "voluntary science" and its relationship to the Mathematical Tripos, heavily influenced by Whewell, has been extensively analysed by Harvey Becher.[87]

Whewell, Herschel, Babbage, Peacock and Airy all played a part in the introduction of continental mathematical analysis to Cambridge as a

---

[85] Horn, *University of Edinburgh* , p.98.

[86] David B. Wilson, "The educational matrix: physics education at early-Victorian Cambridge, Edinburgh and Glasgow Universities", in P.M. Harman (ed.), *Wranglers and physicists* (Manchester University Press: Manchester, 1985), pp.12-48, in particular pp.19-24.

[87] See Harvey W. Becher, "Voluntary Science in Nineteenth Century Cambridge University to the 1850's", *British Journal for the History of Science* , 19(1986), 57-87; and Becher, "Whewell and Cambridge Mathematics".

supplement to the techniques of synthetic geometry: but Whewell remained adamant that pure mathematics should be subordinated to applied. Urging the continued expansion of applied mathematics in the curriculum in the 1830s, he gradually became convinced that the establishment of pure analysis as a subject in its own right threatened to erode the foundations of a Cambridge liberal education. Whewell's and Airy's shared style of "mixed mathematics", blending analytical techniques with the demands of particular physical problems, became the paradigm. But a reluctance to see the untrammeled use of analysis without application to physical problems meant that later, in the Mathematical Tripos at least, Whewell moved back to the methods of synthetic geometry.[88] John Herschel, one of the founding members of the notorious Analytical Society, argued that analysis should not just be a tool for mixed mathematics: it also deserved to be developed in its own right.[89] But Forbes was more closely allied to Whewell and Airy.[90]

Forbes's course was strong in physical subjects not well-represented in Cambridge Tripos questions, or in the teaching of William Meikleham in Glasgow.[91] Although mathematically less sophisticated, Forbes offered a much broader content than the Mathematical Tripos. In general, the Cambridge wrangler, while expert in mechanics, hydrodynamics, gravitation and optics would be relatively unschooled in heat, electricity and magnetism, topics which were covered in Forbes's lectures.[92] For the Tripos, at least, heat, electricity and magnetism were very much marginal Tripos subjects: there was a much greater concentration on physical optics.[93]

Optics provided a significant point of contact between Cambridge and

---

[88] See Becher, "Whewell and Cambridge Mathematics", passim.
[89] Ibid., pp.10-11.
[90] See, for example, the extensive correpondence from Forbes to Airy over many years in the Airy papers, RGO 6, Cambridge University Library.
[91] Wilson, "Matrix", p.14.

[92] Ibid., p.19.
[93] Ibid., p.16.

Forbes's Edinburgh. The second edition of G.B. Airy's *Mathematical Tracts* which appeared in 1831 contained the undulatory theory of light and so from this time questions on the subject could appear in the Mathematical Tripos.[94] Before his appointment as Astronomer Royal in 1835, Airy had introduced Fresnel's wave theory of light to Cambridge, giving a course of lectures with experimental demonstrations.[95] It was a subject particularly close to the hearts of Whewell and Challis, Airy's successor: Whewell implored Airy to repeat his course the next year: "the want of experimental lectures on that subject for a year...[would] be a real blank in the philosophical discipline of our young mathematicians".[96] During the winter of 1834-5 Forbes had prepared lectures on the wave theory for his own students based on the works of Airy and Herschel.[97]

Forbes's most active research at this time was connected with heat. He effectively made his reputation as an experimental natural philosopher through a series of investigations into the nature of radiant heat which seemed to provide evidence for the unity of heat and light as an undulatory or wave motion in the ether.[98] The bulk of this work was undertaken during precisely the period of Rankine's attendance at the natural philosophy class. On 1 March 1836 Forbes wrote, appropriately enough, to Airy:

> Just a month ago I made the interesting discovery that Dark [i.e. non-luminous] heat is circularly polarized by Total Reflections in Rock Salt...This seems the most unimpeachable of all proofs of its identity of nature with light.[99]

---

[94] Ibid., p.15.

[95] On the national scale, Herschel was a more influential proponent. See G.N. Cantor, *Optics after Newton. Theories of light in Britain and Ireland, 1704-1840* (Manchester University Press: Manchester, 1983), in particular pp.159-66.

[96] See Becher, "Voluntary Science", p.70, where the letter from Whewell to Airy of 28 March 1836 is partially reproduced. Airy gave the lectures: 110 students registered.

[97] Cantor, *Optics* , p.164.

[98] Ibid., pp.170-1. For a discussion of the broader context of such theories see Stephen G. Brush, "The wave theory of heat: a forgotten stage in the transition from the caloric theory to thermodynamics", *British Journal for the History of Science* , 5(1970), 145-67.

[99] Forbes to G.B. Airy, 1 March 1836, RGO 6/368/307, Cambridge University Library.

After his demonstration of the double refraction of heat, Forbes entertained no doubt about the importance of his experimental work and believed that he deserved recognition from the scientific establishment of the Royal Society of London. Two years later, just a few months after Rankine had left the class, Forbes again chose Airy as confidant:

> My object in writing at present is first to ask your advice... Briefly then I think that my Papers on Heat ought to have obtained for me before now the award of the Rumford Medal.[100]

Covert action secured the award. Forbes's experimental work upon this unifying theory provided a valuable resource for Rankine, whose hypothesis of molecular vortices (a complex mechanical atomic model) was partially designed to provide an explanatory mechanism for this apparent identity of radiant heat and light.[101]

During Rankine's time in Forbes's class, lectures were given under the broad headings of: introduction and general; properties of bodies; statics; hydrostatics; dynamics; hydrodynamics; pneumatics; meteorology; heat and the steam engine; optics; electromagnetism; and astronomy.[102] Mechanics, divided into statics and dynamics, formed the nucleus of the course, and occupied almost half of the lectures given in each session.[103] Thus we can trace Rankine's later emphasis on mechanical techniques both in scientific work and, as "applied mechanics", in his academic engineering, back through Forbes and Whewell, to see the primacy of this branch of study within natural philosophy (chapter 8). Although the nature of Rankine's mathematical education remains obscure, for his own "first-division" (highest level) students Forbes recommended study of Poisson's *Mechanics*, Whewell's *Mechanics*, and Airy on the undulatory

---

[100] Forbes to G.B. Airy, 20 September 1838, RGO 6/368/318, Cambridge University Library.

[101] See, for example, Rankine's "On the centrifugal theory of elasticity, as applied to gases and vapours", in W.J. Millar (ed.), *Miscellaneous Scientific Papers* (Charles Griffin & Co.: London, 1881), p.18.

[102] Wilson, "Matrix", p.22.

[103] Ibid., p.24.

theory.[104] Thus, had Rankine not already been conversant with the continental techniques of mathematical analysis through private study, he would have become so through the ethos of Edinburgh natural philosophy. Indeed, more generally, the similarities rather than the differences between mathematics at Cambridge and Edinburgh have recently been emphasized.[105] As a specific example, in the early 1840s William Thomson in Cambridge received lectures by Challis very much in the style of his predecessor, Airy; in Edinburgh in the late 1830s, Rankine was taught by a the young Forbes, saturated with the writings recommended by Whewell, and, as we will see, anxious to stress in particular the wave theory of light.

Forbes's early pupils were enthusiastic. Writing to John Herschel in 1837, Forbes enclosed

> a set of observations...made by some of my pupils...who have formed themselves into a physico-mathematical society - likely I think to infuse a new spirit into this branch of our studies here...[106]

Given Forbes's earlier identification with Herschel, this continued correspondence, and alignment with one of the brightest stars of the Cambridge network, comes as no surprise. In an effort to stimulate still further activity, Forbes soon afterwards offered a prize to the class:

> I have been attempting (not without success) to make [the undulatory theory of light] a subject of study amongst my more advanced pupils. I expect shortly to receive several Essays in competition for a gold medal...[107]

In setting such a prize essay Forbes was following one of the minor recommendations of the Royal Commission of 1826 which had exhibited fervent wishes to Anglicize Scottish university education.[108] Contacts with Herschel were matched by those with Airy: in March 1837, a delighted Forbes informed Airy that five "really respectable compositions" had been

---

[104] Ibid., p.23.

[105] Ibid., p.33.

[106] J.D. Forbes to J.F.W. Herschel, 19 January 1837, HS.7.292, Herschel Letters, Royal Society of London.

[107] J.D. Forbes to J.F.W. Herschel, 14 February 1837, HS.7.293, Herschel Letters, Royal Society of London.

[108] Horn, *University of Edinburgh*, pp.159 and 166.

submitted on this "new subject in Scotland".[109] Though this was Rankine's first session at the University he was already a sufficiently "advanced pupil" to become the recipient of this, his first of many academic honours.[110]

That Forbes should have communicated with Herschel about the prize which Rankine was soon to win is perhaps appropriate. Many years later Rankine testified "how deeply I am indebted to the early study of your [Herschel's] writings for such knowledge of mathematical physics as I possess."[111] This provides strong additional evidence that Forbes recommended Herschel's classic text on scientific method, the *Preliminary Discourse on the Study of Natural Philosophy*, to his more advanced students, Rankine amongst them. This links Forbes once more with the "Cambridge network". In so doing it places Rankine closely within that dominant Cambridge tradition of natural philosophy associated with Whewell, Airy, and Herschel. Rankine's later activities within the Oxbridge dominated Mathematics and Physics Section of the BAAS and his acceptance within a group of younger Cambridge alumni, including William Thomson and G.G. Stokes, therefore appear as a natural extension of his early academic apprenticeship with Forbes (chapter 8).

It is tempting to see links between the Edinburgh teaching and research (particularly that of Forbes) and Rankine's own work. I will briefly consider here three related issues: firstly, the traditional Scottish emphasis placed on the connections between philosophical speculations and scientific methodology; secondly, the question of industrial applicability in Forbes's course and its relation to Rankine's methodology of "engineering science"; and thirdly, Forbes's experimental work, primarily that on radiant heat. The last issue prefaces a

---

[109] Shairp, Tait, and Adams-Reilly, *Forbes*, p.129. Quoted in Smith, "Mechanical Philosophy", p.27.

[110] The prize essay itself has been lost.

[111] W.J.M. Rankine to J.F.W. Herschel, 20 January 1871, HS.14.469, Herschel Letters, Royal Society of London.

discussion of Rankine's earliest surviving paper. Analysing this indicates the complexity of the sources for his work and shows him engaging in contemporarily relevant scientific debate as early as 1840 at which time most obituarists would have us believe that he was devoting all his time and energy to assimilating the skills of the engineer.

The personal philosophical context

During his second session with Forbes, Rankine won a second prize: a gold medal for "An Essay on Methods in Physical Investigation".[112] The essay itself has been lost, which is particularly unfortunate given the relatively prolific methodological essays which Rankine was to produce in his later career.[113] Seen within the context of Scottish pedagogy this emphasis on introspective analysis of scientific methodology fits extremely well.[114] In setting an essay on such a central issue, Forbes demonstrated again his willingness to place himself squarely within the pedagogic traditions of the University of Edinburgh. Indeed, Forbes again offered a prize for the most outstanding essay "on the best method of arriving at truth in physical investigations" in the 1845-6 session.[115] It is surely significant that Forbes actively encouraged his young pupils to view their scientific endeavour as embedded within and arbitrated by a broad methodological and philosophical context.

In spite of the loss of Rankine's early essay, we do know something of his early personal philosophical inclinations: during his University years he read metaphysics, in particular Aristotle, Locke, Hume, Stewart, and "Degerando".[116] Dugald Stewart, professor of moral philosophy at

---

[112] Gordon, "Rankine", p.296.

[113] See in particular, Rankine's "On the use of mechanical hypotheses in science, and especially in the theory of heat", *Proceedings of the Glasgow Philosophical Society*, 5(1860-4), 126-32, which, I believe, should be partly seen as a justification of his own molecular vortex theory at a time when it was falling into disfavour.

[114] See in general Davie, *Democratic intellect*, for a study of Scottish University education at this time.

[115] Wilson, "Matrix", p.24, fn.31.

[116] Gordon, "Rankine", p.296.

Edinburgh University in the late eighteenth century, was perhaps the most influential member of the group of Scottish Common Sense philosophers, one of whom (Thomas Reid) is conspicuously absent from Rankine's reading list.[117] The relations between this group and British natural philosophers has received much attention, particularly in Rankine's case with reference to methodological debates.[118]

A fundamental issue addressed was the use of hypotheses in the practice of science. Reid in particular demanded the rejection of all conjectures, hypotheses and theories, stressing those passages in Newton's works which appeared to do the same: speaking broadly, this philosophy was manifested in a contempt by one group of Scottish natural philosophers for any hypothesis involving unobservable underlying causes which could not be shown to exist independently by inductive methods.[119]

A second tradition, opposed to this "anti-conjectural" stance, sought as one aim of science the reduction of knowledge to a few general principles. Conflict formed, leading to an ambivalence over the use of

---

[117] Horn, *University of Edinburgh* , p.50.

[118] See Richard Olson, *Scottish philosophy and British physics 1750-1880* (Princeton University Press: Princeton and London, 1975), in particular pp.271-86. David Channell has attempted to revise Olson's evaluation of Rankine's writings in "The role of Thomas Reid's philosophy in science and technology: the case of W.J.M. Rankine", in M. Dalgarno and E. Matthews (eds.), *The philosophy of Thomas Reid* (Kluwer Academic: Dordrecht, 1989), pp.447-55. Channell provides no evidence that Rankine read the work of Reid, merely asserting (p.449) that he "was most likely first introduced to Reid's philosophy through the writings of Dugald Stewart". In Channell's partially revised and marginally more convincing version of this paper Reid has been displaced by Stewart (in other respects the text is surprisingly similar) but the lack of contextual analysis and temporal, textual, or even conceptual specificity in the argument leaves substantial doubt as to how exactly such philosophical determinism was achieved. See however, Channell's "W.J.M. Rankine and the Scottish Roots of Engineering Science", in Elizabeth Gerber (ed.), *Beyond History of Science. Essays in Honor of Robert E. Schofield* (Lehigh University Press: Bethlehem, 1990), pp.194-203. He has also pointed out Rankine's (self-acknowledged) debt to Aristotle in his choice of the expressions "potential" and "actual" energy during the early 1850s. See "Rankine, Aristotle and potential energy", *The Philosophical Journal* , 14(1978), 111-4. Cardwell had previously referred to this "Aristotelian dichotomy": D.S.L. Cardwell, *From Watt to Clausius. The rise of thermodynamics in the early industrial age* (Heinemann: London, 1971), p.282.

[119] G.N. Cantor, "Henry Brougham and the Scottish methodological tradition", *Studies in the History and Philosophy of Science* , 2(1971), 69-89, in particular pp.71-4.

the word "hypothesis". Within the second group the analogical use of a hypothesis (in the sense of the application of a general principle, shown inductively to exist in certain circumstances, to a new situation), was acceptable. Frequently such hypotheses, although of inferior logical status, were afforded a high degree of probability. Dugald Stewart and Thomas Brown represented this more lenient attitude towards hypotheses as necessary to the first stages of science viewed as a progressive endeavour. This pragmatic stance was well formed to reconcile Reid's views with those of their own scientific acquaintances.[120] Rankine's "hypothesis of molecular vortices" would appear to fall most closely within this category.

The last in Gordon's list is a less well-known figure, but can ultimately be located within a similar tradition. Joseph Marie de Gérando (1772-1842) was a French politician, philanthropist and philosopher of Italian ancestry who held high administrative posts under Napoleon I. He was the author of many books, including an *Histoire de philosophie* (1803) and, perhaps most importantly here, *Des signes et de l'art de penser, considérés dans leurs rapports mutuels* (1800). This work contributed to the tradition of the *idéologues* who during this period formed the dominant philosophical group in France. Destutt de Tracy (1754-1836) had introduced the term *idéologie* to signify the "science of the analysis of sensations and ideas" and the members of one section of the Second Class of the Institut National (founded 1795), devoting themselves to that study in place of metaphysics, became known as the *idéologues* . They regarded themselves as developing a field opened by John Locke and further exploited by Condillac in which *language* was regarded as essential to all processes of thought. Their influence in Britain was due mainly to the interest shown by the Common Sense philosophers in their work.[121] In this

---

[120] Ibid., pp.75-9.

[121] My account of De Gerando is based on Paul Edwards (ed.), *The Encyclopedia of Philosophy* (7 vols., Collier Macmillan: London, 1967), 7, 387-9.

sense "Degerando" was one representative of a philosophical tradition linking Locke to Stewart and providing Rankine with a coherent if sceptical philosophical education.

I will not discuss the possible influence of these writers in detail here. It is worth commenting more generally, however, that the skilled analysis, construction, and (possibly rhetorical) justification of research methodologies, stimulated by a traditional Scottish predilection for philosophical study, was a useful preliminary exercise for Rankine's construction and presentation of a methodology of "engineering science" in the 1850s (chapter 7). I would suggest further that the cultural emphasis placed upon a self-conscious consideration of hypotheses within scientific theory not only gave Rankine the opportunity to justify his own hypothesis of molecular vortices, upon which his reputation within the scientific community was seen to rest; it also provided him with the opportunity to dismiss the hypothesis of substantial heat (the caloric theory) which he saw, firstly, as opposing his own scientific work and, secondly, as a major impediment to the widespread acceptance of the advantages of the air-engine (chapters 5 and 7). Rankine's interest in the reform of scientific language might provisionally be linked to his reading of De Gerando. The promotion of "energy" physics is only perhaps the most successful example of the territorial use of new or ornate words, often respectably rooted in ancient Greek, in the construction and annexation of scientific concepts and intellectual property. For all these reasons, the philosophical context can be viewed as a very personal one.

The industrial applicability of natural philosophy

During Rankine's first session in the natural philosophy class seventeen lectures were given on "heat and [the] steam engine", according to Forbes's own classification.[122] These topics therefore formed a major part of the curriculum. The connection made between "heat" and the "steam engine" indicates what is for Rankine an early and explicit statement of the application of science to practice. It strengthens, but also qualifies, Michael Sanderson's implication that Forbes was directly committed to making his course industrially applicable.[123]

Pointing up this potential connection with Forbes and a number of practically oriented ex-pupils and natural philosophers (Gordon, Rankine, Maxwell, and Tait) must be done with some care. Sanderson has described the Edinburgh natural philosophy class as particularly "industrially relevant", at least during the late 1850s. At this time Forbes dealt with such down-to-earth topics as boiler safety plugs, tubular bridges, and locomotives,[124] but, as Wilson has shown in his study of natural philosophy in Britain encompassing that earlier period more directly relevant to Rankine, Forbes's class varied considerably from year to year both in size and in content.[125] By 1860 at least Forbes could write of the "intimate and reciprocal" connection between natural philosophy and "The Mechanical Arts, of which we take Civil Engineering to represent the department most cognate to that of Natural Philosophy".[126]

Perhaps more interesting in this context is an indication that Forbes had direct links with the new engineering courses at the University of

---

[122] See table in Wilson, "Matrix", p.22 giving Forbes's divisions of lectures for each university session.

[123] Michael Sanderson, *The universities and British industry 1850-1970* (Routledge: London, 1972), particularly p.158.

[124] Ibid., p.158.

[125] See Wilson, "Matrix".

[126] J.D. Forbes, "Dissertation sixth: exhibiting a general view of the progress of mathematical and physical science, principally from 1775 to 1850", in *The Encyclopaedia Britannica* , 8th edn, 1, pp.795-996. Quoted in Wilson, "Matrix", p.21.

Durham which had been proposed in 1838.[127] Indeed, in the summer of 1840 he wrote to Airy, who supported the style of engineering promoted by the Institution of Civil Engineers (chapter 3): "I beg leave to send you some papers I have set for the Durham Engineer students".[128] It seems clear that Forbes did not actually offer a consistent course in civil engineering at Edinburgh before this date however, since in October of the same year he expressed his reluctance to begin such an endeavour:

> I have...got some hints that if I would work double tides & lecture on Engineering as well as Nat. Phil. I might have something [i.e. an increased income] too. But I fear this new task would both exhaust my physical powers (2 lectures a day is killing work if they are good ones) & wholly draw me away from those branches of science in which I am making some progress...[129]

Forbes had no qualms about his ability to lecture on engineering (as professor of natural philosophy) and, from the evidence of this letter at the very least, regarded engineering as anything but an inappropriate subject of tuition within the University of Edinburgh, even though such a class would compete with his former pupil Lewis Gordon's new course in Glasgow (chapter 6). In harmony with this attitude, Robert Willis and William Whewell worked together to introduce engineering not merely as part of the Cambridge professorial curriculum, but as suitable advanced reading for a liberal education (chapter 1).[130]

Forbes's reticence stemmed only from the already heavy burden of existing work.[131] We can conclude then that although Forbes did not actually lecture explicitly on civil engineering during Rankine's attendance at the natural philosophy class, he did include material of

---

[127] For information on this short-lived course, see R.A. Buchanan, *The engineers: a history of the engineering profession in Britain 1750-1914* (Jessica Kingsley: London, 1989), pp.165-6.

[128] J.D. Forbes to G.B. Airy, 26 June 1840, writing from "Durham College", RGO 6/368/329, Cambridge University Library.

[129] J.D. Forbes to G.B. Airy, 20 October 1840, RGO6/368/334, Cambridge University Library.

[130] Becher, "Voluntary Science", p.68.

[131] Some classes of engineering appear to have taken place in Edinburgh before 1841, however, but they were experimental in nature and did not last long. See Buchanan, *Engineers* , pp.165-6.

direct practical relevance (for example, the steam engine) and he was in general, even at this early stage, sympathetic to the notion of civil engineering as a topic suitable for inclusion within the curriculum of a Scottish University.

This sympathy resulted partly from self-interest. Students in "academic" civil engineering were potential class fee-payers. In the late 1840s and mid 1850s Forbes simultaneously defended his perceived right to teach subjects relevant to engineering and repelled the attempts of those such as Gordon and George Wilson who threatened to define either academic engineering or "technology" in a way which encroached upon natural philosophy (chapter 1, 6 and 7). Indeed, according to Forbes's own classification, lectures on "civil engineering" as such were not given until the session of 1855-6.[132] Significantly, this was the year in which Rankine was appointed to the revivified and potentially competing Glasgow University regius chair of civil engineering and mechanics, and George Wilson became the first professor of technology at the University of Edinburgh. These issues, and the more general question of the extent to which the syllabus of a university class might be modified by such external factors will prove to be of great importance when I come to deal with the Glasgow professorship (chapters 6 and 7).

Charting the heat of the Earth

In a study of what he describes as a "forgotten transition" from the caloric theory to thermodynamics, Stephen Brush identifies James David Forbes as an early supporter of a dynamical undulatory or wave theory of heat which regarded radiant heat and light as essentially the same phenomenon, manifesting the same properties.[133] Forbes was actively investigating the properties of radiant heat (and using his results to lobby for academic honours) contemporaneously with the two university

---

[132] Wilson, "Matrix", p.22.

[133] Brush, "Wave theory", p.155.

sessions of 1836-8. Two papers, based on experimental work relating to the polarization and refraction of heat, immediately pre-date Rankine's attendance at the natural philosophy class;[134] and Rankine began to develop his contentious hypothesis of molecular vortices, itself within this tradition of wave theories of heat[135] as early as 1842 when we can still imagine him to be under Forbes's influence. The longer term relationship was particularly useful for Rankine in connection with his elevation to the scientific elite through presentation of papers on the mechanical action of heat to the Royal Society of Edinburgh of which Forbes was long-serving Secretary (chapter 4).

I now wish to consider, within the contexts that have been sketched so far, Rankine's first known publication entitled "On the laws of the conduction of heat and on their application to some geothermal problems".[136] Significantly, this work appeared in a journal intimately associated with the University of Edinburgh, indicating the continuity in Rankine's research career which has often been denied. During the 1837-8 session (Rankine's second) the budding natural historian Edward Forbes had returned to Edinburgh where he took an active part in the notorious "snowball riots", the subject of much of the contents of his revived and lighthearted journal, the *University Maga*. An inveterate publicist and former of societies, Edward Forbes had founded the "Edinburgh University Club" towards the end of 1839, under whose auspices an "Academic Annual" was published in 1840. (In spite of the title, no others followed.) Broad in scope, to the point of miscellany, the volume included contributions from such eminent (or soon to be so) individuals as Edward

---

[134] James David Forbes, "On the refraction and polarization of heat", *Transactions of the Royal Society of Edinburgh*, 13(1835), 131-68; and "Note respecting the undulatory theory of heat, and on the circular polarization of heat by total reflection", *Philosophical Magazine*, third series, 7(1836), 246-9.

[135] Brush, "Wave theory", p.163.

[136] See *The Edinburgh academic annual for MDCCCXL, consisting of contributions in literature and science by alumni of the University of Edinburgh* (Adam and Charles Black: Edinburgh, 1840), pp.48-65. Internal evidence suggests that the volume was prepared between late 1839 and early 1840. This work was traced by Keith Hutchison.

Forbes himself (on molluscs), George Wilson (on haloid salts), and John Lee, who provided a lengthy historical sketch of the University by way of introduction.[137] The comparative obscurity of this publication does perhaps explain its neglect by historians.[138] The existence of Rankine's paper, however, emphatically explodes the mythical image of an engineer who turned to natural philosophy late in a dilettantish fashion.[139] It strengthens the far more plausible hypothesis of sustained interest in scientific subjects of contemporary concern throughout the 1840s, very probably pre-dating attendance at Forbes's class. My discussion links Rankine's early work closely to a "literary and philosophical" club-joining and publication-promoting culture, the teaching at Edinburgh, and more generally to current subjects of scientific debate in the early 1840s. Further, it shows him making a bid for recognition and acceptance within local academic and, more broadly, contemporary scientific communities.

Rankine stated two primary aims: firstly, to establish the "general differential equation of the motion of heat in solid bodies"; and secondly, having done so, to carry out "the integration of that equation in the case of an homogeneous sphere, which has arrived at a permanent state of temperature, and the application of the formulae thus obtained to an approximative determination of the law of distribution of temperature, which the hypothesis of primitive fluidity assigns to the interior of the earth". He drew upon the work of a broad sample of scientific

---

[137] Edward Forbes (1815-54), *DNB*, prominent, if somewhat eccentric, member of the British Association, and founder of its "Red Lion" club, or which Rankine became a leading member; George Wilson (1818-59), *DNB*, had entered the University in 1832 and in 1855 became its first (and only) professor of technology at Edinburgh University. Lee was Principal of the University from 1840 to 1859. See Horn, *University of Edinburgh*, p.103. Lee's sketch was reissued as *The University of Edinburgh From its Foundation in 1583 to the Year 1839: A Historical Sketch* (David Douglas: Edinburgh, 1884).

[138] Keith Hutchison mentions it (without discussion) in his "Rise of thermodynamics".

[139] Richard Olson asserts more mildly that between 1838 and 1848 "Rankine turned most of his attention to his work as a civil engineer". Olson, *Scottish philosophy and British physics*, p.272.

authorities, almost exclusively French (Fourier, Poisson, Laplace, Dulong and Petit, and Arago: the unremarkable exception was Newton) but showed himself indebted to a far richer intellectual and methodological network.

The validity of Fourier's fundamental equation of heat conduction was under question. The investigations of Fourier, Laplace, and Poisson into the temperature distribution of a homogeneous solid sphere had all been based on Newton's law of cooling, which asserted that

> the velocity of the emission of heat from the surface of a body is proportional to the excess of its temperature above that of the surrounding medium...[140]

However, as long ago as 1813,

> The experimental researches of MM. Dulong and Petit...have proved that the true form of the function [of temperature, u, giving velocity of emission] f.u is $e^{m \cdot u} + C$...The law of Newton has thus been shown to be only an approximation.[141]

In drawing attention to the work of these two authors Rankine was following, most immediately, Forbes and Kelland. Forbes dealt specifically with Dulong and Petit's law of cooling alongside Newton's in his lectures which, in 1833-4, immediately went on to speculate "as to the original form and Temperature of the Globe" and "Their bearing upon Geological facts".[142] In 1837, while Rankine was still studying, Kelland had published his *Theory of Heat* which, in Laplacian style, emphasized the search for a reduction of physical phenomena to inverse square forces. Links existing between Forbes and Kelland made this likely recommended reading for students in the natural philosophy class.[143]

Rankine's paper of 1840 echoed the doubt expressed by Kelland concerning Fourier's use of Newton's law of cooling, rather than that of Dulong and Petit. In a paper presented to the British Association in

---

[140] Rankine, "Conduction", p.49.

[141] Ibid., p.56. Notation slightly altered.

[142] *Edinburgh Almanack* , p.35.

[143] Kelland made significant and, it transpired, hasty criticisms of Fourier's techniques (particularly regarding the use of certain infinite series) which prompted a defensive response from the young William Thomson. See Smith, "Mechanical Philosophy", p.28; Smith and Wise, *Energy and Empire* , pp.166-8.

September 1840 at Glasgow, Kelland strongly reiterated this particular criticism, pointing out, however, the "total inadequacy" of "our experimental knowledge of the transmission of heat...to serve as the test of any precise and accurate theory".[144] Almost a year earlier, before the publication of Rankine's paper, Kelland had raised this issue at a meeting of the Royal Society of Edinburgh.[145]

Kelland appears almost certainly to have been the source of this idea within Rankine's paper. In a report on heat conduction presented to the BAAS in 1841 he asserted that the law of cooling of Dulong and Petit, based on the air-thermometer temperature scale, itself dependent on Dulong and Petit's more famous law of the dilatation of gases, was the correct form "so far as we can see at present".[146] Kelland was particularly critical of Poisson for his initial failure to take into account the new law of cooling, and even then, having remedied this defect in his *Théorie Mathématique de la Chaleur* of 1835, for producing little more than "a display of analytical artifice". It was Poisson's result from this work, based on the assumption that both the internal and external transmission of heat followed the law of cooling of Dulong and Petit, that Rankine, consciously or not, had replicated:

> We have only to add, that M. Poisson's equation has been deduced by Mr. Rankine in the 'Edinburgh Academic Annual,' and applied to the determination of the temperature of a heated globe.[147]

In guiding Forbes in the early 1830s, Whewell laid emphasis on the works of Poisson dealing with heat: these works were an available resource for Rankine, a member of the next intellectual generation. But Rankine believed that Poisson had not adequately applied the new law of cooling to the case of a solid sphere.

---

[144] "On the Conduction of Heat", *BAAS Report*, 10(1840), part 2, 15-16; see also Crosbie Smith, *The Science of Energy* (Forthcoming).

[145] See the *Proceedings of the Royal Society of Edinburgh* for 16 December 1839, p.279.

[146] "On the Present State of our Theoretical and Experimental Knowledge of the Laws of Conduction of Heat", *BAAS Report*, 11(1841), part 1, 1-25. Kelland drew attention to the confused state of theories and the lack of experimental data.

[147] Ibid., p.9.

By making this reference Kelland placed Rankine on the same stage as Poisson and Fourier, albeit in a minor role. In that sense, through the British Association, Rankine had indeed achieved national recognition. But Kelland's description of the "application" made by Rankine "to a heated globe" was a little dismissive. In fact the paper addressed two major contentious geological issues of the day: the hypothesis of the earth's central heat; and the hypothesis of the earth's primitive fluidity or nebulosity, stemming most immediately perhaps from Glasgow professor of practical astronomy J.P. Nichol's nebular hypothesis, and more distantly from Laplace.[148]

In the early 1820s Fourier had analyzed the cooling of the earth assuming it to have had an original or primitive central store of heat. William Whewell had later praised Fourier in his 1835 Report to the British Association. But both Poisson and Lyell criticized this notion of primitive central heat: most importantly for the latter, it seemed to challenge Lyell's steady-state, or uniformitarian (and therefore essentially anti-progressionist) theory of the Earth's geological change.[149] More recently, such geological questions had been a concern of James David Forbes working within the British Association for the Advancement of Science. At the 1836 meeting a committee including Forbes and John Phillips reported on experiments on subterranean temperatures which provide empirical data relevant to this issue.[150] Nichol was largely responsible for popularizing the nebular hypothesis in Britain as a model of progressive development in the heavens and in human society,

---

[148] For an overview of the competing theories see Stephen G. Brush, "Nineteenth-Century Debates about the Inside of the Earth: Solid, Liquid or Gas?", *Annals of Science*, 36(1979), 225-54.

[149] See, for example, Smith and Wise, *Energy and Empire*, pp.192-5.

[150] Crosbie Smith, "William Hopkins and the shaping of Dynamical Geology: 1830-1860", *British Journal for the History of Science*, 22(1989), 27-52. Phillips (1800-74) was the active, long-serving, and increasingly academically-eminent Assistant Secretary of the British Association. See Morrell and Thackray, *Gentlemen of science*, particularly pp.537-8; and *DNB*. Phillips was later a sponsor for Rankine's election to the Royal Society of London.

particularly through his *Views of the Architecture of the Heavens* which was published in Edinburgh while Rankine was a student in 1837.[151]

The main thrust of the paper, then, was to find the "true" law of conduction and the "true" distribution of temperature throughout the earth, on the contemporary hypotheses of primitive fluidity and central heat. This comparatively easy "application" of a scientific "law", written in the language of mathematics, to a practical problem was coherent with the Whewellian ethic of mixed mathematics adopted gladly by Forbes, and partially at odds with what Kelland, at least, by 1841 described as "theoretical writers... [such as Poisson who] have not presented their results in a form sufficiently tangible to direct or suggest the application of experiment to them."[152]

Taking Newton's law with the hypothesis of primitive fluidity implied (via a solution in the form of a sum of exponential functions in the style of Fourier) that most of the Earth's bulk was a fluid nucleus; that there was a relatively thin crust; and that the mean temperature was enormous in comparison to that of the surface. For the geologist in favour of the hypothesis this added substance to the contention that geological change came about through volcanic action, the belief of the geological "Vulcanists". For those against the hypothesis, these conclusions, and in particular the great temperature difference constituted a serious objection.[153] The positive view had been ably promoted by Gustav Bischof in a series of papers published in Jameson's *Edinburgh New Philosophical Journal* between 1836 and 1839; the objection had been made by Poisson's recent *Théorie Mathématique de la Chaleur*.[154]

On the basis of Dulong and Petit, Rankine had derived a non-linear differential equation which was therefore less tractable than Fourier's.

---

[151] Simon Schaffer, "The nebular hypothesis and the science of progress", in James R. Moore (ed.), *History, Humanity and Evolution* (Cambridge University Press: Cambridge, 1989), 131-64.

[152] Kelland, "Knowledge of Conduction", p.24.

[153] Rankine, "Conduction", p.60.

[154] Brush, "Inside the Earth", pp.228 and 230.

However, he succeeded in obtaining a solution for the special case of the Earth considered as a homogeneous sphere undergoing no sensible change in temperature with time (Kelland's "heated globe"). From this, the law of Dulong and Petit plus primitive fluidity or nebulosity implied that "no appreciable portion of the earth retains its original liquid form" and the excess of the mean to the surface temperature was about 1/160 of that calculated in the first method.[155] Since these conclusions argued against the Vulcanists' position, Rankine could be seen as aligning himself with the opposing camp of "Neptunists" and hence with Jameson. Although not explicitly stated, Rankine's deductions appeared to resolve two principal objections to the doctrines of central heat and primitive fluidity, or nebulosity of the earth,, favoured by Williams Hopkins (the Cambridge wrangler-maker and geologist) and Whewell. The first of these was Poisson's; the second related to astronomical considerations which strongly suggested that the earth moved in the heavens as if it were solid, or almost completely so, as Rankine's calculations suggested. Apparent success within this framework must have added plausibility to the validity of his general equation for heat conduction.

On this issue, then, Rankine can be tentatively placed within this Cambridge camp. But curiously he made no explicit statement in this paper regarding his personal alignment to the progressive views which tended to be championed by such "centralists". Indeed, his second calculation, according to the law of Dulong and Petit had been contingent upon the assumption that

> the solid [under consideration] is supposed to have arrived sensibly at a state of equilibrium of temperature, which is certainly the case with respect to the earth.[156]

Methodologically, the paper is interesting too. Although the work of a young writer, we can interpret Rankine's statements here as accurately representing his methodological views, particularly in light of his second

---

[155] Rankine, "Conduction", p.64.
[156] Ibid., p.56.

prize-winning essay for Forbes. The self-conscious and critical references to specific hypotheses (of central heat and primitive fluidity or nebulosity) and the avoidance of hypotheses perceived to be unnecessary for the development of the scientific argument (as to the nature of heat) itself fall within the traditions of Scottish Common Sense philosophy. To obtain the general differential equation for conduction, Rankine's analysis was based on the radiation of heat from "particles" (of an unspecified nature) through an element of surface. A shift of language part way through his argument made possible the introduction of "molecules", and the "flow of heat through faces" of rectangular volume elements (arguing in the style of Fourier), to arrive at a general equation. The analysis depended ultimately on the assumed macroscopic properties of the radiation of heat, which demonstrated Rankine's indebtedness to the experimental work of Forbes; but Rankine provided no explicit hypothesis as to the nature of the "motion of heat", or its cause. Unlike Kelland, who suggested that heat was transmitted by caloric particles forming the atmosphere of atoms, Rankine was conspicuously non-hypothetical in his discussion of the transmission of heat, and made no reference to the existence (or otherwise) of "caloric". His later writings show a pointed antipathy to the caloric theory (chapters 5 and 7).

More strikingly, the central questions of exactness and approximation, and the relation of these to perceptions of scientific truth, were continually stressed. Rankine compared the "approximate law...assumed by Newton, with those of the exact law [of Dulong and Petit]".[157] The experimentally-exact law gave the "true form" of the velocity of emission of heat: Newton's law, being only experimentally approximate, was but an approximation to the truth. By using "the exact...law of radiation" it was possible to get "more near approximation

---

[157] Ibid., p.28.

to the true solution" for the temperature distribution of the earth.[158] This ethic of accurate quantification as the basis of humanly-knowable truth became increasingly dominant in British scientific culture through the nineteenth century. Most conspicuously, and more specifically, it had been advocated by John Herschel[159] in his *Preliminary Discourse* which it seems likely that Rankine had read. Through Whewell and most immediately through Forbes this culture of precision was likely to have permeated the scientific experience of the young Rankine, directing the role of measurement in his early papers and informing his attitude towards experimental evidence within a personally constructed and widely marketed "engineering science" (chapters 7 and 8).

Combining these, the paper strove to test and support geological (and cosmological) hypotheses by incorporating and generating accurate data using the powerful tools of analytical mathematics. Rankine had begun his paper with the assertion that "the geological hypothesis of central heat" led to consequences regarding the internal temperature of the Earth which "have never been rigidly determined by mathematical analysis".[160] Immediately he placed himself within the Cambridge analytical tradition. This beginning of an attempt to mathematize one aspect of geological research was concurrent with a similar movement in Cambridge led by William Hopkins.[161]

In concluding this discussion, I will mention two further related issues. Firstly, it was crucial to have access to reliably accurate experimental and practical information: in this case Rankine derived a value for the rate of increase of temperature of the Earth with depth from the work of Arago on Artesian wells.[162] But he also drew on eminently practical, not to say industrial, sources to obtain a realistic figure for

---

[158] Ibid., p.50.
[159] Smith, "Dynamical Geology", p.28.
[160] Rankine, "Conduction", p.49.
[161] Smith, "Dynamical Geology". William Hopkins, *DNB*. Crosbie Smith has emphasized the combined contemporary importance of the issues of measurement and mathematization.
[162] Rankine, "Conduction", p.58.

the minimum temperature of the supposed fluid nucleus of the earth: "[The] temperature of a glass furnace is usually estimated at about 10,000 centigrade degrees...".[163] Secondly, in his paper Rankine mapped the temperature distribution throughout the interior of the Earth simply as a function of radial distance from the centre: his graph can be viewed as a highly abstracted geological (or geothermal) section charting a "perfect" world to which the "actual" world was but an approximation.[164] The use of a graphical representation extended what Martin Rudwick has described as an increasingly theory-laden visual language of geological science.[165] But going further, this interplay of data taken from the field with high-powered mathematical analysis to derive general solutions of geographical and terrestrial significance shows an extension of the ideals and practices of charting the Earth exemplified in the British Association's "Magnetic Crusade", the Geological Survey[166] and many other such large scale projects carried out in a spirit of "Humboldtian" science.

We can now delineate the resources for Rankine's early work: the traditional Scottish educational emphasis on philosophical and methodological considerations and the avoidance of unnecessary hypotheses in the style of Common Sense philosophy; a reforming education in natural philosophy from Forbes in a fashion which integrated Scottish traditions, was sympathetic to (if not active in) the academic teaching of engineering, and showed respect for Cambridge "mathematical physics"; current critical interest in theories of heat conduction; knowledge of

---

[163] Ibid., p.60.

[164] Ibid., graph facing p.49.

[165] See Martin J.S. Rudwick, "The emergence of a visual language for geological science 1760-1840", *History of Science* , 14(1976), 149-95, in particular pp.164-72 for geological sections, the development of which was initmately connected with mining engineering. Rudwick describes how, in the period up to 1840, each visual form of communication in geology "developed...towards greater abstraction and formalization, and thereby became able to bear an increasing load of theoretical meaning." See ibid., pp.177-8.

[166] See, for example, H.T. De la Beche, *Report on the geology of Cornwal, Devon and west Somerset* (London, 1839), one of the first products of the Geological Survey; and James A. Secord, "The Geological Survey as a research school, 1839-855", *History of Science* , 24(1986), 223-275.

continental techniques of analysis; and exposure to the expertly-orchestrated activities and ideologies of the British Association for the Advancement of Science. Clearly the complexity of personal, social, cultural, philosophical and institutional interaction suggested here makes it meaningless to attempt to place Rankine squarely within any single educational tradition.

Conversely this diversity of links with the University of Edinburgh and allegiance to the Cambridge mathematical physicists proved immensely useful in achieving acceptance of his scientific work, and in gaining initial access to the Royal Society of Edinburgh, the British Association for the Advancement of Science, and finally the Royal Society of London. In numerous ways Rankine's elevation to the Glasgow chair of engineering was facilitated by this strong institutional and social base (chapter 7). But before this came over a decade of experience in the world of practical engineering which enabled Rankine to develop a new and complementary repertoire of supportive social networks. Joining national societies and using them for extensive publication established his reputation as an innovative railway engineer and promoted his social integration within the elite of these practical communities.

CHAPTER THREE

Railway networks: styling the civil engineer

Introduction

From early adulthood Rankine was immersed in a culture of British civil engineering in an era of intensive railway construction. The years of "railway mania", often localized by historians to the two periods of 1836-7 and 1844-8, saw the total length of track in the United Kingdom soar to 5000 miles, with the second of these railway booms stimulating an economic recovery from the recession of the late 1830s.[1] Embedded within this culture and informed by it, Rankine conformed to the norms of a distinctive segment of early-Victorian society and successfully exploited its institutional mechanisms through a network of colleagues and acquaintances to further his career aims. In this section I concentrate on three interconnected themes: the dominating influence of exemplary individuals (David Rankine and John Macneill); the motivation and rewards for literary- and self-publication; and organized societies as platforms for publication, media of self-aggrandizement, and forums of discussion and dissemination. By a careful analysis of Rankine's early engineering publications I will trace the development of a methodology of engineering, and attempt to assess its relevance, impact, and implications both personal and professional. Elements of this methodology were incorporated in Rankine's engineering science.

---

[1] See, for example, Garth Watson, *The Civils: The story of the Institution of Civil Engineers* (Thomas Telford: London, 1988), pp.132-3; J.F.C. Harrison, *The early Victorians 1832-51* (Panther/Granada: St Albans, 1973), p.34. An excellent and substantial guide to the enormous railway literature is George Ottley, *A bibliography of British railway history* (2nd edition, HMSO: London, 1983). For an examination of the extensive Scottish railway network from the point of view of an economic historian see C.J.A. Robertson, *The Origins of the Scottish Railway System 1722-1844* (John Donald: Edinburgh, 1983).

David Rankine and the cogency of comparison

After completing his second Edinburgh session in 1838, without graduating, Rankine left Scotland for Ireland to begin an apprenticeship, the "traditional" (i.e. socially acceptable, standard, and valued) form of education in civil and mechanical engineering. The choice of career was understandable, if only as a consequence of the social position and financial state of his parents. A later commentator explained that "the circumstances of the family made it necessary for him to adopt some profession that would give a not too remote prospect of a livelihood".[2] Beyond this, amongst the professions at this time, both ancient and modern, "none was more in vogue, or apparently more promising of abundant employment, than that of a civil engineer."[3] Clearly in leaving Edinburgh after two years having attended only a limited number of courses, all scientific in content, Macquorn was unprepared for the ancient professions for which the University itself offered more than preliminary instruction: the clergy, the law, and medicine.

Through his father, on the other hand, he had easy access to and ample experience of the world of practical engineering. In 1837-8, presumably during the long university vacations, they worked together on the Leith branch of the Edinburgh and Dalkeith Railway,[4] where David Rankine held the managerial position of superintendent.[5] The main line of this busy coal and passenger-carrying railway had opened late in 1831, while the final completion of its four mile extension to the sea-port of

---

[2] Archibald Barr, "W.J. Macquorn Rankine, a Centenary Address", *Proceedings of the Royal Philosophical Society of Glasgow*, 51(1920-2), 167-87, on p.171.

[3] Lewis D. B. Gordon, "Obituary Notice of Professor Rankine", *Proceedings of the Royal Society of Edinburgh*, 8(1872-5), 296-306, on p.297.

[4] P.G. Tait, "Memoir [of Rankine]", in W.J. Millar (ed.), *Miscellaneous Scientific Papers by W.J. Macquorn Rankine* (Charles Griffin & Co.: London, 1881), pp.xix-xxxvi, on p.xxi; see also Rankine's Admission Certificate, Institution of Civil Engineers.

[5] Gordon, "Rankine", p.297.

Leith came only in July 1838.[6] From 1837 Macquorn acted as resident engineer (paid, on-site employee of the company, distinguished from and inferior to the independent consultant or consulting engineer) for this short but commercially important Leith branch.[7]

It is worth investigating David Rankine a little further as an important exemplar for his son. A man of intelligence and high standing, working actively as a member of the professional engineering community, he provided further resources to draw upon for Macquorn Rankine's creation of a personal methodology of engineering science. In the early years there is evidence to suggest that David Rankine had a deep influence on the career of his son, acting as an early tutor, an obvious example to follow in the choice of profession, and a model for self-publication and self-promotion. Furthermore he proved a vital contact in Macquorn's first employment and for his first major institutional involvement with the Royal Scottish Society of Arts and the Institution of Civil Engineers.[8]

I will discuss David's *A popular exposition of the effect of forces applied to draught* (1828), published during Macquorn's early childhood. ("Draught" here means simply pulling, or traction.) The book is an example of what we might call engineering pamphleteering, designed to disseminate information, or publicize a particular viewpoint, or to

---

[6] For a near-contemporary description of this railway see pp.95-102 of Francis Wishaw, *The railways of Great Britain and Ireland practically described and illustrated* (2nd edition, John Weale: London, 1842; reprinted edition, David & Charles: Newton Abbot, 1969), dedicated to "The Railway Capitalists of the United Kingdom". By 1842 the railway carried 120,000 tons of coal per annum and about 1,000 passengers daily. It was colloquially known as the "Innocent Railway".

[7] See Rankine's Admission Certificate, Institution of Civil Engineers; and W.J.M. Rankine, "Account of the Effect of the Storm of the 6th of December, 1847, on Four Sea Walls or Bulwarks of Different Forms, on the Coast Near Edinburgh; as Illustrating the Principles of the Construction of Sea Defences", *Minutes of Proceedings of the Institution of Civil Engineers*, 7(1848), 186-204, p.187. For the changing managerial and hierarchical structure of the engineering profession see Watson, *Civils*, p.4; and R.A. Buchanan, *The engineers: a history of the engineering profession in Britain 1750-1914* (Jessica Kingsley: London, 1989), pp.54 and 56.

[8] As a more emotive but less tangible argument, we can adduce Lewis Gordon's recollection that Macquorn was rarely separated from either of his parents throughout his life. See Gordon, "Rankine", p.296.

promote a certain interest in the face of opposition. The need for such expository articles reflected the very public nature of the lobbying and debate required at all levels of society for the successful introduction of new technologies in the railway age (e.g., railways versus canals; steam-carriages versus locomotives; locomotives versus horses) and the choice of appropriate railway and canal routes which might be determined through a complex of technological, economic, social, political, and other factors. Macquorn Rankine developed one of the issues raised by his father in his first engineering publication, the *Experimental Inquiry into the advantages attending the use of Cylindrical Wheels on Railways (1842)*.[9] But I suggest, much more broadly, that David's work exemplified a complex network of ideas concerning the practice of engineering, and a framework for the discussion of such ideas. In addition, the *Popular exposition* exhibited quite explicitly the need for an adept and audience-specific presentation. This network of ideas, its explanatory framework, and a conscious admission of the specific demands of the audience were adopted by Macquorn for development and continuous subsequent modification.

Primarily concerned with railways, David's book argued for the introduction of the new prime movers, locomotive engines ("L.Es.") to replace horses for the "draught" of freight and passenger traffic. With due reference to political economy he was willing to make a bold prophecy:

> I conceive that the scale of operation of locomotive steam engines can only be limited by the amount of population, and degree of productiveness of the district in which they are to become instruments of commercial and general intercourse...I look forward with confidence to a time when these machines will, in such districts, have supplanted, in a great measure, the agency of animals in all the great purposes of communication.[10]

David's prose style was matter-of-fact, and the presentation, as the title suggests, deliberately popular, clothing a personal conviction in the

---

[9] Thus David referred to the "rolling of a cylinder, or cylindrical wheel, over a level surface....[Of] it I shall take further notice when dealing of wheels." *Exposition* , p.7.

[10] David Rankine, *Exposition* , pp.64-5.

guise of impartial information.[11] Popular style did not exclude (and perhaps even required) the naming, at least, of many authoritative continental and British sources: Euler, Parent, Vince, Coulomb, Amonton, and Coulomb (on friction). David Rankine showed most respect, however, for the colliery viewer turned civil engineer Nicholas Wood, a man "of great experience in such matters [i.e. the use of locomotives]",[12] whose substantial observations and many experiments had recently been recorded in *A practical treatise on railroads and interior communication in general, with original experiments and tables of the comparative value of canals and railroads...* (1825).[13] In the early 1840s Wood was to sponsor Macquorn's admission to the Institution of Civil Engineers.

David's work exhibited various potent literary technologies and methodological guidelines. Firstly, practical phenomena (such as frictional resistances) should be dealt with and analysed macroscopically, rather than microscopically: direct observations on the large scale led inductively to valid laws of operation.[14] (An appropriate quotation from Bacon graced the title page.) Secondly, experimental observations on the friction of wheel carriages from real examples removed the doubts of those who saw proof as stemming directly from actual practice.[15] Thus, observational data, in order to convince, should be audience-specific: experiments, even those of Wood, carried out somewhat artificially using an inclined plane to determine the friction of wheel carriages might well be inconclusive for a practical audience, however "conclusive and satisfactory such experiments may be deemed by those to whom subjects of

---

[11] It seems likely that the book was designed to persuade the directors of the Edinburgh and Dalkeith railway to use steam-engines rather than horses. If so it was unsuccessful. By the 1840s the railway was one of the few in Britain that continued to rely on animal power.

[12] David Rankine, *Exposition* , p.14.

[13] The book went through several editions. Nicholas Wood (1795-1865) worked with George Stephenson experimenting with locomotives and was one of the judges at the Rainhill trials in 1829. See John Marshall, *A biographical dictionary of railway engineers* (David & Charles: Newton Abbot, 1978), p.241.

[14] David Rankine, *Exposition* , p.6.

[15] Ibid., p.9.

natural philosophy are familiar."[16] For David, substituting a pulley system attempted to reproduce more closely the familiar practical situation best suited to convince his mainly practical audience.[17] Thirdly, in a moralistic and self-justifying spirit, he warned of the pitfalls of making ill-considered and hasty claims by those wishing to promote any engineering innovation:

> From the extravagant ideas that were at first entertained and promulgated, by some persons, concerning the speed of travelling likely to be attained through the employment of L[ocomotive] E[ngine]s, much discredit has fallen upon these machines.[18]

Unguarded assertions could hold back the progress of ideas, material progress, or even the progress of humanity. The engineer had a duty to make measured and considered statements.

There remained one further essential ingredient to his discourse. David's argument, like Wood's, focused upon a *comparison* between two prime movers (the horse and the "L.E."). *Comparison* contrasted an ideal or theoretical "perfection" with the actual "imperfection" of engineering practice and partially defined the duty of the engineer to make the second approach the first. Roads provided one instance of this goal-orientedness:

> ...such a surface [perfectly smooth and free from all obstacles] cannot exist in nature;...but it is...the business of all road-making to approach it as near as possible.[19]

Without a clear objective standard, *comparison* might be a complex process, especially when attempting to evaluate the relative economic merits of two inherently dissimilar prime movers. To compare horses with each other (any two of which were unlike), and with locomotives, one should therefore consider not the power generated, but the work obtained, or the "effect", not in isolation but incorporating economic factors:

> To exhibit the *comparative* effects of two horses, I would multiply together the power, speed, and time of working of each horse, and divide the product by his weight. Indeed we may, for

---

[16] Ibid.
[17] Ibid., p.10.
[18] Ibid., pp.42-3.
[19] Ibid., p.5.

> the formation of the product divided by his weight, include among the factors any number of known circumstances capable of influencing the profitable effect of horses - such as food consumed, durability, etc.[20]

This arithmetical formulation reduced animal agency to number, enabling the calculation and thus the comparison of the profitability of one animal with respect to another, or to a machine: a simple formula gave the "effect" of a horse, which could then be compared to the "effect" of any other prime mover.[21] The reduction of an engineering reality to quantity, number, and then formula enabled a comparison between unlike objects, most succinctly described as the "formulation" of an engineering problem. This process should not be carried out uncritically, of course. As David wryly remarked, "Formulas are rather apt to make nature bend to their deductions".[22]

A comparison "between the effect of the operation of L.Es. and of horses", led to the conclusion that the performance of one locomotive engine was equal to 60 horses on a railway. But in cost terms, an L.E. equalled three horses:

> We have thus in L.Es., one instance more of the great command of power that is acquired through the agency of steam, and of the superiority of machines when brought into *comparison* with animals.[23]

Finally, David Rankine provided a somewhat ambivalent gloss upon the debate over the uneasy relationship, if such it was, between "theory" and practice":

> It has become a sort of proverb among unthinking persons, that "what does very well in theory, may not do in practice." Now, when theory and experiment are not found fully to correspond, one of two things must be the case; wither, first, that, in the theory, all the circumstances of the subject have not been known and provided for; which just proves that the theory is not the theory of the matter at all: or, secondly, that experiment has not reached to the full extent that the theory did contemplate.

---

[20] Ibid., pp.18-24. Quotation on pp.19-20. Emphasis added.

[21] Effect = T(time).V(speed).P("power") = T(12-T)(224/V), assuming V = 12 - T, for speed (V) in miles per hour, and time of working (T) in hours. The formula attempted to allow for the fact that the longer a horse worked each day, the slower it must be expected to move. For David's "power" we might substitute "force".

[22] David Rankine, *Exposition* , p.23.

[23] Ibid., pp.59-63. My emphasis.

> The latter...is the state of the case in question. Indeed, in as far as experiments on locomotive engines have been carried, the results would appear to have rather exceeded, than otherwise, what the theory holds out.[24]

Pamphleteering; popularization; dissemination; preoccupation with prime movers; the importance of large-scale experiment and practical proof; reduction of laws from macroscopic information; the audience-specificity of scientific or technological argument; the potentially anti-progressive dangers of extravagant statement; the validity of comparison between perfect and imperfect, and between competing prime movers through a consideration of work or "effect" which incorporated sensitivity to economic constraints; a preoccupation with the "theory and practice" issue, and the presentation of that issue: all these ideas were aired within David's text; many reflected the predispositions and demands made by a broad engineering culture.

All resurfaced as essential elements of Macquorn Rankine's rhetoric of engineering science (chapter 7). There, in particular, "energy" was promoted as providing the objective standard against which all machines should be measured and by which they should be compared. All heat engines, Macquorn asserted, displayed their essential characteristic (the work done in each cycle) through what he chose to call "diagrams of energy" (theorized indicator diagrams). Air-engines, when compared in this way, both with actual steam-engines and theoretically idealized "perfect engines", promised to become the dominant prime-mover of the mid-Victorian age. As the steam-engine had replaced the horse for many purposes, so it seemed would the air-engine replace the steam-engine (chapter 5).

---

[24] Ibid.,. p.64.

John Macneill and the railway networks of Scotland and Ireland

In 1838, at the age of eighteen and already with experience of railway engineering, Rankine abandoned the unofficial tutelage of his father to become a pupil of John Benjamin Macneill (1793-1880).[25] This eminent engineer had worked early in his career with Thomas Telford, long-serving first President of the Institution of Civil Engineers and one of the great figures in what we might call the age of the heroic engineer.[26] The influence was profound: Macneill went so far as to name one of his sons "Telford". During the 1820s and early 1830s Macneill worked mainly on turnpike roads in the north of England. Under Telford he gained not only technical expertise, but also the parliamentary skills necessary to the nineteenth-century engineer. At this time such experience was required to guide "enabling bills" for new roads, canals and railways through Parliament.[27]

In 1834 Macneill set up as a consulting engineer, with offices in London and Glasgow. Whilst in Scotland he was responsible for the construction of a number of minor railway lines such as the "Slamannan", in Stirling, which occupied him between 1835 and 1838, during which time Macquorn was himself resident engineer for the Leith Branch Railway. Later, under the Irish Railway Commission, he began to control the surveys of the north of that country where eventually he became the leading railway mania engineer.[28]

The geographical and professional proximity to David Rankine up to and including Macquorn's academic apprenticeship help to explain the choice of Macneill as an engineer deemed worthy to be entrusted with the young man's pupillage. There were other similarities. In 1836 Macneill

---

[25] Gordon, "Rankine", p.297. For biographical details of Macneill I follow *DNB*.

[26] See, for example, L.T.C. Rolt, *Thomas Telford* (Longman: London, 1958). For the Institution of Civil Engineers, see Watson, *Civils*.

[27] This function appears to have dictated the site of the offices of the Institution of Civil Engineers in London.

[28] Robertson, pp.196-7.

had undertaken a series of large-scale experiments in canal-boat traction, investigations complementing Rankine senior's *Popular Exposition* which, as we have seen, was concerned primarily with the newer and faster form of transportation provided by railways. It is even possible to see Macquorn preoccupation with the commercial evaluation of competing prime movers as a further extension of this specific example within a general tradition.

But there were other distinguishing features which made Macneill a particularly happy choice. In 1842, towards the end of Rankine's pupillage, he was appointed first professor of engineering at Trinity College Dublin, having recently been awarded an Honorary LL.D. from that establishment. This chair of engineering, one of the earliest in Britain, was rather hurriedly created by the College itself, rather than the Crown, in response to a rival scheme for a Dublin technical college. Macneill held this post nominally until 1852 when he was succeeded by his assistant Samuel Downing.[29] In practice, the pressure and the lure of his own work as a consulting engineer (in 1843, for example, the completion of the Dublin and Drogheda railway was entrusted to him) meant that by 1846 he had effectively retired (chapter 1). During the second period of railway mania, and at a time of great economic revival, it must have been difficult for a competent engineer to stand idle and watch the fortunes of others being made. At a time when the occupancy of a professorship was more often than not terminated by death, this pattern of appointment followed all too soon by unofficial retirement from the early engineering chairs was common. Lewis Gordon had a similarly erratic academic history (chapter 6).

Although largely self-taught, Macneill had a strong predilection for exact science. As well as being a Fellow of the Royal Societies of London and Edinburgh, he was a member of many other literary and scientific societies whose meetings he attended regularly. At the 1843 meeting of the British Association in Cork he was sufficiently esteemed to be made

---

[29] Buchanan, *Engineers* , p.167.

President of Section G (Mechanical Science). Early connections with one who was wholeheartedly committed to the utilities and spectacle of the BAAS, complementing Forbes's great enthusiasm for this organisation, must have further stimulated Rankine's own interest in an institution which was to provide a major forum for the discussion and presentation of his ideas in years to come, both in Section A (Mathematics and Physics) and Section G (chapter 7). In numerous ways, then, Macneill's activities exemplified a set of attainable and attractive targets which served as an early model for Rankine's career: his interest in publication, promotion of academic engineering, involvement with the BAAS, and intimate acquaintance with both the "practical" and "theoretical" aspects of consulting engineering practice.

For approximately four years Rankine was set to work by Macneill on surveys and schemes for river improvements, water-works, and harbours for Ireland, and on the earlier stages of the Dublin and Drogheda railway, one of the first to be built in Ireland.[30] It is likely that Rankine spent some of his time in Scotland and in Macneill's London office for the parliamentary work of the spring of early summer. These practical skills in particular associated with surveying, projecting water-works, and railway engineering all figured prominently in Rankine's initial period as practising civil engineer. This demonstrates once again the continuity in his career.

He worked in the company of Macneill's many other students. P.G. Tait provided a list of some of the more notable amongst them taken from Rankine's journal (now lost): George Willoughby Hemans, Joseph William Bazalgette, William Richard Le Fanu, Matthew Blackiston, John Moffat, and Jonas S. Stawell.[31] Hemans, the son of a poetess and nephew of the Chief Commissioner of Police, continued to be involved with the Dublin and

---

[30] Gordon, "Rankine", p.297; see also Admission Certificate, Institution of Civil Engineers. The Dublin and Drogheda railway was completed in 1844.

[31] Tait, "Memoir", p.xxi.

Drogheda railway, and other railways in Ireland, but like many of Macneill's protégés speculated on the increased need for metropolitan water supply in the later part of the nineteenth century.[32] Le Fanu, a friend of Hemans, became a pupil in Macneill's Dublin office in 1839 and eventually rose to the prestigious position of Commissioner of Public Works in Ireland.[33] Curiously, Macneill appears to have been a favoured candidate to provide pupillage for the sons of the Glasgow professoriate: James Thomson, brother of William Thomson (later Lord Kelvin) and son of the professor of mathematics, Dr James Thomson, entered Macneill's Dublin office in 1840, but stayed only three weeks because of ill health;[34] and Edward Meikleham, son of the professor of natural philosophy studied with Macneill too.[35] In this incidental way Rankine consolidated his links with the Scottish university elite.

Perhaps the most famous of these students, both contemporaneously and retrospectively, was Bazalgette.[36] He became an articled pupil in 1836, like Rankine working on drainage and reclamation works in the north of Ireland. Having completed his pupillage he set up business in Westminster in 1842 as a consulting engineer concerned primarily with railway work, as

---

[32] G.W. Hemans, *Description of the rails, sleepers and fastenings on the Dublin & Drogheda Railway* (London, 1846); *On the railway system in Ireland, the government aid afforded, and the nature and results of county guarantees* (W. Clowes and Sons: London, 1859); *On the future water supply of London* (London, 1866).

[33] W.R. Le Fanu, *Seventy years of Irish life, being anecdotes and reminiscences* (Edward Arnold: London, 1893), p.132. Rankine maintained contact with Le Fanu, with whom he stayed during the 1857 meeting of the BAAS in Dublin. See Rankine to William Thomson, 21 August 1857, R30, ADD MS 7342 (Kelvin), Cambridge University Library. At this meeting Rankine was awarded an honorary LLD from Trinity College. See Board Minutes of Trinty College Dublin, 2 September 1857, Trinity College Archives.

[34] James Thomson, in Sir Joseph Larmor and James Thomson (eds.), *Collected papers in physics and engineering* (Cambridge University Press: Cambridge, 1912), p.xx. It is possible that he met Rankine during this short time.

[35] Crosbie Smith and M. Norton Wise, *Energy and Empire. A biographical study of Lord Kelvin* (Cambridge University Press: Cambridge, 1989), p.51.

[36] For biographical details see *DNB*; and Denis Smith, "Sir Joseph William Bazalgette (1819-1891): Engineer to the Metropolitan Board of Works", *Transactions of the Newcomen Society* , 58(1986-7), 89-111, in particular pp.89-90 for the years spent with Macneill.

were so many at this time of "manic" expansion; but, again following Macneill, he was frequently engaged in the promotion of drainage and water supply systems, for example in Cambridge and Brighton. Bazalgette's most ambitious projects resulted in the creation of London's drainage and sewage network (between 1855 and 1875) and the construction of the Thames Embankment. His high reputation within the engineering profession was marked by election to the Presidency of the Institution of Civil Engineers in 1884. Thus Rankine's fellow students came to form an influential and supportive network in the engineering community, and more immediately provided a useful pool of potential sponsors for his election to the Institution of Civil Engineers.

Continuing the work begun with his father, Rankine became a highly competent and, more unusually, an innovative railway engineer. In 1841, during the later part of his period of apprenticeship, he invented and practised a method of setting out railway curves by "chaining and angles at the circumference", afterwards appropriately and respectfully dubbed "Rankine's method."[37] At the end of his pupillage he returned to Edinburgh[38] and in 1842, no doubt with growing confidence, he carefully prepared for publication his first somewhat cumbrously entitled engineering work: *An Experimental Inquiry into the advantages attending the use of Cylindrical Wheels on Railways, with an Explanation of the Theory of adapting Curves for those Wheels, and its Application to Practice; and an account of experiments shewing the easy draught and the safety of Carriages with Cylindrical Wheels*.[39] At that time the wheels of railway rolling stock were conical in order that vehicles would be self-aligning and so that the outer wheels would have a larger effective

---

[37] Tait, "Memoir", p.xxi; Gordon, "Rankine", pp.297-8.

[38] In the early part of 1842 Rankine gave his address as Gibraltar House, St Leonard's, Edinburgh. See Admission Certificate, Institution of Civil Engineers.

[39] See also Gordon, "Rankine", p.298.

diameter than the inner.[40]

Beyond any comment on the subject of this memoir, obviously grounded in practical railway experience, there was clearly a further act of highly-motivated self-publication here at an early age, coherent with the pamphleteering culture (exemplified by David Rankine, Nicholas Wood, and John Benjamin Macneill) which I have discussed above. Whereas the heat conduction and geothermal *Edinburgh academic annual* paper has been analyzed within an educational and, more broadly, contemporary scientific context as a bid for recognition within this first community (chapter 2), Rankine's first engineering publication was equally targetted to gain respect within a second (and by no means distinct) community of railway engineers. That it succeeded, at least partially, is shown by Lewis Gordon's recommendation of the work to his students of engineering at Glasgow College (chapter 6).

It is unrealistic, however, and of no purpose, to attempt a rigid separation of these communities: Rankine gratefully acknowledged the influence of his mentor James David Forbes (who was surely a representative of the first community and of the British Association's Section A but was equally sympathetic to "scientific theory" in engineering) by making him the dedicatee of this paper on "cylindrical wheels".[41] The expression "easy draught", with its implicit connotations of engineering economy, indirectly testified to the influence of David Rankine, a railway engineer sympathetic to the application of "theory" to "practice", with whom Macquorn's experiments and deductions were carried out.[42] Practical engineers were very often, in varying degrees and directions, scientifically literate; members of the numerous increasingly professionalized scientific elites were equally often practically

---

[40] Barr, "Centenary Adress", p.172. Cylindrical wheels did not come into use, although, in the opinion of Lewis Gordon, they were an improvement on those of conical from.

[41] See "W.J. Macquorn Rankine", *Engineering*, 15(1873), 13-15, on p.13; and chapter 2.

[42] Gordon, "Rankine", p.298.

knowledgeable.[43] As David Rankine had asserted, a general public unease did seem to exist over exactly how effectively "theory" might be applied to "practice". But there existed no clear-cut compartmentalization. Functional hierarchies could be created, such as that existing between Sections A (Mathematics and Physics) and G (Mechanical Science) within the British Association.[44] A rhetorically useful distinction was there to be made, and if adequately refined and suitably presented, this distinction could lead to personally beneficial and concrete results. Even the title of this early opus boldly presented "*an Explanation of...Theory*" and its "*Application to Practice*". This theory and practice dichotomy, and the promotion of *harmony* between the two would become for Rankine a major and explicit preoccupation (chapters 7 and 8).

Societies and self-promotion

Throughout his career Rankine expertly developed an extensive involvement with diverse scientific and engineering societies, both for the purpose of career advancement and for the publication and dissemination of his ideas. We have seen already Rankine's tangential affiliation to Edward Forbes's "Edinburgh University Club". After completing his pupillage a pattern appeared of speedy elevation on to this institutional stage. The first such organization was the Royal Scottish Society of Arts (founded in 1821) which had obtained its Royal Charter, and thus an enhanced prestige within the family of such organizations, as recently as 1841. By this time there was a strong membership of over 400: the ubiquitous James David Forbes was

---

[43] See, for example, R.A. Buchanan, "The rise of scientific engineering in Britain", *British Journal for the History of Science*, 18(1985), 218-33, on p.219. Members of both might self-consciously place themselves within differing audience-specific experimental traditions, the validity of their experiments, as David Rankine had pointed out, depending upon the preconceptions of their audiences, and the function of the experiments carried out: for example, compare Forbes (on the polarization of heat) with Wood and Rankine(s) (on railways).

[44] Jack Morrell and Arnold Thackray, *Gentlemen of science. Early years of the British Association for the Advancement of Science* (Oxford University Press: Oxford, 1981), pp.256-66.

one who played a consistently active role. David Rankine had joined as an ordinary fellow during the society's 1840-1 session and Macquorn was admitted, with the same status, on 12 December 1842.[45] He quickly demonstrated commitment to the society - and to making his own work better known - by making a donation to the library of his *Experimental Inquiry into the advantages...of Cylindrical Wheels*.[46]

The Royal Scottish Society of Arts was certainly ambitious in its ostensible utopian aims of rapid knowledge diffusion and the promotion of valuable social harmonization:

> The principal objects of its founders were, to stimulate and reward genius and mechanical industry, and to afford a ready and useful medium of intercourse among men of all ranks, who were engaged either in the pursuits of science or in the various practical departments of the Arts and Manufactures. By means of such an Institution, it was conceived that publicity could be given to discoveries and inventions with the least possible delay, - that while, by public discussion, error and empiricism would be exposed, correct principles and talent would, on the other hand, be evolved, and duly appreciated, - and that, Science and Art being thus united, results would be produced of the utmost importance both to individual enterprise and public utility.[47]

This beginning of what we might call Rankine's institutional development took place in a broad-based public society, professedly interested in the publication and dissemination of useful knowledge, the eradication of established error, and the promotion of progress stemming from a unity between science and art. In practice it may have functioned, like many such societies, as a useful platform for the publication of safely-patented, or, alternatively, unpatentable devices. Liberal doses of rhetoric may well have been required to make such openness palatable in a context of fear of premature revelation of patentable knowledge.[48]

---

[45] See p.7 of "List of Members", bound at the end of *Transactions of the Royal Scottish Society of Arts*, 1(1841); and *Proceedings*, p.37, bound at the end of *Transaction of the Royal Scottish Society of Arts*, 2(1843).

[46] *Proceedings*, p.40, bound at the end of *Transaction of the Royal Scottish Society of Arts*, 2(1843). The donation was made on 23 December 1842.

[47] *Transactions of the Royal Scottish Society of Arts*, 1(1841), p.iii.

[48] See for example the reaction of James Watt II to the violation of an industrialist's coveted privacy in the face of potential industrial espionage: Morrell and Thackray, *Gentlemen of science*, p.264.

This was a society numbering among its members many already known to Rankine, including colleagues, former teachers, and relatives. All these ideas will figure prominently in what follows: it will become clear how immensely important Rankine's skilful role within such societies and his exploitation of the opportunities offered him by their existence were to be in promoting and popularizing academic engineering and "engineering science" as the product of a *harmony* between theory and practice.

In 1843 Rankine applied for admission to the London-based Institution of Civil Engineers, before the foundation of the Institution of Mechanical Engineers in 1847 the only national engineering society. Examining the membership classes which existed at this time makes it possible to evaluate the significance of the Associate Membership (rather than full Membership) deemed appropriate for him.[49] It was standard practice for the class to be decided by the current Council,[50] but admission criteria varied substantially during the early years of the Institution from its foundation in 1818. By 1837 there were four tolerably strict categories: Members, who must be over 25 and have at least five years' experience as practising engineers; Honorary Members, who were not engineers but were eminent in science; Associates, who again were not engineers by profession but either pursued recognized branches of engineering (as defined in Tredgold's often-quoted Charter of 1828), or, less specifically, were judged to be qualified to contribute to the advancement of "mechanical science"; and finally Graduates: those undergoing a course of study to become professional civil engineers.[51]

Relatively easy access meant that in practice the Graduate class was

---

[49] The relevance of this will become apparent in light of Rankine's failure to become a full Member and his resignation in 1857 at the time as the founding of the Institution of Engineers in Scotland, of which he was the first President. See chapter 8.

[50] Watson, *Civils*, p.114.

[51] For details see ibid., pp.111-15.

popular and soon became disproportionately large.[52] In an attempt to remedy this situation, more stringent entrance requirements were introduced in 1840 calling for the presentation to the Institution of original papers and plans, placing restrictions on age, and specifying the number of years spent in pupillage. (The last criterion both recognized and reinforced the traditional form of an engineering education undertaken in practice.) Consequently, from about 1843 (the year of Rankine's admittance) the Graduate class declined in numbers and the old policy of admitting young engineers to Associate Membership was resumed.[53] The practically convenient but anomalous nature of this "catch-all" class persisted for many years.[54]

Rankine's admission as Associate comes as no surprise. In 1843 he lacked sufficient experience to pass straight into the class of Members. Since his pupillage was practically complete, and bearing in mind the comparative severity of Graduate entrance requirements, membership of this class was both less attractive and less appropriate. Thus on 7 March 1843, in the ample company of eight others, Rankine made his application as Associate Member of the Institution of Civil Engineers. Serendipitously, on the same date, Prince Albert was elected as Honorary Member. For him the usual formalities were waived.[55]

John Macneill was closely connected with the Institution, most notably through his links with Telford, the first President. After Telford's death, Macneill had been thought sufficiently responsible and in tune with the Institution's oligarchy to be trusted to make suitable abstracts from the ex-President's biography for the first volume of the Institution's *Transactions*, published in 1836. In the same year he had been proposed, unsuccessfully as it turned out, alongside Marc Brunel

---

[52] For example, Rankine's fellow pupil Bazalgette became a Graduate Member in March 1838, on the recommendation of Macneill. See Smith, "Bazalgette", p.89.

[53] Watson, *Civils*, p.117.

[54] Ibid., p.122.

[55] Ibid., pp.118-9.

(with whom Lewis Gordon studied), as one of four Vice-Presidents.[56]

Close to the centre of the Institution's power-base and one of the elite of the engineering community, Macneill proved an eminent and respected sponsor. He proposed Rankine for membership on 7 February 1843, a ballot took place one month later and the application was finally passed by Council at a general meeting on 7 July. Accompanying Macneill, James Thomson, G.W. Hemans, Jonas Stawell, James Smith, John Edward Jones, Thomas Grainger and Nicholas Wood supported the application.[57] Thomson, Hemans and Stawell had been fellow students in Macneill's office. Jones had also trained in Dublin as a civil engineer but settled in London where he worked highly successfully as a sculptor.[58] Of the other signatories, Smith, an alumnus of Glasgow University, was known primarily as an inventive agricultural engineer, but between about 1842 and 1844, the beginning of the second period of "railway mania", he too was employed in the examination and valuation of land for newly projected railway routes.[59] Nicholas Wood we have met before: associate of George Stephenson, eminent advocate of railway locomotives in place of horses and stationary engines, and keen enthusiast for academic engineering education,[60] he had been the critically admired model for David Rankine's expository outpourings.

Thomas Grainger was equally distinguished. Born near Edinburgh and educated at the University there, he had initially trained as a surveyor but from the early 1820s became one of the most active railway engineers of his time, executing, in loose partnership with John Miller, many Scottish railway projects including the Edinburgh, Leith and Newhaven

---

[56] Ibid., pp.23 and 138. See also chapter 6 for Gordon's relation to Brunel.

[57] See Rankine's Admission Certificate, Institution of Civil Engineers.

[58] John Edward Jones (1806-62), *DNB*. His sitters included Queen Victoria and the Prince Consort.

[59] James Smith (1789-1850), *DNB*.

[60] Wood helped to examine students of the Durham University engineering course. See Buchanan, *Engineers*, p.166.

railway (adjacent to the Rankines' Edinburgh and Dalkeith).[61] In addition to these close professional links with Rankine, his father, and Macneill (who was in charge of a number of railway lines designed by Grainger in the late 1830s and early 1840s)[62] he was an eminent man on the institutional scene, twice President of that Royal Scottish Society of Arts with which Macquorn Rankine had recently become affiliated. In the early 1830s Grainger was asked to prepare a report on the vexed problem of the water supply of Glasgow which links him still more strongly with both Lewis Gordon and Macquorn Rankine himself (chapters 6 and 7).

Drawing these threads together, Rankine's admission to the Institution came as the combined result of Macneill's influence, support from fellow students in Ireland, and contacts with railway engineers in and around Edinburgh. Rankine was embedded in the culture of this increasingly pervasive transport technology: he responded to and accommodated the demands made by it. For at least another five years he remained a committed member of the railway community, working on major projects which eventually came to form a complex Scottish network, and publishing, through the medium of the Institution of Civil Engineers, and only there, papers relating to his activities. It is possible to sketch his engineering activities during this time.

From 1844-5 Rankine worked under Joseph Locke[63] and J.E. Errington[64] on the Clydesdale Junction Railway project, and then until 1848 he was employed on various schemes promoted by the Caledonian Railway Company.[65] In 1844 David Rankine had become Secretary to the Caledonian, an event which can have been of no disadvantage to Macquorn at this early stage of

---

[61] Thomas Grainger (1794-1852), *DNB*; Marshall, *Railway Engineers*, p.97; Robertson, *Scottish Railway System*, pp.191-5. Grainger and Miller had been named in no less than 37 mania prospectuses, but by the 1840s Grainger's activities and reputation were in clear decline.

[62] Robertson, *Scottish Railway System*, p.197.

[63] Joseph Locke (1805-1860), one of the railway triumvirate. See Marshall, *Railway Engineers*, pp.142-3.

[64] John Edward Errington (1806-62), railway engineer primarily associated with Locke. See ibid., p.74.

[65] Gordon, "Rankine", p.298; Tait, "Memoir", p.xxvii.

his career.[66] Locke and Errington had been appointed engineers to the Caledonian in 1844. The adventurous scheme, many years in gestation, was to create a continuous rail link between Scotland and England.[67] A bitter contest took place over the route: some favoured passing to the west from Carlisle through Kilmarnock, rather than the more direct central option through Beattock which involved steeper gradients. A Caledonian Railway Act authorizing the second route was finally passed in 1845. In 1846 the Caledonian Railway Company acquired the Clydesdale Junction Company, which had commenced construction of a line from Rutherglen to Hamilton to the south-east of Glasgow in 1845. This allowed the Caledonian to approach Glasgow more directly from the south.[68] It was a major project, both commercially and in terms of man-power. At one point during construction it was estimated that no less than 20,000 men were employed. The first main line section running from Carlisle to Beattock opened to public traffic in September 1847. The following February saw the completion of the great West Coast Route from London's Euston Square to Glasgow and Edinburgh.[69]

After this significant watershed, which coincided with the dramatic collapse of the railway mania in 1848, Rankine's commitment to professional railway engineering seems to have dwindled.[70] A close analysis shows that in the later 1840s and early 1850s he remained in

---

[66] See Minutes certified by David Rankine and letters to him in MS. 6355, National Library of Scotland. See also Robertson, *Scottish Railway System*, p.393, in footnote 143 to Chapter 6. This note shows that Archibald Grahame, Rankine's uncle, was also engaged in negotiations concerning the Caledonian.

[67] The complexities of the rival routes and disputes concerning them are fully discussed in Robertson, *Scottish Railway System*, Chapter 5: "The Battle for the Border", on pp.266-304.

[68] *Centenary of the Caledonian Railway 1847-1947* (London Midland and Scottish Railway: Glasgow, 1947), pp.12-14.

[69] Ibid., pp.2 and 15.

[70] Compare this, however, with the speculations of the obituarist for *Engineering*: "we have been informed that Mr. Rankine might have received the appointment of engineer to the Caledonian Railway had he made any effort to secure it...He was destined to have Science as his mistress, and not be at the beck and call of a board of railway directors..." in "W.J. Macquorn Rankine", *Engineering*, 15(1873), 13-15, on p.13.

Scotland to promote a range of projects in other fields of engineering, most notably water-supply and, albeit briefly, telegraphy (chapter 7). Beginning in 1849 his interest in natural philosophy, which had found little overt expression since 1840, again became publicly dominant during a period of intense publication and self-publication associated with a new group of societies representing not engineering communities but Scottish literary, philosophical and commercial elites. But throughout this railway period (1843-8) he had made expert use of his membership of the Institution of Civil Engineers to push forward an attempt at self-determination within the engineering community.

Publication as self-determination

The *Minutes and Proceedings of the Institution of Civil Engineers* , the ICE's major publication, sought to demonstrate the coherence of a professional body of civil engineers, sanctioning through publication appropriate and acceptable ideals, values, and techniques of practice. Through the meetings of the Institution Rankine could both publicize his work, gain admission to broader networks of leading mid-nineteenth century engineers, and achieve self-determination as a member of this community. Incidental information helps to demonstrate Rankine's commitment to the ICE. By the middle of 1846 the growing Institution needed a larger meeting room: plans to enhance the available facilities and nearly double the number of seats required an estimated £3000. Council asked seven guineas from each Member and four from each Associate.[71] Rankine offered a subscription of five pounds to the Building fund. A not inconsiderable sum, greater than that felt necessary, and donated at an early stage in his career, demonstrated allegiance to the Institution; more specifically, allegiance to its role in providing a major popular platform for dissemination of that part of engineering skill which, loosely, could be

---

[71] Watson, *Civils* , p.215.

verbally transmitted; and more specifically still, satisfaction with the opportunities provided by the Institution's public meetings and publications for his own edification, education, self-determination, and self-publication.[72]

He established his position quickly by offering a series of papers on practical engineering topics illustrating and drawing upon the growing experience of railway work undertaken with his father, with Macneill, and later, more independently, with Locke and Errington. Other papers had been presented to the Institution before his election, but these were not published.[73] I will discuss these published papers in the context of his academic tuition and pupillage to show them relying heavily on this practical experience, merged with an informed predisposition for natural philosophy, influenced by and reacting to ambient cultural concerns. It will become apparent that many of the "practical" and "scientific" arguments presented - many aspects of the "literary technology" - were in fact common to papers delivered in varying contexts, precisely as we would expect with a single individual writing over a relatively short period. In many of the early papers David Rankine provided suggestions and guidance.[74] More pragmatically, as manager of the Edinburgh and Dalkeith Railway he could manufacture opportunities and make available the resources for popularly-convincing large-scale practical "experiments"; or he could provide similarly-contextualized practical "data" as the basis for seemingly uncontentious reasoning before a suitably conditioned audience of engineers. But David Rankine was not a member of the Institution of Civil Engineers, and published nothing in the *Minutes of*

---

[72] Letter from Rankine to Charles Manby, salaried Secretary of the Institution from 1839 to 1859, 9 September 1846, addressed 5 North Charlotte Street, Edinburgh, Acc. No. 68232, Autograph Letters Collection, Wellcome Institute for the History of Medicine, London.

[73] Thus his entrance certificate referred to "a number of original contributions" having already been made. See also *Engineering* , "Rankine", p.13, column b.

[74] Tait, "Memoir", pp.xxi-xxii. The paper on axles, to be discussed, was particularly strongly influenced by David Rankine.

Proceedings. Quite possibly professional commitments, and (before trans-border railways such as the Caledonian) the forty hour journey to London made membership for David an unattractive proposition. In these early years of collaboration, the son acted as an ambassador for their joint work, a disseminator and propagator of a locally engendered but nationally serviceable methodology of "engineering science".

"On the causes of the unexpected breakage of the Journals of Railway Axles" had a good reception at its reading on 7 March 1843, the day of Rankine's election to the Institution. An abbreviated version was reproduced in the *Minutes of Proceedings*.[75] Contemporary enthusiasm for this paper, which led to new methods of journal construction,[76] indicates that it is indeed worth analysing as an example of successful engineering rhetoric. More interesting than the ICE version, however, is an original manuscript carrying a variant title with a curative message: "On the Causes of the accidental Breaking of the Journals of originally sound Railway Axles, And on the means of Preventing it by observing the Law of Continuity in their construction. By W.J. Macquorn Rankine. F.R.S.S.A."[77] The author's recent Fellowship of the Royal Scottish Society of Arts added intellectual weight and persuasive capacity to this work.

Although the subject of the paper might seem wholly practical, the treatment exhibited elements of a not merely empirical approach. In parallel with the heat conduction paper, Rankine was particularly

---

[75] For full documentation see bibliography. The "journal" was the part of the shaft or axle resting on the bearings.

[76] Gordon, "Rankine", p.298.

[77] This early version, dated Edinburgh 23 February 1843, with later annotations in Rankine's hand dated 13 February 1855 which add to the impression of sustained contemporary respect for the paper, is in the Henry Dyer Collection, Mitchell Library, Glasgow. Dyer was a member of the Glasgow University civil engineering and mechanics class in the late 1860s who went on to become Principal of the Imperial College of Engineering in Tokyo. See W.H. Brock, "The Japanese connexion: engineering in Tokyo, London, and Glasgow at the end of the nineteenth century", *British Journal for the History of Science*, 14(1981), 227-43. Glasgow University Library (Special Collections) has a typescript of the revised paper with photographic reproductions of the original plates dated February 1843.

sensitive about the use of hypotheses which were characterized as human constructs having at best a secondary and possibly transitory validity, (Such a characterization was somewhat in the style of Stewart, though applied here to engineering rather than natural philosophy (chapter 2).) Previous explanations of the fracture of axles had relied on "nothing but hypotheses", with the "most accepted reason" being that "the fibrous texture of malleable iron gradually assumes a crystallized structure".[78] Inductive arguments based on a careful examination of a number of axles broken whilst in practical use, complemented with a series of coloured illustrations which, as it were, gave the reader the opportunity to make the practical observation for himself, purported to show this hypothesis to be in error. The breaking of the axles, Rankine believed, was due to an abrupt change in the thickness when the journal met the shoulder: iron fibres in both the journal and the main body of the axles would undergo a sudden reduction in elasticity (on entering the main body) which would decrease their "elastic play" and consequently their ability to withstand shocks. This explanation was corroborated by the positioning of the fissures observed at the neck of each journal.[79]

The paper continued with a suggestion for an improvement in the manufacture of axles (they should be made with a large curve in the shoulder), solving the problem of abruptly changing "elastic play". Axles had been manufactured (not merely designed) according to this plan and had performed successfully under full-scale testing, breaking less easily than the common form.[80] Finally, Rankine considered the effect of vibratory motions upon "molecules of the iron": again, it seemed clear that at any place where there existed an abrupt change in the extent of oscillations, "these molecules must necessarily be more easily torn asunder". (We might draw a further parallel here with Rankine's attribution of tangible

---

[78] Rankine, "Axles", p.105.
[79] Ibid., p.106.
[80] Ibid.

macroscopic qualities to "molecules" on a microscopic scale in his heat conduction essay.) In the "improved form of journals", continuity of form would prevent the harmful action of vibratory movement.[81] It is hardly necessary to point out here the value-laden cogency of a rhetoric of practical improvement brought about by a sensitive but irrevocable dismissal of ill-founded hypotheses through the seemingly keen observation of practical fact.

Our view of this paper can be greatly enriched by comparison with the original manuscript. The investigation came as a topical and safety-conscious response to "the most unforseen and serious accidents", and formed only a part of the "attention [which] has been given to that phenomenon, in order to ascertain its cause, and the means of preventing it."[82] Attention to Rankine was thus also guaranteed and as a vehicle for self-publication the topic was manifestly well-chosen. The fashionable crystallization hypothesis - that "which seems most in vogue" - was dismissed as "incapable of positive proof." Refutation was to come simply, and it would seem uncontentiously, from "the *facts* of which I [Rankine] am about to give an account".[83]

The broken axles, which originated from four-wheeled carriages used on the Edinburgh and Dalkeith Railway, had been collected by Rankine, presumably while still working for this company.[84] He had proceeded to make detailed colour drawings of the key sections, and descriptions of the cracks and fissures, just as a natural historian might do in the field. These "factual" descriptions, records of observation carried out in an environment resembling the practical one as closely as possible, served to dismiss the hypothesis of crystallization and provided the basis for a new explanation which Rankine strategically chose not to refer to as "hypothetical".

---

[81] Ibid., p.107.
[82] Manuscript of "Axles", pp.1 and 4.
[83] Ibid., pp.1-2.
[84] Ibid., pp.2 and 4.

Crucial to this explanation was the common attribution to iron of a "fibrous" quality. On this foundation, assertive statements such as "The power of a fibre to resist a shock, is in the compound ratio of its strength and its extensibility" could be made. In similar vein, "when a molecular vibration is propagated from a smaller mass to a larger, the intensity of the vibrations is diminished in the same proportion as the mass is increased."[85] The apparent geometric generality of such statements, coupled with this recourse to a rudimentary "molecular" model inheriting macroscopic qualities (propagation of vibrations), echo the discourse of the heat conduction paper of 1840. The use of this presentational style stems naturally from Rankine's Edinburgh University education and again belies the idea of an abandoned interest in science, or of a late transformation from engineer to man of science.

Rankine enunciated two key principles: "Continuity of the Superficial Fibres" and "Continuity of Form". Further widening his resources for persuasive argument, he remarked:

> In observing those principles in the construction of machinery, we do but follow the example set us by Nature in such structures as the bones of animals, and the stems and boughs of trees, where toughness is combined with strength.[86]

Beyond this common appeal to the paradigm of "Nature", there seemed to lie a subtler message: the very techniques of what was by implication an uncontentious observation of Nature, exploited most obviously in studies of natural history, might well be valuably applied to such man-made objects as machines. Observing machines in their natural (i.e. practical and functional) environment paralleled the informative and beneficial field observations of the natural historian. Further, in the 1850s Rankine used just such an appeal to "Nature" in the guise of beneficent provider of perfect models for the engineer emulate (chapter 7).

Adopting these "principles of continuity", by forging with a hammer rather than turning with a lathe, had already led not just to new designs,

---

[85] Ibid., pp.10-11.
[86] Ibid., pp.11-12.

but to "improved" axles. The final pre-requisite for such improvements was accurate workmanship: this forging "by good workmen was done so accurately, that...little more than one sixteenth of an inch required to be turned off any part of the journal or shoulder."[87] Accuracy was a shared component of the styles of both the groups of natural philosophers with which Rankine had also sought to associate himself (chapter 2), and, more immediately the communities of engineers. Precise agreement of physical experiment with theory seemed to guarantee true understanding of the natural economy. Accurate workmanship, on the other hand, contributed towards practical efficiency, a central goal for the nineteenth-century engineer (chapter 8).

At the following meeting of the Institution on 14 March 1843 Rankine offered two further papers. The guiding principle of accuracy was reiterated in the first, describing a method of "laying down Railway Curves on the ground" which enabled "circular curves" to be "laid down with accuracy at the first operation". Rankine developed this procedure in 1841 towards the end of his apprenticeship, whilst at work on the Dublin and Drogheda Railway. The product of experience, successfully applied to a specific large-scale railway project, "it has been found in practice that the progressively increasing errors of the old method are entirely avoided."[88] The aim was to provide a simple and, most importantly, precise practical method which, with the aid of a theodolite and a modicum of basic geometry, extended the existing techniques for laying out straight lines.[89]

The second paper publicized David Rankine's "Spring Contractor" (a

---

[87] Ibid., p.9.

[88] "Description of a method of laying down Railway Curves on the ground", *Minutes of Proceedings of the Institution of Civil Engineers*, 2(1842-3), 108-11, on p.109. This technique became known as "Rankine's Method".

[89] During the discussion which followed the question of whether in fact the circle was the most appropriate curve in practice was addressed. See Rankine, "Railway Curves", pp.109-11. Archibald Barr described it in 1921 as "still possibly the best procedure available to railway engineers". See Barr, "Centenary Address", p.172.

device for altering the action of the springs of railway carriages to accommodate variable loads), then in use on the carriages of the Edinburgh and Dalkeith Railway, presented as an improvement in engineering design. This description was enriched with the results of "experiments" expressed "in a tabular form", and details of the construction of the "contractors" (not reproduced in the *Minutes of Proceedings*). These devices promoted a series of advantages such as ease of motion and savings on wear of carriages and track; they were inoffensive in appearance and no more expensive than rollers; and most importantly "they produce the strength and stiffness requisite for the maximum load with less weight of metal".[90] This last condition demonstrated how definite statements could be made concerning the specific requirements of engineering design. Since "maximum load" was catered for, price was not increased, and weight was saved, the logic of this descriptive and (as in David's own *Popular Exposition*) comparative language pointed towards Lieutenant Rankine's innovation as not just an alternative invention, but as an "improvement" on the existing devices available.

The remaining paper of this early group was again closely related to Rankine's early railway work and the Scottish engineering context. It consisted of a "Description of a Safety Drag", designed to prevent accidents to trains on inclined planes. This "apparatus", consisting of an ingeniously-shaped metallic "drag" which could stop a heavy or light train according to its position on the track, had been in practical use on the Edinburgh and Dalkeith Railway since 1832.[91] While bearing the stamp of the dissemination of useful practical knowledge, a paper of this kind enabled Rankine to maintain a prominent popular profile by publicizing work in fact more closely related to David Rankine than to himself: it was

---

[90] "Description of Lieutenant D. Rankine's Spring Contractor", *Minutes of Proceedings of the Institution of Civil Engineers* , 2(1842-3), 111-12, on p.112.

[91] See bibliography. Wishaw, *Railways* , pp.100-1, discussed this ingenious "self-acting stopper.

a further opportunity for Rankine's own self-publication. The very fact that this "self-acting stopper" had been in operation so long (since 1832) perhaps indicates again that Rankine felt the Institution's facilities of publication, popularization and dissemination were there to be actively used and exploited for both altruistic and personal ends.

Rankine had targetted his audience of civil engineers well. The first three of these papers, presented at two meetings one week apart, earned him the reward of a "Walker premium of books",[92] and, we may assume, further high-profile self-determination within the engineering community. Various prize systems existed within the Institution. After Telford's death in 1834, part of the bequest he had made to the Institution was set aside to finance the Telford Medals, the first of which were awarded at the end of the 1835 session. These honorary awards in gold, silver and bronze were made for Original Communications delivered at the Institution's meetings.[93] A second prominent figure was responsible for a similar system of prizes: James Walker was first elected to the Presidency in January 1835.[94] Following his re-election as President in 1841 he offered an annual donation of the interest on "£1000 3% Consols", "to be expended on Premiums, additions to the Library or other purposes conducive to the benefit of the Institution." The Walker Premiums were designed to supplement the existing Telford Prizes or Premiums, but they were shortlived prizes, unceremoniously abolished when Walker's term of office as President ended, rather acrimoniously, in January 1845.[95] But this more than incidental association with Rankine continued. Walker was an alumnus of the University of Glasgow and in 1856, during Rankine's first full session as professor of civil engineering and mechanics, Walker Prizes were established for students in

---

[92] See *Minutes and Proceedings of the Institution of Civil Engineers* , 3(1844), p.7; and Hugh B. Sutherland, *Rankine: his life and times* (Institution of Civil Engineers: London, 1973), p.10.

[93] Watson, *Civils* , pp.23 and 136.

[94] Ibid., p.21.

[95] Ibid., pp.25-6, 29-30 and 140.

the class.[96]

I would like to emphasize the connections between this work and the issues which I have presented surrounding David Rankine in particular and the broader community of engineers. Constructing such short papers - engineering pamphleteering - publicized, disseminated, and even popularized engineering techniques, inventions, and even methodologies. The audience may be expected to have influenced, but not pre-determined, both the content and, if distinguishable, the mode of presentation of such contributions. This we might characterize as a qualified audience-specificity of scientific and technological argument. Thus large-scale experiment and practical proof, the reduction of laws from macroscopic information, the validity of comparison and a preoccupation with the "theory and practice" theme in so far as it concerned hypotheses all reflected and responded to the concerns of the audience.

For the engineering community, Rankine's methodology can be made a little more precise. The introduction of hypotheses must be at best self-consciously done, and if possible avoided; a detailed (and if possible pictorial) description of events or objects could be unproblematically taken as an account of facts with the power to eliminate ill-founded hypotheses; the purpose of such activities in engineering was "improvement" of machines and technologies leading to the progressive improvement of society; practical proof, through the consideration of real axles, full-scale experiments, was both part of the "factual" nature of description and of the justification for "improvements".

Accounts of Rankine's scientific method have in general ignored this specific context of engineering experimentation and publication. I wish to stress the utility for Rankine of certain similarities in these scientific and engineering discourses (chapter 2). Both relied upon accurate measurement, although necessarily validated by different

---

[96] See page facing p.1 of Rankine's *The Science of the Engineer* ; Sutherland, p.11; and Watson, p.154 for information on Walker.

experimental contexts. Accuracy within both contexts (the practical or the physical-experimental) stimulated strong notions of observable fact; hypotheses must be used self-consciously and with care; illustrations had their place in either context either as a quietly imperialist chart of the temperature of the Earth, or as a mundane aid to enable a shared practical observation of broken railway axles. Opportunities for dissemination and self-promotion came with similar institutional structures: although the analogy ought not to be taken too far, the rapid publication of scientific papers for the sake of priority was not unlike the intense engineering pamphleteering stimulated by and conforming to a competitive, public, and scheme-promoting railway culture.

Deconstructing the principles of construction

Rankine submitted one further paper to the Institution which appeared in 1848: "An Account of the Effect of the Storm of the 6th of December, 1847, on Four Sea Walls or Bulwarks, of Different Forms, on the Coast near Edinburgh; as Illustrating the Principles of the Construction of Sea Defences."[97] In spite of the title, the paper again reflected on topics germane to railway construction, since of the illustrative examples, taken from the Edinburgh area, that most elaborately described was the sea wall protecting part of the Leith Branch of the Edinburgh and Dalkeith Railway. "Sea Walls" promoted a lively discussion carried on over three evenings which involved amongst others I.K. Brunel, Scott Russell, and ex-president James Walker.[98] G.B. Airy, the Astronomer Royal and Forbes's confidant,

---

[97] *Minutes of Proceedings of the Institution of Civil Engineers*, 7(1848), pp.186-92, with a summary of the ensuing discussion on pp.192-204.

[98] See also *Engineering*, "Rankine", p.13.

had been invited to attend.[99] I will suggest, however, that rather than being a mark of prestige and an indication of Rankine's acceptance by the engineering elite, this lengthy debate shows that by 1848 some of his methodological ideas were the cause of nervous disquiet: his programme was perceived by some as not merely ill-founded but also potentially damaging to the profession. Perhaps significantly, this was the last paper to be presented to the Institution.

Since the paper commenced with deliberately methodological and justificatory statements it is in no way artificial to analyse it in similar terms, especially in light of the strident methodological responses it stimulated. As an attempt to gain official sanction for an engineering methodology it probably failed, but in doing so it generated a discussion which provides an insight into acceptable contemporary presentations of the engineer's mode of working.

The paper focused on a small number of existing sea defences including a section of sea wall running beside the Leith branch of the Edinburgh and Dalkeith Railway, designed by James Walker, as consulting engineer, and built to a slightly modified design in the winter of 1837 while Rankine was resident engineer for this Leith branch. A record of minute practical observation purportedly presented non-theory-laden observable fact. As in earlier papers the literary argument had a visual complement, this time in the form of detailed naturalistic sectional plates showing individual bricks and stones which contributed to the immediacy of observations which could then be shared by readers. The conclusions of a paper addressing similar issues were "to a certain extent verified, by the facts which have come under the author's observation."[100]

---

[99] On 11 March 1848 the the Institution's Secretary, Charles Manby, wrote to Airy inviting him to attend the meeting which was to take place on 14 March at 8 p.m., and hoping that he might be able to take part in the discussion. But the letter did not reach Airy until 15 March: he replied, helpfully suggesting that such invitations be posted earlier. See RGO 6/401/274 Cambridge University Library. Airy's connection with the Institution went back some years: in June 1842 he had been elected as an Honorary Member. See Watson, *Civils*, p.118.

[100] Rankine, "Sea walls", pp.186-7.

Adding and collecting practical facts so uncontentious as to be merely "recorded" supplemented the store of appropriate knowledge residing in the archives and publications of the Institution and thus added to a fund of such data available to a substantial authorized subset of the professional engineering community.

In a manner which remained unarticulated, hitherto uncertain and approximate principles of practical construction could and would be brought closer to an ideal state: "every addition, however small, to the facts recorded respecting the efficiency of such works, must tend to bring the principles of their construction nearer to certainty...".[101] Referring to this progressive and humanly improving approach to a perfection which might not be achievable but was clearly the target of the engineer reiterated statements of David Rankine which I have discussed above. This "pursuit of perfection" was a key factor in the presentation of Rankine's engineering science, particularly through the comparison of inferior "actual" heat-engines (such as the air-engine) to their superior theoretical counterparts (chapters 4,5, 7 and 8).

Further, it was concordant with the ethic of precision in both contemporary scientific and engineering discourses in Britain. Specific audience requirements seemed to dictate that experiment in a validated scientific context should here be replaced by its equivalent, the collection and recording from practical situations of observable fact. The optimum conditions for effective practical observation were detail and accuracy. Thus Rankine excused his descriptions of the sea walls which he had not constructed as being general in form rather than "affording minutely accurate information respecting the details of their construction."[102] For the Leith branch sea wall, however, he provided exact particulars of construction and form, dimensions, materials, the results of changes made during construction due to rough seas (so prompted

---

[101] Ibid., p.187.
[102] Ibid., p.187.

and informed by practical circumstance and observation), and appropriate all-important economic reductions:

> The gross average cost of the wall was somewhat below twelve shillings per cubic yard.[103]

Analogously with descriptions of many practical experiments undertaken contemporaneously in Britain, such information seemed intended to provide a blueprint for replication.

The "ordeal of experiment" under varying or extreme conditions could analogously come about in practice, at the convenience of nature, through the agency of a storm:

> Almost immediately after the completion of this work [on the Leith Branch Railway], the most violent north-east gale occurred which had been known on that part of the coast for twenty years; but the wall, though exposed to the full force of the waves, did not sustain the slightest damage.[104]

Ten years later, the storm of 1847 destroyed almost all sea defences on the neighbouring coast, but the Leith Branch again withstood the test of nature.

This observation of practical fact required further analysis informed by scientific principle to enable any evaluation of the effective functioning of such artefacts as sea walls. The ideal was to use the technique of comparison to generate some measure of efficiency:

> The efficiency of the surface of a wall to resist the action of the waves, obviously depends on...the power with which the moving particles of the water act on the stones and the surface; and...the force with which those stones resist removal. The object to be attained is to render the moving power of the water as small as possible, and the resisting force of the stones as great as possible, relatively to each other.[105]

Implicitly, this efficiency ought to be maximized; and the greater the efficiency, the greater the measured skill of the constructing engineer.

Behind Rankine's exposition lay a thinly veiled foundation of theory. Referring to, but not entering into "the theory of waves, which involves the highest branches of mathematical analysis", he instead chose a more

---

[103] Ibid., p.189.
[104] Ibid.
[105] Ibid., pp.190-1.

amenable and contextually appropriate style of argument depending rather on those properties "sufficiently obvious to daily observation" in order to reach the conclusion that a vertical surface was that on which waves act with least power, and such a surface provided the strongest resisting forces of stones in a wall. Thus a vertical wall must be the most efficient for these purposes.[106]

It was Rankine's hesitant assertion that this methodological presentation could lead to valid conclusions of useful practical applicability:

> The Author has endeavoured, in drawing general conclusions respecting the construction of sea walls, to avoid going beyond the limits warranted by the facts he has stated. His conclusions may be received with caution, or with dissent; but he trusts that the facts will be considered worth recording.[107]

How convincing the conclusions were can be partially judged by the ensuing discussion.

The validity of the comparisons between sea defences came under close and scrutiny. Thus I.K. Brunel:

> With respect to any comparison between vertical and sloping walls for sea defences, he must repeat his objections to drawing general conclusions from one class of evidence, or laying down general rules to suit all cases.[108]

Similarly, for Vice-President Rendel, a distinguished harbour engineer, considering the details of construction of certain sea walls mentioned by Brunel and those which had been discussed by Rankine, both of which he had direct knowledge of:

> In his opinion there could be no comparison between the two cases.[109]

John Scott Russell was still more dismissive, and in confirming Rendel's view he described such comparisons as "uninstructive" and

---

[106] Ibid., p.191.
[107] Ibid., p.192.

[108] Ibid., p.193.
[109] Ibid., p.196.

"insufficient".[110]

Rankine attempted to salvage something from the situation by claiming that he had been misrepresented, and directing his comments particularly to Scott Russell,

> He begged it to be understood, that in giving this description, he had not pretended to lay down universal rules for the construction of breakwaters in deep water, from effects that had been produced upon walls founded on the beach.
>
> He concurred in the principle, that an engineer ought to be guided by circumstances, in designing works; but he conceived that cases sometimes occurred, where the locality permitted the engineer to create such circumstances as he required.[111]

Conceding that there were inherent limitations to the application of his conclusions, and that individual circumstances must always be taken into consideration, he pointed out that the engineer was not rigidly bound by existing practical conditions, but could in fact manipulate his environment in order, it seemed, to create conditions under which previously generated principles became applicable with validity.

But this general program demanded extensive qualification. James Walker, by now ex-President, attempted to state an acceptable compromise between the two extremes of a formulaic abstractive mathematization and the individualist, non-comparative antithesis:

> Mr. Walker agreed, in the impracticability of laying down abstract rules for the forms of construction of sea defences, suitable for all situations, when so much depended upon the local position, the force acting upon them, the direction of that force, and the quality and dimensions of the material of which the defences were constructed. The engineer must, in all cases, after considering the whole of the circumstances, combine his plan in accordance with scientific laws and practical experience, without attempting to fit an empirical formula to all cases, however dissimilar.[112]

Concluding the published summary of the discussion, Walker emphasized that in practice,

> engineers must not expect to apply, successfully, any general rules in all cases; but must act from the dictates of their own reason, and the experience of former works under similar circumstances.[113]

---

[110] Ibid., p.197.
[111] Ibid., p.200.
[112] Ibid., p.202.
[113] Ibid., p.204.

The engineer as individual of sound and trustworthy judgment provided an essential ingredient for any truly successful engineering enterprise Within the confines of the Institution of Civil Engineers in the late 1840s a reductionist abstractive programme of engineering skill bereft of practical experience could not reasonably be entertained.

Firstly it is necessary to point out that there was no simplistic antipathy towards "science" or "theory" by these engineers. Walker in particular stated that the engineer's plans must be in accordance with scientific law. But there was an integration to be made between this and practical experience.

The major problems, I would suggest, were twofold. Firstly, how exactly might the mid-nineteenth-century engineer carry out and justify an inductive process which manufactured from individual practical cases (for example, four similar sea defences) a set of generally applicable principles (the construction of such defences)? Secondly, and of even greater importance to the profession, if such rules could be easily inferred, formulated, codified, and transmitted, how could engineers maintain their privileged status as receptacles of practical knowledge and vehicles for it, holding territorial control over the processes of engineering works and concomitantly wielding individual and collective economic power? I have already referred to the tensions which existed between the desire to disseminate the details of specific beneficial practices and the wish to safeguard commercially valuable industrial secrets. Deskilling the engineer in this way threatened loss of professional status, social prestige, and income. For the consulting engineer in particular individual practical experience distilled as *judgment* was a valuable commodity: great fortunes were made as increasingly the approval of well-known engineering figures became necessary merely for the realistic promotion of ambitious or expensive engineering projects.[114] The authority of the individual was a commodity tenaciously and self-consciously guarded by the nineteenth-century engineer. Marginalizing the value of individual *judgment*, gained through and constructed by a traditionalized regime of practical experience and institutionalized professional accreditation, threatened to re-define the engineer to his detriment.[115]

Rankine presented a problematic glimpse of induction in engineering. Given the apparent pre-requisite of practical observation and experience, it seemed difficult, firstly to reproduce such observations in sufficient number and variety, and secondly to set acceptable but necessary criteria for evaluating descriptive accuracy. The rhetorically coherent strategy of *comparison* would surely benefit from the existence of a suitable standard which could at least be promoted as having the requisite objective status.

I suggest that provisional solutions were offered to create more amenable conditions for such an inductive process. Firstly, in a series of British Association Committees formed in the second half of the century, on which Rankine played a major role, a national effort was made to collect, codify and reduce large amounts of practical data on the construction, propulsion and economy of steam-powered ships. A central preoccupation was the systematic and formalized recording of such data to enable valid comparisons to be made (chapter 8). Secondly, a reductionist thermodynamic approach to heat engines, reliant on the indicator diagram, facilitated the collection of data in a suitably codified form in order to

---

[114] For example, the need for subscribers to large-scale Scottish railway projects from the 1830s could be answered by the production of a positive report from a sufficiently eminent (often English) engineer. Walker himself came into this category. See Robertson, *Scottish Railway System*, pp.332-3.

[115] There is a parallel here, I believe, with the actuarial profession in the same period, as discussed by Ted Porter (preprint not yet for citation). In general the judgment of the individual actuary was defended against the threatened invasion of precision and formulation. I suggest that preserving the sanctity of judgment (in most cases by controlling through education or professional societies the manner in which it might agreed to be attributed) safeguarded the autonomy of any such professional grouping.

induct, abstract, and compare: this inherently met Walker's stipulation that the engineer's work must accord with scientific law. The rising status of the concept of energy in the 1850s provided a useful standard of measurement and objectification against which to measure comparatively work and waste; re-naming the indicator diagram a "diagram of energy" combined the attributes and advantages of both. Finally, by making machines or structures themselves conform more closely to the most-easily-made theoretical calculations (making practice approximate closer to theory) comparative measurements were easier to make. For example, by making the forms of ships more closely related to stream-line surfaces, theory-led estimates of propulsive efficiency could be made.[116]

A vigorous public promotion of such a methodology gave the possibility of creating an autonomous discipline appropriating the intellectual right to infer such generally-applicable and economically-vivacious principles. Individuals inculcated with this specialist academic training were qualified and accredited with a "certificate of proficiency in engineering science" which conscientiously avoided the direct erosion of the engineer's judgment gained through practical experience. This will form a major theme of the chapter treating Rankine's engineering course at the University of Glasgow, which espoused an "engineering science" (chapter 7). A platform and a locally-supportive institutional environment for "engineering science", more so than the London Institution of Civil Engineers, was achieved through the creation of a broad-based geographically-integrated Institution of Engineers and Shipbuilders in Scotland in the late 1850s, situated in Glasgow and established for the promotion of "engineering science and practice" (chapter 8).

Before examining the establishment of academic engineering at Glasgow

---

[116] See, for example, Rankine's "On Steam-line Surfaces", *Journal of the Royal Society of Arts* , 18(1870), pp.544-6. The investigation show how to determine the ratio of the energy of disturbance of water to the enrgy due to the motion of a vessel having steam-line surces.

College and the institutionalization of Rankine's engineering science, in the next two chapters I discuss the panoply of roles assigned within these debates of the 1850s to one class of heat-engine. Annexed to the cause of energy physics; "realized" in an "improved" form by Rankine and James Robert Napier to be presented as the embodiment of a harmony between theory and practice; paraded as the new source of motive power usurping the steam-engine; adduced as evidence for the supremacy of the new theories of heat; and manipulated as propaganda for the re-vitalization of the Glasgow chair of civil engineering and mechanics: all these roles were assigned to the air-engine.

CHAPTER FOUR

The motive power of air

> Mr Stirling is in Town _ I am laying a trail for getting up a substantial Company for the manufacture of the Engine.[Lewis Gordon, April 1847][1]

> The beautiful engine invented by Mr Stirling of Galston, may be considered as an excellent beginning for the air-engine; and it is only necessary to compare this with Newcomen's steam-engine, and consider what Watt has effected, to give rise to the most sanguine anticipations of improvement.[William Thomson, January 1849][2]

> ...neither the air-engine, nor any other will be made to supersede the steam-engine.[James Joule, November 1850][3]

> The more I look into the subject the more I feel that air will supersede steam.[James Joule, April 1851][4]

> ...it is not unlikely that for marine purposes, and in all districts where either fuel or water is scarce, and perhaps also for locomotives [the air-engine] will ultimately supplant the steam-engine altogether.[W.J.Macquorn Rankine, February 1853][5]

Introduction: Napier, Rankine and the air-engine

> In the same year [1853], along with the late J.R. Napier, [Rankine] projected and patented a new form of air-engine. The patent was afterwards abandoned.[6]

Expanding P.G. Tait's rather concise statement, in the following two chapters I seek to demonstrate the central role played by this "new form of air-engine" in the personal construction of Rankine's "engineering science", his promotion of academic engineering at the University of Glasgow, and, consequently, the launching of his academic career. From this analysis it should become clear why a topic which has been at best of

---

[1] Lewis Gordon to William Thomson, 27 April 1847, G118, Kelvin Papers, Cambridge University Library.

[2] William Thomson, "Account of Carnot's theory" (January 1849), reprinted in *Mathematical and physical papers* (6 vols., Cambridge University Press: Cambridge, 1882-1911), 1, 113-55, quotation on pp.149-50.

[3] James Joule to William Thomson, 6 November 1850, J72, Kelvin Papers, Cambridge University Library.

[4] James Joule to William Thomson, 28 April 1851, J80, Kelvin Papers, Cambridge University Library.

[5] W.J.M. Rankine to J.R. Napier, 7 February 1853, DC 90/3/1, Napier Papers, Glasgow University Archives.

[6] P.G. Tait, "Memoir [of Rankine]", in W.J. Millar (ed.), *Miscellaneous Scientific Papers by W.J. Macquorn Rankine* (Charles Griffin & Co.: London, 1881), pp.xix-xxxvi, p.xxii.

marginal interest within the history of power technology, and the history of thermodynamics, merited sustained and protracted investigation in the 1840s and 1850s not from cranks and optimists but from highly competent engineers and well-versed natural philosophers.[7] Napier and Rankine's "improved air-engine" did not ultimately prove to be the technological and commercial success they had imagined. But it cannot be over-emphasized that for a few years at a crucial stage of Rankine's career many seriously believed that air was destined to replace steam as a safer, more readily available, and more efficient working substance for commercially-applicable heat engines. Understandably the connotations of this were economically and socially profound.

A period of fervent interest in the practical "improvement" of the air-engine between 1850 and 1855 coincided with Rankine's emergence on to the public stage of national and provincial scientific societies. This personal and intellectual consolidation culminated in his admission to the professoriate of Glasgow University.[8] A series of papers, systematically marketed if not systematically planned, appearing in respected scientific journals from 1849 and throughout the early 1850s helped to realize Rankine's aspiration to an established position within the British scientific community, exhibited most conspicuously through his Fellowship of the Royal Societies of Edinburgh (1849) and London (1853).[9] The support of influential networks of friends and colleagues, in particular the sponsorship of James David Forbes, William Thomson and G.G. Stokes,

---

[7] See Donald S.L. Cardwell and Richard Hills, "Thermodynamics and Practical Engineering in the Nineteenth Century", *History of Technology*, 1(1976), 1-20, for a caricature of the "prehistory" of the air-engine, with the machine "at the mercy of the amateurs, the cranks, the incompetent, and the incurably optimistic" (p.3).

[8] Rankine became the second regius professor of civil engineering and mechanics at Glasgow in December 1855.

[9] See the first part of my bibliography; election certificate to the Royal Society of Edinburgh (proposed 24 April 1849; passed 30 June) Acc 10000/47 (Royal Society of Edinburgh Archives) National Library of Scotland; Election Certificate, IX.326, Royal Society of London.

had facilitated this elevation.[10] Articles "On the Mechanical Action of Heat", first published in the *Transactions of the Royal Society of Edinburgh*, and later made more widely known through republication in the monthly issues of the *Philosophical Magazine*, gained Rankine the prestigious biennial Keith Prize for 1851-3.[11] The peripatetic British Association for the Advancement of Science provided a more mobile vehicle for self-aggrandizement. A stint in the 1850s as Secretary of Section A (Mathematics and Physics) led to the Presidency of Section G (Mechanical Science) in 1855. Just a few months later a successful academic campaign saw him replace his willing friend and associate Lewis Gordon in the regius chair of civil engineering and mechanics at the University of Glasgow (chapter 7).

In the space of half a decade Rankine appeared to have effected a public transformation from civil engineer, expert in railway construction and large-scale water supply, to Regius Professor in an ancient Scottish University, mathematician and natural philosopher. In the previous two chapters I have shown that in fact any perceived incompatibility between these two images stems largely from the retrospective caricature of both. However, this putative metamorphosis coincided remarkably closely with an active personal interest in the air-engine most often contemporaneously associated with two rather dissimilar historical actors: the Scottish clergyman Robert Stirling and the dynamic engineer-inventor John Ericsson. As the most striking coincidence, Rankine's election to the Royal Society of London, proposed on 23 February 1853 and successfully balloted for on 2 June,[12] was practically

---

[10] Specifically, Forbes had proposed Rankine for election to the Royal Society of Edinburgh.

[11] For a list of prizes awarded by the RSE between 1827 and 1869, see *Transactions of the Royal Society of Edinburgh*, 26(1869-72), pp.vii-viii. See also the letter from Charles Piazzi Smyth to James David Forbes, 26 April 1852 in J.D. Forbes Papers, St Andrews University Library, for negotiations concerning Rankine's award; and Minutes of the Council of the Royal Society of Edinburgh (17 March 1854), Acc 10000/19, Royal Society of Edinburgh Archives, National Library of Scotland.

[12] See Election Certificate, IX.326, Royal Society of London.

coterminous with the crucial months between a formal exploratory approach to James Robert Napier regarding the air-engine (7 February 1853) and the mutual agreement to petition for a British patent on "Improvements in Engines for the Development of Mechanical Power by the Action of Heat on Air and other Elastic Fluids" (1 June 1853).[13]

More generally, this was a time of prolonged and sometimes angry discussion throughout the British engineering community over whether hot air engines might be employed as safer, smaller and more efficient alternatives to existing steam-engines.[14] Such debates focused particularly on the projected benefits of the application of this prime mover to the shipping industry. As we will see, for a few years Ericsson's "caloric engines" (named in a manner less euphonious but, ironically, more theory-laden than Stirling's) did work successfully and efficiently in experimental, practical, and (increasingly) large-scale form. Practical observations therefore existed as a preliminary basis for commercial and theoretical evaluation (chapter 3). But conflicting theoretical interpretations of the functioning of existing machines, especially in relation to the supposed nature of heat, contributed to the success or failure of rival groups during these discussions. Conversely, and perhaps more interestingly, the air-engine played a more than tangential role in shaping the theories of thermodynamics being constructed at just this time. In the late 1840s and early 1850s W.J.M. Rankine, James David Forbes, William Thomson, Lewis Gordon, James Thomson and James Joule all, in varying degrees and with differing emphases, held the theoretical, academic, practical and commercial ramifications of the air-engine in their minds as they worked independently, within close social networks, and through local and national institutions to present a

---

[13] See letters from Rankine to Napier, 7 February and 1 June 1853, DC 90/3/1, Napier Papers, Glasgow University Archives.

[14] Lynwood Bryant, "The Role of Thermodynamics in the Evolution of Heat Engines", *Technology and Culture*, 14(1973), 152-65, which considers these debates of the early 1850s taking place within the Institution of Civil Engineers.

coherent and utilitarian science of heat reconciling Carnot, Clapeyron and a non-material theory of heat.

Rather than view the air-engine, then, as one rather curious but essentially unimportant cul-de-sac of Rankine's life, I hope to show that it provided a significant technological stimulus for his academic and scientific action. More importantly it suggested a model for his public presentation of that action (chapter 7). Examining the socially, historically, theoretically and practically rich context for the air-engine demonstrates how the rationale for this specific technological development and marketing served so well as a prototype for Rankine's engineering science.

An extensive and almost entirely unexplored collection of letters from Macquorn Rankine to Napier,[15] complemented by letters from the former's uncle John Rankine, convenient citizen of the United States (chapter 2),[16] facilitates a deeper analysis of these issues. This manuscript material was not available to Daub for his otherwise useful article on the air-engines of Stirling and Ericsson;[17] Channell appears not to have considered the air-engine in his studies on Rankine and what

---

[15] Letters mainly in DC 90/3/1, Napier Papers, Glasgow University Archives. James Small appears to have had access to a limited number of these letters in the 1950s. See "The Institution's first President: William John Macquorn Rankine", *Transactions of the Institution of Engineers and Shipbuilders in Scotland*, 100(1956-7), 687-97. Keith Hutchison also appears to have located them in the Glasgow University Archives but has made no use of them in his *W.J.M. Rankine and the rise of thermodynamics* (unpublished PhD thesis, Oxford University, 1976) or elsewhere.

[16] Letters from John Rankine to W.J.M. Rankine, Acc. 8660, National Library of Scotland.

[17] Edward E. Daub, "The regenerator principle in the Stirling and Ericsson hot air engines", *British Journal for the History of Science*, 7(1974), 259-77. He credits Rankine as the only one of the early interpreters of the mechanical action of heat to appreciate the "true value" of the regenerator, perhaps because he was acquainted with the "Stirling cycle" (p.259). I attempt to revise some of Daub's analysis in the light of this detailed correspondence with Napier.

he calls, simply, "engineering science";[18] and Hutchison's technically-oriented analyses of Rankine's thermodynamics have not dealt contextually with the Napier and Rankine engine.[19] Cardwell and Hills, touching on the subject of the air-engine, follow Daub and Hutchison: the part played by Rankine in their history is one of discoverer and disseminator of thermodynamical principles, perhaps working with Napier and John Elder in an advisory capacity, rather than as a practical engineer seeking to market new technology.[20] Clearly the opportunity exists for re-evaluation. As a by-product, this contextualization provides a case-study which questions the value of simplistic analyses of technological change, specifically, those which omit the interconnected roles of, for example, publicity, presentational marketing style, local engineering demands, scientific environment and even academic contexts, choosing to portray technology as either independent of "science", or as an "application" of "theory" to "practice".

I begin by sketching a number of contexts vital for an appreciation of the ideological and methodological significance air-engines in general.

---

[18] The main reference is David F. Channell, "The harmony of theory and practice: the engineering science of W.J.M. Rankine", *Technology and Culture* , 23(1982), 39-52. See also my bibliography. This omission underlines the potential deficiencies of a non-contextual historiography. Rankine's "engineering science" and his academic engineering was part of a context of which heat-engines and, albeit temporarily, air-engines were major, visible and active components.

[19] Keith R. Hutchison, "W.J.M. Rankine and the rise of thermodynamics", *British Journal for the History of Science* , 14(1981), 1-26; "Rankine, atomic vortices, and the entropy function", *Archives International d'Histoire des Sciences* , 31(1981), 72-134; and *Rise of thermodynamics* . Hutchison's analysis of the air-engine in the concluding section of his thesis is based on secondary sources and does not incorporate material from the Napier papers.

[20] Cardwell and Hills, "Thermodynamics and Practical Engineering". They state that thermodynamics led to a "dramatic reversal in the comparative states of science and technology. After 1850 science was decisively in the lead."(p.3). Similarly, they do not "deal with the abstruse aspects of Rankine's thermodynamics..[but]...concentrate on the practical consequences" (p.9). I wish to present a more complex picture than this of the interconnections of "science" and "technology", and hope to show that the air-engine (actually their illustration of this changeover from "technology" to "science") can well be seen as "incorporated" or "embodied" within the formulations and presentations of thermodynamics in the early 1850s. Cardwell and Hills also confuse J.R. Napier with both his father, Robert, and his father's cousin David Napier (1791-1869) (pp.10 and 11).

A section on the air-engine in the early nineteenth century serves to demonstrate how closely interwoven practical, theoretical, and economic considerations could be, firstly, in the projection and development of new power technologies; and secondly, in the shaping and presentation of scientific theory. A discussion of the attitudes of Carnot and Clapeyron towards the air-engine leads to a consideration of William and James Thomson, Lewis Gordon, and James David Forbes working in a rather specific geographical context towards a British representation of the air-engine within the new theories of heat. In particular, William Thomson's construction of the "perfect engine" will be seen as a fertile concept through which to schematize the evaluation of "actual" heat-engines. We will see that James Joule offered the "practical machinist" a semi-ideal but, he hoped, practicable air-engine just before the most extended debates began on Ericsson's engine.

Following a consideration of Ericsson's place as a master-publicist, the next chapter builds upon the contexts already sketched to deal specifically with the Napier and Rankine engine. There I examine the use and public portrayal of the air-engine and its economizer by Rankine and analyse some of the links with his formulation of the mechanical action of heat. An important paper on the geometrical representation of the expansive action of heat will be shown to be primarily dependent on considerations of the "economizer" or "regenerator" principle, and the unifying concept of energy. Combined with this, an analysis of Rankine's correspondence with Napier, seen within the context of "air-engine enthusiasm", in chapter 5 illustrates the main themes of chapter 4 outlined above. In conclusion, I discuss a local re-evaluation of the image of the air-engine as this enthusiasm waned, following the very public failure of Ericsson, Rankine, and Napier to capitalize on the vast potential market in shipping for a more economical and safer alternative to the high-pressure marine steam-engine.

Early air-engines: arguments and applications

During the eighteenth century comparatively little commercial interest was shown in the possibilities of the exploitation of air as the working substance in a heat engine. Between 1700 and 1775 about twelve British patents were lodged in connection with such air-engines.[21] Towards the end of the century, by this criterion at least, interest increased, with a further 23 patents filed in the last ten years. In France, Lazare Carnot reported on the air-engine of the Niepce cousins in 1807: they, like so many, had hoped "to discover a physical power equal to that of the steam-engine without consuming so much fuel."[22]

The motives for investigating the potential of air-engines were not restricted to such basic economics. Sir George Cayley, British experimenter in aviation and aristocratic landowning virtuoso, provides an interesting example.[23] Cayley had a very broad range of interests including railway engineering, agriculture, and technical education: in 1839 he helped to found the Regent Street Polytechnic Institution in London.[24] As an active supporter of the York Philosophical Society, he was one of the few amongst the many well-known aristocrats invited to the initial 1831 York Meeting of the British Association for the Advancement of Science who bothered to attend and take part in the proceedings.[25] Cayley had for years been a prolific inventor. In 1807 he described a novel heat-engine which used a cylinder and piston to compress air, and was intended, it seems, not for any fixed industrial purpose but for

---

[21] Donald S.L. Cardwell, *From Watt to Clausius. The rise of thermodynamics in the early industrial age* (Heinemann: London, 1971), p.151.

[22] Ibid., p.152.

[23] Sir George Cayley, 6th Bart., (1773-1857). See J.L. Pritchard, *Sir George Cayley: The Inventor of Aeronautics* (Max Parrish: London, 1962); C.H. Gibbs-Smith, *Sir George Cayley's Aeronautics, 1796-1855* (Science Museum: London, 1962); and Justin Wintle (ed.), *Makers of Nineteenth Century Culture 1800-1914* (Routledge & Keegan Paul: London, 1982), pp.108-9.

[24] J.O. Thorne and T.C. Collocott (eds.), *Chambers Biographical Dictionary* (Chambers: Edinburgh, 1974), p.245.

[25] Jack Morrell and Arnold Thackray, *Gentlemen of science. Early years of the British Association for the Advancement of Science* (Oxford University Press: Oxford, 1981), pp.91 and 109.

direct application either as a light locomotive engine for turnpike roads or to his own experimental flying machines.[26] This "hot-air engine" was both less bulky than available steam alternatives and substantially safer than the "gunpowder engine".[27] Complementing the argument of economy, considerations of size, safety, availability of resources such as coal and fresh water, the particular requirements of specific applications, the prejudices of potential users, and even the transitory value of novelty, could weigh upon the design of such an engine and its public commercial success.

Depending on the prevalent theoretical viewpoint, more or less compelling arguments might be found and promoted by members of a scientific community for air as a realistic alternative to steam. Thus Delaroche and Bérard observed that the "very low specific heat" of air made it a very suitable "working substance".[28] In any case, the single practical consideration of fuel economy need by no means be the dominant consideration when choosing or designing an effective prime mover:

> It had been understood...in England that where coal was cheap and plentiful it was better economy to use a cheap and inefficient engine than to spend a lot of money on an efficient and economical one.[29]

A complex network of arguments constrained and informed the process of developing any new technology.

For Rankine and Napier, as for any others, it was necessary to

---

[26] See *Nicholson's Journal*, xviii(1807), pp.260 for his description; also Cardwell, *Watt to Clausius*, pp.152 and 197. For an illustration see E. Mendoza (ed.), *Reflections on the Motive Power of Fire by Sadi Carnot and other Papers on the Second Law of Thermodynamics by É. Clapeyron and R. Clausius* (Dover Publications: New York, 1960), between pp.54 and 55, no.5. See also Cardwell and Hills, "Thermodynamics and Practical Engineering", for Cayley's recognition of a "role for the air-engine that the steam-engine could not fulfil"(p.3).

[27] Wintle, *Makers of Nineteenth Century Culture*, pp.108-9.

[28] Cardwell, *Watt to Clausius*, p.153. We will see that the exact values of the principal specific heats of air, as experimentally determined by Delaroche and Bérard, came under the scrutiny of Joule, again in the context of justifications for the air-engine, in the early 1850s (chapter 5).

[29] Cardwell, *Watt to Clausius*, p.157.

exploit the styles and nuances of argument made available to them and to some extent required of them by their local context, and more broadly. An increasingly essential and easily transportable component of this public descriptive style, from the beginning of the nineteenth century in Britain, was the codified discussion of the *economy* of engines. From the time of the first Newcomen engine of 1712 to about 1800 the "duty" of engines had increased from 5 million foot-pounds per bushel of coal to about 30 million.[30] During the period 1810 to 1850, Cornish engines (that is, high-pressure, expansive, condensing steam-engines) increased dramatically in efficiency.[31] Austen's famous engine at the Fowey Consols mine in 1835 achieved a duty of 125 million foot-pounds for one bushel of coal under test conditions, no less than five times Watt's imagined theoretical maximum.[32] The obvious commercial advantage gained by monitoring this large-scale, practical activity meant that from the second decade of the century Cornish engineers organized regular reports documenting the performance of Cornish steam-engines.[33] The monthly *Engine Reporter*, published from 1811 by Joel Lean and later by his sons Thomas and John Lean, provided supposedly independent evaluations of engines in Cornish mines.[34]

Despite these very public successes, a strong undercurrent of interest in air-engines persisted in Britain. One example will turn out to be of particular importance. In 1816 Robert Stirling, born in Perthshire and educated for the church in Glasgow and Edinburgh, invented

---

[30] Cardwell and Hills, "Thermodynamics and Practical Engineering", p.1. A bushel was approximately ninety pounds.

[31] Arthur Woolf's high-pressure compound engine was patented in 1804. Ibid., p.2.

[32] Cardwell, *Watt to Clausius*, p.159.

[33] Ibid., p.156.

[34] Cardwell and Hills, "Thermodynamics and Practical Engineering", p.18; Robert Fox (trans. and ed.), *Reflexions on the motive power of fire. A critical edition with the surviving scientific manuscripts* (Manchester University Press: Manchester, 1986), p.5 footnote 13 (introduction). The *Reporter* appeared regularly until 1880.

and patented a new form of "hot-air engine".[35] Further patents for improvements were filed in 1827 and 1840.[36] Robert had been assisted in drawing up the patents by his younger brother James, a mechanical engineer who became manager of a machine foundry in Dundee.[37] It was there that the engine was shown, if only temporarily, to be a practical proposition: in 1843 a 45 horse-power air-engine was constructed from a modified steam-engine and used successfully to drive machinery at the Stirling foundry for three years. After this period the engine seems to have failed as a result of the heated end of the cylinder burning out under extreme temperature.

In 1827 this engine was made substantially more efficient by the introduction of a device which came to be known either as a "respirator" (hot and cold air passed through it), an "economizer" (it promoted savings of fuel), or a "regenerator".[38] Significantly, the Stirling brothers preferred the term "economizer".[39] The equally theory-laden (and ideologically-loaded) term "regenerator" was suggested in the 1830s by the energetic inventor of a similar "caloric engine", John Ericsson, who, at one time at least, believed that heat lost during the cycle of the engine

---

[35] Robert Stirling (1790-1878), *DNB*; and *The Times*, 11 June 1878, p.5. He later became minister of the Parish Church at Galston in Ayrshire, twenty miles south of Glasgow. He married the eldest daughter of William Rankine (sic), wine merchant of Galston, in 1819. The Stirling engine has been idiosyncratically described as working on Carnot's principles (not published until 1824). See Donald S.L. Cardwell, *James Joule. A biography* (Manchester University Press: Manchester, 1989), p.20).

[36] 1816 (No.4081); 1827 (No.5456); 1840 (No.8652). For comments on John Ericsson's dispute over the Stirlings' priority see Daub, "Regenerator", p.260.

[37] See Frederic Boase, *Modern English biography* (3 vols., Frank Cass & Co. Ltd.: London, 2nd impression 1965), 3, p.759.

[38] In this engine a cylinder containing compressed air was heated at one end and cooled at the other. The heated air acted on a piston to do work. The regenerator, a bulky plunger consisting of many thin strips of metal, moved to the hot end, forcing the air to the other end and cooling it in the process. The air pressure being lower at the cold end the working piston moved back to its original position and the plunger was forced back through the air, heating it again. For a "hypothetical reconstruction of Stirling's thinking" in developing the regenerator principle see Daub, "Regenerator", pp.263-4.

[39] Daub, "Regenerator", p.259.

could be re-used or "regenerated" to produce mechanical work.[40] The regenerator, in all its many forms, was essentially a heat exchanger: by its agency, it was imagined, a large loss of heat due to the condensing action of a steam-engine would, in the air-engine, be eliminated. Not unlike Ericsson, Stirling could baldly assert in 1845 that "the economy [of his engine] depended on the reiterated use of the same air alternatively giving out and absorbing the same caloric".[41] Thus he believed the power of his engine to be "theoretically infinite".[42]

Lewis Gordon had a direct connection with the Stirlings. On the advice of William Cubitt[43] he was sent to the Dundee machine foundry in 1832, five years after the introduction of the air-engine's regenerator. There "he worked for nine months assiduously at bench and forge, to gain a practical acquaintance with the construction of machinery."[44] It seems more than likely that Gordon would have learnt of the details of early forms of the engine at this time. Curiously, we will see that a short time later Gordon may well have gained an indirect critical introduction to Ericsson's caloric engine. At the reading of James Stirling's paper on his air-engine to the Institution of Civil Engineers in June 1845 Gordon was present and took part in the discussion.[45] William, James and Dr James Thomson (their father) collectively met Robert Stirling also in April 1848, at which time the younger James was showing a definite

---

[40] See Daub, "Regenerator", pp.259-77; and "Stirling's Air-Engine", *Mechanics Magazine* , 45(1846), 559-66. Ericsson is discussed later in this chapter.

[41] See *The Engineer* , cxxiv(1917), p.516. For an illustration of Stirling's engine see Mendoza, *Reflections* , between pp.54 and 55, no.6.

[42] James Stirling, "Description of Stirling's Improved Air Engine", *Minutes and Proceedings of the Institution of Civil Engineers* , 4(1845), p.348-361. Quoted in Cardwell and Hills, "Thermodynamics and Practical Engineering", p.4.

[43] William Cubitt (1785-1861), *DNB* , civil engineer. From 1823 he was a Member of the ICE, serving as President form 1850 to 1852. He was knighted in recognition of his supervision of the Great Exhibition of 1851.

[44] Thomas Constable, *Memoir of Lewis D.B. Gordon , F.R.S.E.* (T. and A. Constable: Edinburgh, 1877), p.8. See also chapter 6.

[45] Stirling, "Improved Air Engine", pp.356-61. Sir George Cayley was also there.

interest in developing the engine.[46]

The "economy" of the Stirling and Ericsson engines was often publicly attributed to the repeated use of caloric: thus a naive paraphrase of one contemporary scientific theory was recruited in order to explain the practical question of efficiency. It is difficult to judge how convincing this argument would have been in the 1830s and 1840s in the absence of clear practical evidence. Apparent claims that, through the regenerator, such an engine might produce a perpetual motion were understandably contested.

By the beginning of the 1850s the lack of tangible success for the air-engine, coupled with a history of its uneasy justification in terms of a caloric theory that was undergoing extensive critical re-evaluation, stimulated Napier and Rankine to apply a strong revisionist body of arguments in their attempts to convince a suspicious public of the "advantages of the air-engine". In the sequel I hope to indicate this context of argument: briefly, convincing large-scale practical proof was sought; a carefully stage-managed publicity campaign was planned; and an attempt was made to discount previous "erroneous" theories of the action of the air-engine using the scientific style of the new thermodynamics. The enigmatic regenerator, in particular, could be rescued from theoretical obscurity: the "regenerator principle", as it was later dignified, would play a central part in Rankine's presentation of his theory of the mechanical action of heat to the Royal Society of London. Unlike Stirling and Ericsson, Rankine was in a position to exploit the

---

[46] James recounted that he had asked Stirling "particularly not to tell [him] anything that he did not regard as entirely public, because [he] had some ideas on the subject [him]self". See James Thomson, "Motive power of heat: air engine", Notebook A14(A), Queens University Belfast; and Crosbie Smith and M. Norton Wise, *Energy and Empire. A biographical study of Lord Kelvin* (Cambridge University Press: Cambridge, 1989), p.298. Thus it seems that Cardwell and Hills may have been wrong to state that "It is almost certain that neither of the Stirling brothers had ever heard of Carnot, or read his book." (p.4). I do not wish to suggest that their design was influenced in any way directly by Carnot, but they may ultimately have been introduced at least to Clapeyron through the Thomsons or, as we will see later, Gordon.

platforms offered by scientific societies to justify the air-engine from within. It is to this rich theoretical context that I now turn.

Carnot and Clapeyron: theoretical or practical contexts for the air-engine?

In 1824, at a time of intense interest in power technology, Sadi Carnot (1796-1832) published his now classic *Reflexions on the motive power of fire, and on machines fitted to develop that power*.[47] From 1820 Carnot had studied widely but intensely, concentrating on natural philosophy and economics. His interest in the organization and the economies of different industries led him to develop a store of expert knowledge in the trades of the European countries.[48] From this considered, broad, economic viewpoint Carnot proposed a theoretical discussion of heat engines that used *any* working substance, in methodological accord with his father Lazare Carnot (1753-1823), who, in a treatise offering the *Fundamental Principles of Equilibrium and Movement* (1803), had elaborated a *general theory of the maximum efficiency of machines*.[49] A specific discussion limited to the steam-engine was for Sadi Carnot inherently insufficient:

> Arguments have to be established that apply not only to steam engines but also to any conceivable heat engine, whatever working substance is used and whatever operations this working substance is made to perform.[50]

Such general arguments would enable the determination of the most economical use of heat in the production of power. In practice, of course, air, alcohol vapour, and perhaps liquids or solids might prove more effective for this purpose than steam, in spite of its current technological dominance.[51] From the outset Carnot speculated enthusiastically:

Réflexions sur la puissance motrice du feu et sur les machines propres a développer cette puissance (Bachelier, Paris,

[47] Translated and edited in Fox, *Reflexions*. I draw particularly on Fox's introduction, with notes, on pp.1-57. See also P.M. Harman, *Energy, Force, and Matter. The Conceptual Development of Nineteenth-Century Physics* (Cambridge University Press: Cambridge, 1982), p.45.

[48] Mendoza, *Reflections*, p.xi.

[49] Harman, *Energy, Force, and Matter*, p.48; and Mendoza, *Reflections*, p.x.

[50] Fox, *Reflexions*, (Carnot's text), p.64.

[51] Fox, *Reflexions*, p.2.

> For a long time there have also been attempts to discover whether there might be working substances preferable to steam for the development of the motive power of fire; and that is a question still debated today. Might air, for example, have great advantages in this respect?[52]

Fox has pointed out that while Carnot was writing, steam was not accepted without reservation as the most economical working substance. Alexis-Thérèse Petit, for example, Professor of Physics at the École Polytechnique, had suggested as recently as 1818 that the substitution of air could bring a four-fold saving in fuel.[53] Petit's favourable comparison of the air-engine with the steam-engine resulted, like that of Delaroche and Bérard, from a consideration of specific heats.[54] Following Pietro Redondi, Fox identifies a "somewhat deviant tradition" stretching back to Huygens, and to which contributions were made by Joseph Montgolfier and the Niepce brothers, wherein the use of air as a working substance was a recurring theme.[55] Clément and Desormes, while unenthusiastic in their discussion of one particular air-engine (the Niepce brothers' "pyréolophore") remained convinced that air might well ultimately replace steam as the most economical working substance.[56] Redondi has shown this tradition to be an essential context for Carnot's work. As we have seen, Lazare Carnot was connected with the evaluation of one of its later manifestations. It is not altogether surprising therefore to find in the *Reflexions* the following guardedly optimistic passage:

> Various attempts have been made to create motive power by allowing heat to act on air. By comparison with steam, this gas has both advantages and disadvantages...The use of air for developing the motive power of heat would present great practical difficulties, though ones that are perhaps not

---

[52] Ibid., (Carnot's text), p.63.
[53] Ibid., (Fox's introduction), p.11.
[54] Mendoza, *Reflections* , p.xiii.
[55] Fox, *Reflexions* , p.21; for an early account of work then in progress see Pietro Redondi, "Sadi Carnot et la recherche technologique en France de 1825 à 1850", *Revue d'histoire des sciences* , 29(1976), 243-59.
[56] Fox, *Reflexions* , footnote 68, on p.58; for a picture of the pyréolophore see Mendoza, *Reflections* , illustrations between pp.54 and 55, no.7.

> insuperable. If we could find ways of overcoming them, air would certainly have a significant advantage over steam.[57]

In a footnote, Carnot mentioned "some successful attempts, made quite recently in England, to develop motive power through the action of heat on air."[58] This has been tentatively identified as a reference to the air-engine built to Stirling's design in 1818 for pumping water at a quarry in Ayrshire.[59]

The *Reflexions* were in general ignored, failing to inspire either the majority of practical engineers or the scientific establishment.[60] But those who viewed Carnot most favourably, such as Stéphane Flachat (an associate of Clapeyron) and Louis Franchot, again tended to be associated with this air-engine tradition. Franchot's paper on the theory of air-engines using Carnot's ideas submitted to the Académie des Sciences in 1840 initially attracted little interest. But scientific fashions change. In 1853, the year in which Rankine's interest in the air-engine became noticeably more vigorous, the paper was re-examined. In a climate of growing speculation upon the commercial possibilities of John Ericsson's caloric engine embodied in his ship, the *Ericsson*, Franchot was awarded the Académie's Montyon prize for mechanics.[61]

Carnot's work was successfully re-interpreted, mathematically re-formulated, and introduced to a wider international audience largely through Emile Clapeyron's "Mémoire sur la puissance motrice de la chaleur"(1834)[62] and subsequent translations of it. In particular, Clapeyron introduced into his analysis a graphical pressure-volume

---

[57] Fox, *Reflexions*, (Carnot's text), pp.109-10.

[58] Ibid., p.111.

[59] Ibid., (Fox's notes), p.157. We shall see later that William Thomson, with a perhaps more obvious motive, believed that Carnot was referring to Stirling.

[60] Cardwell, for example, describes it as "too abstract" to interest practical engineers: Carnot's insights and predictions were mostly "the same as those that engineers were working towards, guided not by theory but by intuition and the logic that economic need imposed on design and development." Cardwell, *Joule*, p.101.

[61] Fox, *Reflexions*, pp.38-9; Redondi, "Sadi Carnot", pp.258-9.

[62] *Journal de l'École Polytechnique*, 14, cahier 23, 1834, pp.153-90. Emile Clapeyron (1799-1864).

representation of the cyclic action of heat engines (essentially Watt's "indicator diagram").[63] It was a reading of Clapeyron in 1842, after completing his pupillage with Macneill, that had stimulated Rankine's interest in the subject of the mechanical action of heat:

> My first attempt to apply mathematical reasoning to the subject arose from my seeing the translation, which had just appeared in Taylor's Scientific Memoirs, of Clapeyron's paper on the opposite [i.e. caloric] theory.[64]

William and James Thomson had also been led into Carnot's theory through Clapeyron during the 1840s.[65]

The following principle, reminiscent of earlier work on water-power, was central to Clapeyron's presentation:

> ...in any mechanism designed to produce motive power from heat, there is a loss of force whenever there is a direct communication of heat between two bodies at different temperatures, and it follows that the maximum effect can be produced only by a mechanism in which contact is made only between bodies at equal temperature.[66]

In his treatment Clapeyron represented the (closed) Carnot cycle for a permanent gas (such as air) graphically by plotting a curve of pressure against volume. The area of this closed curve, he remarked,

> will represent the quantity of action developed by the cycle of operations...at the end of which the gas is in precisely its original state.[67]

Since no contact was made between bodies at different temperatures in this development of mechanical force *by a reversible process* , the "action" must be a maximum. Indeed, the existence of such a reversible process implied that

> the maximum quantity of action which the passage of a given quantity of heat from a cold to a hot body can develop is independent of the nature of the agents used.[68]

---

[63] Harman, *Energy, Force, and Matter* , p.49.

[64] Rankine to William Thomson, 19 August 1850, R18, Kelvin Papers, Cambridge University Library. Emile Clapeyron, "On the Motive Power of Heat", *Scientific memoirs, selected from the transactions of foreign academies of science and learned societies and from foreign journals* (Richard Taylor ed.), 1(1837), 347-76.

[65] Smith and Wise, *Energy and Empire* , p.289.

[66] Mendoza, *Reflections* , (translation of Clapeyron), p.75.

[67] Ibid., p.77.

[68] Ibid., p.82.

Capeyron's analysis, like Carnot's, led to this idea that the mechanical effect that could be obtained was independent of the working substance used. There was no particular emphasis on steam, or an any particular form of steam-engine. Rather, for theoretical and expository simplicity, Clapeyron had begun his presentation with a consideration of the action of permanent gases, like air, avoiding the complications of latent heat.[69]

In the final section of his paper, Clapeyron returned to the subject of "the use of heat as a motive force", a part of practical mechanics the "real foundations" of which had been laid, he asserted, by Carnot. For economy he first recommended the expansive use of steam in a steam-engine. Continuing, he emphasised his main contention:

> We have shown elsewhere that the use of gases or any liquid other than water, between the same limits of temperature, would not improve on the results already obtained; but...since the temperature of fire is more than 1000° or 2000° higher than that in a boiler, there is an enormous loss of *vis viva* in the passage of heat from the furnace to the boiler. It is solely through the use of caloric at high temperatures, and through the discovery of media suitable for extracting its motive power, that improvements in the art of utilizing the motive power of heat may be expected.[70]

Clearly there was one readily-available candidate as a working substance suitable for this use of caloric at high temperatures. Air was much more manageable and less dangerous at high temperatures than steam since it produced lower pressures. A recognised potential for the exploitation of the greater efficiency resulting from an increased range of temperature lay in the utilization of air, still practically unproven, notwithstanding the endeavours of Stirling. Seen from this practically- and economically-informed theoretical perspective, an engine using air had advantages over the steam-engine: since air could be used safely over a wider range of temperatures, the practical implication was, potentially, greater efficiency for a suitably-"improved" design of air-engine.

---

[69] Ibid., 82 fol.
[70] Ibid., p.103.

The Scottish connection: the Glasgow Philosophical Society, The Royal Society of Edinburgh, and the Stirling engine

The Glasgow Philosophical Society and the Royal Society of Edinburgh were to emerge as important forums for the presentation and discussion of the work of Carnot and Clapeyron in Britain.[71] (Carnot's ideas were, in most instances, induced from Clapeyron's more widely-available reformulation.) In the local context of Scotland, Robert Stirling's air-engine played a role within such presentations which might initially seem disproportionately large. Investigating a little more closely some of the shared pre-occupations of the close-knit Edinburgh and Glasgow professoriate (in particular J.D. Forbes, William Thomson, and Lewis Gordon) illuminates this apparently mysterious technological anomaly.

During his first session as professor of natural philosophy at the University of Glasgow (1846-7), William Thomson found a Stirling air-engine "in our Augean stables": his attention was drawn once again to Carnot's theory, as he understood it through Clapeyron's paper, which he had read in Paris in 1845, and through subsequent discussions with his brother James.[72] He wrote to James David Forbes, still professor of natural philosophy at the University of Edinburgh, on the subject of the engine in March 1847, saying he intended to get it going as soon as he had time.[73] A month later Forbes was able to congratulate him: "I am glad to hear from M^r Fischer that your Air Engine is so successful."[74]

Some time before April 1847 Lewis Gordon had given an explanation of

---

[71] The essential context of uncertainty and resolution in thermodynamics for the following discussion is given in Smith and Wise, *Energy and Empire*, chapters 9 and 10, pp.282-316 and 317-47.

[72] Ibid., pp.293-4. He may well also have discussed the subject with Lewis Gordon, still apparently active as professor of civil engineering and mechanics at Glasgow at this time.

[73] Ibid., p.294; and letter from Thomson to Forbes, 1 March 1847, J.D. Forbes Papers, St Andrews University Library. For a photograph of a working model of the Stirling engine used by William Thomson in his Glasgow laboratory, see ibid., p.295.

[74] Letter from Forbes to Thomson, 8 April 1847, F 174, Kelvin Papers, Cambridge University Library. Ludwig Fischer(1814-90) was a Cambridge friend of Thomson's. He became professor of natural philosophy at St Andrews University.

Carnot's theory to the Glasgow Philosophical Society.[75] William Thomson had become a member in December 1846, during his first university session. With the hot-air engine now working successfully, on 21 April 1847 he read his first paper in this Glasgow context: a "Notice of Stirling's air engine",[76] considered specifically in terms of Carnot's theory. The paper characteristically emphasized one practical implication of the rather general theory, perfectly in keeping, however, with that tradition which had helped to shape Carnot's original *Reflexions* :

> ...in accordance with Carnot's theory...the mechanical effect to be obtained by an Air Engine, from the transmission of a given quantity of heat, depends on the difference between the temperatures of the air in the cold space above and the heated space below the plunger [or regenerator]; as this difference is considerably greater than that which exists between the boiler and the condenser in the best condensing Steam Engines, it appears that, if the practical difficulty in the construction of an efficient Air Engine can ever be removed to nearly the same extent as already has been done in the case of the Steam Engine, a much greater amount of mechanical effect would be obtained by the consumption of a given quantity of fuel.[77]

A functioning, if not yet commercially viable engine, brought to public awareness, was in some ways convenient for the utilitarian marketing of Carnot theory: that these ideas could so easily and fruitfully be applied was of course a rather cogent argument in the theory's favour. Its success might well be partially embodied, dramatically so, in a successful and practical air-engine, superseding that great motor of mid-Victorian society, the steam-engine.

Thomson's address represented only the most public manifestation of air-engine enthusiasm amongst the Forbes/Gordon/Thomson trio. Only a few days after the Glasgow meeting, Gordon wrote to Thomson from his London address. The connections with the Stirling family from his Dundee apprenticeship, and from his attendance at the Institution of Civil

---

[75] Smith and Wise, *Energy and Empire* , p.296. There is no record of this fascinating event, or how it was received, in the *Proceedings of the Glasgow Philosophical Society* .

[76] *Proceedings of the Glasgow Philosophical Society* , 2(1844-8), 169-70. See also William Thomson, *Mathematical and physical papers* (6 vols., Cambridge University Press: Cambridge, 1882-1911), V, 38-9; and Smith and Wise, *Energy and Empire* , p.296.

[77] William Thomson, "Stirling's engine", p.169.

Engineers reading of James Stirling's paper in 1845, had been renewed under radically different terms:

> I regret much not having been present to hear your exposition of the Stirlings' engine. _ Mr Stirling is in Town _ I am laying a trail for getting up a substantial Company for the manufacture of the Engine.[78]

It does not seem unreasonable to suggest that there was a direct relationship between Gordon's belief in the practical possibilities of the Stirling engine and his earlier exposition on Carnot theory to the Glasgow intelligentsia. It seems quite plausible to suggest that, very possibly in consultation with Thomson, he found the additional theoretical arguments for the superior economy of the engine sufficient justification for the initiation of a large-scale commercial venture. Thus interest in Carnot's theory was, at least temporarily, more than matched by knowledge of its commercial potential.

James David Forbes too, opposite natural-philosophical number of Thomson, and revered teacher of Gordon, remained an active practical collaborator in this air-engine enthusiasm. Thomson wrote to him early the next year, however, hinting at some mechanical difficulty he was experiencing in making adjustments to his model engine:

> I am glad you have got your air engine to work, as I ought to have tried what we were speaking of, with mine, & written to you about it.[79]

In his role as Secretary to the Royal Society of Edinburgh, Forbes was anxious that Thomson should communicate Carnot's theory to a wider public, entreating him to prepare something in April 1848 (the time of the meeting of William, James and Dr James Thomson with Robert Stirling) and again in November.[80] The air-engine, both in actual and potential forms, was to play a suitably prominent role.

---

[78] Lewis Gordon to William Thomson, 27 April 1847, G118, Kelvin Papers, Cambridge University Library.

[79] William Thomson to J.D. Forbes (copy), 11 January 1848, F192, Kelvin Papers, Cambridge University Library. It is likely that they were speaking of improvements leading to greater efficiency.

[80] See Smith and Wise, *Energy and Empire*, p.301.

William Thomson and the duty of perfection

Thomson began to fulfil Forbes's request with his paper "On an absolute thermometric scale founded on Carnot's theory of the motive power of heat, and calculated from Regnault's observations", read before the Philosophical Societies of Glasgow and Cambridge in April and June respectively, and published in the monthly *Philosophical Magazine* for October 1848.[81] The theoretical exposition was succinct, concentrating on the vital issue of thermometric measurement. He showed particular respect for the data recently provided by Victor Regnault, who had been carrying out researches by order of the French government "for ascertaining the various physical data of importance to the Theory of the Steam Engine": the results had recently been published as the 21st volume of the *Mémoires de l'Institut* (1847).[82] The connection ran rather deep: in 1848 Gordon's business partner, Newall, offered £500 "to enable Regnault to complete his experiments on Steam and Effects of gases". Gordon cryptically informed Thomson that "The true <u>Motive</u> - the Sterling [sic] disinterestedness of the offer [of money from Newall] are manifest".[83]

Following Clapeyron's version of Carnot (he had not yet seen the original) Thomson stated that through the "letting down" of heat, mechanical effect could be obtained from a practical heat engine: "a steam-engine, or an air engine for instance". Most importantly, in the ideal case, for a "perfect" engine (that is, one having a reversible cycle) the mechanical effect was maximized, and depended only on the "interval between the temperature of the two bodies between which the heat

---

[81] Presented to the Cambridge Philosophical Society on 5 June 1848. I use William Thomson, *Mathematical and physical papers*, 1, pp.100-6. See also Smith and Wise, *Energy and Empire*, p.300. By the end of November 1848 Forbes seemed to be warning Thomson of the danger of natural philosophy losing the exciting new theory of the motive power of heat to the professor, class, and discipline of civil engineering. See Forbes to Thomson, 27 November 1848, F 198, Kelvin Papers, Cambridge University Library. This point is developed in chapter 6.

[82] William Thomson, "Absolute scale", p.100.

[83] Lewis Gordon to William Thomson, G125 and G126, 2 and 9 October 1848, Kelvin Papers, Cambridge University Library. Regnault was threatened with the cessation of funding due to the 1848 revolution.

is transferred", not on the specific nature of the working substance. This had of course been stressed as much by Clapeyron as by Carnot. With this in mind, Thomson went on to consider what he believed to be Carnot's ideal construction of, respectively, the "perfect" air- and steam-engine.[84] Thus within the ideal, theoretical, but also practically-informed context of this paper, solicited by and written by two current Stirling engine enthusiasts, the air-engine at least in its "perfect" form was given equal prominence with the steam-engine.

The onslaught continued. A few months after writing this paper, late in 1848, Gordon had at last provided Thomson with a copy of Carnot's *Reflexions* , which formed the basis of a lengthy "Account of Carnot's theory of the motive power of heat; with numerical results deduced from Regnault's experiments on steam" given early in January 1849 to the Royal Society of Edinburgh.[85] Again, I wish to stress here the role of the air-engine created by Thomson in this paper. The most obvious specific resources were Clapeyron and (ultimately) Carnot. But equally so, Thomson's relation with the actual air-engines investigated by himself, James Thomson, Gordon, and Forbes, heightened the apparent relevance of the air-engine in its ideal or perfect form as presented here.

He made the general definition that "A perfect thermo-dynamic engine of any kind, is a machine by which the greatest possible amount of mechanical effect can be obtained from a given thermal agency".[86] For Thomson, "perfection" thus entailed as much an economical as a mechanical or theoretical ideal. Carnot had discovered "the criterion for a perfect engine": it should work on the familiar reversible cycle.[87] To clarify

---

[84] William Thomson, "Absolute scale", p.103.

[85] *Transactions of the Royal Society of Edinburgh* , 16(1848-9), 541-74. Reprinted in William Thomson, *Mathematical and physical papers* , 1, 113-55. For Gordon's role in providing the copy of Carnot's treatise see ibid., note on p.100. See also Cardwell, *Joule* , pp.102-3 for an assessment of this paper referring to Thomson's presentation of the air-engine.

[86] William Thomson, "Account of Carnot", p.118.

[87] Ibid., p.119.

this proposition, Thomson chose not to give a general demonstration but rather "applications of it...in the cases of the air-engine and the steam-engine",[88] which, he said, were the cases selected by Carnot "because of their peculiar appropriateness for illustrating the general principles of his theory, no less than on account of their very great practical importance".[89] Thus, as Thomson again betrayed his optimism for the healthy prospects of hot-air through this manoeuvre, we will see that the "theory" was inextricably underpinned by an analysis of the perfect air-engine.

Carnot had not given any practical constructions: rather, he provided "the ideal construction...of an engine in which the economy is perfect. He thus determines the degree of perfectibility which cannot be surpassed; and by describing a conceivable method of attaining to this perfection...he points out the proper objects to be kept in view in the practical construction and working of such machines."[90] Thus Carnot via Clapeyron via Thomson provided a blueprint for effective engineering endeavour. The ideal of perfectibility gave the engineer a target at which to aim, precise knowledge of physical reality by which to measure his practical efforts, and perhaps even more importantly, a widely applicable justification for his efforts to improve heat-engines in general, and the air-engine in particular. The perfect engine presented itself as an ideal objective standard: actual engines could be compared with it, and through this comparison they could be evaluated.

Having given an analysis of Carnot's ideal steam-engine, Thomson provided "Carnot's Theory of the Air-Engine" (in fact his own version of the theory of "the ideal air-engine imagined by Carnot") to find the amount of mechanical effect obtained in one cycle by a fixed quantity of heat, H, falling between absolute temperatures S and T.[91] Since the

---

[88] Ibid.
[89] Ibid., p.120.
[90] Ibid.
[91] Ibid., pp.127-32.

mechanical effect derived from the fall of a given quantity of heat by both an ideal steam-engine and an ideal air-engine must be equal (both were "perfect", so, independently of working substance, derived the maximum effect) Thomson derived from this comparison two expressions for "Carnot's coefficient", m, where

M(Mechanical effect) = H(units of heat).m.t(small temperature difference), or more generally, $M = H\int_{T}^{S} m\,dt$.

This second equation, derived in equal consideration of air and steam, he believed to be fundamental to the study of heat according to Carnot's theory:

> The complete theoretical investigation of the motive power of heat is thus reduced to the experimental determination of the coefficient m.[92]

The "Carnot function" (i.e., the mechanical effect or work one unit of heat would yield through a "perfect" engine restricted to a "fall" of one degree) could be calculated from either air or steam. The latter was preferable only because of the existence of Regnault's accurate data on pressure and latent heat of steam at different temperatures from 0°C to 230°C.[93] Thus Regnault's data provided the beginnings of an answer to this fundamental question by enabling a calculation of Carnot's function.[94]

A convincing argument for the theory came again with a consideration of one peculiarity of the air-engine: if driven in reverse it acted as a

---

[92] Ibid., p.135. Notation slightly altered.

[93] See Thomson's appendix to this paper: Regnault's work on steam had provided the "means of determining with considerable accuracy the values of within a very wide range of temperatures" (p.143). See also Cardwell, *Joule* , p.102.

[94] A footnote on p.136 contains the following: "Rankins (sic) takes it [the density of saturated steam at 100] as 1/1696". It seems more than likely that this was a printer's error. If so, it indicates that Thomson was aware of Rankine's work at the end of 1848, before he had actually published on the theory of heat. Since Thomson was in close contact with Gordon, and Rankine was Gordon's friend, the connection is not at all unlikely. Furthermore, it suggests that Rankine was actively involved with the Forbes/Gordon/Thomson group, specifically with reference to their investigations on the mechanical theory of heat, and that he had some authority within the scientific communities of Edinburgh and Glasgow, even in late 1848.

refrigerator. The theoretical implications of this were striking. By considering the motion of the Stirling air-engine (now an "ice-engine") James Thomson concluded that the freezing point of water must become lower as the pressure to which it was subjected increased. An argument based on the Carnot cycle produced an approximate relation for depression of freezing point with increased pressure. Experimental verification by William Thomson implied the confirmation of the Carnot/Clapeyron theory.[95] A wider range of applications and justifications for the theory was soon forthcoming.

On 30 April 1849 Thomson added a series of notes to his "Account of Carnot", again read to the Royal Society of Edinburgh. Quite explicitly, these notes were intended either to "test" the theory (by showing that m was indeed independent of working substance); to "give striking confirmations of it" (based on the work of Dulong on specific heats of gases and Joule on the heat developed from the compression of air);[96] or to examine "the actual methods of obtaining mechanical effect from heat...with reference to their economy." Just as the tests and confirmations of the first two categories were arguments for the acceptance of Thomson's presentation of Carnot's theory, so too were the valuable utilitarian examinations of the third category.

In such a context of theoretical validation, the air-engine, understandably by now, played its part: the fourth section of this appendix consisted of a "Comparison of the Relative advantages of the Air-

---

[95] For a much fuller analysis of this within its thermodynamic context see Smith and Wise, *Energy and Empire*, pp.297-9. James Thomson presented his "Theoretical considerations of the effect of pressure in lowering the freezing point of water", again to the Royal Society on 2 January 1849, the same date as William Thomson's "Account of Carnot". William soon completed the investigation with "The effect of pressure in lowering the freezing point of water experimentally demonstrated". See William Thomson, *Mathematical and physical papers*, pp.156-64 and 165-69 respectively.

[96] Thomson's analyses both of the work on specific heats and of that on compression depended on the equation for derived by considering the "perfect" air-engine.

Engine and Steam-Engine".[97] This was as much a "comparison" between "perfect" and "actual" engines as it was between air and steam. Beginning again from Carnot, Thomson stressed, analytically, that there were two major factors to be considered: firstly, the "extent of *fall* [of temperature] utilized"; and secondly, the "economy of the engine, with the fall which it actually uses". It was Carnot who had shown the importance of the "fall"; given that, the second factor was taken to be essentially a question of practical mechanics.

> In the first respect [wrote Thomson] the air-engine...has a vast advantage over the steam-engine; since the temperature of the hot part of the machine may be made very much higher in the air-engine than would be possible in the steam-engine, on account of the very high pressure produced in the boiler...On this account, a "perfect air-engine" would be a much more valuable instrument than a "perfect steam-engine". Neither steam-engines nor air-engines, however, are nearly perfect; and we do not know in which of the two kinds of machine the nearest approach to perfection may be actually attained. The beautiful engine invented by Mr Stirling of Galston, may be considered as an excellent beginning for the air-engine; and it is only necessary to compare this with Newcomen's steam-engine, and consider what Watt has effected, to give rise to the most sanguine anticipations of improvement.[98]

Thus it was Carnot, speaking through Thomson, who argued theoretically for the "vast advantage" to be had from the air-engine. A note to this passage contained Thomson's speculation that it had been none other than the Stirling engine which Carnot had referred to in a footnote to his own *Reflexions*.[99] This recourse to personalities seemed to make the practical connection still stronger within the local Scottish context. And comparing Stirling's "beautiful" engine with that of Newcomen was a particularly potent way of showing personal optimism for the prospects of

---

[97] Willliam Thomson, "Appendix to Account of Carnot", pp.149-50. See also Cardwell, *Joule*, p.103. Cardwell does not point out that Thomson was writing about the potential of actual engines in terms of "perfect" engines; nor does he draw attention to Thomson's reference to the Stirling engine.

[98] William Thomson, "Appendix to Account", pp.149-50.

[99] Ibid., p.150. This confirms Fox's similar suggestion.

the fledgling technology.[100]

The rhetoric undoubtedly worked in two ways. Clearly Carnot's theory could be recruited to provide justification and motivation for continued attempts to make valuable "improvements" to the air-engine. But in addition, the worth of the new theory was shown by this easy indication of a potentially valuable practical application. Paraphrasing this argument, Carnot's theory showed that air-engines were worthwhile, potentially even more so than the steam-engines which had done so much to "improve" the nation: if Carnot could lead to such potent results, his must indeed be a worthwhile theory.

Following this enthusiastic evaluation of the possibilities of the air-engine, and in particular the improvements which could be made to the Stirling engine, Thomson turned to a consideration of "the Economy of actual Steam-Engines",[101] this prime mover "being universally employed *at present* as the means of deriving motive power from heat".[102] (Might air, then, soon replace steam?) Again, there was a "comparison" being made here, albeit unstated: the comparison between a "perfect" engine (perhaps using steam, but according to Thomson, independent of working substance in its production of maximum mechanical effect) and an "actual" engine. A

---

[100] See however, William Thomson, "Notes to a Paper on the Motive Power of Heat", *Proceedings of the Royal Society of Edinburgh*, 2(1844-50), pp.241-4. The fourth note is a "Comparison of the Relative Advantages of the Steam-Engine and Air-Engine" (p.243). The reversal of the order of air and steam from the fuller account published in the *Transactions* and republished in the *Mathematical and physical papers* suggests there was much at stake here. We know that in May 1849 Gordon had made comments on the "Account" before its full publication (see letters from Gordon to Thomson, 24 May 1849, G128 and G129, Kelvin Papers, Cambridge University Library). Curiously, this shorter, earlier version is perhaps slightly more ambivalent towards the air-engine. But still its possibilities beckoned: "Carnot points out, that in this respect [i.e. the effective range of temperature], the air-engine has a vast advantage...as there is no limit to the temperature in the hot part, except such as the preservation of materials requires; and, therefore in it an enormously greater portion of the whole fall, from the temperature of the coals to that of the atmosphere, may be made use of"(p.243). Clearly a public testimonial *solely* in favour of the air-engine would have been rash. Note also that Carnot was again personified here.

[101] William Thomson, "Appendix to Account", pp.150-5.

[102] Ibid., p.150. My emphasis.

comparison was being made with an ideal, theory-generated standard.

Pointing out the waste of heat due to the "fall" from the temperature of burning coals to the boiler Thomson suggested that the boiler should be at a temperature as high "as...is consistent with safety" and that steam should be used expansively.[103] For "actual" examples Thomson drew on the expertise of none other than his colleague in the chair of civil engineering and mechanics: "I am indebted to the kindness of Professor Gordon of Glasgow, for the information regarding the various cases given in the text."[104] The famous Fowey Consols engine, it appeared, had in 1845, under experimental conditions, achieved no less than 57.5% of its "theoretical duty", the mechanical effect of a perfect engine working over the same temperature difference with allowances for condensation of steam;[105] and in general Cornish engines had in practice about 25% of their theoretical duty.[106] Thus Thomson did not refer simply to the "efficiency" or "economy" of these engines. The comparison of heat engines with theory, implying perhaps a theoretical subjugation, was encapsulated in this hybrid terminology of "theoretical duty".

In his extensive paper "On the dynamical theory of heat, with numerical results deduced from Mr Joule's equivalent of a thermal unit, and M. Regnault's observations on steam", presented, again to the Royal Society of Edinburgh, in March 1851,[107] Thomson's praise for the air-engine remained undiminished. Figures displayed in a "Supplementary Table of the Motive Powers of Heat", basically derived from Carnot's function, "show the great advantage that may be anticipated from the perfecting of the air-engine" or other heat engines working over temperatures wider than those attainable for steam-engines. In particular, an air engine working between 0°C and 600°C with perfect economy would convert 76% of the whole

---

[103] Ibid., p.151.
[104] Ibid.
[105] Ibid., p.152. By March 1851 William Thomson had revised this estimate upwards to an impressive 67% of the duty, with 18% of the whole heat supplied converted into mechanical effect by that particular engine.
[106] Ibid., p.153.
[107] See William Thomson, *Mathematical and physical papers* , pp.174-316.

heat used into mechanical effect; or working with the economy of the Fowey Consols engine, reassessed at 67% (a figure which represented a practically-attainable target of efficiency), it would convert no less than 51% of the heat used into mechanical effect.[108]

A notable omission from these discussions so far had been concrete data on the performance of any particular air-engine, including Stirling's. (The engine at the Dundee foundry was no longer working.) The projections made by Thomson for the air-engine had been closely tied to his "Account" of Carnot's theory, justified in terms of a comparison with the "perfect" thermodynamic engine. Although his presentation of the economy of the steam-engine also implicitly relied on comparison with the ideal case, he had been supplied with "actual" data by Gordon. Conveniently filling this crucial gap, and working closely with Thomson, James Joule offered the "machinist" an air-engine in outline-sketch, without the Stirling regenerator, not "actual", but at least potentially practicable.

It is clear by now that in projecting an air-engine Rankine and Napier were in no sense isolated inventors. Neither were they bereft of a theoretical justification for their venture. Before examining their actions, and particularly those of Rankine, in more depth, in the next sections I will examine the roles of James Joule, designer of a semi-perfect air engine without regenerator; William Siemens, who attempted to apply the regenerator principle more widely; and John Ericsson, perhaps the most dramatic and certainly the best publicized air-engine enthusiast.

---

[108] William Thomson, "Dynamical theory of heat", pp.198-200.

James Joule: giving confidence to the practical machinist

Thomson's published statements on the air-engine had been dominated by two factors which remained disunited: the advantageous use of a wider range of temperatures by perfect engines; and the promise of Stirling's "beautiful" engine. A more concrete example of the integration of the practical (actual) and theoretical (perfect) aspects of the air-engine can be seen by examining the interest shown in this subject by James Prescott Joule during a period of frequent correspondence and close collaboration with Thomson.[109] Initially sceptical, Joule eventually became convinced of the *potential* economic superiority of air over steam. His conversion found its expression in a curious but revealing mixture of theoretical and practical statements.

As we have seen, the air-engine was already a subject of intense discussion, particularly in relation to the writings on the motive power of heat (later dignified as "thermodynamics") which were rapidly appearing in the learned journals. Writing to the *Philosophical Magazine* late in 1850 Joule introduced a letter of 15 October he had received from William Thomson dealing with Rankine's assertion (made public in February 1850 and announced independently at approximately the same time by Clausius) that saturated steam, expanding and evolving work, must partially condense to supply heat for the expansion of the remainder. For Joule,

> This fact...explains the approach of the economical duty of the steam-engine to that of the air-engine, on which I propose to

---

[109] See Cardwell, *Joule* , pp.113-15.

> make a few observations shortly.[110]

The personal debate with Thomson continued. In November 1850 Joule expressed his opinion that "neither the air-engine, nor any other will be made to supersede the steam-engine."[111] But later he went so far as to project a design for such an air-engine.[112] His position had completely reversed: "The more I look into the subject the more I feel that air will supersede steam."[113] By the middle of June 1851 Joule had become convinced that such a replacement of steam could be practicable and believed it "theoretically possible to convert into force nearly all the heat communicated to the air."[114] He had completed a paper "On the Air-Engine" in May, to be read before the Royal Society of London on 19 June 1851.[115]

Joule seemed, if anything, more assertive than Thomson in his desire to demonstrate the utilities of theory in directing, justifying, and sanctioning the practical activities of the humble engine-designer. He began with a résumé of the public perception of the air-engine:

> It has long been suspected that important advantages might be derived from the substitution of air for steam as a prime mover of machinery. It has been alleged that the air-engine would be safer, lighter, and more economical in the expenditure of fuel

---

[110] Joule to the Editors of the *Philosophical Magazine* , reproduced in William Thomson, *Mathematical and physical papers* , p.170. He wrote later: "This fact would induce the hope that a great portion of the latent heat of evaporation, which is at present almost entirely lost [in the steam engine], might, by an increase of temperature and by extending the principle of expansion, be converted into mechanical effect." See James Joule, "On the Air-Engine", in J.P. Joule, *The Scientific Papers of James Prescott Joule* (2 vols., Taylor and Francis: London, 1884-7), pp.331-42, on p.337). It was recognised that none of the heat used to evaporate the feed water (taking it from about 40 to 140 degrees centigrade) was made available to do work expansively; and that by curtailing the expansive stage of the steam-engine's cycle work was also lost. Thus if some steam was re-condensed to superheat the rest, it seemed a saving was being made, and the economy of the steam-engine might be theoretically greater than imagined.

[111] James Joule to Willia Thomson, 6 November 1850, J72, Kelvin Papers, Cambridge University Library. See also Cardwell, *Joule* , p.113.

[112] Cardwell describes this engine in some detail in *Joule* , p.114-5.

[113] James Joule to William Thomson, 28 April 1851, J80, Kelvin Papers, Cambridge University Library. See also Cardwell, *Joule* , p.127.

[114] James Joule to William Thomson, 17 June 1851, J75, Kelvin Papers, Cambridge University Library. See also Cardwell, *Joule* , p.114.

[115] The paper, dated 6 May 1851, is reprinted in Joule, *Scientific Papers* , 1, pp.331-42.

> than the steam engine. Until comparatively recent times... experimental science was hardly in the state of advancement requisite to enable the physicist...to arrive at conclusions sufficiently certain to give confidence to the practical machinist.[116]

Having distanced himself from such lowly individuals, Joule took his place within the recently-elevated theoretical clique of Thomson, Rankine and Clausius, hoping that

> the following remarks founded on the same general principles, but applied to a particular kind of air-engine, may be interesting to the Royal Society.[117]

This engine he described was simple in the extreme. Unlike Stirling's and Ericsson's, it had no regenerator. Air was compressed by a pump and introduced into a large receiver already containing heated pressurized air; the air in the receiver was heated to bring it back to the original temperature, then allowed to expand to do work against a piston, releasing the same amount of air that had originally been compressed.[118] At this stage all the working parts were idealized.

In order to generate some tangible data, something which had been noticeably absent from Thomson's discussions, Joule estimated the work done in each cycle of his semi-ideal engine. To carry out this calculation it was necessary to know k, the ratio of the specific heats of air.[119] Thomson himself had provided the necessary results from Poisson and from Miller's *Hydrostatics* of 1835 in a letter of 15 January 1851. Working through the analysis for specific volumes of air, temperatures, pressures and sizes of (imaginary) pistons in a way which mimicked the detailed practical descriptions of engines given to the Institution of Civil Engineers but also met the demands of accurate quantification in experimental physics, Joule stated in conclusion:

> This result...informs us of the economical value of the engine,

---

[116] Joule, "Air-Engine", pp.331-2.

[117] Ibid., p.332.

[118] Ibid., pp.332-3.

[119] Joule also assumed Mayer's hypothesis, that the specific heat of a perfect gas is constant at all temperatures. See Keith R. Hutchison, "Mayer's Hypothesis: A Study of the Early Years of Thermodynamics", *Centaurus*, 20(1976), 279-304.

> which is of course great in proportion to its approach to 772 foot-pounds, the theoretical maximum.[120]

This approach became more striking as the semi-ideal engine was imaginarily worked over greater temperature ranges. Joule showed his indebtedness to Thomson in terminology, and reiterated the conclusion of Carnot theory which Thomson had given in his "Account". Thus a table compared the results for his engine with

> the theoretical duty according to Professor Thomson's law, viz. that the range of temperature divided by the maximum absolute temperature is equal to the fraction of the heat converted into force by any perfect engine.[121]

Significantly, in all except the first example, "the economical value of the air-engine is greater than that of the steam-engine calculated by Mr. Rankine".[122] Ironically, it was Rankine's own investigations into steam in terms of the recent theory of the mechanical action of heat, which gave credence to Joule's assertion of the superiority of air.

It should not be imagined that Joule's engine was to him of merely theoretical interest. Although he may not have regarded himself as sufficiently skilled to produce a working model, he did offer "a few observations, with a view to facilitate the labours of those who may be desirous of constructing a good practical air-engine."[123] These concerned such mundane matters as the arrangement of pipes, and indicated an awareness that it was desirable to work at temperatures "under red heat". His most unusual suggestion was that the combustion of fuel could take place within the large receiver to economize heat, weight and space:

> An engine furnished with a receiver of this kind would be strikingly analogous to the electromagnetic engine, and present a beautiful illustration of the evolution of mechanical effect from chemical forces.[124]

Finally, he recommended two of the examples sketched in his paper, with

---

[120] Joule, "Air-Engine", pp.336-7.

[121] Ibid., p.337. Table II on p.339 showed that for increasing temperatures and pressures of the air in the receiver, the efficiency of the semi-ideal engine increased dramatically.

[122] Ibid.

[123] Ibid.

[124] Ibid., p.340.

temperatures of 625 and 925 degrees Fahrenheit, "to the attention of those willing to construct an air-engine". Reiterating the "economic value" of such an enterprise he stated:

> The consumption of fuel in No.3 need not exceed one half, nor that in No.5 one third of that in the most perfect steam-engines at present constructed.[125]

History does not record whether any rude mechanical met this challenge.

We might ask the negative question of why Joule's engine lacked a regenerator, in many ways the most conspicuous and controversial element of Stirling's and Ericsson's engines. There are several possible explanations. Popular justifications of the regenerator had almost always had some more or less naive recourse to the material or caloric theory of heat: re-use of caloric over and over again without loss generated and regenerated work. Understandably such arguments were keenly opposed to Joule's experiments beginning in the 1840s on the interconversion of heat and work. Beyond this, a key asset of Joule's engine was its functional simplicity and, consequently, its amenability to a synthetic calculation of the work done in each cycle. There was no such simple evaluation of the action of the regenerator, in terms of the dynamical (non-material) theory, and Thomson had not dealt with the regenerator in spite of positive references to the Stirling engine. For a comparison with the theoretical value of a perfect engine, in terms of the dynamical theory, to be undertaken, Joule simply could not at this stage incorporate this contentious apparatus into his semi-ideal machine.

For Joule, just as much as for Thomson, the air-engine was an incentive for theoretical study. W.H. Miller had pointed out that the value of k, which Joule used to calculate the work done by his engine, was probably wrong. Like Rankine, he called into question the experimental determination of the specific heat of air at constant pressure made by Delaroche and Bérard. Joule undertook a "New Experimental Determination of the Specific Heat of Atmospheric Air". This calculation of a

---

[125] Ibid., p.341.

fundamental physical constant was made not in any disinterested spirit of pure scientific enquiry. Rather, as a "Note to the foregoing Paper", given to the Royal Society on 23 March 1852, it seemed a necessary measure to correct the numerical tables which had been integral to the argument for the the economic value of the air-engine.[126] As if to emphasise this point, Joule again drew specific attention to three apparently practicable examples, which

> may be suggested to the notice of the practical engineer, the temperature of the receiver being in all cases below that of redness.[127]

Only two weeks later, Joule presented a paper to the commercially-attuned membership of the Manchester Literary and Philosophical Society: "On the Economical Production of Mechanical Effect from Chemical Forces", despite the apparently exclusive emphasis of the title, dealt in general (and in brief) with all categories of prime mover. The air-engine, for example, was a member of the third class (in order, after animals and electro-magnetic engines) of those producing mechanical effect from chemical forces, in this case by exploiting the heat of combustion. In spite of its short length, the paper was dominated by Joule's enthusiasm for the air-engine.

He had created a new opportunity to laud the virtues of the dynamical theory:

> Perhaps the most important applications of dynamical theory are those which refer to the production of motive power from chemical and other actions. To point out the rules for constructing an engine which shall approach perfection as nearly as possible, and to determine the quantity of work which ought to be evolved by a perfect engine of any given class, are objects of the greatest consequence in the present state of society, and which have in fact been to a great extent already accomplished by the labours of those who have taken a correct view of the nature of heat.[128]

---

[126] "Note to the foregoing Paper, with a New Experimental Determination of the Specific Heat of Atmospheric Air", reprinted in Joule, *Scientific papers*, 1, pp.342-7.

[127] Joule, "Note", p.347.

[128] Joule, *Scientific Papers*, 1, pp.363-8, on p.363. Paper originally read 6 April 1852. Reprinted (for a wider audience) in *Philosophical Magazine*, fourth series, 5(January 1853), 1-5.

Not surprisingly, the similarity to Thomson's work was strong: "perfect" heat engines could be defined meaningfully via theory; and in practice the engineer should ensure the approach of real engines to this perfect goal. The standard of comparison (the theoretical duty of a perfect engine, in foot-pounds) had been made available primarily through the efforts of one particular labourer with correct views: Joule himself. The whole passage asked for the rapid success of the dynamical theory of heat to be acknowledged.

The strongest argument for theoretical success and acceptance, in terms of social improvement within this Manchester context, was the generation of powerful evaluative techniques for existing and indeed future engines. To William Thomson was attributed the formula giving the maximum heat convertible into mechanical effect for a perfect engine, being directly proportional to the ratio of the range of working temperatures to the highest: "The extreme simplicity of this very important deduction...is of itself a strong argument in favour of that theory."[129] This formula applied not only to air engines, but to steam engines using expansion to the utmost. However, as Joule made clear, with refreshing historical amnesia:

> Professor Thomson was the first to point out the great advantages to be anticipated from the air-engine, in consequence of the extensive range of temperature which it may be made to possess; and in a paper...["On the Air-Engine"] I described a very simple engine which fulfils the criterion of perfection...[130]

Joule's comparison of the perfect steam-engine working over a realistic pressure (14 atmospheres) and his own engine could lead to only one conclusion: "even in the extreme case which I have adduced...the performance of the steam-engine is considerably inferior to that of the air-engine".[131]

It seemed the dynamical theory of heat had led directly to Joule's

---

[129] Joule, "Economical Production of Mechanical Effect", p.365.
[130] Ibid., p.366.
[131] Ibid., p.367.

air-engine. This engine, embodying the perfection of theory in practical form, was, conveniently, the best example of the beneficial social consequences to be gleaned from the dynamical theory of heat. Despite its unsteady history, despite even the fact that no fully operational model had been made to succeed in practice in the long term, the air-engine was, however transitorily, the great hope for the dynamical theory, its first great world-changing product. In its turn, this anticipation of great consequences and of social change was a compelling argument for the dynamical theory itself.

The Institution of Civil Engineers: hot air debates

Near the end of 1852, Joule sent his paper on the air-engine to many men of science.[132] Beyond his obvious personal hopes for the engine, during the early 1850s there was widespread discussion of its attributes, real or imaginary, in a broad engineering context. In Britain, the Institution of Civil Engineers devoted many meetings to public evaluation of the different forms of engine, and to the efficacy of the regenerator.

It is already clear that any attempt to separate a theoretical from a practical or economic interest in the air-engine is likely to be artificial. It was in the late 1840s and early 1850s that discussion of the air-engine appears to have intensified, broadly speaking, in practical

---

[132] James Joule to William Thomson, 6 December 1852, J130 Kelvin Papers, Cambridge University Library includes a list of those to whom the air-engine paper was sent. Rankine's reply to Joule on being sent papers including "On the Economical production of Mechanical Effect from Chemical Forces" was published, with the permission of the author in the *Philosophical Magazine* , fourth series, 5(January 1853), 6-9 (i.e. immediately following the reprint of Joule's paper.) Firstly, Rankine drew attention to the analogy between the formulae representing the fractions of motive power converted into mechanical effect in electro-dynamic and thermo-dynamic engines. Secondly, and perhaps more importantly, he took this as an opportunity to suggest that only his formulation of the theory of heat, using the hypothesis of molecular vortices, led theoretically (and not empirically, like Thomson's) to a formula in terms of absolute temperatures: $(t_a-t_b)/(t_a-k)$. The constant k did not occur in Thomson's formulation, the one Joule had used in his paper; and in any case, Rankine tended to ignore it in practice. The experiments of Thomson and Joule on the friction of air might however lead to a determination of k.

and scientific contexts. Ignoring for the moment Cayley's aeronautical experiments, a major application was likely to be marine transport. In general the manufacturers of marine steam-engines attempted to balance the problems of the use of high pressure steam, giving smaller engines and releasing more room for cargo, with the need for safety on board ship.[133] As Cardwell has pointed out, "The difficulties with the marine steam-engine compared with the successful mill engine and locomotive directed attention to the possibilities of the air-engine."[134]

In 1850 William Poingdestre gave a "Description of Sir George Cayley's air-engine", which illustrated the wish for re-evaluation.[135] Benjamin Cheverton, who had in 1826 described but not patented a form of gas engine,[136] continued this process speaking again to the Institution of Civil Engineers "On the use of hot air as a motive power".[137] This led to three days of discussion involving many leading engineers including I.K. Brunel and Robert Stephenson. Cheverton, in particular, contemptuously dismissed the claims of perpetual motion machines which men such as Stirling had seemed unwilling to play down.[138]

C.W. (or William) Siemens falls into the category of the more distinguished speakers.[139] Towards the end of these debates he was solicited to offer a paper of a more general nature intended to resolve some of the issues raised in a manner palatable to the Institution while

---

[133] See Cardwell, *Joule*, p.116.

[134] Ibid., p.117.

[135] *Minutes of Proceedings of the Institution of Civil Engineers*, 9(1850), 194.

[136] See Elijah Galloway, *History and Progress of the Steam-Engine* (London, 1835), p.65; and Cardwell, *Joule*, p.118.

[137] *Minutes of Proceedings of the Institution of Civil Engineers*, 12(1852-3), 312-324. Cheverton's address was given on 15 February 1853.

[138] Cardwell, *Joule*, p.117. Cheverton is discussed in Cardwell and Hills, "Thermodynamics and Practical Engineering", pp.4-5.

[139] C.W. Siemens (1823-83), *DNB*, on which my account is based. See also *Dictionary of Scientific Biography*, XII, 424; and William Pole, *Life of Sir William Siemens* (John Murray: London, 1888).

making appropriate reference to the dynamical theory of heat.[140] In no way could Siemens be regarded as a disinterested observer: he had patented a regenerator for the steam engine on 22 December 1847,[141] six months after Gordon had expressed his project to form a company for the manufacture of the Stirling engine (with regenerator).[142] The "regenerative steam-engine" incorporated a component similar to the economiser, but known also as a respirator, to diminish waste of fuel.[143] The idea was to prevent the loss of heat resulting from the products of combustion being discharged at very high temperatures; and to use some of the heat lost in condensing steam prematurely. After use in the cylinder the steam was passed through a metallic "respirator" where it gave up much of its heat to reach the condenser in a partly cooled state. The water from the condenser was afterwards forced back through the respirator, absorbing its heat, to be raised in temperature on its way back to the boiler. In the long run Siemens' application of a regenerator principle to the steam-engine invention was not successful,[144] although he did apply a similar idea to create the "regenerative" furnace, which channelled the products of combustion and fresh air alternately through a brickwork "regenerator" of heat to save on fuel costs.[145]

The regenerator then, in all its multifarious forms, had for Siemens a particular relevance. Indeed, many of the air-engine debates had

---

[140] "On the conversion of heat into mechanical effect", *Minutes and Proceedings of the Institution of Civil Engineers* , 12(1852-3), 571-590. Read on 17 May 1853. Cardwell and Hills suggest that "his understanding [of the new theory] was not quite what it might have been". See "Thermodynamics and Practical Engineering", p.6.

[141] William Conant Church, *The Life of John Ericsson* (2 vols., Sampson Low, Marston, Searle & Rivington: London, 1890), 1, p.209.

[142] Interestingly, Siemens married Anne, daughter of Joseph Gordon, W.S., and sister of Lewis Gordon, in 1859. This suggests there may have been a connection between the families, and perhaps even between Lewis Gordon and William Siemens from the late 1840s.

[143] For Rankine this was worthy of both "public interest", and personal concern: a valuable example of engineering progress, we will see that it also rivaled the Rankine and Napier air-engine (chapter 5).

[144] He dropped the patent in 1859 after twelve years.

[145] Michael Faraday's last lecture, given on 20 June 1862, was on the subject of the Siemens regenerative furnace. See Church, *Ericsson* , 1, p.210.

centred on the curious nature of this device, not in isolation but as it functioned in the engines of Stirling and Ericsson. Ericsson's engine, in particular, had been hailed as the solution to the problem of the marine engine, forced to maintain low steam-pressures for the purposes of safety. But the action of the regenerator had often been described often extravagantly and contentiously. Claims continued to be made which appeared to imply a perpetual motion. The success of Ericsson engine's was difficult to explain on theoretical grounds. But the most obvious evidence, for the caloric engine and its regenerator, was the practical proof to be offered by the caloric ship *Ericsson* .

Given this comparative failure, up to 1853, in realizing the supposed advantages of the air-engine, why did Napier and Rankine expend so much effort in developing their "improved" version? A tentative answer to this intriguing question could be that his own and others' theoretical analyses led to powerful motivation and justification for mechanical improvements if it could be believed that these improvements would ultimately lead to a heat engine more efficient than any existing steam-engine. I hope to show the content of Rankine's analysis itself was influenced by the very pressing concerns of the air-engine (chapter 5). Rankine was fully convinced of the power of mobilizing public opinion through the great practical proof of the air-engine's possibilities offered by John Ericsson. Before investigating this grandiose and ambitious project I return to the 1830s to consider Ericsson's first "caloric engine".

John Ericsson and "the age of caloric"

The energetic, charismatic, Swedish-born inventor and engineer John Ericsson patented his first "caloric engine" in 1833. This air-engine had a "regenerator", as did the Stirlings' engine of 1827, consisting of many small closely-packed copper tubes the function of which was to transfer heat from the warm air leaving the engine to the cold air entering.[146] Its public exhibition in London (Ericsson was based in England between 1826 and 1839) aroused great interest, but also some controversy: Michael Faraday discussed the engine in a lecture at the Royal Institution, but, admitting that he was unsure of the principles of its action, he concentrated on the function of the regenerator. Marc Brunel, on the other hand, was distinctly unimpressed when he saw the experimental model, but he did take the trouble to see it in person.[147] This critical inspection came soon before Lewis Gordon, as we know an air-engine devotee to be, met Brunel, with whom he was to work in the protracted construction of London's Thames Tunnel (chapter 6).[148]

During this earlier period hopes were expressed that the explosive qualities of steam would be avoided through this utilization of air, but it was recognised that effective economical working required temperatures of around 450 degrees Fahrenheit, bringing an entirely new set of practical problems. These high temperatures caused the oxidation of metallic pistons and valves, and the carbonization of organic lubricants. But Ericsson's engines did at least work. In 1838 a new functioning engine with a regenerator constructed from sheets of wire gauze provided, it seemed, direct practical proof of the savings of "waste heat" which could be made.[149]

Between 1840 and 1850, overlapping the period during which the

---

[146] Ibid., p.72. Church provides a lively, readable, and probably somewhat partisan account of Ericsson's career.

[147] Ibid., pp.73-5, and 104. See p.74 for a picture of one of Ericsson's early caloric engines.

[148] Constable, *Gordon*, pp.8-14.

[149] Church, *Ericsson*, 1, pp.76 and 84.

Stirling engine was constructed and working at the Dundee foundry, Ericsson built no less than eight more experimental engines, of progressively larger size and now with regenerators each consisting of a metal box filled with wire meshes. The machines produced a temperature fall between incoming and outgoing air of a full 350 degrees Fahrenheit which practically (and according to Carnot's theory) led to high efficiencies of fuel.[150]

A period of intensive work had begun for Ericsson late in 1847, curiously parallel in time to the attempts of Forbes and William Thomson to reactivate their own model Stirling engines in Scotland, and Gordon's manoeuvres to launch a company to manufacture the engines commercially. On January 14 1848 he wrote "I am at this moment under lock and key with Harrison, who is engaged in the secret operation of stuffing the guts of the regenerator of the caloric, which is in all other respects ready for trial. I have had pressure, and all is tight. The thing must go."[151] Ericsson's engines were increasingly ambitious: the regenerator of a ninth engine, built in 1851, distributed the air through almost thirty million cells by meshes formed from over forty miles of wire. (By this stage, on the other side of the Atlantic, the pages of the *Transactions of the Royal Society of Edinburgh* were beginning to fill with the writings of Thomson and Rankine on the mechanical action of heat.) No doubt on the basis of Ericsson's earlier record of success in large-scale shipping projects, by 1851 a number of New York merchants had been persuaded to provide the funds "to construct a ship for navigating the ocean, propelled by paddle-wheels actuated by the caloric engine."[152]

The *Ericsson* , weighing 2,200 tons and 260 feet in length, had engines which were enormous by contemporary standards: four cylinders of 168 inches in diameter and six foot stroke were joined by four marginally-smaller air-compressing cylinders of 137 inches diameter. Rapidly

---

[150] Ibid., p.185.
[151] Ibid., pp.186-7.
[152] Ibid., pp.188-9.

constructed, she was launched in September 1852 (shortly after the publication of Joule's second air-engine paper) and early in January 1853 (just after Joule had sent his air-engine paper to a number of distinguished men of science) the *Ericsson* began trials under the close and often critical scrutiny of the Press.[153] On 11 February journalists were invited to take a trip in the new vessel and the next day saw the papers suitably crammed with adulatory prose. Thus it was declared that "there were but two epochs of science - the one marked by Newton, the other by Ericsson". Enthusiasm for caloric was unchecked: "the peculiar adaptability to sea vessels of the new motor...is now fully established and it is likely to prove superior to steam for such purposes". Still less temperately, it could be proclaimed that now, surely, "The age of steam is closed, the age of caloric opens."[154] A trip to Washington provided the ideal opportunity for more publicity. On 4 March 1853 the Virginia Legislators gratefully accepted Ericsson's invitation to inspect the caloric ship.[155]

Returning to New York, adjustments were made to the engines on the basis of the trial results. The efficiency was less than expected, by Ericsson at least, the maximum speed was a disappointing eight miles per hour, again less than he had calculated, and the practical problems resulting from the high working temperatures (450 degrees Fahrenheit) continued unabated. One year later, however, on 15 March 1854, the *Ericsson* made a successful trip down New York Bay. All seemed to be going well: a second trial on 27 April saw the ship comfortably reaching a speed of eleven miles an hour.[156]

Disaster struck: a "terrific tornado" caused the ship to tilt so severely that ports inadvertently opened were immediately plunged below

---

[153] See also the index to *The New York Times* for an indication of the extensive coverage afforded to Ericsson's engine.

[154] Quotations from Church, *Ericsson*, 1, pp.189-192.

[155] Ibid., p.194.

[156] Ibid., pp.192-3 and 195-6.

the water level. Within only a few minutes the hold was filled and the ill-fated *Ericsson* sank. Although the ship was refloated by the beginning of May 1854, the cost of putting her caloric engines in working order was considered too great. This, combined with the economically damaging loss of space due to their inordinate size, and no doubt other factors such as the demands of creditors and the negative atmosphere created by adverse publicity, led to her ignominious conversion into a steamer.[157]

Retrospectively Ericsson could assert, philosophically, that his venture had allowed a great question to be forever set at rest: "Can heated air as a motor compete on a large scale with steam?"[158] The caloric engine might well have failed, spectacularly and all too publicly, for marine transport. But on the other side of the Atlantic Napier and Rankine did not share this negative view.[159]

---

[157] Ibid., pp.195-7.

[158] Ibid., p.198.

[159] For other purposes, where a limited, safe, independent, economical and self-managed source of power was in demand, Ericsson's engine and "improvements" of it were eventually extremely successful: by 1870 patents had yielded over $100,000. The engine reached its final form in about 1858: in this case the surface of the cylinder was blasted with cold air to keep the lubricants intact. In 1862 Ericsson was awarded, not without controversy, the Rumford Medal of the American Academy of Sciences "for his improvements in the management of heat, particularly as shown in his caloric engine of 1858." See particularly ibid., pp.206-19. Quotation on p.219.

CHAPTER FIVE

The Napier and Rankine air-engine

Air-engine diary (I)

In this chapter I present a central case-study which gives specific illustrations of the issues of earlier chapters. It provides the opportunity for a close analysis of the processes of patenting, publication, and self-publication in mid-nineteenth century engineering. Furthermore, through this air-engine diary, based upon a wealth of previously un-examined archival material and supplemented by other contemporary and secondary sources, I present arguments for the motivation of Rankine's engineering science.[1] In line with the contexts that I have raised in the preceding chapter, I demonstrate the complex integration of technological, theoretical, practical, academic and other forces.

The second leading actor within this chapter will be James Robert Napier (1821-79),[2] son of Robert Napier (1791-1876),[3] the eminent Clyde shipbuilder and marine engineer, whose firm attained a worldwide reputation for excellence in steam navigation. Like Rankine, J.R. Napier attended the Glasgow High School but he went on to study mathematics, natural philosophy and astronomy with James Thomson, William Meikleham and J.P. Nichol at the Univesity of Glasgow.[4] From 1841 he managed his father's ship-building yard at Govan and in 1853 he and his brother John

---

[1] For other recent examples of this narrative approach see Martin J.S. Rudwick, *The Great Devonian Controversy. The Shaping of Scientific Knowledge among Gentlemanly Specialists* (University of Chicago Press: Chicago and London, 1985), in particular pp.11-14; and Jack Morrell and Arnold Thackray, *Gentlemen of science. Early years of the British Association for the Advancement of Science* (Oxford University Press: Oxford, 1981), pp.165-222: chapter 4, "Diary: the Mechanics of a Meeting".

[2] See John Mayer, "James R. Napier, F.R.S.", *Nature*, 21(1880), 206; Frederic Boase, *Modern English biography* (3 vols., Frank Cass & Co. Ltd.: London, 2nd impression 1965), 2, p.1077; James Napier, *Life of Robert Napier of West Shandon* (William Blackwood & Sons: Edinburgh, 1904), pp.151-206 passim.

[3] For biographical details see *DNB*. Robert was the cousin of David Napier (1790-1869), *DNB*, who was equally distinguished as a marine engineer.

[4] See also chapters 6 and 7.

became partners in the firm of Robert Napier & Sons.[5]

The friendship with Rankine, which appears to have begun in the early 1850s, carried on alongside their association in business and numerous shared connections with such institutions as the BAAS, the Glasgow Philosophical Society, and the Institution of Engineers in Scotland (chapters 7 and 8). But the closeness of their collaboration can best be summed up by Napier's obituarist for *Nature* , John Mayer:

> One of the leading features of Mr. Napier's career was the unbroken intercourse, personal and professional, which was maintained between him and Prof. Rankine. They had numerous joint undertakings in experimental investigation, and each was of very great service to his fellow, and in the end to science. As might well be understood, to no person was Rankine's too early decease a greater loss than to James R. Napier.[6]

The air-engine project was the earliest of these joint undertakings.

On 7 February 1853 Rankine made his first formal approach to Napier on the subject of the air-engine through a confidential letter dispatched from his business address, 59 St. Vincent Street in Glasgow.[7] Napier, it transpired, had earlier expressed an interest in this machine. The most heated debates were to begin only one week later at the Institution of Civil Engineers, following Cheverton's paper (chapter 4), but through the news of Ericsson's exploits, no doubt discussed at the meetings of the Glasgow Philosophical Society, knowledge of the air-engine was widespread. It is impossible to locate the source of Rankine's interest with certainty, but in addition to the general publicity, there are other more specific links: Forbes, who had sponsored Rankine's Fellowship of the Royal Society of Edinburgh and guided his first papers to publication, had a model Stirling engine, presumably for his natural philosophy class; Gordon, with whom Rankine was on the closest of terms, had been apprenticed to James Stirling and had considered forming a company to manufacture the engine in the late 1840s; and William Thomson had been

---

[5] James Robert retired from the firm in 1857.

[6] Mayer, "J.R. Napier", p.206.

[7] Rankine to Napier, 7 February 1853, DC 90/3/1, Napier Papers, Glasgow University Archives. Letters are from this collection unless otherwise stated.

publicly optimistic about the improvement of Stirling's engine, rather than any other, and had presented arguments for its ultimate success based on their shared preoccupation: the dynamical theory of the motive power of heat (chapter 4).

Rankine first brought Napier's attention to Robert Stirling's engine of 1827. (This was the modified engine incorporating the "regenerator" or "economizer". In fact since then further minor improvements had been at least attempted in the engine patented in 1840.) Secondly, he called attention to "Captain Ericsson's" engine which he dated to "1832 or 1833". (Again it was Ericsson's more recent engines of slightly altered form that were promoting so much public discussion.) Both had been "at work in this country", which no doubt provided some comforting practical proof for Napier. Though he gave no example for Ericsson, Rankine commented, in the descriptive-economic language of the Cornish engine reporters (chapter 4), that by Stirling's own account the engines used at the Dundee foundry had produced "a maximum duty equivalent to about 1,800,000 foot-pounds for each lb. of such coal as is capable of evaporating from 9 to 10 times its weight of water in a Cornish Boiler".[8]

The exemplary Fowey Consols engine had produced 125 million foot-pounds for one bushel of coal, or about 1,400,000 foot-pounds per pound. Napier needed no such explicit comparison. Indeed, for Rankine it was the failure to take up an invention with practically-proven economy that needed further explanation: "It is somewhat surprising that the use of such engines has not become general." Novelty, peculiarity, "the difficulty of gaining credit for the results actually produced by them" (that is, the real, large-scale, practical results): all these accounted for the neglect. But there was one more factor, viz. "the paradoxical way in which the principles of their action have been described by the inventors". The problem was the "piece of apparatus like a respirator"

---

[8] Ibid.

which both engines contained,

> for storing up and using over and over again a considerable portion of the heat which produces the alternate rise and fall of temperature.[9]

At least to Rankine's knowledge, both "authors", Stirling and Ericsson, had ignored the heat producing expansion of the air, which did work; and had suggested that

> if they could carry to perfection the operation of storing up & using over again the heat of change of temperature, their engines would produce power without expenditure of heat; that is to say, power out of nothing; a conclusion opposed not only to science, but to common sense, and tending to produce distrust of the alleged efficiency of the engines.[10]

James Thomson, on speaking directly with Stirling in 1848 had five years earlier come to the conclusion that the inventor was more than willing to believe, and have others believe, that the engine was a perpetual source of power.[11] Power without using up heat contradicted Joule, of course, but had been reconcilable with Carnot. The promotion of a "false" but intransigent scientific explanation had disrupted the progress of a potentially valuable machine by creating distrust. The stark suggestion of a perpetual motion was more clearly abhorrent to an audience of practical engineers, to which such presentations would have been directed: it was this conclusion which was most difficult to reconcile with "common sense". Here Rankine rehearsed elements of contemporary debates taking place within the meeting rooms of the Institution of Civil Engineers.

In the late 1820s David Rankine had been particularly critical of those who made unrealistic public claims regarding the action and possibilities of locomotives in debates over their introduction to replace horses on railways (chapter 3). In similar fashion the younger Rankine chastised the disinformation engendered by a later generation of engineers enthusiastically but unguardedly promoting another exciting source of power: the air-engine. Such incautious statements had retarded the rapid

---

[9] Ibid.

[10] Ibid.

[11] See James Thomson, "Motive power of heat: air engine", Notebook A14 (A), Queens University Belfast; and chapter 4.

dissemination of socially-valuable ideas which organizations such as Rankine's first institutional conquest, the Royal Scottish Society of Arts, had espoused (chapter 3).

The effective counter to this adverse publicity was high profile practical proof: a successful large-scale test, the concrete propaganda of actual practice to gain public approval and concordant with the ideals of the Institution of Civil Engineers (chapter 3). Ericsson's ship, in the water since September 1852 and at that moment undergoing trials, provided the ideal active symbol. Rankine was infected with enthusiasm. If they acted quickly, he and Napier might themselves reap the benefits of this great publicity stunt as it promised to remake the image of the air-engine:

> If Captain Ericsson's ship, however, should succeed in crossing the Atlantic, of which there seems to be no reason to doubt, it is evident that public opinion will turn in favour of air-engines, and that a demand for them may be expected to arise at once; and it is not unlikely that for marine purposes, and in all districts where either fuel or water is scarce, and perhaps also for locomotives, they will ultimately supplant the steam-engine altogether.[12]

Thus Rankine joined the gallery of those presenting the dynamical theory of heat who had publicly or privately endorsed this likely supplanter of steam. His expectations were no less moderate than those of Joule, though more specific than Joule's or Thomson's. This is unsurprising, since he was hungrily targetting Napier, as a representative of the Napier shipbuilding company, and a source of the capital he lacked but which was necessary to bring the project to fruition. (From September 1853 Rankine would work in collaboration with J.R. Napier on the design of ships built by Robert Napier.)[13] More realistically too, Rankine emphasised the

---

[12] Rankine to Napier 7 February 1853.

[13] See, for example, Rankine to Napier, 8 September 1853 which deals with details of the strain to be placed upon bolts for the engines of Robert Napier's vessel the *Persia*, iron-built for Cunard in 1856. See Crosbie Smith and M. Norton Wise, *Energy and Empire. A biographical study of Lord Kelvin* (Cambridge University Press: Cambridge, 1989), pp.729-30, which includes Joule's comparative description of the launch of the *Persia* and Brunel's *Great Eastern*.

importance of local conditions (scarcity of fuel or water was particularly relevant to ships) in the acceptance and utility of improvements in design: here that valuable commodity of *judgment*, matured and cultivated only through actual practice, came into its own. Thus Rankine's own practical and commercial knowledge of the locomotive engine had developed and solidified during an Irish apprenticeship and the early years of a professional career (chapter 3).

Stirling and Ericsson were providing large-scale practical proof of the air-engine's success. There remained another form of supportive argument, furnished by Rankine's hard-won role as "man of science". He had "considered the subject of the air-engine attentively" as part of the "investigations connected with the mechanical action of heat" occupying much of his "leisure time".[14] Whereas practical data might provide convincing one-off evaluations, theory could demonstrate what remained to be achieved, setting the limit to which the engineer wished to approach, and measuring the waste which remained to be fruitfully saved and used as work. The exact measure of this difference between theory and practice (the waste) made it possible to make better-informed judgments as to how much capital it would be reasonable to invest in a project of mechanical improvement. Thus,

> neither Stirling's, Ericsson's, nor Joule's [machine]...is calculated to reduce the waste of heat to a minimum, and secure the nearest approach to the theoretical duty. Stirling's engine ...produces only three fifths of the power which it would do if the waste of heat were prevented.[15]

The construction of a "theoretical duty" had of course been used effectively by William Thomson in his analysis of the economy of steam- and air-engines a few years earlier (chapter 4) and was by now common literary property.

---

[14] This remarkable description of Rankine's extensive scientific output as the product of his leisure allows us to glimpse, perhaps, his self-perception: working as a professional engineer to survive; engaging in theoretical pursuits as a secondary activity but by no means one without benefits.

[15] Rankine to Napier, 7 February 1853.

Since it merited Rankine's and Napier's attention, we have further evidence that Joule's engine was no mere scientific oddity but had successfully been presented by Joule as a commercial proposition. Only a few months earlier, in December 1852, Joule had been publicizing his new engine. Some days later Rankine had responded, drawing his attention to a similarity between formulae giving the efficiency of electromagnetic engines and heat engines;[16] it was essential to determine the exact nature of the formula for heat, since Joule's air-engine analysis depended upon it. Thus Rankine had known of Joule's engine since early in December 1852 or before. But his emphasis was on the practically-proven Stirling and Ericsson engines with the theoretically-mysterious regenerator, rather than Joule's semi-ideal engine.

The practical problems of the various forms of engine due to high temperatures had been solved by Stirling, Rankine believed. Mechanical contrivances could bring the performance "very near to the theoretical maximum", giving a marine engine consuming at the most 3/4lb of coal per horse-power per hour. This led to the most exciting prospects for trans-oceanic travel and commerce:

> 240 tons of coal would carry a ship of 500 horse-power to Australia...all that remains to be done is to adopt such contrivances as are necessary in order to economize heat and power to the utmost.[17]

In the not too distant future might Scott Russell's *Great Eastern* , impelled by marine steam-engines, be challenged by a Scottish-Australian *Leviathan* and the air-engine? In order to carry out this scheme Rankine wished to form a mutually beneficial partnership with a man of capital and experience in the manufacture of engines, a harmony of theory and practice with J.R. Napier:

> I propose...to wait upon you...and explain...the improvements I have in view. Should they prove in your estimation to be of a kind likely to succeed in practice, we may perhaps be able to

---

[16] See "On the Mechanical Effect of Heat and of Chemical Forces...In a Letter to J.P. Joule", *Philosophical Magazine* , fourth series, 5(1853), 6-9. The letter was dated 11 December 1852.

[17] Rankine to Napier, 7 February 1853.

> make some arrangement which will ultimately lead to our mutual advantage.[18]

We have every reason to believe that this meeting took place. Extant documents from Napier's personal papers appear to illustrate the results of subsequent discussions between the collaborators.[19] These undated sheets, the retention of which surely demonstrates their value to J.R. Napier, have been hastily covered, predominantly in Rankine's hand. Their roughness makes them difficult to interpret. However, there are compelling reasons to suppose that they constitute part of the explanation Rankine had offered in February: for example, several sheets show rudimentary diagrams of the Napier and Rankine engine,[20] including a tubular bottom to increase the heating and cooling surfaces; a regenerator; and a heat screen.[21]

Rankine had a new set of explanatory tools available: Napier was given a crash course in the dynamical theory of heat. A straight line graph of pressure against volume justified an absolute zero of -458.5° F. All the calculations took place in imperial units - pounds, feet, inches - with temperatures in the Fahrenheit scale, sometimes adjusted to the "Rankine scale of temperature", beginning at absolute zero, but having Fahrenheit rather than centigrade steps.[22] Thus Napier received a British engineer's explanation rather than a continental natural philosopher's.

Rankine wrote down the equation relating pressure, volume and temperature, assuming air to be a perfect gas. Strikingly, next to a simple picture of a piston, he gave a diagram of pressure against volume (such as Clapeyron had used in his memoir of 1834) for a cycle of isothermal expansion, falling pressure at fixed volume, isothermal compression, and increasing pressure at the original fixed volume, the

---

[18] Ibid.

[19] Documents from DC 90/3/3 (not catalogued), Glasgow University Archives.

[20] By June 1853 a provisional patent specification had been filed, so these were unlikely to have been made later.

[21] I explain the function of these later.

[22] For example, the volume in cubic feet of one pound of air at 32 degrees F was given as 26214.4.

higher temperature being no less than 600° F.[23] Shading the contents of the closed line, he wrote next to it a formula for its area, H.[24] At the bottom of the page, in large letters he gave Joule's equivalent: "h = H/772".[25] It is reasonable to infer that it had been made clear to Napier that the area represented the heat expended (H), and this heat could be translated directly into the work obtained. A lengthy calculation in a specific case, again with a detailed pressure-volume diagram with shaded area, showed an engine with an efficiency of one half producing an effective power of 20,540 foot-pounds from twice that "expended in compression", or alternatively, "53.2 in liquid work".

There was more to Rankine's analysis. A further sheet, which ironically had the most detailed picture of the "improved" engine drawn on it upside down, set down equations similar to those published in his paper of 1851 entitled "On the Economy of Heat in Expansive Machines"[26] giving "whole heat expended in expanding the body", H_1; "loss of heat", H_2; "work", as the difference between these; and the fundamental equations:

" Effect/Expenditure = $(H_1 - H_2)/H_1 = (T_1 - T_2)/(T_1 + T_0)$ $T_0 = 458.5°$ Fahr "

and

$$\text{"}\ (T_1 - T_2)/(T_1 + T_0) \times W_1 = \text{useful effect "}$$

This, of course, was the equation to which Rankine had drawn so much attention after seeing Joule's papers on the air-engine (chapter 4). The need to incorporate Rankine's small and elusive constant k (marking the

---

[23] Other sheets show an upper limit of temperature of 650°F, a little over the lower of the two values Joule had recommended for practical use; and a more complex cycle.

[24] This was derivable directly from treating the gas as perfect, with isothermals therefore parabolas. He gave variants on PV.hyplog(r) [notation changed slightly], with r the ratio of the greatest to the lowest volumes of the gas.

[25] Notation slightly altered.

[26] "On the Economy of Heat in Expansive Machines, forming the fifth section of a paper On the Mechanical Action of Heat", *Transactions of the Royal Society of Edinburgh*, 20(1853), 205-10; *Philosophical Magazine*, fourth series, 7(1854), 249-54. Read to the Royal Society of Edinburgh on 21 April 1851.

difference between the scale of temperature resulting from his theoretical work and more standard gas-thermometer scales) was ignored in this rather important practical case.[27] As we might expect, in this context there was no written mention of molecular vortices either. But Rankine had clearly found the new dynamical theory, and the use of the pressure-volume diagram, convenient in convincing Napier of the possibilities of air. In two other contexts - the Royal Society of London, and the lecture room of the class of civil engineering and mechanics class - this abstracted visual representation was to reappear with a richer and more clearly articulated theoretical and rhetorical underpinning (chapter 7).[28]

Finally, Rankine noted down the practical defects of the existing engines of Stirling and Ericsson.[29] Ericsson's was "enormous"; the piston was hot; the cylinder expanded unequally; and there was an inefficient heating surface. As for Stirling's, it too had the last of these problems, but far worse, it was subject to a

> great *waste* of heat, because the air on its way to be cooled passes over the hot surface, and carries off heat to the refrigerator which produces no *useful effect*.[30]

Remedying these defects, the "proposed engine" was

> small & compact, like Stirling's, from working at a high pressure. The *waste* of heat is prevented, by screening the air from the heating surface except when it is expanding. The heating surface is increased by the use of tubes.[31]

---

[27] Rankine used the experimental work of Joule and Thomson on the free expansion of gases (the porous plug experiment) to establish the connections between the gas-thermometer scale and his own absolute scale of temperature, with temperature proportional to his "actual heat", Q, dependent on the theory of molecular vortices. The scales differed by a constant k (approximately 2°C), the temperature on the gas scale of absolute privation of actual heat. See Keith R. Hutchison, "Mayer's Hypothesis: A Study of the Early Years of Thermodynamics", *Centaurus*, 20(1976), 279-304, p.304.

[28] I have discussed the utility of two such representations in earlier chapters: firstly, with reference to Rankine's paper on the heat of the earth (chapter 2); and secondly, within the context of papers presented to the Institution of Civil Engineers (chapter 3).

[29] There is no explicit reference to Joule's engine.

[30] Quotation from documents in DC 90/3/3 (not catalogued, numbered, or dated but internal evidence suggests written between 7 February and 1 June 1853). Emphasis added.

[31] Ibid. Emphasis added.

Clearly then, even in this most informal of documents, the concepts of waste and efficiency were crucial. Small size, made possible through high pressures and temperatures (Ericsson's engine had been worked at about 450°F, rather than the 600°F or 650°F that Rankine was contemplating) had obvious advantages too. As we have seen, one contemporary reason given for the conversion of the *Ericsson* to steam was this huge size of her caloric engine, with correspondingly greater overheads and loss of cargo space. More compact engines were not only better for ships: this essential criterion must be met if Rankine and Napier were to hope to encroach on the market for locomotives.

In summary, the justification and validation of the proposed improvements, mechanical or otherwise, came directly from viewing the principles of the (perfect) air-engine as defined and explicable in terms of the current theories of the mechanical action of heat: the improvement of the (actual) engine was depicted as an application of the new thermodynamics to practice, in harmony with practical, realistic knowledge of existing engines.

Napier found these arguments compelling. By 1 June the new partners were about to present a petition for a British patent for "Improvements in Engines for Developing Mechanical Power by the Action of Heat on Air and other Elastic Fluids".[32] Rankine wrote an "official letter or missive" articulating the exact terms by which future profits were to be divided between them, as they had decided in conversation that day.[33] Both agreed, harmoniously, that it was "unlikely that we should ever have any

---

[32] James Robert Napier and W.J.M. Rankine, *Specification. Engines worked by heated air and other elastic fluids* (Eyre & Spottiswoode: London, 1853). We have seen already the dominating idea of "improvement" in practical devices, and more generally in society at large, demonstrated, for example, through David Rankine's pamphlet of 1828, and the early series of Macquorn Rankine's engineering papers presented to the Institution of Civil Engineers. See chapter 3.

[33] Rankine to Napier, 1 June 1853, with a less formal covering letter of the same date. Their mutual decision was that Napier should be reimbursed all development costs, after which any further profits would be divided equally.

difference about the matter".[34] But the document essentially set out, for the convenience of heirs, the division of intellectual as well as financial property which characterized this collaboration.

For posterity, their roles were to be seen as quite distinct but harmonious in a broader sense:

> The improvements in question were originally invented by me [Rankine] after long study of the principles which govern the action of machines in which the motive power is derived from heat, and of the facts which have been ascertained relative to the subject by experience and observation.[35]

Napier's role was entirely different, but complementary:

> your [Napier's] skill and experience in the construction of engines, and especially of marine engines, and the well-known eminence of the firm with which you are connected, are essential to the practical carrying out of these improvements in an efficient and profitable manner...[36]

Sketched out in simple form was the vision of a harmonious application of theory to practice, the beneficial product of a division of labour between two consenting parties: Napier, a man of capital, well-connected and of good standing within the commercial community, and possessed of sound business sense gained through practical experience; Rankine, ardent student and originator of scientific theory, perspicacious observer of related practical fact, and innovative creator of improvements resulting from timely practical applications of the sciences.[37] Rankine's seviceably rhetoric of the *harmony of theory and practice* was modelled on working relationships such as this with Napier; and in turn met the requirements of both practical engineers and university academics in Glasgow as an effective way of marketing and publicizing a personal methodology of engineering science (chapter 7).

The very next day, armed with this official agreement and

---

[34] Ibid. The "informal" letter.

[35] Ibid. The "formal" letter.

[36] Ibid. Rankine was probably hinting here that the excellent public image of the Napier firm would add to the credibility of the improved air-engine.

[37] We might add a third unwitting character, William Thomson, who had helped to make available the language of "perfect engine" and "theoretical duty" which mediated between "theory" and "practice" (chapter 4).

characteristically not wishing to waste valuable time, Rankine dispatched a letter to his exploitable uncle John in Canandaigua, asking for assistance, both financial and administrative, in securing a patent on the other side of the Atlantic.[38] This haste was understandable given the rapidly changing expectation of marine trade, and the volatile public image of the air-engine, so largely dependent on the success or failure of Ericsson's ship which had by now undertaken its sea trials. On the day of initiating this transatlantic venture Rankine's election to the Royal Society of London, marking his national recognition as man of science, was confirmed.[39]

One week later, on 9 June 1853, the provisional patent was officially deposited at the Office of the Commissioners of Patents in London.[40] The "Letters Patent" had been filed, in both names, with a detailed provisional specification.[41] An introductory paragraph outlined the general aim and structure of their project, with appropriate subservience to the discourse of improvement and a rudimentary indication of the series of operations on which the engine would work:

> The engines which this Invention is calculated to improve are those which develope [sic] mechanical power applicable to the moving of any kind of machinery by successively heating, dilating, cooling, & condensing a portion or portions of air or any other elastic fluid in such a manner that the dilatation takes place at a higher temperature, and the condensation at a lower temperature, and which are known by the names of air engines and caloric engines.[42]

Mechanically, the engine was rather complex. With the gearing shown it was about twenty feet high and ten across: large, but still dwarfed by the "enormous" caloric engines of the *Ericsson*. I will assume, for the sake

---

[38] John Rankine to W.J.M. Rankine, 19 June 1853, Acc. 8660, National Library of Scotland.

[39] See Certificate of Election, Royal Society of London.

[40] Rankine to Napier, 23 June 1853; and Napier and Rankine, *Specification*, p.1.

[41] See Patent A.D. 1853 No.1416, printed as Napier and Rankine, *Specification*. James Robert Napier's copy forms part of DC 90/3/20, Glasgow University Archives. Appropriately enough it has the imprint of John Smith & Son, Booksellers, Glasgow: this company still exists (in 1992) and occupies 59 St Vincent Street, Rankine's office.

[42] Napier and Rankine, *Specification*, p.2.

of brevity, that the elastic fluid was air. There was a central cylinder and piston driving a crank. Above and below the piston, passages led to two almost identical air-tight receivers working in contrary motion to drive the piston. Each receiver had a tubular bottom and top, the bottom efficiently heated by a furnace, the top likewise cooled by water. Moving within the receiver, not together but in a coordinated fashion, were a "heat screen" and a "plunger" designed to fit, repectively, the bottom and top of the receiver, and thus having tubular projections facing, respectively, downwards and upwards. The heat screen, plunger, tubular surfaces, and central compressive cylinder were all outlined in the "explanatory" sketches I have alluded to earlier.

The heat screen was a fairly simple punctured plate with tubes fixed on to it. Its function was to

> regulate the transmission of heat...to the air...in the lower part of the receiver...so that it shall take place... during the expansion of this air...which is the period most favorable for the development of mechanical power, and shall be...cut off at other times when it would be wasted or impede the action of the engine.[43]

The plunger had a much more complex construction. Made of sheet metal it had internal partitions some of which were air-tight and contained "brick dust, fire clay" or other slow conductors of heat; and others which extended right through the plunger and were filled with layers of "wire gauze, or thin perforated metal plates, or wires, or of some substance capable of conducting heat rapidly, and so formed and arranged as to expose a large surface for the communication of heat to and from the air which must pass through": a regenerator in all but name.[44]

Even within the formal, minimalistic confines of a patent specification Rankine and Napier were careful to describe the action of

---

[43] Ibid., p.4.

[44] Ibid., p.3. The words regenerator, respirator, economizer are not used, possibly to avoid patent infringement. Ericsson had been using wire gauze in his engines since 1838. The air-engine documents in Rankine's handwriting that I have analysed above referred to heat "stored in wire gauze".

their plunger with precision. In passing through it from hot to cold, the air gave out "a large portion of its sensible heat". On its return, it recovered "the greater part of the sensible heat formerly lost". There was to be no hint of an assertion that the plunger stored all the heat necessary for the rise in temperature and the expansion of the hot air, an assertion which both Stirling and Ericsson had at least been accused of. After all, the patent specification would ultimately be for public consumption.

In the Rankine and Napier engine, the engine's central piston rose to compress the air above it into one receiver, where it was cooled by the water at the top, as the expanding air from the other receiver, heated at the bottom, did work by pushing from below the piston. As it fell again, the plungers and heat screens moved into their alternative positions to reverse the process:

> The effect of these operations is of a similar nature to that which takes place in all engines driven by the action of heat on an elastic substance viz., that the substance is alternately expanded at a higher temperature, and compressed at a lower, so that the power developed by the expansion is greater than the power consumed by the compression, and a surplus of power remains to drive the machinery.[45]

No details were given on the range of temperatures over which the engine was to be worked, except in the passing recommendation that pressure guages should be used capable of measuring no less than 200psi.[46] (In the papers which I believe to have coincided with the early explanation and discussion of the air engine, this was exactly the maximum pressure used in the most detailed calculation of efficiency.) Several explicit references were made to adjustments which would make the engines suitable for "marine and locomotive engines" (those situations in which, because of compactness and economy, their advantages would be more pronounced): for example the balancing of overhead beams; and modifications for the

---

[45] Ibid., p.9.

[46] Ibid., p.7. In 1860 upper limits were placed on the pressure of steam for Royal Navy vessels at about 20psi. See R.L. Hills, *Power from steam: a history of the stationary steam engine* Cambridge University Press: Cambridge, 1989), p.241.

horizontal engines more suitable for both.[47]

The "improvements" claimed by Rankine and Napier were set out with care at the end of the specification. Many of the minor details, and the regenerator itself, could not be patented since they were either common engieering property, or, more immediately, had been patented already. The regenerator itself fell into this category. But the heat screen and the system of tubular receivers were new. In combination they ought to improve the economy of the engine by facilitating rapid heating and cooling when needed, and screening the air from the furnace when "it is being passed towards the cold end of the receiver to be cooled, when it is not being expanded, and when it is being compressed."[48] These devices, working with the "plunger", seemed designed to make the cycle of operations approximate to isothermal expansion, cooling at constant volume, isothermal compression, and heating at constant volume: that is, to make the practice conform with theoretical "perfection". The particular relevance of this cycle in relation to an air-engine with what Rankine pointedly called a "perfect regenerator" was to be made abundantly clear in the surprising context of the Royal Society of London.

Meanwhile, by 19 June 1853, John Rankine had received his nephew's letter sent more than two weeks earlier. Magnanimously John replied that he was "willing to risk the loss of $500 [the fee for the American patent] on the chance of doing you [Cornie] good."[49] The most pressing concern was to get a small model engine built to satisfy the patent office. Trusting though he was of his nephew's business acumen, he could not refrain from pointing out once again the major problem with the caloric engine:

---

[47] See also Rankine to Napier, 8 October 1853, which refers to specific mechanical arrangements required for marine air-engines of Rankine and Napier's design.

[48] Napier and Rankine, *Specification* , p.10.

[49] John Rankine to W.J.M. Rankine, 19 June 1853, Acc 8660, National Library of Scotland. It commences: "My Dear Cornie...", and cannot have been received before 4 July 1853.

> I have been told that when heat is applied to a cylinder containing air the metal is soon burned away, and that this is one of the difficulties with the Ericsson Engine. This owing, it may be, to the oxygen of the air.[50]

Rankine had been keen to stress to Napier that the Stirling engine had worked successfully in practice. But this problem of oxidation had also afflicted the air-engine of the 1840s constructed in the Dundee foundry, leading to the failure of three separate cylinders until the engine was abandoned in 1847.

Unaware of this impending letter from America, the process of obtaining the British patent continued unabated. By 23 June 1853 Moncrieff, Paterson & Forbes, the Glasgow solicitors acting for Rankine, had received the "Provisional Protection" from the London agents, following the depositation a fortnight ago.[51] The partners were entitled to four months grace, until the beginning of October, in which to decide whether or not to give "notice of intention to proceed" with the application.[52] Rankine urged Napier to act as quickly as possible:

> I beg you will let me know as soon as possible your views...My own opinion is favourable to giving the notice at once; for from what you have told me of the demand for long voyage steamers, I am impressed with the importance of proceeding with as little delay as possible.[53]

Yet again the sense of urgency was heightened. The motivation for this desire to proceed with great haste was obvious, but the act underlined a commitment to the philosophy and methodology of "engineering science" which both enabled and required alacrity in matters of financial economy.

Within a month Rankine informed his uncle that preparations for constructing and shipping to New York the small model engine required were well under way.[54] Less than three weeks later, in early August, John

---

[50] Ibid.

[51] Rankine to Napier 23 June 1853. The original "Letters Patent" and provisional specification, were officially sealed on 9 August 1853. See Patent 1853 No. 1416.

[52] This act involved a payment of £5.

[53] Rankine to Napier 23 June 1853.

[54] John Rankine to W.J.M. Rankine, 10 August 1853, Acc. 8660, National Library of Scotland, refers to a letter received from Macquorn on 22 July.

Rankine replied with detailed advice on which carriers to use, the precise size of the model (one cubic foot), and the question of exactly how the necessary power of attorney was to be granted to him. Earlier he had provided his nephew with the application forms for the American patent.[55] Clearly he had willingly maintained his support for the project.[56]

The legal status of Ericsson's engine was an obvious but necessary topic of discussion: "I presume that Erickson [sic] has taken out a patent here." John advised his nephew to examine the precise specifications in order to avoid any collision or duplication of his own, which could quite possibly lead to dispute:

> The principal [sic] may not be a new invention or discovery on his part but for the particular applications of it he may have been entitled to a patent...[57]

If Rankine's claim included one of these, problems might arise in granting the patent. In the final specification of the British patent made some time later he was particularly careful to safeguard against this eventuality.

By October full-sized drawings of two "model" engines had been prepared, the smaller of which, when constructed, was to be sent to America. Neither had yet been constructed. He sent further full-sized drawings of mechanical parts of the "experimental" engine. The distinction between model and experiment was deliberately made.[58] A model was essentially non-functional. A fully functional experimental engine, on the other hand, was designed and created in order to generate a set of practical experimental data specific in form to the audience of those (primarily engineers and industrialists) potentially interested in taking up the invention. Such "observational fact", the product of engineering experiments, fell into the same category as that presented to a popular or

---

[55] Ibid.

[56] John Rankine agreed to pay the whole expenses, apart from the cost of the model and drawings. See Rankine to Napier, 27 January 1854.

[57] John Rankine to W.J.M. Rankine, 10 August 1853, Acc. 8660, National Library of Scotland.

[58] Rankine to Napier, 8 October 1853. The word "model" is crossed out and replaced by "experimental".

engineering audience by particularly literate engineers like David Rankine and Nicolas Wood (chapter 3); and unlike that idealized data, essentially the product of thought experiment, exhibited by James Joule in his papers on the air-engine (chapter 4). The "facts observed" in the action of an experimental air-engine would be a vital resource, necessary to convince the public at large, and more specifically, the engineering community, of the viability of the "improved air-engine".

The completed drawings and instructions for construction of one "model" at least were sent to James White, an independent instrument maker in Glasgow since 1850, who was later closely connected with the manufacture and marketing of William Thomson's electrical instruments.[59] For the "experimental engine", the mechanical engineers James Gray & Co. were contracted.[60]

On 8 December 1853, at the very end of the period of six months permitted to elapse from the presentation of the Letters Patent, the full specification was filed in the Great Seal Patent Office. It had changed little from its provisional form.[61] New diagrams were added to indicate the structure of the tubular receivers; the suggestion was made that metal strips might be used in the plunger; it was remarked that a simpler single acting engine was possible; and the general description of the effect of operations in heat engines (expansion at a higher temperature, compression at a lower) was conscientiously amended by replacing "compression" with the less active "contraction". Most importantly, it was stressed explicitly that it was the combined mode of action of the mechanical contrivances that represented the patentable improvements, rather than the

---

[59] Rankine to Napier, 27 January 1854; T.N. Clarke, A.D. Morrison-Low and A.D.C. Simpson, *Brass & Glass. Scientific Instrument Making Workshops in Scotland as illustrated by instruments from the Arthur Frank collection at the Royal Museum of Scotland* (National Museums of Scotland: Edinburgh, 1989), pp.252-75.

[60] Rankine to Napier, 27 January 1854.

[61] Napier and Rankine, *Specification* , pp.11-21. This lateness, contrasting with initial rapidity, might be explained as an attempt to maximize the time under which the invention was actually to be protected.

devices themselves. There was to be no danger of patent infringements with Ericsson or the Stirlings. The credibility of the description of that action, of course, depended upon certain assumptions and assertions concerning the theory of the mechanical action of heat. But in all other respects the engine had remained the same since its conception.

Interlude: regenerating hot air at the Royal Society of London

In addition to the protracted arrangements required for the construction of model and experimental engines, and the intricacies of patent law, detailed preparations for "parliamentary business" had engaged much of Rankine's time during November and early December 1853, preventing him from travelling to London to present himself personally for admission to the Royal Society.[62] This task was extended far longer than he had anticipated. In mid-July the next year, hard at work opposing the Caledonian & Edinburgh and Glasgow Arrangement Bill, he bemoaned his long absence from Glasgow.[63] Between December 1853 and July 1854 he had spent a considerable proportion of his time in London, based at the Westminster offices of Lewis Gordon.[64] In May he had found time to contribute to a discussion taking place at a meeting of the Institution of Civil Engineers, a rare occurrence indeed since the presentation of his ambivalently received paper on "Sea Walls" of 1848 (chapter 3).[65]

From Gordon's office he continued to correspond with Napier on the engine, and on other joint projects pursued simultaneously, for which he acted as consulting engineer.[66] One major enterprise was the construction

---

[62] Rankine to Colonel Sabine, 4 November 1853, MC.5.121 (Miscellaneous Correspondence), Royal Society of London. Rankine sent Sabine, Vice-President and Treasurer, £14 for his admission and annual subcription.

[63] Rankine to Napier, 17 July 1854.

[64] 24 Abingdon Street, which had been the offices of Telford.

[65] See Hugh B. Sutherland, *Rankine: his life and times* (Institution of Civil Engineers: London, 1973), p.11.

[66] See Rankine to Napier, 20 December 1853; 24 December 1853; 30 December 1853; 21 January 1854; 27 January 1854; 15 June 1854; 17 July 1854.

of sheds of 25,000 square feet at Govan, partially designed by Rankine (borrowing elements common to railway engineers). These must surely have been for the purposes of shipbuilding and demonstrate the economic optimism of the Napier firm at this time, justifying faith in a concomitant demand for the air-engine. It seems more than likely that Rankine would have benefited from Gordon's expert knowledge and experience of the Stirling engine, and he certainly received direct encouragement. In January Rankine told Napier: "Professor Gordon admires our Air-engine much."[67]

Practical activities had not been allowed to monopolize Rankine's time. Early in January this London sojourn provided the opportunity for the reading of a paper "On the Geometrical Representation of the Expansive Action of Heat, and the Theory of Thermo-dynamic Engines", his first major contribution to the meetings of the Royal Society of London. Notwithstanding its prestigious scientific audience, this extensive essay, which had been in preparation since November 1853 at the very least, exhibited an intense preoccupation with the air-engine.[68]

The paper commenced with an appropriately Whig-historical genuflection:

> The first application of a geometrical diagram to represent the expansive action of heat was made by James Watt, when he

---

[67] Rankine to Napier, 27 January 1854.

[68] Rankine to Colonel Sabine, 4 November 1853, MC.5.121 (Miscellaneous Correspondence), Royal Society of London: "I hope in the course of about a fortnight to offer to the Society a paper on the Geometrical Representation of the Mechanical Action of Heat." By the time it was read (19 January 1854) and printed the title (as given in the text) had become rather more pointed. See *Philosophical Transactions of the Royal Society of London*, 114(1854), 115-76. P.G. Tait described it as nothing less than a "great paper on thermodynamics". See P.G. Tait, "Memoir [of Rankine]", in W.J. Millar (ed.), *Miscellaneous Scientific Papers by W.J. Macquorn Rankine* (Charles Griffin & Co.: London, 1881), pp.xix-xxxvi, on p.xxii. Earlier papers on heat had been read primarily before the Royal Society of Edinburgh and published in its *Proceedings* or *Transactions*. In many cases they were republished in the *Philosophical Magazine*. See bibliography.

> contrived the well-known steam-engine indicator...[69]

A pencil attached to a pressure-gauge described a closed curve on a card whose motion followed that of the working piston. Rankine re-interpreted, for the sake of the Royal Society, in the language of energy:

> ...the area of the...figure, or *Indicator-diagram* ...will represent the motive power, or "potential energy," *developed* or *given out* during a complete stroke, or cycle of changes of volume of the elastic substance.[70]

The practical utility of such diagrams was well known. Renaming them, he appropriated these useful entities to the scientific domain: henceforth they would be called "*diagrams of energy*".[71]

Keen to place himself in the camp of those "scientists of energy" working self-consciously to market a new unifying physical principle,[72] Rankine distanced himself from the promoters of a caloric theory of heat. They may have used such diagrams (Clapeyron certainly had), but their conclusions were "vitiated by the assumption of the substantiality of heat".[73] Of course, such false assumptions and their consequences had,

---

[69] Rankine, "Geometrical Representation", p.339. For a more sophisticated account of the indicator diagram and its supposed inventor (in 1796) John Southern, see R.L. Hills and A.J. Pacey, "The Measurement of Power in Early Steam-driven Textile Mills", *Technology and Culture* , 13(1972), 39-43.

[70] Rankine, "Geometrical Representation", p.340. Rankine had publicly introduced a formal distinction between "potential" and "actual" energy in a somewhat abstruse paper read to the Glasgow Philosophical Society on 5 January 1853: "On the General Law of the Transformation of Energy", *Proceedings of the Glasgow Philosophical Society* , 3(1848-55), 276-80. Republished in the *Philosophical Magazine* , fourth series, 5(1853), 106-17. See also David F. Channell, "Rankine, Aristotle and potential energy", *Philosophical Journal* , 14(1977), 111-14.

[71] Rankine, "Geometrical Representation", p.340, his italics.

[72] See Crosbie Smith, *Science of energy* (Forthcoming).

[73] Rankine, "Geometrical Representation", p.340. In marked contrast to Thomson, Rankine was consistently dismissive of Carnot. I would suggest that this demonstrated in part a desire to present the formulation of the dynamical theory of heat upon his own hypothesis of molecular vortices as distinct not only from Carnot and Clapeyron, but also from Clausius and, in particular, Thomson himself. In the early 1850s Rankine may well have felt himself being gradually swamped by Thomson's papers on thermodynamics, which, foundationally at least, were much less ornate than his own. Since many of the experimentally valuable results were the same, it was important to retain the original hypothesis, and argue for the probability of its underlying reality, in order to avoid his work being undermined. Of course, this is what eventually happened. (See the *Transactions of the Royal Society of Edinburgh* and the *Philosophical Magazine* in the early 1850s for evidence of the gentlemanly duel by publication.)

according to Rankine, contributed greatly to the failure of the air-engine to come into general use.

Having cited Watt and dismissed Carnot and Clapeyron, he traced the origins of the "diagram of energy" back a few years to his own paper "On the Economy of Heat in Expansive Machines".[74] There

> a diagram of energy is employed to demonstrate the general law of the economy of heat in thermodynamic engines according to the correct principle of the action of such machines - viz., that the area of the diagram represents at once the potential energy or motive power which is developed at each stroke and the mechanical equivalent of the actual energy, or heat, which permanently disappears.[75]

Through the indicator-diagram, rigorized, geometrized, given a theoretical pedigree, and appropriated as a "diagram of energy", heat-engines provided unproblematic, unmediated, transparent inscriptions of the motive power they produced in each working cycle.[76] In the wake of Watt's indicator, heat engines in general were re-constituted as a part of the theory: a diagram of energy said all you needed to know about an engine. Heat engines of all kinds made their own mark and did so in the most useful of ways. Their function was to do work: the inscription made it clear exactly how much, in a way concordant with theory. Comparing themselves directly with the objective standard of theory, they charted their essential product (the work done) in the geometrical language of the "correct" theory of heat. In the logical extreme, these charts *were* the theoretical manifestations of heat-engines, however they might be physically embodied in practice.

---

[74] See *Transactions of the Royal Society of Edinburgh*, 20(1853), 205-10; and republished in the *Philosophical Magazine*, fourth series, 7(1854), 249-54.

[75] Rankine, "Geometrical Representation", p.340. Throughout the paper he uses Joule's equivalent of 772 foot-pounds per degree fahrenheit.

[76] I am grateful to Alex Dolby for introducing me to the idea of an "inscription". In fact, the shape of the "true indicator-diagram" need not be the same as that on the card. A portion of the elastic substance might act as a cushion, transmitting pressure to the piston, expanding and contracting without doing work. A simple lemma enabled a transformation to the "true" indicator: but most importantly, the area, representing the work, was the same for both. See Rankine, "Geometrical Representation", pp.364-5.

Beyond these remarkably direct links between the practical function of an engine, its geometrical inscription, the "correct" theory of heat, and the abstraction of energy, equivalent (through Joule) to mechanical effect, the diagram had a great didactic purpose. Theoretical principles were "capable of being presented to the mind more clearly by the aid of diagrams of energy than by means of words or symbols alone".[77] Thus the formalized explanatory techniques of pressure-volume graphs had helped to convince Napier of the advantages of the air-engine less than a year before. Later this pedagogic potential was actualized in the teaching of the class of civil engineering and mechanics the following year (chapter 7).

For the moment I will examine this paper in a broader context. Ostensibly Rankine had two aims: firstly, to illustrate and demonstrate geometrically existing propositions in the theory of heat; and secondly, to apply these demonstrations

> chiefly to the solution of new questions, especially those relating to the action of heat in all classes of engines, whether worked by air, or by steam, or by any other material...[78]

One such solution was to the problem of the mysterious action of the regenerator. Thomson and Joule had not written on the regenerator. Conspicuously, Joule's engine had not included this apparatus. Rankine had generated a timely theoretical response to a question of public concern and pressing commercial importance. The ability to provide an answer argued for the new theories of heat; for Rankine's own work; and most importantly his own formulation of thermodynamics. Thus in a sense the air-engine provided Rankine with a further opportunity to stake his claim to the territory of thermodynamics, and to revitalize his hypothesis of molecular vortices, that which most clearly distinguished his work from Thomson and Clausius.[79]

---

[77] Ibid., p.340.

[78] Ibid. Note the order, with air placed first.

[79] For example, "isothermal curves" were those for which Rankine's "sensible heat" or "actual heat" were constant.

Having re-formulated many of the results of his earlier papers in geometric form a third section dealt with "the efficiency of thermodynamic engines, worked by the expansion and condensation of permanent gases".[80] He began with the fundamental definition:

> The *efficiency* of a thermodynamic engine is the proportion of the whole heat expended which is converted into motive power;... the ratio of the motive power developed to the mechanical equivalent of the whole heat consumed.[81]

The engines were divided into two categories: those without regenerators or economizers; and those which worked "*with* the aid of that piece of apparatus". The efficiency, a ratio of areas and hence of energies, was to be found for each. An immediate corollary was the value of the maximum efficiency for such an engine working between given limits of "actual heat":

> the greatest possible efficiency of an engine without a regenerator will be obtained when the whole reception of heat takes place at the highest limit, and the whole emission at the lowest.[82]

Thus the diagram of energy is bounded above and below by "isothermal curves", and laterally by pairs of "curves of no transmission" (adiabatics). For such a cycle, the ratio of motive power given out to heat expended was equal to $(Q_1-Q_2)/Q_1$, Q_1 and Q_2 being the actual heats at higher and lower isothermals respectively. The similarities between this and the equivalent formula for absolute temperatures given by Thomson (and incidently used as evidence of the advantages of the air-engine) are obvious. But the differences should be stressed, as they were by Rankine, in order to distinguish his work from Thomson's. The direct proportionality between actual heat and temperature measured on a (perfect) gas-thermometer scale was, Rankine believed, an experimentally determined law, which had been anticipated as a deduction from his theory of molecular vortices. In this sense (the predictive ability) he wished

---

[80] Rankine, "Geometrical Representation", pp.364-75.
[81] Ibid., p.364.
[82] Ibid., p.368.

to suggest that his own formulation of the dynamical theory was the more fundamental.[83]

Having derived the criterion quoted above, there followed a section entitled "Of the use of the Economiser or Regenerator in Thermodynamic Engines".[84] In accordance with this most efficient cycle, "part...of the heat emitted during the lowering of the actual heat may be stored up, by being communicated to some solid conducting substance, and used again by being communicated back to the elastic substance when its actual heat is being raised".[85] The apparatus for achieving this was the "economiser of regenerator", used by Robert and James Stirling and Captain Ericsson in different forms. He neglected to describe the form of the "plunger" on the Rankine and Napier engine. These were all actual regenerators. In order to make a successful application of the theory to practice, it was necessary to construct a "perfect regenerator" (no doubt a conceptual companion to the "perfect engine" of Thomson et. al.): a device having an indefinite number of strata, each serving to store up and give out the heat required in an indefinitely small variation of the actual heat (not temperature) of the working substance; a large mass and an extensive surface; a conducting power so great that it could emit and receive heat instantaneously without any difference in temperature between any part of the regenerator and contiguous portions of the working substance; and the property that no heat was lost by conduction or radiation.[86]

With such a perfect device an engine working between the same limits of actual heat as one without would have the same maximum efficiency. In fact the "advantages of a regenerator" (now theoretically demonstrated) were to enable the maximum efficiency to be obtained with less expansion and therefore with a smaller engine.[87] We should recall that one of Rankine's major criticisms of the Ericsson engine was the "enormous" size

---

[83] Ibid., p.376.
[84] Ibid., pp.368-9.
[85] Ibid., p.368.
[86] Ibid., p.369.
[87] Ibid., pp.371-2. Section 30 gives these advantages.

which had decreased its chances of economic viability. Incorporating a regenerator meant that "curves of equal transmission" (for example, those given diagramatically by two parallel lines of constant volume but changing pressure, with actual heat varying for Q_1 to Q_2) could replace the curves of no transmission (adiabatics) in the theoretically most efficient cycle without any diminution of the (maximum) mechanical effect produced. Thus an air-engine with regenerator working on a cycle of isothermal expansion, constant volume (but falling actual heat and falling pressure), isothermal compression, and constant volume (but rising actual heat and rising pressure to original levels) could achieve the same maximum theoretical efficiency with less expansion than an air engine without regenerator working on the standard cycle of isothermal expansion, curve of no transmission, isothermal compression, and curve of no transmission.[88] The first cycle was of course that which Rankine and Napier's own engine attempted to embody practically. The "plunger" moved through the air to facilitate change of temperature (corresponding to change of actual heat) without substantial change of volume, twice: once as it cooled, and once as it was heated. It was this cycle which Rankine appears to have sketched for Napier between February and June of 1853.

One motive for this paper became clear. Rankine had filled a curious but important gap in the theoretical market:

> Owing to the want of a *general investigation of the theory of the action of the regenerator based on true principles*, those who have hitherto written respecting it have either exaggerated its advantages or unduly depreciated them.[89]

False principles and ignorance had led to extravagant claims or dismissals. Correct theories cleared the way for useful and well-considered practical improvements. Rankine's formulation of the dynamical theory was one particularly relevant example of such correct theorizing.

---

[88] Ibid., pp.371-4.

[89] Ibid., p.374. My emphasis. He excused Professor Barnard of the University of Alabama who had calculated the expenditure of heat in Ericsson's engine.

(Significantly, he had not yet made direct recourse to the formula for efficiency in terms of absolute temperatures which characterized Thomson's and Clausius's writings and had been the former's justification for optimism towards the Stirling engine.) As if to underline this deep theoretical connection, a coda to the initial sections of the paper recapitulated the eleven propositions given so far (including those on regenerators, but having no direct connection with steam-engines) condensed into the two most important. These two gave the geometrical application to the case of heat and expansive power of "two axioms respecting Energy in the abstract":

> I. The sum of the Energy in the Universe is unalterable.
> II. The effect, in causing Transformation of Energy, of the whole quantity of Actual Energy present in a substance, is the sum of the effects of all its parts.[90]

These statements had formed the basis of Rankine's paper "On the general law of the transformation of energy" presented to the Glasgow Philosophical Society in January 1853.[91] The second somewhat inscrutable axiom amounted to a generalized statement of a second law of thermodynamics.[92]

Only after having completed this analysis of the regenerator and the air-engine, and having summed up with such grandiose statements on "Energy" did Rankine go on to consider the relationship between his Q (actual heat) and T (absolute temperature). The latter had been unnecessary for his analysis. Having demonstrated the power of his theory in solving the regenerator problem, he was now free to make the connection between Q and T: Mayer's hypothesis implied that they were directly proportional and so isothermals were in fact curves of equal temperature. The diagrams used to convince Napier clearly showed no qualms about this

---

[90] Ibid., pp.374-5.

[91] "On the General Law of the Transformation of Energy", *Proceedings of the Glasgow Philosophical Society*, 3(1848-55), 276-80; *Philosophical Magazine*, fourth series, 5(1853), 106-17.

[92] James Clerk Maxwell's views on the inscrutibility of Rankine's second axiom and its ability to strain "our powers of deglutition" are reproduced at length in Tait, "Memoir", pp.xxix-xxxi.

matter, where curves of equal temperature (rather than constant "actual heat") appeared to define the various cycles. But it was useful in the present context to try to show that the "actual heat" was prior to experimental deductions made about the relationship between temperature and "actual heat".[93] Significantly, although the following sections of the paper dealt with many other forms of engine, and indeed the air-engine itself in practical form, now in terms of temperature of working substances (rather than "actual heat"), it was only the engines using permanent gases (such as air), both with and without a regenerator, which were grouped before Rankine's consideration of the connection between actual heat and temperature. The implication was surely that Rankine's own formulation of the dynamical theory could solve the vitally important problem of the regenerator independently of any empirically determined laws.

Detailed numerical investigations of different categories of engine followed, one conclusion being that an efficient regenerator was important for the economy of fuel in an air-engine. Calculations showed "the great additional bulk of engine required, in order to obtain maximum efficiency without a regenerator."[94] For an engine working between 343 and 35 degrees centigrade the air engine had an efficiency of 1/2; whereas for a steam-engine, taken as one type of vapour engine, working between 140 and 40 degrees centigrade, the maximum theoretical efficiency was only 0.2424. This was unavoidably reduced by incomplete expansion of the steam, and by the fact that the temperature of the water was initially not raised by compression. Taking into account these two factors which mitigated against a vapour engine working on the optimum cycle, the efficiency of the engine fell to 0.1413.[95] Rankine explained his motives for this apparently damning evaluation:

---

[93] Rankine, "Geometrical Representation", pp.376-7. These pages include an explicit attempt to motivate and justify the hypothesis of molecular vortices - after its successes with the air-engine have been given.

[94] Ibid., pp.379 and 385.

[95] Ibid., pp.397-400.

> My object in entering thus minutely into the theory of the efficiency of vapour engines is, not so much to provide new formulae for practical use, as to illustrate the details of the mechanical action of heat under varied and complicated circumstances, and to show *with precision* the nature and influence of the circumstances which *prevent the production, by steam engines, of the absolute maximum efficiency corresponding to the temperatures between which they work*.[96]

I have discussed earlier the rich complex of ideas of precision which permeated both the scientific and engineering cultures that Rankine had been exposed to (chapters 2 and 3). The statement above began to show how, with the aid of the dynamical theory of heat in particular, Rankine believed that the *exact* extent to which practice fell short of theory could be measured. I shall return to this in more detail in chapter 7, and show how such an assertion was useful as a means of integrating the class of civil engineering and mechanics within the University of Glasgow.

It is clear that the problem of the regenerator was commercially worth investigating. Rankine had solved it within his own theoretical framework. As well as justifying his own scientific work he had provided an incentive for public faith, in particular the faith of a scientific community, in the action of the engine he was at that very time seeking to "improve". So far from being peripheral to the "theoretical" presentation of thermodynamics then, the air-engine had appeared, as with Thomson and Joule, as a subject of major consideration of undeniably topical appeal within what was, in terms of Rankine's prestige amongst the intellectual elite of the Royal Society, nothing less than a fundamental paper.

---

[96] Ibid., p.404. My emphasis.

Air-engine diary (II)

Just over a week after reading his Royal Society paper, Rankine wrote to Napier, again from Gordon's office, discussing the British and American patents, and supplying details of the progress of the various models. His tone was vehement and exasperated: Napier needed further arguments for the necessity of an American patent. Rankine explained that their "improvements" were

> the best means of making Ericsson's engine workable...it will be worthwhile for the makers of his engine to pay handsomely for permission to do so;...whatever improvements the Yankees invent, they are sure to patent them in Britain.[97]

However, there were problems. White had had the drawings of the (British) model for two months but had produced nothing yet: "I shall make no remarks for the present less I should do him injustice"; but he toyed with the idea of having the model constructed speedily and stylishly in London. The British patent had "not hitherto been pushed with sufficient vigour", largely, if not entirely, because of the failure to complete the experimental engine then being constructed by James Gray & Co.,

> for until some experiments are made we can scarcely expect anyone to adopt the new principles.[98]

Whatever the prestigious circumstances might be, or however firm the principles, it seemed that theorizing could not hope to replace the much more straightforward proof of practical experiment which was vital to swing public opinion in favour of the new technology.

By June 1854 there had at last been some tangible progress: a model suitable for the U.S. Patent office had been completed (not by White), and was about to be dispatched to John Rankine via Liverpool, soon to be followed by a patent specification drawn up by the solicitors Moncrieff,

---

[97] Rankine to Napier, 27 January 1854.
[98] Ibid.

Paterson and Forbes.[99] But James Gray & Co. had still not managed to make the experimental engine workable, a cause of much disappointment.

By now Ericsson's ill-fated air-ship had sunk (chapter 4). Without this great symbol of the future of the marine air-engine the task of his British rivals was in many ways more arduous. If Ericsson was by now a less formidable competitor, in the minds of the public "the age of caloric" may have plummeted from view as suddenly as the caloric-impelled ship. This practical reality of failure made it still more imperative for Rankine and Napier to provide some practical proof of success.[100] Notwithstanding the British partners' singular lack of convincing data, in July 1854 Napier tentatively raised the possibility of applying the new engine to the ships of the Clyde. Rankine replied abruptly:

> With respect to...your firm taking up the invention, I think it is evident that nothing on this subject can be decided or even discussed until some experiments have been made; for in fact Mr. [Robert] Napier could not reasonably be expected to listen to any suggestion of this kind without some practical evidence of the utility of the invention.[101]

By September "practical evidence" was still not forthcoming. With the engine now patented in the United States, Rankine primed his uncle with an appropriately "short and simple statement of the general principles of our improvements...and the advantages we expect from them".[102] Publicity was all: this paper was designed as instant explanation, free from the vagaries and absurdities that had supposedly

---

[99] Rankine to Napier, 15 June 1854. Rankine had shown the model and drawings to William Carpmael (1804-67) a London agent specializing in patent law, and Secretary to Section G at the 1839 Birmingham Meeting of the BAAS. See Morrell and Thackray, *Gentlemen of science*, pp.306-7. Carpmael approved of them: all documents regarding the U.S. patent were to be submitted to Carpmael before despatch. "His advice has been very useful in the preparation of the model."

[100] Since Rankine and Napier continued with their venture after the failure of Ericsson's ship, and Napier still regarded the engine as a possible replacement for the marine steam-engine, Daub's sweeping statement that "attempts to attain high horsepower outputs with hot air engines were abandoned" following this event needs qualification. See Edward E. Daub, "The regenerator principle in the Stirling and Ericsson hot air engines", *British Journal for the History of Science*, 7(1974), 259-77, on p.259.

[101] Rankine to Napier, 17 July 1854.

[102] Rankine to Napier, 11 September 1854.

impeded Stirling and (less so) Ericsson, and "such as he [John Rankine] may publish in their scientific journals".

Ironically, for such a consummate self-publicist and manipulator of Victorian institutional machinery, Rankine found his hand forced, unable to avoid making a public statement on the Napier and Rankine engine before Section G of the British Association contrary to his previous wish, even though the experimental engine lay unfinished. It was not a simple decision. Rankine's extended soul-searching demonstrates how carefully these seemingly effortless public statements were encoded. It was well-known that they had obtained a patent for their improvements, and the specification had been published. Although he had made no specific mention of their inventions, Rankine had been more than open about his support for the air-engine with its regenerator before the Royal Society. What is more, at the 1853 Meeting in Hull, the debates over Ericsson's engine, so prominent within the Institution of Civil Engineers, had sent waves through the BAAS. As Rankine now informed Napier, William Hopkins, the President, had referred at great length to the "new views" on the nature of heat.

From a Section A perspective which echoed Joule's pronouncements to the Royal Society in guiding the "practical machinist" and William Thomson's statements on the perfection of engines and engineers (chapter 4), Hopkins commended the views which had "recently sprung up" as

> highly interesting theoretically, and important in their practical application, inasmuch as they modify in a considerable degree the theory of the steam-engine, the air-engine, or any other in which the motive power is derived immediately from heat; and it is correct theory alone which can point out to the practical engineer the degree of perfection at which he may aim in the construction of such machines, and which can enable him to compare accurately their merits when the best construction is arrived at.[103]

Furthermore, Rankine reported that Fairbairn, President of Section G had "specially referred to the Air-Engine as a subject of interest". In his

---

[103] William Hopkins, "[Presidential Address", *BAAS Report*, 23(1853), part 1, pp.xli-lvii, on p.xlv.

address, appropriately entitled "On the progress of Mechanical Science", Fairbairn, not given to making rash statements, had spoken of

> the wonders that were likely to be achieved by Capt. Ericsson in the completion and substitution of the caloric for the steam-engine. The public, and particularly the engineering world, were greatly interested by a question of such vast importance as a new motive power...[104]

This juxtaposition, by Rankine, made it quite clear that he believed the air-engine ought to be regarded as an application of recent theory to practice. If he were to remain silent, "it would be taken for granted that I apprehended that the invention would prove a failure":

> Besides it is ten to one that some daft mechanician will read a paper of nonsense on the subject...to which I shall have to reply.[105]

It was very much a question of effective management of the media. A reply in the form of a speech would appear only in the papers, and not in the *BAAS Report*. I would suggest that it was most important that any printed statement be exactly in Rankine's own words so that he might, with Napier's tacit approval, exert absolute control over the engine's public presentation. A well-prepared document could be of great value in terms of publicity for the air-engine, and for the peculiar benefits of "engineering science". The often-stated desire to disseminate practically useful knowledge was a convenient rhetorical cloak behind which to hide a rather more obvious personally beneficial and commercially motivated advertisement. The BAAS provided the opportunity to publicize the invention, and an underlying methodology, on a national scale.[106]

Meanwhile, having dealt with the United States and the BAAS, Napier

---

[104] William Fairbairn, "On the progress of Mechanical Science", *BAAS Report*, 23(1853), part 2, pp.116-7, on p.116.

[105] Rankine to Napier, 11 September 1854. This statement does more than a little to deflate the rhetoric of the *harmony of theory and practice*. See chapter 7.

[106] In a postscript to this letter Rankine suggested painting a sectional model (already constructed) and exhibiting it at the meeting to illustrate the explanation. The obvious place to read a statement would be at a meeting of the Mechanical Science Section of the BAAS (Section G). Rankine would have been the first to acknowledge this as an ideal platform from which to expatiate upon the triumphs of scientific principle applied to practice realized in "improvements" in mechanical design and "advantageous" technologies.

was provided with one or two interim arguments. It was to be remembered that the advantages of the tubular bottom and heat-screen were

> perfectly obvious, and do not require the aid of direct experiment to prove them;...the practical difficulties attending the use of air-engines....such as the burning & cracking of the receivers etc. were successfully overcome by Stirling, whose engine, at the very lowest computation of its performance, was more economical than Mcnaught's.[107]

The abstracted paper, "On the Means of realizing the advantages of the Air-Engine" appeared in the *BAAS Report* .[108] The title itself deserves comment: the "advantages" of the air-engine were taken as established, theoretically, beyond doubt. It was merely the means of bringing them into practice, embodying them in an actual engine, or "realizing" them, that required explanation. There were four main sections, corresponding to those of the larger paper, which might be summarized as i) the mechanical action of heat and its relation to theoretically perfect engines; ii) perfect and actual steam-engines; iii) perfect and actual air-engines; and iv) the Rankine and Napier engine. Many of the arguments used are by now familiar: most obviously the paper was structured to present an image of theory applied to practice, evaluating engineering success in approximating upwards to the maxima of theoretical perfection.

First came an explanation of the fundamental laws of the mechanical action of heat and their application to determine the efficiency of "theoretically perfect engines", working between given limits of temperature. Since efficiency increased with the distance between those limits, and air could be employed safely at temperatures far exceeding those at which the pressure of saturated steam ceased to be safe and manageable, the maximum theoretical efficiency of air-engines consistent

---

[107] Rankine to Napier, 11 September 1854. William McNaught was a Glasgow engineer who had introduced separate expansive cylinders to existing engines from about 1845. These stationary compound engines were substantially more efficient than Woolf's. See Hills, *Power from steam* , pp.157-9.

[108] *BAAS Report* , 24(1854), part 2, 159-60.

with safety was much higher than for steam-engines. For a temperature of 650 degrees Fahrenheit "at which the air-engine has been successfully worked" the pressure of saturated steam was a phenomenal 2100 psi, much higher than could reasonably be sanctioned in practice; for air it was optional, depending on the density of the air.[109]

In the second section the causes of "waste" of heat and power in steam-engines were classified. The "actual efficiency" was compared with both the "maximum theoretical efficiency", and with the "maximum actual efficiency" reasonable to expect from mechanical improvements in design. This of course was essentially an estimate on the basis of experience, but no doubt referred to the inherent causes of inefficient working, such as that due to incomplete expansion which Rankine had dwelt upon in recent paper presented to the Royal Society.

The same was done for air-engines in the next section. The actual efficiencies of the Stirling engine and of Ericsson's engine of 1852 were compared with the efficiencies of theoretically perfect engines for the same limits of temperature. These engines were those for which "satisfactory experimental data have been obtained already", and conveniently filled the worrying gap created by Rankine and Napier's own lack of experimental data. The figures given throughout as measures of efficiency represented pounds of coal consumed per horse-power per hour. (Thus if the price of coal was known, the price of the power could be immediately deduced.) From this analysis, even though the actual consumption of air-engines was about 3 or 4 times the "consumption of a theoretically perfect engine",

> It is thus proved that an air-engine has actually been made to work successfully, and to realize an oeconomy of fuel superior to that of ordinary steam-engines, and, in fact, surpassing the utmost limit to which it is probable that the oeconomy of

---

[109] Moreover, "[The engine] possesses the important and incontestable advantage, that even should an air-receiver burst...the explosion would be harmless, for its force would not be felt beyond the limits of the engine itself, and hot air does not scald." Rankine, "Advantages", p.160.

> double-acting steam-engines can ever be brought.[110]

As if this "proof" were insufficient, Rankine listed the further advantages of the Stirling engine in terms of its compactness, ease of working, relatively small need for repairs in relation to steam-engines, and low oil consumption.

All this had not been enough to "induce practical men to overcome their natural repugnance to exchange a long-tried method for a new one." Worse still, both of these air-engines had been neglected by "scientific" men (note the dichotomy) due to their representation as "instances of *power created out of nothing*, - the popular delusion commonly called "*the perpetual motion*." This reference echoed once more the discussions and debates which had taken place, largely in connection with Ericsson's engine, reiterated Rankine's comments in his first letter to Napier of February 1853, and in his paper presented to the Royal Society of London.

The engines of Stirling and Ericsson "wasted" more than two thirds of the fuel used through two specific causes: deficiency in the extent of the heating surface; and communication of heat from the furnace to the working air "at those periods of the stroke when it is not performing work". Formally Rankine asserted that the

> necessary conclusion is, that the more we remove these two causes of waste of fuel, the more nearly shall we approximate to the theoretical extent of the oeconomy of the air-engine, an extent far exceeding that to which the oeconomy of the steam-engine is restricted; and the more fully, in short, shall we accomplish that which has hitherto been very imperfectly done; i.e. REALIZE THE ADVANTAGES OF THE AIR-ENGINE.[111]

Finally Rankine described his and Napier's engine, with its heat screen intended to prevent both of these deficiencies. There could be no doubt as to the conclusions which should be drawn. It was shown both theoretically and practically that existing air-engines had measureable advantages over all steam-engines, even taking into account any possible future mechanical improvements. Attention should obviously be re-directed

---

[110] Ibid., p.159.
[111] Ibid., p.160.

towards air: Rankine and Napier knew already how air-engines could be improved still further. The only lacuna in this otherwise carefully constructed argument was the key element of practical proof of the efficacy of the heat screen, not in isolation, but in a fully functioning experimental engine.

As the experimental engine tortuously approached practical completion it became ever more necessary to justify and publicize it effectively. By the end of September 1854 an American patent had been granted.[112] A campaign of publicity was waged on both sides of the Atlantic. As chance would have it, illness had prevented Rankine from attending the Liverpool meeting but he had been well enough to send the promised paper, with an abstract, to the Secretary of Section G. In addition to appearing in the *BAAS Report*, the abstract had appeared in various newspapers including *The Times* (on 30 September 1854) and it had been sent much further afield to the "Editors of Newspapers and Periodicals in America & elsewhere."[113] Caution was still necessary. This had given "considerable publicity to the invention", so much so that

> it may be advisable (if there is a reasonable prospect of our having some experiments made soon) not to publish the <u>paper at full length</u> until we have at least a few experimental results to add to it...the absence of experiments...would excite remark.[114]

Rankine had sent the proofs of part of the long paper to his uncle on 6 December 1854. From John's reply it is clear that the missing section had been that dealing with the practical details of the improved engine:

> You say that the printing of the other parts of it awaits the completion of the Engine in course of erection.[115]

They had reached a compromise. Coinciding with Rankine's new-found duties as substitute for Gordon at the University of Glasgow (chapter 7), "On the Means of Realizing the Advantages of the Air-Engine" appeared in

---

[112] Rankine to Napier, 1 November 1854, having just received the information from John Rankine.

[113] Rankine to Napier, 12 October 1854.

[114] Ibid.

[115] Rankine to Napier, 7 February 1855. Contains Rankine's copy of part of John Rankine's letter of 20 January.

the January edition of the *Edinburgh New Philosophical Journal* in truncated form: the first three sections only were published in full. There was to be no doubt about the purpose of this lengthy essay, which at the outset promised to set forth

> the reasons for believing that...such [air-engines] will be found to be the most economical means of developing motive power by the agency of heat.[116]

But the article, although marked "to be continued", had no sequel. We can only assume that it was considered unwise to publish the crucial fourth section, dealing with the "actual engine" of Napier and Rankine, without the experimental results which had been so painfully slow in materializing.[117]

Rankine's uncle had written again on 20 January 1855, urging his nephew "as to the necessity for experiments, and the probable success of the invention in the United States should the result of the experiments be favourable." Rankine gently prodded Napier with this bitter-sweet news:

> You will see from it [the letter] his opinion as to the necessity for experiments, & the probable success of the invention in the United States should the result of the experiments be favourable.[118]

John Rankine recognised that there had been technical problems with the experimental engine. His vehemence reinforced his nephew's in this respect:

> ...if the invention is to be of any pecuniary benefit to you it is very unwise to lose time in affording the only proof of its utility which the practical world will accept. I am aware that there is a strong disposition in the old world against all innovation. In this new world however, the disposition is remarkably the reverse, and I suspect it would have been more conducive to your success had your experimental engine been erected and exhibited here. It is not too late to do this yet, and I wish you would think of the matter and let me hear from you on the subject.

---

[116] *Edinburgh New Philosophical Journal*, new series, 1(1855), 1-32, on p.1.

[117] Indeed it seems likely that the results simply did not meet their high expectations. However, by the end of December Rankine was able to report the result of a consultation with Forbes, the solicitors, about contracts for engines in general which may indicate some optimism at that time. See Rankine to Napier, 26 December 1854.

[118] Rankine to Napier, 7 February 1855.

The importance of the subject was potentially vast:

> The late Secretary of the Navy, when I sent him the abstract of your paper, wrote to me "I consider the subject of infinite importance to every civilized Government, and when in office I gave every encouragement to Ericsson": And so much enterprise is there amongst all classes of our people, that I have no doubt whatever that you would find no difficulty from want of pecuniary means. If there is any feasibility in the invention at all, I rather conclude there would be competition to be connected with it.[119]

With optimism such as this expressed from high places Rankine's "air-engine enthusiasm" loses any remaining trace of impulsive behaviour. Had the engine been a practical success, backing from the U.S. Navy would very likely have made Rankine and Napier substantial fortunes.

Regenerating the engineering chair

Air-engine enthusiasm had also made itself felt in the University of Glasgow. In January 1850 the subject of the Stirling engine had been deemed a subject suitable for William Thomson's natural philosophy class.[120] More recently, during the University sessions of 1853-4 and 1854-5, Watt Prizes were offered to students for essays on "The Comparative merits of the Air Engine and Steam Engine, considered theoretically and practically".[121] The choice of subject clearly reflected the fervent contemporary discussion. But it manifested too the striking congregation of William Thomson, Lewis Gordon, and Rankine himself, all associated to a greater or lesser degree with the University, and all actively promoting the air-engine to the detriment of the steam-engine.

Late in 1854 Lewis Gordon, having practically given up teaching at

---

[119] John Rankine to W.J.M. Rankine, 20 January 1855, copied into Rankine to Napier, 7 February 1855.

[120] See William Thomson, 15 January 1850, lecture 43 in William Smith, "Notes of the Glasgow College natural philosophy class taken during the 1849-50 session", MS Gen. 142, University Library Glasgow; and Smith and Wise, *Energy and Empire*, p.297.

[121] See Prize and Degree List of Glasgow College 1833-63, Glasgow University Archives.

the University after meeting a consistently hostile reaction from colleagues (chapter 6), applied for a room in which to convene his class. By March 1855 the class was being taught by none other than W.J.M. Rankine, lecturing throughout the spring of 1855 on "applied mechanics"; and on heat-engines (chapter 7).[122] Within these lectures, the air-engine played a major role. Useful as propaganda for a scientifically and economically valuable course, the air-engine demonstrated how true practical economy could be directly explicable *theoretically* in terms of the new thermodynamics and the "diagram of energy". This way of dealing with the air-engine provided a model for academic engineering and Rankine's engineering science. Theory provided the justification and motivation for the sustained improvement of practice approximating towards a determined limit of theoretical perfection (chapter 7).

Throughout this period, in the spring and early summer of 1855, hopes for the eventual success of the engine remained high, bolstered by correspondence from John Rankine and publicized through the *Edinburgh New Philosophical Journal* and other journals across the world. Rankine had convinced himself of the engine's superiority, and was anxious to ensure Napier's continued support. He undertook a rapid analysis and dismissal of a steam-engine designed by William Siemens. William Thomson had written to Rankine, describing the engine at work: it used superheated steam between 600 and 212 degrees Fahrenheit "simply as air in an air engine", presumably without condensing, and had a high ratio of actual to theoretical efficiency. But Rankine was adamant: the persuasive power of this comparative method, the fact that the engine lacked a heat screen, and that it had an inefficient heating surface, left him "confident that ours will be more economical". It was true, however, that the vital experiments had still to be made, a matter only too clear as he

---

[122] "Synopsis of Lectures on Heat-Engines delivered at Glasgow in March and April 1855, in connection with Professor Lewis D.B. Gordon's course of Civil Engineering and Mechanics, by W.J. Macquorn Rankine, C.E., F.R.SS Lond & Edin. etc" in DC 90/3/1, Napier Papers, Glasgow University Archives.

plaintively implored:

> Have you got the engine & drawings from Gray yet?[123]

In Belfast, James Thomson (William's brother) was also following developments closely. In August he interrogated Napier:

> What progress are you making with the air engine? Do you mean to bring the subject before the British Association?[124]

During September 1855 the British Association met in Glasgow and the ideal opportunity was made to give a public presentation of "engineering science" fully consistent with the creation of the Napier and Rankine engine. There were indeed intimate connections between this meeting, Rankine's address as President of Section G, and the election to the Glasgow professorship which soon followed. Rankine's use of a rhetoric of *the harmony of theory and practice* promoted the integration of his form of academic engineering within the University of Glasgow and the air-engine had played a vital role in the genesis of this rhetoric. I shall examine this essential academic context in chapters 6 and 7.

We can only guess at the eventual fate of the engine. It was clearly not the great personal or commercial success which so many had hoped for, nor did it fulfil the expectations of Gordon, Thomson, and Joule. Over half a decade Rankine and Napier had worked to make the machine a success, expending time, effort and in Napier's case a substantial amount of money.[125] The experimental engine was finally built: a set of indicator

---

[123] Rankine to Napier, 26 June 1853. Napier probably needed these constant reminders of their imminent success: he was, after all, paying for all the costs of the British development and patent. See Rankine to Napier 21 September 1855, with details of payments made to himself and Moncrieff, Paterson and Forbes totaling £41.13.10.

[124] James Thomson to James Robert Napier, 6 August 1855, DC 90/3/5, Napier Papers, Glasgow University Archives. From 1854 Thomson had held a temporary position teaching engineering at Queens College Belfast. He became professor there in 1857, moving to Glasgow to replace Rankine in 1873 James Thomson, in Sir Joseph Larmor and James Thomson (eds.), *Collected papers in physics and engineering* (Cambridge University Press: Cambridge, 1912), p.xlviii. The letter to Napier also mentions experiments on the power and efficiency of water wheels.

[125] A document (not dated) in DC 90/3/3, Napier Papers, Glasgow University Archives, marked "Cost of Air Engine" gives amounts payable to Moncrieff, Forbes and Patterson (up to 1857), for Patent Stamp, Gray's Act, and Rankine to a total amount of £397.7.6.

diagrams, those most tangible and informative of inscriptions, has survived. Some of these are dated as late as 14 March 1857.[126]

The air-engine was not successfully improved. This episode finally closed with a letter to Napier of 2 June 1860. Seven years after the provisional specification had been made Rankine admitted it was no longer worth carrying on:

> My opinion is in favour of letting the patent expire.[127]

Coda: the demise of the air-engine enthusiasm

In this final section I shall outline the apparent waning of the public prospects of the improved air-engines following Ericsson's dramatic failure and the more personal lack of success in producing a set of convincing experimental data, practical proof for the viability and economy of the Rankine and Napier engine.

On 28 October 1857 Rankine addressed the first meeting of the Institution of Engineers in Scotland, an organisation he had helped substantially to form.[128] He spoke, appropriately enough, on the "Nature and Objects of the Institution", promoting his own conception of scientific engineering:

> If I were required to state in one word what constitutes the characteristic advantage of skilful and scientific practice in the useful arts, I should say - ECONOMY.[129]

---

[126] Indicator diagrams in DC 90/3/14, Napier Papers, Glasgow University Archives. These are very rough, but they appear to show that the engine was worked, in some cases manually, and in others via another (steam) engine with the heat screen in various positions.

[127] Rankine to Napier, 2 June 1860. This was by no means the last of their joint ventures in patenting: see "Improvements [sic] in Boilers and Valvular Mechanisms for Steam Engines", November 1862, No. 3128 (largely for high pressure marine engines, provisionally protected only); and "Improvements [sic] in Rudders", 29 December 1865, No. 3367: "The object of the improvement...is to increase the *efficiency* of the screw for propelling, and of the rudder for steering" (p.1, my emphasis).

[128] "On the Nature and Objects of the Institution", *Transactions of the Institution of Engineers in Scotland*, 1(1857-8), 1-12. See also chapter 8.

[129] Ibid., p.4.

Economy of fuel, he continued, "is, perhaps, the most important subject coming before any one studying practical mechanics."[130]

Beyond suggesting the establishment of measurements of the comsumption of fuel in different furnaces in the city of Glasgow, rather in the fashion of the Leans earlier in the century in Cornwall (chapter 4), Rankine chose to pinpoint the air-engine with its regenerator, as a topic of continued interest with a distinguished history:

> The economy of fuel is a subject that, forty years ago, attracted the attention of the Rev. Dr. Robert Stirling, who invented an apparatus for saving heat, called the "regenerator," or "economiser."[131]

By this method,

> heat which would otherwise be wasted is thus stored up and saved, to be used over and over again. This apparatus, though employed to a limited extent, has never been brought into general use. But recently, Mr. [C.W.] Siemens devised an application of the same principle to furnaces, which seems to have answered well; and it is to be hoped that the use of this principle may be farther developed.[132]

In June 1855 the Siemens steam-engine had been dismissed by Rankine and Napier as a competitor to their air-engine, after a careful consideration of its relative efficiency. But Siemens' regenerative furnace (chapter 4) had become a commercial success.

Steam-engines, on the other hand, seemed to have reached almost the greatest economy shown by theory. Therefore, to "economise further" it was necessary to introduce a new principle such as

> superheated steam, or *heated air*, which is analogous to superheated steam, inasmuch as it can be worked at a high temperature without attaining a dangerous pressure. The theory of this subject is now well understood; and the only difficulty that exists is as to its convenient practical application.[133]

The undoubted references to the air-engine were however rather veiled, in marked contrast to the earlier private and public ebullience. In light of the previous acts of self-publication the suggestion of doubt can

---

[130] Ibid., p.8. I discuss the central role of economy further in chapters 7 and 8.

[131] Ibid., p.8.

[132] Ibid.

[133] Ibid., p.9. My emphasis.

certainly not be explained away as mere reticence. It was becoming clear that only with great practical difficulty could the air-engine be made to revolutionize the production of "mechanical effect". But the existence of indicator diagrams for the Napier and Rankine air-engine suggests that there was more than a little hope that at last some practical proof might be obtained of the advantages over the steam-engine.

The lengthier and more detailed "Report on the Progress and State of Applied Mechanics" read to the Glasgow Philosophical Society on 7 April 1858 contained no explicit mention of the air-engine, or even of the more general "economiser" principle.[134] Indeed, in a section discussing the energy of heat, the Reporters stated that the only elastic substances so far used were water, air, alcohol and ether,

> ...and of these the last three have been used to so limited an extent, that water, operating in the STEAM ENGINE, may be said to be the only vehicle which is extensively used in practice for the mechanical action of heat.[135]

The expression for the "efficiency of the elastic vehicle" was given (in terms of difference in absolute temperature) but now the emphasis was placed firmly on the steam-engine, in spite of many earlier assertions of the air-engine's supposed theoretically superior efficiency on the grounds that it could effectively use a greater range of temperatures than steam.[136] The suggestion was now made that "superheating" would be the "most promising method of increasing the efficiency of steam".[137] No mention of the air-engine was made either in the address given by Rankine as a sequel in November 1861.[138] By then the air-engine patent had finally been allowed to drop.

---

[134] Rankine and Napier were on the committee, of which the former had been the convenor. The report is printed in *Proceedings of the Glasgow Philosophical Society*, 4(1855-60), 207-30. Some alterations were made for the printing in November 1858.

[135] Ibid., p.227.

[136] Ibid., p.228.

[137] Ibid., p.229.

[138] W.J.M. Rankine, "[Presidential Address at the opening of the sixtieth session]", *Proceedings of the Glasgow Philosophical Society*, 5(1860-4), 83-9.

It is perhaps not entirely coincidental that by 29 October 1858, Rankine was in a position to write to Napier on this new "application of theory to practice": "I have considered the subject of superheating steam by hot water coils, and have the following opinions". He suggested superheating steam to about 400 degrees Fahrenheit, providing a rough and ready calculation leading to an estimated fuel consumption per indicated horse power for one example of engine. The conclusion was succinct: "Any amount of superheating however small will save fuel." In a much overwritten postscript he provided Napier with a Provisional Specification: "You should without delay get the invention Provisionally Protected." The original version, so far as it is discernable, dealt only with steam-engines, "with a view to economy of fuel". But for greater generality, the scope was widened to suggest

> heating steam, and other elastic fluids used in working engines, by means of currents of liquid at a high temperature circulating in pipes or passages, round, over, or near to which pipes or passages the steam or other elastic fluid to be heated is made to pass.[139]

Insofar as the Glasgow Philosophical Society Report purported to give the present state of applied mechanics, it was clear that the air-engine was no longer a serious contender for the economical working promoted by engineering science. Superheating steam seemed to offer more immediately realizable advantages and economies, which, as before, Rankine and Napier were clearly avidly seeking to exploit. This "failure" of the air-engine was contingent on other "successes" which were to be presented by Rankine later within the same engineering science framework: the development of the increasingly fuel-efficient compound marine-engine by John Elder, almost certainly with Rankine's close assistance, contributed further to the gradual dissipation of enthusiasm in Scotland for the air-engine as an economical prime mover applicable to marine trade.[140] Having failed the

---

[139] Rankine to Napier 29 October 1858.

[140] Such engines first appeared in 1856, manufactured by the firm of Randolph & Elder. See also Donald S.L. Cardwell and Richard Hills, "Thermodynamics and Practical Engineering in the Nineteenth Century", *History of Technology*, 1(1976), 1-20, p.11.

practical test, the air-engine was no longer a candidate for engineering science economy.

In this chapter I have focused primarily upon the practical context of the air-engine: it has become apparent that personal careers, institutional debates, and the justification of the dynamical theory of heat all drew upon the flamboyant public spectacle of Ericsson's caloric ship, the more sustained enterprises of the Reverend Stirling and his brother James, or the carefully planned presentations of Napier and Rankine. A significant complementary role was created for the air-engine within the hallowed precincts of Glasgow College. In chapter 7 I analyse the complex processes by which the Glasgow chair of civil engineering and mechanics was re-vitalized, processes in which the air-engine again took a major part and which led to the election of Macquorn Rankine in 1855. In order to understand fully the severe difficulties faced by him in establishing academic engineering in Glasgow I now examine the career of the first British professor of civil engineering and mechanics: Lewis Gordon.

CHAPTER SIX

Making space for engineering science: competition in the intellectual market

Introduction

J.B. Morrell has shown how three Edinburgh University professors of the early nineteenth century modified the content of their classes in order to maximize attendances, operating as they did within a system in which student fees were paid directly to the professors themselves; furthermore, internal university politics and external wrangling in Edinburgh directly influenced the nature of the courses taught and the academic appointments made.[1] In an earlier paper[2] Morrell has investigated the struggles of the first regius professor of chemistry at Glasgow University, Thomas Thomson. The administrative power of this University, in particular the election of key professors and control of the substantial College revenues and property (five times the value of that of the University), rested with the Principal and the thirteen professors established before 1761 who constituted the "Faculty" or "College". (The Rector, Dean of Faculty, Principal and all other professors made up the less powerful Senate.) Professors appointed by the Crown to regius chairs founded after 1807, remained outside the College elite.[3] In general, professors

> could lose income if a chair in an allied subject were created and new subjects accepted for graduation. Personal interests

---

[1] J.B. Morrell, "Science and Scottish university reform: Edinburgh in 1826", *British Journal for the History of Science* , 6(1972), pp.39-56.

[2] J.B. Morrell, "Thomas Thomson: Professor of Chemistry and university reformer", *British Journal for the History of Science* , 4(1969), 245-65; see also his "Reflections on the history of Scottish science", *History of Science* , 12(1974), 81-94 for a discussion of related historiographical issues.

[3] For an analysis of the political complexion and institutional structure of the University in this period see Crosbie Smith and M. Norton Wise, *Energy and Empire. A biographical study of Lord Kelvin* (Cambridge University Press: Cambridge, 1989) especially pp.25-32; for a useful summary see Morrell, "Thomas Thomson", p.251. Regius chairs were established in natural history (1807); surgery (1815); midwifery (1815); chemistry (1818); botany (1818); materia medica (1831); forensic medicine (1839); theory of physic (1839); and civil engineering and mechanics (1840). The distinction had appeared after successful litigation by the Faculty against the Crown in 1809 following Lockart Muirhead's appointment to the natural history chair.

> were frequently hostile to change and encouraged recognized teachers to form conservative groupings, keen to preserve their status and monopoly. [At Glasgow] the College Professors strenuously maintained their privileges against the attacks of the Regius Professors led by Thomson.[4]

Thus, specifically in Thomson's case and by extrapolation much more generally, the process of institutionalization of an autonomous discipline depended crucially upon the forces of local circumstance.[5] In the next chapter I will show that to a significant degree Rankine's manoeuvres in re-forming the Glasgow University engineering course, which centralized engineering science and the methodology of the air-engine, were guided and dictated by pressures parallel to those which beset Thomson. To understand fully the context of Rankine's appointment to the regius chair, and to complete the historical picture, it is necessary first to recapitulate the troubled academic career of the Chair's first occupant, Lewis Gordon.[6]

A discussion of the early years of the engineering chair provides an excellent insight into the tense administration of the College in the early 1840s, throwing into stark relief Rankine's necessary dealings with the Faculty from 1855. Following closely on Thomson's experience of profound and active discontent, College squabbles focusing upon and combining political issues, the legal niceties of the regius professors' status, and the negotiable boundaries of engineering as an academic subject exploded in a maelstrom of sustained and bitter dispute between Gordon and the University administrators. This remarkable display of personal animosity, divided loyalty, and vested interest demonstrated the

---

[4] Morrell, "Thomas Thomson", p.253. See also James Coutts, *A history of the University of Glasgow, from its foundation in 1451 to 1909* (Robert Maclehose: Glasgow, 1909).

[5] Morrell, "Thomas Thomson", p.262.

[6] This chapter overturns many aspects of the paltry and misleading account given by C.A. Oakley, *A history of a faculty: engineering at Glasgow University* (University of Glasgow: Glasgow, 1973), pp.2-8. I also seriously question Mackie who states that engineering was "happily free from controversy" and that "almost automatically, and without serious opposition, it combined academic research with the promotion of enterprise in the life of the community". See J.D. Mackie, *The University of Glasgow 1451-1951. A short history* (Jackson, Son & Company: Glasgow, 1954), p.266.

enormous advantage of strong internal support and expert diplomacy in such an academic bid. Far from being automatic, acceptance and integration could be denied in the most forthright terms to a candidate (and a discipline) ill-prepared and inopportune. Particularly for a subject which might require laboratory equipment and space, experimental demonstrations, or illustrative models, there was a great deal more involved than simply walking into College at the beginning of the session and commencing lectures. Indeed, the unwished-for occupation of cherished space by *things* (other than books, students or professors) could lead to the exclusion, or restyling, of an entire subject; intuitions of the behaviour of potential students on grounds of occupation or social station might form the basis of equally cogent arguments for defence against invasion. In significant contrast, Rankine's calculated public and private campaign, which consciously built upon Gordon's experience, called upon existing internal support, substantial advance preparation, intimate knowledge of and by local Glasgow communities of engineers and other notables, diplomatic skill geared to this chosen context, and a conception of how engineering could be made academic in a non-threatening but substantial way, effectively tailored and efficiently marketed.

Lewis Dunbar Brodie Gordon

Before discussing Gordon's tenure of the Glasgow chair I outline his education and early career as a civil engineer, marking in passing both the contrasts and the striking similarities with Rankine.[7] Lewis Gordon was born in Edinburgh on 6 March 1815, the fourth son of Joseph Gordon, staunch liberal and distinguished member of the Society of Writers to the Signet, the senior corporation of solicitors in Scotland and one of the

---

[7] My account is based on Thomas Constable, *Memoir of Lewis D.B. Gordon, F.R.S.E.* (T. and A. Constable: Edinburgh, 1877), in particular pp.1-45.

oldest and most prestigious elites of the Scottish legal profession.[8] Lewis attended the Edinburgh High School, where he made the acquaintance of Edward Strathearn Gordon and mixed with others who were to become influential members of mid-Victorian society.[9] After studying briefly in Finchley, concentrating on mathematics in preparation for a place at the East India Engineering College at Addiscombe which did not materialize, he decided to become a civil engineer. Like Rankine he took steps to develop a broad portfolio of practical experience and, just as importantly, to infiltrate networks of engineering patronage (chapter 3). Lacking the immediate family connections which had opened professional doors for Rankine, Gordon looked further afield, arranging to work at James Stirling's machine foundry in Dundee for nine months in 1832. During this brief but calculated apprenticeship Gordon may have made his first acquaintance with the Stirlings' air-engine (chapter 4). Returning to Edinburgh, he enrolled in Jameson's natural history class and attended Forbes's lectures on natural philosophy given in the University during the session of 1833-4. Both classes were to be chosen by Rankine three years later (chapter 2). Gordon became "a favorite pupil"[10] of Forbes and since their friendship continued after Gordon left the University it is quite likely that the first two professors of engineering at Glasgow became

---

[8] See A.R.B. Haldane, "The Society of Writers to her Majesty's Signet", *Journal of the Law Society of Scotland*, 15(1970), 35-8. Together with the Faculty of Advocates they constituted the Scottish College of Justice. Historically any Court of Sessions action required a "summons" setting out the facts of the case and the remedy required. Each summons must be "signeted", that is, sealed with the Royal Signet and authenticated only by a Writer to the Signet, or W.S.

[9] Edward Strathearn Gordon, Lord Gordon of Drumearn (1814-79), *DNB*, practised as a lawyer, served as a Conservative MP and ultimately becoming Lord Advocate of Scotland.

[10] Constable, *Gordon*, p.8.

acquainted through their mutual professor of natural philosophy.[11]

Through the 1834 Meeting of the British Association, which Forbes had worked so assiduously to bring to Edinburgh,[12] Lewis Gordon met and impressed another BAAS enthusiast, Marc Brunel, who subsequently offered him employment on the recently-revived Thames Tunnel project.[13] After a few months spent dutifully supplementing his mechanical knowledge with the necessary skills of the architect, Gordon joined the project's resident engineer, Richard Beamish,[14] in London where he stayed until late 1836 working as one of group of assistant engineers hand-picked by Brunel. Retrospectively Beamish attested to their "constancy, courage, and ability", sterling qualities, no doubt, for the aspiring civil engineer or indeed any Victorian gentleman, but also coded reference to the agreement of Gordon and his colleagues to work long shifts under the ever-present threat of inundation and poisonous gas.[15] Such praise found a more

---

[11] See Forbes to J.T. Harrison (advanced course student in Rankine's second session 1836-7), 7 September 1838: "There has been a considerable break-up...amongst your associates in the Nat. Phil. Class...I have kept my eyes pretty well upon those with whom you were more particularly associated...Lewis Gordon is now studying at Freiberg...I heard from him not long ago.". Quoted in J.C. Shairp, P.G. Tait, and A. Adams-Reilly, *Life and letters of James David Forbes* (Macmillan and Co.: Londodn, 1873), p.139. See, however, Oakley's unsubstantiated assertion that since "Rankine had spent his early years on the railways in Ireland - this first brought them [Gordon and Rankine] into contact": Oakley, *Engineering at Glasgow*, p.9. There is no other record of Gordon visiting or working in Ireland, though had he been there in the summer of 1838 the two might conceivably have met. It is not true, however, that both attended Forbes's class in 1836-7. See Smith and Wise, *Energy and Empire*, p.36.

[12] Jack Morrell and Arnold Thackray, *Gentlemen of science. Early years of the British Association for the Advancement of Science* (Oxford University Press: Oxford, 1981), pp.103-4 and 128; and my chapter 2.

[13] Constable, *Gordon*, pp.8-14; Marc Isambard Brunel (1769-49), *DNB*. Brunel was Vice-President of Section G in 1836; in 1842 he spoke to this Section on the Tunnel, which was not completed until 25 March 1843. This venture had earned him a knighthood in 1841. Morrell and Thackray, *Gentlemen of science*, p.265; R.A. Buchanan, *The engineers: a history of the engineering profession in Britain 1750-1914* (Jessica Kingsley: London, 1989), p.193. For an account of the second period of construction, beginning late 1834, see Richard Beamish, *Memoir of the life of Sir Marc Isambard Brunel* (Longman, Green, Longman, and Roberts: London, 1862), pp.282-304.

[14] Beamish, an "ardent phrenologist", approvingly described his young assistant's "[c]oronal surface [as] elevated and capacious". Constable, *Gordon*, p.12.

[15] Beamish, *Brunel*, p.290.

concrete manifestation in the recommendation, with Brunel and Thomas Page (another assistant on the Thames Tunnel), that Gordon was "a proper person to become a Member" of the Institution of Civil Engineers.[16] Like Rankine he was admitted to the class of Associates (chapter 3).[17] Through a network of friends and colleagues Gordon was rapidly attaining the full trappings and accredited status of a professional engineer.

These London years had not been without problems, however, and their end was marked by an event illustrating both the ambition and the lapses in diplomacy of one who "occasionally manifested youthful rashness in the maintaining of his views, and in dealing with those of persons of confessed authority".[18] The foul atmosphere within the tunnel, a recurring cause of illness, and the extremely dangerous working conditions had led Beamish first to demand of Brunel a higher salary and ultimately to leave altogether. Page and Gordon protested that they would not serve under another resident engineer:

> the introduction of a stranger...[would be] so strikingly anomalous, that to act under him would be to admit our incompetency...we should have the additional mortification of finding the result of our exertions transferred to the credit of one whose direction during this most important period was purely nominal.[19]

In the event, Page was appointed Acting Engineer. Despite an increase in salary Gordon left a month later in September 1836.[20]

After an unsuccessful attempt to find work as the resident engineer for a scheme to deepen the river Tyne, Gordon left Britain for Freiburg in Saxony where he studied at the School of Mines (established in 1765) from

---

[16] Admission certificate no.352, Institution of Civil Engineers (proposed 25 January 1836 and admitted 16 February). Thomas Page (1803-77), *DNB* , had a distinguished career, constructing many bridges and London's Albert Embankment.

[17] Again like Rankine he never achieved full membership of the Institution.

[18] Constable, *Gordon* , p.19.

[19] Joint report by Page and Gordon made to Brunel on 24 August 1836, quoted without further identification in Paul Clements, *Marc Isambard Brunel* (Longmans, Green and Co.: London, 1970), p.219.

[20] Clements, *Brunel* , p.220. See, however, Beamish, *Brunel* , p.296, who, in a passage which rather glosses over the termination of his own work on the tunnel, implies that Gordon left following a break down in his health in September 1836.

September 1838.[21] Robert Jameson had studied there thirty years earlier and might well have recommended this centre of practical and geological learning to his recent student.[22] Gordon absorbed and later transmitted much from these extensive continental travels which had formed no part of Rankine's educational itinerary. At Freiburg he took courses in mineralogy, geology, physics, chemistry, metallurgy and mathematics, the last of these with Julius Weisbach. Gordon developed a lasting friendship with Weisbach, whose two volumes on mechanics he translated and published in the 1840s.[23] In Britain Gordon ardently promoted the concept of *Mechanische Wirkung*, which he translated as the "mechanical effect" of a moving power.[24] Weisbach's aim had been to apply mathematics to the action of machines, making divisions in his texts by *thesis* and *praxis*,[25] an intellectually utilitarian dichotomy of theory and practice which Gordon was soon called upon to defend in Glasgow.

Returning to Scotland late in 1839 he began to practice as a civil engineer in partnership with Lawrence Hill junior. There were many links between Gordon, Rankine, and the Hills. The engineer's father, Glasgow lawyer Lawrence Hill senior (1791-1872), enthusiastically supported the long campaign which finally brought the British Association to Glasgow in September 1840.[26] (At the meeting Gordon spoke to Section G on the turbine water wheel.)[27] For generations successive members of the Hill

---

[21] During the late 1830s he also studied briefly at the École Polytechnique. See Constable, *Gordon*, p.42. It is probable that from 1837 to 1838, a period curiously blank in Constable's account, Gordon was in Edinburgh. This accords with my suggestion that Gordon and Rankine were in contact during this time. For the Freiburg School of Mines see George S. Emmerson, *Engineering education: a social history* (David & Charles: Newton Abbot, 1973), p.48.

[22] The geologists Bischoff, Lyell and John Phillips, long-standing servant of the British Association had all received part of their education at Freiburg. See Constable, *Gordon*, p.29.

[23] Julius Weisbach, *Principles of the mechanics of machinery and engineering* (2 vols., London, 1848). Substantial preparations had been made by autumn 1839. See Constable, *Gordon*, p.41.

[24] Smith and Wise, *Energy and Empire*, p.291.

[25] Constable, *Gordon*, p.32.

[26] Morrell and Thackray, *Gentlemen of science*, p.204; the campaign is analysed in great detail on pp.202-22.

[27] *BAAS Report*, 10(1840), part 2, pp.191-2.

family had been Factors (or land-agents) to Glasgow College.[28] Macquorn Rankine was related to the Hills as was Gordon through the half-brothers William and Allen Thomson who both become Glasgow professors (chapter 2). Ninian Hill, father of the two Thomson's wives, was, like Gordon's father, a Writer to the Signet in Edinburgh.[29] A strong and intricate network of institutional, professional and family connections bound this group of Scottish citizens together. The most tangible product of these interactions, the chimney of the St Rollox Chemical Works, dominating the horizon at 436 feet (three times the height of Nelson's column) and known throughout the Glasgow district as "Tennant's Stalk", was projected by Rankine and designed by Gordon and Hill, to be constructed, under close and admiring public scrutiny between 1841 and 1842.[30]

By then Gordon had become the first regius professor of civil engineering and mechanics in the University of Glasgow. Two participants in his bid for the chair can be identified: his candidacy had been supported by James David Forbes in a testimonial delivered to Lewis's father early in July 1840. Joseph Gordon's position within society and the legal community made him well-placed to coordinate the approaches made to Normanby, the Home Secretary in Melbourne's by now unstable Whig administration.[31] Forbes, wielding the authority of a prestigious academic position, praised his former pupil's knowledge of natural

---

[28] David Murray, *Memories of the old College of Glasgow: some chapters in the history of the University* (Jackson, Wylie and Co.: Glasgow, 1927), p.247; and see, for example *The Glasgow University Calendar, for the Session 1863-4* (G. Richardson: Glasgow, 1863), p.12.

[29] See chapter 2.

[30] It remained for years the tallest chimney in the world. See R.M. Bancroft and F.J. Bancroft, *Tall Chimney Construction* (John Calvert: Manchester, 1885), pp.37-40; Nancy Crathorne, *Tennant's Stalk: The Story of the Tennants of the Glen* (Macmillan: London, 1973), pp.107-9. The chemical works were owned by Charles Tennant & Co, with the building of the chimney under the authority of John Tennant (1796-1878). See also Peter J.T. Morris, Colin A. Russell, and John Graham Smith, *Archives of the British Chemical Industry 1750-1914: A Handlist* (British Society for the History of Science: Stanford in the Vale, 1988).

[31] Constantine Henry Phipps (1797-1863), *DNB*, first Marquess of Normanby from 1838, was Secretary of State for Home Affairs from 1839 to 1841 towards the end of Viscount Melbourne's Whig administration of 1835-41.

philosophy, his acquaintance with European teaching methods, and in general his "excellent talents".[32] In private Gordon greeted the prospect of this new but unconfirmed employment with an enthusiasm which verged on levity, observing ironically to his sister:

> there is a chance that I may have the honour of professing Engineering and Mechanics to the Glasgow students, and that they may have the honour and advantage of hearing me profess to them!...how excellently content I shall be! Absurdity laid aside for ever *then* - as it is *now*![33]

On 5 August 1840, a month before the meeting of the BAAS, Gordon received a Commission from Victoria recommending his appointment.[34] The impetus for the new chair came most obviously from Edinburgh and in Scotland it was in the *Scotsman* that the news was first announced. The *Glasgow Herald* commented laconically that it had learned from its Edinburgh-based rival that

> the Queen has been pleased to appoint Mr. Lewis D.B. Gordon, of this city, Regius Professor of Civil Engineering in the University of Glasgow.[35]

This odd displacement illustrates the anomalous nature of the establishment of the chair. Unlike other regius professorships in forensic medicine and practice of physic, recently created by the Whig government with Lord John Russell as Home Secretary,[36] it came without

---

[32] Forbes to Joseph Gordon, 6 July 1840, J.D. Forbes Papers, St Andrews University Library. Joseph Gordon had asked Forbes for a testimonial on 24 June.

[33] Quoted in Constable, *Gordon*, pp.42-3.

[34] Glasgow University Minutes of Senate, 89(1829-45), pp.252-3.

[35] *Glasgow Herald*, Friday 14 August 1840.

[36] Smith and Wise, *Energy and Empire*, p.30.

reference to the wishes of those in authority within the University.[37] However dear the subject might be to the hearts of the Glasgow public, what mattered most initially was the response of the Faculty: they were aggrieved that "a new professorship has been instituted without [the College's] previous knowledge...embracing practical objects which had not entered into their contemplation."[38] The Glasgow College professoriate greeted their new colleague with more than surprise. Rankine's recollection of Gordon's class - "the attendance...was at the outset so small that he was induced for some sessions to discontinue his lectures"[39] - merely recorded the final consequence of extended hostility: dispute over the scope of Gordon's course and the provision of a classroom, which Coutts, with admirable understatement, described as giving "rise to more than the usual amount of discussion",[40] developed into a wrangle within Senate and Faculty which carried on for years.

---

[37] The Commissioners for Visiting the Universities of Scotland, appointed by Melbourne in 1836, recommended the establishment of the two chairs in their report of March 1839, whilst they "reiterated that all University Chairs should have equal privileges". There was no suggestion of the creation of an engineering chair, however. See *British Parliamentary Papers* ; Mackie, *University of Glasgow* , p.259. Oakley suggests, unconvincingly, that the chair was a consequence of "the youthful Queen's recognition of [Watt's] achievements" following the centenary of his birth (1736); and, more plausibly but without evidence, believes it to have been supported and perhaps even suggested by Sir Robert Peel, Rector of the University in 1836. But in 1840 Peel was in opposition. See Oakley, *Engineering at Glasgow* , pp.4-5. Subsequent events detailed below suggest that Andrew Rutherfurd, Whig Lord Advocate, might have been instrumental in the chair's creation. See also Archibald Barr, "W.J. Macquorn Rankine, a Centenary Address", *Proceedings of the Royal Philosophical Society of Glasgow* , 51(1920-2), 167-87, on p.174: "I have the impression [writing in 1921], gathered in conversation with Professors of the past generation, that Gordon had a good deal to do with the movement which resulted in its [the chair's] formation."

[38] Draft minute of Faculty, written by Duncan Macfarlan, Principal of Glasgow College, between 22 and 27 January 1841, P/CN/Macfarlan 479, Glasgow University Archives.

[39] W.J.M. Rankine, "Opening Remarks on the Objects of the [Mechanical Science] Section", *BAAS Report* , 25(1855), part 2, pp.201-2, on p.202.

[40] Coutts, *University of Glasgow* , p.390.

Machinations of mechanics: the repulsive forces of natural philosophy

The new professorship had an inauspicious beginning. Amidst an atmosphere of confusion and distrust the University Senate took the provocative step of refusing to accept Gordon's Commission. Robert Buchanan, professor of logic, moved "that it should lye on the Table till next meeting when Mr Gordon should be requested to attend." The professor of moral philosophy, William Fleming, seconded the motion which was carried unanimously: Gordon was to be summoned by the College Clerk.[41] Fleming and Buchanan, known by their students as "Moral Will" and "Logic Bob",[42] were ardent supporters of Principal Macfarlan's tory faction within the College and so their motives may have been in part political.[43] Although the Faculty remained for the present predominantly tory, each new whig professor shifted the balance of the Senate, where Gordon and the other regius professors did have voting rights, towards the liberals. But a further motive for this act must surely have been justifiable shock at the hasty introduction of a subject completely alien to the university curriculum based on a broad, humanistic and democratic appreciation of the literary and philosophical arts, aimed mainly at young students, and only later followed by more advanced training in divinity and in the legal or medical professions.[44]

The contrast with the response accorded to the new regius professor of midwifery at the same meeting of Senate is striking. John Pagan presented his Commission for the recently vacated chair without opposition of any kind,[45] simply being asked to fulfil the usual requirements: the delivery of a Latin essay as a trial of ability; subscription to the confession of faith; and swearing allegiance to the Queen as prescribed by

---

[41] Senate, 89(between 5 August 1840 and 27 October 1840), p.251. Buchanan had succeeded Jardine as professor of logic in 1827. Coutts, *University of Glasgow*, p.349.

[42] Coutts, *University of Glasgow*, p.383.

[43] Smith and Wise, *Energy and Empire*, p.28.

[44] See G.E. Davie, *The democratic intellect* (2nd edition, Edinburgh University Press: Edinburgh, 1964); W.M. Mathew, "The origins and occupations of Glasgow students, 1740-1839", *Past and Present*, no.33(1966), 74-94.

[45] Senate, 89(between 5 August and 27 October 1840), p.250. Commission dated 20 July 1840.

law.[46] At the next Senate meeting he met these requirements and was promptly admitted to the University.[47] Pagan filled a vacancy in an established chair (founded 1815), in the strong faculty of medicine, with existing accommodation, facilities and what had become traditional rights and privileges. Close on his heels was Lewis Gordon and the impending arrival of a new professorship, outside any faculty, with no provision to the College for accommodation and little internal support; neither were his forthright politics calculated to win him support within the Faculty.

On 27 October Gordon appeared before the Senate. William Ramsay, Cambridge-educated humanity professor and current Vice-Rector, delivered an uncompromising directive:

> the Senate...had been desirous to meet with him in reference to his not encroaching or interfering with any of the present classes in the University.[48]

Only after an explicit expression of compliance was his Commission accepted, recording blandly Victoria's motivation for the establishment of the already troubled chair: its "importance in the Education of Youth and for the Public advantage"; and her desire to give "all suitable Encouragement to Public Seminaries of Learning".[49] Gordon was granted "all Rights and Privileges which belong to any other Professor"; and the existing members of the College were instructed, perhaps with more necessity than usual, to "admit and receive him...to the peaceable exercise and profession" of his duties.[50] An essay entitled "de relatione Scientiae ad artes industriae" provided Gordon with ample opportunity to capitalize on the common rhetorical currency of dichotomies of "theory and practice", or of "science and art". Should it be found satisfactory, confession of faith and the oath to the Queen would guarantee Gordon's

---

[46] Ibid., p.251.
[47] Senate, 89(27 October 1840), p.251.
[48] Ibid., p.252.
[49] Ibid., pp.252-3. The Commission, dated 5 August 1840, is signed by Normanby.
[50] Ibid.

admittance to the University.[51]

It was not to be so simple: before meeting these conditions Gordon presented an official response to the charge of potential curricular trespass which was dangerously bereft of humility. Wishing neither to placate nor ingratiate, he asserted his rights to independence in forging a disciplinary definition for the first engineering chair in Britain. For that part of his title which had caused particular concern, he explained:

> "Mechanics" may be translated Doctrine of machines...it is proposed to shew the application of those fundamental principles of Mechanical Science on which are based the abstract speculations of mechanical philosophy to the physical and material objects that present themselves in the Workshop and the Factory. The Intimate Connexion of the Physical Sciences is finely illustrated in the contrivances and processes of the Arts of the Engineer; and the recurrence to fundamental principles which will be necessary in my course of instruction will I trust, be deemed ought else than an encroachment on or interference with the chairs entrusted with the Mathematical mechanical and analytical Sciences...[My] willing Compliance ...on this point must not be construed into an admission on my part, that my reception into the...University...is in any degree contingent on...such an explanation, or on the inference which members of Senate may draw from it.[52]

The emphasis laid upon practical machines as illustrating the principles of mechanical science was in good accord with the dual scheme of engineering education promoted by Whewell and Robert Willis in Cambridge: Willis's text on kinematics showed the embodiment and utility of abstract mechanics (chapters 1 and 2). The espousal of "Mechanical Science" had resonated with the teaching of Scottish natural philosophy, and the serviceable ideology of the recently formed Section G of the BAAS. But Weisbach was a more immediate resource: Gordon's first skeleton syllabus commenced with the fundamental principle of the "Mechanical Effect

---

[51] Ibid., p.253.

[52] Memorandum from Gordon with letter to Clerk of Senate (William Meikleham Jr.), 2 November 1840, in Senate, 89(10 November 1840), pp.254-5.

produced by Forces, and its Measure".[53] Moving outside existing traditions he was importing an alien and potentially discordant style of teaching.

Potent and fashionable assertions of the "Intimate Connexion of the Physical Sciences",[54] and the careful distinction between *his* "Mechanics" (later forcibly qualified as "practical mechanics")[55] and the "Mathematical mechanical and analytical Sciences" of other professors were insufficient to win allies in the small scientific professoriate of Glasgow College. An explanation of "Mechanics" (rather then "Civil Engineering") is likely to have been solicited by those whose intellectual territory (and class fees) were under most obvious threat of erosion: James Thomson, professor of mathematics;[56] John Pringle Nichol, political economist, advocate of the progressionist nebular hypothesis (chapter 2) and professor of practical astronomy;[57] and, either in person or by proxy, William Meikleham, ailing professor of natural philosophy.[58] All three were Faculty professors, with Thomson and Nichol forming the nucleus of a small but increasingly powerful Whig faction rivalling the Principal's party.[59]

At the time of Gordon's appointment Glasgow natural philosophy was in

---

[53] It continued: "Physical and Mechanical Properties of Materials... Experiments on the Resistance of Materials. Friction. Doctrine of Mechanics. Animal-power[,]...Water-power and [their] Recipient Machines. Steam-power and the Steam-Engine." See Constable, *Gordon*, p.43. Gordon sent Macfarlan "the first part of my syllabus, such as up to the present I have been able to arrange it" on 13 November 1840. See Glasgow University Minutes of Faculty, 85(13 November 1840), pp.24-5.

[54] The first edition of Mary Somerville's perenially popular *Connexion of the Physical Sciences* was published in London as recently as 1834.

[55] *The Glasgow University Calendar, for the session MDCCCXLIV-XLV* (G. Richardson: Glasgow, 1844), pp.2 and 21.

[56] Smith and Wise, *Energy and Empire*, in particular pp.3-19 and 32-7.

[57] Nichol was appointed to the chair in 1836. See ibid., pp.37-41; Simon Schaffer, "The nebular hypothesis and the science of progress", in James R. Moore (ed.), *History, Humanity and Evolution* (Cambridge University Press: Cambridge, 1989), pp.131-64.

[58] He was appointed in 1803. See Smith and Wise, *Energy and Empire*, pp.83-4.

[59] Thus in 1836 Nichol, with Thomas Thomson, had supported the introduction of a University Board of Visitors with strong regulatory powers over College administration. Morrell, "Thomas Thomson", p.260.

a precarious state. Meikleham had been seriously ill since the late 1830s but would not resign his post.[60] Temporary arrangements had been made: for the latter part of the 1838-9 session Thomas Thomson and Nichol shared the tuition of the class; and for 1839-40 Nichol performed these duties alone. Speculation was rife over when the chair would be vacated, and who might be Meikleham's successor.[61]

James David Forbes, comfortably ensconced in Edinburgh, received strong but conflicting signals which he confided to Airy:

> I have received repeated offers of, or rather solicitations to allow myself to be put in nomination for a situation (in Scotland) for which the inducement held out is the more than doubling my present professorial income [from £300 to £700]...It has been suggested to me from different quarters that my present appointment might...be improved by the interference of Government...and that they might think themselves justified in doing so in order to secure my services permanently for Edinburgh.[62]

Given Forbes's tendency towards anglicizing reform and his Whewellian allegiance these offers probably originated with the Oxbridge moderate reformers of the Faculty (Ramsay and Lushington, professor of Greek) possibly supported by Nichol and James Thomson who by late 1842 were resigned to the idea that an independent candidate would have greater chance of success against an extreme candidate chosen by the Principal's party.[63] The directive issued to Gordon by Ramsay on behalf of the Senate less than two weeks after Forbes had written to Airy appears almost certainly (on Ramsay's part at least) to be a strategic precautionary measure: attempts were being made to lure Forbes to Glasgow with the promise of an increased salary; the level of remuneration, dependent on class fees, simply could not be guaranteed in the face of uncurtailed

---

[60] He did not expire until 6 May 1846. For some time the ground had been prepared for William Thomson's claim to the post. He was elected on 13 October 1846. Smith and Wise, *Energy and Empire*, pp.113-7.

[61] For an account of the changing fortunes of Forbes and others as candidates for the natural philosophy chair from 1841 see ibid., pp.101-16.

[62] Forbes to Airy, 15 October 1840, RGO 6/368/330-1, Cambridge University Library.

[63] Smith and Wise, *Energy and Empire*, p.102. The professor of natural philosophy was elected by existing Faculty professors.

competition from Gordon, should he be permitted to encroach on the class territory of natural philosophy. Similar motives can be attributed to Thomson and Nichol. A chair of natural philosophy with duties, authority and fees diminished by the opportunism of a dynamic new professor was a position less attractive to their favoured reforming candidates, even possibly to Nichol himself whose chair of practical astronomy amounted to little more than a sinecure.

Responding to Forbes, Airy discounted the possibility of additional aid for Edinburgh, but drew attention to the generous endowment of Nichol's province, the new Glasgow Observatory: "the selection of the best foreign instrument for it will lend materially to raise its reputation". In such acts he discerned a governmental "desire to raise the University".[64] Forbes saw Gordon's chair as an odd example of munificence:

> Government seems to have money to endow new Professorships... the Civil Engineering Chair...has got £300 of fixed salary - & I have even got some hints that if I would work double tides & lecture on Engineering as well as Nat. Phil. [in Edinburgh] I might have something too...[65]

There were no qualms about setting up an engineering course at Edinburgh in direct competition with Gordon in Glasgow: Forbes's reservations concerned the reduction of time for personal research. Subsequent events make it quite clear that Forbes would have objected to the establishment of a separate chair of engineering at Edinburgh (chapter 7), but, as had been the case, he felt himself able to support the new Glasgow chair. Thus, at precisely the time of Gordon's appointment tentative plans were being made to establish engineering as an academic subject in Edinburgh too, dovetailing with natural philosophy, and taught by the professor of that discipline (chapter 2).

---

[64] Airy to Forbes, 19 October 1840, RGO 6/368/332-3, Cambridge University Library.

[65] Forbes to Airy, 20 October 1840, RGO 6/368/334, Cambridge University Library. Gordon's salary was in fact £275 per annum the largest of any regius professor. See Oakley, *Engineering at Glasgow*, p.5; Barr, "Centenary Address", p.176.

Until the election of William Thomson in September 1846,[66] this state of flux and uncertainty within the natural philosophy curriculum remained a symptom of Meikleham's failing health in Glasgow. As speculation over replacements continued, finally, in 1840, David Thomson, B.A. of Trinity College Cambridge, took responsibility for the class, teaching mathematical and experimental courses of natural philosophy until the end of the 1844-5 session. By this time he was stipulating Poisson's *Mécanique* , and Samuel Earnshaw's *Mechanics* as required texts for the examination leading to a degree with the highest distinction.[67] He had convincing local credentials, having entered Glasgow College at the age of fifteen and studied mathematics with James Thomson before going to England.[68] But his assistantship was temporary. In this first session he struggled to find his feet, and he lacked both the status of professor and a vote in Senate or Faculty meetings.[69] With Meikleham now rarely attending Faculty meetings, defence of natural philosophy was necessarily mediated through other Faculty members. In leading the anti-invasionary campaign Ramsay, another alumnus of Trinity who had once been considered a possible candidate for the Glasgow mathematics chair, spoke also on David Thomson's behalf.[70]

The weakness of the natural philosophy chair made it all the more necessary that Gordon's curriculum should be explicitly delimited. A

---

[66] Smith and Wise, *Energy and Empire* , pp.113-7.

[67] See David B. Wilson, "The educational matrix: physics education at early-Victorian Cambridge, Edinburgh and Glasgow Universities", in P.M. Harman (ed.), *Wranglers and physicists* (Manchester University Press: Manchester, 1985), pp.12-48, on pp.29-30 for a brief discussion of David Thomson's course.

[68] William Leslie Low, *David Thomson, M.A. Professor of Natural Philosophy in the University of Aberdeen. A Sketch of his Character and Career* (D. Wylie & Son: Aberdeen, 1894), pp.8-9; and Smith and Wise, *Energy and Empire* , pp.108-9. He had been proposed by Meikleham. See Coutts, *University of Glasgow* , p.384.

[69] In 1845 he became professor of natural philosophy at King's College Aberdeen. William Leslie Low, *David Thomson* , p.12; Coutts, *University of Glasgow* , p.384; *Glasgow University Calendar...MDCCCXLIV-XLV* , p.2. Later he stated: "I should certainly have sunk under the labours of my first session, had not [William Thomson] kindly undertaken to assist me...". Quoted in Smith and Wise, *Energy and Empire* , p.108.

[70] Coutts, *University of Glasgow* , p.380.

clarification of boundaries was vital in such an intellectually crowded academic context encompassing chairs of chemistry, mathematics, practical astronomy, and natural history, now destablized by the introduction of civil engineering and mechanics.

Accommodating engineering

The reaction to Gordon was complex: politically an ally of Nichol and James Thomson, the terms of his Commission threatened the future integrity of the scientific chairs. For the Principal's party there was no direct prospect of "encroachment", but there was a deep political and ideological clash: the new professor promised to impose upon the ancient University "practical objects which had not entered into their contemplation."[71] Thus no immediate answer was made to Gordon's independent manifesto of mechanics: a Senate committee was formed to prepare an appropriate response.[72] Gordon had not been present at the meeting of 10 November up to this point. He was now called in: his Latin essay was approved, certificates testifying to his oath of allegiance and subscription to the confession of faith were produced and finally he was admitted as regius professor of civil engineering and mechanics.

By 1840 there was considerable competition amongst schools of technical education in Glasgow. Anderson's University and the Glasgow Mechanics Institute attracted large annual attendances to locations in the centre of the growing city.[73] It was in Gordon's interests that a nominal

---

[71] Draft minute of Faculty, written by Duncan Macfarlan, Principal of Glasgow College, between 22 and 27 January 1841, P/CN/Macfarlan 479, Glasgow University Archives.

[72] Senate, 89(10 November 1840), p.255. The committee comprised Macfarlan, William MacTurk (tory professor of ecclesiastical history), and William Couper, joint keeper of the Hunterian Museum and professor of natural history.

[73] Oakley, *Engineering at Glasgow* , p.4; for Anderson's University (originally Anderson's Institution, founded after the death of John Anderson, professor of natural philosophy at Glasgow University) and for British Mechanics Institutes see Emmerson, *Engineering education* , pp.91-110. By 1850 there were over 600 mechanics institutes with a combined membership of more than 100,000.

University connection should be substantiated and legitimated through provision of teaching space within the grounds of the College. At the beginning of the 1840-41 session, Gordon presented a request to the Faculty for a classroom. He wished to lecture on three days each week from the start of December and indicated his preference for "an hour in the forenoon, or between 12 & 2 in the afternoon". Adequate accommodation, he suggested, meant not one but two rooms in the College itself. Gordon hoped to establish a collection of illustrative models, apparatus and materials, following the pedagogic style of natural history and experimental natural philosophy, housing them in a small workshop in which engineering experiments could be carried out. Thus

> besides the use of a lecture room at certain hours it would be very convenient - perhaps necessary - that a room should be provided in which such apparatus might be deposited, and which would serve at the same time as an anteroom for the private use of the Professor...I shall take an early opportunity...to afford you any further explanation you may require, but at the moment I am suffering under the Dentist's hands so that I shall not be out of the house for a day or two...[74]

A politically balanced committee made up of Macfarlan, James Thomson, Nichol and Macfarlan's ally George Gray considered this less than modest application.[75] On 24 November they presented a report prepared in Nichol's absence but of which he later expressed complete approval.[76] They had found

> That there is no accommodation within the walls of the College ...for that purpose, nor any means of providing such accommodation...the only accommodation which the Faculty can afford to Mr Gordon is the use of the Chemistry Class Room at such times, and to such an extent, as may not interfere with the convenience of the Professor of Chemistry.[77]

The Faculty approved without dissent. James Thomson and Nichol were

---

[74] Gordon to Macfarlan, 13 November 1840, in Faculty, 85(13 November 1840), pp.24-5.

[75] Gray was professor of oriental languages from 1839 to 1850. See Coutts, *University of Glasgow*, pp.393-4; Smith and Wise, *Energy and Empire*, p.21.

[76] Nichol had been "called away to Edinburgh at the time the Committee reported". But "having read said report he entirely concurred in it". See Faculty, 85(22 January 1840), p.35.

[77] Faculty, 89(24 November 1840), p.26. Report prepared 21 November 1840.

unwilling and, considering the lack of space and limited resources of the College, very possibly unable to support Gordon's more grandiose requests, in spite of their concurrence with his political, reforming, and religiously latitudinarian views.[78] The qualified allocation of Thomas Thomson's classroom within the new chemistry building in Shuttle Street represented a pragmatic compromise; but it placed two regius professors in direct competition for space, and possibly even for students since Gordon might well have been expected to give some emphasis to metallurgy and the related subjects which had been prominent amongst his Freiburg studies.[79] Most insensitively, the Faculty had made this allocation without the vital support of Thomas Thomson.

Given the struggles which had been going on for the past twenty years between Thomson and the Faculty as he sought to establish and then maintain his own rights and those of the other regius professors, it is not surprising that he was reluctant to relinquish any part of the Shuttle Street building which represented his most tangible success, even though the removal of his class to it in 1831 had deposited him outside the College walls.[80] In 1827 controversy over the elections to key medical chairs, in which the regius professors were allowed no part, had fuelled the animosity between Macfarlan and Thomas Thomson.[81] More recently, in 1835, with the return of the Whig government, Thomson and his former pupil John Tennant of the St Rollox chemical works had planned parliamentary action to remove the distinction between Faculty and regius professors which, although unsuccessful, had aroused Macfarlan's ire still further.[82] By 1840 Thomson's position and health had weakened: competition from

---

[78] Smith and Wise, *Energy and Empire* , p.134.

[79] During the academic holidays Gordon had travelled widely in Europe, visiting mines and smelting works in Silesia, Bohemia and Hungary. Constable, *Gordon* , pp.32-3.

[80] The new building, costing the College £5,000, had been opened in 1831. But "Thomson's dignity was compromised in that his department was extramural". See Morrell, "Thomas Thomson", p.254.

[81] Ibid., p.252.

[82] Ibid., pp.256-9.

Thomas Graham at Anderson's University[83] and the incompetence of the Glasgow medical professors saw his class numbers fall dramatically from 138 in 1836 to only 50 in the 1839-40 session, with a corresponding diminution of fees. From 1841 his lecturing duties and laboratory supervision were to be increasingly undertaken by an assistant, his nephew R.D. Thomson.[84]

Thomas Thomson communicated alarm at the idea of sharing his classroom with the new and relatively unknown professor. Bitter messages passed between Thomson and Macfarlan, who responded with a characteristically succinct assertion of the Faculty's power to allocate rooms as it thought fit, denying any possibility of finding a room within the College. Sweetening this pill he added: "Dr Thomson will observe that the permission granted by the Faculty...is limited to the conditions of its being consistent with the convenience of the Prof. of Chemistry."[85] Unsatisfied, Thomson sought further arguments for Gordon's exclusion: he demanded safeguards for the contents of his room. Macfarlan was intransigent:

> The Principal will of course lay Dr Thomson's note...before the Faculty...and it is not for him to anticipate their answer. As an individual, he thinks it impossible that they can give any Guarantee for the conduct of ["students" deleted] pupils over whom they have no control.[86]

Thomson and Macfarlan perceived and utilized in opposition the alien status of Gordon's students, very likely to be civil engineers in pupillage or apprenticeship, dissimilar in age, temperament and discipline from the existing student body. Macfarlan's power "as an individual" meant that effectively a corporate refusal to guarantee good behaviour had

---

[83] See also chapter 2. Graham was related to Rankine.

[84] Morrell, "Thomas Thomson", pp.255 and 261-2.

[85] Macfarlan to Thomas Thomson (draft copy), 25 November 1840, P/CN/Macfarlan 469, Glasgow University Archives.

[86] MacFarlan to Thomas Thomson (draft copy), 28 November 1840, P/CN/Macfarlan 470, Glasgow University Archives, in response to Thomson's letter of 26 November. Perhaps the pointed use of "pupils" signalled Macfarlan's belief that those attending Gordon's course would be undergoing engineering "pupillage", in contradistinction to the "students" attending other classes of the University.

been issued. Thomson's attitude towards the incursion cannot have been softened by his identification of the Faculty's decision with Macfarlan.

Senate met again on 4 December, with Gordon present as professor for the first time.[87] Also in attendance were Thomas Thomson and, in a rare appearance, the ailing William Meikleham. One month of deliberations upon Gordon's letter clarifying the curricular meaning of "Mechanics" had produced a reply designed to counter any declaration of academic autonomy:

> ...they esteem it to be their right, and...duty, to superintend the teaching of all the Classes in the University, and to insist on their being conducted in such a manner as...will not interfere with the appropriate duties or encroach on the just privileges of any existing Professorship.[88]

By this stage questions of curricular control had been inextricably linked to the privileges of accommodation and to the preservation of income from student fees. For those with political and petty-political reasons for wishing to maintain College authority *and* for those who, either politically or through kindred subject area, might have appeared as natural allies, too great a degree of autonomy was threatening. Rather than enter into dialogue to negotiate acceptable boundaries for an appropriate locally-styled academic engineering, the right of Senate to "superintend the teaching of all the Classes in the University" and thus effectively to dictate the nature of Gordon's course was reasserted. Although Gordon's generous fixed salary of £275 per annum was paid by the Crown, no provision was made for accommodation or apparatus. Since "just privileges" included existing room allocations, the Faculty could veto Gordon's class: he was simply denied the two rooms within the College which were to him necessary teaching space.

Neither Gordon nor Thomas Thomson were prepared simply to accept the

---

[87] It was standard practice in these meetings for each professor present to be listed by name followed by an abbreviation of the latin translation of the post occupied. In the list of those attending this meeting Gordon was without the standard abbreviated title which even William Meikleham junior, the Clerk of Senate (C.S.U.), was given. The persistance of this omission indicated Gordon's low prestige and anomalous status, even within Senate.

[88] Senate, 89(4 December 1840), pp.258-9.

situation and wrote to the Clerk of Senate and Macfarlan respectively restating their demands. But the Faculty refused to compromise further, insisting they had no means of making additional rooms available, standing fast to their allocation of Thomson's room:

> This they repeat their readiness to do, being satisfied that his lecturing there at any hour after 12 o'clock noon will not interfere with the convenience of the Professor of Chemistry...[89]

The Faculty's powers now extended to divining Thomas Thomson's convenience. The original committee of Macfarlan, James Thomson, Nichol and Gray was reappointed with "The Principal Convenor, to intimate this resolution to Mr Gordon, to receive any communication which he may think proper to make, and to give every explanation which they may deem necessary or proper."[90]

As the professors' problems multiplied and Macfarlan attempted to dictate the course of events within the College by assuming personal control, Gordon, lacking substantial internal support, seized the initiative by calling upon powerful external connections. Since April 1839 Andrew Rutherfurd had been Lord Advocate, the highest officer of the Scottish legal system, and Whig MP for Leith Burghs near Edinburgh.[91] Rutherfurd's political leanings made him a potential ally for Gordon and a formidable opponent of the tory element of the Faculty. Gordon's access to Rutherfurd may have been facilitated by Joseph Gordon's influential legal status. Moreover Rutherfurd had a record of involvement with

---

[89] Faculty, 85(8 December 1840), p.27. These letters have not survived, with the exception of the drafts from Macfarlan to Thomson already referred to.

[90] Ibid. Macfarlan wrote to Gordon on 9 December: "I shall be happy to receive, for the information of the Committee, any communication which you may be pleased to make to them. Copy in Faculty, 85(10 December 1840), p.28.

[91] Andrew Rutherfurd (1791-1854), *DNB*, was solicitor-general for Scotland in Melbourne's second administration from 1837 before promotion to Lord Advocate. He resigned his position on the formation of Sir Robert Peel's administration in September 1841. A popular figure in the city of Glasgow also, he was chosen as Lord Rector of the University on 15 November 1844. See Senate, 89(20 November 1844), p.333. In 1845 Rutherfurd introduced a Bill for the abolition of the much-disputed Scottish university religious tests. The Bill was unsuccessful but reform came in 1853. See Smith and Wise, *Energy and Empire*, p.47.

College issues in support of the regius professors: Thomas Thomson only a year ago had asked for the assistance of his former pupil, in obtaining an increase in salary with notable success.[92]

Rutherfurd wrote directly to Macfarlan at the beginning of December, urgently pressing *Professor* Gordon's case:

> I have just heard, not without regret and surprise, from the Regius Professor of Civil Engineering in your University...that he has been refused the use of a Lecture Room within College, and other accommodation necessary for the discharge of his important duties. I say refused, because it has been stated that the Class Room of the Professor of Chemistry which alone was offered, could not from the nature of his course and constant use of apparatus be used safely or conveniently by any other teacher...it is impossible for me to imagine that those who have the charge or disposal of the Buildings of the College should not be most anxious to do every thing in their power for the accommodation and convenience of a Chair which Her Majesty has been graciously pleased to establish in your university. Nor can I overlook the vast importance of such a Chair to your city, which owes so much of her prosperity and affluence to her manufacturing industry and progress in the Arts.[93]

Rutherfurd's ardent support for Gordon and Thomas Thomson is fully consistent with the contention that the creation of the engineering professorship had in itself been a political gesture by the Whigs. His "regret and surprise" were directed full-square at Macfarlan, whom he clearly perceived to be out of touch with the broader community of Glasgow, which saw the city's affluence, progress and improvement as stemming from its engineering and manufacturing industry. This discourse was of course common currency and harmonized with the still more grandiose pronouncements of the Presidents of the BAAS at the recent Glasgow meeting: thus "raised through the industry and genius of her sons, to a pinacle of commercial grandeur, well can this city [Glasgow] estimate her obligations to science".[94]

On receipt of Rutherfurd's letter, Macfarlan hastily called another

---

[92] Morrell, "Thomas Thomson", p.261.

[93] Lord Advocate Rutherfurd to Duncan MacFarlan, 8 December 1840, P/CN/MacFarlan 474, Glasgow University Archives. The letter was of such importance as to be transcribed in full into Faculty, 85(10 December 1840), p.29.

[94] The address of R.I. Murchison and Edward Sabine is reported in *BAAS Report*, 10(1840), pp.xxxv-xlviii. Quotation on p.xxxv.

Faculty meeting. He had answered rapidly but briefly, nervously reiterating to the principal legal officer of Scotland the distinction between his individual identity and the corporate shield of the Faculty:

> As an Individual Member of that Body I may be permitted to say, what I feel confident the Record of their proceedings will fully establish, that they have shown the utmost readiness to accommodate Mr Gordon, to the extent of the means now at their disposal.[95]

The Faculty expressed their approval of Macfarlan's conduct, and while stressing that they felt themselves to be responsible only to the Visitors of the University, "to testify their high respect for the personal character and public station of the Lord Advocate" they instructed the Principal to provide Rutherfurd with all the details of their dealings with Gordon over his room.[96] This he promptly did.[97]

With the coming of the new year the old problems remained unsolved. Responding to Gordon, Macfarlan again stated that the Faculty had done "all in their power" to provide accommodation "consistently with their duty, and the means at their disposal". He seemed anxious to suggest that the dispute had arisen from Gordon's failure to cooperate with Thomas Thomson, whose reservations he belittled:

> The only objection stated by that Gentleman arises from the danger to which he considers that some part of his apparatus may ["has been" deleted] be exposed, [sic] Against...this risk he demands a Guarantee which I am satisfied you will have no ["difficulty" deleted] hesitation to give him.[98]

Playing Thomson off against Gordon, Macfarlan insisted that safeguards should be provided by the new professor of engineering: adhering to the assertion he had made "as an individual" in November, the Faculty would not be responsible for the conduct of these alien students. But Gordon had been speaking directly to the professor of chemistry: Thomson wanted a

---

[95] Macfarlan to Rutherfurd, 9 December 1840, in Faculty, 85(10 December 1840), p.30.

[96] Ibid.

[97] Rutherfurd to Macfarlan, 16 January 1841, in Faculty, 85(22 January 1841), pp.35-7.

[98] Macfarlan to Gordon (draft copy), 11 January 1841, P/CN/Macfarlan 480, Glasgow University Archives.

guarantee for the safety of his apparatus expressly from the Faculty before admitting "any Lecturer or Body of students other than his own". He would not accept a guarantee from Gordon, who anyway regarded it

> quite out of the question, both as regards compliance with what he requires and what I humbly conceive to be my own just right under Her Majesty's commission which confers on me all the right [sic] and privileges of any other Professor in the University of Glasgow, without subjecting myself to any extraneous responsibility...My commission I conceive entitles me to accommodation within the walls of the College, and I now must beg leave respectfully to demand protesting as I hereby do, that if this my demand be not complied with, the Rector, Principal, Masters and Professors of the University, at least such of them as are parties to the refusal to me of my just rights, shall be liable for the loss and damage I sustain through such refusal.[99]

Thomson had by now come to regard this escapade as one more in a long line of demeaning acts in which the Faculty attempted to exert authority over the regius professors. Gordon refused to be drawn towards infighting with Thomson. (Indeed given Thomson's friendship with John Tennant and Gordon's later association with the construction of Tennant's Stalk only a few months later, it is more probable that, as far as possible in such an explosive situation, they were acting concordantly.) Once again Gordon raised the stakes, belligerently threatening legal action against the entire College. In demanding equality with existing professors he revived the debate over the distinction between regius and Faculty professors: if it remained the Faculty must be prepared to take full responsibility, including if necessary acting as guarantors, for the accommodation over which they persisted in exercising control.

The response was a predictable reaffirmation: the initial proposal for accommodation remained in force.[100] Clearly no party was likely to back down. Thomson was unprepared to have his actions and "convenience" summarily dictated; and Gordon, not wishing to antagonize Thomson, was aware that if this original dispute were to have an unsuccessful outcome then he would be unlikely to occupy anything but an anomalous position

---

[99] Faculty, 85(15 January 1841), pp.33-4.
[100] Ibid., p.34.

within the University curriculum; the Faculty had unflinchingly maintained their corporate position.

Prompted by communications from Thomson and Gordon, Rutherfurd fired off a second missive, significantly less veiled than the last. He had been briefed on existing room allocations: the law classroom was appropriated for only one hour daily, but there had been no students in the present session; the mathematics classroom was used for only three or four hours; the classrooms of logic and moral philosophy for only two each; and had there been any students of astronomy (there were not) they would have required only one more hour in the moral philosophy classroom each day. It cannot have been accidental that Rutherfurd chose to single out Faculty classes exclusively. But neither was it diplomatic to point an accusing finger at Gordon's most likely allies, James Thomson and Nichol as professors of mathematics and astronomy. The natural philosophy and medical classrooms, Rutherfurd could understand, were not suitable, but for just those reasons that made it impossible for Thomas Thomson to make available his classroom, adjacent to a chemical laboratory which was itself in constant use. Gordon had specified other accommodation within the College, and underneath the chemistry classroom which was unoccupied.

Rutherfurd thus took issue with Macfarlan's assertion that "the record of the proceedings of the College will prove that the Faculty have shown the utmost readiness to accommodate Mr Gordon to the extent of the means now at their disposal." Far more alarmingly he gave notice that he had been asked

> to consider the propriety of instituting...the proceedings that may be necessary for ascertaining the rights and privileges of the Regius Professors...In forming my opinion on this subject it may be of some importance to know, <u>whether</u> the Faculty mean to say, that in point of fact...there is no means of furnishing any accommodation to the Regius Professor of Civil Engineering and Mechanics, <u>or</u> whether they mean to say that they consider themselves entitled to withhold such accommodation which he might occupy without inconvenience to [any] other Professor?...I trust you will excuse the liberty I take in requesting an answer to this question, as, independently of other considerations, the answer of the Faculty may of itself determine the course I shall

> think it proper to recommend.[101]

This letter was tantamount to a declaration of war and required rapid and concerted action. Unable to reach any consensus after "some deliberation", the Faculty adjourned for the weekend, with a meeting to take place on the following Monday, 25 January. A committee was formed to draw up a response consisting of Alexander Hill (tory),[102] Robert Buchanan (tory) and William Ramsay (moderate reformer). Considering the attendance at this meeting, restricted of course to Faculty professors, Nichol, the only overtly whig representative in James Thomson's absence, was not on this committee.[103] On the following Monday, still no decision was reached and no report was made: again the Faculty adjourned.[104]

An extensive report was at last produced at the meeting of 27 January. I suggest this represented a compromise reached between all sections of the Faculty in the necessity of presenting a united front. The Faculty now asserted strategically its collective belief that there were "two subjects distinct in character and unequal in importance":[105] Gordon's accommodation; and the status of the regius professors.

On the first issue the Faculty piously observed: "So far from overlooking Mr Gordon's convenience, or showing indifference to the success of his Class" they quickly tried to find space "where he might best enjoy the facilities designated in [his original] letter". Their arrangement, they imagined, "would be perfectly acceptable to Mr Gordon and neither hurtful nor disagreeable to any other party" and (presumably *pace* Thomas Thomson) "they authorized that Gentleman [i.e. Gordon] to teach in the best room at their disposal". Others rooms were simply not "fitted to meet Mr Gordon's desires". The unmanageability of *things* provided arguments mitigating against Gordon's entry into the College:

---

[101] Rutherfurd to Macfarlan, 16 January 1841, transcribed in Faculty, 85(22 January 1841), pp.35-7.

[102] Tory professor of divinity from 1840. See Coutts, *University of Glasgow*, p.393; Smith and Wise, *Energy and Empire*, p.28.

[103] Faculty, 85(22 January 1841), p.34.

[104] Faculty, 85(25 January 1841), p.38.

[105] Faculty, 85(27 January 1841), p.38.

> The Law class room for instance, can only be reached by two narrow winding stairs along which it would be extremely inconvenient to introduce or remove models or large apparatus, and neither in it or in any other of those specified, is there a place for depositing such apparatus permanently, nor could any of them allow of space adequate to such an object, being portioned off.[106]

Blame was laid upon Thomson, first in asking for a guarantee for his apparatus - something "unheard of in similar cases, and which seemed quite unnecessary under the exercise of that degree of precaution and spirit of mutual accommodation, which the limited number of Class rooms in the College, had now laid as a duty on many of the Professors" - and more recently for stating the impossibility of anyone but himself using the chemistry classroom. The Faculty expressed its collective surprise that "Mr. Gordon...seems to decline to avail himself of what...is his undoubted right."

The second issue was less easily dealt with. The Faculty steadfastly refused to make the connection with Gordon. Pleading that all his "applications were as frankly received and carefully considered, as if he had possessed full and acknowledged title to demand all that was so readily granted him" and thus refusing, rather pedantically, to admit that they might have been asserting any right to withhold accommodation to a regius professor, they nimbly sidestepped the issue of the Faculty/regius professor hierarchy. However, there was a sting in the tail:

> ...should Mr. Gordon's application, be converted into in [sic] occasion for questioning the validity of rights which have hitherto been considered inherent in them as an independent corporation, or should any other circumstance give rise to an invasion of their privileges, they will not shrink from the responsibility of resorting to the most suitable means, of defending a constitution, handed to them in trust, and which in so far as it was ever impugned, has been ratified by the Supreme Judicatory of the Land.[107]

The report was agreed to by Macfarlan, Buchanan, Fleming, Ramsay, James Thomson, Nichol, and Gray. If there were to be a test case, the Faculty would be prepared: notwithstanding the lofty assertion of legal rectitude

---

[106] Ibid.
[107] This report occupies most of Faculty, 85(27 January 1841), pp.38-41.

they were worried. It transpired that Macfarlan was, rather conveniently, visiting Edinburgh during the next week. He was "authorized to take the opinion of Counsel on this business".[108]

It had taken no less than three meetings of intense debate, between 22 and 27 January 1841, for the Faculty to reach sufficient consensus to enable them to generate a response to Rutherfurd's letter agreeable to all. An extensive draft report in Macfarlan's hand exists, dealing with identical issues, sharing some arguments but far less temperate in style. It provides a fascinating insight into the motivation of Faculty members and the activities of the days during which no decision could be reached. In spite of its putative representation of the Faculty line, it did not reach the Faculty Minutes: thus we are led to the conclusion that the document is a discarded reply to Rutherfurd, toned down for diplomatic reasons, or, more likely, to make possible the presentation of a united front (incorporating the whig James Thomson and the more radical Nichol) in the face of threatened action from the Crown. Many explicitly or implicitly critical references to the actions of Whig administrations from 1835 to the present were absent from the report which I have discussed as it finally appeared with full Faculty sanction.

This document detailed the College-sponsored lectureships in chemistry, botany, materia medica, natural history, and other branches of medicine. From the beginning of the century many of these had been elevated to regius professorships: "On each such Foundation...the College cheerfully continued the accommodation which they were in use to afford to the Lecturers." Little stress was laid upon the fact that Thomas Thomson, for example, as a College-sponsored lecturer had received £70 per annum whilst on becoming regius professor he received nothing from the College and only £50 from the Crown;[109] or that when John Couper was created regius professor of material medica he lost entirely the £70 a year paid

---

[108] Ibid., p.41.
[109] Morrell, "Thomas Thomson", p.251.

by the College to his predecessor and the Crown too refused to pay any salary at all.[110]

Furthermore, improvements to accommodation had been made, using the salaries saved and the rents of the Archbishopric of Glasgow which had traditionally gone to the College, or more recently the £800 pounds paid in lieu. But this had been withdrawn by the Whig administration "and diverted to other purposes".[111] The University Commissioners of 1836 had in fact recommended the redirection of the money to a University Court, which would supersede the Faculty in administrative power, for distribution within the whole University, rather than leaving it to be spent by the Faculty.[112] But the University Court had not been created, and instead the annuity had been divided in 1840 amongst the regius professors to provide salaries, or increases in salaries. Thomas Thomson, with Rutherfurd's support, had done rather well, receiving £200 of the total.[113] No doubt this was yet another reason for Macfarlan's annoyance with the regius professor of chemistry. Gordon's generous fixed salary of £275 was part of this trend. Adding curricular insult to financial injury,

> a new professorship has been instituted without [the College's] previous knowledge, and embracing practical objects which had not entered into their contemplation.[114]

When asked to provide a classroom and apparatus room "they neither had the same motives for complying which had induced them to continue or improve the previously existing accommodation of their Lecturers on becoming Professors" nor did they have the same funds. Despite this, they had given Gordon the use of the chemistry class room, there being no class

---

[110] Ibid., p.255.

[111] The annual payment of £800 had come into effect in 1825 and was renewed for 14 years, expiring in May 1849. Coutts, *University of Glasgow*, pp.363 and 423.

[112] Ibid., pp.423 and 414.

[113] Morrell, "Thomas Thomson", pp.261-2.

[114] Draft minute of Faculty, written by Duncan Macfarlan, Principal of Glasgow College, between 22 and 27 January 1841, P/CN/Macfarlan 479, Glasgow University Archives.

in the College which could be appropriated, even temporarily, without "inconvenience or injury to the business of the College". Again it appeared that the main hindrance was the additional apparatus room Gordon had required. But there were other more or less convincing arguments against Gordon's use of a College room:

> A Regard to the health of the Students forbids the continued and crowded occupation of one Room for successive hours without intervals for ventilation...it has been proved by experience that the introduction of Students engaged in different pursuits into the same apartment encumbered as it must often be by the drawings, models and various memorials of its former occupants has any thing but a salutary effect on their attention and habits.[115]

These were the reasons for the Faculty's action,

> without taking into consideration any ["claim" deleted] alleged claim which Mr Gordon might imagine himself to have to be furnished with the extensive and costly accommodation which he requires at the expense of the College.[116]

It was true that the College received no financial aid for the departmental activities of the new regius professors and this became increasingly a genuine source of the anger directed by the Faculty against the regius professors.[117] They refused to believe that Rutherfurd could support Gordon's position:

> The supposition that a corporation such as the College (especially with its resources essentially crippled and diminished by the Crown) is bound to incur expense to an indefinite amount in order to provide accommodation to an indefinite extent for each of the indefinite number of Professors whom the Sovereign may be advised to appoint, appears to them too monstrous to be entertained for a moment by a Person of your Lordship's recognized intelligence...[118]

If not, then they must take legal action, believing that decisions of the Supreme Civil Court of 1772 and 1810 laid down the rights of regius professors; and that they had already stated their views to Commissioners of Visitation in 1826-30 and substantiated their grounds for dissent with

---

[115] Ibid.
[116] Ibid.
[117] Morrell, "Thomas Thomson", p.263.
[118] Draft minute.

the Commissioners' conclusions.[119] Neither did they agree with the views expressed by the Commissioners of 1836-9,

> but they beg leave humbly to observe, that these both admit the independence of the College and point to a legislative Enactment as affording the only means by which the Changes which they recommend can be effected.[120]

It was abundantly clear that Gordon represented the thin end of the wedge. Macfarlan and the majority of the Faculty were aggrieved by the withdrawal of the rents in lieu of the lease of the Archbishopric of Glasgow, leaving them with a substantially reduced College income. The statements regarding the immiscible nature of different student classes and segregation on grounds of physical and moral health veiled greater fears about the erosion of the traditional role of the College: provider of a distinctively Scottish education rooted in the arts, notably divinity, humanity, logic, natural philosophy and moral philosophy. Gordon's was simply a radical departure from the style of tuition resident in the College: his course would embrace "practical objects which had not entered into their contemplation." None of these statements, in the main directed against the actions and attitudes of the Whigs, found any place in the minute as it finally appeared in the official university record. This strongly suggests that throughout the escapade Macfarlan's attitude was being partly controlled by the more liberal members of the Faculty, those less ardently antipathetic to reform of the College structure and ideals, such as James Thomson and Nichol.

---

[119] This Royal Commission had been established to promote reform in 1826 and was renewed by William IV in 1830 on the death of George IV. For details see Mackie, *University of Glasgow*, pp.246 and 255-8.

[120] Draft minute.

Resolution of internal forces

By the beginning of the next session many things had changed. In May 1841 Gordon had survived a half-hearted attempt to discredit the legitimacy of his occupation of the chair in the face of objections to his having signed the confession of faith before the presbytery of Edinburgh rather than that of Glasgow.[121] More dramatically, the fall of the Whig administration in September 1841 had prompted Rutherfurd's resignation as Lord Advocate, though he remained an active MP.[122] With this loss of such a commanding position and the change of political will following the ascendency of Peel, threats of legal action against the College dwindled.[123] No further connections were made between Gordon's room and the status of the regius professors.

But neither had a permanent solution been found. Next October Gordon again asked for a room.[124] The inevitable committee reported that they could see no room better than that offered the previous year; but "if the Faculty are disposed to entertain his application" then he should be allowed to use the law classroom (which had been denied last session) for one hour each day. Triumphantly, they lay down stringent conditions which he was required to meet, covering precisely those points which he had adamantly rejected before. Thus they stipulated that

> this permission be granted for the present Session only; that it shall be granted by the Faculty and accepted by Mr. Gordon as purely a matter of favour, and not as a right, and as it is probable that his Lectures may be attended by persons not otherwise Students that he shall be held responsible for their conduct within the walls of the College.[125]

The Faculty approved, but only

---

[121] Smith and Wise, *Energy and Empire* , p.44.

[122] See Andrew Rutherfurd, *DNB* .

[123] Soon after Rutherfurd's letter the regius professors submitted a memorial deploring their state of inferiority to the Faculty. The Faculty answered, but James Thomson dissented to their report, an action which led to a great amount of vitriol being poured upon him. Gordon's state had provided the opportunity for rebellion amongst the regius professors, supported by at least one member of the Faculty. See Faculty, 85(1839-48), pp.67-78. But the abolition of the distinction did not actually come about until 1858.

[124] Faculty, 89(20 October 1841), p.55.

[125] Faculty, 85(29 October 1841), p.64.

> on the distinct understanding by all Parties that this Grant is a matter of favour on the part of the Faculty, and does not imply their acknowledgement of any right possessed by Mr. Gordon to demand accommodation from the Faculty.[126]

We can only assume that this grudging offer was accepted.

At the beginning of the next year Gordon made a similar request which was met this time with a more relaxed reply: he was again allowed the use of the law classroom for the current session.[127] But the peace did not last. Just before the beginning of the 1843-4 session Allan Maconochie, professor of civil law since only 1842, who was confined to his residence "in consequence of a severe attack of illness", wrote a strident letter to the Faculty asking them in no uncertain terms not to renew their permission for Gordon to use the law class room, which was clearly by now in danger of becoming an established privilege. As a new professor it was vital that Maconochie circumvent this threatened erosion of rights by stealth.[128] Appointed by Peel's government and holding moderate conservative views, Maconochie was initially allied to the Principal's faction within the College.[129] The professor of law objected to a member of another faculty (Arts) being allowed to "intrude" in this way; and found himself "determined most resolutely and at all hazards to defend" the "unchallenged right privilege and endowment of the Chair which I have the Honor to occupy". He requested "the removal to a more appropriate site of the boxes of stones and machinery pertaining to the teaching of a branch of Science altogether disconnected with that of law" in order that he might not have to be called upon to "vindicate the privileges of which he was "the most immediate Guardian". The Faculty, he wrote, had

> no more right to intrude another Teacher into my chair than it has to authorize the Professor of Anatomy to hang his supernumerary Horrors or carry on particular dissections in the

---

[126] Ibid.

[127] Faculty, 85(20 November 1842), p.90.

[128] The letter is transcribed in Faculty, 85(24 October 1843), p.114-5.

[129] He later turned towards a qualified support of the reforming party of James Thomson, supporting the abolition of religious tests in 1846 for example. Smith and Wise, *Energy and Empire* , pp.28-30 and 43.

Divinity Hall.[130]

In Gordon's absence Dr William Thomson, professor of medicine (or practice of physic) appointed by the Crown at the end of Russell's Whig administration in October 1841, Gordon's close relation, and ardent supporter of the increasingly confidant Whig faction within the Faculty, acted quickly to remove the prospect of the College gates again being closed against him. Thomson delivered a letter the tact of which was frankly beyond Gordon:

> On behalf of my friend Professor Gordon who is at present in England I beg to request that the Faculty will renew their permission to him to deliver his course of lectures in the law Class-room or in such other Class-room as they may appoint during the ensuing Session.[131]

The Faculty again declared their right to consider "the whole of the College Property including the several Class rooms as under their management". But for Maconochie (a member of the Principal's party), they could state that the Law classroom had long been used for that purpose, and that he needed the space for storing Session Papers. Since Gordon's permission "was in both cases limited to the then existing Session during which no lectures were delivered by him", Maconochie should have the exclusive occupation of the room. However, steps were taken to consider where Gordon's next residence might be: this time Gordon's self acknowledged "friend" and ally Dr William Thomson was one of those on the committee formed to make a decision. Gordon was successfully, if

---

[130] Faculty, 85(24 October 1843), p.115.

[131] Letter to Macfarlan, dated 27 October 1843, in Faculty, 85(27 October 1843), p.115. William Thomson (1802-52), *DNB* . He was admitted as professor of medicine on 29 October 1841. See Faculty, 85(20 October 1841), p.55; and Faculty, 85(29 October 1841), p.64. For William Thomson's close alliance with Nichol and James Thomson, see Smith and Wise, *Energy and Empire* , pp.21 and 104-7.

temporarily, housed.[132]

Public neglect, personal interest and the motive power of heat

The motives behind such treatment from the Faculty over accommodation and the Senate over curriculum were complex: it is clearly not enough to say that "the initial development of engineering within the university was impeded by the old distinction between theory and practice."[133] Antipathy by the dominant tory faction of the University to the actions of a whig administration had made Gordon unpopular, an unwanted, financially and spatially demanding outsider foisted on the University by external powers at a time when College income had recently been reduced and who with a salary of £275 per annum might well have been expected to fend for himself.[134] The weakness of the natural philosophy chair put "civil engineering and *mechanics* " under close scrutiny both from moderate reformers, currently soliciting nominations for Meikleham's replacement with offers of lucrative teaching, and potential allies with their own favoured candidates, but also their own worries, personal or vicarious, about curricular encroachment. The alien quality of the subject and the potential students provided arguments for exclusion. One aspect of

---

[132] The full committee consisted in addition of Alexander Hill and William Ramsay. Faculty, 85(27 October 1843), p.116. A draft of this minute exists in Macfarlan's hand with a few significant alterations indicating i) that it was clearly prepared before the meeting, and before Dr William Thomson's note; and ii) that the misleading assertion that Gordon had delivered no lectures in either session (he had lectured somewhere, if not in the College, during the 1841-2 session) was added later. Maconochie's plea may have been conceived as a way of removing Gordon from the College in his absence, since the original draft refers to a committee being formed " *in the event of Mr. Gordon renewing his application* to be accommodated with a Room in the College". See P/CN/Macfarlan 617, Glasgow Unversity Archives. Emphasis added.

[133] David F. Channell, "The harmony of theory and practice: the engineering science of W.J.M. Rankine", *Technology and Culture* , 23(1982), 39-52, on p.43.

[134] The regius chair may well have been "a bid to regain support" in the University by the current Whig government. Smith and Wise, *Energy and Empire* , p.30.

Gordon's styling of academic engineering - its "embracing [of] practical objects" - had circuitously generated the most alarm. In asking for an additional apparatus room Gordon had found himself outside the College in the new chemistry building. The dwindling but still irascible Thomas Thomson had taken this to be one more dismissive act by the Faculty against himself with which he refused to concur. Attempting to escalate the debate into a trial of Faculty against the Crown on behalf of the regius professors meant that there was no hope of a peaceful solution to Gordon's immediate problem.[135]

The nature of the University administration, whereby most of the authority was vested in the Faculty, leaving the regius professors to form a second and inferior rank, provides a further clue; and general lack of space within the Old College of Glasgow at least partially excused the initial failure to provide Gordon with a room. But as Thomas Thomson's new chemistry buildings costing £5000 and financed by the College illustrated, where the institutional will existed money could be found.[136] By the 1820s, however, the controlled evolution of Thomson's course had stimulated annual attendances of over 200. The obstacles placed in Gordon's path by an increasingly rigid Faculty with which his undiplomatic dealings were signally unsuccessful contributed to his failure to create and sustain an academic course attractive to the aspiring engineers of the industrial community of Glasgow. What Gordon described as "Neglect by the Public" meant that by the 1850s the chair of civil engineering and mechanics had become a sinecure.

Gordon's retrospective account of 1852, by which time he was clearly not teaching, charting the efforts required to obtain sufficient accommodation expressed the bitterness he felt over the hostility that had been shown towards him. Responding to Allen Thomson, professor of anatomy

---

[135] When Rankine became professor his treatment was initially dogged by this historical legacy of animosity, manifested as a refusal to give any concessions to the troublesome chair of civil engineering and mechanics (chapter 7).

[136] Morrell, "Thomas Thomson", p.254.

from 1848 and half-brother of Dr William Thomson, who was then Convenor of a Committee "on the present state of the College Buildings", Gordon took the opportunity to direct a tirade against the College authorities:

> For six years, during which I devoted my time exclusively to fulfill my Commission, the accommodation afforded to me in the Law class room, or the Natural History class room or the Practice of Medicine class room was so limited, so unsuited to the requirements of the class, in regard to exhibition of models of experiments, or of drawings that I attribute the neglect by the Public of the advantages held out by the Crown in instituting the Professorship in great measure to this want of accommodation. I have not collected apparatus for experiments because there was no room afforded me in which to place it. The models and drawings I have had, have been broken and damaged in consequence of this total want of accommodation.[137]

The practice of medicine class room was of course his friend Dr William Thomson's. This statement does require some modification, however. Gordon was by 1852 partly speaking in justification of his absence from the University. There is evidence that by 1847 he had been assigned a single room of his own, although no details are to be found in the Faculty records: a plan of the entire College produced to satisfy Treasury requirements and giving the allocation of each room shows that there was indeed a small L-shaped engineering classroom in the south wing, between the classes of moral philosophy and ecclesiastical history.[138]

Despite these difficulties there was an engineering class of some kind for most years of Gordon's tenure of the professorship.[139] Thus in spite of his lack of a classroom, he was in a position at the end of the 1840-41 session to award prizes to four students for examinations and for

---

[137] Accession 3409 (dated 6 February 1852), Glasgow University Archives.

[138] See plan of the Old College, submitted to the Faculty by the architect John Baird on 28 August 1847 in order to satisfy the requirements of the Treasury, and apparently afterwards not submitted to the University Commissioners until 30 March 1849. See Accession 12721, Glasgow University Archives; and Oakley, *Engineering at Glasgow*, p.7: "Eventually an upper floor room on the west side of the Inner Quadrangle, above the Natural Philosophy apparatus room, was allocated to Engineering Studies...a small attic room with one window, the highest in the building".

[139] Constable blandly asserts: "After delivering his lectures [Gordon] had the satisfaction to find that he had got through the first session with comfort to himself and profit to his pupils". Constable, *Gordon*, p.44.

essays "On the Theoretical Principles involved in the Construction of Machinery", "On the Principle of Vis Viva and its relation to Mechanical Effect" (maintaining his affiliation to Weisbach) and "On Certain Physical Properties of Matter in relation to the Doctrine of the Strength of Materials."[140]

In the next session, now squatting in the law classroom, Gordon again had students (at least three), one of whom was James Thomson, the son of the mathematics professor.[141] In 1840 Thomson had taken an M.A. with honours in mathematics and natural philosophy at Glasgow College. After only three weeks spent in John Macneill's engineering office in Dublin, during which time Rankine was also Macneill's pupil (chapter 3), ill-health forced his return to Glasgow.[142] His friend McClean wrote to him on 15 November 1841, reflecting James's high hopes for the course and demonstrating his own:

> I am glad to find that you will be able to attend the Civil Engineering Class this session - no doubt you will derive much benefit from it. If Mr Gordon has published the heads he proposes lecturing on, I will be much obliged by your sending me a copy.[143]

Subsequently Gordon enthusiastically (and diplomatically) praised James Thomson as "Most distinguished Student and Essayist in the Class of *Applied Mechanics*", having written on "Overshot Water Wheels". Others in the 1841-2 session had displayed "Eminence in Civil Engineering" (Andrew Stein of Greenock); and obtained rewards for the best essay on "methods of Founding in different kinds of compressible soils" (Charles B. Ker).

---

[140] Prize and Degree List of Glasgow College 1833-63, Glasgow University Archives, p.90. Presumably there were more than four students but class lists and calenders do not survive for this year.

[141] See James Thomson, "Civil engineering class notes, 1841", A4, MS13, Queens University Belfast.

[142] Sir Joseph Larmor and James Thomson (eds.), *Collected papers in physics and engineering* (Cambridge University Press: Cambridge, 1912), pp.xix-xx.

[143] Quoted in Larmor and Thomson (eds.), *James Thomson Papers*, p.xxi. In 1849 James Thomson moved to London to work with Gordon there. Ibid., p.xxxix-xl. James Thomson's recommendation of Rankine's admission to the Institution of Civil Engineers in 1843 demonstrates (transitively) a further link between the first two professors of engineering at Glasgow.

Stein attended Gordon's course in both of these first two sessions.[144] But beyond 1841-2 there are no details of any prizes awarded to students of civil engineering and mechanics even though the University prize lists do exist.[145] This suggests once again the low status and marginal nature of Gordon's class.[146]

For the 1844-5 session, during which David Thomson was teaching natural philosophy as Meikleham's assistant, Gordon advertised in the *University Calendar* : on each occurrence his class was given the name "Civil Engineering and Practical [sic] Mechanics".[147] This important qualification both explained and limited the course in line with the anti-invasionary fears of natural philosophy and mathematics. Gordon's class was scheduled to meet at 7 p.m., an hour justified by Rankine retrospectively as an attempt to facilitate a wider audience: "not only young civil engineers' assistants, but young men engaged in mechanical engineering works and in workshops" could attend.[148] In fact Gordon offered two separate courses, one comprising topics in civil engineering and the other discussing the principles of mechanics relevant to machines, properties of materials and related subjects.[149] "Civil Engineering and Practical Mechanics" was placed in the faculty of arts. But engineering played no part in any other curriculum:[150] considered simply as an academic subject not counting towards any degree, and certainly not regarded as part of a liberal education, civil engineering and mechanics

---

[144] Prize and Degree List of Glasgow College 1833-63, p.103. From 1857 Thomson was Professor of Civil Engineering at Queen's College Belfast, until 1873 when he was chosen to replace Rankine at Glasgow.

[145] One more student may be identified: John Elder (1824-69), the eminent Glasgow marine engineer. See W.J.M. Rankine, *A Memoir of John Elder: Engineer and Shipbuilder* (William Blackwood and Sons: Edinburgh and London, 1871), p.4; Smith and Wise, *Energy and Empire* , p.730.

[146] These awards are not visible again until the session of 1856-7, Rankine's first full session as professor.

[147] *Glasgow University Calendar, for...MDCCCXLIV-XLV* , pp.2 and 21. This is the only calendar available before 1863-4.

[148] [Devonshire], *Royal Commission on Scientific Instruction and the Advancement of Science* , Minutes of evidence: 23 February 1872 (W.J.M. Rankine), question 9509.

[149] *Glasgow University Calendar, for...MDCCCXLIV-XLV* , p.21.

[150] Oakley, *Engineering at Glasgow* , p.7.

might have expected limited student numbers. One of Rankine's major aims on becoming professor was to integrate his course with those of other professors at the University to rectify this institutional isolation (chapter 7).

Syllabuses of lectures published in 1847 and 1849 show that Gordon had not given up his efforts to develop a strong and coherent course.[151] These texts were partly bibliographic in nature: as well as Adam Smith on economy and Newton's *Mathematical Principles of Natural Philosophy* , Gordon recommended Willis for kinematics and Rankine on the "Use of Cylindrical Wheels on Railways" (chapter 3).

He continued to offer two separate courses in literal accordance with his title. The first, "engineering" dealt with communications (roads, canals, railways); hydraulics; and the strength and stability of structures. The second, "mechanics" sailed dangerously close to natural philosophy: mechanical effect was there, dynamometers, gravitation, forces and their effects, impact or shock, vis viva, and the conditions of the maximum effect of machines. This dual system was no doubt designed to attract two classes of students. But it ran the risk of antagonizing two interest groups: simplistically, the established engineers, who might see a threat to their apprenticeship and pupillage fees; and the (academic) "mechanical philosophers" who had clearly already been worried at the Gordon's impolitic annexation of mechanics. During Rankine's bid for the professorship in 1855 he was to work hard publicly and rhetorically to promote a reconciliation, adjoining to the discourse of "theory" and "practice" a distinct third element, uniting, as it were, Gordon's two courses into one having no obvious opponents (chapter 7).

Significantly, Gordon stressed the mechanical action of heat. Thus the final section of this second part began portentously, paraphrasing Tredgold's famous Charter of the Institution of Civil Engineers:

> All the forces or powers of nature, which it is the business of

---

[151] See bibliography.

> the engineer to adapt to the uses of commerce and manufactures, are referrable to the effects of HEAT and ANIMAL EXERTION.[152]

Ending this fundamental paragraph with keen sensitivity to current engineering enthusiasms and betraying his own preoccupations of this time (chapter 4), he pointed out, that

> this is the manner of producing power in the air-engine, by the heat of a fire.[153]

The whole of the last fourteen pages was taken up with investigations of heat, temperature, and gases, including references to the ongoing experiments of Regnault which by late 1848 and early 1849 were so vital to Thomson's "Account of Carnot Theory" (chapter 4).[154]

Beyond these syllabuses, which suggest (but do not prove) that classes were formed, there is evidence of his taking part in the more mundane activities of University administration, although his attendances at Senate meetings were at best irregular, and from 7 January 1850 there were simply none. With appointments to the Rectorship of the University of the Marquis of Breadalbane and Lord Rutherfurd, both Whigs, in 1840 and 1844 respectively, and Dr William Thomson's election to the Faculty chair of medicine in 1841 Gordon was not without sympathetic allies.[155] But indications of his lack of enthusiasm for the engineering post, and his difficulty in getting students, dated back much earlier than his disappearance from Senate. Even after his friend and associate William Thomson was appointed Professor of Natural Philosophy in 1846, things did not become substantially smoother for Gordon. Indeed, in certain key ways, individual constraints may have increased.

In April 1847 most University classes were still meeting, but Gordon

---

[152] Lewis D.B. Gordon, *Civil Engineering and Mechanics. Engineering Aphorisms and Memoranda: a synopsis of lectures to be delivered session 1847-8* (Griffin and Co.: Glasgow, 1847), part 2, p.39.

[153] Ibid.

[154] Ibid., pp.43-56.

[155] For Breadalbane's election see Faculty, 85(24 November 1840), p.26. In the mid-1840s Gordon was Inspecting Engineer at Breadalbane's mines in Perthshire: the Marquis and the Marchioness "delighted to speak of Gordon" to his Freiburg friend Thost. See Constable, *Gordon*, pp.34-5. Rutherfurd made Nichol his Vice-Rector.

was in London, and missed Thomson's presentation to the Glasgow Philosophical Society on the Stirling air-engine which was capturing the public imagination (see chapter 4):

> I regret very much not having been present to hear your exposition of the Stirlings' Engine. Mr. Stirling is in Town - I am laying a trail for getting up a substantial Company for the manufacture of the engine -
>
> When you hear it said that I have left Glasgow & its Professorship of Engineering you may in the mean time contradict it: though truth to say I am most willing to give up my charge.[156]

The 1847 syllabus, with its emphasis on theories of heat may have been an attempt to attract elusive students to the course. But in spite of this notice of "lectures to be delivered", on 20 December Gordon was again in London: his colleague William Thomson wrote to him, referring to notes on Clapeyron's paper on the theory of heat, and asking "how matters go in the metropolis especially with ref^{ce} to engineering".[157] In February the next year Gordon wrote to the Senate to explain his continued absence from the University,[158] but the matter was eclipsed by violent debate over William Thomson's natural philosophy class. Thomson was clearly trying to strengthen the position of natural philosophy within the University. Although by statute it was compulsory that candidates for BA attend both natural philosophy and moral philosophy courses, it transpired that students had been awarded the degree without attending the first of these. It was asserted, however, that all students must take moral philosophy and that the combination of mathematics and natural philosophy would not suffice as a substitution. Thomson's attempt to force a natural philosophy student who had not taken moral philosophy led to a division in the Senate and acrimonious discussion lasting from

---

[156] Gordon to Thomson from 24 Abingdon Street London, 27 April 1847, G118, Kelvin Papers, Cambridge University Library.

[157] William Thomson to Gordon from Glasgow College 20 December 1847, G124, Kelvin Papers, Cambridge University Library.

[158] Senate, 90(19 February 1848), p.49. The letter was "ordered to lie on the table till next meeting"; a reply was drawn up "to be laid before the next Meeting of Senate" but since neither letter nor reply are in the Minutes we can only guess at the contents. It must surely have been a serious matter, however, since it necessitated Senate's consideration and approval. See Senate, 90(20 March 1848), p.55.

January through to the end of April.[159]

In this combative and expansionist mood it seems unlikely that Thomson would have been prepared to allow even his friend Gordon to encroach on the intellectual territory of Glasgow natural philosophy. Gordon had provided Thomson with a copy of Carnot's original memoir late in 1848; Gordon's knowledge of and enthusiasm for the Clapeyron/Carnot theory of heat, and for the Stirling air-engine had been shared (chapter 4). Now Gordon wished to reap some small academic benefits, making his class more attractive by offering lectures on the subject of heat. Towards the end of November 1848, a timely note was dispatched from the professor of natural philosophy in Edinburgh to his counterpart in Glasgow. Directly following a plea that Thomson provide "an abstract of the Motive Power of Heat for the RSE", Forbes expressed his disquiet at the signs of subversive activity from their colleague:

> Last night I looked over the new part of Gordon's Syllabus of his lectures. Entre nous, it appears to me a most important trespass on the subject of Natural Philosophy. His class may be unimportant just now: but a principle so important is involved, that I think you ought to make a mild but decided remonstrance against the Invasion which would confine Natural Philosophy to Physical Astronomy, Optics, & Electromagnetism.[160]

Gordon, it seemed, hoped to annex not just mechanics, but the exciting and potentially economically valuable theory of the motive power of heat in an attempt to rescue the ill-defined and possibly foundering discipline of Glasgow academic engineering. Forbes no doubt wished to remain on good terms with his former pupil. But the scrap of professional advice he offered Thomson illustrates just how important the question of intellectual territory was, how jealously such territory had to be

---

[159] Senate, 90(10 January to 26 April 1848), pp.46-60.

[160] Forbes to Thomson, 27 November 1848, F198, Kelvin Papers, Cambidge University Library. David Wilson has referred to this letter (Wilson, "Matrix", p.21, fn.25 but mistakenly attributes it to concern over "Lewis Gordon's lectures as new [sic] professor of engineering". By 1848 Gordon had been professor for eight years. Such high-handed curricular control, which was demonstrated if anything still more clearly at the time of the founding of the Edinburgh Chair of Technology (1855), was entirely characteristic of Forbes. See chapters 1 and 7.

guarded; and how an explicit transgression merited concerted defence.[161] At this stage, Forbes, and probably Thomson too, were determined to keep the theory of heat for themselves and for natural philosophy.[162]

It is impossible to recover the form of the promised remonstrance. In January 1849 with cholera claiming many inhabitants of Glasgow, including James Thomson senior, Gordon felt no urgency to return "seeing the little importance of [his] duties".[163] By May he had come to a decision regarding his final syllabus of lectures, possibly delayed under pressure:

> I shall expect you to send me the proofs you mentioned [of Thomson's "Account of Carnot's Theory"] soon now, as I begin to make up my mind to let the printing of my work proceed and should wish to revise the Commentaries on Carnot with your paper before me.[164]

Eventually disillusionment with the chair became complete. With several years' engineering business in hand, mainly concerning railways, Gordon wrote apologetically to his father in mid November 1851:

> I am in considerable doubt about going to Glasgow at all this year. I have not advertized nor taken any trouble in the matter, nor do I at present intend doing so. But I am not quite certain about this being the correct thing.[165]

Like his colleagues in London and Dublin, Vignoles and Macneill, Gordon had been lured away from the academic world by the lucrative prospects of

---

[161] Contrast this with Oakley: "He did not lack encouragement, however. This came particularly from Professor William Thomson (later Lord Kelvin)". Oakley, *Engineering at Glasgow*, p.8.

[162] Gordon stated thirty years later that he had been "met with much jealously by the Professors of Natural Philosophy and Mathematics" at Glasgow, forcing him to lean towards "a practical course of Engineering, embodying the essence of collected experience". Since he referred to his syllabus of 1848 as demonstrating this, the professor of mathematics referred to could only be James Thomson; and the professor of natural philosophy at this date in this year at least was William Thomson. See Constable, *Gordon*, p.277. A theory of *heat-engines* suitably related to natural philosophy was to be one element of Rankine's course of academic engineering in Glasgow a few years later. See chapter 7.

[163] Gordon to Thomson, 13 January 1849, G127, Kelvin Papers, Cambridge University Library.

[164] Gordon to Thomson, 24 May 1849, G129, Kelvin Papers, Cambridge University Library.

[165] Quoted in Constable, *Gordon*, p.53, a letter to his father 15 November 1851 from 24 Abingdon Street in London.

engineering practice (chapters 1 and 3). From the very beginning he had juggled teaching with business, working in partnership with Hill and later with Charles Liddell and R.S. Newall after the end of each session.[166] The formation of a company to manufacture the Stirlings' engine in 1847 (chapter 4), the well-publicized and collaborative design and construction (with Hill and Rankine) of Tennant's Stalk in 1841-2, and the ambitious plans (with Hill) to supply Glasgow with water from the northerly Loch Katrine mooted in 1845,[167] not to mention railway work (with Liddell and Hill) in England, Scotland and Wales,[168] and consultancy (with Hill) for Breadalbane's mining operations:[169] all these were undertaken during Gordon's tenure of the professorship. From the early 1850s a new function was found for the production of wire ropes, which Gordon had introduced to Britain after witnessing their use in mines in Germany: the protection of the electric wires used in submarine cables.[170] As Newall's company in Gateshead rapidly manufactured many thousands of miles of cable for the expanding international network, still more of Gordon's time was diverted from his academic duties.

Opposition from within the University and steadily increasing business commitments, diversified and consolidated during the economic recovery of the middle 1840s led by the railway mania, and given a new

---

[166] Constable, *Gordon* , p.44.

[167] "Report on the Plan of supplying the City of Glasgow with water from Loch Katrine, as proposed by the Glasgow Loch Katrine water Co.", pp.79-87 in volume entitled "Report of projected water works for Glasgow", D-WA, Strathclyde Regional Council Archives; John Burnet, *History of the Water Supply of Glasgow* (Bell & Bain: Glasgow, 1869), p.22; Constable, *Gordon* , p.45.

[168] Constable, *Gordon* , p.46. In the late 1850s Gordon and Hill projected a means of connecting the Aryshire and Monkland Junction railway "thereby effecting the shortest most convenient uninterrupted communication between the East and West of Scotland. Besides affording the greatest scope for centralizing the Province, the line proposed entirely avoids the harbour, interferes with little valuable property and is a means of affording additional bridge accommodation to the city." See the detailed proof copy plan Acc 12713, Glasgow University Archives.) The plan involves a railway junction in the centre of the college grounds.

[169] Constable, *Gordon* , p.46.

[170] Ibid., pp.46-9 and 53; Smith and Wise, *Energy and Empire* , pp.664-7. Wire ropes were patented in Britain by Gordon, Liddell and Newall.

impetus by submarine telegraphy made the decision to abandon the chair still less painful. By the early 1850s Gordon had abandoned academic engineering in Glasgow. But he retained the ability and the desire to secure the regius chair for a candidate of his own choosing: W.J.M. Rankine.

CHAPTER SEVEN

The harmony of theory and practice: constructing engineering science

> ...he who studies the sciences that bear upon his art, has before him, in natural objects, and in the order of the universe, structures in which there is no waste of material, and machines in which there is no loss of power. Thence he learns to see in each work of human art how far it falls short of perfect efficiency; and although perfect efficiency be unattainable, he learns to judge in what direction practice ought to strive, in order to approximate to perfect efficiency as nearly as is possible to human skill...the theory of a structure or machine sets before the mind of the engineer an *ideal* perfectly efficient model, not capable of being fully realized, but serving as a guide to the efforts of practical improvement.[W.J.M. Rankine, 4 November 1856][1]

Introduction: the rhetoric of engineering science

James David Forbes's jurisdiction in the self-appointed role of guardian of natural philosophy was not limited to Glasgow, where he had kept a keen and authoritarian eye upon Lewis Gordon (chapter 6). In 1855 George Wilson had found himself under great pressure from Forbes to define the nature and limits of the course of instruction he intended to give as the first regius professor of technology at the University of Edinburgh. In so doing Wilson had openly admitted the problems he faced, so similar to Gordon's, in avoiding curricular encroachment and respecting the existing rights of his colleagues (chapter 1). Wilson's initial willingness to cooperate had been singularly lacking during Gordon's first few months as professor at Glasgow. In an address which acted to allay the fears of recently gained colleagues, to further his academic acceptance, and to advertise his course amongst the Edinburgh public, a constituency of potential fee-paying students, Wilson chose to further his academic acceptance by portraying the chair of technology as a necessary

---

[1] W.J.M. Rankine, *Introductory lecture on the science of the engineer, delivered to the class of civil engineering and mechanics in the University of Glasgow, on the 4th of November, 1856* (Richard Griffin: London, 1857), p.9.

consequence of the "industrialness of man".[2]

When called upon to justify the Glasgow chair only a month later, Rankine too presented an address drawing upon a wide range of resonant cultural resources. Asked to describe the structure of the Glasgow University engineering course before the Devonshire Commission sixteen years later he replied:

> [We] instituted a department of engineering science...consisting of a course of study in the various branches of science that are applicable to engineering...we do not profess to teach pure practice, but the *art of applying scientific principles to practice* ; and we do not want our certificate [of Proficiency in Engineering Science to indicate] that the holder of it was fit to practise the profession, but only...that he possessed the requisite scientific knowledge.[3]

By then Rankine had had many years to rehearse such statements. His emphasis on the application of scientific principles in engineering teaching was characteristic of this period of intense debate over scientific and technical instruction. But over a decade earlier substantially the same idea had been promoted by the editors of *The Engineer* :

> There is a science of the application of science, and one of no minor importance...[4]

Less stridently, William Fairbairn, addressing the Manchester Mechanics' Institution in March 1852, had spoken of "the necessities which exist for a knowledge of science in union with practice".[5] George Biddell Airy, as

---

[2] George Wilson, *What is technology? An inaugural lecture delivered in the University of Edinburgh on November 7, 1855* (Sutherland and Knox: Edinburgh, 1855), p.13.

[3] *Royal Commission on Scientific Instruction and the Advancement of Science (Devonshire Commission)* , Minutes of Evidence, 23 February 1872 (W.J.M. Rankine), question 9506. My emphasis.

[4] *The Engineer* , 1(1856), p.3; quoted in David F. Channell, "Engineering science as theory and practice", *Technology and Culture* , 29(1988), 98-103, p.99.

[5] William Fairbairn, *Useful information for engineers* (2nd edition, Longman, Brown, Green, Longmans, & Roberts: London, 1856), Lecture V: "On the Necessity of Incorporating with the Practice of the Mechanical and Industrial Arts a Knowledge of Practical Science", reprinted in C.A. Russell and D.C. Goodman (eds.), *Science and the rise of technology since 1800* (John Wright and Sons Limited in Association with the Open University Press: Bristol, 1972), pp.262-6, quotation on p.264; William Pole (ed.), *The Life of Sir William Fairbairn, Bart* (London, 1877).

President of the British Association in 1851, had used the expression "engineering science" whilst describing the activities of Section G in his address to the meeting assembled at Ipswich.[6] Indeed, an imprecise feeling that the "scientific" and "practical" elements of engineering ought to be formally combined was common at least as far back as the 1810s, especially amongst those engineers who wished to raise the status of professional engineering within Britain.[7] Henry Robinson Palmer, promoting the foundation of the Institution of Civil Engineers, wrote that

> while the principles of systematic education for most of the learned and scientific professions...are actively encouraged, not even an attempt seems to have been made towards the formation of any special source of information or instruction for...the...Civil Engineer...[who] is a mediator between the Philosopher and the working Mechanic; and like an interpreter between two foreigners must understand the language of both ...Hence the absolute necessity of possessing both practical and theoretical knowledge.[8]

Engineering science then, if taken naively as the art of applying scientific principles to practice, merely extended a traditional flexible rhetoric. Going further than this, Rankine attempted explicitly to *fix* the concept through the syllabus, scope and structure of his academic teaching (and later his systematic textbooks), skilfully catering for the expectations of potentially opposing groups in Glasgow and further afield. Since the idea of engineering science was elastic, Rankine's public utterances might still be varied according to audience so much as to appear mutually contradictory. Portraying John Elder qua "engineering scientist", commercial judgment and "sagacity" were seen as central (chapter 8);[9] yet for a Victorian public with its consciousness collectively directed towards more lofty spiritual ideals, engineering

---

[6] *BAAS Report* , 21(1851), part 1, p.xlix.

[7] I investigate later the way in which Rankine utilized *caricatures* of "theory" and "practice" to further his academic aims.

[8] Quoted in [Institution of Civil Engineers], *A brief history of the Institution of Civil Engineers* (Institution of Civil Engineers: London, 1928), pp.10-11. Palmer is described as the man "to whom more than to any other person the foundation of the Institution may be attributed". Ibid., p.12.

[9] See W.J.M. Rankine, *A Memoir of John Elder: Engineer and Shipbuilder* (William Blackwood and Sons: Edinburgh and London, 1871).

science made engineering "not a mere profitable business, but a liberal and a noble art".[10] The superficial divergence of these statements merely indicates the broad range of rhetorical uses engineering science could serve, tailored to suit and reflect diverse and partially conflicting complexes of views and preconceptions.[11]

Shortly after Wilson had given his introductory address in Edinburgh, Rankine too had armed himself with a complex of arguments designed to support the Glasgow chair of civil engineering and mechanics. Reinterpreting and manipulating the vagaries of prevailing rhetorics of "theory" and "practice", Rankine gained substantial intellectual capital by promoting a *harmony of theory and practice*.[12] Briefly, large-scale industrial "practice" was seen as providing the empirical data on which to base "scientific" progress; it also formed a testing ground - "practical proof" - for the applications of scientific principles to practice. Utilising this rhetoric, public expositions of the nature, purpose, and value of engineering science aimed to provide it with a credible foundation, easing its acceptance into the University while simultaneously showing it to be of industrial importance. Since the *harmony of theory and practice* also demonstrated the separation of Rankine's engineering science from "pure science" within the university and "pure practice" in industry, fears of transgressing traditional boundaries were assuaged.

---

[10] Rankine, *Science of the engineer*, p.16; also quoted in Lewis D.B. Gordon, "Obituary Notice of Professor Rankine", *Proceedings of the Royal Society of Edinburgh*, 8(1872-5), 296-306, on p.302.

[11] For a discussion of the kinds of analysis I attempt see, for example, the introduction to L.J. Jordanova (ed.), *Languages of nature* (New Brunswick, 1986), pp.15-47.

[12] Rankine's inaugural address was entitled "De Concordia inter Scientiarum Machinalium Contemplationem et Usum", or "The Harmony of Theory and Practice in Mechanics". See also his *Introductory lecture on the harmony of theory and practice in mechanics, delivered to the class of civil engineering and mechanics in the University of Glasgow on January 3 1856* (Richard Griffin & Co.: London and Glasgow, 1856). This was republished and incorporated in part as an introduction to his *Manual of Applied Mechanics* (Richard Griffin & Co.: London, 1858). This introduction is reprinted in Russell and Goodman, *Science and technology*, pp.266-71 (page references to this reprint). "Applied mechanics" had a broad interpretation, encompassing, in particular, marine engineering.

The analysis given of the machinations behind the patenting of the air-engine improvements provides a revealing precedent for Rankine's rhetoric and further clues to its genesis.

Before discussing this public marketing of engineering science (in particular at the British Association meeting of 1855) and the subsequent career of Rankine within the University, I recount what can only be seen as the careful preparation for an assault on the chair beginning late in 1854 and, I believe, planned much earlier. The contrasts with Gordon's experience are obvious: my analysis will suggest explanations for the differences in terms of changes in Glasgow University's administrative structure, the assistance of powerful internal allies and the skilful manufacture and exploitation of opportunities for public rhetoric. Above all, it will become clear that Rankine had been interacting at all levels with the culture, institutions, and individuals of Glasgow and its environs, gaining, making, and using local knowledge.

Local knowledge: the Glasgow Philosophical Society

Viewed as candidates for the Glasgow professorship, Gordon and Rankine differed substantially in the degree to which they were integrated within the elite institutional culture of Glasgow *prior* to election.[13] The Glasgow Philosophical Society provided a meeting point and a focus of influence for a surprisingly full complement of prominent Glasgow citizens. Soon after becoming professor, William Thomson had presented his first paper to the Society on the subject of the Stirling air-engine; and Lewis Gordon had used the Society to introduce Glasgow to Carnot's

---

[13] This is not to suggest that Gordon did not *later* develop strong local institutional networks. See also A. Kent, "The Royal Philosophical Society of Glasgow", *The Philosophical Journal*, 4(1967), 43-50; and for an excellent analysis of the Society's revival and allegiance to Glasgow University, under the Presidency of Thomas Thomson, see J.B. Morrell, "Reflections on the history of Scottish science", *History of Science*, 12(1974), 81-94.

theory of heat (chapter 4). But whereas Gordon only become a member of the prestigious Glasgow Philosophical Society in December 1840, after becoming professor, Rankine had been dynamically engaged in its activities for three years before his appointment to the Glasgow chair.[14]

During this period Rankine had the opportunity to develop and consolidate many links with local individuals established no doubt during the 1840s as he practised as a railway engineer (chapter 3). Furthermore, the meetings of the society provided a forum for the tailored presentation of his engineering work, alone or with his business partner John Thomson;[15] an amenable environment for discussion of his scientific work; a platform for larger scale publicly utilitarian projects; and the necessary basis for consolidating institutional networks, exemplified in the courting of the British Association for the Advancement of Science leading up to the 1855 meeting. In diverse ways and for diverse groups these activities sharpened Rankine's Glasgow profile, defining a public image in much the same way as his earlier publications and activities centred on the Institution of Civil Engineers had done (chapter 3). An increasingly close embedding within the Glasgow context went hand in hand with appointment to and subsequent success in the Glasgow chair. Gordon in 1840 was well-travelled abroad, but comparatively unknown in Glasgow. His successor in 1855 was an integral part of the Glasgow scene, an experienced administrator and self-publicist, who knew how to exploit local institutional structures and existing social networks.

Rankine climbed rapidly in the Philosophical Society's hierarchy. In his first full session he was elected Member of Council, alongside his friend James R. Napier (chapter 5),[16] and William Thomson. Allen Thomson,

---

[14] Gordon and Rankine were elected on 2 December 1840 and 4 February 1852 respectively. See *Proceedings of the Glasgow Philosophical Society*, 3(1848-55), pp.3 and 219 respectively.

[15] John Thomson, son of Dr William Thomson, Glasgow professor of medicine until 1852, was elected to the Society on 19 November 1851. Ibid., p.219.

[16] Napier had been elected to the Glasgow Philosophical Society on 23 January 1850. His election diploma is in DC 90/3/13, Napier Papers, Glasgow University Archives.

professor of anatomy at the University, was Vice-President for this 1852-3 session.[17] Although Rankine held no office the next year it was he that proposed five new Members of Council in 1853, with Napier and William Thomson maintaining their posts.[18] The following year Rankine was joined on the Council by his mechanical engineering friend Walter Neilson, with Allen Thomson taking the highest position as President.[19] By November 1855, with Allen Thomson still President, Rankine had been elevated to Vice-Presidency, with the Council including William Thomson, J.R. Napier, and Walter Neilson.[20] All of these figures were to continue to play active roles as office-bearers and contributors to the proceedings of the Society. Personal allegiances cohered to form an integrated institutional presence in Glasgow.

The broad nature of the society, fully representing the progressive whig interests of the city of Glasgow dominated by its engineering culture, supported and in some cases led by the University professors, gave Rankine the opportunity to present both engineering projects and scientific work. Thus, for example, whilst he could comfortably read a paper with John Thomson on "Telegraphic Communication between Great Britain and Ireland" (17 November 1852), exhibiting specimens of cable manufactured by Gordon's associate R.S. Newall (chapter 6), the Glasgow Philosophical Society was also a suitable venue for discussion of his more theoretical offerings "On the General Law of the Transformation of Energy" (5 January 1853) and "Outlines of the Science of Energetics" (2 May

---

[17] *Proceedings of the Glasgow Philosophical Society*, 3(1848-55), p.265. Like the University, the Society had an annual "session" beginning in November.

[18] Ibid., p.328.

[19] Ibid., p.363. Neilson was a major force in the foundation of the Institution of Engineers in Scotland, of which Rankine was the first President.

[20] *Proceedings of the Glasgow Philosophical Society*, 4(1855-60), p.5.

1855).[21] This latter work, in turn, although asserting universality and ultimately made central to late nineteenth century physics through the unifying construct of "energy", was just as much a local, exportable product, linking Rankine with William Thomson.[22]

Beyond these individual presentations Rankine worked assiduously in committee to lobby for projects of local importance, coordinating the dispatch of a memorial to the Treasury, arguing for enhanced and commercially vital features (increased scale, contour lines, marking of ground levels) on the new Ordnance Survey Maps of Lanark, Ayr and Renfrew;[23] advocating the generous scale of ten feet to the mile for a new map of the Municipality of Glasgow;[24] and in January 1855 pointing out the importance of ensuring the representation of Glasgow instrument makers (such as the maker of his model air-engine, James White) at the Universal Exhibition to be held in Paris.[25] One venture not directly connected to the Philosophical Society but at least presented in a similarly altruistic manner was the (unsuccessful) revival by Rankine and Thomson of Gordon and Hill's plan to bring water from to Glasgow from Loch Katrine (chapter 6). In the aftermath of major outbreaks of typhus and cholera sanitation and water supply were placed high on the Glasgow political agenda.[26]

Most characteristic of these projects to promote and display civic pride was the campaign to bring the British Association to Glasgow again.

---

[21] *Proceedings of the Glasgow Philosophical Society*, 3(1848-55), pp.265, 275, and 381. For full references to papers see bibliography. The first submarine cable (not including river and harbour cables) was the Dover-Calais line (1850-1). An England-Ireland cable was actually laid in 1853 soon after Rankine and Thomson's suggestion. See Vary T. Coates and Bernard Finn, *A Retrospective Technology Assessment: Submarine Telegraphy. The Transatlantic Cable of 1866* (San Francisco Press: San Francisco, 1979).

[22] See Crosbie Smith, *The Science of Energy* (Forthcoming).

[23] *Proceedings of the Glasgow Philosophical Society*, 3(1848-55), p.275.

[24] Ibid., p.293.

[25] Ibid., pp.364-5.

[26] See Hugh B. Sutherland, *Rankine: his life and times* (Institution of Civil Engineers: London, 1973), pp.11-13; Stephanie M. Blackden, *The development of public health administration in Glasgow 1842-1872* (unpublished PhD thesis, Edinburgh University, 1976, p.376), and more generally Chapter 14: "A Triumph of Municipal Enterprise - the Water Supply of the City".

Rankine himself had been cultivating links with the Association since 1850, acting as Secretary to Section A up to and including the 1852 meeting.[27] At the Ipswich meeting in 1851 he had made a significant addition to his scientific acquaintance by meeting G.G. Stokes, no doubt introduced to him by William Thomson.[28] From 1852 the Philosophical Society had been working to arrange a second meeting in their city. Deputations in previous years had repeatedly failed to elicit a positive response, but by 8 February 1854 Andrew Liddell, who had done so much to bring about the first Glasgow Meeting in 1840, moved once more that the Council issue an invitation, having now "reason to believe [it] would be cordially accepted".[29] By 1 November 1854 he could at last report the successful outcome of the deputation to the Liverpool meeting.[30] Rankine was directly involved in the organization of a meeting which provided him with a timely opportunity to present a widely publicized justification for the existence of the engineering chair, and a manifesto for engineering science in Glasgow.[31] Before this took place, however, Lewis Gordon had taken preliminary steps to reform the Glasgow University engineering class, with Rankine a willing deputy.

---

[27] See *BAAS Reports* for 1850 to 1852.

[28] Rankine to Stokes, 1 October 1851, R107, Stokes Correspondence, Cambridge University Library.

[29] Ibid., p.296 and 330. The run up to the 1840 meeting and its aftermath are analysed in Jack Morrell and Arnold Thackray, *Gentlemen of science* (Oxford University Press: Oxford, 1981), pp.202-22. See also chapter 6.

[30] Ibid., pp.333 and 355. Liddell died soon afterwards. A memorial describes, inter alia, the importance of his role in bringing the BAAS to Glasgow on both occasions. See ibid., pp.356-7.

[31] See also Rankine to William Gourlie(1815-65), *DNB*, 21 August 1855, Access. No. 67430, Autograph Letters Collection, Wellcome Institute for the History of Medicine. Rankine enclosed a copy of a reply from the Earl of Dundonald, who could not attend the meeting; and gave a list suggesting other notables who might be invited, including the Duke of Buccleuch, T.B. Macaulay, Palmerston and others.

The motive power of heat: perfecting the engine and the engineer

On 7 December 1854, one month after the news that the British Association was indeed to visit Glasgow in less than a year's time, Lewis Gordon renewed his attempts to gain access to the College. Writing to Hugh Blackburn, professor of mathematics since 1849 and currently Faculty Clerk, he expressed the most economical of requests:

> Will you oblige me by asking permission for me from the Faculty to use the Hebrew Classroom for my lectures at an afternoon or evening hour when it is not otherwise employed.[32]

With the memory of the early 1840s still very much alive, the Faculty, whilst making a small concession, reasserted their controlling influence over College property. The Hebrew classroom was unavailable, but

> if [Gordon] will make arrangements with the servant supplying coals to the Classrooms for the heating of the room the Faculty will allow him for this session and at any hour when not otherwise occupied the use of the Classroom generally used by the Professor of Natural History, unless any Classroom allowed him in former years seem more convenient to him.[33]

Gordon accepted this offer. His motives were clear. By the end of March 1855 the Faculty were again voicing anti-invasionary disquiet on discovering that the professor of civil engineering and mechanics was abusing the privilege granted him:

> [He] has not for some time lectured in the room assigned to him ...a stranger has been teaching a Class there...[The] Faculty Resolve that in assigning a room to any one for teaching a Class it is to be understood that the permission to lecture in one of their Class rooms is purely personal and is not to be considered to extend to the Deputies of the persons so accommodated without special permission of the Faculty.[34]

The mysterious "stranger" was in fact W.J.M. Rankine. The irony of this epithet was particularly strong since Rankine had actually been engaged by the College with John Thomson in various engineering duties connected with

---

[32] Letter transcribed into Glasgow University Minutes of Faculty, 87(8 December 1854), pp.137-8.

[33] Ibid.

[34] Faculty, 87(30 March 1855), pp.172-3.

surveying College property and installing drains between 1852 and 1854.[35] Gordon's attempt to smuggle him into the University through the back door, however, had been detected.

It is difficult not to see the initial request for a room as a preparation for the lectures which Rankine was to give in the early part of 1855. He had, after all, spent much of the period between December 1853 and July 1854 with Lewis Gordon in London (chapter 5). There was ample opportunity for lengthy discussions on how to resuscitate the ailing Glasgow chair at a time when Rankine was overwhelmingly concerned with the great potential of the much-admired air-engine. Rankine's links with many engineers both through the day-to-day activities of his profession and through influential friends associated with the Glasgow Philosophical Society, coupled with Gordon's contacts, guaranteed "a numerous attendance of students."[36] Napier himself attended the class.[37]

If Gordon had lectured at all it had not been for long: Rankine gave courses from January to April 1855 firstly on applied mechanics; and secondly on heat-engines (not only steam engines) treated as an appropriate application of scientific principles to an area of practical

---

[35] Faculty, 86(19 November 1852), p.366; Faculty, 87(14 April 1854), pp.71-2. Many of the plans survive: Accs. 694, 704, 711, 29104, 29104A, 20862, 20863, 35903, Glasgow University Archives. Acc. 705 is a "Plan of drains connected with College houses and proposed tubular drains" (July 1852). John Thomson appears as something of an expert on drains. See his best-selling *The Advantage of tubular drainage, as compared with Brick Sewers, in their application to Houses and Cities* (Glasgow, 1852).

[36] W.J.M. Rankine, "Opening Remarks on the Objects of the [Mechanical Science] Section", *BAAS Report*, 25(1855), part 2, 201-2, on p.202.

[37] Rankine to Napier, 7 November 1855, DC 90/3/1, Napier Papers, Glasgow University Archives. There are copies of Rankine's lectures on heat-engines annotated by Napier in DC 90/3/35.

engineering having vast commercial importance.[38] The topic had already been introduced to the University. We should no longer be surprised to learn that Watt Prizes were offered to students during the sessions of 1853-4 and 1854-5 for essays on "The comparative merits of the Air Engine and Steam Engine, considered theoretically and practically".[39] Beyond the general publicity it had received, the air-engine had of course been and remained a subject of pressing concern to Lewis Gordon, William Thomson, and Macquorn Rankine (chapters 4 and 5).

No record of the first series has survived.[40] But lectures from the second series were written up into a detailed synopsis of over forty pages, lithographed, and circulated amongst friends, students, and colleagues. Rankine's was aware of the commercial value of these carefully-prepared pages: "This work is copyright".[41]

It is important to stress that the lectures dealt with heat-*engines* , not merely heat. There was very little discussion of heat conduction and no mention of Fourier, an omission strategically designed and probably negotiated to avoid any overlap of interests with William Thomson, by now professor of natural philosophy.[42] The lectures did give a full resumé of

---

[38] Gordon, "Rankine", p.302; W.J.M. Rankine, *Synopsis of Lectures on Heat-Engines delivered at Glasgow in March and April 1855, in connection with Professor Lewis D.B. Gordon's course of Civil Engineering and Mechanics* (lithographically printed for private circulation, 1855). There is a second copy (not annotated) in DC 90/3/1, Napier Papers, Glasgow University Archives. On page 1, there is a variant title ("Synopsis of Lectures on Engines worked by Heat: to be delivered ["at the University of Glasgow" deleted], in connection with... Professor...Gordon's course of Civil Engineering and Practical [sic] Mechanics") which suggests that Rankine was ousted from the University following his discovery. Gordon's retrospective description of the second series of lectures as dealing with the "Application of Thermodynamics to the Theory of the Steam Engine" is both anachronistic (with respect to the use of "themodynamics") and fails to do justice to the content.

[39] See the Glasgow University Prize and Degree Lists, Glasgow Unversity Archives, for these years.

[40] However, I discuss later the primary importance of "applied mechanics" in Rankine's engineering science methodology (chapter 8).

[41] Rankine, *Heat-Engines* ,, p.1.

[42] They were clearly in contact at this time: see, for example, letter from Rankine to Thomson, 17 March 1855, written inside the title page of Rankine's "Abstract of a paper on the general law of the transformation of energy", in Y1-h.7, Glasgow University Library, Special Collections. The letter includes comments on Lamé.

contemporary heat theory, conspicuously and consciously slanted towards practical utility. At the very outset, under "General Laws of the Motive Power of Heat", Rankine gave a strong justificatory reminder of the "Practical Use of a Knowledge of such Laws".[43]

In many ways the lectures exhibited striking similarities to the Royal Society paper "On the Geometrical Representation of the Expansive Action of Heat" (chapter 5). Certain explanatory devices developed in that paper proved to be well-suited to the didactic purpose at hand: the theory-laden "diagram of energy" (a pressure-volume diagram for an elastic body) reappeared,[44] with its practical counterpart, the "actual indicator diagram" displaying heat, work and (thermal) efficiency for those taught to read it from the theoretical perspective dictated by Rankine.[45] Though he used both symbolic and geometric arguments, the emphasis on these tangible, non-algebraic "diagrams" fitted well with Scottish mathematical, philosophical and pedagogic traditions.[46] Clearly in Glasgow there was a local relevance scientifically and practically for the underlying artefacts: "energy" presented through the Glasgow and Edinburgh scientific societies; and the work generated by heat-engines in industrial Glasgow.

Amongst the extended analyses of heat-engines, the air-engine with its essential component, the economiser, again came first and again was assigned a prominent expository role. The structure of the lectures, as laid out in a "Summary of Principles", was geared towards a comparison between "perfect" and "actual" engines, a distinction strikingly reminiscent of the usage earlier capitalized upon by Thomson (chapter 4),

---

[43] Rankine, *Heat-Engines* ,, p.1.

[44] Ibid., p.17.

[45] Ibid., pp.18 and 31. The inversion of the order in which they appeared, with respect to the Royal Society paper, was perhaps significant. Whereas initially "practice" was shown to be guiding "theory", now the indicator diagram was by implication a secondary application of the theory of the motive power of heat to practice.

[46] Thus, for example, "Isothermal Curves for a perfect gas are hyperbolas". See ibid., p.17; Richard Olson, "Scottish philosophy and mathematics 1750-1830", *Journal of the History of Ideas* , 32(1971), 29-44.

and readily designed to give a directive for the activities of the engineer. Rankine instructed the engineer to strive to improve the "actual" towards the "perfect" goal where "perfection" itself was defined implicitly in terms of the theory of the motive power of heat.

Other aspects of the exposition demonstrated Rankine's indebtedness to Scottish methodological traditions, of which a self-conscious attitude towards the use of hypotheses in physical theories was particularly pointed (see chapter 2). Thus the lectures considered the "General character of Physical Theories, without or with Hypotheses".[47] I suggest that in fact this attitude served Rankine's purposes rather well. In carefully discussing rival hypotheses regarding heat, he gave himself the opportunity to laud his own hypothesis of molecular vortices,[48] and to warn against the caloric theory of heat, which "is specially to be guarded against, as leading to Errors, both scientific and practical".[49] This it was, according to Rankine, that had so manifestly retarded the progress of the air-engine (chapter 5).

Other allegiances were clear: to Lewis Gordon, to whose published synopses he referred;[50] to James Joule, who had proved experimentally, following others' anticipations, the fundamental law (the "first law") of the interconvertibility of heat and mechanical effect;[51] to William Thomson; to Regnault for varied experimental work;[52] and to his friend Napier for the results of practical investigations on the conduction of

---

[47] Heat was either i) a "Certain Class of Sensations" or ii) the state or condition of bodies producing that class of sensations, so far as the properties of that state can be ascertained by experiment. Rankine issued a firm methodological stricture: "This second meaning will be strictly adhered to, to the exclusion of all Hypotheses." See Rankine, *Heat-Engines* , p.1.

[48] Thus "Laws have been anticipated by this hypothesis, and afterwards confirmed by experiment." For one interpretation of the place of Rankine's molecular vortex hypothesis within his speculations on heat see Keith R. Hutchison, "W.J.M. Rankine and the rise of thermodynamics", *British Journal for the History of Science* , 14(1981), 1-26, particularly pp.3-6.

[49] Rankine, *Heat-Engines* , p.1.

[50] Ibid., p.4.

[51] Ibid., p.12.

[52] Ibid., pp.4 and 6.

heat.[53]

With the rhetoric of energy physics by now available, Rankine exploited it to the full. Above all, heat was to be "considered as a species of Energy; that is [the] capacity to perform Work",[54] classified in terms of "actual" (e.g. motion, heat, light, electric currents) and "potential" (e.g. pressures, attractions, repulsions, chemical affinities). Most importantly, "All kinds of Energy are expressible in units of work."[55] Given this general statement, it became possible to define the "efficiency" of a heat-engine as a simple numerical ratio of the external work done to the energy of the heat expended.[56]

For any given limits of temperature there was a maximum efficiency, described through a "diagram of energy" having two isothermals bounded by two curves of no transmission (Carnot cycle). By considering this cycle he reached the fundamental law that the greatest possible efficiency of a heat-engine working between two given absolute temperatures is the ratio of the difference of those temperatures to the higher of them.[57] This allowed a "necessary loss of heat"; and implied the following directive for engineering practice:

> Every project for making an engine give more than the above efficiency must involve a fallacy.[58]

Moreover,

> Actual Engines give less than the above efficiency, owing to causes of Waste of Heat and Power.[59]

The realizable object was clearly to identify and then diminish "waste" so that "actual engines" might be made to approach "perfect engines". Indeed, the rhetoric might be summarized thus: the task of the engineer was to approach perfection.

However, rather than be dependent on the cycle of expansions and

---

[53] Ibid., p.11.
[54] Ibid., p.14.
[55] Ibid.
[56] Ibid., p.19.
[57] Ibid., p.20.
[58] Ibid.
[59] Ibid.

compressions described above, there were "Other Means of alternately heating and cooling a substance".[60] Exactly as in the Royal Society paper, Rankine introduced a discussion of the

> "Economiser, Regenerator, or Respirator, invented by the Rev. Dr. Stirling; improved by James Stirling & Captain Ericsson; applied to the Steam-Engine by C.W. Siemens; - composed of plates or wires of solid conducting material, to store heat during cooling of elastic fluid & restore it during heating."[61]

The "Theoretical Diagram of Engine with Economiser" consisted of two isothermal curves, bounded by "any pairs of equal transmission".[62] As in the Royal Society paper, he emphasised that for a "perfect economiser", the efficiency was equal to the maximum theoretical efficiency.[63] He reiterated that in the past there had been promoted "fallacies as to the action of the Economiser. No actual economiser can save all the heat of Temperature."[64] But now his exposition of the theory of the motive power of heat enabled him "to compute the expenditure of Heat in a Perfect Air-Engine".[65] By calculating the heat absorbed , and the heat converted into mechanical effect per pound of air per stroke, he could show directly that the efficiency was equal to $(t-t^1)/t$, that is, the maximum theoretical efficiency of any heat-engine working between the absolute temperatures t and t^1.[66] For two typical limits of temperature he calculated the efficiency of a perfect engine: translated into comprehensible engineering units, this engine required only 0.73 lb of coal per horsepower per hour.

Having thus dealt with perfect air-engines, he presented

> Actual Air-Engines: causes of waste of Heat in them. Their practical difficulties.[67]

---

[60] Ibid., p.21.
[61] Ibid.
[62] That is, any pair of curves for which $F - F^1$ is the same for each pair of points of intersection with an isothermal curve, where F is Rankine's heat factor, a function such that heat, $H=\int t\,dF$, where t is absolute temperature.
[63] Rankine, *Heat-Engines* , p.21.
[64] Ibid., p.22.
[65] Ibid.
[66] Ibid., p.23.
[67] Ibid.

Now there was a theoretical standard against which they could be measured: the "actual consumption" of Stirling's engine and that of Ericsson was three times the theoretical consumption. Here again was a strong argument for perfecting the air-engine. Some steps has already been taken along this promising path: he outlined the

> Means of preventing waste of heat, in Napier & Rankine's engine.[68]

It is important to appreciate that the entire analysis of air-engines and economisers preceded the discussion of vapour engines. In Rankine's treatment the air-engine appeared as the first application of the theory of the motive power of heat. Undoubtedly such an analysis of the working substance air, treated as a perfect gas, was substantially simpler than the following considerations of vapours, and compound engines. Air could be treated as a "perfect gas, whereas the law of elasticity for steam was "not yet known".[69] Most importantly, the air-engine's cycle, visualized in a particularly simple diagram of energy, was as efficient as the cycle of an ideal Carnot engine. Simplicity of exposition; novelty and topicality in light of the exploits of Ericsson and Stirling; the great hope of material improvement saving waste, not to mention promotion of the Napier and Rankine engine: all guaranteed for the air-engine pride of place in his lectures presented to the Glasgow students.

An analysis of other forms of engines followed according to the same scheme of comparing perfect with actual but was complicated by the need to introduce a discussion of latent heats.[70] The "Theoretical Diagram of a Perfect Vapour-Engine"[71] required modifications to allow for i) omitting heating by compression (this gave an efficiency of only 0.208, 15/16 of the maximum theoretical efficiency); and ii) incomplete expansion (efficiency 0.068, 3/10 of the maximum theoretical efficiency). With

---

[68] Ibid.

[69] Ibid., p.3.

[70] For steam and ether Rankine gave tables relating to saturated vapour pressures emblazoned with the motto "never before published", an indication of the value of attending this course. Ibid., pp.25 and 27.

[71] Ibid., p.28.

neither expansion nor condensation, the efficiency was only 0.044, and the energy displayed only 1/5 of the maximum theoretical efficiency.[72] Clearly all of these values compared unfavourably with the air-engine. A specific example led to a consumption of coal per horsepower per hour as 4.725 lb.[73] Although Rankine did not make an explicit statement, this result for a perfect vapour engine was far higher than that for the actual air-engines of Stirling and Ericsson.

Having dealt with other forms of engine,[74] he finally discussed Siemens regenerative steam-engine, with its action compounded of a condensing steam-engine and that of a super-heated steam-engine with an economiser to store the heat of temperature.

> Its object being to obtain a great range of temperature without excessive pressure; - being the same with that of the Air-Engine.[75]

Immediately after this pointed reminder of the air-engine's merits came a "Summary of Principles", no doubt intended to encapsulate the rationale of the entire course. Rankine had treated the important subject of furnaces and their efficiency at some length. In the summary he gave a simple analysis in terms of useful, wasteful, and theoretically determined factors: thus the "total heat of combustion" consisted of the sum of the (avoidable) waste heat of the furnace, the (unavoidable) theoretical loss of the engine, the (avoidable) waste heat of the engine, the work of prejudicial resistance, and the useful work done. This sum was only possible within a theoretical context which allowed the inerconvertibility of heat and work. The implication was clear: each avoidable loss of heat or work should be minimized.

Rankine then gave a chain of efficiencies: some, like the efficiency of a perfect heat-engine (E_p), were theoretically determined; others, like

---

[72] Ibid., p.29.

[73] Ibid., p.32.

[74] Double cylinder engines, composite vapour engines (using steam and ether), and super-heated engines.

[75] Rankine, *Heat-Engines* , p.39.

the efficiency of the furnace (E_f), the mechanism (E_m), were empirically measurable. Crucially, Rankine chose to define the efficiency of an actual heat-engine E_a as $(1-i)E_p$. He called i the "coefficient of imperfection", varying between 0.1 and 0.8. The smaller the coefficient of imperfection, the more efficient was the actual heat-engine. Finally, re-synthesising, the resultant efficiency was given by $E_r = E_f.E_a.E_m$, or $E_f.E_p(1-i).E_m$. Then the "useful work" was simply the total heat of combustion multiplied by E_r. Thus each independent factor had its part to play in analysing, naming, defining, and measuring the wasted work. Each factor must be increased as far as possible towards 1 (except E_p). But the quantity i in particular represented the degree to which an actual heat engine remained to be perfected by the engineer. In evaluating the engine, it evaluated the engineer.

With the coming of the BAAS to Glasgow in September the opportunity arose for a public presentation of the underlying methodology implicit in these lectures. Designed to please both local and (in printed form) national audiences, the rhetoric of the *harmony of theory and practice* drew on academic, industrial, institutional, and moral resources to argue for academic engineering and engineering science in Glagow.

Harmony of theory and practice within the British Association

> ...in many cases the best, and in some cases the only means of impressing on the public mind the truth and the importance of scientific principles consists in their practical application, which thus re-acts beneficially on the diffusion and the appreciation of theoretic knowledge.[W.J.M. Rankine, 13 September 1855][76]

On 12 September 1855, just over fifteen years after receiving his Commission Gordon at last offered his resignation. It was accepted, and the University Senate instructed Principal Macfarlan to inform the Home Secretary of the new vacancy.[77] There was a rapid response: Pagan and

---

[76] W.J.M. Rankine, "[Opening Remarks to Section G of the British Association in Glasgow, 1855]", reported in *Glasgow Herald*, 14 September 1855, p.5.

[77] Glasgow University Minutes of Senate, 90(12 September 1855), p.264.

Rainy, regius professors of midwifery and forensic medicine, joined by Macfarlan, attempted to force through general assent to a statement to the Government suggesting that

> notwithstanding the high talents and acknowledged ability of the late Professor the number of Students attending the class of Civil Engineering had been very small, and that the endowment might with propriety be devoted to purposes of greater and more immediate importance in connection with the higher branches of University education.[78]

No doubt Pagan and Rainy were contemplating a redistribution of Gordon's generous salary of £275 per annum. The motion was promptly passed; but this renewed attempt to excise civil engineering and mechanics from the College had been more than a little underhand. By this time in the evening several members of the Senate likely to oppose such a move had departed. Serendipitously Allen Thomson remained. Immediately he registered his dissent,

> both on the grounds of its general inexpediency and of its being passed in a meeting of Senate at which from the departure of members only a small number of professors were present.[79]

At the next meeting of Senate J.P. Nichol added his voice in protest

> against the resolution and procedure of the Senate at last meeting...on the ground that a step of such importance ought not to have been taken without due notice being given to all the Members of Senate.[80]

Gordon's resignation was indeed strategically timed. Even before the end of the winter session preparations for the British Association had been well under way. Classrooms in the College itself were to be used for some of the gatherings.[81] On 12 September the Glasgow meeting of the British Association for the Advancement of Science had been opened. At the first general meeting the Duke of Argyll, Rector of the University and a consistent advocate for technical instruction spoke to the assembled masses:

> There is one aspect in which we do not require to plead the

---

[78] Ibid.
[79] Ibid., p.265.
[80] Senate, 90(5 November 1855), p.266.
[81] See Faculty, 87(27 February 1855), p.159.

> cause of science as an element of education...I mean that in which certain applied sciences are recognised as essential bases of professional training, as, for example, when the engineer is trained in the principles of mechanics and hydrostatics, or the the physician in those of chemistry.[82]

His words were repeated only days later in the *Glasgow Herald*, eager to give the fullest coverage of events at the meeting, including details of locally organized events and conversaziones, abstracts of papers presented, and accounts of discussions that had taken place. In the face of such rhetoric, Pagan's manoeuvre was indeed inexpedient.

The following morning the transactions of the Sections began. Section G provided the setting for a discussion of "Mr Rankine's important practical tables of the latent heat of vapours", recently offered to his class. Ironically, "Dr. Robert Stirling, the original inventor of the heat economiser or regenerator" was singled out by the *Herald* as a notable participant in the ensuing debate (chapter 4).[83] Rankine had also raised the issue of the new patent law introduced in October 1852, a subject of close personal concern as the Napier and Rankine air-engine approached its practical realization (chapter 5). That £50,000 per annum was raised for the Treasury through patents alone was surely one of many "symptoms of disease in the...system". David Brewster, amongst others, had expressed himself "in favour of patents being granted gratis, as a matter of right, justice, and morality". Thus reported the *Manchester Guardian*.[84]

But for Rankine the high point of the meeting was the delivery of his keynote speech to the large and receptive audience of the Mechanical Science Section. The *Glasgow Herald* printed it in full one day later, bringing it to a still broader audience.[85] By this time, particularly after deputized for Gordon in the spring, Rankine was a clear and public candidate for the Glasgow professorship. Through the BAAS he presented his manifesto for Glasgow academic engineering. Less than two months

---

[82] Speech reported in the *Glasgow Herald*, 14 September 1855, pp.6-7, on p.7.

[83] *Glasgow Herald*, 14 November 1855, p.7.

[84] *Manchester Guardian*, 20 September 1855, p.4.

[85] *Glasgow Herald*, 14 September 1855, p.5.

later, following his appointment as professor of engineering, his inaugural address developed the rhetoric of engineering science further.

The publicity campaign thus did not end with the dispersal of the British Association: on 21 December, with the University winter session well under way, an advertisement appeared in the *Glasgow Herald*:

> UNIVERSITY OF GLASGOW
> CIVIL ENGINEERING AND MECHANICS
>
> Professor Macquorn Rankine will deliver the Introductory Lecture of his Course at the College, in the Old Humanity Class-Room, on THURSDAY the 3d of January, 1856, at 7 p.m.
> Fee £2,5s. 59 St.Vincent Street, Glasgow 20th Dec 1855.[86]

Again the *Herald* fulfilled its reporting duties: the following morning a summary of the "Introductory Lecture of the Course of Civil Engineering and Mechanics" was given to the Glasgow public, beginning with all the melodrama that could be mustered: "Last night Professor Macquorn Rankine delivered his first introductory lecture to a crowded audience in the College...[87] I shall examine the ideas set out in these public documents together.

In his opening address as President of the Mechanical Science Section at the second Glasgow meeting of the British Association for the Advancement of Science,[88] Rankine outlined a philosophy of knowledge designed to stake out territory for an academic subject constructed as intermediary between "theory" and "practice". Ostensibly reviewing the original purpose of Section G, Rankine presented an explicit definition of the relationship between "theory" and "practice" appropriate for the sectional structure of the BAAS and for the organization and intellectual values of the University. He made the following analogy:

> The chair [of Civil Engineering and Mechanics] bears the same relation to the Chair of Natural Philosophy, which Section G of the British Association bears to Section A [Mathematics and Physics]...[89]

---

[86] *Glasgow Herald*, 21 December 1855, p.2.
[87] *Glasgow Herald*, 4 January 1856, p.4.
[88] W.J.M. Rankine, "Opening Remarks on the Objects of the [Mechanical Science] Section", *BAAS Report*, 25(1855), part 2, pp.201-2.
[89] Rankine, "Opening Remarks", p.202.

With calculated symmetry, Rankine's inaugural address to the University delivered soon after in December 1855 asserted:

> What Section G is to Section A in the British Association, this class...is to those of Physics and Mathematics in the University.[90]

Through this analogy the prestige of the BAAS could be used to promote the engineering chair, and vice versa. The argument gained strength from the British Association's notable popularity in Glasgow. At both meetings Section G in particular proved to be extremely active: the 1855 gathering saw the largest number of subsequently published Mechanical Science papers (36) in any year for the period 1841-71, a total previously surpassed only during the Association's first visit to Glasgow in 1840.[91] In general both Section G and the engineering chair were given support by the assertion of interconnections with the traditionally hierarchically dominant Section A (Mathematics and Physics) and the university chairs of natural philosophy and mathematics.[92]

Rankine displayed polarized caricatures of two forms of knowledge - "theoretical" and "practical" - which encapsulated the two *economies* of nature and of commerce.[93] Pure science

> ...has for its object to improve the mind of the cultivator intellectually and morally...each subject requires to be treated so as to investigate how the phenomena are connected with the general economy of nature...[94]

---

[90] Rankine, "Harmony of Theory and Practice", p.269.

[91] Figures from *BAAS Reports* ; there were 41 papers published in Section G for 1840, compared with, for example, 3 in 1845 (Cambridge) and 6 in 1847 (Oxford). 42 papers were actually *read* in 1855 (Glasgow). *Proceedings of the Glasgow Philosophical Society* , 4(1855-60), p.1.

[92] See Morrell and Thackray, *Gentlemen of science* , pp.267-75. Natural philosophy and mathematics were Glasgow Faculty professorships.

[93] Rankine wrote relentlessly about this distinction between types of knowledge. Thus, for example, David Elder, father of the marine engineer John Elder, "learnt the practical part of his trade as an apprentice to his father, and its scientific principles by the private study of mathematical books during intervals of leisure." Rankine, *Memoir of Elder* , p.3.

[94] Rankine, "Opening Remarks", pp.201-2. The common sense philosopher Dugald Stewart, with whom Rankine has been most convincingly linked, advocated "economoy of thought as a prime end of science". See Richard Olson, *Scottish philosophy and British physics 1750-1880* (Princeton University Press: Princeton and London, 1975), p.107.

Such a definition fitted well within the broad, humanistic, and democratic traditions of Scottish education.[95] More specifically, Robert Jameson's course of natural history in Edinburgh had been saturated with references to the perfectly ordained mutual relationships between all natural objects and the uses of classes of objects (such as rocks and minerals) in the general "economy of nature" (chapter 2). This potent expression, indicating a tightly ordered system admitting no wasted action, had been extensively used in the previous century and maintained wide currency in scientific circles and further afield, through such popular and improving texts as Whewell's *Bridgewater Treatise*.[96]

In contrast, purely practical knowledge

> ...enable[s] the cultivator to *judge* of materials and workmanship, and of questions of convenience and commercial profit, to manage and direct the execution of work...[97]

Such knowledge "can be acquired by experience in business alone".[98] Rankine's denial of the possibility of a practical university engineering course allayed the fears of the more traditional industrialists. He pledged by implication that an academic course under his control could not interfere with the system of apprenticeship and pupillage. Neither would he hope to create an artificial environment in which that most valuable commodity, engineering *judgment*, might be inculcated. Previous experience, exemplified by the hostile reaction from the Institution of Civil Engineers greeting his paper on the "Principles of the Construction Sea Defences" (chapter 4), had impressed upon Rankine the inviolability of the engineer's practically-obtained commercial skill.

---

[95] See G.E. Davie, *The democratic intellect* (2nd edition, Edinburgh University Press: Edinburgh, 1961).

[96] William Whewell, *Astronomy and general physics considered with reference to natural theology* (first published 1833; 7th edition, H.G. Bohn: London, 1852), for example pp.91 and 114. See also Smith and Wise, *Energy and Empire*, pp.89-99. In *Michael Faraday: Sandemanian and Scientist* (Macmillan: Basingstoke, 1991), Geoffrey Cantor has analysed the manifestations in Faraday's scientific work of his conception of nature as an economical system fashioned by God. See in particular pp.168-74 and 256-8.

[97] Rankine, "Opening Remarks", p.201. My emphasis.

[98] Ibid., p.202.

The distinction between "theory" and "practice" had thus been made in a way calculated to fit with academic and industrial preconceptions. There was a very personal model for this general proposition. By 1 June 1853 Napier and Rankine had reached an advanced stage in their application to patent an "improved" air-engine and it became necessary to come to a formal agreement on the division of future profits. In so doing they had chosen to characterize their association, for public consumption, as a division of labour leading to fruitful collaboration between a skilled, experienced businessman and an erudite, innovative man of science keen to make timely practical applications of theory (chapter 5).

Although "purely scientific knowledge" and "purely practical knowledge" were distinct - "the states of mind required in practical operations and in scientific study are so different that a sudden change from...one...to the other at different periods of the day is injurious to both"[99] - they were interdependent. There existed a *harmony* between them, reflecting that relationship of complementary expertise between Rankine and Napier, which for its maintenance required Rankine's supplementary role as repository of the *techniques of invention based on scientific principle*. More generally, the imperative exploitation of this harmony for both intellectual and financial profit stimulated and made necessary the development of a third form of knowledge, nurtured by the British Association's Mechanical Science Section:

> The special utility of this Section arises from the fact, that the application of scientific principles to practice is a study of itself, distinct alike from pure science and from pure practice.[100]

This study was presented as *diversely beneficial*. In the industrial context of Glasgow, rhetorical resources were plentiful: the legendary James Watt shone out as "the brightest example of that combination of

---

[99] *Devonshire Commission*, Rankine's evidence, question 9509.

[100] Rankine, "Opening Remarks", p.201. Compare with Rankine, *The science of the engineer*, p.13: "The application of those principles [of the art of the engineer] to practice is an art of itself".

practice and science."[101] Praising the local abundance of "striking instances of the *successful application of mechanical science to practice* "[102] Rankine hinted at high dividends to be paid for the industrial community for supporting this third study. The initial motive offered to Napier for cooperation with Rankine had been financial: "Should [the improvements] prove to be of a kind likely to succeed in practice, we may perhaps be able to make some arrangement which will ultimately lead to our mutual advantage."[103] In general, time and money would be "wasted" by a lack of communication between men of science and men of practice;[104] and by implication, great material advantage would be gained by the promotion of such communication through the study of the "application of scientific principles to practice":

> ...the benefit which might be derived [from results of important investigations on practical subjects] from their application is for years lost to the public; and valuable practical principles which might have been anticipated by reasoning, are left to be discovered by slow and costly experience.[105]

This dominant *urgency* of technical development underpinned by science had again been a major facet of the campaign to "realize the advantages of the air-engine". At a time when marine trade was fast expanding, the race for more economical sources of propulsive power was on:

> ...from what you have told me of the demand for long voyage steamers, I am impressed with the importance of proceeding with as little delay as possible.[106]

This study of the application of scientific principles to practice (previewed in Rankine's lectures on *applied* mechanics, and heat-engines) then represented a third economy, that of transference of information between theoretical and practical domains, which might be described as the economy of engineering science. Developing this study would stimulate a

---

[101] Rankine, "Opening Remarks", p.202.
[102] Ibid. Emphasis added.
[103] Rankine to Napier, 7 February 1853, DC 90/3/1, Napier Papers, Glasgow University Archives.
[104] The concept of "waste" is discussed later.
[105] Rankine, "Harmony of Theory and Practice", p.267.
[106] Rankine to Napier, 23 June 1853, DC 90/3/1, Napier Papers, Glasgow University Archives.

more efficient passage of knowledge, manifested in a greater understanding of the economies of nature and of commerce, which in turn promised financial rewards. The economy of engineering science "which provides the greatest effect with the least possible expenditure of material and work" was in absolute contrast to that reprehensible waste resulting from its opposite, the unscientific approach to practice:

> In too many cases we see the strength and the stability...supplied by means of massiveness, and of lavish expenditure of material, labour, and money...[107]

This *harmony of theory and practice* rhetoric also argued for the location of engineering science within the existing University structure. First, the analogy drawn between University and BAAS implied that this "distinct study" had become *academically* necessary. Second, Rankine pointedly described medicine, a subject of high academic priority in the Scottish universities, as "another branch of practical science"; chairs of surgery and practice of physic demonstrated "the art of applying scientific principles to practice", thereby complementing those theoretical chairs of anatomy and physiology. Consequently the existing theoretical chairs of mathematics and natural philosophy simply made the

> institution of a Chair of Mechanics and Engineering...an endeavour to place Mechanical Science on the same footing with that of Medicine.[108]

Pragmatically three at least of these current occupants of the chairs mentioned (Allen Thomson, William Thomson and Hugh Blackburn), as friends or allies of Rankine, would have been unlikely to object to such a characterization.

More universally, engineering science had a moral value. The practically trained members of society who lacked theoretical knowledge

> too often spend their money, waste their lives, and it may be lose their reason in the vain pursuit of visionary inventions...many a man who might have been a useful and happy member of society, becomes a being than whom it would be hard to

---

[107] Rankine, "Harmony of Theory and Practice", p.268.

[108] Ibid., p.269. It was valuable, as part of a continuing lobby to have engineering fully recognized as a profession, to make the comparison with medicine.

find anything more miserable.[109]

In summary, the benefits of this communication between theory and practice were diverse. Its absence resulted in social problems, university inadequacies and commercial waste. For these reasons engineering science was advocated as socially, academically and commercially necessary.

To motivate teaching methods for this study Rankine again contrasted the modes of acquisition of knowledge in his dual caricature: for pure theory "exactness is an essential feature"[110] whereas for pure practice the engineer must "judge of the quality of materials and workmanship, and of questions of convenience and commercial profit".[111] Synthesizing these, the engineer trained in the application of scientific principles to practice should be ready to

> ...compute the theoretical limit of the strength and stability of a structure, or the efficiency of a machine of a particular kind - to ascertain how far an actual structure or machine fails to attain that limit...to determine to what extent, in laying down principles for practical use, it is advantageous...to deviate from the exactness required by pure science.[112]

These, then, were the central ideas of Rankine's engineering science: *computation* in opposition to rule-of-thumb; *theoretical limits* making it possible to measure by exactly how far practice fell short of theory; *efficiency* providing a yardstick for engineering progress; and *compromised exactness*. The first three features had been exemplified in the lectures on heat-engines given six months previously. This final feature represented the modification of the precision of pure science by practical and therefore primarily economic considerations (chapter 8).

To clarify the specific influences of *measurement*, *efficiency*, and *economy* on the development of this engineering science methodology I now discuss the re-establishment of academic engineering in Glasgow, viewed first as a "division of intellectual labour", and secondly as a "valuable"

---

[109] Ibid., p.268.
[110] Ibid., p.269.
[111] Ibid., p.270.
[112] Ibid. See also epigraph to this chapter.

complement to the practical education of an engineer.

Engineering science as division of labour within the University

By giving engineering science *definition* , Rankine enabled its *differentiation* ; stating the aims of the engineering scientist also described what lay outside the domain of academic engineering and voiced sentiments well calculated to calm fears of academic and industrial colleagues. Differentiation removed the possibility of curricular encroachment, if not necessarily obviating competition for students' fees. Moreover, the construction of the separate academic discipline of engineering science extended the cultural traditions surrounding Adam Smith in promoting a new cooperative "division of intellectual labour". Economy of intellectual and material effort would be achieved by concentrating the teaching of that "distinct study" in the hands of the professor of civil engineering and mechanics - an "engineering scientist" - who was provided with a "natural" domain of practice - the University - and a distinct domain of intellectual authority - "engineering science".

Beyond any generalized public support in his bid for the chair, Rankine had received Lewis Gordon's ardent recommendation.[113] Family links with the influential Grahams may also have been useful (chapter 2). Other allies external to the University aided the appointment made by Gray as Home Secretary in Palmerston's Whig administration. It is enlightening, but by now unsurprising, to find amongst this group James Robert Napier. Deputising for Gordon earlier in the year had been an acute preparation:

> I have got an intimation from the Home-Office which places my appointment beyond a doubt. I am deeply indebted to you [Napier] for the effect which the testimonial of the

---

[113] Constable, *Gordon* , pp.44-5. A extract reproduced from Rankine's notebook reads: "I am in a great measure indebted to him [Gordon] for my success in obtaining the Professorship...".

> class, headed by you, must have had in promoting my success, both as a certificate of my qualifications, and as tending to prevent the abolition of the chair.[114]

By this time Rankine had almost twenty years' practical experience of civil engineering (chapters 3 and 5). As a Fellow of the Royal Societies of London and Edinburgh, and a leading figure within the Glasgow Philosophical Society he had an established position as a member of national and local scientific elites. Successful demonstration of teaching ability, shown most effectively by the testimony of the students themselves, could only add to his acceptability as candidate for the chair purporting to span practical and theoretical disciplines.

Rankine presented himself to the University Senate in December 1855.[115] His commission "was read with all due respect" by the Senate of the University.[116] There were no visible problems, in marked contrast to Gordon's experience. Symbolically, whereas for his Latin dissertation Gordon had been asked to define the "relation" or "connexion" between the sciences and the industrial arts Rankine discoursed on the *harmony of theory and practice* in mechanical science: "De concordia inter Scientiarum machinalium contemplationem et usum". An oath of allegiance to the Queen, a declaration eschewing subversion of the Church of Scotland (Moncrieff's Act of 1853 replaced the stringent requirement of religious tests which Gordon had been required to meet with an innocuous declaration), and a final Latin oath led to his admission to the University as professor of civil engineering mechanics on 10 December 1855. Whilst Gordon had waited many years to be given any title within Senate, Rankine was immediately accorded the status of "Scientae Machinalis Professor".[117]

---

[114] Rankine to Napier, 7 November 1855, DC 90/3/1, Napier Papers, Glasgow University Archives.

[115] Senate, 90(3 December 1855), p.273.

[116] Commission dated 7 November 1855. Transcribed in ibid., p.272-3.

[117] Senate, 90(10 December 1855), pp.278-9. The religious certificate read: "I will never directly nor indirectly to teach or inculcate any opinions opposed to the Divine Authorship of the Holy Scriptures or to the Westminster Confession of Faith...I will not exercise the functions of the said office to the prejudice or subversion of the Church of Scotland as by Law established or the doctrines and privileges thereof." Quotation on p.279.

By 1855 the situation in the University had changed markedly from the 1840s. Gordon, lacking strong internal support, had met with reactions ranging from indifference to open hostility at a time of deep political division, financial and disciplinary insecurity and general unrest within the College (chapter 6). His territorial ventures had been repulsed by colleagues, leaving him to place more emphasis on practice than had been his wish. Paradoxically, it was the practical elements of his teaching which had given others, such as Macfarlan and Maconochie, arguments for his exclusion from the College. For his successor, however, the environment promised to be less confrontational.

The appointment of William Thomson to the chair of natural philosophy in 1846 and his friend from Cambridge student days Hugh Blackburn to that of mathematics in 1849, following the death of James Thomson, presented Rankine with useful allies,[118] wielding the administrative power of the Faculty that he himself lacked.[119] J.P. Nichol had demonstrated his support for the continuance of the professorship directly in November.[120] The existing links with Thomson in particular were extremely strong. From April 1850 they had corresponded extensively on the subjects of Rankine's theory of the motive power of heat, founded on a hypothesis of molecular vortices, his papers on elasticity, and his work on sound.[121] William Thomson's name headed the list of those recommending Rankine's admittance to the Royal Society of London early in 1853.[122] The association had its

---

[118] Rankine maintained a close friendship with the Blackburn family. His *Songs and Fables*, (2nd edn, Maclehose: Glasgow and London, 1874), are illustrated by "J.B.", Hugh's wife Jemima. See also Robert Fairley (ed.), *Jemima: Paintings and Memoirs of a Victorian Lady* (Canongate: Edinburgh, 1988).

[119] The distinction between Faculty and non-Faculty Professors was not abolished until the passing of the Universities Act of 1858. James Coutts, *A history of the University of Glasgow, from its foundation in 1451 to 1909* (Robert Maclehose: Glasgow, 1909), pp.342-3.

[120] Soon after becoming professor, Rankine contributed articles to Nichol's *Cyclopaedia of the Physical Sciences* (London and Glasgow, 1857).

[121] Letters from Rankine to William Thomson, R16-28 in Kelvin Papers, Cambridge University Library.

[122] Election Certificate IX.326, Royal Society of London. The form appears to have been filled out by Thomson, judging by the handwriting.

practical side too: Thomson's earliest patent, for "Improvements in electrical conductors for telegraphic communication", was taken out jointly, in 1854, with Rankine and his business partner John Thomson.[123]

A fourth sympathetic figure within the Faculty was of course Allen Thomson. He had been a second sponsor for Rankine's entrance into the Royal Society but closer to home he was, as we have seen, a leading light in the Glasgow Philosophical Society.[124] Speaking as President of that organization on 7 November 1855 (coincidentally the same day that Rankine received his Commission for the regius professorship) Thomson reviewed with satisfaction the result of the recent British Association Meeting. He chose to mention first amongst a variety of circumstances contributing to the success of this occasion "the attractions which Glasgow presents as one of the greatest seats of the *successful application of scientific principles to important, useful, and practical objects*".[125]

It is not surprising therefore that Rankine "dealt more persuasively with the faculty [sic] than Gordon had done".[126] Thomson's support (and Nichol's) could be guaranteed by Rankine's adept diffusion of the potential conflict over the meaning of "Mechanics" which had been been so contentious for Gordon. For Rankine's class, this would be distinct from "astronomical mechanics", and from "physical mechanics" relating to the transmission of sound and light. Furthermore,

> They [i.e. mechanics] are also so far to be kept distinct from *pure* and *abstract* mechanics, that in treating specially of mechanics as applied to engineering, certain fundamental principles are to be taken for granted, the demonstration of which forms part of the course of Natural Philosophy. To that course, also, must be left all mechanical problems, which are interesting in a scientific point of view only, and not practically useful.[127]

---

[123] A complete list of William Thomson's patents provides an appendix to S.P. Thompson, *The Life of William Thomson, Baron Kelvin of Largs* (2 vols., Macmillan: London, 1910); see also Rankine to W. Thomson, 19 June 1855, R1, Kelvin Papers, Glasgow University Library. The patent was abandoned.

[124] Election Certificate IX.326, Royal Society of London.

[125] *Proceedings of the Glasgow Philosophical Society*, 4(1855-60), pp.1-3, on p.2. Emphasis added.

[126] Coutts, *University of Glasgow*, p.390.

[127] Rankine, *Science of the engineer*, pp.9-10.

Thus Rankine differentiated his course from Thomson's, and even implied that civil engineering students' understanding would be enhanced by attending the natural philosophy class.

Powerful allies within the University, and particularly the good will of Blackburn and William Thomson (it had been the professors of mathematics and natural philosophy that Gordon had blamed for his lack of success) meant that the mundane but necessary process of finding accommodation was far less agonizing than it had been for his predecessor.[128] Rankine wrote to Blackburn, as Faculty Clerk:

> I beg leave respectfully through you to request that the Faculty of Glasgow College will allow me the use of a Classroom for my lectures in the buildings of the College. I contemplate lecturing in the evening probably from seven until eight.[129]

The committee formed to consider this application conveniently included Rankine's two friends Allen Thomson and Blackburn himself.[130] A month later they reported positively. Rankine was prepared to take very little at first, rather than demanding two rooms; and to swallow his pride sufficiently to concur in the heavy-handed assertion of control made by one faction of the Faculty, surely an echo of the old guard in their dealings with Gordon:

> [The committee] agreed with Mr Rankine that the room under the Library known as the Old Humanity Classroom was the most convenient place in the meantime for his Lectures and that it was necessary to introduce gas into a side room and provide a chair. *That they had read the subjoined statement to Mr Rankine who assented to it and remarked that it was unnecessary as he was aware the Faculty had power to make its own conditions*.
> The paper is as follows - The College will agree to give Mr Rankine the use of the room under the Library at such times as may be agreed on for the personal delivery to his class of his lectures on Civil Engineering and Machinery [sic] on condition that such sum as the Faculty deem sufficient be raised by the Class or Mr Rankine to cover the expense of light firing cleaning and extra work of the College servants, but the College reserves to itself the right to occupy the room in any manner at other hours and to recall this permission when it is found expedient all on the understanding that in such case no claim for the use of another room is to be founded on the present

---

[128] See chapter 6.
[129] Faculty, 87(11 December 1855), pp.240-1.
[130] Ibid.

accommodation.[131]

Ironically, Rankine had advertised and given his introductory lecture there a week before. However, both gas and chair were magnanimously provided.

Rankine persevered. For the next session he was initially allowed the use of the Examination room.[132] Soon after, with the direct assistance of his Faculty friends, steps towards a rather more permanent occupation were taken:

> Mr. W. Thomson, Dr Allen Thomson and Mr Blackburn were appointed a Committee to put gas in the late law Classroom which Mr Rankine is now to be allowed to occupy for his Class, and to report as to other improvements in it.[133]

The fact that no such positive act had been forthcoming during Gordon's tenure of the chair had been a major disincentive (or excuse) not to teach a course of civil engineering and mechanics in the University. Intellectual space presupposed the carving out and occupation of physical space. With "the Blackboards, which have come out of the old Latin Classroom" put up, a pulpit installed, and a ventilator in the roof a distinct possibility "if the cost did not exceed £8" civil engineering and mechanics had truly succeeded in establishing itself within the College walls, becoming in every sense an academic subject.[134] Pragmatically, by December 1859, at which time yet another bid was being made to raise support for new buildings to ease the increasingly cramped situation in the Old College, Rankine had been allocated an adequate teaching room for his exclusive use.[135]

Whereas Gordon had found difficulty in forming a substantial class, with external support from the local engineering community in particular

---

[131] Faculty, 87(11 January 1856), pp.244-5.

[132] Faculty, 87(29 October 1856), p.288. See also Coutts, *University of Glasgow*, p.390.

[133] Faculty, 87(20 February 1857), p.334.

[134] Faculty, 87(24 April 1857), p.357; Faculty, 88(23 December 1857 and 14 December 1858), pp.25 and 105.

[135] Dimensions 33ft 3in X 17ft 3in, at front 11 feet high, at back 8ft 4in high. From "Survey" (26 December 1859) describing 17 teaching rooms: an Appendix to the *General Report of Commissioners under Universities, Scotland, Act, 1858*, in *Sessional Papers*, xvi(1863), p.335f.

and internal administrative good will Rankine could ensure that there were engineering students in all years following his first complete session of 1856-7.[136] (Whereas any mention of Gordon's class had quickly disappeared from the University prize lists Rankine's students were again represented in this official publication.) The class lists for "scientiae machinalis" show a steady increase from 13 in 1864-5 to 47 in 1869-70, dropping away to 33 in the final session of 1872-3.[137] An increasing number of students attended the course for two successive sessions. The recording and publication of class lists and class prize winners for the engineering course is one more incidental indication of Rankine's rapid and successful integration within the University's structure.

The scientific quartet of Rankine, William Thomson, Blackburn and Allen Thomson formed the nucleus of an influential and intellectually cohesive group within the University which fostered strong external links with industry in Glasgow and further afield. The financial consequences of these links were evident in the "New College Buildings" campaign of the 1860s: a deputation in 1867 to the Prime Minister consisted precisely of this quartet.[138]

The apportionment of academic prizes also demonstrated this close and expansionist collaboration. In September 1856, just before the beginning of Rankine's first full session, the eminent engineer and alumnus of Glasgow College James Walker (see chapter 3) established Walker Prizes "of books or mathematical or surveying instruments", to be awarded each year to "students who shall have duly entered themselves as attending the Class

---

[136] See Prize and Degree Lists of Glasgow College 1833-63, Glasgow University Archives.

[137] See Class Lists of Glasgow College (beginning 1863-4 session), Glasgow University Archives.

[138] Draft minute book of subcommittees on New College Buildings II, pp.109-18, Accession 2202, Glasgow University Archives.

of Civil Engineering and Mechanics".[139] Competitors were to be jointly examined by Blackburn, William Thomson and Rankine, who, along with Macfarlan (until his death in 1857), were appointed trustees. In line with Scottish democratic traditions a further prize was to be awarded by vote of the class. Rankine himself had of course been the recipient of one of Institution of Civil Engineers' short-lived Walker Prizes in the early 1840s.

The group showed an increasingly powerful manipulation of existing university procedures for academic reward and recognition.[140] "Breadalbane Scholarships" were originally intended to promote study in a wide range of subjects including natural history, but by 1856 they had been redirected towards "the encouragement of pure and applied science". For this and following sessions the examiners were again William Thomson, Hugh Blackburn and Macquorn Rankine, joined by Thomas Anderson (professor of chemistry) and occasionally Nichol. Scholarships (one each) in "Pure Science" and "Practical Science" was to be awarded. For the second students must be conversant not only with works of Poncelet, Morin and Willis, but also "Papers by Joule, Rankine, Thomson in the London and Edinburgh Transactions" on heat, Pambour on locomotives and the steam-engine, and Miller's chemistry. In particular, the "scholar in Practical Science will be expected to have attended both the classes of Engineering and of Chemistry before the end of next Session".[141] When Breadalbane later discussed the possibility of making his Scholarships more permanent, Nichol, Blackburn, Thomson, Rankine and Anderson reported, taking the

---

[139] *The Glasgow University Calendar, for the session 1863-4* (G. Richardson: Glasgow, 1863), pp.93-4; *List of deeds and documents and excerpts from deeds and documents of foundation of bursaries, scholarships, fellowships, &c., in the University of Glasgow* (Edinburgh, 1891), pp.91-2.

[140] *Glasgow University Calendar* , (1863-4), pp.97 and 101; *Glasgow University Calendar* , (1864-5), pp.99-100.

[141] Senate, 90(1 December 1856), p.315. For subsequent examiners and reports on the Scholarships see: Senate, 90(26 October 1858), p.361; Senate, 90(6 December 1858), p.366; Senate, 90(20 December 1858), p.369. By April 1860 sections of Rankine's *Manual of Applied Mechanics* had become canonical, prescribed for examination beside, for example Herschel on astronomy. See Senate, 91(13 April 1860), pp.73-4.

opportunity to suggest a revision of the regulations. In particular they suggested that all candidates ought now to be examined in "Chemistry and Practical Mechanics as well as on the other specified branches of science": testifying to the degree of cooperation and mutual accommodation existing between the various examiners, they remarked that the course "of instruction as it now operates within this University removes all hardships from such a condition".[142]

Both the Walker Prizes and Breadalbane Scholarships gave official sanction to the class of civil engineering and mechanics within the university, and through the conditions laid down in their regulations integrated Rankine's subject with the other disciplines of natural philosophy, mathematics and chemistry. The anomalous nature of Gordon's class had been compounded by his inability to bring about such interdisciplinary integration.

By 1862 Rankine had systematized his teaching by the introduction of a Certificate of Proficiency in Engineering Science, which formalized academic engineering as a five-fold division of intellectual labour, integrated within the existing University structure. He had originally proposed a "Diploma of C.E." in October 1859. There was a viable model on which to base such a qualification. Courses leading to a Diploma (or Licence) in Civil Engineering, linked to the arts degree, had been taking place in Trinity College Dublin (where Macneill had taught in the early 1840s) since 1841, with over 130 such Diplomas awarded up to 1861.[143]

The professors of natural philosophy, mathematics, chemistry (Anderson) and natural history (Rogers) worked with Rankine to consider the state of engineering education in the University in Glasgow, making "such suggestions to the Senate as may appear to them expedient".[144] In

---

[142] Senate, 91(24 March 1859), p.8; Senate, 91(29 April 1859), pp.25-6.

[143] R.A. Buchanan, *The engineers: a history of the engineering profession in Britain 1750-1914* (Jessica Kingsley: London, 1989), p.167. In 1861 the degree course of Master of Engineering was introuced.

[144] Senate, 91(21 October 1859), pp.33-4.

December 1859 their suggestions amounted to the creation of a new course, sanctioned by the Senate and leading to a "Diploma in Civil Engineering and Mechanics". In addition to attendance at lectures of each of the professors mentioned above, students must show proficiency in mechanical drawing. Most importantly, a concession was to be explicitly made to the apprenticeship system of engineering education: every candidate

> shall, before receiving his Diploma, have been for two years in the employment of a Civil Engineer or a Mechanical Engineer, as a pupil, apprentice, or assistant, or shall have been for the like period engaged in superintending the execution of works of Civil or Mechanical Engineering.[145]

Moreover, without such practical experience, the candidate might only be awarded a certificate of attendance and of having passed the exams. Not until completion of the stipulated "period of employment in business" could he be granted the diploma.

However strong the internal and external support for this new qualification, ultimate authority rested (since the Universities Act of 1858) with the Scottish University Commissioners. Their judgment, when finally announced in 1861, was succinct and dismissive:

> [If] by a Diploma is meant anything else than a Degree the Commissioners do not think that there should be any University distinction except a Degree and that they do not consider Civil Engineering a proper department in which a degree should be conferred.[146]

Ironically, opposition to the academic integration of engineering came not from academics, or from the industrial community, but from the Commissioners' idea of precisely what was acceptable as an academic subject.

Rankine was undaunted and immediately reformed his original committee of scientific professors.[147] Within months a new report had been prepared: all reference to degrees, diplomas, and civil engineering had

---

[145] Senate, 91(9 December 1859), p.50. I shall consider this emphasis on practical training in the next section.

[146] Letter from John Berry, Secretary to the Scottish Universities Commission in Edinburgh transcribed in Senate, 91(1 November 1861), p.146.

[147] Ibid., p.148; and Senate, 91(29 November 1861), p.155.

been expunged; in particular the stipulation of a period of engineering practice had vanished. But in all other respects, in particular the composite nature of the course of study, the projected course was identical: Rankine's "Committee on Instruction in *Engineering Science* " had, appropriately enough, agreed that the University would do well to reward candidates with a Certificate of Proficiency in Engineering Science.[148] In terms of satisfying the Commissioners, and the new University Court, at least, there was much in a name. The rhetoric of engineering science had served its purpose once more and by a somewhat curious route "engineering science" had become enshrined in the jargon of the University. The course was approved, syllabuses published, and finally at the end of the 1862-3 session the first Certificate of Proficiency in Engineering Science (there was only one candidate) was awarded.[149]

This lengthy but ultimately successful action had come about largely as the result of cooperation between Rankine and his allies. The two year course consisted of classes given by his colleagues in mathematics, natural philosophy (one or two sessions), inorganic chemistry, geology and mineralogy (one session), and civil engineering and mechanics (two sessions) taught by Rankine himself. Emphasising the "principles" of machines, hydraulics, and surveying and levelling created an impression of science displacing empiricism, a quasi-mathematical rigour suitable for the University, without overlapping Blackburn's Euclid, algebra, analytic trigonometry and geometry, and calculus; dealing with the "Stability of Structures", and the "Strength of Materials", built upon, rather than directly competed with, the "Elements of Statics and Dynamics" of the natural philosophy class; the steam engine viewed as one "Prime Mover" driven by the "mechanical action of heat" was suitably distanced from

---

[148] Senate, 91(14 February 1862), p.174. The report was printed and circulated to Senate members and others. See single printed sheet, Acc 36407, Glasgow University Archives.

[149] Senate, 91(7 November 1862), p.207; Senate, 91(17 April 1863), p.241; Senate, 91(1 May 1863), p.251.

Thomson's treatment of heat as "experimental" science, as dynamical theory, or, for more advanced students directly through Fourier's *Théorie Analytique de la Chaleur*;[150] finally, discussing roads, railways, canals and waterworks, provided an introduction to the more directly practical aspects of engineering.[151] Rankine's course was distinct but, he believed, complementary within the university, an independent subject nevertheless dependent on the teaching of others for the complete inculcation of engineering science.

Avoiding conflict with industrialists: practical proof, public opinion and the importance of scale

Since Rankine's students were mainly destined for engineering practices, his course had to be seen to produce engineers more useful to industry than those without university education.[152] The industrial community therefore directly influenced Rankine's teaching: without students, as Lewis Gordon had experienced, there was no Glasgow academic engineering.

This community constituted one source of benefaction to the

---

[150] Joseph Fourier, *Théorie Analytique de la Chaleur* (Paris, 1822).

[151] See *Glasgow University Calendar...1863-4* for full course details.

[152] *Devonshire Commission*, Rankine's evidence, question 9542, shows the positions of some of Rankine's more successful pupils by 1872: chief engineers of the "principal dockyard in India" and of the docks at Pernambuco, Brazil; borough engineer at Liverpool; and "manager of the most important mechanical engineering works in London". Henry Dyer (who attended the course from 1869-71) played a vital role in the establishment of the Imperial College of Engineering, Tokyo. See W.H. Brock, "The Japanese Connection: Engineering in Tokyo, London, and Glasgow at the End of the Nineteenth Century", *British Journal for the History of Science*, 14(1981), 227-43.

University.[153] But there might also be hostility towards a non-traditional form of education which presaged the abandonment of the lucrative apprenticeship system through which most engineers entered the profession.[154] Fleeming Jenkin remarked wryly that

> young Englishmen and their parents crowd the doors of the offices and workshops, offering premiums of £300 or £500 for the mere permission to pass three years unheeded inside the magic gates.[155]

Earlier attempts to provide cheap training for engineers which combined the practical and scientific elements felt to be necessary had met with little success. Significantly, the course at the University of Durham with which Forbes had been connected (chapter 2), though intended as an *alternative* to apprenticeship, had not been accepted as such amongst professional engineers.[156]

Whether it was possible to teach the "practical" element of engineering in a closed academic environment remained contentious: Fleeming Jenkin believed not and argued forcefully against workshops attached to universities for engineering teaching. He was, however, strongly committed to the introduction of engineering *laboratories* as places in which to teach the "art of measurement".[157] For Rankine, however, the "true laboratory for students of engineering science is to be

---

[153] For example, during the buildings appeal of the 1860s. At the close of the winter session in 1872, the University Principal intimated that Mrs Elder had set aside £5000 "as a supplementary endowment in connexion with the Chair of Civil Engineering, in memory of her husband, Mr. John Elder." *The Times*, 4 May 1872, p.11. The income from this endowment between Martinmass 1872 and the date of Rankine's death amounted to over £26 and constituted a rise in salary of about one third. See Rankine's Inventory, SC 36/48/70, Scottish Record Office. The augmented income came "in acknowledgement of the high respect in which Mr. Elder held the present distinguished incumbent of that Chair." See *List of deeds...&c., in the University of Glasgow*, p.104.

[154] Buchanan, *Engineers*, pp.162 and 168.

[155] Fleeming Jenkin, *A lecture on the education of civil and mechanical engineers in Great Britain and abroad* (Edmonston & Douglas: Edinburgh, 1868), p.10.

[156] Buchanan, *Engineers* ', p.166. The course first ran in 1838; accommodation and tuition costs were still relatively high at £80-£100 a year.

[157] Fleeming Jenkin, "On Science Teaching in Laboratories" in Sidney Colvin and J.A. Ewing (eds.), *Papers Literary, Scientific, etc. by the late Fleeming Jenkin, F.R.S., LL.D. with a Memoir by R.L. Stevenson* (2 vols., Longmans & Co.: London, 1887), ii, pp.183-90.

found in the workshops of such cities as Glasgow, and amongst the earthwork, masonry, carpentry, and ironwork of engineering structures in progress".[158] It was essentially a question of *scale* :

> If...we set up a mechanical workshop...[or]...a mile or two of railway...this would be worse than useless. The difference between doing things on a small scale...and doing things on a great scale, as in actual practice, is so great that the students would only be led to fancy that they had more knowledge than they really did possess..[159]

A further insight into Rankine's attitude to scale is revealed in a response to John Scott Russell who in 1856 offered assistance towards a "practical essay on the Strengths of the forms used in naval architecture".[160] It seemed likely that a series of preliminary experiments would be required, which might lead to a "valuable paper on the strength of materials". Russell wished to know "whether it [was] practicable to carry such a proposal into effect."[161] Rankine sought Napier's valued advice:

> I am pretty confident his proposal is impracticable. The series of experiments...would cost a very large sum if done in such a style as to be of any service; would occupy a great deal of time, & waste a great deal of material and workmanship; and where is the money to come from?...the publication of the results would not repay [the outlay this would involve.][162]

The symbiosis of intellect and commerce, which paralleled the collaboration of Rankine and Napier, motivated concern that useful results could only be obtained from Russell's projected experiments if carried out on a sufficiently large scale. Practical considerations of time and expense dominated in this engineering environment, subordinating benefits

---

[158] W.J.M. Rankine, "Introductory Remarks [as President of the Institution]", *Transactions of the Institution of Engineers in Scotland*, 13(1869-70), 1-12, on p.12.

[159] *Devonshire Commission* , Rankine's evidence, question 9511. See also Graeme Gooday, "Teaching Telegraphy and Electrotechnics in the Physics Laboratory: William Ayrton and the Creation of an Academic Space for Electrical Engineering in Britain 1873-1884", *History of Technology* , 13(1991), 73-111, p.79.

[160] For a biography see George S. Emmerson, *John Scott Russell: a great Victorian engineer and naval architect* (John Murray: London, 1977).

[161] Russell to Rankine, June 24 1856, transcribed in Rankine to Napier, June 27 1856, DC 90/3/1, Napier Papers, Glasgow University Archives.

[162] Rankine to Napier, 27 June 1856, DC 90/3/1, Napier Papers, Glasgow University Archives.

potentially justifiable and worthwhile in terms of "pure science".[163] Carrying out small-scale experiments, or modelling, would be of no immediate commercial value, there being no guarantee of the applicability of a naive "scaling up" of results; further, experiments of a type and scale adequately representing the industrial context, and in particular integral economic factors, carried out simply to provide data for a "scientific" paper would be *wasteful* of time, labour, and money. The air-engine exploits had exemplified such issues all too clearly.

Small-scale workshop teaching, like small-scale testing, omitted interaction with a complete commercial environment, especially that experience of the economics and specifics of practice tenaciously defended as inherent in skilled engineering judgment (chapter 3). For example, the quantification of fuel and construction costs, and interest charges on capital investment, required direct experience:

> It is...the business of the engineer to ascertain those data with reference to the special situation and circumstances of the proposed work.[164]

The belief that small-scale modelling, in both testing and teaching, could not adequately represent this essence of engineering qualified the apparent advantages in terms of cost and convenience.[165] In this sense, large-scale testing *made* Rankine's engineering science, which attempted to capture the "economy of practice", further (and self-consciously) distinguishing it from pure science.

---

[163] Russell had earlier carried out a series of costly experiments "on the Form of Ships" with support from the BAAS. Morrell and Thackray, *Gentlemen of science*, pp.322-3.

[164] W.J.M. Rankine, "On the Power and Economy of Single-Acting Expansive Steam-Engines", in W.J. Millar (ed.), *Miscellaneous Scientific Papers by W.J. Macquorn Rankine* (Charles Griffin & Co.: London, 1881), pp.288-99, on p.299. Read before the Royal Society of Edinburgh on 21 April 1851.

[165] For this reason, the laboratory, which Gooday has argued was increasingly becoming the domain of natural philosophy, was fundamentally inadequate, even for that part of engineering which might be portrayed as "scientific". See Graeme Gooday, "Precision measurement and the genesis of physics teaching laboratories in Victorian Britain", *British Journal for the History of Science*, 23(1990), 23-51.

The monitoring of large-scale activity had profound implications for design, providing the most direct and credible evidence, and evaluation, of engineering success. As one example among many, consider Rankine's description of an 1865 sea trial, of no less than 1100 nautical miles, initiated to test the three forms of marine engine used in the *Arethusa*, *Octavia*, and *Constance*.[166] As the ships were deemed to be equally well constructed,

> the comparison between them must therefore be regarded as showing how the efficiency of the boilers, engines, and mechanism was affected *by the principles embodied in their respective designs*.[167]

Suitably controlled practical tests, when *correctly* interpreted, magnified the effects of applied principles filtered through practice. (It was of course largely for Rankine to dictate what constituted correctness, as it had been his prerogative to dictate the correct reading of the indicator diagram re-incarnated as the "diagram of energy".) Here was "practical proof"[168] that the application of a scientific principle had a measurable and valuable effect in a practical and commercial situation.[169]

Just as importantly, prior "practical proof" was essential to gain market support for new designs. Rankine's early papers delivered to the Institution of Civil Engineers had built upon the practically proven success of, for example, his "improved" railway axles, or David Rankine's

---

[166] Rankine, *Memoir of Elder*, p.40f.

[167] Ibid., pp.40-1. Emphasis added.

[168] Rankine used this expression explicitly in relation to an earlier trial of the *Constance* and the *Octavia*. Ibid., pp.45-7. See also chapter 3.

[169] This idea of large-scale testing found one of its grandest manifestations in the extended British Association reports on "Steam-ship Performance" (1859-63). Having collected an enormous quantity of practical data from large sea trials another committee was appointed some years later "to analyze and condense the information contained in the Reports of the 'Steam-ship Performance' Committee" (1867-8). Much of the debate centred on i) the standardization of recording techniques and the related issue of ii) how the data should best be "reduced": both Rankine and John Scott Russell played a prominent part in what seems to me to be strikingly analogous to what Cannon has described as Humboldtian science. See *BAAS Reports* for 1859-63 and 1867-8; and Susan Faye Cannon, *Science in Culture: The Early Victorian Period* (Science History Publications: New York, 1978).

"safety drag" (chapter 3). More recently, Napier and Rankine had avidly monitored the most public fate of the *Ericsson*, which embodied the principles of the unorthodox "caloric engines", as it promised, and then dramatically failed, to cross the Atlantic (chapter 4):

> If Captain Ericsson's ship...should succeed...public opinion will turn in favour of air-engines, and...a demand for them may be expected to arise at once...[170]

Later, it became essential for Napier and Rankine to manufacture tangible experimental evidence of a full-scale engine to have any hope of success with the wide community of engineers (chapter 5): "until some experiments are made we can scarcely expect anyone to adopt the new principle."[171] Particularly after Ericsson's failure, it was unlikely that Robert Napier would develop a favourable attitude towards the engine "without some practical evidence of...utility".[172]

The use of the large scale to win public approval was equally important in relation to attitudes towards science: amongst many engineering employers and the general public, there was apathy or antipathy towards the use of "scientific" knowledge in a "practical" context. In 1852 Fairbairn felt it necessary to defend the use of theory, "which creates so much alarm in the minds of practical men", as "neither more nor less than a series of definite rules by which practice is governed."[173] Rankine himself testified to Gordon's experience in Glasgow:

> ...there was a decided prejudice...against scientific knowledge in any man engaged in any practical occupation...it drove his practical knowledge out of his head, and the two things were inconsistent. And the same prejudice existed to some extent when I got the appointment.[174]

But such a public testimony, rather than being a bare statement of fact,

---

[170] Rankine to Napier, 7 February 1853, DC 90/3/1 Napier Papers, Glasgow University Archives.

[171] Rankine to Napier, 27 January 1854, DC 90/3/1, Napier Papers, Glasgow University Archives.

[172] Rankine to Napier, 17 July 1854, DC 90/3/1, Napier Papers, Glasgow University Archives.

[173] Fairbairn in Russell and Goodman, *Science and technology*, p.264.

[174] *Devonshire Commission*, Rankine's evidence, question 9544.

created the opportunity to define candidates for the *appropriate* use of theory within practice, as both Fairbairn and Rankine did, albeit in different ways.

An example neatly illustrates the preceding points. Early in 1855 Rankine wrote to Napier: "It would be very serviceable to me just now if you could furnish me with any *facts from your experience* serving as data to compute the resistance of water to ships".[175] By 1857 Rankine had developed a generally applicable formula for the skin-resistance of ship hulls by examining the large body of empirical data provided him. J.R. Napier had been required by the purchasers of the steamer *Admiral* in 1858 to meet strict conditions "as to draught of water, cargo, speed, power, and consumption of coal". These he could only hope to meet "by being able to compute beforehand the resistance and propelling power of the ship at any required speed, *from the drawing of her lines* , with very great precision". Using Rankine's formula enabled the fulfilment of these stringent conditions with exactitude. This work advertised the consistency and benefits of science in harmony with practice, theorist in harmony with practical man. Furthermore, it exemplified the advantages of the large scale both as a source of applicable data having, for Rankine at least, indisputable practical value and as a test-bed providing instant and tangible "practical proof".[176] Such ideas had been present already in Rankine's own experience as a practical railway engineer in the 1840s, presenting work suitably prepared for the audience of the Institution of

---

[175] Letter from Rankine to Napier, 17 February 1855, DC 90/3/1, Napier Papers, Glasgow University Archives. For Rankine's attitude towards the seemingly incontestable nature of "facts" derived from transparent observation in engineering context see chapter 3.

[176] P.G. Tait, "Memoir [of Rankine]", in W.J. Millar (ed.), *Miscellaneous Scientific Papers by W.J. Macquorn Rankine* (Charles Griffin & Co.: London, 1881), pp.xix-xxxvi, on p.xxxiii; details relating to the *Admiral* in W.J.M. Rankine, "Opening Address [to the Institution of Engineers in Scotland]", *The Engineer* , 6(1858), 327-8, on p.327, (29 October 1858). Ironically, the formula was of such commercial value that on Napier's insistence it was announced publicly only in the form of an anagram. See W.J.M. Rankine, "Resistance of Ships", *Philosophical Magazine* , fourth series, 16(1858), 238-9, (letter to the editors dated 26 August 1858).

Civil Engineers (chapter 3).

Given the prevailing views on apprenticeship, and the prioritized importance of scale, Rankine was able to customize his syllabus to make academic engineering acceptable in Glasgow while retaining (suitably negotiated and presented) scientific content. He sidestepped the problems encountered by the promoters of the Durham engineering course by selling academic engineering - through his construction of engineering science - as an essential *complement* to apprenticeship, in no sense replacing that practical knowledge which, he asserted, could only be acquired by experience of the large scale. The question of the practical relevance of scientific knowledge was displaced by shifting the teaching of "pure science" on to the willing shoulders of University colleagues (such as William Thomson, Hugh Blackburn, and Thomas Anderson) and stressing the newly constructed subject of engineering science, founded in the "tradition" of the *harmony of theory and practice* , which by its name, and by Rankine's example, asserted itself as appropriate, valuable and necessary to engineering.

The accreditation of engineering science added to its appeal and status within the University but might still be seen as an attempt to disturb the existing industrial status quo, producing an alien class of certified engineers, beyond professional control. To avoid potential conflict an addition to Rankine's course syllabus removed any lingering doubts:

> ...the Senate has had in view to avoid altogether any competition with the offices of Civil Engineers, or the Workshops of Mechanical Engineers, or any interference with the usual practice of pupilage [sic] or apprenticeship.[177]

In a communication to the Institution of Civil Engineers designed to be incorporated into a *Report on the Education and Status of Civil Engineers* , Rankine amplified this, in accordance with the *harmony of theory and practice* rhetoric, adding somewhat deferentially:

---

[177] See *Glasgow University Calendar...1863-4* , p.34.

> ...they [the members of the Senate] have accordingly adopted a system which is capable of working in *harmony* with that of pupilage [sic] or apprenticeship, by supplying the student with that scientific knowledge which he cannot well acquire in an office or workshop, and avoiding any pretension to give him that skill in the conduct of business which is to be gained by practice alone.[178]

Thus rhetorical harmony implied and promoted social harmony. Formalized through a synthesis of precision measurement, accurate workmanship and economy, this social harmony was to be crystallized in Rankine's engineering science.

---

[178] [Institution of Civil Engineers], *The education of civil engineers, in the United Kingdom and in foreign countries* (Institution of Civil Engineers: London, 1870), pp.9-10. Emphasis added.

CHAPTER EIGHT

Conclusion

Precision measurement and accurate workmanship

By 1855 Rankine was a well-established man of science. He had been actively involved in the Royal Society of Edinburgh from 1849 following his election through the sponsorship of Forbes, his former teacher of natural philosophy (chapters 2 and 4). Since 1850 the British Association meetings had provided a national platform for publication of his work and aggrandizement within scientific circles: reciprocating, he gave his services as Secretary of Section A (Mathematics and Physics) in 1850, 1851 and 1852.[1] The accolade of a Fellowship of the Royal Society of London followed in 1853 (chapter 4). Through this institutional involvement, extensive publication,[2] and correspondence or collaboration with other members of local and national scientific elites (William Thomson, Stokes, Forbes, Piazzi Smyth),[3] Rankine consolidated his position within the scientific community.

The key factor in this elevation to scientific eminence was his work on the mechanical action of heat, initially based on a complex mechanical atomic model dubbed the hypothesis of molecular vortices.[4] Writing later in justification of this contemporarily somewhat controversial foundation he argued:

---

[1] See *BAAS Reports*. 1850 was Rankine's first year as a member of the Association. The three meetings were held as far afield as Edinburgh, Ipswich and Belfast.

[2] See bibliography for the numerous contributions to the *Philosophical Magazine* for the years 1853, 1854 and 1855.

[3] Letters from Rankine to G.G. Stokes, R107, RS19-20 and RS31 in Stokes Correspondence, Cambridge University Library. Forbes guided the publication of his former pupil Rankine's first papers on the mechanical action of heat by the R.S.E. See Rankine to Forbes, 26 August 1849, J.D. Forbes Papers, St Andrews University Library. Piazzi Smyth, "On a Mode of Cooling the Air of Rooms in Tropical Climates", *BAAS Report*, 20(1850), part 2, p.188, gives one example of collaboration.

[4] This area has been studied by Keith Hutchison: see, in particular, "W.J.M. Rankine and the rise of thermodynamics", *British Journal for the History of Science*, 14(1981), pp.1-26; see also Edward E. Daub, "Atomism and Thermodymanics", *Isis*, 58(1967), 293-303.

> ...to establish that degree of probability which warrants the reception of a hypothesis into science, it is not sufficient that there should be a mere loose and general agreement between its results and those of experiment...The agreement should be mathematically exact to that degree of precision which the uncertainty of experimental data renders possible.[5]

From his student days in Forbes's Edinburgh University natural philosophy class Rankine had been a devotee and a practitioner of this research methodology of precision. Indeed, his first published paper had clearly identified truth in physical theories (specifically in that case the laws of cooling) with accurate experimental measurement (chapter 2). Two papers, apparently submitted through Forbes, to the *Edinburgh New Philosophical Journal* in the second half of 1849 had applauded the precision of Victor Regnault's experimental data on the elasticity of steam, to the obvious detriment of the less stringent procedures of Andrew Ure.[6] Thus Rankine's presentation of the common search for understanding and explanation of the "economy of nature" was directed by the precision measurement which characterized the basis of knowledge within mid-nineteenth century British natural philosophy.[7]

Equally, Rankine had many years of practical experience, first as a pupil of Macneill in Ireland and then as a resident railway engineer during the "mania" in Scotland and the north of England (chapter 3). More

---

[5] Quoted in P.G. Tait, "Memoir [of Rankine]", in W.J. Millar (ed.), *Miscellaneous Scientific Papers by W.J. Macquorn Rankine* (Charles Griffin & Co.: London, 1881), pp.xix-xxxvi, on pp.xxvii-xxviii; originally, "On the use of Mechanical Hypotheses in Science, and Especially in the Theory of Heat", *Proceedings of the Glasgow Philosophical Society*, 5(1864), 126-32.

[6] "On an equation between the temperature and the maximum elasticity of steam and other vapours", *Edinburgh New Philosophical Journal*, 47(July 1849), 28-42; "On a formula for calculating the expansion of liquids by heat", *Edinburgh New Philosophical Journal*, 47(October 1849), 235-9. See also Rankine to Forbes, 26 August 1849, J.D. Forbes Papers, St Andrews University Library. These papers demonstrate Rankine's knowledge of Regnault earlier than in "late 1849" which Olson has implied. See Richard Olson, *Scottish philosophy and British physics 1750-1880* (Princeton University Press: Princeton and London, 1975), p.272.

[7] See M. Norton Wise and Crosbie Smith, "Measurement, work and industry in Lord Kelvin's Britain", *Historical Studies in the Physical and Biological Sciences*, 17(1986), 147-73; Graeme Gooday, "Precision measurement and the genesis of physics teaching laboratories in Victorian Britain", *British Journal for the History of Science*, 23(1990), 25-51.

recently, in a diversely active partnership with John Thomson he had been by turns consulting engineer, surveyor, early submarine-telegraphist, and, more ambitiously, promoter of a system for supplying Glasgow with water from Loch Katrine (chapter 7). The air-engine project had absorbed much of his time as a professional engineer from the early months of 1853 (chapter 5). From this authoritative vantage point one aspect of "advance" in engineering workmanship characterized for Rankine the "economy of practice":

> Accurate workmanship in machines is the most effectual means of diminishing friction, wear, and breakage, of obtaining economy of time, money and materials, and of insuring efficiency of action.[8]

Engineering could benefit in other ways from the practice of precision. For example, referring to the very precise specifications to be met by Napier's ship *Admiral*, Rankine ominously warned the Institution of Engineers in Scotland that, in practical calculations linking the power and required speed of a ship, "an error in excess is as fatal as an error in defect".[9] Economically, overpowering a ship (by the manufacturer) was just as dangerous as underpowering (for the buyer). Accuracy had its place in practice just as much as in theory.

A modification of the ideas of precision and accuracy provided a directive for the economy of engineering science. The uses of precise measurement in science teaching, particularly in physics laboratories, have been studied by Gooday[10] and the integration of similar methods within academic engineering, though not directly advocated by Rankine, became an issue of much debate in the last decades of the nineteenth century. Candidates for the Rankine's Certificate of Proficiency in Engineering Science from 1862, having attended William Thomson's class,

---

[8] James Robert Napier, Walter Neilson and W.J.M. Rankine, "Report on the Progress and State of Applied Mechanics", *Proceedings of the Glasgow Philosophical Society*, 4(1855-60), pp.207-30, on p.219. Rankine was Convenor of this Committee.

[9] Rankine, "Opening Address [to the Institution of Engineers in Scotland]", *The Engineer*, 6(1858), 327-8, on p.327.

[10] Gooday, "Precision measurement".

for example, would be trained in the precision measurement of natural philosophy: in this sense the scientific precision was taken wholesale into academic engineering in Glasgow. For the class of civil engineering and mechanics, however, ideas of absolute precision were necessarily modified by economic factors:

> There is a special mode of treating such principles [of mathematics, natural philosophy, chemistry and geology] where they are to be applied practically...different from a purely scientific treatment...For any given practical purpose there is a certain degree of precision required inferior to the precision required for purely scientific purposes; and the student ought to be able to judge of the degree of precision that is wanted in applying science to a particular practical purpose, in order that time and labour and expense may not be wasted on an unnecessary degree of precision.[11]

Thus the economy of engineering science concentrated on that "certain degree of precision" required for a "particular practical purpose". Within Rankine's caricature of knowledge which (in order to admit "the art of applying scientific principles to practice") polarized "theory" and "practice" (chapter 7), both accurate workmanship and the achievement of scientific precision could be seen as activities demanding potentially infinite workshop or experimental resources. For the engineer, working within commercial constraints, time and labour had an associated cost. In the economy of practice, it might be well worth sacrificing accuracy, an expensive quantity, to minimize the total cost of an operation. Although accuracy in workmanship promoted efficiency of action, its pursuit without regard to the cost incurred in achieving it was unsound. The third economy of engineering science, supposedly embodied in Rankine's teaching of the class of civil engineering and mechanics, aimed to carry out the necessary optimization, producing for the practical engineer the best possible financial strategy. Smith, Wise and Gooday have previously shown how ideas of moral and economic value were integrated through precise measurement. Linking academic engineering to science through a modification of the guiding features of precision and accuracy, therefore

---

[11] *Devonshire Commission* , Rankine's evidence, question 9506.

strengthened its moral character and gave it further value within the university that it might otherwise have lacked.

Economy and efficiency in engineering practice

The culture of mid nineteenth-century Glasgow was permeated by the theme and rhetoric of economy.[12] Placing Rankine firmly within this tradition contextualizes his emphasis on economy in engineering. The interactions between the Glasgow Philosophical Society, of which Gordon and Rankine were members (chapter 7), and the dominant and economically motivated community of industrial engineers suggest the existence of a "dialectic of economy". Constructing academic engineering as "pure science" motivated and modified by economy, Rankine shared the cultural values of the Society; but seen as an engineer he was part of that much broader influence which helped to shape its overriding philosophy.

Economy - "the production of every desired effect by those means which are exactly adequate to produce it, and no more"[13] - and particularly financial economy, was of paramount importance to the nineteenth century engineer. For power sources of all kinds, and especially for heat-engines, in the nineteenth century and earlier the language of description and discussion was very much one of economy and duty (chapter 4).[14] For some, the very purpose of the profession was the creation of individual and national prosperity. Thus Jenkin defined engineers as "those whose business it is to produce wealth by skilled industry and by intelligent invention...those men on whom the material

---

[12] M. Norton Wise (with the collaboration of Crosbie Smith), "Work and waste: political economy and natural philosophy in nineteenth century Britain", three parts in *History of Science*, 27(1989), 263-301 and 391-449; and 28(1990), 221-61.

[13] Napier, Neilson and Rankine, "Report on Applied Mechanics", p.208.

[14] See also Donald S.L. Cardwell, *From Watt to Clausius. The rise of thermodynamics in the early industrial age* (Heinemann: London, 1971).

power of our country rests."[15] Even the innovative engineer should be financially dominated, as Rankine's friend the marine engineer John Elder remarked, designing

> different forms of boilers for different circumstances, the object being to construct all his work so as to give the best return to the capitalist that employs him.[16]

Independently of any such employer, the great promise of Napier and Rankine's improved air-engine would be realized, it was hoped, through *economy* of energy: "all that remains to be done is to...*economize* heat and power to the utmost."[17] More generally, submissions to the BAAS Mechanical Science Section during this period demonstrated the development and dissemination of techniques for the improvement of shipping economy, or railway economy, as a national characteristic of the more academically-inclined engineers.[18]

Heat-engines were most avidly monitored, particularly in Cornwall where coal was expensive: as a result these "Cornish engines" had become in many cases the ideals of economy. In a paper of the highly productive early 1850s Rankine proposed to

> investigate and explain the method of determining the rate of expansion, and consequently, the dimensions and proportions of a Cornish engine, which...shall perform a given amount of work at the least possible pecuniary cost, taking into account the expense of fuel, and the interest of the capital required for the construction of the engine.[19]

The analysis, which was based directly on Rankine's work on the mechanical

---

[15] Fleeming Jenkin, *A lecture on the education of civil and mechanical engineers in Great Britain and abroad* (Edmonston & Douglas: Edinburgh, 1868), p.3.

[16] Quoted in W.J.M. Rankine, *A Memoir of John Elder: Engineer and Shipbuilder* (William Blackwood and Sons: Edinburgh and London, 1871), p.47.

[17] Rankine to Napier, 7 February 1853, DC 90/3/1, Napier Papers. Emphasis added.

[18] For example, John Scott Russell, "Economical and Effective Proportion of Engine Power to the Tonnage of the Hull in Steam Vessels", *BAAS Report*, 10(1840), part 2, 188; Charles Blacker Vignoles, "On the Economy of Railways in respect of Gradients", ibid., 193. Also William Fairbairn, "On the Economy of the Expansive Action of Steam in Steam-Engines", *BAAS Report*, 14(1844), part 2, 98 (title only).

[19] W.J.M. Rankine, "On the Power and Economy of Single-Acting Expansive Steam-Engines", in W.J. Millar (ed.), *Miscellaneous Scientific Papers by W.J. Macquorn Rankine* (Charles Griffin & Co.: London, 1881), pp.288-99, p.288.

action of heat, led to an equation incorporating, on equal terms, variables representing theoretically or empirically measurable quantities (pressure, resistance) and economic factors (fuel cost, interest on capital costs). A minimization generated the optimal rate of expansion for the engine and led, as Rankine had promised, to the optimum rate of expansion and hence to the dimensions of the engine.

This extreme example of systematized wealth creation dispelled the image of engineering economy as a product of ad hoc method and evolutionary progress: Rankine had described such "empirical progress" as

> that which has been going on slowly and continually from the earliest times to the present day, by means of gradual amelioration in materials and workmanship, of small successive augmentations of the size of structures and power of machines, and of the exercise of individual ingenuity in matters of detail.[20]

In marked contrast, he proposed an engineering science methodology whereby increased economy in engineering projects could be achieved rapidly through an application of science to practice, synthesized with acknowledgement, quantification and integration of financial constraints. Using quantified economy to promise optimal numerical "solutions" to formulated engineering "problems" (in the style of, for example, David Rankine: chapter 3), was powerful propaganda for academic engineering. The industrial sector of Glasgow society would thus have a natural interest in giving continued support to engineering at the University. Extending this, economy, directed and controlled by *efficiency*, acted on pure science to create a discipline retaining certain qualities - especially the appearance of precision and accuracy - conducive to its academic acceptance.

Two of Rankine's published works display respectively the general and the specific applicability of these arguments of "efficiency" and

---

[20] W.J.M. Rankine, *Introductory lecture on the science of the engineer, delivered to the class of civil engineering and mechanics in the University of Glasgow, on the 4th of November, 1856* (Richard Griffin: London, 1857), p.5.

"economy" to engineering.[21] As a preliminary remark it should be noted that the very presentation of such arguments depended upon Rankine's prolific versatility as a writer and publicist.

The first text, a "Report on the Progress and State of Applied Mechanics", produced by J.R. Napier, Walter Neilson, and Rankine for the Glasgow Philosophical Society,[22] took a quasi-axiomatic, didactic approach, highlighting the achievement of economy through a precise definition of efficiency.[23] Allen Thomson, as President of the Society in November 1856, had ambitiously suggested a series of reports "on the present state and recent advancement of various branches of science", probably in imitation of those of the British Association.[24] "Applied Mechanics" was the first to be produced and, significantly appeared in the same year as the *Manual of Applied Mechanics*, again first in Rankine's systematic series of class texts which attempted to define and colonise the intellectual territory of academic engineering.[25] Central to the engineering course, and by analogy with the role of mechanics in natural

---

[21] Many others encapsulate similar arguments. See, for example, "On the Economy of Heat in Expansive Machines", *Transactions of the Royal Society of Edinburgh*, 20(1853), 205-10 (read 21 April 1851); and, in a completely different context, "On the Theoretical Limit of the Efficiency of Propellers", *The Engineer*, 23(11 January 1867), 25.

[22] Napier, Neilson and Rankine, "Report on Applied mechanics".

[23] Napier, Neilson and Rankine were the three main proponents of the Glasgow-based Institution of Engineers in Scotland, founded, appropriately enough, for the "promotion of Engineering Science and Practice". See the first volume of the IES General Minute Book, UGD 168/1/1, pp.1-8. Preliminary meetings beginning in March 1857 took place in Rankine's office at St. Vincent Street; and in the buildings of the Glasgow Philosophical Society. It is perhaps significant that the original rules of order, which appear to have been drawn up by Rankine, included no category of "Associate Membership". Rankine had been elected to this class in the Institution of Civil Engineers, did not become a full member after fourteen years: and resigned in the same year the IES was formed, with Rankine first President.

[24] *Proceedings of the Glasgow Philosophical Society*, 4(1855-60), p.41.

[25] The *Manual of Applied Mechanics* (Richard Griffin & Co.: London, 1858) went through 21 editions. See bibliography. The other texts were *A Manual of the Steam Engine and Other Prime Movers* (Richard Griffin & Co.: London and Glasgow, 1859); *A Manual of Civil Engineering* (Charles Griffin & Co.: London, 1862); and *A Manual of Machinery and Millwork* (Charles Griffin & Co.: London, 1869). David Channell has discussed the *Manual of Applied Mechanics* in his *A Unitary technology: the engineering science of W.J.M. Rankine* (unpublished PhD thesis, Case Western Reserve University, 1975), pp.62-116.

philosophy, applied mechanics was made the foundation of engineering science. A course of applied mechanics, embodying in its name the central precept of "the application of scientific principles to practice", had complemented the lectures on heat-engines, auguring the success of the air-engine, given by Rankine early in 1855.

Secondly, Rankine's *Memoir of John Elder* emphasized the guiding principle of economy in the practice of an engineer,[26] particularly in Elder's development of the compound expansive steam engine, contemporaneously with and notably more successfully than the air-engine (chapter 5). As an ex-student in the Glasgow engineering class (chapter 6) who combined scientific knowledge, practical skill and "commercial sagacity",[27] and as a man able (posthumously) to endow the Glasgow department of engineering with £5000, Elder could be presented by Rankine as a role model for the academic engineer. The *Memoir* can be read, and perhaps was intended to be read, as "the economic success of engineering science".

Economy neatly linked the practical and the scientific aspects of applied mechanics, *measuring* the subject's progress towards *perfection* :

> In the perfecting of Applied Mechanics, whether as a science or as an art, the end aimed at, and the criterion by which true is to be distinguished from false progress, may be expressed by the word ECONOMY.[28]

Heat-engines, and in particular the air-engine, had been analysed within precisely this framework: the progress of the actual engine was measured by its approximation to the ideal goal of its perfect counterpart (chapter 7). Establishing economy as the sole guide for improvement distinguished applied mechanics from pure science, itself motivated rather by precise fitting of data with theory. Since applied mechanics was essentially the application of scientific principles to practice, with the efficacy of

---

[26] W.J.M. Rankine, *A Memoir of John Elder: Engineer and Shipbuilder* (William Blackwood and Sons: Edinburgh and London, 1871). The Blackwood Papers, National Library of Scotland, contain information regarding the motivation for the writing of this work.

[27] Rankine, *Memoir Elder* , pp.11-12.

[28] Napier, Neilson and Rankine, "Report on Applied Mechanics", p.208.

that application evaluated by economy of means, Rankine's academic engineering, with applied mechanics centrally placed, was pure science *regulated by economy*, particularly economy in its financial sense.

Economies of finance, energy or work, and "intellectual effort", were all significant to the academic engineer. Rankine argued that intellectual economy could be realized through the academic division of labour arising from the differentiation of academic engineering in Glasgow, in the same way that, for him, the formation of a separate Mechanical Science Section had enabled necessary British Association business to be carried out in a more appropriate manner (chapter 7).

Through the allied concept of *efficiency*, economy in the first two senses was supplied with an appropriately precise definition:

> The EFFICIENCY of a machine is its economy of power or energy; that is the ratio of the useful work performed to the energy exerted...The great end of improvement in machines is to diminish the lost work, so as to make the efficiency approximate to *unity*.[29]

In Rankine's lectures early in 1855 this "efficiency of the mechanism" had been abbreviated as E_m (chapter 7). The lost work was referred to in a particularly potent manner as "waste of means", or simply "waste".[30]

For heat-engines, the "EFFICIENCY OF THE ELASTIC VEHICLE" or "maximum theoretical efficiency", which depended only on the temperature difference of the source and sink, would in fact be less than unity;[31] but since it could still be calculated exactly it merely represented another definite limit to which practice should aspire: E_p, the efficiency of a perfect engine working on a Carnot cycle. In particular, since the air-engine with regenerator could be worked over a much wider temperature range at lower and therefore safer pressures than was possible for existing steam-engines, especially marine engines, it had a far greater maximum

---

[29] Ibid., pp.225-6.

[30] Ibid., p.208.

[31] Ibid., p.228. If t and t_1 are respectively the absolute temperatures of the source and sink, then the 'efficiency of the elastic substance' is $1-t_1/t$. Thus with either t or t_1 fixed, the efficiency increases as the temperature difference $(t-t_1)$ increases.

theoretical efficiency. By approaching this limit in practice, air would be both a safer and a more efficient alternative to steam. The examples of Stirling and Ericsson appeared to show that, by these criteria, the air-engine was already more closely approximating "perfection" than any existing steam-engine (chapters 4,5 and 7).[32]

Improvements in engineering design - increases in efficiency - equated with economies of power which produced financial benefits through saving fuel, for example. However, for any increase in efficiency of energy there might well be a corresponding increased cost in its production, leading to a decrease in financial economy. For example, of the factors of efficiency specified by Rankine for the marine steam engine, dependent on separate sources of waste,[33] each could be increased, but economy of financial means had to be respected:

> The object of improvements in the economy of the marine steam-engine is to increase as far as practicable, consistently with due regard to economy in first cost, each of the four factors of efficiency.[34]

"First cost" made explicit those essential financial considerations which were as important to the academic engineer as the quasi-scientific search for an efficiency of unity, and which were fundamental in distinguishing engineering science from pure science. The analysis of the Cornish steam-engine appeared to demonstrate the power of the science of the engineer in reconciling such issues. Whatever the perceived theoretical advantages of Napier and Rankine's air-engine improvements, the financial implications of local circumstances had to be observed:

> ...it is not unlikely that for marine purposes, and in all districts where either fuel or water is scarce, and perhaps also for locomotives, [air-engines] will ultimately supplant the steam-engine altogether.[35]

In general, the mechanical engineer with "commercial sagacity" approached

---

[32] W.J.M. Rankine, "On the Means of realizing the advantages of the Air-Engine", *BAAS Report*, 24(1854), part 2, pp.159-60.

[33] Combustion of fuel in the boiler, conversion of water into steam, mechanical friction and fluid friction associated with the propeller.

[34] Rankine, *Memoir of Elder*, p.10.

[35] Rankine to Napier, 7 February 1853, DC 90/3/1, Napier Papers.

design by asking:

> Whether the economy in working to be attained by means of a given increase in expenditure is sufficient to warrant the additional expenditure?...regard must be had to...the length of the voyage, the intended speed, the price of fuel, and the nature of the traffic...[Knowing only]...the mechanical principles of his art...might lead him into needless expense in the production of a degree of mechanical efficiency not required by the circumstances of particular cases; he ought also to have a sound judgment regarding the commercial result of the adaptation of engines of a given kind to a given vessel, intended for a given trade.[36]

Using efficiency to make engineering economy precise thus safeguarded engineering from the sacrifice of financial economy through over emphasis on a "scientific" degree of precision, but retained and integrated accuracy, regulated by economy.

The principle of efficiency applied

Efficiency, the basic measure of economy, was fundamentally a *quantitative* concept, as accurate as required, which for a machine compared "theoretically" available energy with "practically" useful work. More generally, efficiency, as

> the proportion borne by the means exactly adequate to produce an effect, and the means actually employed, can be expressed by a numerical ratio.[37]

As such, efficiency was susceptible to symbolic or geometrical mathematical treatment. It had been given axiomatic status within applied mechanics and therefore also within academic engineering. Extending and modifying it to take into account the economy of large-scale engineering projects provided a directive for a more complex but still ideally quantifiable discipline. The introduction of such secondary quantifiable aims within engineering science - in particular, the modifying factors of

---

[36] Rankine, *Memoir of Elder*, pp.10-11. This sensitivity to local conditions "so as to secure economy in execution and working" had been described by Rankine as a principle of Civil Engineering "peculiar to itself". See Rankine, *Science of the engineer*, p.13.

[37] Napier, Neilson and Rankine, "Report on Applied Mechanics", p.208.

financial economy - presented no methodological inconsistency with applied mechanics, the basic aim of which was numerical: a search for an efficiency of unity for structures and machines, or for heat-engines the efficiency of a perfect engine.

Efficiency promoted an analytic/synthetic approach which made engineering science a little more like pure science. Rankine's analysis of the economy of the marine steam-engine, for example, postulated a chain of four *independent* efficiencies: synthesis merely required multiplication of the corresponding numerical ratios;[38] similarly the general analysis of heat-engines had again been summarized for Rankine's earliest engineering students in the form of a chain of independent efficiencies multiplied together (chapter 7).

Most significantly, efficiency demonstrated the reliance of engineering science on theory. The very definition of the concept depended for its integrity on the acceptance by the scientific community of Joule's experimental "proof" of the interconvertibility of heat and work, the construction and diffusion of the concept of "energy" and, most personally for Rankine, "energetics" (or a general energy physics).[39] In treating heat-engines Rankine pointedly distinguished between the "perfect" (or theoretical) and "actual" (or practical), even introducing a "Coefficient of Imperfection", which in a single number enabled the engineering scientist to measure directly the efficiency of the second in terms of that of the first (chapter 7). The creation and use of such terminology amplified the sense of an almost spiritual aspiration to the perfection of theory driving engineering science.[40]

---

[38] Rankine, Memoir of Elder, pp.9-10.

[39] W.J.M. Rankine, "Outlines of the Science of Energetics", in Millar (ed.), *Miscellaneous Scientific Papers*, pp.209-28. Read before the Glasgow Philosophical Society 2 May 1855. Donald S.L. Cardwell, *James Joule. A biography* (Manchester University Press: Manchester and New York, 1989).

[40] Recall that if i is the coefficient of imperfection, E_a the efficiency of an actual heat-engine, and E_p the theoretically determined efficiency of a perfect heat-engine, then $E_a = (1-i)E_p$.

As a further example, Rankine's economic analysis of the Cornish steam-engine, mentioned earlier, occurred as a supplement to a paper "On the Mechanical Action of Heat".[41] This implied already that the generation of such engineering "solutions" required scientific literacy, in this case a knowledge of the developing science of thermodynamics. Rankine later described how John Elder had increased the "efficiency of steam" for the compound engine by combining high rates of expansion with the re-introduction of the steam-jacket, abandoned due to

> an erroneous theory of...heat...it was not to be expected that it should be reformed except by an engineer who had studied and understood...thermodynamics.[42]

Only a scientifically educated engineer could hope to maximize all types of efficiency. Engineers without such education, Rankine implied, might cling to erroneous theories causing both scientific and practical harm. One such theory, that of the substantial nature of heat, had, for Rankine, seriously impeded the general acceptance of the air-engine, a realizable machine which, according to the arguments of the true theory of heat, was likely to supplant the steam-engine (chapters 4 and 5).

By measuring practical value in terms of theoretical value, efficiency linked science with experiment. Given natural philosophy as knowledge through precise measurement, academic engineering was made precise at one remove through efficiency: "useless" work or waste represented "precisely" the amount by which a machine, structure, or heat engine fell short of theoretical perfection. Thus either Stirling's or Ericsson's air-engines produced "only three-fifths of the power which it would do if the waste of heat were prevented".[43] Steam-engines, even of the best conceivable design, would necessarily waste substantial amounts of heat, more even than these two actual air-engines.

This approach, in itself, was not peculiar to Rankine: in 1840, Lewis

---

[41] See Millar (ed.), *Miscellaneous Scientific Papers*, pp.234-99.
[42] Rankine, *Memoir of Elder*, pp.27-8.
[43] Rankine to Napier, 7 February 1853, DC 90/3/1, Napier Papers, Glasgow University Archives.

Gordon had compared "useful effect" with "theoretical effect".[44] But to characterize the central directive of the academic engineer as the quest for this approach of practice to theory measured by efficiency was a *choice* made by Rankine for *his* interpretation of academic engineering within context: Rankine's academic engineer could assess the value of his practical efforts directly in terms of his approach to the perfection of theory, representing as it did the perfect economy of nature (chapter 7). Pursuing this analogy further, an efficiency of unity implied that the practical engineer had achieved the status of the pure scientist; the practical had reached the "best possible" state. "Measuring" engineering in this way and linking it to "pure science" integrated it academically and gave it respectability. This institutional strengthening was a *numerical* distillation of the *harmony of theory and practice* rhetoric by which Rankine had chosen to define links between Sections A and G of the British Association, and similarly between the chairs of natural philosophy, mathematics, and civil engineering and mechanics at Glasgow.

In a still broader sense, and again within Rankine's caricature of knowledge, "intellectual" efficiency could be used to describe the transference of information from the "pure scientist" to the "practical man". Since one purpose of the engineering scientist was largely to make available the results of the pure scientist for practical engineering, the more efficiently this could be done, the greater economy in engineering practice could be achieved. Thus intellectual efficiency had correlative and immediate benefits for practical economic efficiency. Clearly, in the light of the political economy of Adam Smith, the division of labour within the university created by the construction of engineering science led to a second kind of intellectual efficiency: in terms of "means of education", the most economical inculcation of knowledge.

In avoiding hostility, Rankine used a rhetorical *harmony of theory and practice* to promote social harmony between university theorist and

---

[44] "On the Turbine Water-Wheel", *BAAS Report*, 10(1840), part 2, pp.191-2.

practical engineer. This rhetoric had been chosen to reflect idealized partnerships not just between disciplines, but between individuals such as Napier and Rankine himself. The first fruits of their intense and lasting collaboration had been the Napier and Rankine air-engine which had promised so much but ultimately failed through want of materials and in the face of competition from better forms of steam-engine.

Deftly structuring the Glasgow engineering course to avoid conflict with diverse groups, Rankine incorporated and synthesized ideas fundamental to academia and industry to construct academic engineering, firstly as a beneficial, coherent and non-threatening extension of existing academic subjects, particularly mathematics and natural philosophy; and secondly as an essential source of consultation, the complement to large scale engineering industry. The ideas of precision, accuracy and economy, internalized through his own academic and practical apprenticeships, were synthesized through efficiency to create engineering science.

Efficiency in Rankine's applied mechanics (and therefore in his academic engineering) took on the central status that precise measurement held in natural philosophy and the other academically accepted sciences. The concept of efficiency relied ultimately upon the idealization of engineering practice, whether of machines, structures or heat-engines. The latter had proved particularly susceptible to this treatment: perfect heat-engines, the scientific counterparts to actual engines, represented the fixed ideal to which practice should strive to approximate. The degree of success, the closeness of approximation was shown directly in the single numerical quantity, efficiency. Efficiency was thus analogous to precision; and since efficiency was essentially the accurate measure of economy, Rankine's academic engineering, informed by and embedded within a rich Glagow context, was essentially pure science regulated by economy.

BIBLIOGRAPHY

1. Archival Sources

Full details are given in the footnotes to the text. The following collections have been particularly useful:

Adam Smith Business Record Centre, Glasgow: UGD 10 (Neilson Papers); UGD 168 (Institution of Shipbuilders and Engineers in Scotland Archives)

British Museum Library, London: Add. MS 41077 (James Croll).

Cambridge University Library: RGO 6 (Greenwich Royal Observatory, Airy); Add. MS 7342 (Kelvin); Add. MS 7656 (Stokes).

Edinburgh University Library, University Archives: botany class lists; mathematics class lists; natural philosophy class lists; matriculation indexes; matriculation albums; transcipts of arts and law matriculation signatures.

Glasgow University Archives: Minutes of Senate; Minutes of Faculty; Prize and Degree List of Glasgow College 1833-63; Class Lists of Glasgow College 1863- ; DC 9 (Macfarlan Papers: also catalogued as P/CN/Macfarlan); DC 90 (Napier Papers); Acc. 12721 and Acc. 12713 (in Map and Plan Collection); Acc. 3409; Acc. 3848; Acc. 4380; Acc. 4554; Acc. 5223; Acc. 5957; Acc. 6032; Acc. 23613; Acc. 36322.

Glasgow University Library (Special Collections and Manuscripts): Kelvin Papers; MS Gen. 1084.

Institution of Civil Engineers, London: Admission Certificates.

Institution of Electrical Engineers, London: Faraday Papers.

Mitchell Library, Glasgow: Henry Dyer Collection; Portrait Collection (Glasgow Room); Glasgow Grammar School Class Books.

National Library of Scotland, Edinburgh: MSS 4173, 4192, 4203, 4214, 4225, 4267 and 4281 (all Blackwood Papers); MSS 785, 1704, 3448 (Lee), 3519, and 6355 (Caledonian Railway Company); Acc. 8660; and Acc. 10000 (Royal Society of Edinburgh Archives).

Queens University Belfast: MS 13 (James Thomson Manuscripts).

Royal Society of London: Election Certificates; Herschel Letters; Lubbock Letters; Miscellaneous Correspondence; Referees Reports.

Scottish Record Office, Edinburgh: SC 36/48/70 and SC 36/65/171 (Rankine's Inventory and Testament).

St Andrews University Library: J.D. Forbes Papers.

Strathclyde Regional Council Archives, Glasgow: D-WA (Report of projected waterworks of Glasgow).

Trinity College Library, Dublin: Board Minutes.

Wellcome Institute for the History of Medicine, London: Autograph Letters Collection.

2. Published works by Rankine alone or in collaboration with others

Note: Arrangement is as far as possible chronological, according to date of writing; date at which a paper was first read in full or abstract form; or date of first publication. Later reprints and editions have been grouped with the original article, pamphlet, or book. Locations for some rare works (usually books, or first editions of books) are given in square brackets beneath each entry. The standard collection of Rankine's works is W.J. Millar (ed.), *Miscellaneous Scientific Papers* (Charles Griffin & Co.: London, 1881).

"On the laws of the conduction of heat and on their application to some geothermal problems", in *The Edinburgh academic annual for MDCCCXL, consisiting of contributions in literature and science by alumni of the University of Edinburgh* (Adam and Charles Black: Edinburgh, 1840), pp.48-65.
[Copy in Edinburgh University Library MS. JA.2385.]

An Experimental Inquiry into the advantages attending the use of Cylindrical Wheels on Railways, with an Explanation of adapting Curves for those Wheels, and its Application to Practice; and an account of experiments shewing the easy draught and the safety of Carriages with Cylindrical Wheels (R. Grant & Son: Edinburgh, 1842).
[Copies in British Museum Library and John Crerar Library Chicago.]

"On the causes of the unexpected breakage of the Journals of Railway Axles; and on the means of preventing such accidents by observing the Law of Continuity in their construction", *Minutes of Proceedings of the Institution of Civil Engineers* , 2(1842-3), 105-8.
[Read 7 March 1843, the meeting at which Rankine was elected Associate of the Institution. Discussion pp.107-8.]

"Description of a method of laying down Railway Curves on the ground", *Minutes of Proceedings of the Institution of Civil Engineers* , 2(1842-3), 108-11.
[Read 14 March 1943. Discussion pp.109-11.]

"Description of Lieutenant D. Rankine's Spring Contractor", *Minutes of Proceedings of the Institution of Civil Engineers* , 2(1842-3), 111-12.
[Read 14 March 1843.]

"Description of a Safety Drag, or apparatus for preventing accidents to Trains ascending inclined plains, used on the Edinburgh and Dalkeith Railway since 1832", *Minutes of Proceedings of the Institution of Civil Engineers* , 3(1844), 284-6.
[Read 4 June 1844.]

"Account of the Effect of the Storm of the 6th of December, 1847, on Four Sea Walls or Bulwarks of Different Forms, on the Coast Near Edinburgh; as Illustrating the Principles of the Construction of Sea Defences", *Minutes of Proceedings of the Institution of Civil Engineers* , 7(1848), 186-204.
[Read 14 March 1848. Discussion pp.192-204.]

"On an equation between the temperature and the maximum elasticity of steam and other vapours", *Edinburgh New Philosophical Journal* , 47(July 1849), 28-42; *Journal of the Franklin Institute* , third series, 19(1850), 121-5, 181-7; *MSP* , 1-12.

"On a formula for calculating the expansion of liquids by heat", *Edinburgh New Philosophical Journal* , 47(October 1849), 235-9; *Journal of the Franklin Institute* , third series, 19(1850), 49-50; *MSP* , 13-15.

"A conjecture as to the forces which produce the tails of comets", *Edinburgh New Philosophical Journal*, 48(1850), 92-4.

"Ueber die mechanische Theorie der Wärme", *Poggendorff Annalen der Physik und Chemie*, 81(1850), 172-6.

"Abstract of a Paper on the Hypothesis of Molecular Vortices, and its Application to the Mechanical Theory of Heat", *Proceedings of the Royal Society of Edinburgh*, 2(1844-50), 275-88.
[Read 4 February 1850.]

"On the Mechanical Action of Heat, especially in Gases and Vapours", *Transactions of the Royal Society of Edinburgh*, 20(1853), part 1, 147-90; *Philosophical Magazine*, fourth series, 7(1854), 1-21, 111-22 & 172-85; *MSP*, 234-84.
[For *Philosophical Magazine*, prefatory remarks on pp.1-3. Footnotes added and experimental results changed: paper previously read to the Royal Society of Edinburgh 4 February 1850.]

"On the centrifugal theory of elasticity, as applied to gases and vapours", *Philosophical Magazine*, fourth series, 2(December 1851), 509-42; *MSP*, 16-48.
[Read to the Royal Society of Edinburgh 4 February 1850.]

"On the Anomaly-Ruler; and Instrument to assist in the graphic representation of the place of a Gravitating Projectile in an Elliptic Orbit", *Philosophical Magazine*, third series, 37(1850), 291-2.
[Dated Glasgow August 1850.]

"On the Vibrations of Plane-Polarised Light", *Proceedings of the Royal Society of Edinburgh*, 3(1850-7), 3-4; *Philosophical Magazine*, fourth series, 1(June 1851), 441-6; *MSP*, 150-5.
[*Philosophical Magazine* article dated Glasgow August 1850. Read to the Royal Society of Edinburgh 2 December 1850.]

"On the Laws of the Elasticity of Solids", *BAAS Report*, 20(1850), part 2, 2-3.
[Read to BAAS Section A at Edinburgh 1 August 1850.]

"On the Laws of Elasticity of Solids", *Journal of the Franklin Institute*, third series, 20(1850), 348-50.

"Laws of the elasticity of solid bodies", *Cambridge and Dublin Mathematical Journal*, 6(February & May 1851), 47-80, 178-81, 185-6; *MSP*, 67-101.
[Written 1850.]

"Note as to the Dynamical Equivalent of Temperature in Liquid Water, and the Specific Heat of Atmospheric Air and Steam, being a supplement to a paper on the Mechanical Action of Heat", *Transactions of the Royal Society of Edinburgh*, 20(1853), part 2, 191-193; *Proceedings of the Royal Society of Edinburgh*, 3(1850-7), 5-6. *MSP*, 285-7.
[Read 2 December 1850.]

"On the re-heating of jets of air, and the relation between the temperature and the compression of the same", *Edinburgh New Philosophical Journal*, 51(1851), 128-30.

"On Laplace's theory of sound", *Philosophical Magazine*, fourth series, 1(1851), 225-7.

[Dated London February 1851.]

"On the Law of the Compressibility of Water at different Temperatures", *Philosophical Magazine*, fourth series, 1(1851), 548-9.
[*Philosophical Magazine* article dated London March 1851. Read to the Royal Society of Edinburgh 7 April 1851.]

"On Poisson's investigation of the theory of sound", *Philosophical Magazine*, fourth series, 1(1851), 410-11.
[Dated London 2 April 1851.]

"On the Economy of Single-acting Expansive Steam Engines, and Expansive Machines generally; being Supplements to a Paper on the Mechanical Action of Heat", *Proceedings of the Royal Society of Edinburgh*, 3(1850-7), 60-4.
[Read 21 April 1851.]

"On the Power and Economy of Single-acting Expansive Steam Engines, being a supplement to the fourth section of a paper On the Mechanical Action of Heat", *Transactions of the Royal Society of Edinburgh*, 20(1853), part 2, 195-204; *Philosophical Magazine*, fourth series, 7(1854), 239-49; *MSP*, 288-99.
[Read 21 April 1851.]

"On the Economy of Heat in Expansive Machines, forming the fifth section of a paper On the Mechanical Action of Heat", *Transactions of the Royal Society of Edinburgh*, 20(1853), 205-10; *Philosophical Magazine*, fourth series, 7(1854), 249-54; *MSP*, 300-6.
[Read 21 April 1851.]

"On the Theory of Sound", *Philosophical Magazine*, fourth series, 2(1851), 36.

"On the Mechanical Theory of Heat", *Philosophical Magazine*, fourth series, 2(1851), 61-5.

"On the Velocity of Sound in Liquid and Solid Bodies of Limited Dimensions, especially along prismatic masses of liquid", *BAAS Report*, 21(1851), part 2, 4-6; *Cambridge and Dublin Mathematical Journal*, 6(November 1851), 238-67; *MSP*, 168-99.

"Summary of the Results of the Hypothesis of Molecular Vortices, as applied to the Theory of Elasticity and Heat", *BAAS Report*, 21(1851), part 2, 3-4.

"On the Centrifugal Theory of Elasticity, and its connection with the Theory of Heat", *Proceedings of the Royal Society of Edinburgh*, 3(1850-7), 86-9; *Transactions of the Royal Society of Edinburgh*, 20(1853), part 3, 425-40; *MSP*, 49-66.
[Read 15 December 1851.]

"On the Hypothesis of Molecular Vortices, or Centrifugal Theory of Elasticity, and its Connection with the Theory of Heat", *Philosophical Magazine*, fourth series, 10(1855), 354-63, 411-20.
[Read to the Royal Society of Edinburgh 15 December 1851. Verbal alterations, and changes in notation. Some repetitions removed and dated notes added.]

"On the Computation of the Specific Heat of Liquid Water at Various Temperatures, from the Experiments of M. Regnault", *Proceedings of the Royal Society of Edinburgh*, 3(1850-7), 90-1; *Transactions of the Royal Society of Edinburgh*, 20(1853), part 3, 441-4.

[Read 15 December 1851.]

W.J.M. Rankine and John Thomson, *On the Means of Improving the Water Supply of Glasgow* (George Richardson: Glasgow, 1852).

W.J.M. Rankine and John Thomson, *On the Means of Improving the Water Supply of Glasgow. Second Letter* (George Richardson: Glasgow, 1852).
[Dated Glasgow 29 March 1852.]

"On Telegraphic Communication between Great Britain and Ireland, by the Mull of Cantyre" (with John Thomson, C.E.), *BAAS Report*, 22(1852), part 2, 128; *Proceedings of the Glasgow Philosophical Society*, 3(1845-55), 265-6.
[Read to the Glasgow Philosophical Society 17 November 1852.]

"Remarks on the Mechanical Process for Cooling Air in Tropical Climates proposed by Prof. C. Piazzi Smyth", *BAAS Report*, 22(1852), part 2, 128-9.

"On the Causes of the Excess of the Mean Temperature of Rivers above that of the Atmosphere, recently observed by M. Renou", *Philosophical Magazine*, fourth series, 4(1852), 355-8; *BAAS Report*, 22(1852), part 2, 30-1.
[Read to BAAS at Belfast 2 September 1852.]

"On the Reconcentration of the Mechanical Energy of the Universe", *Philosophical Magazine*, fourth series, 4(November 1852), 358-60; *BAAS Report*, 22(1852), part 2, 12; *Edinburgh New Philosophical Journal*, 54(1853), 88-101; *MSP*, 200-2.
[Read to BAAS at Belfast 2 September 1852.]

"On the laws of elasticity", *Cambridge and Dublin Mathematical Journal*, 7(November 1852), 217-230, 231-4; *MSP*, 101-18.

"On the Non-polarization of the Aurora Borealis", *Philosophical Magazine*, fourth series, 4(1852), 452.
[Letter to editors dated 22 November 1852.]

"On the Mechanical Effect of Heat and of Chemical Forces...In a Letter to J.P. Joule", *Philosophical Magazine*, fourth series, 5(1853), 6-9.
[Dated 11 December 1852.]

"On the Absolute Zero of the Perfect Gas Thermometer, being a Note to a Paper on the Mechanical Action of Heat", *Proceedings of the Royal Society of Edinburgh*, 3(1850-7), 160; *Transactions of the Royal Society of Edinburgh*, 20(1853), part 4, 561-3; *MSP*, 307-9.
[Read 4 January 1853.]

"On the General Law of the Transformation of Energy", *Proceedings of the Glasgow Philosophical Society*, 3(1848-55), 276-80; *Philosophical Magazine*, fourth series, 5(1853), 106-17; *MSP*, 203-8.
[Read 5 January 1853.]

"On the Mechanical Action of Heat, Section VI.- A review of the Fundamental Principles of the Mechanical Theory of Heat; with remarks on the Thermic Phenomena of Currents of Elastic Fluids, as illustrating those Principles", *Proceedings of the Royal Society of Edinburgh*, 3(1850-7), 162-7; *Transactions of the Royal Society of Edinburgh*, 20(1853), part 4, 565-589; *The American Journal of Science and Arts*, second series, 18(1854), 64-6; *MSP*, 310-38.
[Read 17 January 1853.]

"Mechanical Theory of Heat - Specific Heat of Air", *Philosophical Magazine*, fourth series, 5(1853), 437-9.
[Dated Glasgow 25 April 1853.]

"On the Application of the Law of the Conservation of Energy to the Determination of the Magnetic Meridian on board Ship, when out of reach or out of sight of Land", *Proceedings of the Royal Society of London*, 6(1853), 303-4; *Philosophical Magazine*, fourth series, 6(1853), 140-1.
[Read 28 April 1853.]

"Mechanical Theory of Heat - Velocity of Sound in Gases", *Philosophical Magazine*, fourth series, 5(1853), 483-6.
[Dated Glasgow 6 May 1853.]

"On a proposed Barometric Pendulum, for the Registration of the Mean Atmospheric Pressure during long Periods of Time", *Philosophical Magazine*, fourth series, 6(1853), 432-7; *BAAS Report*, 23(1853), part 2, 26.
[Introductory remarks dated Glasgow 27 October 1853. Paper dated Glasgow 9 July 1853. Read to Section A of the BAAS at Hull 10 September 1853.]

"General View of an Oscillatory Theory of Light", *Philosophical Magazine*, fourth series, 6(December 1853), 403-14; *BAAS Report*, 23(1853), part 2, 9-10; *MSP*, 156-67.
[Read to Section A of the BAAS at Hull 10 September 1853.]

James Robert Napier and W.J.M. Rankine, *Specification. Engines worked by heated air and other elastic fluids* (Eyre & Spottiswoode: London, 1853).

"On the Geometrical Representation of the Expansive Action of Heat, and the Theory of Thermo-dynamic Engines", *Philosophical Transactions of the Royal Society of London*, 114(1854), 115-76; *Philosophical Magazine*, fourth series, 7(1854), 288-91; *MSP*, 339-409.
[Read to the Royal Society 19 January 1854.]

"On the Mechanical Action of Heat. Section VI. Subsection 4.- On the Thermic Phenomenon of Currents of Elastic Fluids. Supplement.- Of a Correction applicable to the results of the previous reduction of the experiments of Messrs Thomson and Joule", *Proceedings of the Royal Society of Edinburgh*, 3(1850-7), 223-4.
[Read 6 March 1854.]

"On some simultaneous Observations of Rain-fall at different points on the same Mountain-Range", *Philosophical Magazine*, fourth series, 8(1854), 444-8; *BAAS Report*, 24(1854), part 2, 46-7.
[Rankine's observations originally made on the Pentland Hills in 1845. Read to Section A of the BAAS in Liverpool September 1854.]

"On Formulae for the Maximum Pressure and Latent Heat of Vapours", *Philosophical Magazine*, fourth series, 8(December 1854), 530-5; *BAAS Report*, 24(1854), part 2, 58-9; *MSP*, 410-6.
[Read to Section A of the BAAS in Liverpool September 1854.]

"On the Means of realizing the advantages of the Air-Engine", *Edinburgh New Philosophical Journal*, new series, 1(1855), 1-32; *BAAS Report*, 24(1854), part 2, 159-60; *Journal of the Franklin Institute*, third series, 30(1855), 246-330.
[Full paper dates from 1854. N.B. Not volume 2(1855) for the

Edinburgh Philosophical Magazine article.]

"On the Expansion of certain Substances by Cold", *Philosophical Magazine*, fourth series, 8(1854), 357-8.
[Dated Glasgow 10 October 1854.]

"On the General Integrals of the Equations of the Internal Equilibrium of an Elastic Solid", *Proceedings of the Royal Society of London*, 7(1854-5), 196-202; *Philosophical Magazine*, fourth series, 9(1855), 301-5.
[Read to Royal Society 11 January 1855.]

"Note on the Determination of the Magnetic Meridian at a Distance from Land", *Proceedings of the Glasgow Philosophical Society*, 3(1848-55), 376-8.
[Read 24 January 1855.]

"Note on the Approximate Determination of the Azimuth of a Star by Geometrical Construction, its Declination and Altitude, and the Latitude of the Place of Observation being given", *Proceedings of the Glasgow Philosophical Society*, 3(1848-55), 378.
[Read 24 January 1855.]

"On the Mechanical Action of Heat:- Supplement to the first Six Sections and Section Seventh", *Proceedings of the Royal Society of Edinburgh*, 3(1850-7), 287-92.
[Read 19 February 1855.]

"Outlines of the Science of Energetics", *Proceedings of the Glasgow Philosophical Society*, 3(1848-55), 381; *Edinburgh New Philosophical Journal*, new series, 2(1855), 120-41; *MSP*, 209-28.
[Read to the Glasgow Philosophical Society 2 May 1855.]

"On Axes of Elasticity and Crystalline Forms", *Philosophical Transactions of the Royal Society of London*, 146(1856), 261-86; *Philosophical Magazine*, fourth series, 11(1856), 301-3; *MSP*, 119-50.
[Read to the Royal Society 21 June 1855.]

"Opening Remarks on the Objects of the [Mechanical Science] Section", *BAAS Report*, 25(1855), part 2, 201-2.

"On Practical Tables of the Latent Heat of Vapours", *BAAS Report*, 25(1855), part 2, 208.

"On the Operation of the Patent Laws", *BAAS Report*, 25(1855), part 2, 208.

"Concluding Address [to the Mechanical Science Section]", *BAAS Report*, 25(1855), part 2, 211.

"On Pressures of Saturated Vapours", *Philosophical Magazine*, fourth series, 10(1855), 255-7.
[Dated Glasgow 21 September 1855.]

"On Pressures of Saturated Vapours", *Philosophical Magazine*, fourth series, 10(1855), 334-5.
[Dated Glasgow 6 October 1855.]

"On the Principle of Isorrhopic Axes in Statics", *Philosophical Magazine*, fourth series, 10(1855), 400.
[Dated Glasgow 26 October 1855.]

Introductory lecture on the harmony of theory and practice in mechanics, delivered to the class of civil engineering and mechanics in the University of Glasgow on January 3 1856 (Richard Griffin and Company: London and Glasgow, 1856).
[Copies in Library of Royal Society of London and British Museum Library]

Mechanical Laws, Formulae, and Tables pt.1 (Glasgow, 1856).
[Only first part published. Copy in British Museum Library.]

"On the Mathematical Theory of the Stability of Earthwork and Masonry", *Proceedings of the Royal Society* , 8(1856-7), 60-1; *Philosophical Magazine* , fourth series, 12(1856), 468-70.
[In the *Philosophical Magazine* a letter to G.G. Stokes as Secretary of the Royal Society dated 18 February 1856, on research during preparation of lectures.]

"On the strength of railway axles", *Proceedings of the Glasgow Philosophical Society* , 4(1855-60), 13.
[Read 20 February 1856.]

"On the stability of factory chimneys", *Proceedings of the Glasgow Philosophical Society* , 4(1855-60), 14-18.
[Read 5 March 1856.]

"On Heat as the Equivalent of Work", *Philosophical Magazine* , fourth series, 12(1856), 103-4.
[Dated Glasgow 2 July 1856.]

"On the stability of loose earth", *Proceedings of the Royal Society of London* , 8(1856-7), 185-7; *Philosophical Transactions of the Royal Society of London* , 147(1857), 9-28; *Philosophical Magazine* , fourth series, 13(1857), 292-3.
[Read to Royal Society 19 June 1856.]

Introductory lecture on the science of the engineer, delivered to the class of civil engineering and mechanics in the University of Glasgow, on the 4th of November, 1856 (Richard Griffin: London, 1857).

[W.J.M. Rankine] in J.P. Nichol, *Cyclopaedia of the Physical Sciences* (London and Glasgow, 1857).
[Some articles by Rankine on heat contained. Second edition 1860.]

"On the compressibility of water", *Proceedings of the Royal Society of Edinburgh* , 3(1857), 58-9.

"On the invariant sum of the products of the coefficients of a pair of homogeneous functions", *Quarterly Journal of Pure and Applied Mathematics* , 1(1857), 357-9.

"On the Principle of the Transformation of Stuctures", *BAAS Report* , 27(1857), part 2, 189.

Institution of Engineers in Scotland...On the nature and objects of the Institution. An introductory address (W.Mackenzie: Glasgow, 1857).
[Copy in British Museum Library.]

"On the Nature and Objects of the Institution", *Transactions of the Institution of Engineers in Scotland* , 1(1857-8), 1-12.
[Read 28 October 1857.]

"On a blowing-fan", *Transactions of the Institution of Engineers in Scotland*, 1(1857-8), 25-9.
[Read 25 November 1857.]

A Manual of Applied Mechanics (Richard Griffin & Co.: London 1858).

[Contains the "Preliminary Dissertation on the Harmony of Theory and Practice", p.1-11.

First edition reprinted as volume 39 (second division - applied sciences) in Edward Smedley, Hugh James Rose and Henry John Rose, *Encyclopaedia Metropolitana, or System of Universal Knowledge: on a methodical plan projected by S.T. Coleridge* (second revised edition, 40 vols., London, 1848-58).

Translation of seventh edition by A. Vialay as *Manuel de mécanique appliqueé* (Paris, 1876).

Many editions: 2nd revised edn Griffin, Bohn & Co.: London, 1861; 3rd edn C. Griffin: London, 1864; 4th edn revised by W.J. Millar, 1868; 5th edn 1869; 6th edn 1872; 7th edn revised by Edward Fischer Bamber, 1873; 8th edn Charles Griffin: London, 1876, revised by Bamber (copy in Royal Society of London); 11th edn revised by Millar, 1885; 15th edn revised by Millar, 1898; 16th edn revised by Millar, 1901; 17th edn revised by Millar, 1904; 20th edn revised by Millar, 1919; 21st edn revised by Millar, 1921.]

"On the Elasticity of Carbonic Acid Gas", *Philosophical Magazine*, fourth series, 15(1858), 303-5.
[Letter to editors dated Glasgow March 1858.]

James Robert Napier, Walter Neilson and W.J.M. Rankine, "Report on the Progress and State of Applied Mechanics", *Proceedings of the Glasgow Philosophical Society*, 4(1855-60), 207-30.
[Read 7 April 1858. Some additions and alterations made for printing in November 1858.]

"Applied Mechanics", *The Engineer*, 6(1858), 98.
[Letter to the editor dated Glasgow 2 August 1858. Published 6 August 1858.]

"Steam Propulsion, the Admiral", *The Engineer*, 6(1858), 196, 217.

"Resistance of Ships", *Philosophical Magazine*, fourth series, 16(1858), 238-9; *Journal of the Franklin Institute*, 43(1862), 22-9.
[For the *Philosophical Magazine* a letter to editors dated Glasgow 26 August 1858. An anagram of the "resistance formula".]

"Opening Address Delivered to the Institution of Engineers in Scotland", *The Engineer*, 6(1858), 327-8.

"Mackintosh's System of Warfare", *The Engineer*, 6(1858), 393.

"On the working of certain furnaces", *Transactions of the Institution of Engineers in Scotland*, 2(1858-9), 88-9.

"On a method of estimating the probable evaporative power of fuel and efficiency of boilers", 2(1858-9), 125-9.

"On the thermo-dynamic theory of steam-engines with dry saturated steam, and its applications to practice", *Proceedings of the Royal Society of London*, 9(1857-9), 626-8; *Philosophical Transactions of the Royal Society of London*, 149(1859), 177-92, 743-4.
[Dated 27 December 1858. Read 27 January 1859.]

W.J.M. Rankine, J.W. Slater and P.E. Dove, *The Imperial Journal of the Arts and Sciences* (2 vols., William Mackenzie: Glasgow, 1859).

A Manual of the Steam Engine and other Prime Movers (Richard Griffin & Co.: London and Glasgow, 1859).
[Translation of 8th edn by G. Richard as *Manuel de la machine à vapeur et des autres moteurs* (Paris, 1878).
Many editions: 6th edn, 1873; 12th edn, 1888; 13th edn revised W.J. Millar, 1891; 14th edn revised Millar, 1897; 17th edn revised W.J. Millar, 1908.

"On the Thermodynamic Theory of Steam-engines with dry Saturated Steam, and its application to practice", *Philosophical Transactions of the Royal Society of London* , 149(1859), 177-92; *Proceedings of the Royal Society of London* , 9(1857-9), 626-28; *Philosophical Magazine* , fourth series, 18(1859), 71-3.
[Abstract of a paper read to the Royal Society 27 January 1859.]

"On the Conservation of Energy", *Philosophical Magazine* , fourth series, 17(1859), 250-3.
[Letter to editors dated Glasgow 12 March 1859.]

"Note to a Letter 'On the Conservation of Energy'", *Philosophical Magazine* , fourth series, 17(1859), 347-8.
[Letter to editors dated Glasgow 13 April 1859.]

"Supplement to a Paper 'On the Thermodynamics of Steam-engines with dry Saturated Steam, and its application to practice'", *Proceedings of the Royal Society of London* , 10(1859-60), 183; *Philosophical Magazine* , fourth series, 17(1859), 460.

"Condensed Abstract of a First Set of Experiments, by Messrs. Robert Napier and Sons, on the Strength of Wrought Iron and Steel", *BAAS Report* , 29(1859), part 2, 242-3; *Journal of the Franklin Institute* , 39(1860), 67-8.

"Density of Steam", *Philosophical Magazine* , fourth series, 18(1859), 316-17; *Proceedings of the Glasgow Philosophical Society* , 4(1855-60), 285-6; *Transactions of the Institution of Engineers in Scotland* , 3(1859-60), 53-5.
[For *Philosophical Magazine* a letter to editors dated Glasgow 24 September 1859. Paper read to Glasgow Philosophical Society 18 January 1860.]

Table of distances for rifle-firing at targets (Lithographed on a card. Glasgow, 1860). [BL 1881.a.3.(110.)]

Miniature Targets for Position and Aiming Drill within doors (Maclure and Macdonald: Glasgow, 1860).

"On the application of transversals to engineering field-work", *Transactions of the Institution of Engineers in Scotland* , 4(1860-1), 16-22.

"On the Resistance of Ships", *BAAS Report* , 31(1861), part 2, 263-4.

"Appendix to a Paper 'On the Resistance of Ships'", *BAAS Report* , 31(1861), part 2, 264.

"[Presidential Address: Applied Mechanics]", *Proceedings of the Glasgow Philosophical Society* , 5(1860-64), 83-9.
[Read 6 November 1861.]

"Remarks on some experiments made by Messrs Isherwood, Stimers, and Long, Chief Engineers in the U.S. Navy, on the liquefaction of steam in the cylinder of an engine working expansively", *Transactions of the Institution of Engineers in Scotland*, 5(1861-2), 61-6; *The Engineer*, 13(1862), 132.

A Manual of Civil Engineering (Charles Griffin & Co.: London, 1862).
[BL 8766.b.27]
[R.S.L.]

[Translation of 12th edn by F. Kreuter as *Handbuch der Bauingenieurkunst* (Vienna, 1880).

Many editions: 3rd edn revised, 1864; 4th edn revised, 1865; 5th edn revised, 1867; 7th edn revised 1871; 8th edn revised 1872; 15th edn revised by W.J. Millar, 1885; 17th edn revised Millar, 1889; 18th edn revised Millar; 1899; 20th edn revised Millar, 1898; 21st edn revised Millar, 1900; 22nd end revised Millar, 1904; 23rd edn revised Millar, 1907; 24th edn revised Millar, 1911.]

"On Steam Expansion and the American Experiments", *Scientific American*, new series, 6(1862), 249.

"Remarks on Mr Froude's theory of the rolling of ships", *Transactions of the Institution of Naval Architects*, 3(1862), 22-45.

"On the fracture of railway axles", *Transactions of the Institution of Engineers in Scotland*, 6(1862-3), 43-4.

"On the use of mechanical hypotheses in science, and especially in the theory of heat", *Proceedings of the Glasgow Philosophical Society*, 5(1860-4), 126-32.
[Read before 29 January 1862.]

"On a Dew-bow seen on the surface of mud", *Philosophical Magazine*, fourth series, 23(1862), 245.
[Letter to editors dated Glasgow 6 February 1862.]

"Resistance to the conduction of heat", *Philosophical Magazine*, fourth series, 23(1862), 336.
[Letter to the editors dated Glasgow 17 March 1862. Corrections to tables in *Steam-engine and other Prime Movers*.]

"On the Density of Steam", *Transactions of the Royal Society of Edinburgh*, 23(1861-4), 147-55; *Scientific American*, new series, 12(18??), 48; *MSP*, 417-26.
[Read 28 April 1862.]

"On the Exact Form and Motion of Waves at or near the Surface of Deep Water", *Philosophical Magazine*, fourth series, 24(1862), 420-22; *BAAS Report*, 32(1862), part 2, 5-7; *Transactions of the Royal Society of London*, 153(1863), 127-38; *MSP*, 481-94.
[Dated Glasgow 30 September 1862. Abstract of a paper read to Section A of the BAAS in 1862. Read to Royal Society 27 November 1862.]

John Francis Walker (editor), Prof. J. Eadie, E. Lankester, Prof. F. Bowen, W.J.M. Rankine, *The Imperial Dictionary of Universal Biography: a series of original Memoirs of distinguished Men of all ages and all nations* (3 vols., William Mackenzie: London, Glasgow and Edinburgh, 1857-63).
[Copy in British Library. Volume 2 contains Rankine's biographical essay "Sir William Fairbairn".]

"On the comparative straining action of different kinds of vertical oscillation upon a ship", *Transactions of the Institution of Naval Architects* , 4(1863), 205-10.

"Address of the President [of the Mathematics and Physics Section]", *BAAS Report* , 33(1863), part 2, 1.

"Abstract of an Investigation on Plane Water-lines", *BAAS Report* , 33(1863), part 2, 180-2; *Philosophical Magazine* , fourth series, 26(October 1863), 303-6.
Read to BAAS at Newcastle August 1863.]

"On the Application of Barycentric Perspective to the Transformation of Structures", *Philosophical Magazine* , fourth series, 26(November 1863), 387-8; *MSP* , 562-3.

"On the Expansive Energy of Heated Water", *Philosophical Magazine* , fourth series, 26(November & December 1863), 388-91, 436-7; *Transactions of the Institution of Engineers in Scotland* , 7(1863), 8-15; *Les Mondes* , 6(1864), 77-8; *Journal of the Franklin Institute* , third series, 47(1864), 119-20.
[Article for *Philosophical Magazine* dated 5 October 1863. Note on pp.390-1 added 19 October 1863. Published November issue. Paper read 28 October 1863. Supplement on pp.436-7 dated Glasgow 4 November 1863. Published December issue.]

"On the action of waves upon a ship's keel", *Transactions of the Institution of Naval Architects* , 5(1864), 20-34.

"On the isochronous rolling of ships", *Transactions of the Institution of Naval Architects* , 5(1864), 35-7.

"On the uneasy rolling of ships", *Transactions of the Institution of Naval Architects* , 5(1864), 38-42.

"On the computation of the probable engine-power and speed of proposed ships", *Transactions of the Institution of Naval Architects* , 5(1864), 316-33.

"Principle of the Equilibrium of Polyhedral Frames", *Philosophical Magazine* , fourth series, 27(February 1864), 92; *MSP* , 564.
[Dated Glasgow 9 January 1864.]

"On the Dynamical Theory of Heat", *Philosophical Magazine* , fourth series, 27(March 1864), 194-6.
[Letter to editors dated Glasgow 15 February 1864.]

"On the Hypothesis of Molecular Vortices", *Philosophical Magazine* , fourth series, 27(April 1864), 313.
[Letter to editors dated Glasgow 1 March 1864.]

"Summary of the Properties of certain Stream-Lines", *BAAS Report* , 34(1864), part 2, 20; *Philosophical Magazine* , fourth series, 28(October 1864), 282-8; 29(January 1865), 25-8.
[Read at BAAS in Bath 19 September 1864. *Philosophical Magazine* article dated September 1864. Supplement dated Glasgow University 19 November 1864.]

"On some of the Strains of Ships", *BAAS Report* , 34(1864), part 2, 187-8.

"On Units of Measure", *BAAS Report* , 34(1864), part 2, 188.

"On the History of Energetics", *Philosophical Magazine*, fourth series, 28(November 1864), 404.
[Letter to editors dated Glasgow 5 October 1864.]

"On the approximate Graphic Measurement of Elliptic and Trochoidal Arcs, and the Construction of a Circular Arc nearly equal to a given Straight Line", *Philosophical Magazine*, fourth series, 29(January 1865), 22-5.
[Dated Glasgow University 19 November 1864.]

"On plane water-lines in two dimensions", *Philosophical Transactions of the Royal Society of London*, 154(1864), 369-91; *Proceedings of the Royal Society of London*, 13(1864), 15-17; *MSP*, 495-21.
[Read 26 November 1864.]

"Note as to two events in the history of steam-navigation", *Memoirs of the Manchester Literary and Philosophical Society*, 2(1865), 301-2.

"On the mechanical principles of the action of propellers", *Transactions of the Institution of Naval Architects*, 6(1865), 13-39.

"Elasticity of vapours", *Philosophical Magazine*, fourth series, 29(April 1865), 283-5.
[Letter to editors dated Glasgow University 18 February 1865. Postscript dated March 1865.]

"Expansion of Steam", *Scientific American*, new series, 12(1865), 3.

"On Expansion", *Scientific American*, new series, 12(1865), 7.

"Rectification approximative d'arcs d'ellipse et de trochoide, et construction d'un arc de cercle de longueur donnée", *Annales du Génie Civil*, 4(1865), 243-6.

"On Rational Approximations to the Circle", *Philosophical Magazine*, fourth series, 29(June 1865), 421-6.
[Dated Glasgow University April 1865.]

"On Saturated Vapours", *Proceedings of the Royal Society of Edinburgh*, 5(1866), 449-51; *Philosophical Magazine*, fourth series, 31(March 1866), 199-201; *Annales de Chimie*, 8(1866), 378-81; *The Engineer*, (16 March 1866).
[Read to Royal Society of Edinburgh 1 May 1865.]

"On the Second Law of Thermodynamics", *Philosophical Magazine*, fourth series, 30(October 1865), 241-5; *BAAS Report*, 35(1865), part 2, 13-14; *The Engineer*, (November 1865); *Annales du Génie Civil*, 5(1866), 187-9; *MSP*, 427-31.
[Read to BAAS in Birmingham September 1865. *Philosophical Magazine* article dated Glasgow University 4 September 1865. "Appendix" dated 6 September 1865.]

"On Thermodynamic and Metamorphic Functions, Disgregation, and Real Specific Heat", *Philosophical Magazine*, fourth series, 30(December 1865), 407-10.
[Dated Glasgow University 15 November 1865.]

"On the Tenacity of Some Fibrous Substances", *The Engineer*, (29 December 1865); *Transactions of the Institution of Engineers in Scotland*, 9(1866), 29-36.

I. Watts, F.K. Barnes, J.R. Napier and W.J.M. Rankine, *Shipbuilding, theoretical and practical. Illustrated by...engravings from drawings ...by some of the most eminent shipbuilders* (W. Mackenzie: London, 1866).
[Rankine was corresponding and general editor and main contributor.]

Useful Rules and Tables relating to Mensuration, Engineering, Structures, and Machines (W. Mackenzie: London, 1866).
[Many editions: 2nd edn 1867; 3rd edn 1872; 6th edn revised by W.J. Millar, 1883 with electrical engineering appendix by Andrew Jamieson; 7th edn revised by Millar, with appendix by Jamieson, 1889.]

"On Simple Rules for Practical Calculations of the Efficiency of Steam", *The Engineer* , 21(5 January 1866), 1.

"Sur la calcul de l'effet utilé de la vapeur", *Cuyper, Revue Univ.* , 20(1866), 1-14.

"Règles simples pour le calcul pratique du travail utile de la vapeur", *Annales du Génie Civil* , 5(1866), 85-91.

"On the Expansion of Saturated Vapours", *Philosophical Magazine* , fourth series, 31(March 1866), 197-8; *Annales de Chimie* , 8(1866), 374-7.
[Letter to editors dated Glasgow 12 February 1866.]

"On finding the most economical rates of expansion in steam engines", *Transactions of the Institution of Naval Architects* , 7(1866), 144-7.
[Received 7 March 1866. Read 23 March 1866.]

"On finding the most economical rates of expansion in steam-engines", *Transactions of the Institution of Naval Architects* , 7(1866), 144-7; *The Engineer* , 21(6 April 1866), 248.

"On a Graphical Method of Finding the Mean Pressure of Expanding Steam", *The Engineer* , 21(13 April 1866), 261.

"Graphische Methode zur Bestimmung des mittleren Druckes des expandirenden Dampfes", *Der Civilingenieur* , 12(1866), 219-26.

"On the estimation of the evaporative power of fuel", *Proceedings of the Glasgow Philosophical Society* , 6(1864-8), 123-6; *Les Mondes* , 15(1867), 627-34, 669-80; *Polytechnisches Journal* , 189(1868), 41-9; *Journal of the United Service Institution* , 11(1868), 218-36; *The Engineer* , (4 May 1866).

"On a Provisional Theory of the Resistance of Ships' Armour", *The Engineer* , 21(29 June 1866), 463.

"On the Theory of Explosive Gas Engines", *The Engineer* , 22(27 July 1866), 55; *MSP* , 464-70.

"On a Table of Pairs of Stars for approximately finding the Meridian", *BAAS Report* , 36(1866), part 2, 21-2.

"On the Theory of the Influence of Friction upon the Mechanical Efficiency of Steam", *BAAS Report* , 36(1866), part 2, 147; *Journal of the Franklin Institute* , third series, 52(1866), 388-92; *Revue Universelle de Mines* , 21(1867), 71-7; *The Engineer* , (7 September 1866).

"Remarks on the Experiments of the [BAAS] Committee upon the Resistance of Water to Floating and Immersed Bodies", *BAAS Report* , 36(1866), part

2, 147-8.

"Dynamical Principles of Newton and Measure of Moving Force", *The Engineer* , 22(26 September 1866), 305-6.
[Continuation dated 5 November.]

"On the Theoretical Limit of the Efficiency of Propellors", *The Engineer* , 23(11 January 1867), 25; *MSP* , 544-9.
[Dated Glasgow 26 December 1866.]

"On the Phrase 'Potential Energy', and on the Definitions of Physical Quantities", *Proceedings of the Glasgow Philosophical Society* , 6(1864-6), 186-91; *Philosophical Magazine* , fourth series, 33(February 1867), 88-92; *Annales de Chimie* , 13(1868), 73-9; *MSP* , 229-33.
[*Philosophical Magazine* article dated Glasgow University 9 January 1867. Read to the Glasgow Philosophical Society 23 January 1867.]

"Some remarks on apparent negative slip", *Transactions of the Institution of Naval Architects* , 8(1867), 68-9; *The Engineer* , (1867).

"Economy of Fuel Comprising Mineral Oils", *United Service Institution* , (April 1867). [J.R.N.]
[See also F.N.M. Moigno, *Actualités scientifiques etc.* (1869), which contains "Sur l'economie des diverses sortes de combustibles, y compris les huiles minerales" in a section: "Chaleur degagée dans la combustion".]

"Longitudinal Collision of Elastic Bars", *The Engineer* , (14 June 1867).

"On the Want of Popular Illustrations of the Second Law of Thermodynamics", *The Engineer* , 23(28 June 1867); *MSP* , 432-8.

"De la nécessité de vulgariser la second loi de la thermodynamique", *Annales de Chimie* , 7(1867), 258-66; *Les Mondes* , 14(1867), 710-16.

"Illustrations of the second law of thermodynamics", *The Engineer* , 23(1867), 580.

"Examples of the Application of the Second Law of Thermodynamics to a Perfect Steam-Engine and a Perfect Air-Engine", *The Engineer* , 24(2 August 1867), 85; *MSP* , 439-53.

"On the Theory of a Class of Air Engines", *The Engineer* , 24(23 August and 8 November 1867), 141, 393.

"Théorie de machines à gaz", *Revue Universelle des Mines* , 21(1867), 63-70.

"Sur la théorie d'un système de machines à air", *Les Mondes* , 15(1867), 583-91; 16(1868), 285-92.

"Steamship Performance", *Engineering* , 4(1867), 272.

"On the Approximate Drawing of Circular Arcs of given lengths", *Philosophical Magazine* , fourth series, 34(October 1867), 284-6; *Les Mondes* , 16(1868), 158-62; *BAAS Report* , 37(1867), part 2, 5.
[*Philosophical Magazine* article dated 27 August 1867. Read to BAAS at Dundee September 1867.]

"Approximate Lengths of Circular Arcs", *The Engineer* , 24(27 September 1867), 273.

"Address [as President of the Mechanical Science Section]", *BAAS Report*, 37(1867), part 2, 149-52.

"On the Use of Moveable Seats for Slide-Valves" (with James Robert Napier), *BAAS Report*, 37(1867), part 2, 156-7.

"On Isoperimetric Regular Polygons", *Philosophical Magazine*, 34(November 1867), 365-7; *Les Mondes*, 16(1868), 162-3.
[Dated Glasgow University 10 October 1867.]

"On the Approximate Rectification of Circular Arcs; being a second Supplement to a Paper read to the British Association", *Philosophical Magazine*, fourth series, 34(1867), 381-2; *Les Mondes*, 16(1868), 163-5.
[*Philosophical Magazine* article dated Glasgow University 16 October 1867.]

"Longitudinal Collision of Elastic Bars", *The Engineer*, 23(1867), 530.

"Note on Mr. Merrifield's new method of calculating the statical stability of a ship", *Proceedings of the Royal Society of London*, 15(1867), 396-7.

"On a Property of Curves which fulfil the condition $d^2\phi/dx^2 + d^2\phi/dy^2 = 0$", *Proceedings of the Royal Society*, 15(1867), 468-9; *Philosophical Magazine*, fourth series, 34(July 1867), 65-6; 35(1868), 244; *Les Mondes*, 16(1868), 206-7; *MSP*, 565-7.
[Read 9 May 1867.]

"On the Straining Actions upon Arched Ribs", *The Engineer*, 25(3 January 1868), 2.

"On the Drying of Steam by Wiredrawing, and on its Liquefaction by Expansive Working", *The Engineer*, 25(21 February 1868), 123.

"On Curves fulfilling the equation $d^2\phi/dx^2 + d^2\phi/dy^2 = 0$", *Philosophical Magazine*, fourth series, 35(March 1868), 244.
[Undated letter to editors.]

"On waves which travel along with ships", *Transactions of the Institution of Naval Architects*, 9(1868), 275-81; *The Engineer*, (17 April 1868).

"Description of a Chimney at the West Cumberland Haematite Iron Works", *Transactions of the Institution of Engineers in Scotland*, 11(1867-8), 157-63; *The Engineer*, (8 May 1868).
[Received and read 22 April 1868]

"On a Governor Adjustable for Various Speeds", *The Engineer*, 25(24 April 1868), 289.

"On waves in liquids", *Proceedings of the Royal Society of London*, 16(1868), 344-7; *Philosophical Magazine*, fourth series, 36(July 1868), 52-5.
[Read 7 May 1868.]

"On a Probable Connexion between the Resistance of Ships and their Mean Depth of Immersion", *BAAS Report*, 38(1868), part 2, 194-5; *The Engineer*, (28 August 1868).

"Elementary Demonstration of Propositions Relating to Waves", *The Engineer*, 26(4 September 1868), 175.

"Elementary Demonstrations of Propositions Relating to Stream Lines", *The Engineer*, 26(16 October 1868), 285; *MSP*, 522-9.

"Strength and Stiffness of Corrugated Iron", *The Engineer*, 26(13 November 1868), 355; *Revue Universalle de Mines*, 27(1870), 617-23.

A Manual of Machinery and Millwork (Charles Griffin & Co.: London, 1869). [BL 08768.aa.13]
[Many editions: 5th edn revised by W.J. Millar, 1883; 7th edn 1893.]

"Summmary of the Principles of the Strength and Qualities of Wood and Metals", in *The Cyclopaedia of Machine and Hand Tools* (W. Mackenzie: London, 1869) [BL 1812.a.33.] [SML 620F]
[Also "An essay on the strength and qualities of wood and metals". Copies of both in Library of the Royal Society of London.]

"Account of experiments on Mr. Alexander Morton's Ejector-Condenser", *Transactions of the Institution of Engineers in Scotland*, 12(1869), 73-104; *The Engineer*, (1 January 1869).
[Read 1868]

The "Ejector-condenser": Morton's patent. Reports of experiments on steam engines at the Albert Works, Glasgow, and at Ryesholm Pit, near Dalry, Ayrshire (John Graham: Glasgow, 1869).

"Morton's Ejector-Condenser", *Engineering*, 7(1869), 48.

"On the Centrifugal Force of Bands in Machinery", *The Engineer*, 27(5 March 1869), 165.

"De la force centrifuge des courroies dans les machines", *Les Mondes*, 19(1869), 614-19; *Revue Universalle de Mines*, 27(1870), 424-9.

"On the Calculation of the Stress in Propeller shafts", *Transactions of the Institution of Naval Architects*, 10(1869), 139-43; *Les Mondes*, 20(1869), 28-33; *The Engineer*, (26 March 1869).

"On the Centrifugal Force of Rotating Shafts", *The Engineer*, 27(9 April 1869), 249.

"Des effets de la force centrifuge sur les axes de rotation", *Les Mondes*, 20(1869), 132-5; *Revue Universalle de Mines*, 27(1870), 430-2.

"On the Thermal Energy of Molecular Vortices", *Transactions of the Royal Society of Edinburgh*, 25(1867-9), 557-66; *Proceedings of the Royal Society of Edinburgh*, 6(1866-9), 590-2; *Philosophical Magazine*, 38(September 1869), 247-8; 39(March 1870), 211-21.
[Read 31 May 1869.]

"On the Dynamical Principles of the Motion of Velocipedes", *The Engineer*, 28(6 and 27 August, 3 and 10 September 1869), 79, 129, 175; *The Engineer*, 29(7 January 1870), 2.

"Sur les principes dynamiques du mouvement des vélocipèdes", *Les Mondes*, 21(1869), 371-5, 484-90, 555-62, 772-5.

"Summary of the Thermodynamic Theory of Waves of Finite Longitudinal Disturbance", *BAAS Report*, 39(1869), part 2, 14-15.

"Introductory Remarks [to the Institution of Engineers in Scotland]",

Transactions of the Institution of Engineers in Scotland , 13(1869-70), 1-12.
[Read 26 October 1869.]

"On the Outflow of Steam", *The Engineer* , 28(26 November and 3 December 1869), 358; *Van Nostrand's Eclectic Engineering Magazine* , 2(1869), 116.

"On the Thermodynamic Theory of Waves of Finite Longitudinal Disturbance", *Philosophical Transactions of the Royal Society of London* , 160(1870), 277-88; *Proceedings of the Royal Society of London* , 18(1870), 80-83; *Philosophical Magazine* , fourth series, 39(April 1870), 306-9; *MSP* , 530-43.
[Read 16 December 1869.]

"On Steam-line surfaces", *Journal of the Society of Arts* , 18(1869-70), 544-6.

"Sur la résistance de la tôle ondulée", *Revue Universelle des Mines* , 27(1870), 617-23.

"Ueber den Ausfluss des Dampfes", *Der Civilingenieur* , 16(1870), 35-50.

"Sur les lois de l'écoulement de la vapeur", *Les Mondes* , 22(1870), 90-5, 391-7; 23(1870), 153-61.

"On stream-line surfaces", *Transactions of the Institution of Naval Architects* , 11(1870), 175-81; *Engineering* , 9(1870), 267-8.

"Remarks on Mr. Heppel's theory of continuous beams", *Philosophical Magazine* , fourth series, 40(1870), 457-60; *Proceedings of the Royal Society of London* , 19(1871), 68-71.
[Read 3 February 1870.]

"On the Mathematical Theory of Stream-lines, especially those with four Foci and upwards", *Proceedings of the Royal Society of London* , 18(1870), 207-9; *Philosophical Transactions of the Royal Society of London* , 161(1871), 267-304, 305-6; *Philosophical Magazine* , fourth series, 39(June 1870), 460-2.
[Read 10 February 1870.]

"On the Working of Steam in Compound Engines", *The Engineer* , 29(11 March 1870), 145; *MSP* , 454-63.

"Diagrams of Force in Framework", *Proceedings of the Royal Society of Edinburgh* , 7(1869-72), 171-2.
[Letter to Secretary of Royal Society of Edinburgh dated Glasgow 2 June 1870. Read 6 June 1870.]

"On the Mathematical Theory of Combined Streams", *Proceedings of the Royal Society of London* , 19(1871), 90-4; *Philosophical Magazine* , fourth series, 41(January 1871), 67-71.
[Read to Royal Society of London 16 June 1870.]

"On Thermodynamics", *Philosophical Magazine* , fourth series, 40(August & October 1870), 103-4, 291-3; *Les Mondes* , 24(1871), 106-7.
[*Philosophical Magazine* letters to editors dated Glasgow 5 July and 10 September 1870.]

"An Investigation of the Mathematical Theory of Combined Streams", *BAAS Report* , 40(1870), part 2, 18; *The Engineer* , (30 September 1870).

"On the Thermodynamic Acceleration and Retardation of Streams", *Philosophical Magazine*, 40(October 1870), 288-91; *BAAS Report*, 40(1870), part 2, 18-19; *The Engineer*, (7 October 1870). [Read to Section A of BAAS at Liverpool September 1870.]

"Lecture on Stream Lines and Waves in Connection with Naval Architecture", *The Engineer*, (23 September 1870); *Nature*, 2(6 October 1870), 460-2.
[Read to BAAS at Liverpool Philharmonic Hall, 19 September 1870.]

"Stream Lines and Waves, in Connection with Naval Architecture", *Engineering*, 10(1870), 233-52.

"On the Explosive Energy of Heated Liquids", *The Engineer*, 30(11 November and 23 December 1870), 323, 423; *MSP*, 471-80.

"Inclining a Ship in Order to Find Her Centre of Gravity", *The Engineer*, 30(18 November 1870), 339.

"On the Meteor of November 19, 1870", *Philosophical Magazine*, fourth series, 40(1870), 440.
[Letter to editors dated Glasgow 23 November 1870.]

A Memoir of John Elder: Engineer and Shipbuilder (William Blackwood and Sons: Edinburgh and London, 1871). [SML 92ELD]
[Second edition Robert Maclehose: Glasgow, 1883.] [R.S.L.]

"Sur les frottements rotatoires dans les machines à vapeur", *Les Mondes*, 26(1871), 627-37.

"On the Hypothesis of Molecular Motions in Thermodynamics", *Philosophical Magazine*, fourth series, 41(January 1871), 62-6.

"On the rolling of ships", *Journal of the Society of Arts*, 20(1871-2), 371-2; *Transactions of the Institution of Naval Architects*, 13(1872), 62-6; *Les Mondes*, 27(1872), 611-12, 694.

"On sea-waves", *Proceedings of the Royal Institution*, 6(1872), 355-6.
[From 1871.]

"On Journal Friction in Steam Engines", *The Engineer*, 32(27 October 1871), 283; *Van Nostrand's Engineering Journal*, 6(1871), 379.

"On Flour-Mill Explosions", *Proceedings of the Glasgow Philosophical Society*, 1872. [J.R.N.]

"Remarks on the stability of mastless ships of low freeboard, as affected by the waves", *Annals of the Royal School of Naval Architects*, 2(1872), 136-8.

"Sur la force explosive des liquides chauffés", *Revue Universelle des Mines*, 31(1872), 65-71.

"Theorie des hydraulischen Widders", *Der Civilingenieur*, 18(1872), 297-302.

"On the Decomposition of Forces externally applied to an Elastic Solid", *Transactions of the Royal Society of Edinburgh*, 26(1869-72), 715-27; *Proceedings of the Royal Society of Edinburgh*, 7(1869-72), 611-12.
[Received 5 January 1872. Read 15 January 1872.]

"Report on the Design and Construction of Masonry Dams", *The Engineer*, 33(5 January 1872), 1-2; *MSP*, 550-61.

"On Actual Energy", *Philosophical Magazine*, fourth series, 43(February 1872), 160.
[Letter to editors dated Glasgow 23 January 1872.]

"Hydraulic Ram", *The Engineer*, 33(1872), 55.

"On the Mathematical Theory of the Hydraulic Ram", *The Engineer*, 33(8 March 1872), 163.

"Remarks on the Theory of Air and Steam Engines", *The Engineer*, 34(1872), 293; *Van Nostrand's Eclectic Engineering Magazine*, 8(1872), 152.

"On waves in liquids", *Transactions of the Institution of Naval Architects*, 14(1873), 170-8.

"Binary Vapour Engines", *The Engineer*, 35(1873), 395.

W.J.M. Rankine and Edward Fischer Bamber, *A Mechanical Textbook, or Introduction to the Study of Mechanics and Engineering* (Charles Griffin & Co.: London, 1873). [SML 620]
[Intended as an introduction to the manuals. Third edn 1884.]

Songs and Fables with illustrations by J.B. (2nd edition, Maclehose: Glasgow and London, 1874).
[1st edition also 1874 according to the Royal Society Catalogue and British Museum Library.]

3. Published works by other authors

G.B. Airy, *Mathematical tracts on the lunar and planetary theories, the figure of the earth, precession and nutation, the calculus of variations, and the undulatory theory of optics* (2nd edition, Cambridge, 1831).

[American Academy of Sciences], [Obituary of W.J.M. Rankine], *Proceedings of the American Academy of Arts and Sciences* , 9(1874), 276-8.

E.A. Allcut, "Macquorn Rankine - A Founder of Thermodynamics", in E.G. Semler (ed.), *Engineering Heritage. Highlights from the History of Mechanical Engineering. Volume Two* (Heinemann Educational Books Ltd.: London, 1966), pp.32-5.

W.H.G. Armytage, *A social history of engineering* (Faber and Faber: London, 1961).

Eric Ashby, *Technology and the academics* (Macmillan: London, 1966).

R.M. Bancroft and F.J. Bancroft, *Tall Chimney Construction* (John Calvert: Manchester, 1885).

Jonathan Barnes (ed.), *The complete works of Aristotle. The revised Oxford translation* (2 vols., Princeton University Press: Princeton, 1984).

Archibald Barr, "W.J. Macquorn Rankine, a Centenary Address", *Proceedings of the Royal Philosophical Society of Glasgow* , 51(1920-2), 167-87.

E. Scott Barr, "Anniversaries in 1970 of interest to physicists", *American Journal of Physics* , 38(1970), 50-8.

Derek Beales, *From Castlereagh to Gladstone 1815-1885* (Nelson: London, 1969).

Derek Beales, *The political parties of nineteenth-century Britain* (The Historical Association: London, 1971).

Richard Beamish, *Memoir of the life of Sir Marc Isambard Brunel* (Longman, Green, Longman, and Roberts: London, 1862).

Harvey W. Becher, "William Whewell and Cambridge mathematics", *Historical Studies in the Physical Sciences* , 11(1980), 1-48.

Harvey W. Becher, "Voluntary Science in Nineteenth Century Cambridge University to the 1850's", *British Journal for the History of Science* , 19(1986), 57-87.

Sir James Bell and James Paton, *Glasgow: Its Municipal Organisation and Administration* (James Maclehose and Sons: Glasgow, 1896).

Geoffrey Best, *Mid-Victorian Britain 1851-75* (Fontana: London, 1979).

Ronald M. Birse, *Engineering at Edinburgh University: a short history 1673-1983* (University of Edinburgh: Edinburgh, 1983).

Jemima Blackburn, in Robert Fairley (ed.), *Jemima: Paintings and Memoirs of a Victorian Lady* (Canongate: Edinburgh, 1988).

Stephanie M. Blackden, *The development of public health administration in Glasgow 1842-1872* (unpublished PhD thesis, Edinburgh University, 1976).

Frederic Boase, "W.J.M. Rankine" in *Modern English biography* (3 vols., Frank Cass & Co. Ltd.: London, 2nd impression 1965), 3, 37-8.

Asa Briggs, *The age of improvement, 1783-1867* (Longman: London, 1959).

W.H. Brock, "The Japanese connexion: engineering in Tokyo, London, and Glasgow at the end of the nineteenth century", *British Journal for the History of Science* , 14(1981), 227-43.

Stephen G. Brush, "The wave theory of heat: a forgotten stage in the transition from the caloric theory to thermodynamics", *British Journal for the History of Science* , 5(1970), 145-67.

Stephen G. Brush, "Nineteenth-Century Debates about the Inside of the Earth: Solid, Liquid or Gas?", *Annals of Science* , 36(1979), 225-54.

Stephen G. Brush, *Statistical Physics and the Atomic Theory of Matter, from Boyle and Newton to Landau and Onsager* (Princeton University Press: Princeton, 1983).

Lynwood Bryant, "The Role of Thermodynamics in the Evolution of Heat Engines", *Technology and Culture* , 14(1973), 152-65.

R.A. Buchanan, "Gentlemen engineers", *Victorian Studies* , 26(1983), 407-29.

R.A. Buchanan, "Institutional proliferation in the British engineering profession 1847-1914", *Economic History Review* , second series, 38(1985), 42-60.

R.A. Buchanan, "The rise of scientific engineering in Britain", *British Journal for the History of Science* , 18(1985), 218-33.

R.A. Buchanan, "The diaspora of British engineering", *Technology and Culture* , 27(1986), 501-24.

R.A. Buchanan, *The engineers: a history of the engineering profession in Britain 1750-1914* (Jessica Kingsley: London, 1989).

John Burnet, *History of the Water Supply of Glasgow* (Bell & Bain: Glasgow, 1869).

Susan Faye Cannon, *Science in Culture: The Early Victorian Period* (Science History Publications: New York, 1978).

G.N. Cantor, "Henry Brougham and the Scottish methodological tradition", *Studies in the History and Philosophy of Science* , 2(1971), 69-89.

G.N. Cantor, *Optics after Newton. Theories of light in Britain and Ireland, 1704-1840* (Manchester University Press: Manchester, 1983).

G.N. Cantor, *Michael Faraday: Sandemanian and Scientist. A Study of Science and Religion in the Nineteenth Century* (Macmillan: Basingstoke, 1991).

G.N. Cantor and M.J.S. Hodge (eds.), *Conceptions of ether. Studies in the history of ether theories 1740-1900* (Cambridge University Press: Cambridge, 1981).

Donald S.L. Cardwell, *From Watt to Clausius. The rise of thermodynamics in the early industrial age* (Heinemann: London, 1971).

Donald S.L. Cardwell, *The organisation of science in England*, (revised edition, Heinemann: London, 1972).

Donald S.L. Cardwell, *James Joule. A biography* (Manchester University Press: Manchester, 1989).

Donald S.L. Cardwell and Richard Hills, "Thermodynamics and Practical Engineering in the Nineteenth Century", *History of Technology*, 1(1976), 1-20.

Sadi Carnot, in Robert Fox (trans. and ed.), *Reflexions on the motive power of fire. A critical edition with the surviving scientific manuscripts* (Manchester University Press: Manchester, 1986).

David F. Channell, *A unitary technology: the engineering science of W.J.M. Rankine* (unpublished PhD thesis, Case Western Reserve University, 1975). Diss. Abstr. Int., 1976, 36:4668-A; University Microfilms order no. 75-27896.

David F. Channell, "Rankine, Aristotle and potential energy", *The Philosophical Journal*, 14(1978), 111-4.

David F. Channell, "The harmony of theory and practice: the engineering science of W.J.M. Rankine", *Technology and Culture*, 23(1982), 39-52.

David F. Channell, *William John Macquorn Rankine, F.R.S.E., F.R.S.* (University of Edinburgh: Edinburgh, 1986).

David F. Channell, "Engineering science as theory and practice", *Technology and Culture*, 29(1988), 98-103.

David F. Channell, "The role of Thomas Reid's philosophy in science and technology: the case of W.J.M. Rankine", in M. Dalgarno and E. Matthews (eds.), *The philosophy of Thomas Reid* (Kluwer Academic: Dordrecht, 1989), pp.447-55.

David F. Channell, *The history of engineering science: an annotated bibliography* (Garland: New York and London, 1989).

David F. Channell, "W.J.M. Rankine and the Scottish Roots of Engineering Science", in Elizabeth Gerber (ed.), *Beyond History of Science. Essays in Honor of Robert E. Schofield* (Lehigh University Press: Bethlehem, 1990), pp.194-203.

William Conant Church, *The Life of John Ericsson* (2 vols., Sampson Low, Marston, Searle & Rivington: London, 1890).

E. Clapeyron, "On the Motive Power of Heat", in Richard Taylor (ed.), *Scientific memoirs, selected from the transactions of foreign academies of science and learned societies and from foreign journals*, 1(1837), 347-76.

T.N. Clarke, A.D. Morrison-Low and A.D.C. Simpson, *Brass & Glass. Scientific Instrument Making Workshops in Scotland as illustrated by instruments from the Arthur Frank collection at the Royal Museum of Scotland* (National Museums of Scotland: Edinburgh, 1989).

Paul Clements, *Marc Isambard Brunel* (Longmans, Green and Co.: London, 1970).

Vary T. Coates and Bernard Finn, *A Retrospective Technology Assessment:*

Submarine Telegraphy. The Transatlantic Cable of 1866 (San Francisco Press: San Francisco, 1979).

Sidney Colvin and J.A. Ewing (eds.), *Papers Literary, Scientific, etc. by the late Fleeming Jenkin, F.R.S., LL.D. with a Memoir by R.L. Stevenson* (2 vols., Longmans & Co.: London, 1887).

Thomas Constable, *Memoir of Lewis D.B. Gordon, F.R.S.E.* (T. and A. Constable: Edinburgh, 1877).

G. Cook, "Rankine and the theory of earth pressure", *Géotechnique* , 2(1950-1), 271-9.

James Coutts, *A history of the University of Glasgow, from its foundation in 1451 to 1909* (Robert Maclehose: Glasgow, 1909).

Nancy Crathorne, *Tennant's Stalk: The Story of the Tennants of the Glen* (Macmillan: London, 1973).

Stephen H. Cutcliffe and Robert C. Post (eds.), *In Context: History and the History of Technology. Essays in Honor of Melvin Kranzberg* (Lehigh University Press: Bethlehem, 1989).

Edward E. Daub, "Atomism and Thermodynamics", *Isis* , 58(1967), 293-303.

Edward E. Daub, "Waterston, Rankine, and Clausius on the kinetic theory of gases", *Isis* , 61(1970), 105-6.

Edward E. Daub, "The regenerator principle in the Stirling and Ericsson hot air engines", *British Journal for the History of Science* , 7(1974), 259-77.

Edward E. Daub, "Sources for Clausius' entropy concept: Reech and Rankine", in E.G. Forbes (ed.), *Proceedings of the XVth International Congress of the History of Science Edinburgh 10-19 August 1977* , (published 1978), 342-58.

G.E. Davie, *The democratic intellect* (2nd edition, Edinburgh University Press: Edinburgh, 1964).

H.T. De la Beche, *Report on the geology of Cornwall, Devon and West Somerset* (Longman, Orme, Brown, Green: London, 1839).

[Devonshire], *Minutes of the Royal Commission on Scientific Instruction and the Advancement of Science (Devonshire Commission)* .

Dictionary of National Biography .

Harold I. Dorn, *The art of building and the science of mechanics: a study of the union of theory and practice in the early history of structural analysis in England* (unpublished dissertation, Princeton University, 1970). Diss. Abstr. Int., 1971, 31:4081-A; University Microfilms order no. 71-1592.

Pierre Duhem, in P.P. Wiener (ed.) *The aim and structure of physical theory* (Princeton University Press: New York, 1954).

[Edinburgh University], *The Edinburgh University Almanack MDCCCXXXIII* (Maclachlan & Stewart: Edinburgh, 1833).

[Edinburgh University], *The Edinburgh academic annual for MDCCCXL, consisting of contributions in literature and science by alumni of* *the University of Edinburgh* (Adam and Charles Black: Edinburgh, 1840).

Paul Edwards (ed.), *The Encyclopedia of Philosophy* (7 vols., Collier Macmillan: London, 1967).

R.L. Ellis, "Memoir of the late D.F. Gregory", *Cambridge Mathematical Journal* , 4(1845), 145-52.

George S. Emmerson, *Engineering education: a social history* (David & Charles: Newton Abbot, 1973).

George S. Emmerson, *John Scott Russell: a great Victorian engineer and naval architect* (John Murray: London, 1977).

[Engineer], "W.J.M. Rankine", *The Engineer* , 35(1873), 3 January 1873, 1-2.

[Engineering], "W.J. Macquorn Rankine", *Engineering* , 15(1873), 13-15.

William Fairbairn, "On the progress of Mechanical Science", *BAAS Report* , 23(1853), part 2, pp.116-7.

William Fairbairn, *Useful information for engineers* (2nd edition, Longman, Brown, Green, Longmans, & Roberts: London, 1856).

James David Forbes, "On the refraction and polarization of heat", *Transactions of the Royal Society of Edinburgh* , 13(1835), 131-68.

James David Forbes, "Note respecting the undulatory theory of heat, and on the cicular polarization of heat by total reflection", *Philosophical Magazine* , third series, 7(1836), 246-9.

Robert Fox, *The caloric theory of gases from Lavoisier to Regnault* (Clarendon Press: Oxford, 1971).

Elijah Galloway, *History and Progress of the Steam Engine* (T. Kelly Instruments Publishing Company: London, 1835).

Chester H. Gibbons, *Materials testing machines* (Pittsburgh, 1935).

C.H. Gibbs-Smith, *Sir George Cayley's Aeronautics, 1796-1855* (Science Museum: London, 1962).

C.C. Gillispie (ed.), *Dictionary of Scientific Biograpahy* (16 vols., Scribners: New York, 1970-80).

[Glasgow], *Memoirs and portraits of one hundred Glasgow men who have died during the last thirty years* (2 vols., J. Maclehose and Sons: Glasgow, 1886).

[Glasgow University], *The Glasgow University Calendar, for the session MDCCCXLIV-XLV* (G. Richardson: Glasgow, 1844).

[Glasgow University], *The Glasgow Univesity Calendar, for the session 1863-64* (G. Richardson: Glasgow, 1863).

[Glasgow University], *List of deeds and documents and excerpts from deeds and documents of foundation of bursaries, scholarships, fellowships, &c., in the University of Glasgow* (Edinburgh, 1891).

Graeme Gooday, "Precision measurement and the genesis of physics teaching laboratories in Victorian Britain", *British Journal for the History of Science* , 23(1990)., 25-51.

Graeme Gooday, "Teaching Telegraphy and Electrotechnics in the Physics Laboratory: William Ayrton and the Creation of an Academic Space for Electrical Engineering in Britain 1873-1884", *History of Technology* , 13(1991), 73-111.

Lewis D.B. Gordon, "On the Turbine Water-Wheel", *BAAS Report* , 10(1840), part 2, 191-2.

Lewis D.B. Gordon, *Civil Engineering and Mechanics. Engineering Aphorisms and Memoranda: a synopsis of lectures to be delivered session 1847-8* (Griffin and Co.: Glasgow, 1847).

Lewis D.B. Gordon, *A synopsis of lectures on civil engineering and mechanics* (R. Griffin & Co.: Glasgow, 1849).

Lewis D. B. Gordon, "Obituary Notice of Professor Rankine", *Proceedings of the Royal Society of Edinburgh* , 8(1872-5), 296-306.

M. Gowing, "Science, technology and education: England in 1870", *Oxford Review of Education* , 4(1978), 3-17.

I. Grattan-Guinness, "Work for the workers: advances in engineering mechanics and instruction in France, 1800-1830", *Annals of Science* , 41(1984), 1-33.

A.R.B. Haldane, "The Society of Writers to Her Majesty's Signet", *Journal of the law Society of Scotland*, 15(1970), 35-8.

P.M. Harman, *Energy, Force, and Matter. The Conceptual Development of Nineteenth-Century Physics* (Cambridge University Press: Cambridge, 1982).

P.M. Harman (ed.), *Wranglers and physicists. Studies on Cambridge mathematical physics in the nineteenth century* (Manchester University Press: Manchester, 1985).

J.F.C. Harrison, *The early Victorians 1832-51* (Panther/Granada: St Albans, 1973).

G.W. Hemans, *Description of the rails, sleepers and fastenings on the Dublin & Drogheda Railway* (London, 1846).

G.W. Hemans, *On the railway system in Ireland, the government aid afforded, and the nature and results of county guarantees* (W. Clowes and Sons: London, 1859).

G.W. Hemans, *On the future water supply of London* (London, 1866).

C.A. Hempstead, "An Appraisal of Fleeming Jenkin (1833-1885), Electrical Engineer", *History of Technology* , 13(1991), 119-44.

Sir James B. Henderson, *Macquorn Rankine: An Oration. Delivered in the University at the Commemoration of Benefactors on 15th June, 1932* , (Jackson, Wylie and Co.: Glasgow, 1932).

John Herschel, *Preliminary Discourse on the Study of Natural Philosophy* (first published London, 1830; new edition Longman, Brown, Green & Longmans: London, 1851).

T.J.N. Hilken, *Engineering at Cambridge University 1783-1965* (Cambridge University Press: Cambridge, 1967).

R.L. Hills, *Power from steam: a history of the stationary steam engine* (Cambridge University Press: Cambridge, 1989).

R.L. Hills and A.J. Pacey, "The Measurement of Power in Early Steam-driven Textile Mills", *Technology and Culture* , 13(1972), 39-43.

William Hopkins, "[Presidential Address", *BAAS Report* , 23(1853), part 1, pp.xli-lvii.

D.B. Horn, *A Short History of the University of Edinburgh 1556-1889* (Edinburgh University Press: Edinburgh, 1967).

Keith R. Hutchison, "Der ursprung der entropiefunktion bei Rankine und Clausius", *Annals of Science* , 30(1973), 341-64.

Keith R. Hutchison, "W.J.M. Rankine and the entropy function", *Proceedings of the XIVth International Congress of the History of Science 1974* , Tokyo-Kyoto, (published Tokyo, 1975), 2, 281-4.

Keith R. Hutchison, *W.J.M. Rankine and the rise of thermodynamics* (unpublished PhD thesis, Oxford University, 1976).

Keith R. Hutchison, "Mayer's Hypothesis: A Study of the Early Years of Thermodynamics", *Centaurus* , 20(1976), 279-304.

Keith R. Hutchison, "W.J.M. Rankine and the rise of thermodynamics", *British Journal for the History of Science,* 14(1981), 1-26.

Keith R. Hutchison, "Rankine, atomic vortices, and the entropy function", *Archives International d'Histoire des Sciences* , 31(1981), 72-134.

[Institution of Civil Engineers], *The education and status of civil engineers, in the United Kingdom and in foreign countries* (Institution of Civil Engineers: London, 1870).

[Institution of Civil Engineers], *A brief history of the Institution of Civil Engineers, with an account of the Charter Centenary Celebration June 1928* (Institution of Civil Engineers: London, 1928).

[Institution of Naval Architects], "Memoir of the Late W.J.M. Rankine, F.R.S., LL.D., &c.", *Transactions of the Institution of Naval Architects* , 14(1873), 235-9.
[Reprinted from the *Proceedings of the Royal Society* .]

Joseph Irving, *The Book of Scotsmen* (Alexander Gardner: Paisley, 1881).

Fleeming Jenkin, *A lecture on the education of civil and mechanical engineers in Great Britain and abroad* (Edmonston & Douglas: Edinburgh, 1868).

Fleeming Jenkin, in Sidney Colvin and J.A. Ewing (eds.), *Papers Literary, Scientific, etc. by the late Fleeming Jenkin, F.R.S., LL.D. with a Memoir by R.L. Stevenson* (2 vols., Longmans & Co.: London, 1887).

L.J. Jordanova (ed.), *Languages of nature* (New Brunswick, 1986).

J.P. Joule, *The Scientific Papers of James Prescott Joule* (2 vols., Taylor and Francis: London, 1884-7).

Philip Kelland, "On the Conduction of Heat", *BAAS Report*, 10(1840), part 2, 15-16.

Philip Kelland, "On the Present State of our Theoretical and Experimental Knowledge of the Laws of Conduction of Heat", *BAAS Report*, 11(1841), part 1, 1-25.

A. Kent, "The Royal Philosophical Society of Glasgow", *The Philosophical Journal*, 4(1967), 43-50.

Martin J. Klein, "Gibbs on Clausius", *Historical Studies in the Physical Sciences*, 1(1969), 127-49.

David M. Knight, *Atoms and Elements. A Study of Theories of Matter in England in the Nineteenth Century* (Hutchison: London, 1967).

C.G. Knott, *Life and scientific work of Peter Guthrie Tait* (3 vols., Cambridge University Press: Cambridge, 1911).

Thomas S. Kuhn, "Energy Conservation as an Example of Simultaneous Disovery", in Marshall Clagett (ed.), *Critical Problems in the History of Science* (University of Wisconsin Press: Madison, 1962), pp.321-56.

John Lee, *The University of Edinburgh From its Foundation in 1583 to the Year 1839: A Historical Sketch* (David Douglas: Edinburgh, 1884).

George Lees, *Elements of Arithmetic, Algebra, and Geometry, for Use of the Students in the Edinburgh School of Arts* (Adam Black & William Tait: Edinburgh, 1826).

W.R. Le Fanu, *Seventy Years of Irish Life, being Anecdotes and Reminiscences* (Edward Arnold: London, 1893).

[London Midland and Scottish Railway], *Centenary of the Caledonian Railway 1847-1947* (London Midland and Scottish Railway: Glasgow, 1947).

David Allan Low (ed.), *The Whitworth Book* (Longmans & Co.: London, 1926).

William Leslie Low, *David Thomson, M.A. Professor of Natural Philosophy in the University of Aberdeen. A Sketch of his Character and Career* (D. Wylie & Son: Aberdeen, 1894).

Peter Lundgreen, "Engineering Education in Europe and the U.S.A., 1750-1930. The Rise to Dominance of School Culture and the Engineering Professions", *Annals of Science*, 47(1990), 33-75.

J.D. Mackie, *The University of Glasgow 1451-1951. A short history* (Jackson, Son & Company: Glasgow, 1954).

R.M. Macleod & J.R. Friday, *Archives of British men of science* (Mansell, 1972, microfiche).

John Marshall, *A biographical dictionary of railway engineers* (David & Charles: Newton Abbot, 1978).

James D. Marwick, *Glasgow. The water supply of the city from the earliest period of record; with notes on various developments of the city till the close of 1900* (Robert Anderson: Glasgow, 1901).

W.M. Mathew, "the origins and occupations of Glasgow students, 1740-1839", *Past and Present*, no. 33(1966), 74-94.

J.C. Maxwell, "Tait's Thermodynamics", *Nature*, 17(1878), 257-9 & 278-80.

John Mayer, "The Late Professor W.J. Macquorn Rankine", *Nature*, 7(1872-3), 204-5.

John Mayer, "James R. Napier, F.R.S.", *Nature*, 21(1880), 206.

[Mechanics Magazine], "Stirling's Air-Engine", *Mechanics Magazine*, 45(1846), 559-66.

E. Mendoza (ed.), *Reflections on the Motive Power of Fire by Sadi Carnot and other Papers on the Second Law of Thermodynamics by E. Clapeyron and R. Clausius* (Dover Publications: New York, 1960).

W.J. Millar (ed.), *Miscellaneous Scientific Papers by W.J. Macquorn Rankine* (Charles Griffin & Co.: London, 1881).

J.B. Morrell, "Thomas Thomson: Professor of Chemistry and university reformer", *British Journal for the History of Science*, 4(1969), 245-65.

J.B. Morrell, "Practical chemistry in the University of Edinburgh, 1799-1843", *Ambix*, 16(1969), 66-80.

J.B. Morrell, "Science and Scottish university reform: Edinburgh in 1826", *British Journal for the History of Science*, 6(1972), 39-56.

J.B. Morrell, "Reflections on the history of Scottish science", *History of Science*, 12(1974), 81-94.

Jack Morrell and Arnold Thackray, *Gentlemen of science. Early years of the British Association for the Advancement of Science* (Oxford University Press: Oxford, 1981).

Jack Morrell and Arnold Thackray (eds.), *Gentlemen of science. Early correspondence of the British Association for the Advancement of Science*, Camden fourth series: volume 30 (Royal Historical Society: London, 1984).

Peter J.T. Morris, Colin A. Russell, and John Graham Smith, *Archives of the British Chemical Industry 1750-1914: A Handlist* (British Society for the History of Science: Stanford in the Vale, 1988).

D.F. Moyer, "Energy, thermodynamics, hidden machinery: Rankine, Thomson and Tait, Maxwell", *Studies in the History and Philosophy of Science*, 8(1977), 251-68.

David Murray, *Memories of the old College of Glasgow: some chapters in the history of the University* (Jackson, Wylie and Co.: Glasgow, 1927).

James Napier, *Life of Robert Napier of West Shandon* (William Blackwood & Sons: Edinburgh, 1904).

James Robert Napier, *List of Prof. Macquorn Rankine's Papers* (Glasgow, 1878).

"Rankine, William John Macquorn", *Dictionary of National Biography*.

J.B. Neilson (ed.), *Fortuna domus. A series of lectures delivered in the University of Glasgow in commemoration of the fifth centenary of its foundation* (Glasgow University Press: Glasgow, 1952).

John Henry Newman, *The Idea of a University* (Longmans: London, 1896).

J.P. Nichol, *Views of the Architecture of the Heavens* (William Tait: Edinburgh, 1837).

C.A. Oakley, *A history of a faculty: engineering at Glasgow University* (University of Glasgow: Glasgow, 1973).

Richard Olson, "Scottish philosophy and mathematics 1750-1830", *Journal of the History of Ideas* , 32(1971), 29-44.

Richard Olson, *Scottish philosophy and British physics 1750-1880* (Princeton University Press: Princeton and London, 1975).

George Ottley, *A bibliography of British railway history* (2nd edition, HMSO: London, 1983).

E.M. Parkinson, "Rankine", in C.C. Gillispie (ed.), *Dictionary of Scientific Biography* (16 vols., Scribners: New York, 1970-80), 11, 291-5.

S.D. Poisson, *Théorie Mathématique de la Chaleur* (Paris, 1835).

William Pole (ed,), *The Life of Sir William Fairbairn, Bart* (London, 1877).

William Pole, *Life of Sir William Siemens* (John Murray: London, 1888).

[Popular Science Monthly], "Sketch of Professor Rankine", *Popular Science Monthly* , 12(1877-8), 236-7.
[See p.129 for a portrait.]

J.L. Pritchard, *Sir George Cayley: The Inventor of Aeronautics* (Max Parrish: London, 1962).

V.V. Raman, "William John Macquorn Rankine: 1820-1872", *Journal of Chemical Education* , 50(1973), 274-6.

David Rankine, *A popular exposition of the effect of forces applied to draught* (John Smith and Son: Glasgow, 1828).

Pietro Redondi, "Sadi Carnot et la recherche technologique en France de 1825 à 1850", *Revue d'histoire des sciences* , 29(1976), 243-59.

Joan L. Richards, *Mathematical visions: the pursuit of geometry in Victorian England* (Academic Press: London, 1988).

C.J.A. Robertson, *The Origins of the Scottish Railway System 1722-1844* (John Donald: Edinburgh, 1983).

L.T.C. Rolt, *Thomas Telford* (Longman: London, 1958).

L.T.C. Rolt, *Victorian engineering* (Penguin: Hammondsworth, 1974).

[Royal Society of London], "Obituary of W.J.M. Rankine", *Proceedings of the Royal Society of London* , 21(1873), i-iv.

Martin J.S. Rudwick, "The emergence of a visual language for geological science 1760-1840", *History of Science* , 14(1976), 149-95.

Martin J.S. Rudwick, *The Great Devonian Controversy. The Shaping of*

Scientific Knowledge among Gentlemanly Specialists (University of Chicago Press: Chicago and London, 1985).

C.A. Russell and D.C. Goodman (eds.), *Science and the rise of technology since 1800* (John Wright and Sons Limited in Association with the Open University Press: Bristol, 1972).

John Scott Russell, "Economical and Effective Proportion of Engine Power to the Tonnage of the Hull in Steam Vessels", *BAAS Report* , 10(1840), part 2, 188.

[Samuelson], *Minutes of the Select Committee on Scientific Instruction (Samuelson Commission)* .

Michael Sanderson, *The universities and British industry 1850-1970* (Routledge: London, 1972).

Simon Schaffer, "The nebular hypothesis and the science of progress", in James R. Moore (ed.), *History, Humanity and Evolution. Essays for John C. Greene* (Cambridge University Press: Cambridge, 1989), pp.131-64.

James A. Secord, "The Geological Survey as a research school, 1839-1855", *History of Science* , 24(1986), 223-75.

J.C. Shairp, P.G. Tait, and A. Adams-Reilly, *Life and letters of James David Forbes* (Macmillan and Co.: London, 1873).

Robert H. Silliman, "William Thomson: smoke rings and nineteenth century atomism", *Isis* , 54(1963), 461-74.

James Small, "The Institution's first President: William John Macquorn Rankine", *Transactions of the Institution of Engineers and Shipbuilders in Scotland*, 100(1956-7), 687-97.

James Small, "Engineering", in J.B. Neilson (ed.), *Fortuna domus* (Glasgow University Press: Glasgow, 1952), pp.335-55.

Crosbie Smith, " 'Mechanical Philosophy' and the Emergence of Physics in Britain: 1800-1850", *Annals of Science* , 33(1976), 3-29.

Crosbie Smith, "Natural philosophy and thermodynamics: William Thomson and the dynamical theory of heat", *British Journal for the History of Science* , 9(1976), 293-319.

Crosbie Smith, "William Thomson and the creation of thermodynamics", *Archive for the History of the Exact Sciences* , 16(1977), 231-88.

Crosbie Smith, "William Hopkins and the shaping of Dynamical Geology: 1830-1860", *British Journal for the History of Science* , 22(1989), 27-52.

Crosbie Smith, *The Science of Energy* (forthcoming, 1993).

Crosbie Smith and M. Norton Wise, *Energy and Empire. A biographical study of Lord Kelvin* (Cambridge University Press: Cambridge, 1989).

Denis Smith, "Sir Joseph William Bazalgette (1819-1891): Engineer to the Metropolitan Board of Works", *Transactions of the Newcomen Society* , 58(1986-7), 89-111.

Mary Somerville, *The Connexion of the Physical Sciences* (London, 1834).

Sir Richard V. Southwell, "W.J.M. Rankine: a commemorative lecture delivered on 12 December, 1955, in Glasgow", *Proceedings of the Institution of Civil Engineers* , 5(1956), 177-93.

James Stirling, "Description of Stirling's improved air engine", *Minutes and Proceedings of the Institution of Civil Engineers* , 4(1845), 348-61.

Hugh B. Sutherland, *Rankine: his life and times* (Institution of Civil Engineers: London, 1973).

[P.G. Tait], "The Late Professor Macquorn Rankine", *Glasgow Herald* , 26 December 1872, 4 and 28 December 1872, 4.

P.G. Tait, "Memoir [of Rankine]", in W.J. Millar (ed.), *Miscellaneous Scientific Papers by W.J. Macquorn Rankine* (Charles Griffin & Co.: London, 1881), pp.xix-xxxvi.

S.P. Thompson, *The Life of William Thomson, Baron Kelvin of Largs* (2 vols., Macmillan: London, 1910).

James Thomson, in Sir Joseph Larmor and James Thomson (eds.), *Collected papers in physics and engineering* (Cambridge University Press: Cambridge, 1912).

John Thomson, *The Advantage of tubular drainage, as compared with Brick Sewers, in their application to Houses and Cities* (Glasgow, 1852).

William Thomson, "Notes to a Paper on the Motive Power of Heat", *Proceedings of the Royal Society of Edinburgh* , 2(1844-50), pp.241-4.

William Thomson, *Mathematical and physical papers* (6 vols., Cambridge University Press: Cambridge, 1882-1911).

J.O. Thorne and T.C. Collocott (eds.), *Chambers Biographical Dictionary* (Chambers: Edinburgh, 1974).

Stephen P. Timoshenko, *History of strength of materials* (McGraw-Hill: New York, 1953).

Isaac Todhunter, in Karl Pearson (ed.), *A history of the theory of elasticity and of the strength of materials from Galilei to Lord Kelvin* (2 vols., Cambridge, 1886-93; reprint edition, New York, 1960).

Charles Blacker Vignoles, "On the Economy of Railways in respect of Gradients", *BAAS Report* , 10(1840), part 2, 193.

E.G. Walker, *The life and work of William Cawthorne Unwin* (George Allen & Unwin: London, 1947).

Garth Watson, *The Civils: The story of the Institution of Civil Engineers* (Thomas Telford: London, 1988).

Julius Weisbach, *Principles of the mechanics of machinery and engineering* (2 vols., London, 1848).

William Whewell, *Mechanics of engineering* (Cambridge, 1841).

William Whewell, *Astronomy and general physics considered with reference to natural theology* (7th edition, H.G. Bohn: London, 1852).

Martin J. Wiener, *English culture and the decline of the industrial spirit 1850-1980* (Harmondsworth: Penguin, 1985).

Robert Willis, *A system of apparatus for the use of lecturers and experimenters in mechanical philosophy, especially in those branches which are connected with mechanism* (London, 1851).

Robert Willis, *Principles of mechanism* (Parker: Cambridge and London, 1851).

David B. Wilson, "The educational matrix: physics education at early-Victorian Cambridge, Edinburgh and Glasgow Universities", in P.M. Harman (ed.), *Wranglers and physicists. Studies on Cambridge mathematical physics in the nineteenth century* (Manchester University Press: Manchester, 1985), pp.12-48.

David B. Wilson (ed.), *The correspondence between Sir George Gabriel Stokes and Sir William Thomson, Baron Kelvin of Largs* (2 vols., Cambridge University Press: Cambridge, 1990).

David B. Wilson, "P.G.Tait and Edinburgh Natural Philosophy, 1860-1901", *Annals of Science*, 48(1991), 267-87.

George Wilson, *What is technology? An inaugural lecture delivered in the University of Edinburgh on November 7, 1855* (Sutherland and Knox: Edinburgh, 1855).

George Wilson and Archibald Geikie, *Memoir of Edward Forbes* (Macmillan and Co.: Cambridge and London, 1861).

Justin Wintle (ed.), *Makers of Nineteenth Century Culture 1800-1914* (Routledge & Keegan Paul: London, 1982).

M. Norton Wise and Crosbie Smith, "Measurement, work and industry in Lord Kelvin's Britain", *Historical Studies in the Physical and Biological Sciences*, 17(1986), 147-73.

M. Norton Wise and Crosbie Smith, "Work and waste: political economy and natural philosophy in nineteenth century Britain (I)", *History of Science*, 27(1989), 206-301.

M. Norton Wise and Crosbie Smith, "Work and waste: political economy and natural philosophy in nineteenth century Britain (II)", *History of Science*, 27(1989), 391-449.

M. Norton Wise and Crosbie Smith, "Work and waste: political economy and natural philosophy in nineteenth century Britain (III)", *History of Science*, 28(1990), 221-61.

Francis Wishaw, *The railways of Great Britain and Ireland practically described and illustrated* (2nd edition, John Weale: London, 1842; reprinted edition, David & Charles: Newton Abbot, 1969).

Nicholas Wood, *A practical treatise on railroads and interior communication in general, with original experiments and tables of the comparative value of canals and railroads* (Knight & Lacey: London, 1825).