THE ROAD TO LOCKPORT: HISTORICAL BACKGROUND OF DISTRICT HEATING AND COOLING

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ABSTRACT

The idea of district heating can be traced back to Roman hypocausts, some of which warmed multiple buildings. They were reintroduced into Europe during the Renaissance and slowly evolved into modern hot air, hot water, and steam heating systems. Major heating milestones are summarized, along with requirements to conserve fuel and abate smoke. Early district-heating proposals in London (1623 and 1820s), Pennsylvania (1869), Warsaw and Zürich (1872) are discussed, as are steam systems actually installed at the U.S. Naval Academy (1853), the Philadelphia Centennial Exposition, and a hot water cogeneration system at the Banstead Downs Asylum in England (1876). Birdsill Holly—a Lockport, New York, inventor—installed the first successful commercial district heating system there in 1877. By 1890, more than 50 were installed, many of which are still operating today. District cooling began shortly after that, with successful introduction of systems using brine and ammonia.

INTRODUCTION

Artificial heating of buildings is an enormous industry, touching virtually everyone who lives outside tropical climates. The history of heating, however, has received little attention from historians of technology. Although this history spans many centuries and involves a multitude of interrelated factors including fuels, ventilation, materials, and smoke abatement, the major technological developments were simply divided by the location of the warming fire. One branch encompasses stoves and fireplaces, where the fire is located in or adjacent to the space to be warmed. The other branch removed the fire entirely outside the conditioned space, and, in the case of district heating, completely removed it from the building. The historical foundations of district heating converged in the upstate New York town of Lockport, where Birdsill Holly installed the first successful commercial district heating system, founding an industry that has since installed thousands of district heating and cooling systems.

ANCIENT TECHNOLOGY

The technology of district heating can be traced back to Roman engineering practices, which were reintroduced during the European Renaissance along with science, law, and politics. These devices included the furnace, boiler, pipes, greenhouses, waterworks, and the steam engine, all of which were used by the Romans. In addition, artificial incubators and smokejacks were imported from Africa and Asia, respectively.

The advantages of moving the fire outside the room were known to the Romans, who built thousands of hypocausts in buildings throughout Europe, North Africa, and Britain, some heating more than one building. Unfortunately, we know very little about these devices, since none has survived intact and few documents from that era survive to explain how they were engineered, constructed, and operated. Experiments on reconstructed hypocausts show that they were effective appliances that used combustion gases to warm the floors and walls of the occupied space, rather than delivering warmed air directly. Many heated water for the popular Roman baths while simultaneously warming the surrounding bathing area. Hypocausts generally burned wood, and shortages of this fuel during the later Roman period were a significant factor in the fatal crippling of the Roman economy (Krell 1901; Fusch 1910; Rook 1978).

As Roman rule disintegrated across Europe, hypocausts fell into disuse but never completely disappeared, as examples can be found in buildings constructed in Germany and Switzerland throughout the Middle Ages. Roman boilers heated water for bathing, and pipes of metal and wood were used to distribute hot and cold water, but it is not certain that hot water or steam was used to heat Roman buildings. The first known use of hot water for heating is in the village of Chaudes-Aigues in the Cantal region of France, where a geothermal source was warming several houses by the early fourteenth century and today provides heating for about 150 residences. A resurgence in the practice of communal bathing during the fourteenth and fifteenth centuries stimulated construction of many Roman-style baths in Italy, most complete with hypocaust and hot water. Designs were based on old Roman building manuals, particularly those of the Roman architect Vitruvius, supplemented by careful examination and measurement of nearby extant ruins (Edwards 1982). Architects soon learned how to apply this apparatus for general warming, and by 1550 Italian scientist Guillermo Cardano could write that an entire book would not have been

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sufficient to explain all of the inventions unknown to the ancients, including furnaces in houses (Cardano 1550).

The Romans had also built artificially heated greenhouses to grow plants, and this practice was reintroduced into fifteenth-century Italy, where it was seen by George Ripley, an English cleric and alchemist who introduced the concept into England. He was put to death in 1490 for profane conjuring, including making a pear tree fructify in winter.

Thomas More located his 1517 *Utopia* in a temperate climate, thereby avoiding the need to explain how utopian houses were heated. The inhabitants, however, bred "a vast quantity of poultry by a wonderful contrivance . . . the hens do not brood over the eggs, but the farmers, by keeping a great number of them at a uniform heat, bring them to life and hatch them." Artificial incubators had been used in ancient Egypt by priests, who jealously guarded the operating details. Gian Baptista della Porta used his knowledge of ancient Egypt to construct a successful incubator in Naples around 1588, earning him a reputation as a sorcerer and with it the unwelcome attention of the Inquisition. Perhaps aware of Ripley's fate, he wisely gave up his experiments (Devaux 1892). Work on incubators was continued outside the reach of the church by men such as Cornelis Drebbel, who improved incubator efficacy significantly in the early 1600s by adding a thermostat to regulate the heat (Gibbs 1948).

Roman cities were supplied with water from extensive aqueducts, and many Roman engineering details were included in the London water supply built in 1582 by the Dutch inventor Peter Morice. These included a waterwheel-driven pump to force water to a hilltop reservoir, where it flowed through lead pipes to numerous houses. Water had earlier been in more limited applications, such as providing hot and cold running water to English castles as early as 1150. Morice's system was soon overtaxed, however, and a second was built in 1613 to bring "a new river" to London. This system was more successful and portions of the piping were used for more than 300 years.

The Greek manuscripts describing Hero of Alexander's æolipile, or rotary steam engine, were rediscovered and translated during the Renaissance and had an enormous and immediate influence on technological development. In 1594, English lawyer and gardener Hugh Plat, clearly influenced by Hero, described a means to dry gunpowder without danger of fire, using water that may be "heated in another room, for the more safety against fire." Hero's writings also led to the development of the steam engine.

All of this information was available by the early seventeenth century and almost certainly was used by Cornelis Drebbel in proposing a district heating system for London. The City of London had depended on coal since consuming its accessible forests for fuel and timber during the reign of Elizabeth I, who herself had to live "greatly grieved and annoyed with the taste and smoke of coal." Attempts to outlaw coal burning in London dated back to 1306, but despite numerous fines and imprisonments, the lack of alternatives forced increased dependence on this noxious but plentiful fuel. Smoke was exacerbated by periods of cold weather, which, before accurate thermometers, was measured by the freezing over of the Thames. During the bitter winter of 1622-23, for instance, it froze from the last week in November to mid-December and from January 20 to February 12. Heavy carriages could cross the river and entrepreneurs set up "booths that sold drinks and other things upon the ice."

Cornelis Drebbel, whose incubator and thermostat have been mentioned, also built a working submarine and introduced lenses and thermometers into England. A man of many talents, Drebbel approached Charles, Prince of Wales and future king, in early 1623 and proposed that "since water had now been brought to London and was distributed by means of artificial pipes, a similar system could be adopted for the supply of heat." Furthermore, "every householder would be able to roast and boil their food without the need for burning wood or other fuel." Drebbel wanted £20,000 sterling to execute this scheme, but the prince was more engrossed in hurrying off to Madrid to woo the Spanish Infanta. She was not impressed, Charles had to settle for a French bride, and Drebbel went to work for the Royal Navy. London kept its smoke for another three centuries (Harris 1961).

Perhaps more details of Drebbel's fantastic scheme will be found, but without question he had described a system of district heating, complete with distribution to individual houses for heating and cooking. Was it practical? Without knowing more, it is impossible to say. At the very least it would have been a challenge, even for a man of Drebbel's talents.

Over the next century, improvements in heating technology were confined to fireplaces and stoves, but still driven by the "little Ice Age," conservation of scarce fuel, and smoke abatement. The introduction of oranges and other exotic and expensive tropical plants also helped develop heating technology, as people attempted to grow them locally. England's climate is not naturally friendly to orange trees, but during a long spell of mild winters in the mid-1600s simple stoves had sufficed to heat rudimentary greenhouses, giving many English gentlemen the fruits of luscious tropical gardens. The winter of 1683-84 produced the longest frost in English history (freezing the Thames from early December to February 5) and John Evelyn reported his substantial horticultural losses to the Royal Society, including even the demise of his prized tortoise. Evelyn found that common stoves not only failed to provide a uniform heat, but "wasted and vitiated the stagnant and pent-in air, without any due and wholesome succession of a more vital, and fresh supply." His solution was to install a new type of air furnace "such as chemists use in their laboratories." The furnace, which could burn "any sort of fuel whatsoever," was erected on the outside wall of the greenhouse, heating outside air passing in pipes through the firebox and underneath the floor to the far end of the greenhouse. A thermometer governed a register that controlled the amount of airflow to maintain the desired temperature. Air was exhausted through a ceiling-level opening into the furnace chimney, ensuring thorough ventilation of the space (Evelyn 1691). Shortly thereafter, Sir Dudley Cullum adopted Evelyn's hot-air furnace to his Suffolk house (PTRS 1694).

Early in the eighteenth century, Nicholas Gauger of Paris wrote a book describing various improvements to stoves and chimneys which was translated into English in 1715 by the Huguenot chemist John Desagüliers. Five years later Desaguliers obtained a patent for the use of steam heating in manufacturing. Although he wrote several important scientific works, he does not mention if or how steam was ever used in this manner, although he did provide an excellent description of his human-powered mechanical ventilator that exhausted air from the House of Commons. The French scientist A.F.L. Réaumur found time to make improvements to incubators, hoping to reduce the price of chicken in Paris and fulfill Henry IV's dream that every peasant could have a chicken in his Sunday pot. In 1745, Colonel William Cook described to the Royal Society a method for heating houses with steam from a kitchen boiler, using a series of pipes placed along the outside walls of a house. In 1749, Benjamin Franklin installed a hot-air furnace that heated 10 row houses in Philadelphia. Matthew Boulton and James Watt used steam and hot water for heating as early as 1777, not only in their own Soho Manufactory, but in a number of other facilities. Watt also experimented with a steam radiator around 1784, while Boulton installed steam heating in a house in 1795 and planned an expansion to serve four others nearby. A factory complex designed by Boulton and Watt in 1796 included a separate boilerhouse. By the early 1800s several steam systems were heating houses, greenhouses, and factories, but little attention had been given to the theoretical and scientific aspects of heating. This changed with the appearance of American expatriate Benjamin Thompson.

Thompson, born in Massachusetts, lived in Rumford, New Hampshire, and remained loyal to the Crown during the difficulties of 1776, serving George III as both soldier and spy. Like most Loyalists, he chose to leave the new United States of America and return to England, where he was rewarded with a pension and knighthood. Unable to find employment there, Sir Benjamin entered the service of Carl Theodor, Elector of Bavaria, where he worked tirelessly to ameliorate the living conditions of the poor as a means of promoting political stability. When Carl Theodor became Holy Roman Emperor, he made Thompson Count Rumford.

Rumford performed many practical experiments on the nature and uses of heat, including classifying the insulating values of various materials. In 1802, he proposed that the French Academy heat its building with steam. He noted that the boiler "can without any inconvenience be placed outside the hall, and even at a considerable distance, it may be put in an out-of-the-way place, where there will be every security against accidents from fire, and at the same time ease in storing the wood intended for the boiler, and in regulating its consumption." He also invented the first expansion joint for steam piping.

Where steam engines were put to use, steam heating usually appeared as well. Manufacturers heated their houses with steam piped from their factories; Matthew Murray's residence was known as Steam Hall. Most early steam engines were powered by steam only slightly above atmospheric pressure and depended on the vacuum caused by condensation to move a piston. An Oxford brewer patented the use of the condensed water for heating purposes, but cogeneration development was slow until the high-pressure engine made it possible to eliminate Watt's cumbersome condenser while making the exhausted steam available for thermal purposes.

Oliver Evans was the greatest promoter of high-pressure steam engines in America, and he always noted the many uses for the exhaust steam. Exhaust from one of Evans' engines heated the Middletown Wollen Manufacturing Company in Connecticut in 1811 and the practice was quickly adopted by other steam engine users. James Nasmyth often used this process in his English factories, and its use was of incalculable value in economically justifying the introduction of steam engines into factories that otherwise used water power and a separate heating system. Edwin Chadwick, the great sanitary reformer, noted in 1842 that several factory owners used the waste steam from their engines to heat water for public baths (Chadwick 1842).

Hot water was also used as a heating medium. Swedish engineer Mårten Triewald is credited with using hot water in a greenhouse in 1716. William Stuckley's 1724 travel guide to England, *Itinerarium Curiosum*, included a description of an old Roman hypocaust found near Hereford that used lead pipes to distribute water. Stuckley thought this "an excellent invention for heating a room, and might well be introduced among us in winter time." In 1777, the same year that Boulton and Watt were using hot water in their Soho factory, a multitalented Frenchman, Bonnemain, introduced it into the Château du Pecq near Saint-Germain-en-Laye, where it worked successfully and remained in service for several decades. Bonnemain also used hot water successfully in an incubator, utilizing a clever thermostat with a dial to easily change the temperature setpoint. Although Bonnemain wrote a pamphlet on his incubator in 1816, his application of hot water for heating buildings is of greater interest here. In the early 1780s a Bonnemain-type system was used to heat Potemkin's Taurida Palace in St. Petersburg, Russia, an enormous structure of three separate buildings, including a heated conservatory and a ballroom where a regiment of soldiers could drill.

Hot water warmed at least one English greenhouse by 1800 and was commonly used in St. Petersburg in the early years of the nineteenth century. The Marquis de Chabannes, a French adventurer who had fought in the American Revolution and left France during its own, introduced a hot-water system quite similar to Bonnemain's into Britain in 1816, which one account claims that Chabannes saw during an earlier visit to St. Petersburg. Chabannes installed his system in several London buildings, but soon returned to greater adventures on the continent. Hot water appears again in 1822 in an English greenhouse, but its constructors claim to have had no knowledge of earlier systems, although accounts of them appeared regularly in English gardening journals.

After the late 1820s, hot water heating was widely used throughout Britain. Low-temperature systems were initially more popular, but high-temperature water was promoted by another American expatriate, Jacob Perkins, who had moved to England in the 1820s and experimented with superheated water. His son, Angier March Perkins, patented a high-temperature hot water system in 1832 that circulated 400°F (204°C) hot water in small, thick-walled tubes originally fabricated from surplus rifle barrels. These became very popular and were installed throughout Great Britain and Europe, with at least a few introduced into the United States at the Philadelphia Penitentiary, Colonel Thomas Perkins' residence in Boston, and the New York Customs House. Hot-water heating systems were also installed in Russia in the 1840s by Immanuel Nobel, father of dynamite inventor Alfred Nobel.

Systems that combined media also came into use. A single boiler in a building could supply several steam or hot water coils in ventilating systems located throughout a building, avoiding construction of a single large ventilator while giving greater control over the supply air temperature. Angier Perkins made steam in remote locations using a hot-water-powered steam generator. Walworth and Nason installed a hot water system in the White House in 1853, using low-temperature hot water to avoid the odors introduced by air contacting high-temperature metals. The new wings added to the U.S. Capitol building in the mid-1850s each had a steam boiler plant in the basement to supply steam to radiators and coils. These were soon expanded into the original Capitol building to replace hot air furnaces.

Circulation of hot water and hot air depended on convection prior to the introduction of forcing devices. The introduction of Desaguliers' hand-powered ventilator has been mentioned, which was followed by mechanical ventilators. The first hot water circulating pump, powered by a chimney smokejack, was introduced by Busby in 1832. As buildings became larger and more complex, advocates of hot air, hot water, and steam all improved their apparatus to make them viable in the larger structures. All heating systems, however, still required a fire, with the exception of some early solar apparatus and a short-lived attempt to make heat by using a waterwheel to turn one large metal disk against another.

Large buildings had been heated for centuries with individual stoves and fireplaces in each room, but servicing these multiple fires became a nightmare as bituminous coal came into use and labor costs rose. Steam boilers began to be used in smaller heating systems but, unless properly maintained and operated, they could easily explode. Introduction of pumps and elevators to move water and people to higher floors greatly increased the need for power and thus more powerful boilers. Authorities responded by regulating boilers and licensing boiler operators, providing much-needed safety but at an increase in costs. At the same time, smoke abatement ordinances began to appear in American cities, often copied from older British laws. Heating was becoming even more of a nuisance.

In this environment, the concept of centralizing the production of heat was becoming very attractive. In an 1808 letter, the engineer Robertson Buchanan wrote: "It occurs to me, that steam might be applied for warming buildings in London, in many instances, with great advantage. For instance, the bed-rooms of large inns and hotels; as also large warehouses or shops, where a number of neighboring buildings might be warmed from one boiler, which would save much in attendance and fuel, as well as in the cost of the apparatus" (Buchanan 1808). Prominent British architect J.C. Loudon suggested adding a central boilerhouse to small country estates for heating the residences, greenhouses, stables, and other buildings, while also providing power for the various mills, machines, and pumps used on the premises (Loudon 1817). In 1812, B. Deacon proposed to supply hot air for heating and ventilating to all the houses in Red Lion Square from a small ornamental building. The English firm of Conrad Loddiges and Son introduced a district steam system into its Hackney nursery in 1819. An Englishman traveling in Paris in 1828 reported that city "to be very favorably circumstanced for being heated by public companies," although he was unprepared to say "whether steam or hot water would be better adapted for this purpose." A trash-burning district steam system was operating at a British customs office in 1828. Many similar proposals were advanced in England after the 1820s, often designed to relieve the miserable living conditions in worker housing and to abate the enormous smoke problem that had accompanied the industrial revolution there. Angier Perkins said that he could "heat a whole parish from one fire," and the eminent engineer Marc Isambard Brunel noted in 1836 that "the laying on a heat supply to a long range of dwellings by Mr. Perkins' system from one common source . . . would be of inestimable importance in London where the high price of fuel is a burden to the poor." Dr. Charles Barham, a colleague of the reformer Chadwick, added that heat from any number of factories "might be distributed over extensive districts, and buildings might be warmed and workshops supplied with warm water." Given the enormous body of writings calling for such systems of heating, it is likely that some were actually built, although no specific evidence supports this speculation. A proposal to establish a General Steam Supply

Company was made to Sir William Fairbairn in 1858, but he wrote that he "could not look upon this project as one likely to succeed."

The technology to build such systems was certainly available by 1851, when a remote boiler plant supplied the enormous Crystal Palace Exhibition in London. Two years later a district steam system installed by the Baltimore firm of Hayward, Barlett & Company was heating 20 buildings in that city with a cubic content of "half a mile," while a second warmed the new buildings of the new United States Naval Academy at Annapolis, Maryland. The Academy's faculty examined the system in early 1854 and made several suggestions for correcting problems with the underground piping, but also recommended that the system be expanded to supply steam to other buildings. The system appears to have worked well, for it was expanded after the Civil War and, greatly modified, still operates today. America was slowly adopting district heating. By 1867, Illinois' new capitol building was supplied with steam through a tunnel from a boiler plant several hundred feet away. Pennsylvania granted a charter to the Steam Heating Fuel Company of Pennsylvania on July 2, 1869, giving authority for the company "to dig such trenches in, along and across the public streets, lanes, roads, alleys and side-walks, for the purpose of laying, re-laying, taking up and repairing their pipes for the distribution of steam heating." A low-temperature hot water district heating system with cogeneration was installed in 1876 at the Banstead Downs Asylum in Surrey, England.

The general quality of American steam engineering was greatly improved by the many young men who served in the U.S. Navy's engineering branch during the Civil War. It is not surprising that these men made major advances in heating and many other fields after the war. Another result of the war was the introduction of direct-pressure water supply systems into American cities. Prior to the war, water pressure at a hydrant was only provided by gravity, which severely constrained construction and growth of water systems. Steam- and water-powered pumps had been used since Roman times to fill reservoirs and standpipes, but gravity was the sole means of maintaining pressure in distribution lines. The fire engine had been invented to deliver water under pressure, but even replacing the hand-powered engines with steam did not produce a satisfactory solution. Even under the best of conditions, firemen had to be notified, respond to the engine house, make a fire to raise steam, and move the entire apparatus to the fire scene. This rarely could be accomplished in less than 45 minutes and often required much longer, during which an initially small fire could become an uncontrollable inferno. In freezing weather, it was not uncommon for the entire engine apparatus to become a solid block of ice, leaving fires to rage unchecked.

The city of Lockport, New York, faced such a problem during the winter of 1862-63. Most of the city's volunteer firemen, who relished the uniforms and pageantry of parades as much as, if not more than, fighting fires, had enlisted, leaving the fire department in less qualified hands. Several fires struck Lockport that winter and only extraordinary luck prevented the city from burning to the ground. A local manufacturer, Birdsill Holly, decided that enough was enough and set out to find a solution. Holly was from a family of mechanics and already held 19 patents, including the rotary pump used on the Silsby fire engine. His solution was to install a turbine-powered rotary pump on the water race that served the Holly Manufacturing Company and thus control the speed of the pump with a pressure regulator that would maintain a constant water pressure by controlling the flow of water passing the turbine. The water was delivered through a network of underground pipes to hydrants, and firemen responding to a fire now only had to bring hoses, connect them to the hydrant, open a valve, and play water on the fire (Pierce 1993).

It was an idea of marvelous simplicity, and it does not appear that Holly intended to install others, for he had solved Lockport's immediate problem. Word of the system soon spread, however, and in 1865 he installed one in his hometown of Auburn, New York, which also served as a domestic water supply, whereas Lockport's had been designed for fire service only. Other installations followed and Holly patented his idea in 1869. Later improvements included automatic alarm systems and variable pressure controls that permitted fire department officials to increase water pressure during large fires. His marketing efforts were greatly aided by the great fires in Chicago (1871) and Boston (1872), both of which burned despite proximity to enormous bodies of water that could not be brought to bear on the fire. Holly prevailed in several patent infringement lawsuits against others, and the Holly Manufacturing Company sold hundreds of systems throughout the United States and Canada. Many cities that originally had relied on reservoirs, including New York and Philadelphia, installed direct-pressure water systems for fire protection in the early twentieth century.

Like other American inventors, Holly became bored with success and dabbled with other ideas, including a proposed steel-frame skyscraper in the early 1870s. Finding no one else interested in this, he dug up his backyard in the summer of 1876 and installed 500 feet (152 m) of steam line to test the feasibility of sending steam through underground pipes. Finding it successful, he ran a line to warm a neighbor's house and persuaded several Lockport businessmen to invest a total of $25,000 in the Holly Steam Combination Company, which was incorporated in early 1877. He obtained patents on various components used in the system, such as expansion boxes and meters. The company purchased a used boiler and installed several thousand feet of pipe under the streets of Lockport to test the concept on a larger scale during the following winter. Concluding that it was successful, the company offered to sell rights to use the system in other cities. Auburn, which had earlier enjoyed the second Holly water system, also installed the second Holly steam system in the summer of 1878. The gas company in

Springfield, Massachusetts, installed a system that used its existing steam boilers, making it the first American public utility to offer a complete system of affordable heat, light, and power. A third system was installed by the Detroit Steam Supply Company. Another was installed at the National Home for Disabled Volunteer Soldiers in Dayton, Ohio, which had previously purchased a Holly water system. In addition, companies were formed in Toronto, Ontario; Berlin, Germany; and New York City and Rochester, New York, but for various reasons did not install systems that year.

The steam systems all operated successfully and nine more were installed the following year, including commercial systems in Troy, New York; Dubuque, Iowa; Belleville, Iowa; Milwaukee, Wisconsin; and London, Ontario. Institutional customers included the Clifton Springs (New York) Sanitarium; the Western House of Refuge in Rochester, New York; the Binghamton, New York, insane asylum; the Syracuse railroad yard of the Delaware, Lackawanna & Western Railroad; and in A.T. Stewart's Garden City development on Long Island. The latter was the first of many systems that were installed in planned and corporate communities.

Again, all were successfully installed and operated during the winter. The story in 1880 is much the same, with new Holly systems going into Burlington, Iowa; Hartford, Connecticut; and Denver, Colorado, while competitors installed systems in New York City and the new town of Pullman, Illinois. In addition, Holly installed a new type of system in Lynn, Massachusetts, which took advantage of cogeneration. Although many individual buildings used exhaust steam from engines for heating, the Lynn system utilized two distribution mains. The first main delivered steam at 80 psig from the boiler plant to customers' engines. The exhaust from these was then collected and distributed in the second pipe at about 5 psig.

Holly's initial steam meter was not particularly accurate and was rarely, if ever, used in these early systems. Contracts were typically for a specific amount based on the customer's prior fuel purchases. This was not perfect, but appeared to be adequate for normal weather. Unfortunately, the winter of 1880-81 was very severe in the Midwest and Northeast, and was memorialized later in *The Long Winter*, Laura Ingalls Wilder's book about a bitterly cold season in South Dakota. The worst blow fell on the Milwaukee Steam Supply Company, which was then in its second season. Like many steam plant operators, the Milwaukee company purchased the cheapest coal possible, which was virtually coal dust there. It did make steam at a low cost, but the plant happened to be across the street from Milwaukee's city hall and the offices of Dr. Orlando Wight, city public health office and antismoke crusader. Wight had already served notice on the company to cease and desist making smoke before the winter turned foul, and was proceeding with court action at the time the company went bankrupt in April 1881.

The subsequent proceedings show that the company had no meters, not just on customer services but none anywhere in the plant. Management had not even bothered to weigh its coal or keep track of how much had been purchased. On the other side of the ledger, many customers had not paid for steam and the company had not pursued them, since the managers had spent their time expanding the system to sell more steam. The new managers promptly discovered that the coal company had been shorting deliveries by at least half. Customers were dunned and, when no payment was made, the company had to dig up the street to pinch the pipes shut, since no street valves had been installed and the delinquent customers refused access to the valves inside the building. More than one fight between customers and steam company employees was reported in the Milwaukee papers. As a final resort, the plant was taken over by its remaining customers and operated as a cooperative, but the debts were so enormous that the financial situation was untenable. The plant shut down and Milwaukee had to wait more than a decade for another company to try again.

In 1881 the stock of the Holly Steam Combination Company and the rights to Holly's steam patents were purchased by investors associated with Standard Oil and the New York Steam Company. The new firm, the American District Steam Company, was very circumspect about its operation and, as far as is known, never published a list of its customers or installations. Some of this was due to competitive systems that had appeared in the district heating marketplace. Even before Holly had dug up his backyard, John A. Coleman of Providence had patented a district steam fire-suppression system that also was useful for heat and power. Another patent was granted in 1876 to William Bliss of Springfield, Massachusetts, for a hot air district heating system. A franchise for such a system was granted in Cincinnati in 1880, but it does not appear that the system was installed, and it was very unlikely that it worked if it was installed.

More formidable competitors were to be found in the streets of New York. William C. Baker's United States Heat and Power Company, which had installed the system for the Pullman plant in Chicago, obtained a franchise to install a system in lower Manhattan and it was actually installed by the American Heat and Power Company in late 1881, the same time that the New York Steam Company was installing its system. The American company was faced with the problem of its pipes exploding, sending pavement and insulating lampblack through store windows and onto passersby. After about six months of operation, it shut down in the face of a grand jury investigation of the explosions. A second system was installed by William E. Prall's National Superheated Water Company, which, like the Perkins system, distributed 400°F hot water. This was flashed into steam in each building and returned as condensate to the plant. Each of these systems promoted its usefulness in cooking and, in November 1880, the Prall company hosted a banquet for the American Society of Civil Engineers at its 125th Street plant that was entirely prepared with superheated water (except for the French champagne). Prall was unable to attract adequate financing for his system for several years until Theodore N. Vail decided to invest his telephone fortune in the district heating business. Companies were formed in several cities and a large system was installed in the heart of Boston. The Boston Heating Company ran successfully for almost two years, when it was discovered that the open return pipes had corroded out. The company was unable to solve the problem and was forced to dissolve, costing Vail several hundred thousand dollars and making high-temperature hot water unwelcome in the United States for 50 years.

As quickly as they had appeared, the competitors faded away and the steam business belonged to Holly for most of the 1880s. At least 50, and probably more, Holly systems were installed in this period. Most were single-pressure systems, although a second Lynn-type system was installed in New Haven, Connecticut, in 1882, while the San Francisco Steam Company, formed in 1886, bought exhaust steam from the many isolated plants in that city and sold it to other customers. Holly steam companies provided steam to power many early electric light companies in Hartford, Burlington, and several in New York. The New York Steam Company was itself in the electric lighting business for a time in the mid-1880s, selling the exhaust steam to nearby buildings. It did not take long for the profit potential of exhaust steam to be recognized by the electric light industry. In 1886 Albany Edison was chartered to provide steam as well as electricity and it was soon supplying several customers. The following year Boston Edison did the same, starting a system that has continued operations to the present day. The great blizzard of March 1888 proved the value of district heating, as steam customers were often the only ones who had heat, since fuel could not be delivered through the blocked streets. The following year several more Edison electric stations added district heating revenues, including Indianapolis, Kansas City, Rochester, Philadelphia, Duluth, and Chester, Pennsylvania.

Companies in the late nineteenth century not only sold heat, but were paid to take it back. The New York Steam Company promoted the use of steam-powered absorption chillers in 1885 to increase summer steam loads. What became the district cooling industry had many false starts in the 1880s before companies began offering this service in several American cities. Two different cooling technologies were used, not including a compressed-air system that provided power and cooling in Norwalk, Connecticut. The first of these systems was based on older ideas and distributed brine through a system of underground mains similar to that of a low-temperature hot water system. The Manhattan Refrigerating Company currently operates a brine system that dates back to 1890.

The other method of district refrigeration was to distribute ammonia at up to 150 psig. This would be expanded on a customer's premises and returned through a vapor line, with a third line providing a vacuum. This was the more widely used system, and one of the original refrigeration companies provided ammonia service in St. Louis until the 1960s, when it was unable to afford the cost of moving lines to avoid a new highway.

Although primarily concerned with cold-storage applications, many of these systems also provided space cooling and humidification control in hospitals, restaurants, and office buildings, although commercial air conditioning did not become widespread until the early 1930s. District heating companies in Seattle and Baltimore first supplied district cooling before entering the heating business. In addition, many heating companies made and sold artificial ice before residential refrigerators became popular.

District heating and cooling today provides a significant portion of thermal energy supplied to institutions and urban areas throughout the world. With the exception of certain systems operated by American electric utilities, district heating has grown and prospered since its introduction more than a century ago. This growth will undoubtedly continue as the substantial economic, environmental, and safety costs of installing and maintaining individual buildings' heating and cooling apparatus become fully realized by building owners and operators. The history of this technology clearly shows that the fundamental purposes for which district heating and cooling were first conceived and installed have not only remained valid, but increased in importance over the past century.

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