Developing New Alloys for Furnaces

Conquering Corrosion

By James R. Brodrick, Ph.D.
Member ASHRAE
and
Alex Moore

During the 20th century, concerns about corrosion in the components of furnaces and vent systems limited the upper efficiency level for safe practice. The initial entry into the condensing regime resulted in many setbacks and financially ruined businesses.

More than 50 years after the onset of corrosion problems, a remedy was found. Materials research played a key role in reducing the corrosion problem. Market forces, such as fuel price variations, first reduced and then accelerated the R&D that was needed to overcome the corrosion problem. A brief, selected history is provided on the key players, dates, and events of this R&D quest. But, have the R&D costs and ensuing benefits paid off for the U.S. consumer?

The first reported occurrence of condensation in heating systems and corrosive effects was made in trade literature as early as 1901. Condensation apparently was common in flues of natural gas furnaces and boilers. A number of gas installations were placed in Buffalo, N.Y., and " . . . almost every person has an iron pipe put into his chimney to carry off the water."[1,2]

As gas and oil replaced coal as the heating fuel for homes in the 1920s and 1930s (largely due to convenience), manufacturers developed packaged units. A gas-fired unit was developed by Carlyle Ashley for Carrier-Lyle Corporation and was marketed as the "Weathermaker" furnace beginning in 1928. The design was significant because it was the first high-efficiency gas furnace. The heat exchanger was made of chrome-nickel, low-carbon iron.

The Weathermaker's patent states, *"Since it is desirable to use gas… as a fuel in heating and air-conditioning systems, the effect of corrosion due to condensation resulting after the gas firing or combustion process must be guarded against by the use of a material capable of withstanding corrosive action. If, however, the range of temperature of gases is controlled so that condensation takes place at a given point or within a limited area, then the use of corrosion-resistant metal is confined to this area with consequent saving both in initial cost and in operation and with increased effectiveness in heat interchange efficiency."*[1,3]

However, even with the precautions taken and the materials used, the Weathermaker suffered corrosion problems due to the condensation of combustion gases that gave the unit its high efficiency. These heat exchanger corrosion problems forced the company to withdraw the Weathermaker from the market.[4] During the push for higher efficiency equipment in the wake of the 1970s energy crisis, the history of condensation and corrosion repeated itself.

The period of the late 1930s through the 1960s saw little substantive change in package furnaces. Efficiencies remained relatively low compared to today's levels. The fear of condensation-related corrosion, together with a lack of competitive or economic incentives for manufacturers, contributed to the absence of efficiency gains during the mid-1900s. Cabinet size was reduced as blowers evolved from belt driven to direct drive. Cast-iron burners were replaced by steel. The product mix shifted ultimately away from coal to gas and oil, but also steadily shifted from oil toward gas during this period.

Improved Efficiency

Prior to 1979, even the so-called "high-efficiency" furnaces approached an Annualized Fuel Utilization Efficiency (AFUE) of only 60%. AFUE is the heat transferred to the conditioned space divided by the fuel energy supplied, calculated on an annual basis. The oil price shocks of 1973 and 1979 changed the economic ground rules that allowed such low efficiency levels.

To respond to market and regulatory needs, manufacturers developed furnaces that operated in the condensing range of efficiency (greater than 82% steady-state efficiency). With the condensing of the combustion gases for efficiency gains, it was found that the traditional metals used for heat exchangers experienced corrosion. In some instances, condensation also occurred in chimneys and venting systems.

Materials research and development (R&D) was needed to solve the corrosion problem. Several R&D funding institutions set out to find the solution. The

About the Authors

James R. Brodrick, Ph.D., is the senior energy R&D analyst at D&R International, Silver Spring, Md. He was chair of the ASHRAE Program Committee. **Alex Moore** is a senior engineer at D&R International.

Canadian Gas Research Institute (CGRI) started research in the late 1970s, and was soon joined by the U.S. Department of Energy (DOE) and the newly formed Gas Research Institute (GRI). Generally unknown or forgotten by industry is the important contribution made by the DOE, which issued a general request for proposals for High-Efficiency Concepts for Warm Air Furnaces in 1979.

The DOE collaborated with GRI to develop materials and furnace design techniques for condensing gas furnaces, and eight contracts were awarded: four by the DOE via Brookhaven National Laboratory and four via GRI. The program was conducted in cooperation with CGRI.

The early CGRI work on corrosion-resistant materials for condensing gas furnaces indicated that relatively common stainless steels (304, 304L, 314, and 314L) appeared to be a good choice.[5,6] With the corrosion problem apparently solved, GRI and CGRI redirected their R&D programs, with GRI targeting condensation-related venting issues.[7] The industry produced heat exchangers using common, low-carbon 304 stainless steel, but soon discovered a serious new corrosion problem—pitting and corrosion in areas of manufacturing-induced stress.

	Cumulative Energy Savings (Quads, 10^{15} Btu)	Cumulative Consumer Dollar Savings (Million $)*	Cumulative Carbon Emission Reduction (Million Metric Tons)
1985	0.01	$68	0.2
1990	0.10	$587	1.5
1995	0.32	$1,887	4.6
2000	0.71	$4,609	10.3
2005	1.31	$8,725	18.9

* Based on the average U.S. gas price for each year.

Table 1: Benefits of condensing gas furnaces.

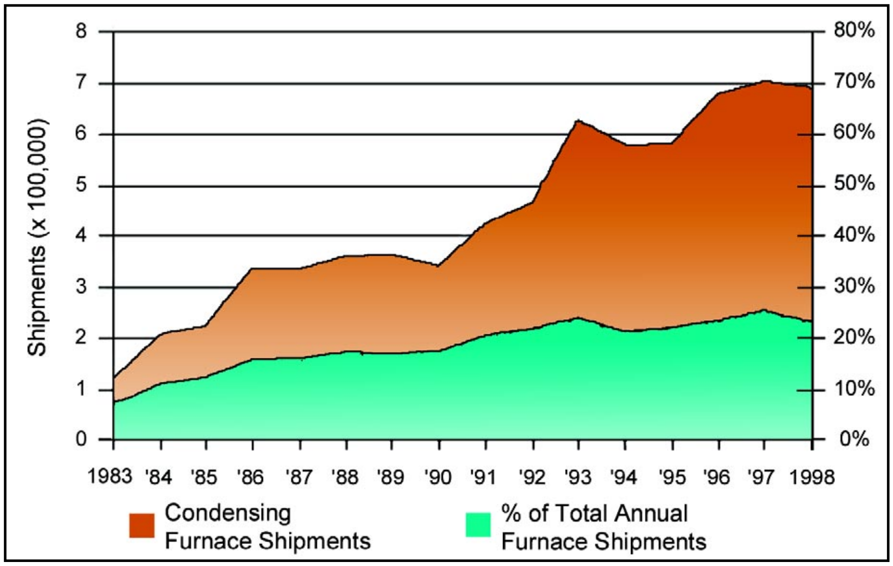

Figure 1: Condensing gas furnace shipments and market share.

The 304 stainless steel heat exchangers experienced serious corrosion damage after just a few years of operation. The manufacturers were quick to act, recalling the affected condensing furnaces and absorbing the cost of replacing failed equipment for consumers. Manufacturers, contractors, and consumers wanted answers.

An element of the DOE research program at Battelle, funded by GRI, determined that the corrosion stemmed from a chloride ion mechanism, generated by chloride-containing compounds such as common household cleaning products, not identified in earlier R&D. Further DOE/GRI-supported research evaluated the problem. Many metals were tested at Battelle Columbus Laboratories, under contract to the DOE/Brookhaven National Laboratory and GRI.[8]

The solution to the corrosion problem in gas furnaces came interestingly enough from the DOE-sponsored materials research for oil furnaces.[8,9] The research identified highly alloyed, stainless steels as successfully resistant to corrosive condensate. The materials recommended by the research were ferritic stainless steel alloys with a high chromium and molybdenum content (such as 29-4C), and two austenitic, nickel-chrome alloys with high molybdenum content (AL-6X and 254 SMO).[10,11,12] The high chromium content provides general corrosion protection, and the molybdenum provides resistance to pitting corrosion that can occur in stainless steels.

The DOE contributed to the success of condensing gas furnaces in three ways. It identified technical problems and potential solutions that gave industry the direction it needed to develop high-efficiency furnaces. The DOE helped alert industry to the potential corrosive failures of early heat exchangers, and gave direction to resolving the problem through installation modification, design guidance, and materials research that led to the use of highly corrosion-resistant alloyed stainless steel. Finally, the DOE coordinated technology transfer programs, information flow, and general forums for the gas industry, its manufacturers, and its research and development agencies in the United States and Canada. GRI-sponsored test procedures and standards also advanced the technology.

Energy, Economic, & Environmental Benefits

Technology R&D made possible the highly efficient, cost-effective condensing gas furnace with an expected service life of 20 years, thus enabling condensing technology to successfully remain on the market and become an established part of today's heating market. From initial sales of about 116,000 units in 1983, condensing gas furnaces sales have grown to 688,000 units in 1998 (*Figure 1*), which represents more than 23% of 1998 gas furnace sales.[13,14,15] "Condensing furnaces are an important part of our product line," says a major HVAC manufacturer. Within gas warm-air heated homes, the 6.3 million condensing gas furnaces in use as of 1997 represent an estimated 17% of the national population.[15,16] This research program has paid off handsomely.

As of 1998, the cumulative energy savings from U.S.-made condensing furnaces is 531 trillion Btu (equivalent to the average annual output from twenty-four 1,000-MW nuclear power plants or more natural gas than is used in all the homes in both Pennsylvania and Texas). Consumers have saved a cumulative $3.3 billion from lower gas utility bills (*Table 1*).[15,17] In addition, the environmental benefit from U.S. higher efficiency furnaces installed since 1983 is 7.7 million metric tons of carbon (equivalent to the carbon emissions from U.S. residential propane use each year).[15,18] All of these benefits result from an R&D investment of $1.8 million by the DOE and a similar amount from GRI. It should be noted that GRI also funded considerable research on condensation-related corrosion of venting systems.

Revisit Unfinished R&D?

But is this the end of the story? The DOE was forced to abandon its R&D effort on condensing gas furnaces when Congress discontinued funding. It may be possible to substitute less expensive materials for the highly alloyed stainless steels determined to be the best choices for condensing heat exchangers.

While industry has made some advances in developing non-metals and non-metal coatings (plastics, polymers, ceramics, and glass) on steel, other breakthroughs may be attainable, such as alternative designs and fabrication methodology using metallic materials. The cost premium for high-efficiency condensing furnaces might be reduced if this R&D were to be revisited. Also, cost-effective, condensing gas water heaters and venting system advancements might be achieved.

What Does the Future Hold?

What other advances await residential heating systems? While predicting technology pathways is difficult at best, discussion is occurring on a number of fronts. Work is continuing by GRI and others on gas absorption and engine-driven heat pumps. Ground-coupled, or geothermal heat pumps are making inroads in many areas of the country. A quantum change in satisfying home heating and energy needs may come with the advent of a commercial proton-exchange-membrane fuel cell.

A fuel cell produces electricity silently, without combustion. Hydrogen fuel, which can be obtained from natural gas or methanol, and oxygen from the air are electrochemically combined in the fuel cell to produce electricity. Electric conversion efficiency is approximately 40%. With hydrogen as a fuel, heat and pure water vapor are the only by-products.

Warm-Air Furnace Time Line

1600-1700

- Louis Savot of France invented the circulating fireplace (early 1600s)
- First free-standing warm air stove, probably the "Furnus Acapnos" (smokeless stove) invented by the Parisian Dalesme (late 1600s)
- First centrally heated building in U.S., Massachusetts Medical College – gravity hot air (1616)
- The earliest stove in North America, probably the cast iron box stove (or Holland type stove) invented by Dr. John Clarke of the Massachusetts Bay Colony (1652)

1790s

- Central hot air systems (with ducts leading to individual rooms) became more prevalent in the U.S. (1795)

1830s

- First central heating furnace, of the gravity type later commonly seen, was invented in Worcester, Mass. (1835)
- Airtight stove invented by Isaac Orr (1836)
- Furnaces become mass marketed (1834-1842)

1840s

- Robert Briggs began to design and install hot water heating systems in the U.S.
- The first true radiator, the "mattress" radiator, invented by Stephen Gold (1842)
- James Walworth and Joseph Nason introduced the Perkins high-pressure hot water heating system into the U.S. (1842)
- Hot air registers were first made in the U.S. (>1845)
- Stove with thermostatic draft control invented by F. P. Oliver (1849)

1850s

- Sectional cast iron boilers (1850)

1860s

- Oil burning furnaces and boilers appeared in U.S.
- Hot blast central heating systems by B. F. Sturtevant
- Samuel Gold patented a cast iron radiator with a pin type extended surface — designed for indirect radiation (1862)
- Joseph Nason and Robert Briggs developed a vertical tubular radiator in which iron pipes were screwed into a cast iron base (1863)

1870s

- Package fan forced "unit heater" sold by B. F. Sturtevant Co. (1870)
- John Mills invented water tube boiler
- Frederic Tudor developed the vapor-type steam heating system featuring differential pressures and modulated radiators

1880s

- Steel-encased furnaces appeared
- Household hot water systems appeared
- Thermostatic control, first applied to large building systems, applied to furnace/boiler draft in residences

1890s

- "Argand" gas burner in use in heating devices (common method still used) employing a dampered mixing tube for gas and primary air leading to a perforated burner (1890)
- Cast iron sectional radiators generally available
- Dampered registers invented by Charles Foster (1895)

1900s

- Use of natural gas limited because of condensation problems in flues
- John Spears patented "Vento" system with extended surface radiator designed to replace bare pipe banks in hot blast (fan type) heating systems (1903)
- Night setback thermostats using mechanical clocks introduced (1906)
- Emerson Electric added a disk fan blower to the return side of the furnace, marking the advent of the forced-air residential furnace (1908)

1910s

- Manufactured gas introduced into house heating in Baltimore (1915)
- Thermostatically controlled oil and gas burners introduced (>1917)

1920s

- Domestic oil burners became popular
- Lightweight heating surface appears — the first being the "Aerofin" spirally wrapped copper fins on copper tubes developed by Lawrence Soule (1922)
- Squirrel cage blowers used with residential hot air furnaces (1925)
- Reuben Trane introduced enclosed steel cased radiator cabinet using finned tubes — the first of the convector type units (1926)
- Package furnaces incorporating a burner, blower, humidifier and filter (late 1920)
- High efficiency, gas-fired furnace developed by Carlyle Ashley for Carrier-Lyle Corp.— marketed as the "Weathermaker" (1928)

1930s

- Central year-round air-conditioning furnaces introduced by Frigidaire and others — normal efficiency units using cast iron or steel heat exchangers (1931)
- General Electric oil furnace package boiler (1932)
- Many manufacturers of package gas furnaces, some with provision for comfort cooling (late 1930s)

1930-1970

- Little substantive change in package furnaces, efficiencies remain relatively low, cabinet size reduced, product mix steadily shifted from oil toward gas

1970s

- OPEC Oil Embargo – fuel price shock (1973)
- CGRI starts initial R&D (1979)
- DOE/BNL – Battelle starts corrosion R&D on heat exchanger materials, metallurgy, designs, and fabrication (1979)
- Iran Revolution – fuel price shock (1979)

1980s

- Iran/Iraq War – fuel price shock (1980)
- GRI and CGRI research suggests common stainless steels as solution, GRI redirects R&D program to address venting concerns (1981-82)
- Initial citings of furnace failures in the field due to corrosion in heat exchangers, major consumer product recalls (1982-83)
- DOE/BNL program at Battelle (funded by GRI) – initial evidence identifies chloride ion as corrosion mechanism (1982)
- GRI funds investigation to establish presence of chloride ion in household air (1983)
- DOE/BNL program at Battelle – conclusive evidence of chloride mechanism (1984)
- GRI-sponsored conference at BCL – "Industry Update on Recent Corrosion Research for Condensing Heat Exchangers" (1985)
- DOE/BNL corrosion program closes (1987)

1990s

- Condensing gas furnaces continues to penetrate residential market

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However, capturing hydrogen from other fuels will produce various emissions—CO_2, some CO, and possibly SO_x and NO_x. In a residential application, using the fuel cell's waste heat for space and water heating would increase the overall efficiency significantly, to about 75%.

There are five main types of fuel cells, each named after the electrolyte used: phosphoric acid, molten carbonate, solid oxide, proton-exchange membrane (PEM), and alkaline. The PEM fuel cell seems to possess the most potential for residential applications with some manufacturers estimating market roll-out within the next few years.[19]

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Oil Heating Market

- In 1997, warm-air oil furnaces heated 3.8 million U.S. households.
- Oil-fired heating system sales (including steam and hot water systems) are about 200,000 units per year and represent primarily a replacement market.
- The average AFUE levels of oil-fired equipment have exceeded 80% since 1987.
- Oil-fired systems do not condense until efficiencies reach the 87% to 89% range due to the hydrogen-to-carbon ratio of fuel oil, which is lower than that of natural gas. While affected by the amount of excess air, the flue gases of different fuels have different dew-point temperature, but usually range from about 115°F to 140°F (46°C to 60°C) for residential furnaces and boilers.[8] Oil-fired flue gases tend to have lower dew points than that of natural gas.
- Oil equipment manufacturers generally do not produce condensing equipment since relatively high efficiencies can be achieved without the additional expense of handling corrosive condensate.

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