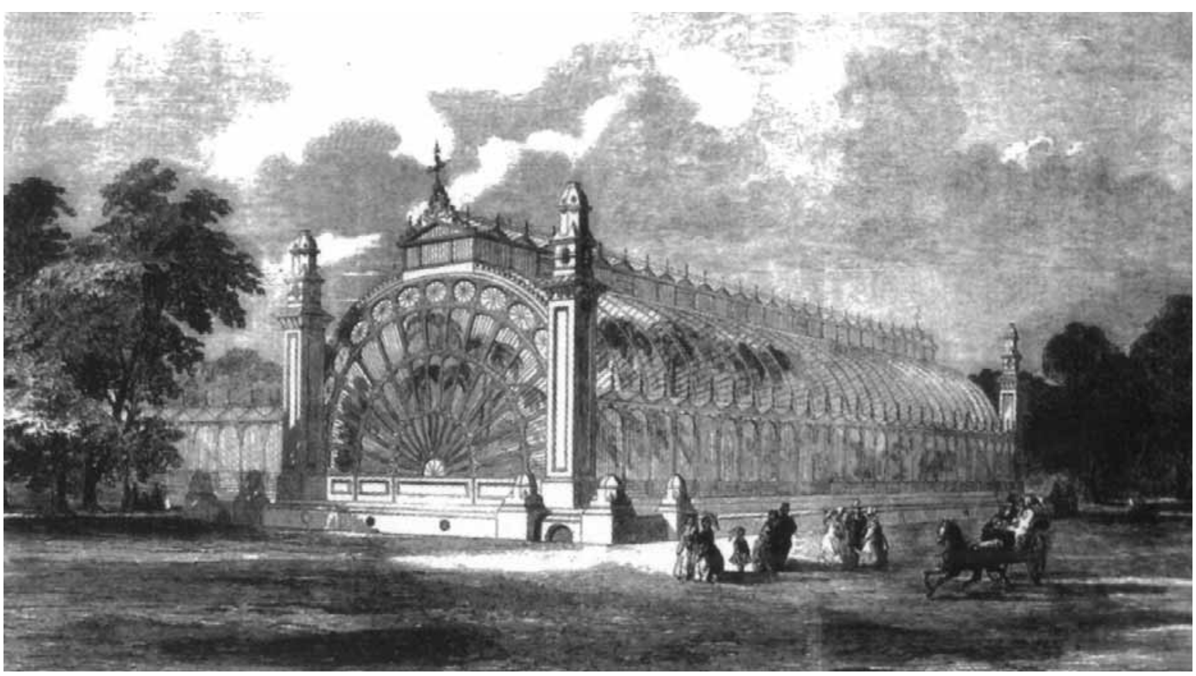
Paxton's early ambitions for a unified system of environmental control involving mechanical and passive technologies were partially realised in the Crystal Palace of 1851.

# The Crystal Palace, environmentally considered

*Henrik Schoenefeldt*

In the nineteenth century, horticulturists such as John Claudius Loudon and Joseph Paxton, aware of the new environmental possibilities of glasshouses that had been demonstrated in the context of horticulture, contemplated the use of fully-glazed structures as a means to creating new types of environments for human beings. While Loudon suggested the use of large glass structures to immerse entire Russian villages in an artificial climate,[1] Henry Cole and Paxton envisioned large-scale winter parks, to function as new types of public spaces. These indoor public spaces were intended to grant the urban population of London access to clean air, daylight and a comfortable climate.[2] Although glasshouses had only been experienced in the immediate context of horticulture, designed in accordance with the specific environmental requirements of foreign plants, rather than the requirements of human comfort and health,[3] they were perceived as a precedent for a new approach to architectural design primarily driven by environmental criteria. The environmental design principles of horticulture were discussed extensively in nineteenth-century horticultural literature such Loudon's *Remarks on the Construction of Hothouses* (1817), *Paxton's Magazine of Botany* (1834-49) and the *Transactions of the Horticultural Society of London* (1812-44). Since the purpose of glasshouses was to facilitate the cultivation of an increasing variety of foreign plants in the temperate climate of Northern Europe, the creation of artificial climates tailored to the specific environmental needs of plants became the primary object of the design. The glasshouses not only provided a context for the application of contemporary mechanical and structural technology, but also rendered visible the ecological dimension of the built environment, as for example, the effect of temperature, humidity, solar radiation and air movement on the health of plants. A wide range of horticulturists, surgeons, social and health



1 Paxton's proposal for an urban *Sanitarium*, 1851. *Illustrated London News*, 5 July 1851, p. 11

reformers contemplated applying the technical and environmental reasoning behind the horticultural glasshouse to the design of the built environment in general, with the intention of using glasshouses as a means of improving people's health in major industrial cities.[4] The horticulturist Joseph Paxton was a major proponent of this idea.

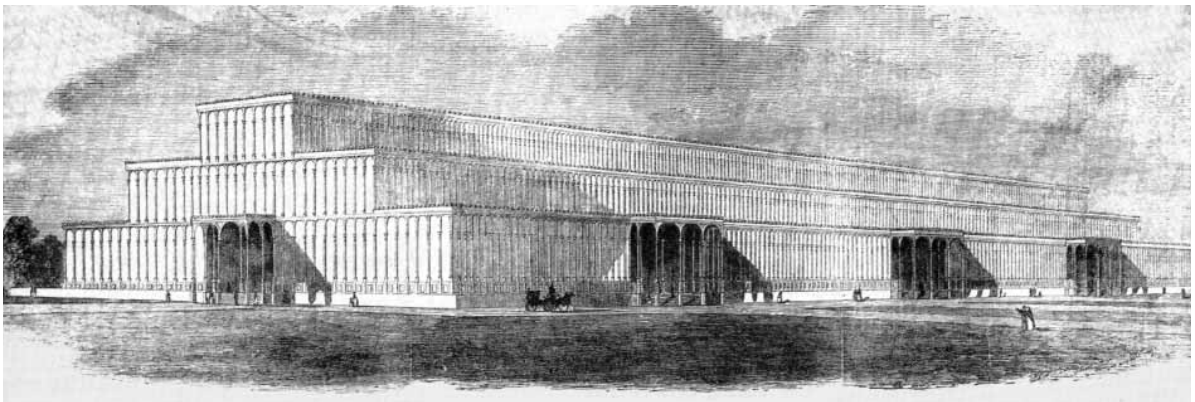
Paxton articulated the larger social and environmental aspirations behind his idea of public glasshouses in a number of hypothetical design proposals and written accounts in pamphlets and journal articles.[5] When he received the commission to design the Great Exhibition building, he was also able to put these ideas at least partially into practice. The Hyde Park Crystal Palace was a pioneering attempt to adapt the tradition of horticultural glasshouses to human rather than plant habitation. Its history illustrates the difficulties of making fully-glazed structures climatically suitable for human beings. But as shown in a large number of contemporary accounts detailing the extreme climatic conditions that periodically occurred inside the Crystal Palace during the Great Exhibition in 1851, the ideal climate promised by the conceptual glasshouses was not successfully delivered by the actual built form.

There are many publications which address the history of the Crystal Palace in terms of its construction and aesthetic, as for instance Hitchcock's *Early Victorian Architecture in Britain,* Giedion's *Space Time and Architecture,* McKean's *Crystal Palace* and Chadwick's *The Works of Sir Joseph Paxton*.[6] In contrast, the intention of this article is to discuss the environmental history of this building illustrating how the environmental design aspirations influenced its construction, form and spatial arrangement. It includes a discussion of Paxton's larger socio-environmental visions as a driving force behind the idea of glasshouses for human beings, a description of the environmental strategies and technologies employed, and a study of the building's environmental performance. It compares the climate that Paxton originally intended to achieve with the real climatic conditions which occurred inside the building during the Great Exhibition. The latter is based on temperature measurements taken during the period of the exhibition and written accounts of people's perception of the climate inside the Crystal Palace. These measurements have hitherto not been discussed in print by architectural historians but are crucial if we are to appreciate the significance of the Crystal Palace.

**Paxton's broader environmental aspirations**

The idea of utilising all-glass structures and mechanical environmental systems as a means to achieve healthy environments, not only for tender plants but also for the population of the nineteenth-century industrial city, was the locus of Paxton's broader socio-environmental aspirations. Paxton illustrated his ideas in a series of hypothetical design projects, pamphlets, newspaper articles and lectures. In *What is to be done with the Crystal Palace*?, Paxton proposed that all-glass structures equipped with mechanical equipment to regulate the internal climate could be adapted to create health enhancing environments for the population of large industrial cities.[7] These would comprise large spaces with an abundance of daylight, fresh air and a comfortable climate throughout the whole year. This pamphlet outlined Paxton's proposal for converting the Crystal Palace into a public winter garden and was part of a series of hypothetical projects in which he illustrated his larger socio-environmental aspirations towards the use of glasshouses for human functions.

Contemporary newspaper articles and pamphlets indicate very clearly that the Crystal Palace from the earliest stages in the design was conceived as a prototype of the kind of glass buildings that Paxton intended to promote as indoor public spaces. The first account of Paxton's proposal for the Crystal Palace in the *Illustrated London News* on 6 July 1850 included a brief account of Paxton's intention to convert the Crystal Palace into a public winter garden, which, by providing an expansive interior space, would allow people to take extensive indoor promenades and coach rides whatever the season.[8] In the summer, he proposed to remove the vertical glazing to open the building up to its surrounding landscape and to 'give the appearance of a continuous park and garden'.[9] In *What is to be done with the Crystal Palace* and in a letter to the *Times* titled, 'Shall the Crystal Palace Stand or Not?', Paxton gave a more detailed description of his project and the underlying environmental and social aspirations. Apart from providing a very large, well lit and sheltered space, the interior of the winter garden was to comprise an autonomous artificial climate, insulated from the variable weather and the polluted atmosphere of nineteenth-century London.[10] The climate was to resemble the summer climate of southern Italy during the winter, and during the summer period the 'winter temperature of that country [...] would be about 10 degree colder than the ordinary heat of our dwelling houses'.[11] In contrast to the Hyde Park building, with its translucent roof which diffused the sunlight and the opaque wooden infill panels on the ground floor, both of which restricted the visual connection with the outside, the envelope of the winter garden was intended to be totally transparent. It was to facilitate free admission of direct sunlight and to connect the interior visually with its surroundings, turning the building into a display case through which the interior picturesque park and garden could be observed from the outside.[12] Paxton's proposal represented an attempt to utilise glasshouses as a means of reinstating a healthy human habitat within the environment of the emerging industrial cities which, as numerous articles in the *Civil Engineer and Architect's Journal* and the *Builder* illustrated, were confronted with poor hygienic conditions, overcrowding, lack of daylight, air and water pollution.[13] The prospect of providing the general population of large cities, which suffered among other ailments from tuberculosis, various skin diseases and bronchitis, with daylight and fresh air and large spaces for exercise and recreation at any



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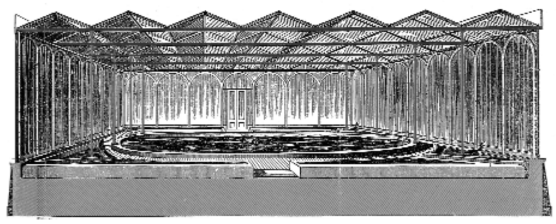
2 External perspective of Paxton's original proposal. *Illustrated London News*, 6 July 1850, p. 13

3 Sectional perspective of the Victoria Regia house interior, showing the light iron structure supporting the glass envelope. *Civil Engineer and Architect's Journal*, October 1850, p. 324

4 Exterior of the Victoria Regia house, Chatsworth, 1850. *Civil Engineer and Architect's Journal*, October 1850, p. 324



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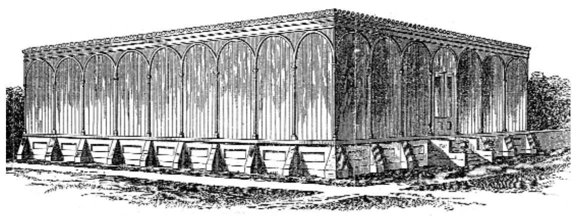

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time of the year, resonated with contemporary efforts to improve public health through environmental reforms and new public parks, as proposed among others by the Metropolitan Sanitary Association, Health of Towns Association,[14] and the surgeons Sir Francis Seymour Haden and Dr. Smith.[15]

Inside Paxton's proposed winter parks, plants were not only intended to provide the urban population with access to the experience of the natural world, but were also conceived as an integral part of the environmental system. Paxton conceived the interior as a type of self-contained biosphere, in which plants and animals, including human beings, mutually participate in the sustenance of an internal carbon dioxide and oxygen cycle. Animals functioned as the producers of carbon dioxide, which plants need for photosynthesis, while the plants in turn maintained the oxygen levels of the atmosphere.[16] The concept of an atmosphere sustained by plants reflected Justus Liebig's research into the influence of plants and animals on the chemistry of the earth's atmosphere, which was discussed in a serial entitled *'On Gardening as a Science'* in *Paxton's Magazine of Botany* in 1842.[17]

Paxton's idea of the glasshouse as a provider of artificial human habitats climaxed conceptually in a project titled *Sanitariums for exercise of invalids and others in all weather [1]*.[18] This project was based on Paxton's proposal for an exercise room for the London Chest Hospital near Victoria Park.[19] In this article, Paxton proposed the erection of a glasshouse with a totally mechanically-controlled indoor environment to function as an urban *Sanitarium*,[20] providing in all seasons a large, generously daylit indoor space for physical exercise with a climate designed to permit easy respiration for people suffering from lung diseases. This artificial environment, representing a reproduction of the health regenerating climates of distant seaside or mountain resorts, was to be composed of a purified air with adequate levels of humidity and oxygen, controlled by a type of air-conditioning system. The external air was to be drawn in via a subterranean duct, then was warmed and filtered before it entered the building's interior, where parts of the air were recirculated through the filtration apparatus for a second time and finally exhausted to the outside via flues in the corners of the building.[21] Again plants were to be introduced as oxygen producers. The Crystal Palace itself represented Paxton's first attempt to adapt a fully-glazed structure for exclusively human functions and both the Hyde Park Crystal Palace and its successor in Sydenham, represented prototypes of Paxton's visionary glasshouse projects.

**The Crystal Palace**

In July 1850 Paxton submitted his proposal for the Great Exhibition building which was first published in the *Illustrated London News* on 6 July 1850 *[2]*.[22] Paxton's intention was to create a temporary structure largely constructed from standardised and prefabricated components of glass, wood and iron, which would allow the building to be assembled, dismantled and re-erected within a short period of time. He contemplated the possibility of reusing the structure as a mobile exhibition shelter or converting it into a winter garden for public use after the Great Exhibition. The structure was to cover 21 acres of ground floor exhibition space, totally open in plan, with no internal partitions, and 25 per cent of additional exhibition space for lighter articles was to be provided through first floor galleries.

The design of the Great Exhibition building, according to Paxton's own account, represented an adaptation of the principles of a structural system that he had employed previously in the design of a glasshouse for the *Victoria Regia* water lily in Chatsworth in 1850 *[4]*.[23] The Victoria Regia house demonstrated the possibility of not only covering but also daylighting a floor plan of potentially any depth, in this case a floor area measuring approximately 60 feet by 49 feet *[3]*. The synthesis between engineering concerns, the spanning of large spaces economically, and environmental design issues, provision of maximum daylight, that the Regia house had demonstrated, became a distinctive feature in Paxton's approach to the design for the Great Exhibition, where the problem of both the lighting and spanning of large spaces had to be resolved on a gigantic scale.[24]

**Paxton's environmental design strategy and objective**

*'The current of air may be modified by the use of coarse open canvas, which by being kept wet in hot weather, would render the interior of the building much cooler than the external atmosphere.'*[25]

An account of Paxton's original design in the *Illustrated London News*[26] included a detailed account of how he intended to light, ventilate and cool the interior of the building, indicating that environmental concerns had been an integral part of his design from the beginning. The intention of the following section is to illustrate the environmental design strategies that Paxton employed in order to adapt a fully-glazed structure to fulfil the environmental requirements of an exhibition building. These requirements, as outlined in an article in the *Illustrated London News* on 6 July 1850, were the creation of a uniformly lit exhibition space which was well ventilated and sufficiently cool during the hot summer period. In contrast to Paxton's visionary winter parks, the means of environmental control that were employed inside the Crystal Palace were exclusively passive.

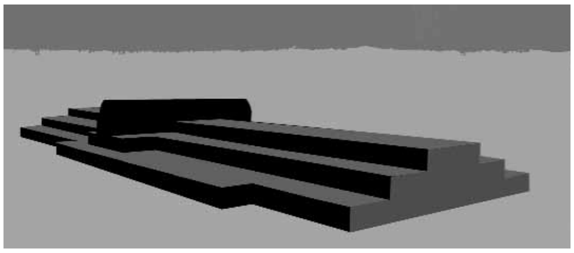
**Lighting and solar control**

*'The light, indeed, will be almost as bright as in the open air, still gentle tempered and diffused by the canvas covering over the outside of the roofs and all the south side of the building.'*[27]

The construction system, the building form and the internal spatial arrangement of the Crystal Palace in Hyde Park were partly determined by the aspiration of achieving maximum transparency. Internally, the Palace was intended to be open and transparent to meet the requirement for free circulation, flexibility, surveillance and unobstructed views over the exhibition.[28] In terms of the lighting strategy, the transparency of the overall structure and the glass envelope was to facilitate the transmission of equal quantities of daylight into any part of the building.

One of the major environmental objectives which drove the design of the Crystal Palace was the creation of a uniformly lit interior space, using daylight as the only source of light.[29] The aspiration towards providing uniform levels of light in the entire building corresponded with Paxton's notion of a uniform, non-hierarchical order, intended to provide all exhibitors with equal spatial and environmental conditions for fair competition, which Paxton believed to be the essence of the Great Exhibition.[30] Paxton's original proposal was a totally symmetrical, uniform structure composed of a sequence of identical bay frames.[31] In the final scheme this uniformity was broken by the insertion of a circular glass vault over the transept, which functioned as structural bracing and allowed two mature elm trees to be preserved inside the building.[32]

Through the use of a framing system made of wood and iron components, with its large spans and slim members, the physical structure of the building was reduced to a filigreed three-dimensional frame. The result was a large open and transparent space, with minimum obstructions to daylight and views. The central aisle and the transept formed wide open-plan spaces, unobstructed by intermediary supports. The central aisle, running from east to west, was one large open space with a width of 72 feet, a length of 1848 feet and a height of 72 feet, which was covered with a free spanning roof of iron and glass. The transept, measuring 408 feet in length and 73 feet in width, was covered by a glazed circular vault. To maintain the transparency of the iron structure, the roof and vertical elevations were almost completely glazed, using two glazing systems. The glazing of the vertical elevations comprised identical prefabricated window units, measuring 7.5 by 14 feet, which were



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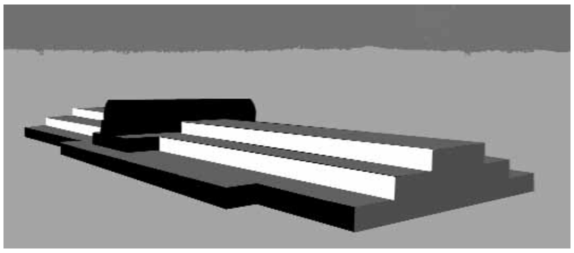

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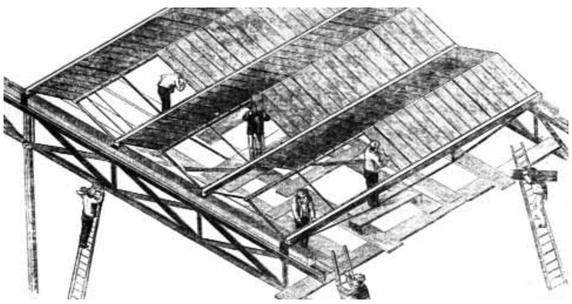

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installed as infill panels between the external iron columns and intermediate timber stiles and were held in place by six brackets, permitting easy installation, replacement and removal. To provide wall space for exhibition purposes, the largest portion of the elevation on the ground floor was filled with wooden infill panels instead.[33]

The horizontal part of the roof was covered with ridge and furrow glazing, which, as in the Victoria Regia house, discussed earlier, made it possible to cover and adequately daylight an extremely deep plan space on the ground floor, measuring 408 feet by 1848 feet *[7]*. While Paxton had since 1834 used the ridge and furrow principle to glaze a number of glasshouses, he developed the system further to improve it in terms of transparency, first in the design for the Great Stove in Chatsworth and again at the Crystal Palace. At Chatsworth, Paxton deployed the ridge and furrow principle to create a fully-glazed curvilinear envelope, increasing the transparency of the structure by enlarging the spacing of the ridge and valley rafters, which had become possible through the manufacture of longer sheets of glass, measuring 3 feet by 10 inches.[34] In the Crystal Palace the spaces were further increased by the use of sheets measuring 4 feet in length.

In order to subdue and temper the intense sunlight and glare created by this extreme transparency, translucent screens of calico were hung externally in-between the ridge beams of the roof glazing and covered the entire surface of the highly exposed horizontal section of the roof *[6, 9]*. As a result the interior was illuminated by a relatively uniform, diffused light. By employing the shading on the external, rather than the internal surface of the glass, Paxton intended to shield the glass more effectively from direct solar radiation. The solar gains accumulating externally between the glass and the screens were to be removed by the wind.[35] Aware of the magnitude of the problem of overheating in the summer, Paxton originally proposed additional shading in front of the vertical surfaces of the entire south elevation *[5]*.[36]

The minimisation of opaque surfaces also governed the internal layout of the building as these would have obstructed the flow of daylight, and cast shadows, creating dark and light spaces. While the central aisle, the transept, the first floor galleries and the low single-storey spaces on the northern and southern perimeter of the building had direct access to top light from the roof, the deck of the first floor gallery was punctured by a sequence of courts, to bring top light down to the ground floor spaces below *[8]*. As a consequence, the galleries were reduced to a network of shallow bridges, with a depth of 24 feet. Since the daylight regime put a limit

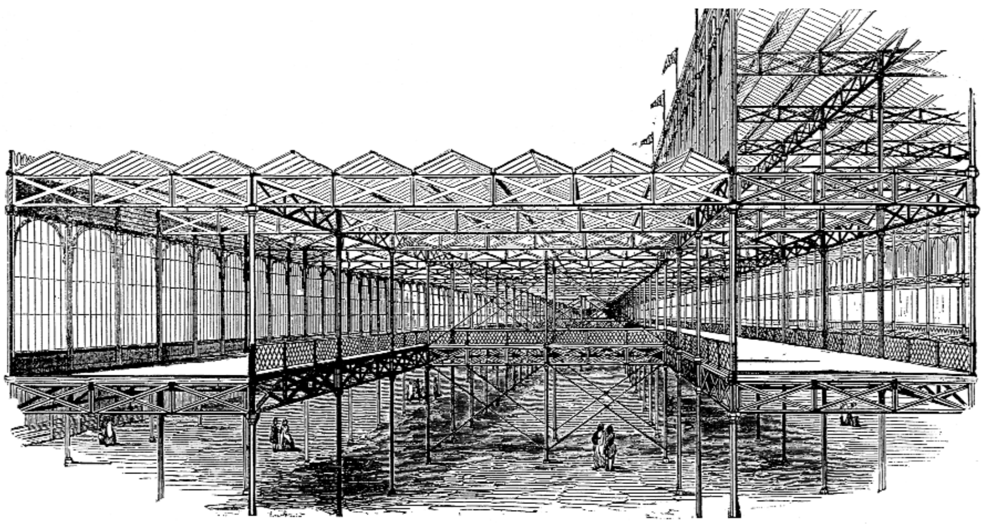
5 Aerial view of Crystal Palace showing canvas shading covering south elevation and ridge and furrow glazing

6 Aerial view of Crystal Palace showing canvas shading used in the executed design

7 Ridge and furrow roof under construction. *Illustrated London News*, 16 November 1850, p. 396

8 View into one of the courts cut into the first floor gallery. *Illustrated London News*, 1 February 1851, p. 72

9 Diagrammatic cross section: environmental design strategy. Key: a: vertical glazing, a.I: timber infill panels, b: high level ventilators, c: external canvas shades, d: low level ventilators, 1: internal courts, 2: first floor galleries, 3: central nave



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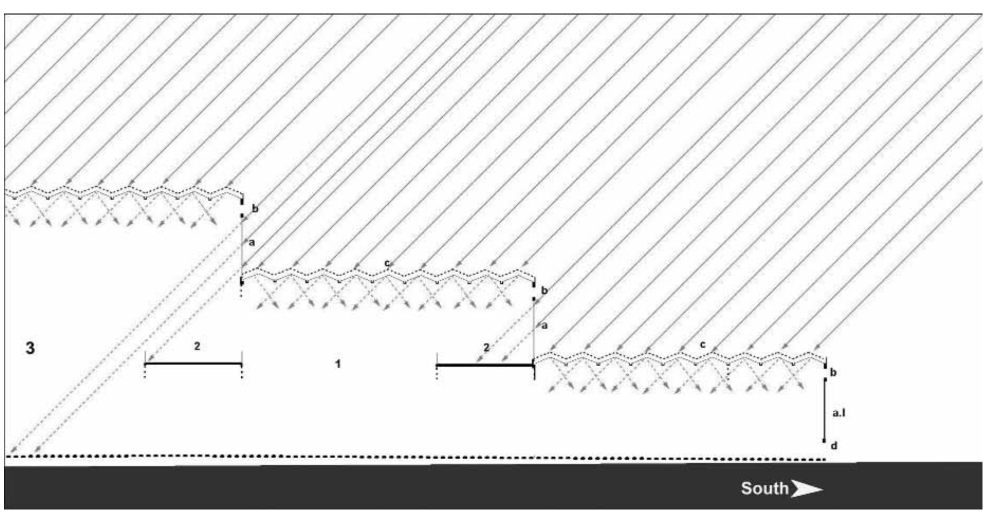


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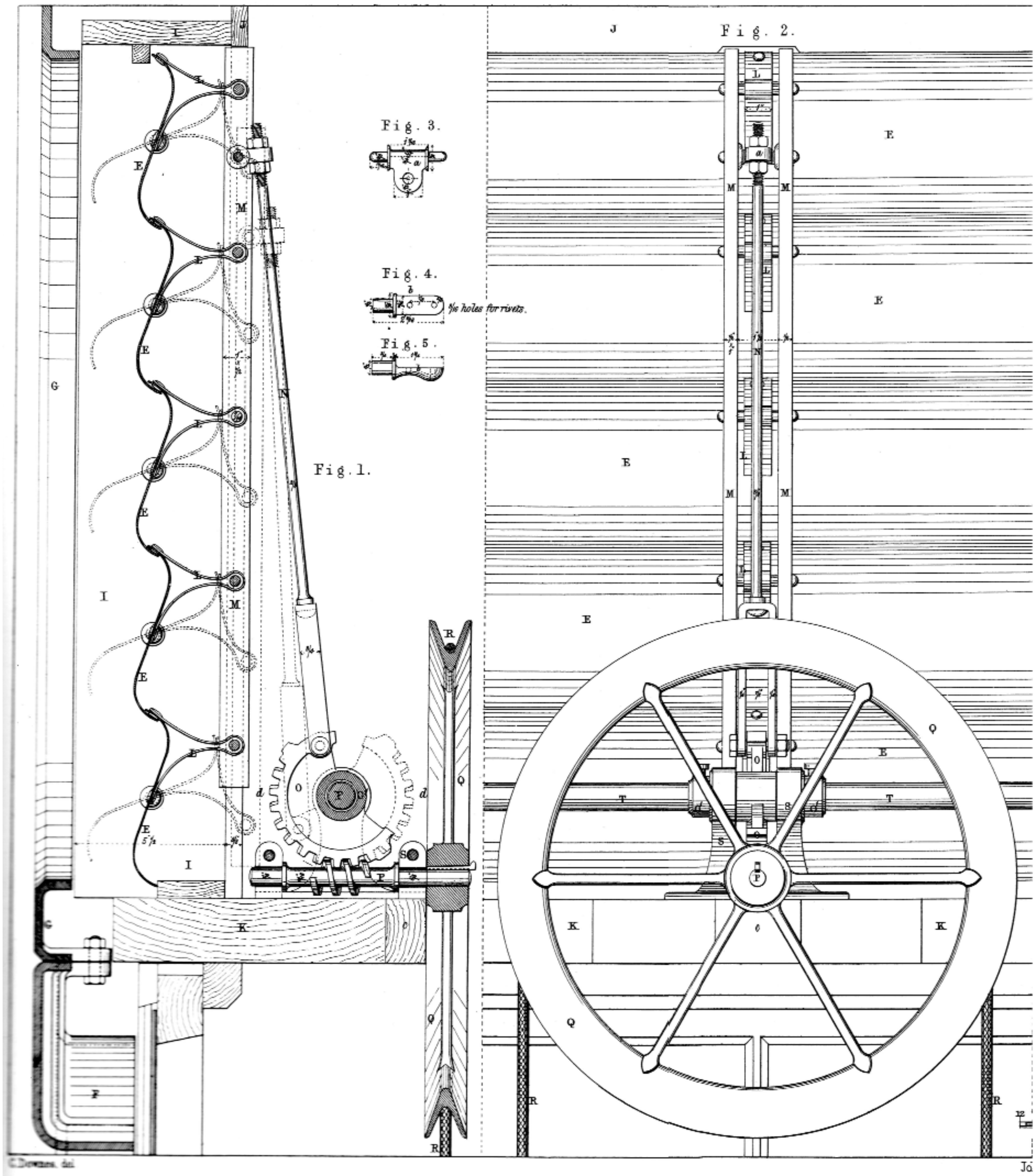


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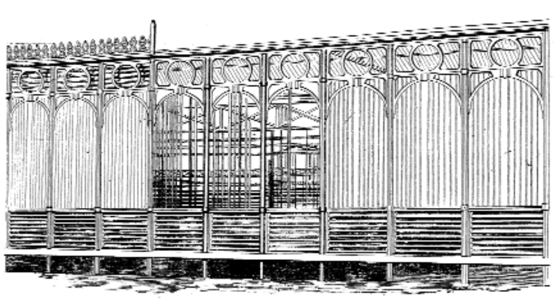
10 Cross section (left) and elevation (right) of operable ventilator. Charles Downes and Charles Cowper, *The Building Erected in Hyde Park for the Great Exhibition of the Works of Industry of all Nations, 1851* (London: John Weale, 1852), plate 27

11 External view of the low and high level ventilators on the ground floor. *Illustrated London News*, 7 December 1850, p. 432



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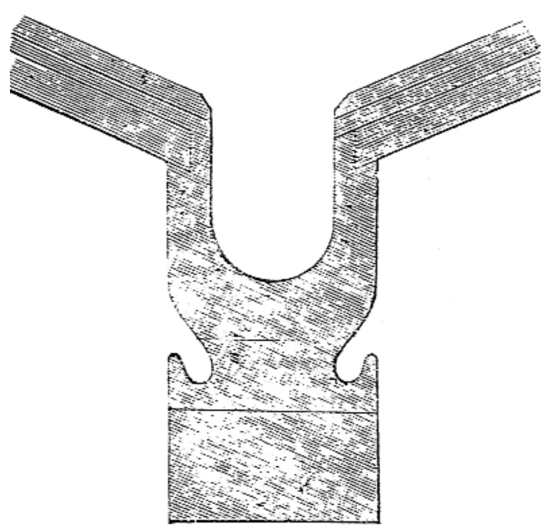

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on the extent to which multiple storeys could be inserted inside the volume of an extremely deep plan building, it was practically a single-storey building with a secondary level of shallow bridges; its volume was divided into three tiers of diminished width, forming the shape of a stepped pyramid in cross section. Since the Crystal Palace in Hyde Park was intended as a temporary structure, to be used in the period from start of May to the middle of October, Paxton, in terms of climatic control, was primarily concerned with the control of potentially high solar gains during the hot summer months. He proposed to adopt a passive shading, cooling and ventilation strategy, which, however, was only partly implemented.

## Ventilation

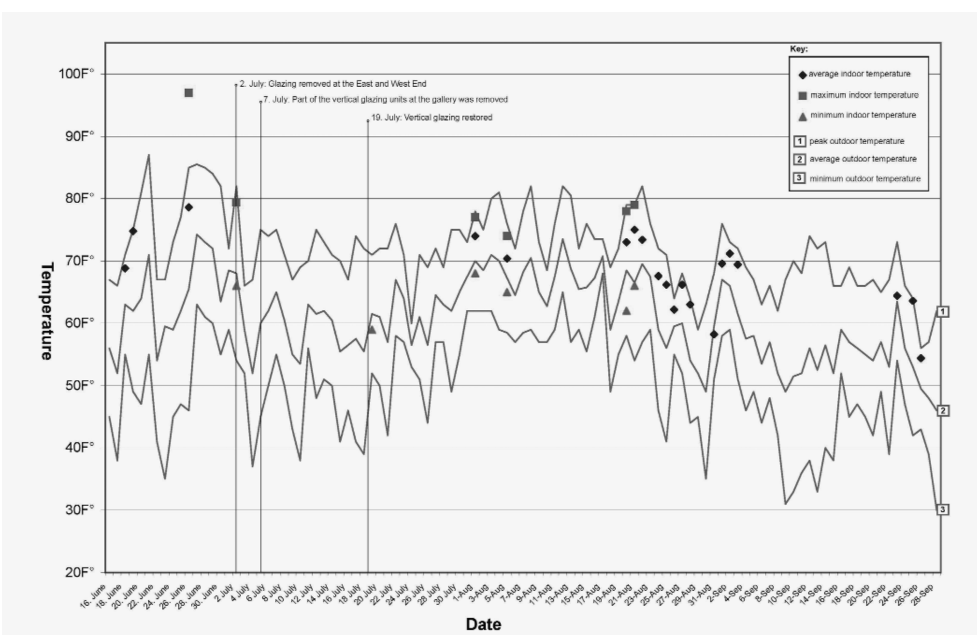
> *'In a building destined to be occupied from day to day, and from morning till evening, during the hottest portion of the year, by a large concourse of persons of all nations, including large masses of those who regard not the bath as a necessary part of their daily occupation, it is the utmost importance to pay very great attention to the mode of introducing continually streams of fresh air, so as to keep the internal atmosphere as pure and undefiled as possible.*'[37]

The intention behind the ventilation strategy was to provide thermal comfort on hot summer days, by facilitating the controlled movement of air and by discharging hot air. Apart from solar gains, there were other major heat sources: large crowds of visitors, operation of steam driven machinery and live demonstrations of industrial manufacturing processes. It was also necessary to guarantee a continuous supply of fresh air in a building accommodating up to 80,000 people at any time.[38] Due to the large volume of the structure, which comprised 33 million cubic feet,[39] the ventilation rate required to provide eight litres of fresh air per second and person was relatively low. For instance, two air changes would be required if there were 65,000 visitors inside the building. The system was also to deal with the issue of smell and humidity in a public building intended to be shared by large crowds of people.

The ventilation system of the Crystal Palace comprised continuous horizontal rows of ventilators built into the top section of the vertical facades on each of the three levels. On the ground floor, additional ventilators were introduced at low level in most of the bays *[11]* and another two rows of ventilators were introduced underneath the glass vault in the east and west. The ventilation rate was regulated by means of horizontal metal louvres which were manually opened or closed by a wheel and cord mechanism, facilitating the operation of a 216 feet row of ventilators from one position.[40] The ventilators were regulated by the Royal Sappers and Miners, who kept a two hourly register and systematically monitored the internal temperature in the whole building by means of 14 thermometers installed in different parts of the building.[41] The S-shaped louvre blades were designed to prevent rain entering the building when the ventilators were open, and thereby permitting continuous ventilation *[10]*.[42] Although Paxton intended to use the ventilators as the primary instrument for ventilation, the air entering the building from the space below ground floor via the three eighths of an inch gaps between the 3 inch by 9 inch floor boards,[43] which in total added up to an area of approximately 40,800 square feet of opening, must have contributed considerably to the air-flow in the building. Driven by the buoyancy of the internal atmosphere, external air would have been drawn into the interior from the space underneath the floor boards, which was up to 5 feet deep. To give a comparison, the total ventilator area shown in the drawings was 40,800 square feet.[44] To prevent the accumulation of condensation under the glass roof (arising from large crowds of people in the building), so-called *Paxton´s Gutters*, with internal condensation drains on both sides of the wooden valley gutters connected to the general system of drainpipes, were used *[12]*.[45]

12 *Paxton's Gutter* with internal condensation drains and external rain gutter. *Illustrated London News*, 16 November 1850

13 Temperature recorded inside the Crystal Palace between 18 June and 26 September 1851



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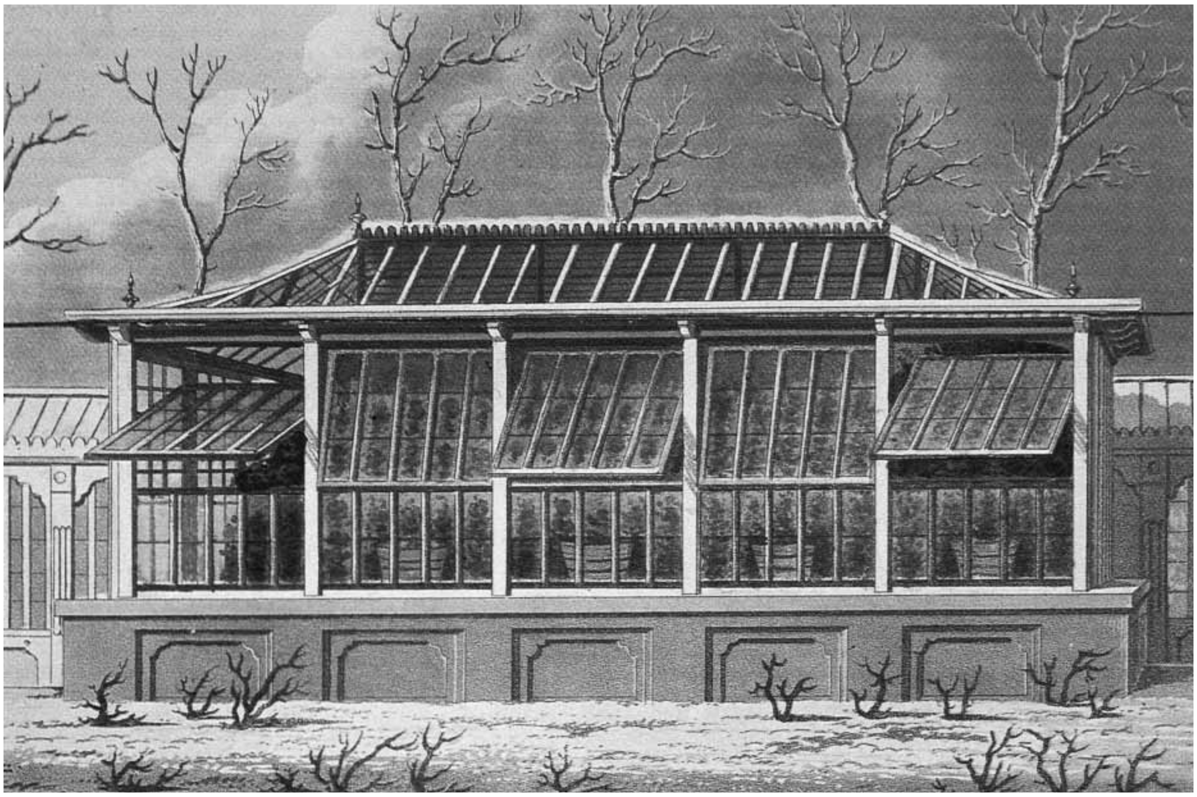

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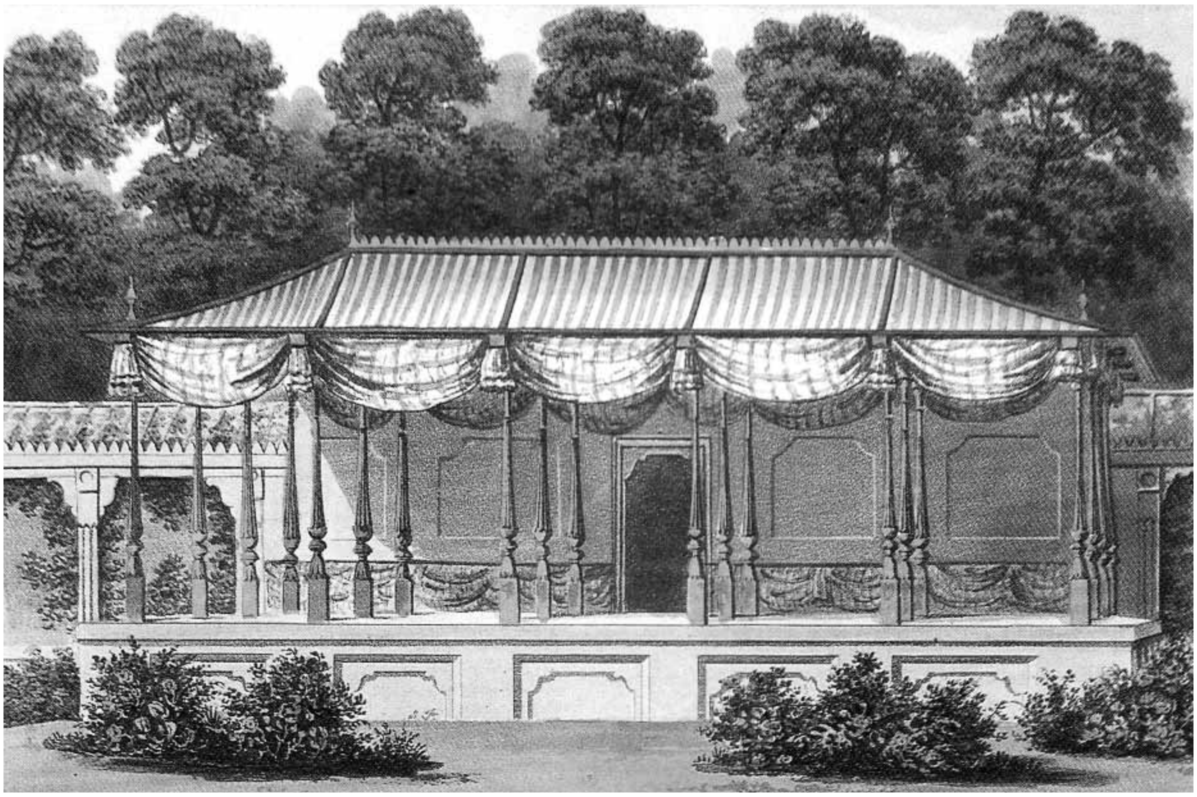
## Cooling

Aware that the indoor temperature could not be cooled down by natural ventilation during the hot summer period, Paxton, in his original proposal, intended to employ a passive technique for cooling the supply air, which he described as the Indian plan of ventilation.[46] He suggested moisturising the calico screens during periods of extreme heat in the summer. The stream of supply air, he believed, would be cooled down before it entered the interior of the building through the ventilators in the vertical glazing.[47] Paxton claimed to have done a small-scale experiment in a house at Chatsworth, in which he used wet canvas to cool the air temperature of a room from 85°F to 78°F in one hour.[48] In the Crystal Palace, he believed, this system could facilitate a lowering of the indoor temperature below the external temperature. In a lecture in August 1850, printed in the *Journal of Design and Manufactures*, Paxton proposed an alternative system, which was comprised of a large-scale version of a *Punkah fan*, a traditional Indian fan made of cloth hung from the ceiling and operated by servants. The proposal was to install large sheets of canvas underneath the glass roof kept in a perpetual movement to fan the interior air and by being moisturised during extremely hot summer days, to cool the internal atmosphere by evaporation.[49]

## Reconstruction of the climatic conditions inside the Crystal Palace

> *'On Saturday the oppressive heat proved too great even for the attraction of the Crystal Palace, and since it was opened we have hardly seen so small an attendance there. In vain did ladies appear in the thinnest muslin dresses, and gentlemen walk about with their hats in their hands. The wind would not blow in such a direction as to secure a thorough draft, and in the desperate effort to find relief from their suffering some clustered around the fountains.'*[50]

Numerous articles and letters in the *Times* give witness to the actual environmental conditions which existed inside the Crystal Palace between May and September 1851. These articles permit an insight into what one could call the climatic history of the Great Exhibition, since they contained accounts of people's reception of the indoor climate and of measures taken by the management to improve it etc. In addition, numerous articles in a wide range of contemporary newspapers included quotes of the temperature originally monitored inside the building by means of 40 thermometers installed in different parts of the interior in May 1851 by an exhibitor named Mr. Bennet of Cheapside.[51] It was a decision of the Royal Commission of the Great Exhibition in March 1851 to offer thermometer-makers 'space for the exhibition of thermometers of all kinds, in order to test the efficiency of the system of ventilation adopted in the building'.[52] Men of the Royal Sappers and Miners, who were responsible for controlling the ventilation, monitored and kept a register of the interior temperature. Between 19 May and 14 October readings were taken daily from each of 14 thermometers at two hourly intervals between 9am and 6pm except for the period after 9 September when the last reading was taken at 5pm.[53] Three additional thermometers were installed outside the building to monitor the external temperature corresponding with the internal temperature.[54] No information was given about where exactly in the building these thermometers were installed, however.



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14 Repton's 'Design for an Orangerie', 1808, winter mode. Humphry Repton, *Designs for the Pavilion at Brighton* (1808)

15 Repton's 'Design for an Orangerie', 1808, summer mode. Repton, *Designs for the Pavilion at Brighton* (1808)

To reconstruct the indoor temperature inside the Crystal Palace, individual temperature measurements taken during the opening hours of the exhibition and published in 57 articles in contemporary newspapers such as the *Times*, *Morning Chronicle*, *Daily News* and the *Illustrated London News* between 18 June and 9 October 1851 were compiled. A large number of these articles listed the average temperature measured across the building at two hourly intervals between 10am and 6pm. In addition, climate data taken from London weather reports in the *Times* and the *Gardener's Chronicle* was collected to reconstruct the temperatures that prevailed outside the building. All this data has been consolidated in a graph *[13]*. On 27 June 1851, for the first time since the opening of the exhibition in May, the *Times* gave an account of the climate inside the Crystal Palace, reporting of extremely high indoor temperatures inside the building which were unprecedented. The intense direct solar heat gave rise to a temperature of 104°F; the outside air temperature was up to 83°F in the shade; this caused even greater extremes of heat in the interior of the Crystal Palace, with a maximum air temperature of 97°F in the afternoon and a daily average of 78.7°F.[55] According to a brief retrospective note on the climate in the Crystal Palace in the *Times* on 16 September, the temperature inside the building in the period before this incident was considerably lower, with average and periodically chilly temperatures during May and most of June. This extreme heat, which continued to occur inside the building on the following days, was perceived as extremely uncomfortable by both visitors and the staff and the *Times* gave several accounts of people's desperate attempts to find ways of adapting themselves to these conditions.[56] The management, having consulted visitors and exhibitors about the extreme heat in the building, removed the glazing units of the east and west elevation on 2 July,[57] with the intention to reduce the indoor temperature and 'to secure a refreshing thorough draught from end to end of the interior'.[58] It reported that it lowered the indoor temperature at ground level,[59] but hot and stuffy air continued to accumulate at the upper part of the building.[60] To improve the climate at gallery level, parts of the glazing in the north and south galleries were removed on 7 July, causing a more uniform temperature across both levels.[61] Around 19 July when the indoor temperature had fallen to 59°F, the glazing was restored and the ventilators were used to regulate the indoor temperature in response to varying degrees of solar gain and visitor numbers.[62]

In August and September, peak indoor temperatures followed closely the outdoor peak temperatures, while the average indoor temperature in the same period was constantly between 2°F and 8°F above the average outdoor temperature and the minimum indoor temperature was continuously between 5°F and 6°F higher than the minimum outdoor temperature. Excluding nine anomalous days between July and September, the peak indoor temperature never fell below the level of the outside peak temperature. The press stopped reporting specifically on the climate for most of July, but reported on the indoor temperatures inside the building very regularly from the end of July to the 9 October. The highest indoor air temperatures that were quoted in this period ranged between 74°F and 78°F.

The measurements for August and September show that the climate inside the Crystal Palace was very variable both through the day and between days. On 1 August, for instance, the indoor temperature rose from 68°F at 10am, to 72°F at noon and arrived at peak temperatures of 77°F at 2pm, which prevailed until 6pm.[63] On 5 August the indoor temperature varied by 9°F, with a minimum of 65°F and a maximum of 74°F and on 20 August by 16°F, with the indoor temperature varying between 62°F and 78°F. Strong temperature variations between daily average temperatures were recorded in the period between 22 August and 3 September. The average indoor temperature dropped from 73°F on 22 August to 58°F on 30 August but rose to 69°F on 3 September.

The weather data of the end of June demonstrated that the variability of the indoor temperature was partly the result of fluctuating solar gains caused by the changing conditions of the sky, and partly down to varying solar intensity. On 26 June, the temperature measured in the direct sun was 104°F, 24°F higher than the day before, while the air temperature in the shade had only risen by 10°F; 26 June and the following four days were reportedly cloudless days and the intensity of the sun continued to increase to 112°F on 27 June.[64]

As indicated by the official statistics of the Great Exhibition and articles, the great variability in visitor numbers, largely the result of different ticket prices for particular days of the week, ranging from one to five shillings, also had an immediate effect on the air quality, humidity and temperature inside the building. While on one-shilling days (typically from Monday to Thursdays) visitor numbers at any one time were up to 80,000, the highest number of visitors on five-shilling days, typically on Saturday, was 20,000.[65]

The temperature records and account of the climate inside the Crystal Palace indicate that the ventilation and shading strategy employed in the Crystal Palace was not capable of preventing extremely high indoor temperatures during the hottest period of the summer in 1851. Even after removing a large portion of the vertical glazing, the peak indoor temperature could only be lowered to the level of the peak external air temperature. It also showed that the climate inside the building was subject to daily temperature fluctuations with 10°F to nearly 20°F between the daily minimum and peak temperatures. Paxton's intention of creating a moderate and pleasant internal environment which he expressed in his hypothetical glasshouse proposals was not fulfilled.

By opening the building to the external atmosphere, the building consisted primarily of a horizontal canopy which guarded visitors against the effects of direct solar radiation while enabling the outside air to pass with minimal obstruction through its now semi-outdoor space. The Crystal Palace in its closed and open state, resembled Humphry Repton's unrealised proposal for a fully-glazed orangery. Designed for the Prince Regent at the Royal Pavilion in Brighton, the idea was to regulate the varying quantities of solar gain across the seasons by closing or opening the entire glass envelope to the external atmosphere. In two illustrations, published in 1808 in *Designs for the Pavilion at Brighton*, he depicted the summer and winter mode of the orangery as two distinct building types.[66] The 'open pergola', resembling the Crystal Palace with its glass walls removed, intended to minimise solar gains and encourage maximum ventilation during the summer months, and the 'glasshouse' type resembling the fully-glazed Crystal Palace, aiming at collecting solar heat to raise low indoor temperatures during the winter and the mid-season *[14, 15]*.

While horticulturists had developed powerful means to mechanically raise the indoor temperature inside glasshouses during cold periods, there was no technology to actively lower the extreme summertime temperatures inside fully-glazed buildings. The removal of glass sashes, which in the case of the Crystal Palace happened in response to an emergency, represented the deployment of a common ventilation strategy in horticulture, where ventilation was the primary method by which extreme indoor temperatures could be reduced. Paxton's ridge and furrow glasshouse of 1834, for instance, had sliding sashes which enabled the entire south elevation to be opened to the outside during extreme temperatures.[67] Nonetheless, Paxton's proposal to combine natural ventilation with an evaporative cooling system, indicated that he aspired to use technologies that would help to physically lower the temperature inside fully-glazed structures.

## Conclusion

Although it seems that Paxton did not make the step to fully exploit the environmental possibility of the mechanically regulated glasshouse environments of horticulture, he anticipated the idea of summer cooling fully-glazed structures before mechanical refrigeration and air-conditioning technology was available. His original design included a sophisticated ventilation and passive cooling system by which he intended to actively cool the internal atmosphere of the building below the level of the outside air temperature, but was restricted from implementing it in its entirety. The strategy that was adopted in the executed design was not sufficient to maintain adequate climatic conditions for human beings inside the Crystal Palace during the hottest period of the Great Exhibition.

The Crystal Palace, despite its problems in operation, still represented a first step towards the kind of glass buildings with mechanically-controlled indoor climate which formed the core of Paxton's broader socio-environmental vision. Paxton, perceiving innovative design and modern technologies as means by which the social and environmental issues of the emerging industrial cities of the nineteenth century could be resolved, proposed the use of such structures as a new type of public space that was adapted to the immediate social and environmental needs of its population. The ability to combine mechanical environmental systems, to manufacture controlled atmospheric conditions inside large buildings tailored to specific requirements of human health and comfort, with fully-glazed structures by which extremely large spaces could be effectively enclosed and day-lit, offered the opportunity to make public urban life independent from the climatic variability and periodically hazardous atmospheric conditions of the open air within urban areas. Paxton aspired to totally controlled autonomous climates inside glass buildings, and never accomplished these fully in his own designs. In the second Crystal Palace in Sydenham, the subject of current research by the author, Paxton incorporated a warm water heating apparatus but abandoned the canvas shading system in order to admit direct sunlight into the building and to expose the optical brilliancy of the glass skin, previously veiled by the external calico.[68] He did not take the final step of combining the passive cooling, ventilation and solar control strategy of the Exhibition building, that intended to render it suitable for summer use, with the mechanical heating apparatus for the cold season, into one integrated cooling, heating and ventilation system, which would have allowed the temperature of the internal atmosphere to be actively lowered or increased in response to the great temperature fluctuations, while maintaining a continuous supply of fresh air for large crowds of people.

**Notes**

1. John C. Loudon, *An Encyclopaedia of Gardening* (London: Longman, Hurst, Rees, Orme, and Brown, 1822), p. 926.
2. Denarius (Henry Cole), *Shall We Keep the Crystal Palace to Have Riding and Walking in All Weather among Flowers – Fountains – and Sculpture?* (London: John Murray, 1851) and Joseph Paxton, *What Is to Become of the Crystal Palace?* (London: Bradbury & Evans, 1851).
3. Paxton, p. 12.
4. For instance Francis S. Haden, *A Medical Man's Plea for a Winter Garden in the Crystal Palace* (London: John van Voorst, 1851).
5. *Times*, 28 July 1851 and *Illustrated London News*, 5 July 1851.
6. Henry-Russell Hitchcock, *Early Victorian Architecture in Britain* (London: Trewin Copplestone, 1972), pp. 530–71; Sigfried Giedion, *Space Time and Architecture, the Growth of a New Tradition* (Cambridge, Mass.: Harvard University Press, 1967), pp. 249–255; John McKean, *Crystal Palace: Joseph Paxton and Charles Fox* (London: Phaidon, 1994); George F. Chadwick, *The Works of Sir Joseph Paxton, 1803–1865* (London: Architectural Press, 1961).
7. Paxton, p. 12.
8. *Illustrated London News*, 6 July 1850, p. 6.
9. *Times*, 14 November 1850, p. 4.
10. *Times*, 28 July 1851, p. 6.
11. Ibid.
12. Ibid.
13. For instance 'Windows and Light', *The Civil Engineer and Architect's Journal*, 14 (1851), 543; 'The Light and Health Taxes', *Builder*, 8 (1850), 161.
14. Lewis Mumford, *The Culture of Cities* (London: M. Secker & Warburg, 1938), p. 170.
15. Haden, p. 12; Dr. Smith, 'The Report on the Air and Water of Towns', *The Civil Engineer and Architect´s Journal*, 9 (1848), p. 311.
16. Paxton, p. 8.
17. 'On Gardening as a Science', *Paxton´s Magazine of Botany*, 8 (1842), p. 106.
18. *Illustrated London News*, 5 July 1851, p. 11f.
19. Chadwick, p. 137.
20. According to René Dubois the term 'Sanitarium' comes from the root *sanitas* and implies healthy living in a salubrious and pleasant environment. René Dubois, *Mirage of Health* (London: George Allen and Unwin, 1960), p. 23.
21. *Illustrated London News*, 5 July 1851, p. 11f.
22. *Times*, 15 July 1850, p. 4.
23. At a lecture of the Society of Arts in November 1850, *Times*, 14 November 1850, p. 4.
24. For a more detailed account see: Henrik Schoenefeldt, 'The All-Glass Building, its Predisposing Causes' (unpublished M.Phil Dissertation, University of Cambridge, Wolfson College, 2007), pp. 36–39.
25. *Illustrated London News*, 6 July 1850, p. 13.
26. Ibid.
27. 'Exhibition of 1851, Monthly Report of Progress', *Journal of Design and Manufactures*, 4 (1850), 29–32; 50–55 (p. 51).
28. *Illustrated London News*, 6 July 1850, p. 6.
29. *Times*, 14 November 1850, p. 4.
30. McKean, p. 19.
31. *Times*, 1 January 1851, p. 3.
32. Chadwick, p. 111.
33. *Illustrated London News*, 15 November, p. 379.
34. *Times*, 14 November 1850, p. 4.
35. *Illustrated London News*, 19 October 1850, p. 323.
36. *Times*, 14 November 1850, p. 4.
37. *Illustrated London News*, 28 December 1850, p. 520.
38. *Illustrated London News*, 9 August 1851, p. 208 and 18 October 1851, p. 486.
39. *Illustrated London News*, 19 October 1850, p. 323.
40. Michael Wigginton, *Glass in Architecture* (London: Phaidon, 1996), p. 44.
41. Commissioners for the Exhibition of 1851. First report of the Commissioners for the Exhibition of 1851, Her Majesty's Stationery Office, London (1852), p. 67.
42. 'Exhibition of 1851, Monthly Report of Progress', p. 31.
43. *Illustrated London News*, 16 November 1850, p. 386.
44. Commissioners for the Exhibition of 1851, pp. xxix, 67.
45. *Illustrated London News*, 16 November 1850, p. 380.
46. Ibid, p. 386.
47. Ibid.
48. *Times*, 14 November 1850, p. 4.
49. 'Exhibition of 1851, Monthly Report of Progress', p. 31.
50. *Times*, 30 June 1851, p. 5.
51. *Times*, 16 September 1851, p. 5.
52. *Times*, 29 March 1851, p. 5.
53. Commissioners for the Exhibition of 1851, p. 67.
54. Ibid.
55. *Times*, 16 September 1851, p. 5.
56. *Times*, 30 June 1851, p. 5; 4 July 1851, p. 5; 1 July 1851, p. 5.
57. *Times*, 16 September 1851, p. 5.
58. *Times*, 27 June 1851, p. 5.
59. *Times*, 1 July 1851, p. 5.
60. *Illustrated London News*, 11 October 1851, p. 471.
61. Ibid.
62. Ibid.
63. *Times*, 2 August 1851, p. 5.
64. *Times*, 1 July 1851, p. 8.
65. *Illustrated London News*, 9 August 1851, p. 208 and 18 October 1851, p. 486.
66. Humphry Repton, *Designs for the Pavilion at Brighton* (London: for J. C. Stadler; and sold by Boydell and Co. The letterpress by T. Bensley).
67. 'Observations on the Construction of Hot-House Roofs', *Paxton's Magazine of Botany*, 2 (1836), 80–85 (p. 84).
68. *Times*, 28 July 1851, p. 5.

**Appendix**
The following articles in the *Times* [**T**], *Daily News* [**DN**], *Morning Chronicle* [**MC**], *Bristol Mercury* [**BM**], *Hull Packet & East Riding Times* [**HP**], *Manchester Times* [**MT**], *Newcastle Courant* [**NC**], *Preston Guardian* [**PG**], *Liverpool Mercury* [**LM**], *Examiner* [**E**] included references to the temperatures recorded inside the Crystal Palace, which have been used to compile this graph:

**June:** 27 June 1851, p. 5 [**T**] / 30 June 1851, p. 5 [**T**] **July:** 05 July 1851, p. 2 [**PG**]/ 15 July 1851 [**PG**] **August**: 2 August 1851, p. 5 [**T**] / 2 August 1851, p. 6 [**BM**] / 6 August 1851, p. 8 [**T**] / 8 August 1851, p. 4 [**NC**] / 15 August 1851, p. 5 [**MC**] / 20 August 1851, p. 5 [**MC**] / 21 August 1851, p. 6 [**MC**] / 21 August 1851, p. 5 [**T**] / 22 August 1851, p. 5 [**DN**] 22 August 1851, p. 6 [**T**] 23 August 1851, p. 3 [**T**] / 25 August 1851, p. 5 [**T**]/ 25 August 1851, p. 3 [**MC**] / 26 August 1851, p. 5 [**T**] / 27 August 1851, p. 4 [**T**] / 28 August 1851, p. 4 [**T**] / 29 August 1851, p. 5 [**T**] / 29 August 1851,
p. 5 [**HP**] **September:** 1 September 1851, p. 5 [**T**] / 2 September 1851, p. 5 [**MC**] / 2 September 1851, p. 8 [**T**] / 3 September 1851, p. 5 [**T**] / 3 September 1851, p. 6 [**DN**] / 4 September 1851 [**DN**] / 4 September 1851, p. 5 [**T**] / 5 September 1851, p. 6 [**DN**] / 6 September 1851, p. 569 [**E**] / 6 September 1851, p. 5 [**MC**] / 9 September 1851, p. 6 [**DN**] / 12 September 1851, p. 6 [**MC**] / 13 September 1851, p. 5 [**DN**] / 15 September 1851, p. 5 [**DN**] / 16 September 1851, p. 5 [**DN**] / 17 September 1851, p. 5 [**DN**] / 18 September 1851, p. 5 [**DN**] / 20 September 1851, p. 5 [**DN**] / 23 September 1851, p. 5 [**DN**] / 24 September 1851, p. 5 [**DN**] / 24 September 1851, p. 5 [**T**] / 26 September 1851, p. 5 [**DN**] / 26 September 1851, p. 4 [**T**] / 27 September 1851, p. 5 [**T**] **October:** 1 October 1851, p. 5 [**DN**] / 2 October 1851, p. 5 [**DN**] / 3 October 1851, p. 5 [**DN**] / 4 October 1851, p. 5 [**DN**] / 6 October 1851, p. 5 [**DN**] / 7 October 1851, p. 5 [**DN**] / 8 October 1851, p. 5 [**DN**] / 10 October 1851, p. 5 [**DN**] / 13 October 1851, p. 5 [**DN**] / 13 October 1851, p. 1 [**MT**] / 15 October 1851, p. 5 [**DN**]

References to the temperature inside the Crystal Palace were also made in the *Illustrated London News*, 11 October 1851, p. 471.

Weather reports published in the *Times*: 9 May 1851, p. 7 / 3 June 1851, p. 5 / 1 July 1851, p. 8 / 2 August 1851, p. 5 /12 August 1851, p. 6/ 22 August 1851, p. 8/ 3 September 1851, p. 8

Weather reports published in the *Gardener's Chronicle*: 21 June 1851, p. 392 / 28 June 1851, p. 408 / 15 July 1851, p. 424 / 12 July 1851, p. 440 / 19 July 1851, p. 457 / 26 July 1851, p. 472 / 2 August 1851, p. 488 / 23 August 1851, p. 536 / 30 August 1851, p. 552 / 6 September 1851, p. 568 / 13 September 1851, p. 584 / 20 September 1851, p. 600/ 27 September 1851, p. 617/ 4 October 1851, p. 632 / 11 October 1851, p. 648.

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**Biography**
Henrik Schoenefeldt studied at the Prince's Foundation, Portsmouth University and TU-Wien. In 2007 he was awarded an M.Phil in Environmental Design at the University of Cambridge, where he is currently a PhD. student, pursuing research into the history of all-glass buildings under the supervision of Professor Alan Short.

**Author's address**
Henrik Schoenefeldt
University of Cambridge
Wolfson College
Barton Road
Cambridge
CB3 9BB
UK
*hos21@cam.ac.uk*