Central Heating and Forced Ventilation: Origins and Effects on Architectural Design

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The three major methods of heating buildings, based on hot air, hot water, and steam, were all developed in the late 18th and early 19th centuries, largely in Great Britain. At the same time, forced ventilation, based either on the drawing power of heat or on the use of mechanical means like the fan, was also established. The greatest application of the new equipment was made by the engineer David Boswell Reid at the Houses of Parliament starting in 1834.

Many problems had to be overcome. Medical doubts about ventilation, the rivalry between architects and engineers, and difficulties in reconciling design with equipment were all attacked, and by the last quarter of the 19th century largely solved. Publications of the last two decades of the century standardized the technology and made it readily available to the architect, engineer, and general public.

Use of the new technology made possible many new architectural developments. Prison, theater, greenhouse, and hospital were all largely dependent on central heating and forced ventilation. In other building types new levels of comfort and increased standards of safety were made possible. Perhaps the most profound change was in the conception of the building itself. Buildings could be seen literally in terms of living organisms or machines. Reid even defined architecture as the act of enclosing and servicing an interior atmosphere, a notion not developed until the 20th century.

BY THE middle of the 19th century a glance over the skyline of London would have left little doubt that a new age of technology had arrived. Above a horizon blackened by the smoke of hundreds of factories, the city's venerable church steeples could hardly be seen, lost in the shade of great industrial stacks and the bristling towers of recently erected buildings. Concealed behind these towers and invisible to a casual observer were more modern marvels: heating flues, ventilation passages, water reservoirs, elevator shafts, and sanitary installations. The three great towers of the New Houses of Parliament were all used for ventilation needs. The central tower was, in fact, designed long after the bulk of the building and specifically at the request of the engineer in order to house an enormous air exhaust (Fig. 1). At Guy's Hospital, the intake and exhaust shafts of the new ward block constructed in the 1850s rose well above the building's roof forming great towers to either side (Fig. 2). Even these would have been dwarfed by Alfred Waterhouse's proposed Law Courts, whose ventilation tower would have risen high above everything else in London (Fig. 3).[1]

The rapidly expanding and ever more complex skyline was made possible by the contemporary development of new technologies. In addition to advances in central heating and forced ventilation, innovations in structural systems, lighting, water delivery, and waste disposal were making possible a revolution in architectural design. Recently scholars have considered some of these developments, notably the story of iron framing. Most of the other innovations, however, have hardly been studied at all despite their obvious importance and a voluminous 19th-century documentation. This article offers some reasons for the long period of neglect, and shows how the development of central heating and forced ventilation was an essential determinant in 19th-century architecture.[2]

1. On the new Houses of Parliament see discussion below. On the new wing of Guy's Hospital, designed by Rhode Hawkins with a heating and ventilating system by John Sylvester, see *Builder*, XI, 1853, 116; and XVI, 1858, 280; Arthur-Jules Morin, *Etudes sur la ventilation*, Paris, 1863, I, 34–54. On the Waterhouse competition design: Alfred Waterhouse, *Courts of Justice Competition, General Description of Design*, London, 1867.

2. In Henry-Russell Hitchcock's standard *Architecture: Nineteenth and Twentieth Centuries*, 3rd. ed., Harmondsworth, 1969, there is an entire chapter entitled "Building with Iron and Glass," but it is difficult to find a single reference to heating, ventilation, water supply, sewage disposal, or artificial lighting. On several of these subjects standard histories of technology like Singer, Holmyard, Hall, and Williams's *A History of Technology*, Oxford, 1956, have information, but on central heating and mechanical ventilation there is virtually nothing. There has been no full scholarly study of the subject in this century. A recent popular history can be found in Lawrence Wright's *Home Fires Burning*, London, 1964. Another study aimed at a more specific audience but still a work of popularization rather

Early Central Heating and Forced Ventilation

It is probable that the earliest form of central heating in modern Western Europe was based on the old Roman hypocaust, in which the combustion products from a fire were carried in flues under the floor or through the walls of a room. These heated surfaces in turn warmed the space by radiation This system was certainly known and used in 18th-century Europe, especially in greenhouses. Whether it survived from antiquity or was rediscovered, however, is a tantalizing question. The method was occasionally used in the 19th century for public buildings, but due to the danger of fire, it did not become common until the development of electric radiant panels in the 20th.[3]

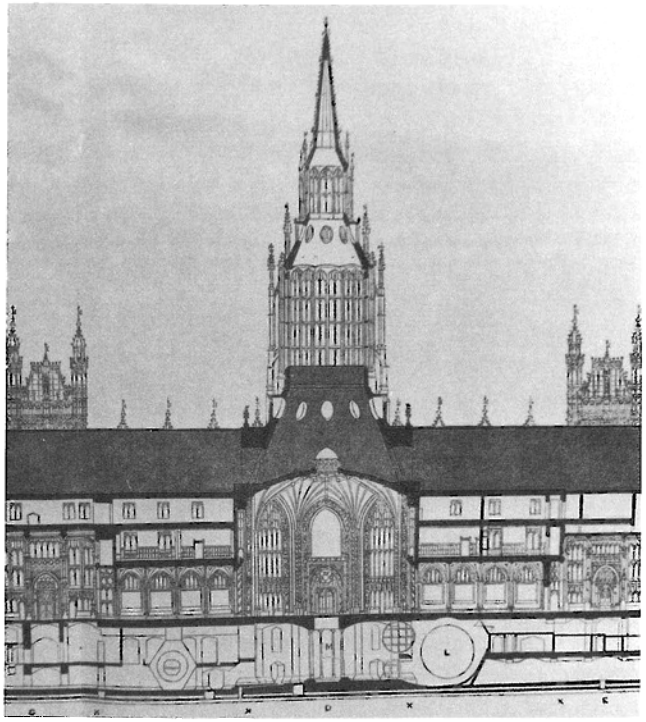


Fig. 1 London, Houses of Parliament, 1840–1865, longitudinal section through central tower showing heating and ventilation spaces (*Building News*, 31 December 1858).

A more significant change was the transformation of the common closed stove into hot air central heating. In theory this was very simple. It only required moving the stove outside the rooms to be heated and allowing air warmed by it to pass into them Although this had been suggested at least as early as the 17th century by John Evelyn (Fig. 4),[4] a continuous and rapid development was not started until William Strutt heated a new fireproof mill building in Derby with a single hot air furnace in 1792–1793.[5] Strutt was a key figure in a group of scientists, industrialists, engineers, and social reformers in the British Midlands which included individuals such as James Watt, Matthew Boulton, Josiah Wedgewood, Jeremy Bentham, and Robert Owen. They introduced innovations in lighting, fireproof construction, heating, and ventilation and employed them all in their mills.[6]

than original research is Reyner Banham's provocative and influential *Architecture of the Well-tempered Environment*, London, 1969. This book is disappointing in its treatment of the 19th century, which is derived almost entirely from secondary sources. Two important and informative reviews of Banham's book which should be consulted are those of John Kouwenhoeven in *Technology and Culture*, XI, January 1970, 85–93, and Kenneth Frampton in *Oppositions*, Winter 1976, 86–89. N. S. Billington attempted to cover the whole field in "A Historical Review of the Art of Heating and Ventilation," *Architectural Science Review*, II, 1959, 118–130, but the article is inaccurate and incomplete. A still-useful exploration of a more narrow topic is A. F Dufton's "Early Application of Engineering to the Warming of Buildings," *Newcomen Society Transactions*, XXI, 1940–1941, 99–107. The best treatments of heating and ventilation which have appeared to date have been in books dealing with specific architectural programs, notably John Hix, *The Glass House*, London, 1974, Mark Girouard, *The Victorian Country House*, Oxford, 1971, and Jennifer Tann, *The Development of the Factory*, London, 1970. All of these contain excellent chapters on the subject. While this article deals primarily with Britain since most of the important developments before 1860 occurred there, several good studies have considered American material, notably Benjamin Walbert III, "Infancy of Central Heating in the United States 1803–45," *Association for Preservation Technology Bulletin*, III, 1971, 76–87 and Eugene Ferguson's very interesting essay, "An Historical Sketch of Central Heating, 1800–1860" in Charles Peterson, ed., *Building Early America*, Philadelphia, 1976, 165–185. The best summary in French is the chapter "Le Confort et l'Hygiene domestique" in Maurice Daumas, *Histoire générale des techniques*, 3 vols., Paris, 1962–1968, III, 516–523.

3. John Evelyn, writing in 1691, indicated that heating greenhouses by the radiation from flues in floors and walls was by no means a novelty, *Kalendarium Hortense, or the Gard'ners Almanac*, n.p., 1691, 134. Quatramère de Quincy, *Architecture: Encyclopédie d'Architecture*, 3 vols, Paris, 1788–1825, I, 151, 638, apparently believed that the technique was a survival from classical times in Russia but had been lost in the rest of Europe. The question of how much Renaissance and Baroque architects knew about Roman hypocausts requires much more study A good description and illustrations of a hypocaust-heated greenhouse of the 18th century can be found in William Chambers, *Plans and Elevations of the Gardens and Buildings at Kew*, London, 1763, pl. VII. The revivals of this technique in the 19th century were surprisingly numerous. See, for example, the hypocaust-heated cottage proposal of John Claudius Loudon, *Manual of Cottage Husbandry, Gardening and Architecture*, London, 1830; Edwin Chadwick, "Sanitary Principles of School Construction," *Journal of the Royal Society of Arts*, XIX, 1871, 856–860; Douglas Galton, *Healthy Hospitals*, Oxford, 1893, and for a description of the pioneer reinforced concrete Ward House at Port Chester where hot smoke circulated between the floors: W. E. Ward, "Beton in Combination with Iron as a Building Material," *American Society of Mechanical Engineers Transactions*, IV, 1882–1883, 396, fig. 2.

4. Evelyn, *Kalendarium Hortense*, 155–162. A large number of German examples, some dating back to medieval times are cited in Hermann Vetter, "Aus der Geschichte der Zentral-Heizungstechnik bis zum Jahre 1870," *Gesundheits-Ingenieur*, Festnummer zur VI. Versammlung der Heizungs- und Lüftungsmänner, XXX, June 1907, 13–18.

5. On the Belper mill see Robert S. Fitton and A. P. Wadsworth, *The Strutts and Arkwrights 1758–1830*, Manchester, 1958, 197, 200–205, M. Egerton, "William Strutt and the Application of Convection to the Heating of Buildings," *Annals of Science*, XXIV, 1968, 73–89.

6. The two most important groups were the Birmingham Lunar Society and its offshoot the Derbyshire Philosophical Society. The contributions of

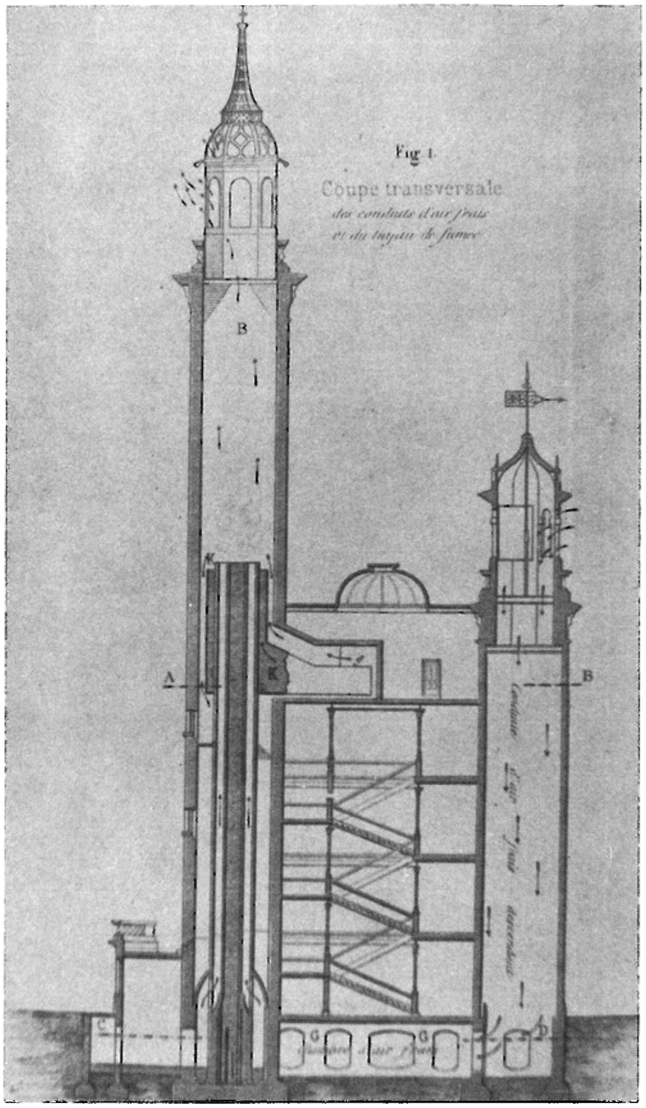


Fig. 2. London, Guy's Hospital, new ward block, 1850s, section showing heating and ventilation system designed by John Sylvester (A. J. Morin, *Etudes sur la Ventilation*, Paris, 1863, I)

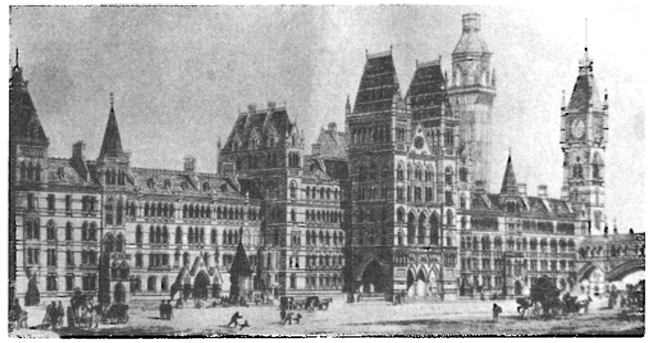


Fig. 3. Alfred Waterhouse, perspective view of Courts of Law competition project (*Building News*, 12 April 1967).

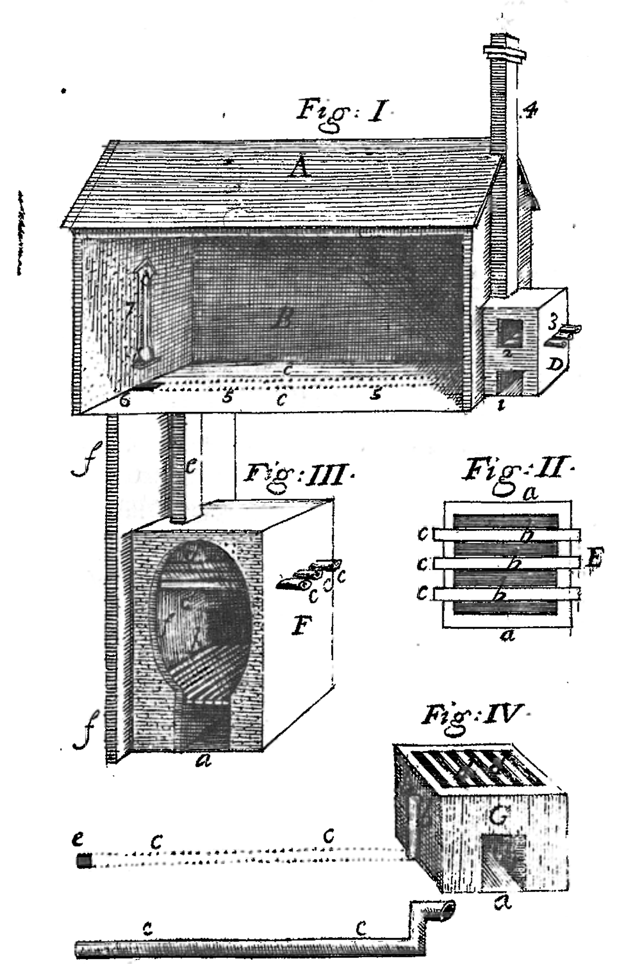


Fig. 4. John Evelyn, scheme for a greenhouse heated by a hot air furnace (Evelyn, *Kalendarium Hortense*, London, 1691. By permission of Houghton Library, Harvard University).

Strutt never published his Derby mill installation or patented his inventions, but his protégé, the engineer Charles Sylvester, has left an excellent description of a system at the celebrated Derbyshire Infirmary, designed and equipped by Strutt between 1806 and 1810 (Fig. 5). At the center of the infirmary heating system was a large "cockle stove" (Fig. 6), actually a furnace in today's terminology. Air was brought to this stove through an underground passage 70 yards long and four feet in section. This passage used the naturally moderate underground temperatures to preheat the air in winter and cool it in summer. The air was further heated if necessary, and allowed to flow up into the building through a great masonry duct near the center of the structure. In this

this group have not been fully realized. Not only did they make immense contributions to building techniques, but men like the Benthams and Robert Owen leaned heavily on this technical aspect in their Utopian schemes.

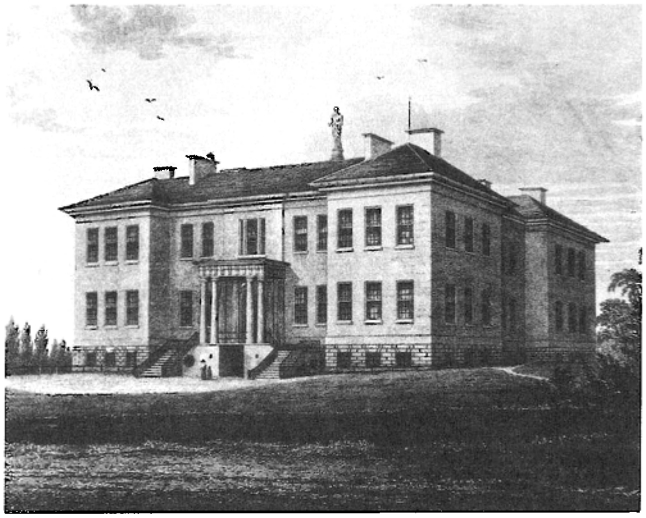


Fig. 5 Derby, Derbyshire Infirmary, 1806–1810, perspective view (Charles Sylvester, *Philosophy of Domestic Economy*, Nottingham, 1819).

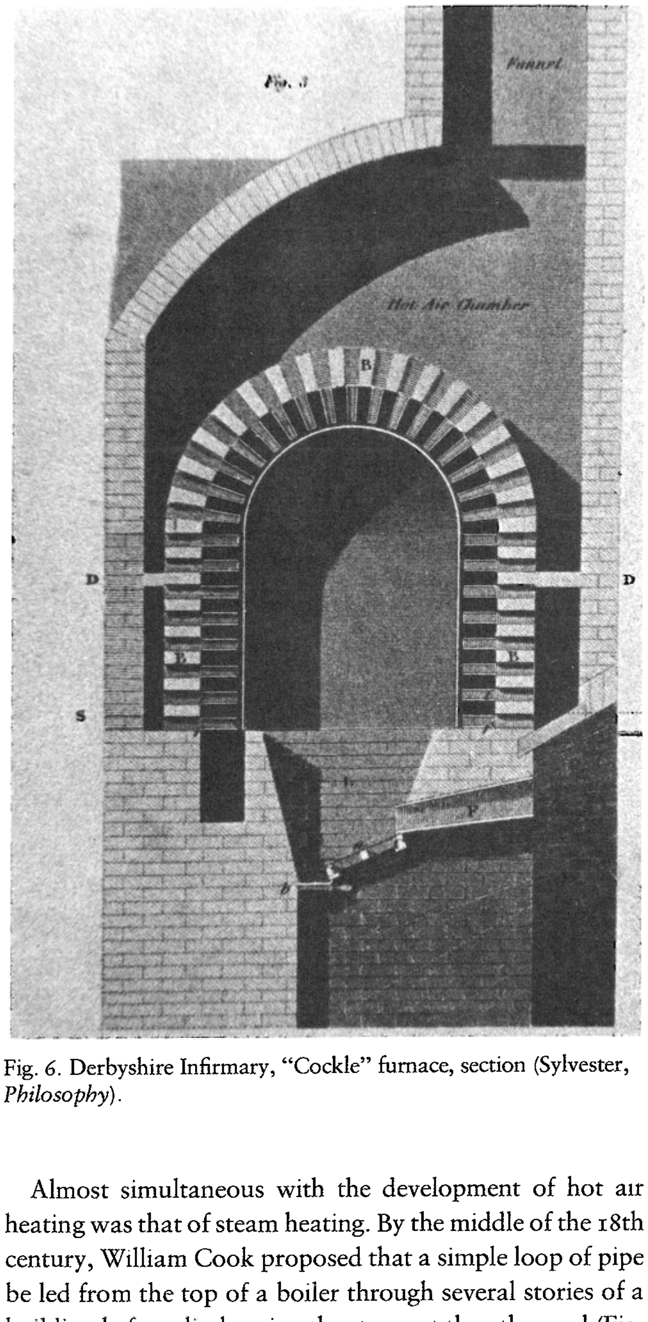


Fig. 6. Derbyshire Infirmary, "Cockle" furnace, section (Sylvester, *Philosophy*).

"gravity" system, the air moved solely because of the reduced density of the warmer air, and ventilation was achieved at the same time as heating.[7]

Hot air central heating usually did not require a great investment or special engineering skills, and a number of installations were made in the first several decades of the 19th century Probably the most important of these was the work of the Marquis J B. M. F de Chabannes, involved in almost every branch of heating and ventilation. Chabannes's installations at the House of Commons and elsewhere were described in two books that he published about 1818.[8] By the late 1820s, the pioneer period in hot air central heating was over With the development of refinements in furnace design, mechanical air movers, and cheaper ducts, hot air central heating became the common means of warming small buildings during the rest of the 19th century [9]

Almost simultaneous with the development of hot air heating was that of steam heating. By the middle of the 18th century, William Cook proposed that a simple loop of pipe be led from the top of a boiler through several stories of a building before discharging the steam at the other end (Fig. 7) [10] The earliest actual installations, however, seem to have

7. Charles Sylvester, *The Philosophy of Domestic Economy*, London and Nottingham, 1819. This book was very widely distributed and translated. In France it appeared as early as 1824 in translation in *Annales de l'Industrie* An earlier article, but much less influential, described the Strutt heating system at the General Hospital in Nottingham J. Clarke, "Report from the General Hospital near Nottingham," *Edinburgh Medical and Surgical Journal*, III, 1807, 309–311; IV, 1808, 17. On Strutt's authorship of the plans for the Derbyshire Infirmary see also C. L. Hacker, "William Strutt of Derby," *Journal of the Derbyshire Archeology and Natural History Society*, LXXX, 1960, 49–70.

8. *On Conducting Air By Forced Ventilation*, London, 1818, and *Appendix . . . Being a Continuation of the Description of the Patent Apparatus*, n.d , but which, based on internal evidence, also appeared about 1818.

9. The use of hot water or steam coils in the furnace instead of the direct action of a fire on a metal surface allowed a much milder, more constant temperature and avoided the "scorching" of the air about which contemporaries so often complained. This still can be classified as a hot air system, however, because the major means of distribution of the heat was still by hot air in ducts. For the use of sheet metal for ducting, largely an American development, see "Brief History of the Warm Air Heating Industry," *Sheet Metal Worker*, XXXXV, January 1954, 58–59, *Builder*, XXIII, 1865, 654.

10. *Philosophical Transactions*, 1745, 370. Hugh Plat, *Garden of Eden*, London, 1653, also illustrated a steam system but apparently all that he intended was to allow live steam itself to enter the greenhouse Many claims are made for very early steam systems. Most of these claims, for example for a Merovingian installation cited by Louis Hautecoeur, *Histoire de l'Architecture classique en France*, 7 vols., Paris, 1943–1957, VI, 37, or the 1788 system of Wakefield of Norwich described in *Society of Arts Journal*, XVIII, 1800, 353–400, are not actually steam heating systems.

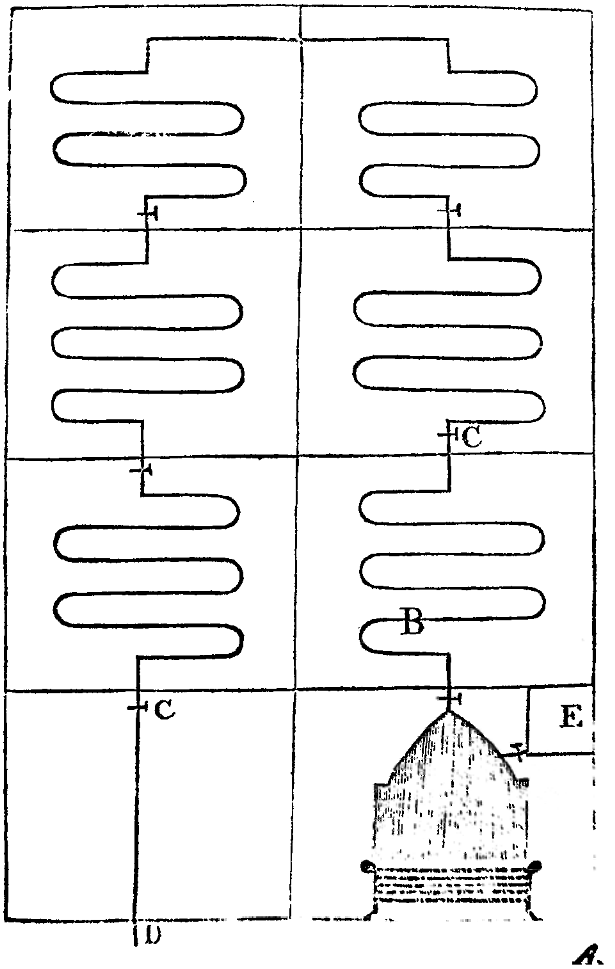


Fig 7 William Cook, schematic diagram of a scheme for heating a building by steam (*Philosophical Transactions*, 1745)

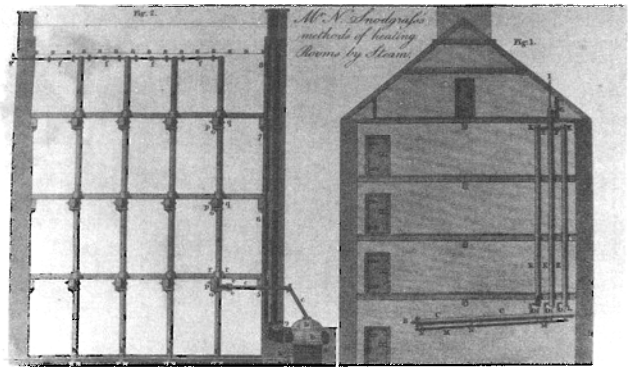


Fig. 8. Neil Snodgrass, right: installation of steam heating at mill near Dornoch, Scotland, c. 1800; left: scheme for steam heating using structural columns to carry the steam (*Transactions of the Society of Arts*, 1806)

been the work of Matthew Boulton and James Watt in the last two decades of the 18th century.[11] They produced one of the first large scale steam heating operations at the famous Twist Mill at Salford, designed about 1799 for their friend George Lee In this seven-story structure, the hollow iron bearing columns were used to carry the steam.[12] Apparently no illustrations were published, but a scheme proposed some years later by the Scot, Neil Snodgrass, probably closely resembles the system at Salford (Fig. 8, left side). In fact, Snodgrass may have been the first to install large-scale steam heating, this in a mill near Dornoch in northern Scotland in 1799. Here a boiler placed outside the main mill room produced steam which was carried by a pipe through an end wall into the room, then up vertical tubes placed near the wall Condensation simply ran down outside the same tubes (Fig. 8, right side) [13]

Robertson Buchanon's pioneer treatises, *An Essay on the Warming of Mills and Other Buildings by Steam*, Glasgow, 1807, and *A Treatise on the Economy of Fuel*, Glasgow, 1815, discussed these and other installations in industrial buildings. Steam and supervising engineers were the two requisites. The development of steam heating in non-industrial buildings was slower, but in 1818 Chabannes published descriptions and plates of his large-scale installations, and by the time of Thomas Tredgold's 1824 *Principles of Warming and Ventilating*, this method of heating had become well established. After intense development in the third decade of the 19th century, it gradually superseded hot air as the preferred method of heating large buildings. During the rest of the century, the main changes were modifications in the "direct" and "indirect" heating surfaces, piping systems, and boiler designs.[14]

11. Watt reportedly heated the writing room of his own house in the winter of 1784–1785, while Boulton heated a factory structure in 1795–1796, installed a system in the library of his friend Dr Withering of Birmingham, and helped correct defects in a system not erected by himself at the house of the Marquis of Lansdowne, Bowood Park Buchanon, *Treatise*, xii–xiv The last was one of two heating systems using steam patented in the 1790s, one by James Hoyle of Halifax, which was similar to Cook's scheme, *Repertory of Arts*, I, 1794, 300; the other, which used the steam to heat hot air, was patented in 1793 by Joseph Green; *ibid*, 21, 24.

12 Buchanon, *Treatise*, xv. A. W. Skempton and H. R. Johnson, "The First Iron Frames," *Architectural Review*, CXXXI, 1962, 183, Tann, *Factory*, 111, Bernan, *Theory and Practice*, 253

13. The Snodgrass installation was published in *Transactions of the Society of Arts*, XXIV, 1806, 118–128 and reprinted in *Philosophical Magazine*, XXVII, March 1807, 172–181. On early greenhouse steam heating see John Claudius Loudon, *Remarks on the Construction of Hothouses*, n.p, n.d, apparently printed about 1817, and Hix, *Glass House*, 479–488 On the poorly documented but important work of Benjamin Thompson, Count Rumford, at the Royal Institution about 1800 see his *Complete Works*, 4 vols., Boston, n.d., III, 479–488 and W. J. Sparrow, *Knight of the White Eagle*, London, 1964, 175–176.

14 In "direct" heating the hot surfaces are placed in the room to be heated

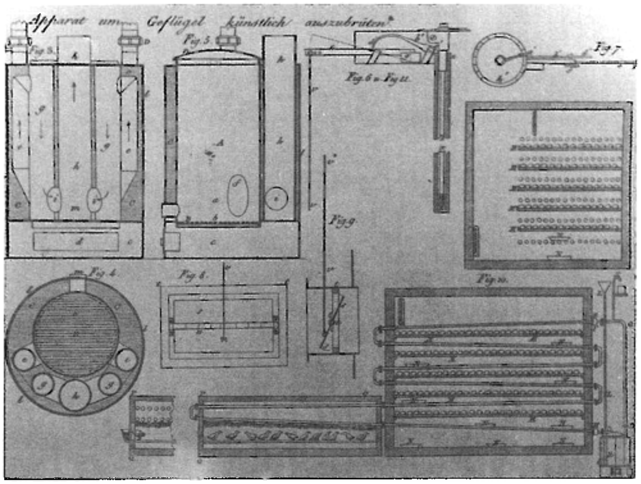


Fig. 9. Bonnemain, hot water heating scheme for chicken incubator at Pecq (Hermann Vetter, "Aus der Geschichte der Zentralheizungstechnik bis zum Jahre 1870," *Gesundheits Ingenieur*, xxx, Festnummer vi, 2 June 1907)

It is surprising that a third type of central heating, based on the circulation of hot water, was not much developed until the fourth decade of the 19th century, since a fairly sophisticated application of the method had already been made in the 1770s by a Frenchman named Bonnemain in a chicken incubator which he operated near Paris (Fig. 9) Bonnemain's methods, although repeatedly described in French journals and official reports, were not widely used.[15] There were scattered attempts to employ hot water heating, especially in greenhouses, during the following decades, but except for brief references in Chabannes's books, hot water was not described in any of the pioneer works on central heating. In fact, Tredgold stated in 1824 that the method was impractical.[16] By 1836, however, in a new edition of his *Principles of Warming and Ventilating*, he included a supplement by Joseph Bramah that described and illustrated systems at the orangery of Windsor Palace and at Westminster Hospital [17] This was the first time that hot water heating was presented to a wide audience and thereafter development was rapid By the time Charles Hood published the first edition of his *Practical Treatise on Heating Buildings by Hot Water* in 1837, he could describe hot water heating as relatively common [18]

Ordinary low pressure hot water heating, which is the kind described above, usually required large, cumbersome pipes Jacob Perkins, an American engineer residing in London, and his son Angier March, attempted to solve this problem. Their high pressure hot water system allowed the use of much smaller pipes that could be more easily concealed The first patents were taken out in 1831, and the first installations were made in 1832. By 1837, when Charles Richardson published his book on high pressure hot water heating entitled *Practical Treatise of the Warming and Ventilation of Buildings*, it had come to be widely used. Employing this method, one relatively short circuit of pipe was capable of heating the large Register Office building in Edinburgh (Figs. 10 and 11) [19]

In contrast to early central heating, first used in greenhouses and industrial buildings and developed because it was relatively inexpensive, forced ventilation[20] was from the

In "indirect" systems they are usually placed in the basement or below the floor with ducts to the rooms. On the American development of the vertical tube and cast-iron sectional radiator see John Mill's rambling but informative *Heat, Science and Philosophy of its Production and Application to the Warming and Ventilating of Buildings*, Boston, 1890, and A. M. Daniels, "History of the Development of the Radiator," *Domestic Engineer*, cxxx, January 1930, 49–55.

15. There are again many unfounded literary references to early hot water systems. Bonnemain's system seems to be the first for which definite data is available. His installation was inspected in 1782 by a committee of the Académie des Sciences and a report was issued The Faculté de Médecine made a report in 1788 and the Société d'Agriculture another in 1790: *Feuille du Cultivateur*, viii, An 7, 327 The apparatus seems to have been in operation for many years, "Régulateur de température," in C.-P. Laboulaye, ed., *Dictionnaire des Arts et Manufactures*, 3 vols., Paris, 1845, iii, 12, but was not described in English publications until the 1830s. Boulton and Watt also claimed to have used hot water well before 1800 in a letter to *Gardeners' Magazine*, iv, 1829, 30, but on this see the reasonable skepticism of the editors of *Architectural Magazine*, iii, 1836, 479. By the 1830s English horticulture magazines like *Gardeners' Magazine* and *Horticultural Transactions* were full of descriptions of hot water heating.

16. Thomas Tredgold, *Principles of Warming and Ventilation*, 2nd ed, London, 1824,12.

17. *Ibid.*, 3rd ed., Bramah Appendix, pls. 2 and 3.

18. Hood, *Practical Treatise*, 1 Most of the hardware for early hot water heating was the same as that used for steam.

19. On Perkins see Greville and Dorothy Bathe, *Jacob Perkins*, Philadelphia, 1943. The original system at Edinburgh, apparently devised by Adam for the original construction in 1774–1778 made use of a central pedestal stove with flues under the floors. J. Lees-Milne, *The Age of Adam*, London, 1947, 132–135. The Perkins system, although widely used in Britain, was dangerous because of the high temperatures and pressures which were generated. On this see Wyatt A. Papworth, *Notes on the Causes of Fires*, London, 1853, 17, and the ensuing pamphlet war including John Davies and G. V. Ryder, *Report on Perkins' System*, London, 1841, and Angier March Perkins's reply, *An Answer to Messrs. Davies and Ryder's Report*, London, 1841

20. In this article two principal types of ventilation will be distinguished "natural" or "gravity" ventilation, the kind which takes place through open doors or windows or occurs when a fire is burning in a fireplace, in other words when no special provisions are made; and "forced" ventilation, where a special system is installed and energy is expended to move the air. In practice the distinction is often a very fine one, but the idea that ventilation can be "forced" is important historically. Forced ventilation is of two types in "heat-aided" ventilation the drawing power of a fire or other heat source is used to extract the air from a room; in mechanical ventilation a fan or bellows is used to extract the air, or more commonly, to force air into a room.

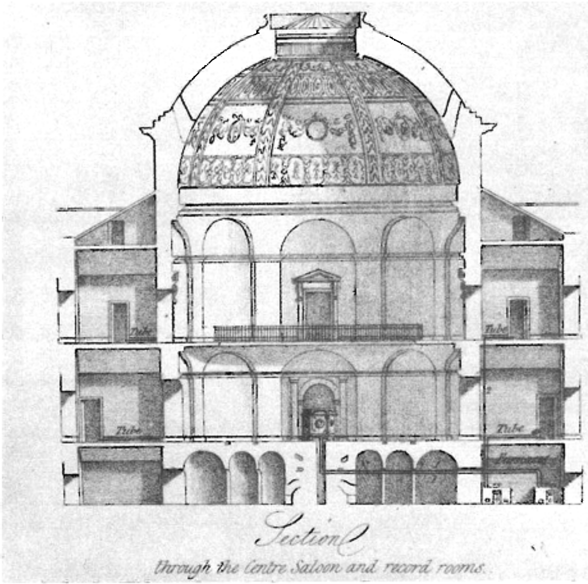


Fig. 10. Edingurgh, Register Office, section showing high pressure hot water system (Richardson, *Treatise*).

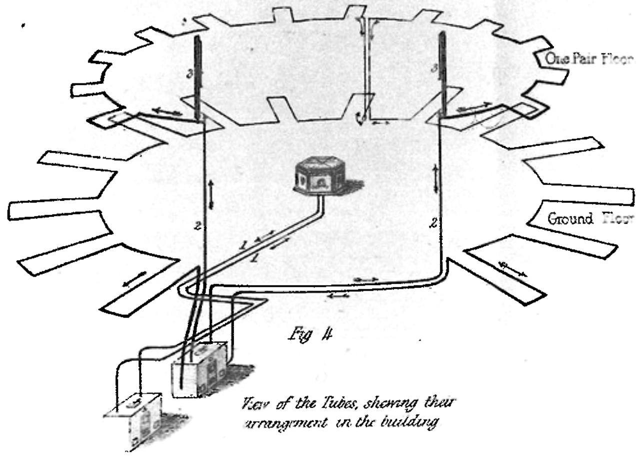


Fig. 11 Edinburgh, Register Office, diagram of high pressure hot water system (Richardson, *Treatise*).

beginning motivated by considerations of health It was widely believed that mysterious agents in stagnant air caused disease.[21] For this reason ventilation was deemed crucial in mines, ships, prisons, and hospitals.

The simplest means of forcing air was to use the drawing power of a ventilating fire At a very early date fire was maintained at the top of mine shafts. A very well known, although unsuccessful, application of this principle to buildings was made by John Theophilus Desaguliers at the House of Commons in London, where he installed ventilating fires in the already existing pyramidal air tubes in the roof. Despite the increasing interest and growing literature on ventilation in the late 18th century, and the increasing attention to the connection between ventilation and health, practical application lagged. As late as 1811, the eminent British scientist Sir Humphrey Davy failed completely in his attempt to use Desaguliers's methods at the House of Lords [22]

Chabannes supplied one of the first detailed descriptions of the large-scale use of heat-aided ventilation in his books of 1818. He ventilated the Covent Garden Theater with heat from its gas chandelier in addition to special ventilating fireplaces (Fig 12) This use of the chandelier for ventilation purposes became very common in 19th-century theaters. At the House of Lords, however, he used steam cylinders to supply the drawing power, for there was fear of fires burning over their Lordships' heads. Elsewhere he used the drawing power provided by the flue of the hot air furnace, producing a very neat self-contained system that became common in many 19th-century buildings.[23]

All of these ventilation systems had a common problem. They were delicate since they depended on slight differences in air temperature and pressure. An open window or a door in an incorrect place could disrupt the air flow One remedy

21 The medical research which supported the need for increased ventilation is a complex subject. On this see Richard Shryock, *The Development of Modern Medicine*, Philadelphia and London, 1936, 206–274, and more specialized articles on the state of knowledge about disease transmission in the early 19th century; Edwin Ackerknecht, "Anti-Contagionism between 1821–1867," *Bulletin of the History of Medicine*, XXII, 1948, 562–593, J. K. Crellin "Airborne Particles and the Germ Theory of Disease 1860–1880," *Annals of Science*, XXII, 1966, Phyllis Richmond, "Some Variant Theories in Opposition to the Germ Theory of Disease," *Journal of the History of Medicine*, IX, 1954, 290–303. An interesting study of 18th-century means to deal with these problems can be found in Rembert Watermann, "Methoden zur Reinigung der Luft in Hospitälern (18. Jh)," in *Atti del Primo Congresso europeo di Storia Ospitaliera*, Reggio Emilia, 1960, I, 1338–1349. With the development of the germ theory of disease and antiseptic surgery in the second half of the 19th century the whole problem of ventilation became much less vexed because the mysterious disease agents which had plagued earlier physicians could now be isolated and studied. Ventilation was no longer the cure-all in hospitals.

22. The Commons ventilation pyramids were originally installed, according to legend, by Christopher Wren and are presumably the cylindrical shafts visible in the section of the old House in M. H. Port, ed , *The Houses of Parliament*, New Haven, 1976, 10. The problem which Desaguliers attempted to remedy was to stop the cold air from falling into the room. See his *Course of Experimental Philosophy*, London, 1743–1744, and an account of a similar system in Samuel Sutton's *Historical Account of a new Method for Extracting the Air out of Ships*, London, 1749. On Davy's experiments see Richardson, *Popular Treatise*, 102–106, pl. 16, and *House of Lords Journal*, XLVII, 1810, 453.

23. On Covent Garden, see Chabannes, *On Conducting Air*, 25, *Appendix*, pls. 1, 2; *Journal of Science and the Arts*, V, 1818, 300, pls. 6–8. On the House of Lords see Chabannes, *Appendix*; and Richardson, *Popular Treatise*, 100–102.

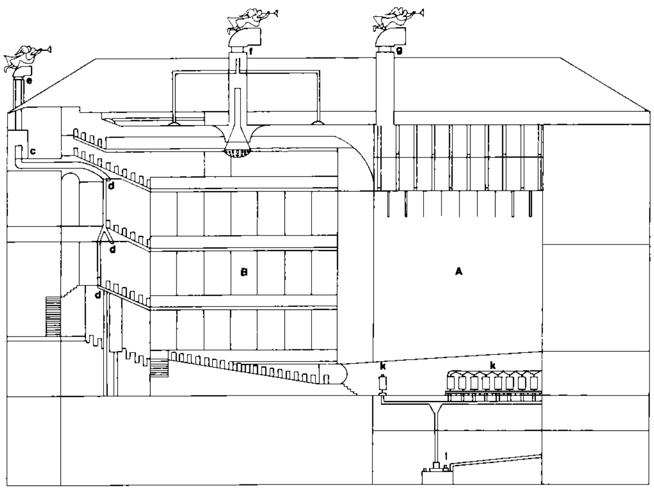


Fig. 12. London, Covent Garden Theater, section showing heating and ventilation by the Marquis de Chabannes. (A) Stage, (B) Auditorium, (c) "Ventilating fireplace," (d) Ventilation tubes, (e–g) Air exhaust stacks, (k) Steam cylinders, (l) Boiler (redrawn by Carey Wintergreen from J. B. M. F. de Chabannes, *On Conducting Air by Forced Ventilation*, London, 1818).

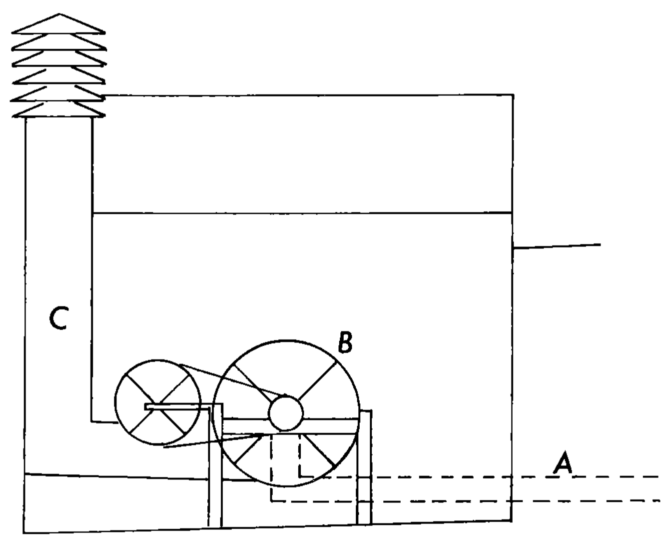


Fig. 13. London, old House of Commons, diagram of John Theophilus Desaguliers's ventilation fan. (A) Pipe conveying the air from the House of Commons, (B) Centrifugal fan, (C) Exhaust stack (Richardson, *Treatise*).

was to seal all openings in a building. An ingenious proposal of this kind specifying fixed windows and a revolving door was made early in the 19th century,[24] but such solutions were generally rejected as being too drastic. To avoid unreliable ventilating fires, engineers turned to air pumps and fans with some success. This led to the development of a second major type of forced ventilation, now known as mechanical ventilation.

The principle was again an old one. Agricola had described fans and bellows; both devices were used in the 18th century.[25] Stephen Hales employed bellows to ventilate Newgate Prison, and Desaguliers installed fans at the old House of Commons after failure of his heat-aided ventilation (Fig. 13).[26] In each case the great obstacle was securing an ample power supply. In 1845 for example, the *Builder* revealed that ventilation of the Queen's opera box by fans required the simultaneous labor of two men during the entire evening.[27] Water power, springs, and falling weights were all tried but without great success. It was not until steam power was readily available that mechanical ventilation became more effective.[28]

The major demonstrations of both kinds of forced ventilation, heat-aided and mechanical, were made by David Boswell Reid. Reid (1805–1863) had been a successful physician in Edinburgh in his early years. In 1831 he became a fellow of the Royal College of Surgeons in Edinburgh, and was soon named to the chair of chemistry at the University. In 1833, he started his own classes in a laboratory which he designed and built for his numerous experiments in heating and ventilation.[29]

After the destruction of the old Houses of Parliament in 1834, Reid was called to testify before the committee appointed by Commons to consider arrangements for any new chamber to be built. Of all the voluminous testimony before this committee, Reid's was by far the most knowledgeable and persuasive. He proposed an entire architectural scheme which he claimed would satisfy the most important needs of the House by producing good acoustics, adequate lighting, and satisfactory heating and ventilation (Fig. 14). This scheme, Reid maintained, would solve the problems with

24. This was the scheme of a man named Vallance described in Walter Bernan (pseud. for Robert Meiklaham), *On the History and Art of Warming and Ventilating Rooms and Buildings*, 2 vols., London, 1845, II, 95; and *London Journal of Arts and Sciences*, II, 26; *ibid.*, III, 292.

25. Georg Agricola, *De Re Metallica*, Basel, 1657, 200–214.

26. Stephen Hales, *Treatise on Ventilation*, London, 1758, II, 32–40. See also the remarks in the chapter "Gaol Fever" in the dissertation on prisons by Robin Middleton, University of Essex, 1975. On Desagulier's fan see *Course of Experimental Philosophy*, 2 vols., London, 1734–1744, II, 563–564. The fan was apparently still in place in 1791, according to Bernan, *History and Art*, II, 84.

27. *Builder*, III, 1845, 361.

28. On Benford Deacon's system of falling weights, for example, see Bernan, *History and Art*, II, 88–90.

29. On Reid see *Dictionary of National Biography*, 22 vols., London, 1921–1922, XVI, 870–871. On the Edinburgh lecture and classrooms see the introduction by Elisha Harris to Reid's last book, *Ventilation in American Dwellings*, New York, 1858.

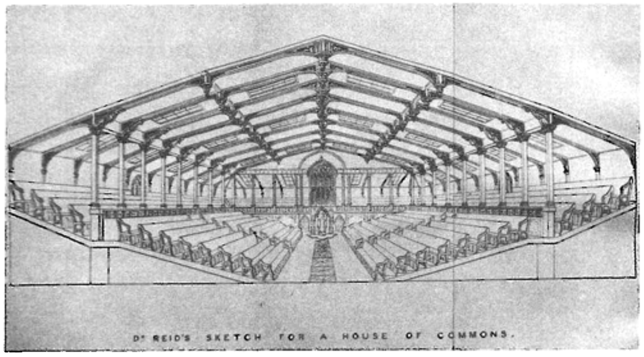


Fig. 14. David Boswell Reid, perspective drawing of project for new House of Commons chamber (W. S. Inman, *Principles of Ventilation, Warming and the Transmission of Sound*, London, 1836).

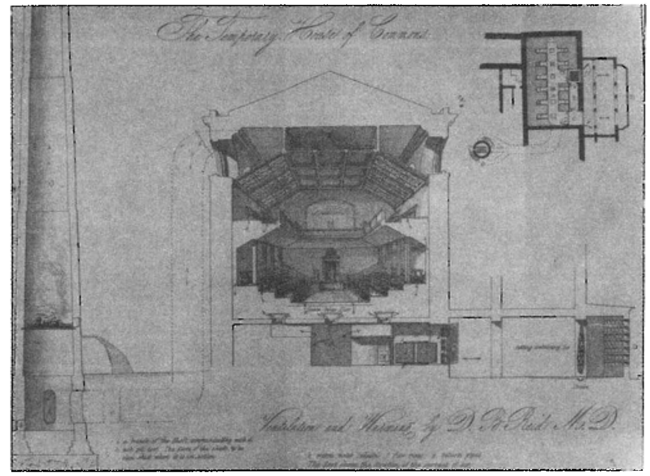


Fig. 15 London, Temporary House of Commons, perspective drawing showing heating and ventilating as installed by David Boswell Reid (Richardson, *Treatise*).

which architects and engineers since the days of Christopher Wren had struggled unsuccessfully[30] The committee invited Reid to test his ideas at small scale in the Temporary House of Commons (actually the old House of Lords refitted for the Commons after the fire)

Reid had to modify his scheme to fit the existing architectural shell (Fig. 15) He used a hot water boiler found in place, but altered it and planned a long duct like Strutt's to bring air from a neighboring courtyard where it was thought to be pure The air was passed through damp sheets and sprays of water to filter it, then heated by the hot water apparatus or cooled by large blocks of ice placed in the duct. The air was then allowed to rise into a large open space under the House floor, and from there enter the chamber itself through thousands of holes drilled in the floor. To avoid drafts Reid had the holes covered with a coarse horsehair carpet. The used air was extracted through raised panels in a glass ceiling which Reid had installed. This ceiling was probably his most ingenious invention. It functioned as a sounding board, provided the openings needed for air extraction, allowed the natural light from clerestory windows to enter, blocked drafts from those windows, and created a space in which gas jets for illumination could be placed without allowing their products of combustion to enter the chamber (Fig. 16) The air was drawn out of the chamber into the area above the glass roof by the heat of a special ventilating fire placed at the base of a great stack, which in turn discharged the air at a point well above the surrounding buildings.[31]

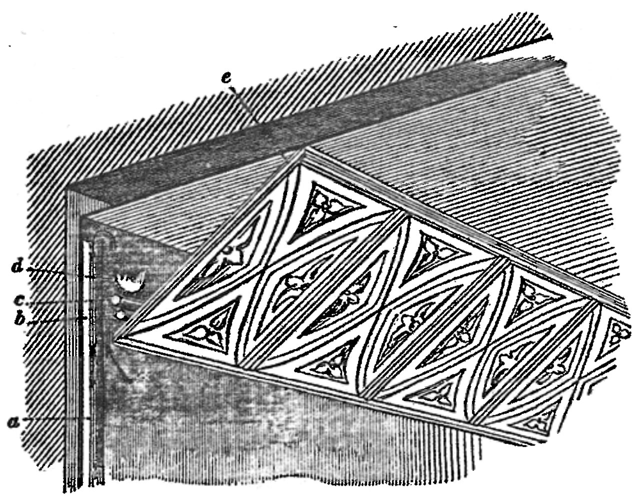


Fig. 16. David Boswell Reid, system of gas lighting behind the glass ceiling panels (Reid, *Illustrations*).

There were complaints, notably about dust which flew up into members' faces when it was dislodged from the carpets, but the great majority of observers seemed to agree that the installation was a great success.[32] Certainly the principles which Reid used here and described in his 1844 book, *Illustrations of the Theory and Practice of Ventilation*, were very

30. "Report of the Select Committee Appointed to Consider the best Mode of Warming and Ventilating the new Houses," *Parliamentary Papers*, 1835, (583.), XVIII. 37. This was printed in abridged form in W. S. Inman, *Principles of Ventilation, Warming and Transmission of Sound*, London, 1836.

31 Reid, *Illustrations*, 270–300.

32. Even Alfred Barry had to admit that Reid's temporary House of Commons scheme worked well. Alfred Barry, *The Life and Works of Sir Charles Barry*, London, 1867, 167 Most engineers were lavish in their praise. Neil Arnott stated in 1852, for example, "Until the late House of Commons existed as ventilated by Dr Reid, there never was in the world a room in which 500 persons or more could sit for 10 hours, day after day for long periods not only with perfect security to health, but with singular comfort."

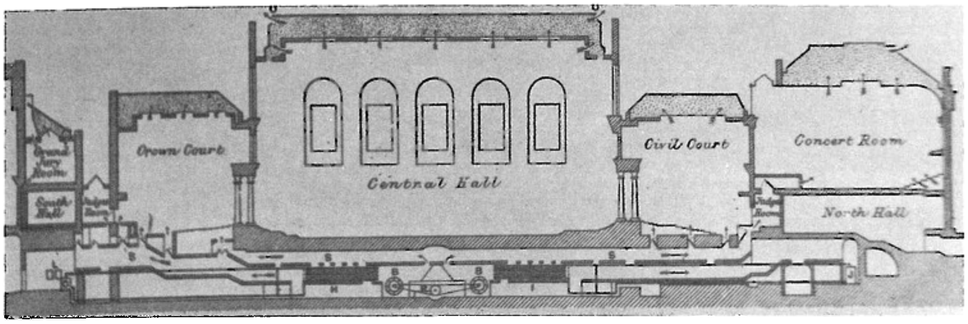


Fig. 17. Liverpool, St. George's Hall, constructed 1841–1854, longitudinal section showing heating and ventilation system installed by David Boswell Reid (*Civil Engineer and Architects' Journal*, XXVII, 1864)

influential. His most novel feature, the glass ceiling with provisions for lighting and ventilation, became a favorite 19th-century device and was frequently used to great architectural effect, as in the bazaars of Owen Jones, for example. The common 20th-century dropped acoustical ceiling incorporating air diffusers, registers, and lighting fixtures is similar in concept.[33]

The first scientific application of mechanical ventilation was also made by Reid. At St George's Hall in Liverpool, designed by Harvey Lonsdale Elmes and built 1841–1854, Reid used four large steam-driven fans to force air, filtered and warmed according to need, into a huge reservoir or "plenum" under the hall. From this plenum, the air escaped into the hall, somewhat as it had done at the Temporary House of Commons, through thousands of holes near the floor. Here, however, pressure produced by the fans forced tempered air into the room and drove the used air in the room out through holes in the ceiling (Fig. 17). This system had been in operation for years and had been thoroughly tested before it was published in 1864.[34] By this time Reid's principles were almost universally accepted and applied.

Unfortunately for Reid, all of these successes were completely overshadowed by events in London. The story of the heating and ventilating of the New Houses of Parliament, by far the most complex installation of the century, is too long to relate in detail, and the narrative has been obscured by partisan accounts.[35] The basic lines of the story, however, are clear. In 1839, after several years' successful trial of his principles at the Temporary House of Commons, Reid was appointed heating and ventilating engineer of the New Houses of Parliament. At first all went well. Reid insisted that his ventilation system required many design alterations, the most important of which was the addition of a new central tower as air exhaust stack. Barry calculated that the additional expense would run to over 50,000 pounds but was quite willing to make the changes, especially since it allowed him to design the great new tower which, he admitted, improved his design (Fig. 1).[36] Soon, however, the cost of Reid's modifications started to climb rapidly, and tempers grew short as the completion of the building was repeatedly delayed. By 1846 relations between the architect and engineer had broken down completely. Reid was stripped of his responsibilities for most of the building, retaining control only over the Commons Chamber and its adjacent spaces. Barry took control of the heating and ventilating of the Lords' Chamber, installing a system quite similar in most respects to that designed by Reid.[37]

The situation soon degenerated further. Reid's position in relation to the architect had never been made clear and each had considerable authority. Reid complained that Barry's design blocked access to air intakes and outlets. Barry charged that Reid removed structural columns and

Parliamentary Papers, 1852, (402.), XVI, 5, 190. Tomlinson, writing in his *Popular Treatise*, 218, in 1850 was of the same opinion. He called it "one of the most extensive and upon the whole, most successful experiments in the warming and ventilation of a building that have been made."

33. Michael Darby and David Van Zanten, "Owen Jones's Iron and Glass Buildings of the 1850's," *Architectura*, IV, 1974, 53–75. Another interesting example is Bassett Keeling's Strand Music Hall discussed in *Builder*, XXII, 1864, 771, and James S. Curl, *Victorian Architecture, its Practical Aspects*, London, 1973.

34. On St. George's Hall, Liverpool, see Quentin Hughes, "Neo-Classical Ideas and Practice: St. George's Hall, Liverpool," *Architectural Association Quarterly*, V, 1973, No. 2, 36–44. Hughes shows that Reid was involved as early as 1841 when construction started, but he does not speculate on Reid's influence on an Elmes design for the Assize Courts crowned with an enormous stack. Compare the illustration on the first page of Hughes's article with Fig. 29 here taken from Reid's *Illustrations*.

35. The only summary to date of the heating and ventilation of the new Houses is in Port, *Houses of Parliament*, 115–119 and 218–231. This account is flawed by the violently anti-Reid bias obtained by consulting architectural rather than engineering journals. For the two sides of the struggle see A. Barry, *Sir Charles Barry*, 146–181, and Elisha Harris's introduction to Reid, *Ventilation in American Dwellings*, xx–xxx.

36. *Parliamentary Papers*, 1841, Sess. II, 51 I. 161–173.

37. A simple description is found in the *Athenaeum*, 3 April 1847, which reports a lecture by Michael Faraday to the Royal Institution on the subject.

was not only jeopardizing the building's solidity but also compromising its fireproofing. Finally, in September 1852, the inevitable occurred and Reid was dismissed altogether. Amid great hostility, he departed for the United States where he continued to write and lecture until his death in 1863.[38] The heating and ventilating of the Houses of Parliament remained a constant problem and a succession of men made alterations in the next decades, bringing the total cost of the mechanical equipment by the end of the century to the remarkable sum of over a half million pounds.[39]

Reid's failure, despite his many earlier successes, was due to a number of factors. Undoubtedly one was his own difficult personality. Another was the scale of the Parliament buildings and the fact that Reid was called in long after the bulk of the building had been designed. Probably most important, however, was the basic conflict between the architect and the engineer. Earlier in the 19th century, the architect himself was usually able to understand and apply rudimentary heating and ventilating technology. But by mid-century matters became so complicated that a new professional, the heating and ventilating engineer, was needed. Reid did more than any other person to advance the standing of such a group by arguing persuasively that heating and ventilation affected the health of the building's occupants and was, therefore, more important than any other aspect of design. He was given unprecedented authority to put his ideas into effect. Events at the New Houses of Parliament made clear, however, that authority divided between architect and engineer was disastrous. The decision to return complete design authority to the architect was a momentous one for both professions. In the future the role of the engineer was clear; he supplied the architect with technical expertise, but it was the architect who made final decisions.

By the time this settlement was reached, a number of the other problems which had plagued heating and ventilation installations earlier in the century were starting to be resolved. Most of the basic equipment used well into the 20th century had been developed and refined. New scientific advances resolved some medical problems, and the almost religious opposition to central heating and forced ventilation by figures like Florence Nightingale subsided.[40] Wildly escalating demands for more air and better temperature control began to taper off.[41] The second half of the 19th century saw an outpouring of technical treatises that described all systems and provided tabulated data which made the principles and performance of each comprehensible to engineer and architect alike.[42]

38. On Reid's final years see *Dictionary of American Biography*, 20 vols., New York, 1928–1958, xv, 475, and his late works, "Progress of Architecture in Relation to Ventilation, Warming etc.," *Annual Report of the Smithsonian Institution*, 1859, 156–213, and his *Ventilation in American Dwellings*. A list of further Reid installations can be found in *Institution of Civil Engineers*, LV, 1879, 156. For an appraisal of Reid's role see John Shaw Billings, *Ventilation and Heating*, New York, 1893, 35–36.

39. Port, *Houses of Parliament*, 226–231.

40. Florence Nightingale, *Notes on Hospitals*, London, 1863, 75–79.

41. On the changing bases for calculating ventilation needs, see George T. Palmer, "What Fifty Years have done for Ventilation," in M. P. Ravenel, ed., *A Half Century of Public Health*, New York, 1921, 338–340. Between the first decade of the 19th century and the 1860s, the amount of air considered necessary jumped from four cubic feet per person per minute to over 60, a figure well above even today's strictest standards. Compare, for example, Tredgold, *Principles*, 73 with Edmund A. Parkes, *A Manual of Practical Hygiene*, London, 1878, 94. For standards today see *Handbook of Fundamentals of the American Society of Heating, Refrigerating and Air Conditioning Engineers*, New York, 1972, 421. Heating requirements, too, showed a marked rise from a temperature of 60° F. or lower in the early 19th century to 70° and even higher, especially in the United States in the 20th. On this see Galton, *Healthy Hospitals, Observations on Some Points Connected with Hospital Construction*, Oxford, 1893, 50, for the outlook in 1865, and William McGuiness and Benjamin Stein, *Mechanical and Electrical Equipment for Buildings*, 5th ed., New York, 1971, 127, for an update.

42. David Boswell Reid spoke frequently of a book of architecture of over 1,000 pages with only one paragraph on heating and ventilation: *Illustrations*, 74. He was probably referring to Joseph Gwilt, *Encyclopedia of Architecture*, London, 1842. The material was considerably augmented in later editions, perhaps because of Reid's criticisms. By the late 19th century almost every major architectural treatise had a section on heating and ventilation. At the same time appeared a flood of new engineering books which, instead of championing a single system, attempted to give information about all competing systems. One of the first of these was the curious *On the History and Art of Warming and Ventilating Rooms*, London, 1845, written by Robert Stuart Meikleham under the pseudonym Walter Bernan. Meikleham had written an earlier sketch of the same subject in 1825. Much better organized was Charles Tomlinson, *Rudimentary Treatise on Warming and Ventilation*, London, 1850 (with seven further editions by 1878); Thomas Box, *Practical Treatise on Heat as Applied to the Useful Arts*, London, 1868 (and many later editions) that provided tables of data. By the last quarter of the 19th century, the Americans started to dominate the field. The earlier works of Louis Leeds, Luther Bell, and others would hardly have been noticed by British architects and engineers, but with the publications by William J. Baldwin, *Steam Heating for Buildings*, New York, 1881, and *Hot Water Heating and Fitting*, New York, 1889, the situation changed. John Shaw Billings, *Principles of Ventilation and Heating and their Practical Application*, London and New York, 1884, and *Ventilation and Heating*, New York, 1893, made major contributions to the field. Engineers from other countries also started to produce major treatises. France, which always had a lively interest in the subject, saw the appearance of the first edition of Eugene Péclet's great study, *Etude sur la Chaleur*, 2 vols., Paris, 1828, with later editions in 1843, 1860, and 1878. Arthur-Jules Morin produced his major work, *Etudes sur la Ventilation* in 1863. A good bibliography up to the 1870s can be found in Charles Joly, *Traité pratique du chauffage et de la ventilation*, Paris, 1869. The Germans produced a very large bibliography but it seems that little of it was widely influential outside Germany. For an excellent bibliography of German titles see *Handbuch der Architektur*, "Anlagen zur Versorgung der Gebäude mit Licht, Warme und Wasser," 3rd part, 4th vol., 119–121, 332–334, 356–359, 393–394.

Technology and Design

In *Architecture of the Well-tempered Environment*, Reyner Banham argues that central heating and forced ventilation developed largely apart from architectural design, and that it was left to designers of the early 20th century to bridge the gap. He advanced three different ways in which this integration could take place and cited an example of each.[43]

Charles Rennie Mackintosh's Glasgow School of Art showed how technology could be used to help solve design problems, in this case the use of large areas of north-facing glass in a chilly city.[44] In the Belfast Hospital the architectural design was completely subordinated to the efficiency of heating and ventilation.[45] The final form of Frank Lloyd Wright's Larkin Building was influenced by the desire to express the building's ventilation system in the exterior massing by means of four massive corner towers.[46]

Banham concludes from these three examples that certain ideas put forward by Sigfried Giedion and other apologists of the Modern Movement require revision. They had advanced the idea that much of the architectural production of the 19th century was compromised by a fundamental dichotomy between technology and the reactionary Battle of the Styles, a problem which was only solved by the great masters of the early Modern Movement. Giedion's attention was focused on structural matters.[47] Banham offers environmental controls as a new class of technology, and finds a similar dichotomy; this also is resolved in the period around the turn of the century. The new technology made possible stylistic advances at the Glasgow School of Art. It was even more important in the Larkin Building where it became a major factor in determining the form of the building. Finally, Banham implies that even a building whose style was very unmodern like the Belfast Hospital should be admitted to the history of the early Modern Movement because in it the technology clearly determined the major lines of the design.

This viewpoint obscures many of the major goals of 19th-century architects. Most were not interested in making every building a direct expression of its structural system or in constructing the whole edifice around mechanical systems. They used both kinds of technology instead to increase safety and comfort, lower costs, and to overcome problems created by their program. If this is accepted as a legitimate goal, it becomes apparent that 19th-century architects and engineers frequently succeeded in integrating aesthetic considerations with a concern for environmental comfort. Contemporary accounts clearly indicate, for example, that Reid's installation at St. George's Hall in Liverpool was a perfectly adequate component in Elmes's splendid design. At Charles Barry's Reform Club, surely a building in which aesthetic requirements were paramount, similar attention was paid to the mechanical equipment. According to Digby Wyatt, the building proved that "the most minute attention to comfort and the satisfactory working of utilitarian necessities are compatible with the exercise of the most delicate sense of refinement and hardihood of genius."[48]

Examples of each of Banham's three points can be found considerably before 1900. An excellent illustration of the use of environmental technology to solve design problems is John Soane house and museum. Here the architect, after trying a number of expedients, turned to the newly developed Perkins high pressure hot water system as the only way he could make his complex interlocking rooms comfortable without encumbering the spaces (Fig. 18). Using this system, he could conceal the small bore pipes under the bases of the marble antiquities in the Belzoni Chamber, place a coil of pipes under the table in the Monk's Room, and run a circuit of piping around the base of his many skylights to counter the flow of cold air which would otherwise fall from the glass.[49] Another example was Osmaston Manor in Derbyshire where the architect, H. I. Stevens, decided that the

43. Banham, *Well-tempered*, 71–92.

44. In the plan published by Banham on page 85 it seems that Mackintosh placed the hot air registers on the inside walls. This is presumably the reason for the subsequent addition of radiators in the window bays which Banham deplores as destroying the spatial concept. The cold air would probably have cascaded down from those windows as originally planned, setting up violent currents.

45. The architects were forced to abandon all the features which had made the pavilion plan so widely accepted in the 19th century: the grassy courts between the wards, the regularity of the plan, the view from the patients' windows. Perhaps the only hospital which imitated this scheme and carried its defects further was Le Corbusier's unexecuted Venice project of 1965: Le Corbusier, *Oeuvre complète 1957–1965*, Zurich, 1965, VII, 140–151. On the failure of the Belfast scheme to influence later hospitals see H. Percy Adams, "English Hospital Planning," *Transactions of the Royal Institute of British Architects*, XXXVI, 1929, 6.

46. Wright's claim that his building was a "simple cliff of brick hermetically sealed (one of the first 'air conditioned' buildings in the country)," Frank Lloyd Wright, *An Autobiography*, 2nd ed., New York, 1943, is simply misrepresentation. By 1943 the use of "air conditioning" had become standardized. It referred to buildings having temperature and humidity control, and no evidence has been presented that the Larkin Building had the latter.

47. Sigfried Giedion, *Space, Time and Architecture*, 3rd ed., Cambridge, MA, 1954, 181–182, 209–216.

48. A. Barry, *Sir Charles Barry*, 95. On the Reform Club heating and ventilation, see Edward Crecy, *Encyclopedia of Civil Engineering*, London, 1861, 1227.

49. This system is described and illustrated in the pioneer heating treatise by Soane's pupil, Richardson, *Popular Treatise*, 51. Sir John Summerson has kindly supplied this information: "The heating system installed here by Soane appears to have been extended in 1891 and reconstructed in 1911 with a new furnace and four circulations instead of three. The 1911 installation was superceded in 1964."

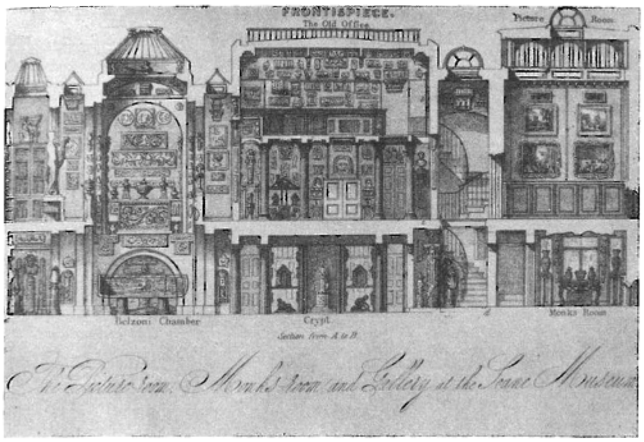
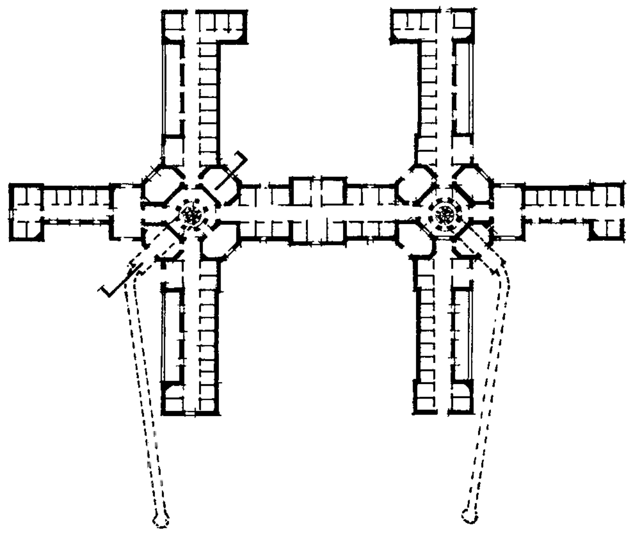


Fig. 18. London, John Soane's Museum, section showing Perkins's high pressure hot water apparatus installed 1831 (Richardson, *Treatise*).



prominent elevated site called for a horizontal design with low roof terraces in the style of James I. To avoid marring the skyline with stacks and to keep the smoke away from the terraces which were to be used by the residents, he turned to John Sylvester, who designed and installed a large hot air central heating and ventilation system that required only a single exhaust stack located a considerable distance from the house.[50]

Subordination of a building's design to requirements imposed by heating and ventilation equipment can be found at Watson and Pritchett's Wakefield Asylum, constructed 1816–1818. A furnace based on Strutt's designs was placed at the bottom of circular stairwells centrally located in each of two sets of radiating wings. The warmed air rose into the well and escaped into the wards through a series of increasingly large transom windows. This system was admirably coordinated with the need for surveillance, since the stairway and transoms were also used to provide uninterrupted views into the various wards (Fig. 19).[51] A much more logical solution to the problem posed by the architects of the Belfast Hospital had been demonstrated in 1875 at the New York Hospital designed by George B. Post. The central heating and mechanical ventilation allowed the wards to be stacked vertically, solving all of the problems tackled at Belfast, but without sacrificing the windows (Fig. 20).[52]

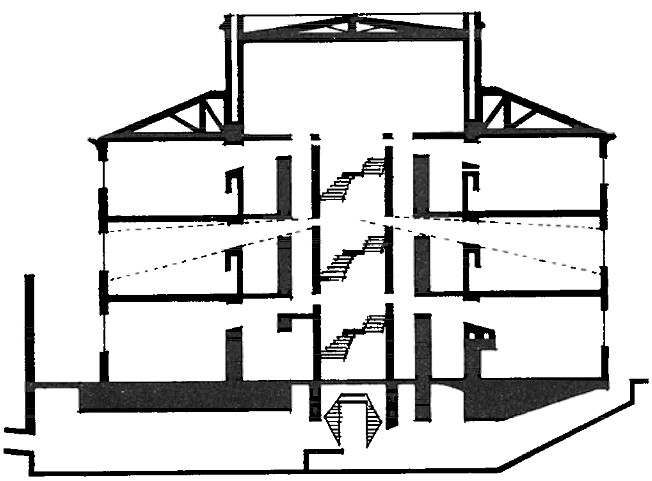


Fig. 19. Wakefield Asylum, constructed 1816–1818, section showing heating system designed by Charles Sylvester (redrawn by Donald Prowler from C. Watson and J. P. Pritchett, *Plans, Elevations and Descriptions of the Pauper Lunatic Asylum lately erected at Wakefield*, York, 1819).

Earlier architects had even used air intake and exhaust towers for expressive purposes (Fig. 2). J. C. Loudon delighted in this kind of imagery, for example in a design for a group of 80 cottages all heated by a single fire at the base of a great stack located in the exact center of the quadrangular complex (Fig. 21). Henry Hornbostel, the early 20th-century American architect, by no means a "modern" designer,

50. The major source on this house is H. I. Stevens, "Remarks on the System of Smoke Conduction and Ventilation adopted at Osmaston Manor," *Transactions of the Royal Institute of British Architects*, April 1851 and reprinted in *Builder*, IX, 1851, 308–309.

51. On the Wakefield Asylum see C. Watson and J. P. Pritchett, *Plans, Elevations and Descriptions of the Pauper Lunatic Asylum lately erected at Wakefield*, York, 1819.

52. On the New York Hospital, see Society of the New York Hospital, *Report of the Building Committee together with an Address delivered on the Occasion of its Inauguration*, New York, 1877, and Eric Larabee, *The Benevolent and Necessary Institution. The New York Hospital 1771–1951*, Garden City, NY, 1971.

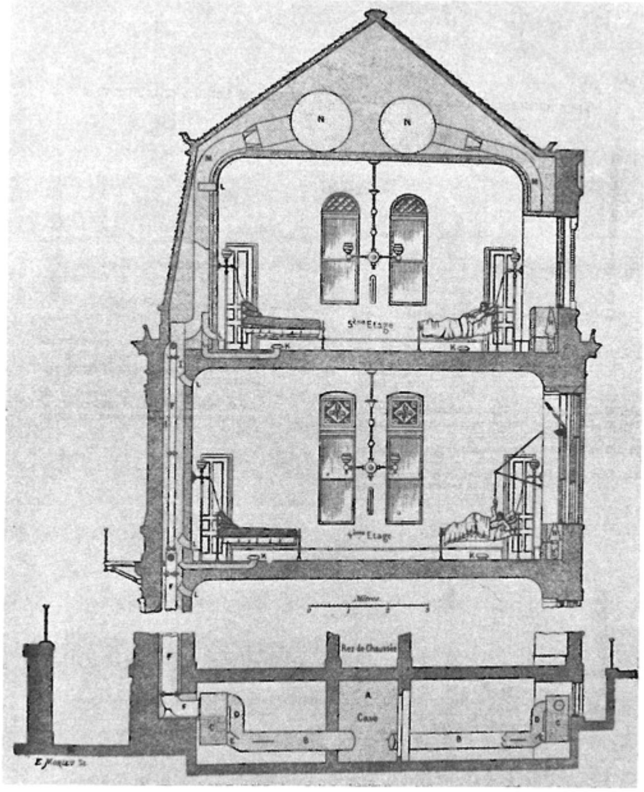


Fig 20. New York, New York Hospital, constructed 1875–1877, section showing the hot air heating system (Casimir Tollet, *Les Hôpitaux modernes au XIXe Siècle*, Paris, 1894)

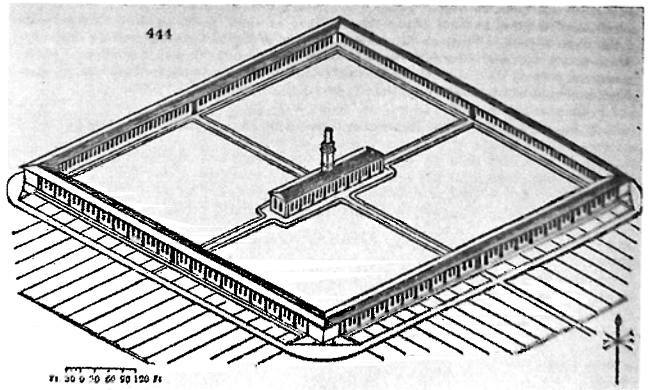


Fig. 21. John Claudius Loudon, scheme for 80 cottages heated by a single central heating plant, perspective of quadrangle (Loudon, *Encyclopedia of Cottage, Farm and Villa Architecture*, London, 1833)

planned the entire Carnegie Institute of Technology around a building called Machinery Hall, crowned by a single stack large enough to serve the central heating plant (Fig. 22) [53]

The integration of environmental technology and building design started early in the 19th century, and its acceptance depended on many developments outside the realm of architecture and engineering, in fields such as chemistry and medicine.[54] The equipment itself underwent a continual process of refinement to meet rapidly increasing demands put on it by users. Architects found themselves forced to change the ways they designed buildings. Some changes, like the necessity of providing giant air towers, were obvious. More important in the long run were modifications that were hardly noticed. In many cases only registers, radiators, and deep recesses in ceiling rosettes betrayed the fact that major innovations were located behind the walls and that an ever larger percentage of the cubic footage of the building was being used for equipment of all kinds (Fig. 23) At Edinburgh house of Sir John Robison, the heating and ventilation system designed by the Sylvesters was extensive and al-

53. For the Loudon scheme see his *Encyclopedia*, 250. The Pittsburgh building is a very important American monument that has never received the attention it deserves. There are brief references in *American Architect and Building News*, XCII, no. 1650, August 1907, James Van Trump and Arthur Ziegler, *Landmark Architecture of Allegheny County, Pennsylvania*, Pittsburgh, 1957, 104–105, also discusses it.

54. See fn. 21.

Fig. 22. Pittsburgh, Carnegie Institute of Technology, now Carnegie-Mellon University, designed by Henry Hornbostel, view along axis of campus toward Machinery Hall.

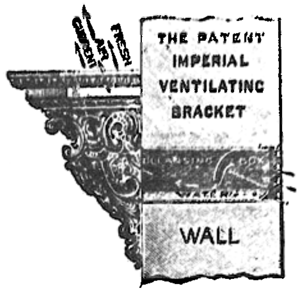


Fig. 23.

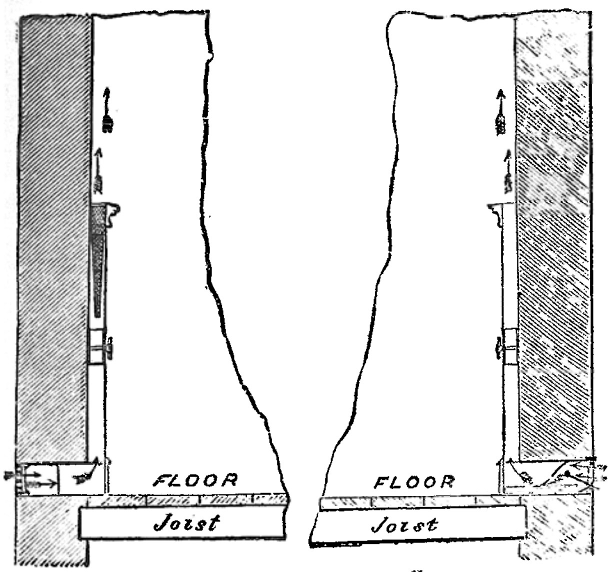


Fig. 23. Ventilation devices (Joseph Constantine, *Practical Ventilating and Warming*, London, 1881).

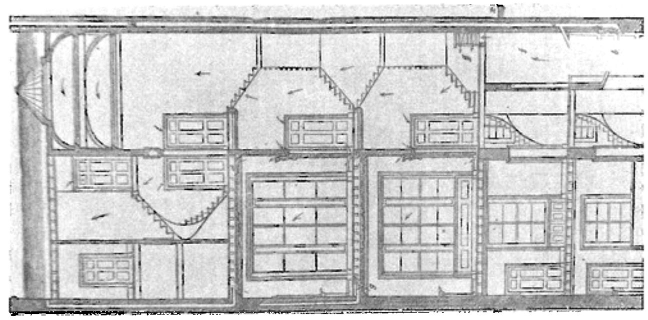


Fig. 24. Edinburgh, Sir John Robison House, section showing heating and ventilating apparatus designed by Charles and John Sylvester, 1830s (London, *Encyclopedia*).

most invisible, since it used the stairwell for air delivery from a cockle furnace placed under the stairs, and a system of ornamental cornices and moldings in each room to allow the air to enter and be extracted (Fig. 24).[55]

To conserve heat, architects became more aware of the value of thick plate glass, double glazing, hollow brick and cavity wall construction, weatherstripping, insulation, double doors, and entrance vestibules. They even recommended

55. This house is similar to but earlier than the Sanbourne House of J. Drysdale and the Octagon of Dr. John Hayward in Liverpool discussed in Banham, *Well-tempered*, 36–39. All of these houses were probably adaptations of a system first used in William Strutt's own house probably in the first or second decade of the century Loudon, *Remarks*, 67 On the Robison house see the description by architect John Milne of November 1839 published in Loudon, *Encyclopedia*, 1198–1204

Fig. 25. Baltimore, Johns Hopkins Hospital, erected 1885–1887, chief designer John Shaw Billings, view of Common Ward interior (*Description of the Johns Hopkins Hospital*, Baltimore, 1890).

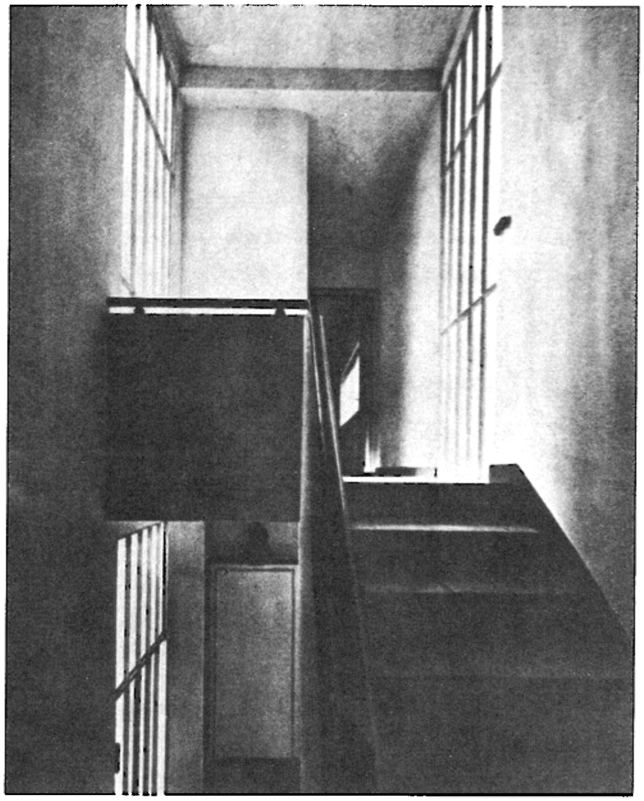


Fig. 26. Le Corbusier, Villa at Vaucresson, 1922, view in stairhall (*Oeuvre complète, 1901–1929*)

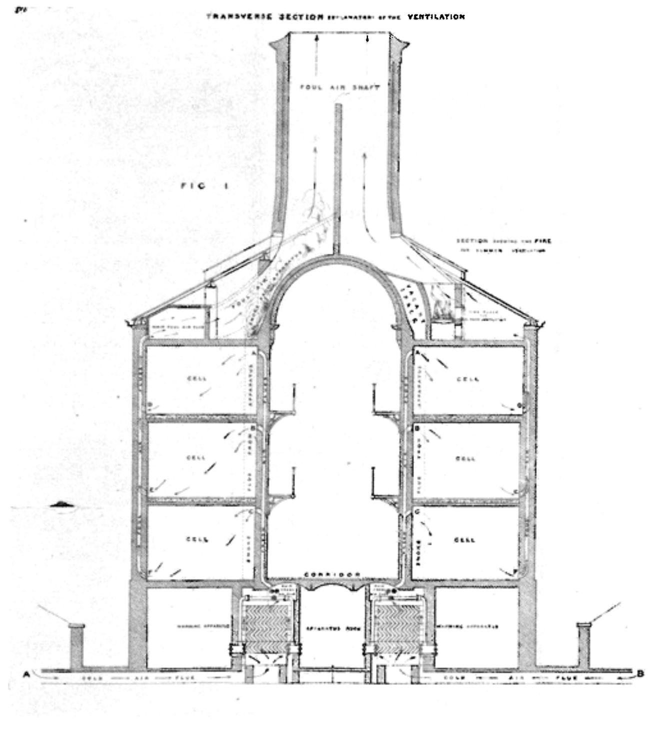


Fig. 27 London, Pentonville Prison, erected 1841–1842, chief designer Joshua Jebb, section showing hot air heating and heat-aided extraction ventilation system (*Report of the Surveyor General of Prisons on the Construction, Ventilation and Details of Pentonville Prison*, London, 1844)

the elimination of curtains and draperies, particularly in hospitals, as well as moldings and applied ornament, because these impeded air flow They specified rounded corners and the use of hard, bright, impervious substances to allow for easy cleaning. The equation of plain, light-colored surfaces with light and air became an article of faith in the great Public Health Movement of the mid- and late 19th century (Fig. 25), and their associations with health made them increasingly attractive in buildings of all kinds in the early 20th century (Fig. 26) [56]

The use of the new technology also had more profound and immediate results on 19th-century architecture. The development of some building types depended on new methods of environmental control. The great increase in the size of greenhouses was accomplished only with major experimentation in central heating. The iron and glass exhibition halls of the late 19th century likewise required comprehensive schemes of heating and ventilating for year-around use When the Crystal Palace was moved to Sydenham for year-around use, Paxton had to provide it with a large hot water heating system The theater could never have developed as it did in the 19th century without great advances in fireproofing, lighting, and ventilation. Penitentiary authorities in the early 19th century demanded absolute isolation for prisoners. Operable windows would have allowed communication between cells, and individual fireplaces would have required officials to enter. The remedy at the first major penitentiaries like Eastern State in Philadelphia or Pentonville in London, was to seal off each cell, then service it from a major central heating and ventilation system. At Pentonville, the designer, Joshua Jebb, devised a scheme in which air was warmed by hot water coils in the basement, rose through ducts in the corridor walls, and entered the cells at the top (Fig. 27) The air was extracted at the bottom of each cell, drawn up through flues on the prison's outside walls, and

56. The literature on these subjects is enormous. On the public health movement, the key early document for this study is "Report of the Commission appointed by the House of Commons to inquire into the best Practical Method of Warming and Ventilating Dwelling Houses," *Parliamentary Papers*, 1857, (320. Sess. 2), XLI, 309ff. On double glazing, see Wyman, *Practical Treatise on Ventilation*, London, 1804, 126. Drysdale and Hayward even suggested that whole buildings could be made of two layers of thick opaque glass with a cavity between them. John Drysdale and John Hayward, *Health and Comfort in House Building*, London, 1872, 66. On hollow walls, Tredgold, *Principles*, 201. On weather stripping, *Builder*, XXIII, 1865, 655. On 19th-century hospitals, see my unpublished dissertation, *The Architecture of the Hospital 1770–1870 Design and Technology*, University of Pennsylvania, 1976.

expelled into the atmosphere by the drawing power of a ventilating fireplace established at the base of a great stack. Each cell became a completely independent unit.[57]

The new technology had many other benefits. It allowed a measure of control over the supply of air introduced into buildings, an important feature in cities with very dirty air. Steam fans made it possible to drive this air through filters and sprays of water to purify it (Fig. 28). Fire danger was reduced because fewer fires were needed in buildings; or they could be banished altogether and placed in central boiler houses, a step that marked a great advance in building safety, when coupled with noncombustible materials and new fire-fighting equipment. The new technology also allowed a more intensive use of buildings. Legislative bodies could sit longer hours, and libraries, museums, and public buildings could stay open at night after gas lighting was introduced and the means of ventilating the lights perfected.[58]

Ultimately the new methods made possible higher, deeper buildings with lower ceilings, and permitted them to be more closely packed together in the city by providing air and artificial light to all parts of the interior. Functions that previously had to be separately housed because of odor or noise problems, notably the kitchens and bathrooms, could be located in the same structure. The architect was able to ignore local climatic conditions and orientation, since problems could be overcome by equipment. The triumph of these developments was the sealed glass box of the International Style, which could be built on any site in the world and all of whose functions could be placed anywhere in the building. Such a solution was not developed in the 19th century, although the technology was available, because few architects saw the desirability or the necessity of doing so.

These design changes constitute the most obvious effects of the new technology. In the long run, however, the technology was more important in changing fundamental assumptions about the nature of buildings. In most 18th-century structures, the occupant had some control over the immediate environment. Almost every room had its own light and heat source that could be simply regulated. By the mid-19th century, however, in a building with central heating, gas lights, running water, and waste disposal, the rooms were connected to a larger system. With automatic controls and

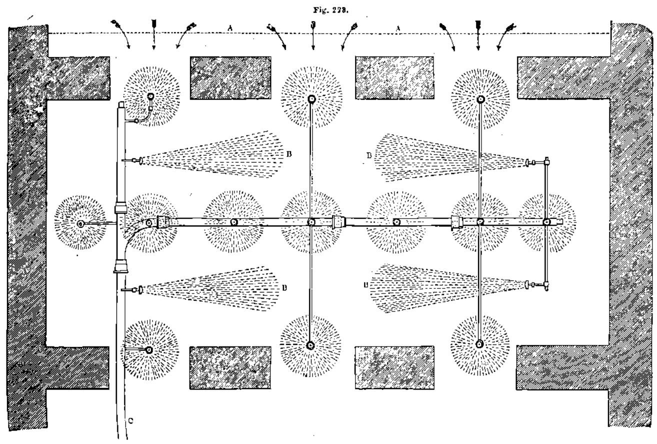


Fig. 28. David Boswell Reid, system of air filtering using sprays of water adopted for use at the Temporary House of Lords in the 1830s (Reid, *Illustrations*).

fixed windows, the occupant was less in control of the surrounding atmosphere. The autonomy of the building itself was drastically reduced as its systems increasingly came to be connected to supply lines from outside the structure. Already in 1819, Loudon had suggested heating a quadrangle of 80 farm houses with a single fire (Fig. 21). Reid suggested central ventilation for a whole architectural complex in Liverpool (Fig. 29). Finally these visions became reality with the work of the American Birdshill Holly, who pioneered district steam heating starting in 1879 in Lockport, New York.[59]

Nineteenth-century writers were aware that these developments were altering the concept of architecture. The old analogy between buildings and living organisms was given a new, more literal significance. The British Museum heating system was described by the *Builder*: "All of this space is as dark as a coal pit, but by the lantern light a curious image of large pipes connected with the boilers may be seen reminding one of the leading arteries which might convey blood through the body of some enormous giant."[60] The French architectural writer César Daly extended this organic analogy to the building as a whole when he wrote that architects knew how to make beautiful forms, but they had to learn how to make their buildings imitate nature and breathe.[61]

Daly, whose *Revue générale d'architecture* was widely read, was even more emphatic in describing Barry's Reform

57. The best source for Pentonville Prison is Joshua Jebb, *Report of the Surveyor General of Prisons on the Construction, Ventilation and Details of Pentonville Prison*, London, 1844. See also "Description of the System of Ventilation and Warming Adopted at the Model Prison, Pentonville," *Mechanic's Magazine*, XLIX, 1848, 26–30. On the Crystal Palace, *Tallis' History and Description of the Crystal Palace and the Exhibition of the World's Industry in 1851*, London, n.d., 105.

58. Banham, *Well-tempered*, 45–70.

59. On Loudon's scheme, see Loudon, *Remarks*, 58. On Reid's, see fn. 34. On Holly, see S. Morgan Bushnell and Frederick Burton Orr, *District Heating, A Brief Exposition of the Development*, New York, 1915, 1–17.

60. *Builder*, XVI, 1858, 289.

61. *Revue générale d'Architecture*, II, 1844, 118–121.

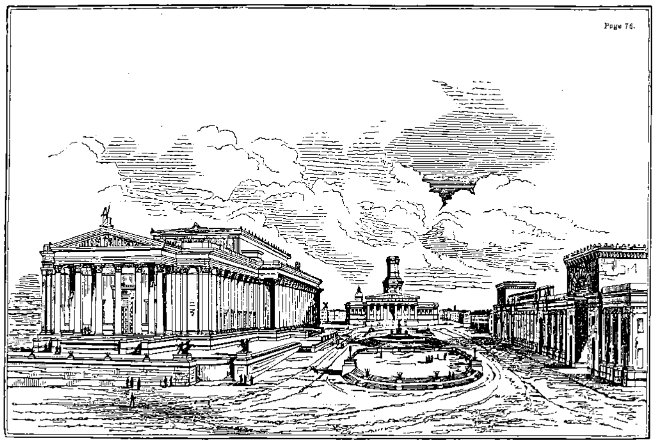


Fig. 29. David Boswell Reid, design for a great central stack for the heating of the civic complex in Liverpool, perspective showing Elmes's St. George's Hall on left, Lime Street Station on right, and porticoed building with a huge ventilation flue in distance (Reid, *Illustrations*).

Club. In an important article in 1857, Daly called this building modern not because of the style but because of its equipment. He wrote that the heating, ventilating, water supply, and electrical bells made of the Club a living organism with a kind of circulation and nervous system, instead of a simple mass of stone. The building was modern because it harnessed modern science and made it the servant of man.[62]

David Boswell Reid used another analogy, that of the machine. Already in the late 18th century this kind of comparison had been made in relation to hospitals, a program in which ventilation was the most pressing problem. Jacques René Tenon, for example, wrote in 1788 that a hospital was an instrument which aided healing.[63] In the description of his plan for a hospital, the physician LeRoy was even more explicit when he called the hospital a machine for treating the sick.[64] Reid extended this analogy, calling the House of Commons, for example, a "piece of apparatus" in his ventilation scheme for the Houses of Parliament.[65] William MacKenzie obviously echoed Reid's own words when he described St. George's Hall in Liverpool as an "immense pneumatic machine."[66]

Reid, in fact, went much further than any of his contemporaries in redefining architecture. "The great and primary object of architecture," he wrote, "is to afford the power of sustaining an artificial atmosphere."[67] And elsewhere: "Though the invisible air is apt to be forgotten amidst the more obvious attractions of architectural art, still in a practical point of view, the visible structure is only the shell or body of that interior atmosphere without which existence could not be supported."[68] This was a radical statement at a time when architectural writers defined architecture in terms of construction or aesthetic principles. It is a notion which only in the 20th century—with the development of the primacy of space over mass, the use of thin walls, inflatable structures, thermal barriers, and the greatly increased concern with energy consumption—has become readily comprehensible and acceptable.[69]

In sum, we have seen that most of the techniques of present day heating and ventilation were developed by the mid-19th century. By this time, many architects were well aware that changes were required by the technology and were exploiting the changes made possible by it, achieving results that satisfied both occupants and critics. Finally, new notions of architecture—buildings defined as systems, as tools, as membranes enclosing space—notions not fully developed until the 20th century, were at least considered as early as the mid-19th century by David Boswell Reid and his contemporaries.

62. *Ibid.*, 1857, 346. Daly's statements about this building make it clear how important he considered the equipment: "Le Club de la Réforme offre des traits essentiellement modernes. Nous ne faisons pas allusion ni au style architectural de la façade, qui est de l'école italienne, ni à la distribution de plans, si intelligent qu'elle soit, mais à quelque chose de plus intime, qui ne frappe pas les yeux, qui n'éveille même pas tout d'abord l'attention, mais qui se fait cependant sentir partout et en tout, et qui aboutit a réaliser un confortable largement étendu.

"C'est que cet édifice n'est pas une masse inerte de pierre, de brique, et de fonte; c'est presque un corps vivant avec son système de circulation sanguine et nerveuse.

"Dans ces murs si immobiles aux regards, circulent en effet des gaz, des vapeurs, des fluides, des liquides; en les sondant attentivement on y découvre des cheminées, des conduits des fils—les artères, les veines et nes nerfs de ce nouvel être organisé—par lesquels se transportent la chaleur en hiver, l'air frais en été et en toute saison la lumière, les eaux chaudes, les eaux froides, la nourriture du corps et tous ces nombreux accessoires que réclame une haute civilization. Par ces voies secrètes la volonté elle-même se manifeste, les ordres de service circulent, les pendules se règlent, et grace à ce secours, les abominables fils de fer des sonnettes cessent d'enlaidir les corniches des appartements. Dans ce monument la science moderne est notre servante."

63. Jacques René Tenon, *Mémoires sur les hôpitaux de Paris*, Paris, 1788.

64. Jean Baptiste LeRoy, "Précis d'un ouvrage sur les hôpitaux," *Histoire de l'Académie des Sciences*, 1787, 598.

65. Reid, *Illustrations*, 275.

66. William Mackenzie, "The Mechanical Ventilation and Warming of St. George's Hall, Liverpool," *Civil Engineer and Architects' Journal*, XXVII, May 1864, 136.

67. Reid, *Illustrations*, 70.

68. *Ibid.*

69. To cite just two definitions roughly contemporaneous with Reid's: Robert Stuart Meikleham, in his *Encyclopedia of Architecture*, New York, 1854, 263, defined architecture as the "art of forming dwellings or buildings of any kind. It may be divided into two parts, the essential and the ornamental." Léonce Reynaud, *Traité d'Architecture*, 3rd ed., Paris, 1867–1870, I, 1, calls architecture "L'art des convenances et du beau dans les constructions." A more recent book which considers some of Reid's concerns is James Marston Fitch, *American Building, the Environmental Forces that Shape It*, New York, 1947.