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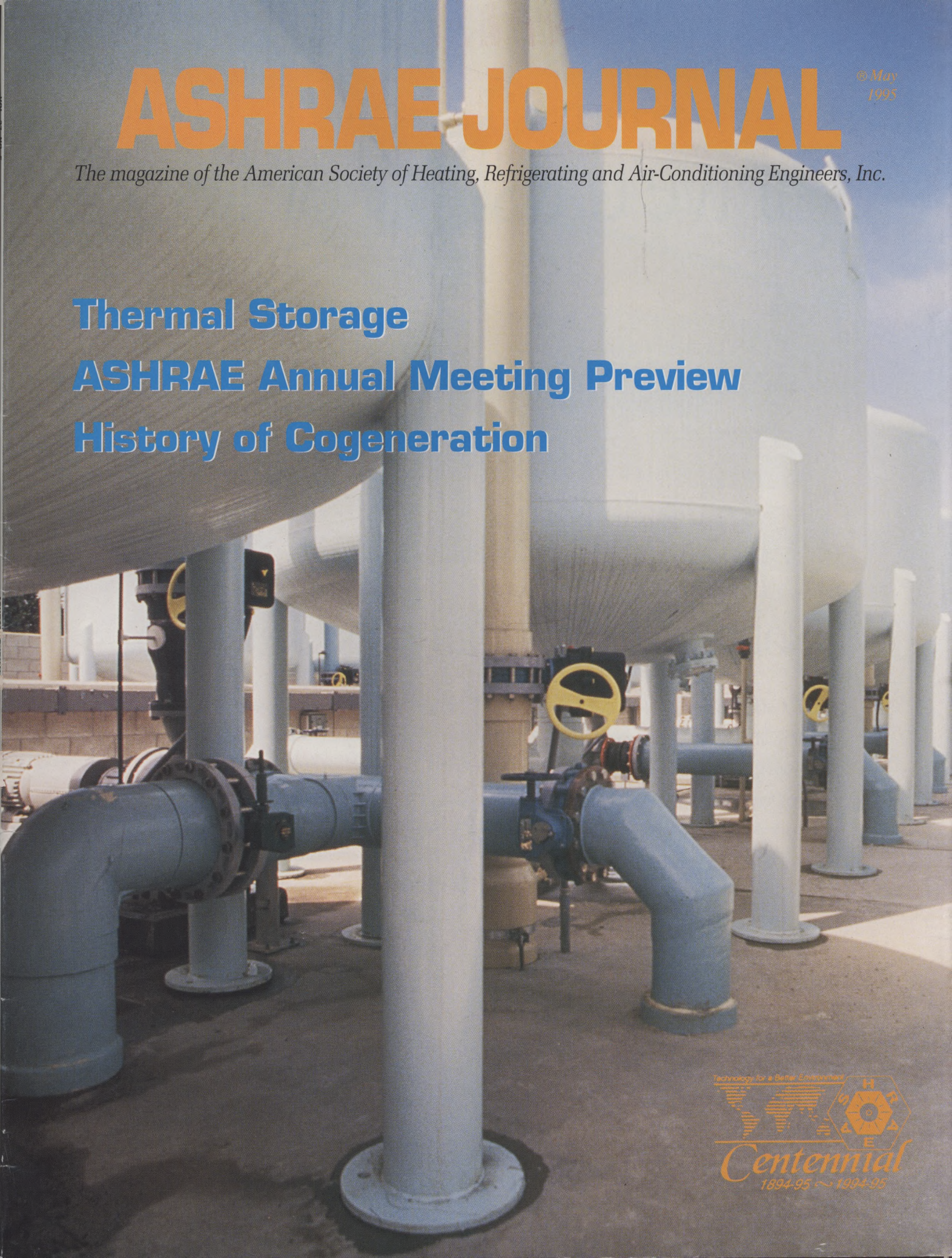

Thermal Storage

ASHRAE Annual Meeting Preview

History of Cogeneration

Technology for a Better Environment

Centennial

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A History of Cogeneration before PURPA

The concept and principles of thermal power generation have been forgotten and relearned several times over the past 600 years

By Morris A. Pierce, Ph.D.

Among the intended goals of the Public Utility Regulatory Policy Act of 1978 (PURPA) was increasing the efficiency of thermal electric generation in the United States by combining heat and power generation. Although the term *cogeneration* was coined during the legislative process to describe this concept, the idea itself is actually very old.

The mechanical combination of heat and power can be traced to the smokejack, a hot air turbine powered by heated air rising through a chimney (see *Figure 1* and *Figure 2*). The smokejack was introduced into Europe in the 14th Century by Tartars who had been captured and sold in Italian slave markets.[1] A smokejack appears in a pre-1350 German painting[2] and, by the time Leonardo da Vinci sketched one a century later,[3] they were widely used to turn spits, replacing the muscles of a child or dog turnspit.

The French traveler Montaigne saw smokejacks in Germany and Italy in the late 16th Century,[4] while English diarist John Evelyn in 1685 mentioned "the smokejack in my brother's kitchen chimney, which has been there near a hundred years."[5] Benjamin Franklin suggested in 1758 that a smokejack might even produce power in summer from a chimney's natural draft.[6] Although not particularly powerful or efficient, smokejacks performed useful work at low cost and spawned several useful descendents, including propellers and gas turbines.

The smokejack soon faced competition from ancient Greek and Roman steam technologies, including the æolipile, which was a small boiler used to force air flow. The Roman architect Vitruvius described the æolipile as a

> *hollow bronze ball, with a very small opening through which water is poured into them. Set before a fire, not a breath issues from them before they get warm; but as soon as they begin to boil, out comes a strong blast due to the fire.*[7]

By the 16th Century, æolipiles were used for artisans' furnaces and space warming. A nozzle contained the steam until superheated to produce a dry, invisible vapor stream. Jacob Rivius, in a 1548 commentary on Vitruvius,[8] recommends adding perfume to the æolipile "to cause a pleasant temperature, to freshen the spirit, and rejoice the heart."

The hot blast of the æolipile could also induce drafts in chimneys with or without smokejacks, and by 1629 was directly driving a small steam turbine or steam jack connected to a spit or lathe, allowing a single fire to provide power, process heat and space warming.[9] John Bailey of New York City patented a domestic steamjack in 1792 and advertised it in newspapers in that city.[10]

Although such apparatus was certainly appreciated by the canine population, power measured in dog units was not enough to drive the Industrial Revolution. James Watt developed more powerful engines and a larger unit of measure—the horse. Watt's separate condenser greatly increased efficiency, but still used steam only slightly above atmospheric pressure, depending on the condenser vacuum for most of the power. One of Watt's salesmen advised him in 1776 that,

> *some attempt has been made to apply the Fire Engine to the purpose of turning mills for squeezing the Sugar Cane in the West Indies, & that it is supposed that the same fire which is used to boil the sugar, will be sufficient to produce steam to work the mill. If this should be practicable, it would be a matter of infinite consequence to the Islands & to the Public & would occasion a very great demand for your Invention.*[11]

About the author

Morris A. Pierce is the energy manager for the University of Rochester, New York, where he implemented several energy conservation programs and is currently installing a cogeneration plant. He received a degree in mechanical engineering from the US Military Academy at West Point, a masters degree in history from the University of Northern Colorado and a PhD in history from the University of Rochester. Pierce is currently researching and writing a history of district heating and cooling.

Watt and his partner Matthew Boulton saw the merits of the idea and soon expanded their services to include steam and hot water heating in customers' factories. Steam for both heating and power was supplied from a common boiler sized to handle the total load.

Around 1805, Scottish engineer Robertson Buchanan installed such a system in the mill of H. Houldsworth & Co., whose engine had "only the power of sixteen horses," while the boiler was "equal to that commonly used for a steam-engine of twenty-one horses power." The "surplus power of five horses" was just enough to warm the 250,000 ft^3 (7080 m^3) mill building, yielding a simple rule-of-thumb: one boiler horsepower could heat 50,000 ft^3 (1416 m^3).[12]

Sutton Thomas Wood, a brewer in the university town of Oxford, received a patent in 1784 for using "the same steam which arises during the process of trade or manufacture" for the additional purpose of working a steam engine.[13] He also claimed the use of hot water from the engine condenser for use in other trade and manufacturing purposes. Before the end of the 18th Century, Wood was using byproduct process heat to power a steam engine, and then yet again to provide heat for other processes. The ancients, indeed, have stolen our best ideas.

Although Watt also patented a high pressure engine that exhausted to the atmosphere, he opposed the use of high pressure steam because of the danger of boiler explosions. However, higher pressures offered significant improvements in fuel economy and, after Watt's patents expired, several were developed.

For example, Richard Trevithick obtained a patent for an improved high pressure engine in March 1802,[14] with the exhausted steam "directed and applied to heating fluids or any useful purpose." However, Trevithick apparently never exploited this characteristic of high pressure engines other than to heat feedwater.[15]

Engineer-historian Eugene S. Ferguson argues persuasively in a recent book that engineers can only design what they can visualize.[16] This certainly describes the career of Oliver Evans, who as a 17-year-old in Delaware saw a friend produce an explosion with water heated in a plugged gun barrel, from which he conceived of using high pressure steam to propel "land-carriages."

Although Evans received the first of several high pressure steam engine patents in 1787, it was only in 1802 that he had one engine grinding plaster of Paris in his Philadelphia shop. Evans advertised in 1804 that the exhaust from his new engine could "be applied to boil for Distilleries, Breweries, Dye Factories, Soap Factories, Paper Mills, &c. saving all the fuel now used for those purposes."[17]

Although frustrated in his primary interest of improving transportation in the new country, Evans' Mars Works in Philadelphia was busy filling orders for his new Columbian steam engine for stationary applications. One steam engine was sold to the Middletown Manufacturing Company in Connecticut, which used the exhaust to heat its mill in 1811. The mill superintendent, Arthur W. Magil, wrote the following year that "the steam that has done its work enables us to warm our rooms in winter, so that the risk from fire is greatly lessened."[18]

Although Evans had himself designed hot air heating apparatus and promoted the use of exhaust steam for manufacturing purposes, he had not grasped the concept of warming buildings with exhaust steam. However, he was a quick study and, on a sales call to a mill near Baltimore, Evans noted "a copper pipe run through all their apartments enough to condense for 100 horse-power," which by Buchanan's rule-of-thumb suggests a building of 5 million ft^3 (141 600 m^3). In May 1813, Evans wrote to his son George, who built Columbian engines in Pittsburgh, that he had found,

> *a great improvement in the application of my Steam engine. I warm a factory by conveying the steam by light copper pipes through all the apartments so that the steam condensed to water will run back to the supply pump.*[19]

The great advantage was that "the same fuel that they use [for heating] would drive the Engine to work their Machinery." Once visualized, the rest was easy and Evans admitted, "is not this astonishing that this was not sooner seen in all the 7 years" he had been installing engines.[19] Fortunately, Arthur Magil in Connecticut did see it, although how the vision got into his head is unknown to us.

Evans began marketing combined heat and power apparatus with some success. The license for an engine sold in 1814 to the Providence Dyeing, Bleaching and Calendering Company in Providence, Rhode Island, recommends using the exhaust steam to "warm the apartments of factories" or "to distill spirits, etc."[20] A March 1815 letter from Providence reported that Evans'

> *new method of warming apartments, by the waste of the steam of the engine, we consider a new and valuable discovery, consequently the expense of fuel chargeable to the engine is proportionably lessened.*[21]

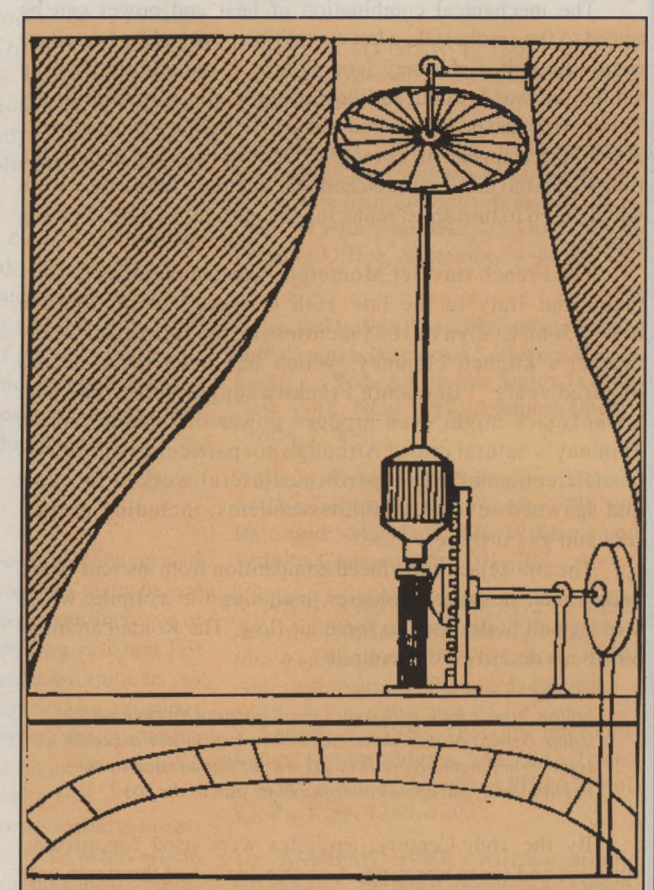

Figure 1. Smokejack from John Wilkin's *Mathematical Magic* (1680).

Although Evans died shortly thereafter, he had almost singlehandedly established high pressure steam engines and cogeneration in America. Furthermore, he had sketched out a scheme for cooling factories using an absorption refrigeration machine powered by engine exhaust.[22]

The Columbian steam engine business was carried on by Evans' sons and former associates, including Mark Stackhouse, a former mechanic who had moved to Pittsburgh to work with George Evans. Stackhouse built many engines for steamboats, including one in 1825 that George Rapp used to move his utopian Harmonist Society from Indiana to their new community of Economy, on the Ohio River just below Pittsburgh.

Rapp was a capable technologist and demonstrated his satisfaction with the steamboat engine by having Stackhouse build two more for Economy's new wool and cotton mills. A German visitor the following year recorded that the engine exhaust steam provided process heat for textile fulling and in the winter also warmed Economy's factories and workshops.[23]

English factories had adopted cogeneration for process and space heating by the 1820s, and it slowly made its way into other applications.[24] Charles Busby patented a means of circulating fluid through pipes "for warming or cooling the interior of buildings" in 1832, using a small rotary pump powered by a smokejack in the boiler chimney.[25]

Neil Snodgrass, who installed the first steam heating system in Glasgow in 1799, wrote in 1834 that,

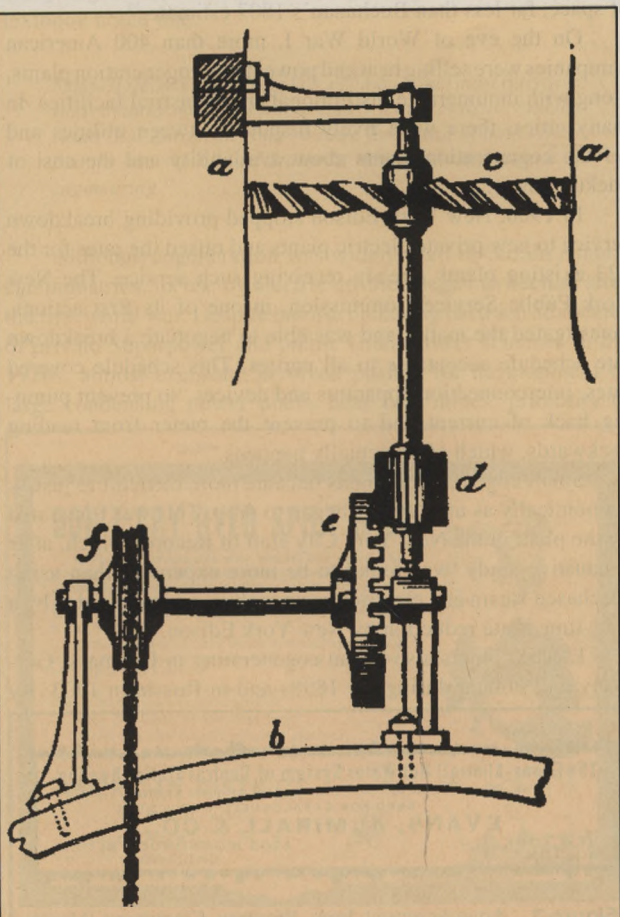

Figure 2. Smokejack from *Century Dictionary and Encyclopedia* (1899).

> *Where steam engines are employed to drive the machinery, the surplus steam for a great part of the year is sufficient to heat the factory, thus saving the whole expense of fuel nearly.*[26]

A decade later, Edwin Chadwick's report on sanitary conditions in Great Britain connected health and cleanliness, emphasizing the benefits of frequent bathing. Chadwick noted that although factories were especially dirty places,

> *in every place where there is a steam engine, hot water, which is commonly allowed to run waste, is already provided in abundance for warm or tepid baths, not only for the workpeople, but, where there are numerous engines, for the whole population.*[27]

Chadwick credited the idea to a gentleman who observed "clean hot water running away from the steam engine of a manufactory" and suggested it be used to supply public baths. Several were built by private entrepreneurs who charged a penny for baths, with discount plans for families, groups and frequent bathers.[27]

Other novel uses for engine exhaust steam also appeared, such as the French manufacturer who used exhaust steam to raise pineapples in 1847.[28] Walworth and Nason applied steam engines to mechanical ventilators in the 1850s and used the exhaust steam to temper the outside air. Their 1851 catalog notes that "exhaust steam from an engine can be applied efficiently for warming."[29]

Charles E. Emery, a former naval engineer noted for his steam engine trials, detailed the relative advantages of heating with exhaust and live steam in 1870. Emery concluded that "the system of heating by exhaust steam may be applied with advantage in nearly every establishment where a non-condensing steam engine is in use."[30]

Centralized energy systems became more widespread in the 1870s and cogeneration was incorporated in many of them. In 1876, Sir Frederick Bramwell installed a hot water district heating system for the numerous buildings of the new Banstead Downs Asylum near London, heating the water with the exhaust from the circulating pump engine.[31]

Birdsill Holly's district steam heating system, which originally supplied only high pressure steam for heat and power purposes, was modified in 1880 to incorporate a second steam pipe to collect and resell engine exhaust steam to other customers. The San Francisco Steam Company, formed in 1886, had no steam plant at all, instead purchasing exhaust steam from the numerous engines in downtown San Francisco and reselling it to others.[32]

Almost every building that used steam engines to power elevators, pumps and other machinery used the exhaust steam for heating. Charles H. Manning reported that even factories that had originally located in Lowell and Lancaster because of low cost water power found steam power less expensive, because the necessity of making steam for process and space heating lowered the incremental cost of steam power below even the lowest cost water power, plus providing greater reliability.[33] The Lancaster Mill in 1896 was warming its entire factory with warm water from its condenser hot well and, in the summer, circulated cold water in the same pipes to cool the building.[34]

Shortly after electric lights appeared in the 1880s, the Edison Company for Isolated Lighting published testimonials from customers whose lighting plant provided excellent light at very low cost because the exhaust steam was used for heating.[35] A.F. Upton described the power plant of the future to the National Electric Light Association in February 1886, from which "exhaust steam will be used for heating neighboring buildings."[36]

Edison companies in Albany and Boston were cogenerating in 1887 and several more were doing so by 1889, including Philadephia, Rochester, Duluth and Kansas City. Electric station cogeneration was such a good idea that it was promptly outlawed by the Pennsylvania legislature in May 1889, although electric companies in that state soon found a loophole that let them continue to do so.[37]

Edward P. Bates of Syracuse told the 1892 convention of the Master Steam and Hot Water Fitters Association that "we are beginning to regard heat and power as synonymous terms." Homer T. Yaryan of Toledo installed his first low temperature hot water cogeneration system that same year and was soon followed into that market by Quimby N. Evans and Juan Almirall. Electric plant managers were specifically targeted by these and other firms specializing in exhaust steam (see *Figure 3* and *Figure 4*). A Detroit utility plant used exhaust steam to evaporate salt.[38]

The American Society of Heating and Ventilating Engineers (ASHVE) received a detailed description at its 1901 meeting on the application of exhaust steam, including the recommendation that each boiler horsepower could warm 7,500 ft^3 (212 m^3) of space, far less than Buchanan's 1807 estimate.[39]

On the eve of World War I, more than 400 American companies were selling heat and power from cogeneration plants, along with innumerable institutional and industrial facilities. In many cities, there were lively disputes between utilities and private cogeneration plants about availability and the cost of backup power.

In 1906, New York Edison stopped providing breakdown service to new private electric plants and raised the rates for the 123 existing plants already receiving such service. The New York Public Service Commission, in one of its first actions, investigated the matter and was able to negotiate a breakdown rate schedule acceptable to all parties. This schedule covered rates, interconnection apparatus and devices "to prevent pumping back of current and to prevent the meter from reading backwards, which often actually happens."[40,41]

Small cogeneration plants became more difficult to justify economically as utility rates began to drop. This was illustrated by the plant in the New York City Hall of Records which, after exhaustive study, was found to be more expensive than using purchased steam and electricity, a conclusion greatly aided by a well-timed rate reduction by New York Edison.[42]

Electric plants also began cogenerating in Denmark, Germany and Poland during the 1890s and in Russia in 1903. By

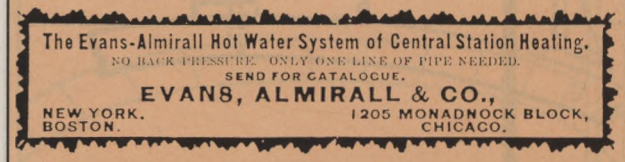

Figure 3. Advertisement from *Western Electrician* (March 28, 1903).

1914, German engineers were recovering heat from internal combustion engines to warm factory buildings.[43] Around 1926, this practice was adopted by that most ubiquitous of cogeneration applications, the automobile.

European cogeneration development was further aided by establishment of energy planning agencies which, in the United States, were limited to electricity planning. The most extreme example was the Russian Commission for Elaborating the Plan for the Governmental Electrification of Russia, better known by its Russian initials GOELRO. Two hundred engineers were assigned to search out the best heat and power technology in the world, which resulted in cogeneration, or *teplofikatsiia* in Russian, becoming a key part of Soviet power planning.[44]

The first World Power Conference, held in London in 1924, devoted only a short report to waste heat utilization. However, the second conference in Berlin six years later hosted an entire session on Combined Heat and Power, with participants from Germany, Finland, France, Italy, Austria, Czechoslovakia and the United States.

Topics covered the entire landscape of centralized versus decentralized cogeneration plants, including a presentation by a German engineer who pointed out the tremendous advantages that cogeneration would yield to the German economy. Soviet electric planners shortly thereafter made a case for large centralized cogeneration plants, while their counterparts in Nazi Germany argued for decentralized cogeneration. A 1929 British textbook noted that,

> *Exhaust steam engineering has, of course, had most intensive study in those countries where coal is scarce or dear, with the result that European countries are far ahead of both Great Britain and the United States in this important branch of engineering.*[45]

Although cogeneration was widely used in certain American industries, its use by electric utilities began to decline after the first world war. Despite intense bickering between advocates of private Superpower and public Giant Power schemes in the 1920s, almost everyone involved pushed for development of large condensing power plants near coal mines, primarily to

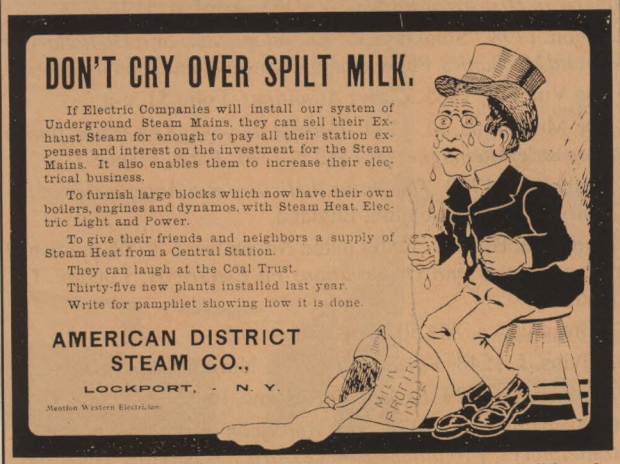

Figure 4. Advertisement from *Western Electrician* (May 2, 1903).

avoid the transportation-related coal shortages that had plagued the country in the war winter of 1917–18.

Only a handful of engineers raised the issue of including cogeneration in American energy planning. Quimby Evans' son, Ira, wrote several articles in the 1920s that advocated inclusion of cogeneration in electric power planning, but to little avail.[46,47]

A 1926 editorial in *Power* magazine pointed out the inherent thermodynamic advantages of cogeneration over even the most advanced condensing plants. Even though "a kilowatt-hour can be produced today with about one-third the expenditure of heat units of twenty-five years ago," the editorial noted, current plants only operated at "about a twenty-five per cent overall thermal efficiency," with the potential for significant improvements "not promising." However, high pressure steam turbines, even operating against a high exhaust pressure, can produce a kilowatt-hour for "considerably less than five thousand heat units," an efficiency of nearly 70%.[48]

Not all electric utilities followed this trend, and the drop in electric sales during the Great Depression of the 1930s led to several creative cogeneration partnerships, often avoiding stranding of excessive power generation investment. A few notable examples were the Southeastern Production Company plant in Mobile, Alabama that served the International Paper Company, the Point Breeze Plant near Baltimore for Western Electric, and the Deepwater Power Station for a DuPont plant in New Jersey.

ASHVE member David Myers wrote a book about the power situation in 1935, in which he noted that customers with the most attractive cogeneration opportunities often received very attractive rate reductions from their electric utilities. His advice still rings true, "Buy power when it should be bought and make it when it should be made."[49]

The commercial introduction of the gas turbine during the late 1930s included several schemes to utilize the hot exhaust gases. Industrial success with gas turbines and heat recovery (including aircraft jet engines) led the gas industry to recognize the combination as a means to counteract the All-Electric marketing efforts of electric utilities.[50]

The Park Plaza shopping center in Little Rock, Arkansas reportedly had "the nation's first privately owned all-purpose utility plant powered by a gas turbine."[51] *Power* magazine in 1962 reported an upsurge in onsite power generation due to attractive gas rates, efficient gas turbines and engines, and "growing acceptance of air conditioning, which makes it possible to develop a good heat balance over the year."[52]

The editor of *Heating, Piping and Air Conditioning* noted in 1970 that "the onsite energy concept has gained ground steadily over the past several years."[53] In response, an electric utility executive replied that only 525 such plants had been installed in the prior decade, a "pitifully small total in spite of the tremendous and vigorous promotion the concept has had."[54] In the meantime, the gas industry sponsored research to use fuel cells as "onsite energy packages for shopping centers and large industrial and apartment buildings."[55]

The coal industry, meanwhile, developed similar programs, including one that produced coal gas in addition to electricity and steam, which was given the name "tri-generation."[56] Cogeneration was also used in waste incineration plants[57] and the new atomic energy plants. The US Air Force used the PM-1 air-transportable nuclear cogeneration plant to provide heat and power for remote radar stations.[58]

Total energy was a fundamental element of the Modular Integrated Utility System developed by the Department of Housing and Urban Development in the early 1970s, as well as the Argonne National Laboratory's Integrated Community Energy System.

Electric utilities, not surprisingly, opposed these non-utility generating plants. They especially fought interconnection and excess power purchase requirements, both of which were incorporated into PURPA by its sponsor, who was coincidentally a senator from the natural gas producing state of Louisiana.

One 1978 study reports that cogeneration produced about 15% of America's electric power in 1950, but by 1977 had dropped to only 5%, which would imply that the amount cogenerated remained fairly constant or even grew slightly during that period.[59]

Conclusion

Although this article presents an all too brief overview of the rich history of cogeneration, it will hopefully demonstrate that valuable lessons can be learned from careful study of the history of heating, ventilation and air conditioning. While thermal power generation is, and always has been, rigidly bound by thermodynamic laws that even Congress cannot amend, the principles of efficient heat and power generation have been forgotten and relearned several times. ■

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