GAS-FIRED VS. ELECTRIC RESISTANCE MELTING OF ALUMINUM ALLOYS

by Frank B. Smith – Founder and CEO, Rayteq LLC

Early in his career, at the University of California at Berkeley's Department of Mechanical Engineering, the author participated in fascinating studies examining the effects of metal casting variables on light metal casting quality. These studies were privately funded by several well-known U.S. aerospace foundries that were looking for ways to consistently obtain stronger, better castings.

Melting Comparison Studies – One particular UC Berkeley study compared melting in a gas-fired crucible furnace with an electric resistance crucible furnace. Primary A356 aluminum alloy was melted in silicon carbide crucibles in both furnaces, brought to the same pouring temperature, degassed with ultra dry nitrogen, skimmed, and poured into green sand molds and permanent molds. To obtain meaningful results, hundreds of test bar samples were cast, test bars pulled, and the results recorded, plotted, and subjected to statistical analysis.

The results were profound: Tensile strength, yield strength and elongation properties were almost uniformly superior in the electrically melted samples regardless of the type of molds used. The mean mechanical properties of test bars melted in the gas-fired furnace reached only 80% of the mean values of electrically melted test bars (see Figure 1 below).

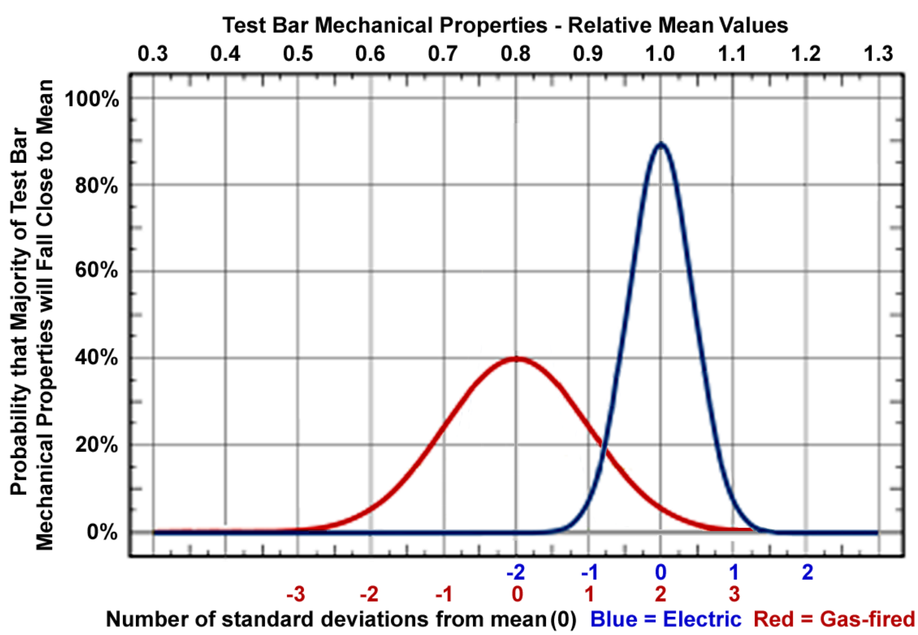


FIGURE 1 – NORMAL PROBABILITY DISTRIBUTION CURVES FOR TEST BAR CASTINGS PRODUCED FROM ELECTRIC RESISTANCE AND GAS-FIRED CRUCIBLE FURNACES

Of perhaps greater significance, the mechanical properties of the electrically melted castings, in addition to displaying higher tensile and yield strength and elongation values than the gas melted samples, were much more uniform and consistent. These statistical “bell curves” tell the story—the blue bell curve for the electrically melted test bar samples is taller and narrower than the red bell curve for the natural gas melted samples. This means that the electrically melted test bar samples demonstrated mechanical properties that were much more consistent and tightly grouped while the natural gas melted test bars had a much wider variation in mechanical properties. Some natural gas melted test bars tested significantly below the red curve mean.

Closer examination of the broken test bars under optical magnification indicated why: The natural gas melted test bars almost invariably broke at a dross inclusion, a hydrogen gas bubble, or even just a thin film of aluminum oxide, while the electrically melted test bars rarely showed any dross, oxide or hydrogen porosity at the breaks.

When the study began there was a general expectation that the results for the gas-fired crucible and electric crucible furnaces would be the same because it was assumed that the silicon carbide crucibles effectively isolated the molten aluminum from the source of the heat. But when the results were shown to differ, further investigation discovered why.

Leakage of Combustion Products – The first step was to determine how effectively the molten aluminum in the gas-fired furnace was isolated from the furnace’s combustion chamber. It turned out there was no isolation at all. This was because the sealing gasket between the top of the crucible and the underside of the steel furnace cover was made of compressible fiber insulation to allow the crucible to expand without cracking, a practice still followed today. Because of the positive pressure in the combustion chamber and the porous fiber gasket, combustion gasses freely penetrated the gasket, immediately coming into contact with the surface of the metal bath (see Figure 2 illustration below).

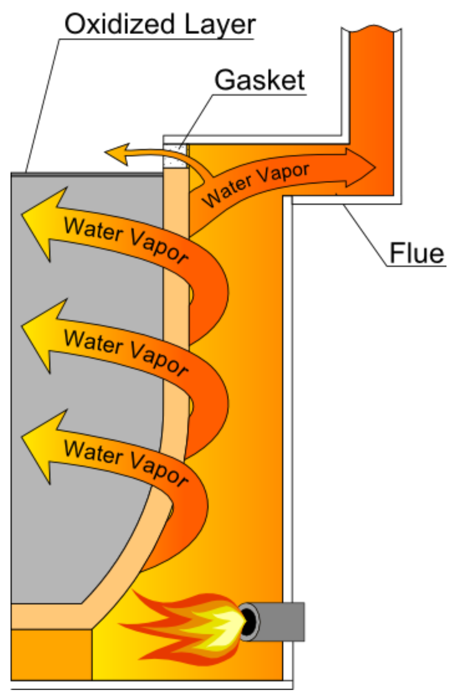


FIGURE 2 – PRODUCTS OF COMBUSTION LEAK THROUGH CRUCIBLE GASKET TO REACT WITH MOLTEN ALUMINUM

Because molten aluminum is highly chemically reactive, it instantly reacts with the water vapor which is present in all products of combustion according to the following equation:

$$2\ Al + 3\ H_2O \rightarrow Al_2O_3 + 3\ H_2\uparrow$$

The Al_2O_3 is, of course, aluminum oxide which in its purest form is sapphire, the second hardest substance known to man, and is also referred to as dross which produces hard spots in castings. The H_2 is hydrogen gas which is highly soluble in molten aluminum and completely insoluble in solid aluminum, appearing as porosity in finished castings which can produce surface roughness, casting fractures, leaky castings, unsealable machined surfaces, etc.

Effect of Relative Humidity – Since the test bar castings were produced by different furnaces on different days, it was possible to measure the relative humidity inside the foundry and compare it with the outside relative humidity. With the electric furnace, the relative humidity was always the same inside and outside. But with the gas-fired furnace, even though it had a flue that piped most of the combustion gases outside, the relative humidity inside the foundry was always significantly higher. This meant, in addition to the combustion gases that were penetrating the crucible gasket, there was additional water vapor present in the air that was coming from various leaks in the burners, refractories, flue pipes, etc. which could react with the molten aluminum

The net result was that the water vapor coming from both sources was quickly reacting with the molten metal, resulting in higher metal losses and much greater contamination of castings from oxide, dross, and hydrogen gas, all of which degraded the mechanical properties of the test bar castings produced from metal taken from the gas-fired crucible furnace.

This phenomenon is well known to aluminum foundries operating in the South and other areas of the country that suffer from seasonal high relative humidity. When the dew point reaches a certain value, scrap rates due to excessive dross and hydrogen gas can increase to intolerable levels. Aluminum alloys containing more reactive elements like magnesium and zinc lose some of these elements to oxidation, altering the alloy composition. Alloys such as Almag 35, which contains magnesium, develop thick dross layers, putting casting quality at risk. One might reasonably ask why such foundries would worsen the problem by employing gas-fired melting furnaces that increase the relative humidity.

Skimming Test Verifies Reaction with Combustion Products – Today's metal casters can conduct their own qualitative tests to verify that combustion gasses are indeed present and reacting with molten aluminum in gas-fired crucible furnaces. Simply skim the molten metal surface, do not further disturb it, and watch what happens. The observer should note that the clean, skimmed surface will slowly darken, the surface will change from a shiny, reflective surface to a dull, non-reflective surface, and the oxide "skin" which was thin after skimming will progressively become thicker and darker. This is all caused by water vapor in the products of combustion from the furnace reacting with the molten aluminum.

Now do the same test with molten aluminum in an electric resistance crucible furnace. After skimming, the surface will appear highly reflective like the photo on the following page and the shiny surface will remain that way much longer than on the gas-fired furnace. Also, the oxide "skin" will remain thin much longer. After a lengthy period of time, depending on the relative humidity of the air inside the shop (particularly if there are gas-fired furnaces operating in the same air space) the surface will slightly darken but at nowhere near the rate of the gas-fired furnace. This demonstrates that the metal stays much cleaner substantially longer in an electric resistance melting furnace.

SIMPLE SKIMMING TEST DEMONSTRATES ALUMINUM SURFACE REACTION WITH PRODUCTS OF COMBUSTION. NOTE CLEAN, HIGHLY REFLECTIVE SURFACE IN ELECTRIC MELTING FURNACE ABOVE. PHOTO COURTESY SKS DIE CASTING & MACHINING, ALAMEDA, CALIF.

Metal Loss in Gas-Fired Reverbs – It should be noted that the contamination is substantially worse in gas-fired reverb furnaces of both the dry hearth and wet bath types, and the amount of metal lost to dross and oxide is even higher than crucible-type furnaces. This is because the molten aluminum is in constant direct contact with the products of combustion which include water vapor.

Impressed and inspired by the results during his personal participation in these revealing studies, the author made a major course change in his career path by deciding to start a new business building reliable electric resistance furnaces to supply to metal casters interested in consistently obtaining the best possible mechanical properties in aluminum alloys.

Gas vs. Electric Case Study – The author's first electric resistance melting furnace customer was Jerry Keating, president of SKS Die Casting, now located in Alameda, California in the San Francisco Bay Area. SKS was supplying die cast aluminum slip rings for IBM commercial computer systems which had to meet IBM's very difficult QC requirements. These small aluminum rings were cast from 380 alloy in a multi-cavity die and packed in cartons containing 2,000 rings each. According to the terms of the contract, if IBM found only two castings in the box which did not meet their inspection criteria, the entire box of 2,000 was returned to SKS for remelting and recasting.

At the time, while SKS melted most of their aluminum alloy in gas-fired crucible furnaces, they also operated three "antique" electric channel induction furnaces. They quickly discovered that they could not meet IBM's quality requirements using the gas-fired furnaces because of hard spots, dross inclusions, and changing alloy composition. They could, however, produce acceptable castings with the electric channel furnaces. Unfortunately, when the channel furnace refractory supplier stopped mixing asbestos fibers in the channel lining cement because of the health hazard, the unreinforced refractory in the furnaces quickly failed and ran out making the channel furnaces unreliable.

Anxious to retain his IBM contract, SKS's Mr. Keating purchased the author's first electric resistance melting furnace to replace the failing channel furnaces and the rest became history. The IBM parts produced from metal melted in the author's new electric resistance furnaces easily met IBM's stringent quality requirements and Mr. Keating became a believer. He then replaced all of his gas-fired furnaces with the author's electric resistance melters. Some years later he purchased what turned out to be the 1,000th electric resistance furnace manufactured by the author. All of these electric furnaces including old #1 are in full production operation today.

Major Industry Shift to Electric Melting – In subsequent years the author's company supplied the light metal casting industry around the world with more than 2,000 electric resistance melting and holding furnaces and launder system modules for use in producing aluminum and magnesium alloy castings for the automotive, electrical equipment, electric motor, aircraft, aerospace, military, home appliance, hand tool, hardware and fittings industries, as well as the primary metals industries and universities and research laboratories. Along the way the author's company replaced literally *hundreds* of gas-fired furnaces of all types with clean, quiet and efficient electric resistance furnaces for all the reasons outlined above.

What has changed in the years between the author's pioneering university studies, which were followed by a major migration over to clean electric melting in all phases of the metal casting industry, and today? Natural gas-fired furnaces still generate the same percentage of water vapor in their products of combustion as before, molten aluminum alloy is just as chemically reactive as before, and when the two come into contact with each other the formation of dross, oxide, hydrogen porosity, hard spots in castings, higher levels of scrap castings, change in alloy composition, etc. continues as before. One thing that *has* changed, however, is the cost of natural gas.

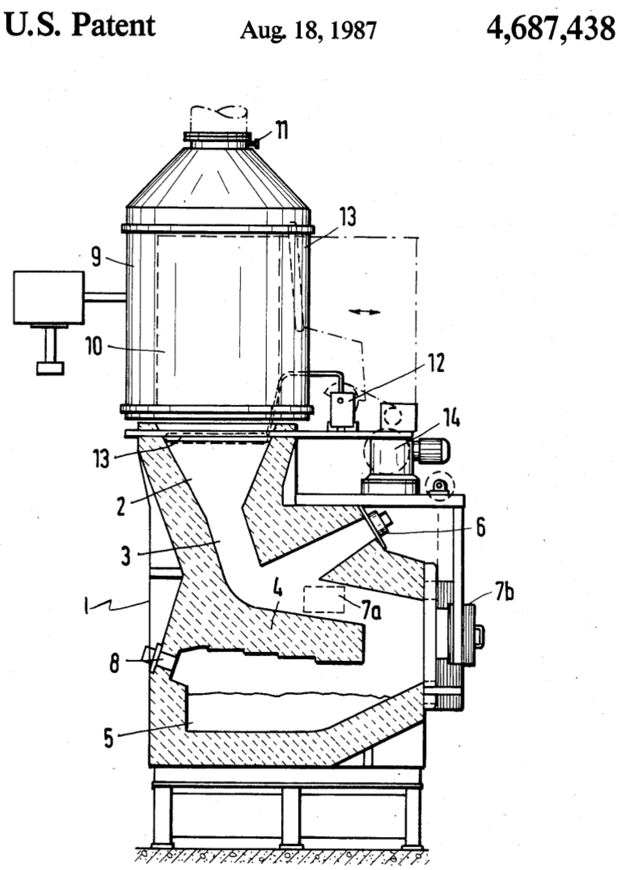
Dropping Natural Gas Prices – In the past several years during the economic downturn the cost of natural gas has plummeted from around $9.00 per dekatherm down to $3.00 per dekatherm, and this has certainly influenced the choice of furnaces for use in melting aluminum. When comparing gas-fired melting with conventional electric resistance melting, if only the cost of energy is taken into consideration, natural gas melting is often judged to be cheaper.

Fortunately today, a group of electric furnaces operating under the control of Rayteq's *Fleet Commander*™ demand management software will have utility costs roughly equivalent to the cost of gas-fired melting, even in high electric cost areas like California and the New England states. This is not only because Rayteq's electric furnaces equipped with the *Fleet Commander*™ interactive demand management system enjoy reduced utility demand charges, but also because they are completely sealed and have very efficient linings while gas-fired furnaces have flues which lose an enormous amount of heat, leaving them with only a small fraction of the electrical efficiency.

The Heavy Cost of Metal Loss – The oxidation of aluminum alloys by the products of combustion from gas-fired furnaces comes at a steep price. Melting aluminum ingot in Rayteq electric furnaces keeps metal losses low, typically 1% to 1½% of the metal melted, while gas-fired crucible furnaces with porous crucible gaskets can easily lose 3% to 5% to dross. Wet bath reverb furnaces, where moisture-containing combustion gasses directly contact the surface of the bath, suffer worse losses, typically ranging from 4% to 7% while dry hearth reverbs, where combustion gasses impinge directly on the metal while it is melting, can lose as much as 8% to 15%. At today's cost of aluminum alloy these losses can drive total gas-fired furnace melting costs several times higher than Rayteq's electric resistance furnaces which makes the current low cost of natural gas seem much less appealing.

Shaft/Tower Melters – Natural gas-fired shaft melters, also called tower melters, have reappeared on the aluminum casting scene in recent years. All of them are variations on the same theme—forcing combustion products up through a lined shaft filled with downward moving charge material to recover waste heat and thereby improve fuel efficiency. The better models are equipped with well-engineered instrumentation and microprocessors to automate the charging and melting cycles and to minimize melt losses.

Most shaft melters on the market today represent a major improvement over their dry hearth reverb predecessors, reducing metal oxidation by limiting the time the vulnerable just-melted aluminum is exposed to combustion products. Unfortunately, their effectiveness in this respect is often exaggerated. Taking advantage of the fact that metal loss is much more difficult to measure in continuous melters than batch melting furnaces, competing shaft/tower melter manufacturers have engaged in contests of who can claim the lowest metal losses, and the claims are approaching the absurd, even though nature's laws of chemistry remain unchanged. Highly reactive molten aluminum and the water vapor in products of combustion still react as they always have, and products of combustion are still in contact with molten metal in shaft/tower melters with metal losses comparable to wet bath reverbs, all the claims notwithstanding. (See patented shaft melter below.)



U.S. PATENT No. 4,687,438 FOR AN ALUMINUM MELTING SHAFT FURNACE ASSIGNED TO STRIKFELDT & KOCH GMBH IN GERMANY, 1987

Molten Metal Transfers – No discussion about the causes of aluminum alloy oxidation and resulting metal loss and casting defects would be complete without mentioning the major impact that molten metal transfers have in aluminum casting operations. Molten aluminum is highly vulnerable to contamination from contact with water vapor and oxygen whenever it is transferred. This is because its exposed surface area is very high during most transfers and the transfer process itself generates turbulence which further exposes more molten metal. When aluminum is sitting quietly in a furnace with only its surface exposed, particularly an electric furnace that generates no products of combustion that can impinge on that surface, it is relatively well protected from additional contamination by a thin film of aluminum oxide.

But during transfers, which by their very nature are unavoidably turbulent, the reverse is true. As the molten metal is poured through the surrounding air, the freshly exposed molten aluminum around the perimeter of the poured stream is exposed to water vapor and oxygen in the atmosphere and this exposed stream has *no film of aluminum oxide* to protect it. Worse yet, during the transfer, the surface area of the transferring metal suddenly increases. By how much? Let's do the math.

RAYTEQ MODEL DC-720 HAS BEEN MELTING RIGHT AT A DIE CASTING MACHINE TWO SHIFTS PER DAY, FIVE DAYS PER WEEK SINCE JUNE, 2009 WITH ALL ORIGINAL RAYTEQ HIGH-POWER HEATING ELEMENTS STILL IN OPERATION. PHOTO COURTESY OF A & B DIE CASTING, HERCULES, CALIFORNIA.

As an example, Rayteq's Model DC-720 electric resistance melting furnace melts 720 lbs/hr of aluminum, its crucible top inside diameter is 40 inches, which yields a surface area of 1,257 in^2, and its crucible capacity is 2,650 lbs. Since the density of molten aluminum is approximately 0.086 lbs/in^3, the molten aluminum in the crucible occupies 2,650 lbs divided by 0.086 lbs/in^3 = 30,814 in^3. Meanwhile, a stream of molten aluminum being poured from a ladle or tilting furnace might well have a diameter of 2 inches and so the cross-sectional area of that stream would be pi times the radius squared or 3.14 in^2. If we divide that area into the 30,814 in^3 volume occupied by the 2,650 lbs of molten aluminum, the total length of that 2 inch diameter stream will be 30,814 in^3 divided by 3.14 in^2 = 9,813 inches, and the exposed surface area of that stream will be 2 inches diameter X pi X 9,813 inches of length = 61,659 in^2. Yet the exposed surface area of the molten aluminum in the electric furnace is only 1,257 in^2. Thus the ratio of the exposed surface area of the turbulent moving stream of molten aluminum to the exposed surface area of the quiet metal bath in the electric furnace is 61,659 in^2 divided by 1,257 in^2 = **49 to 1!** And this calculation does not

MOLTEN METAL STREAM FROM TILTING CRUCIBLE-TYPE ALUMINUM MELTING FURNACE HAS INCREASED SURFACE AREA WHICH REACTS WITH WATER VAPOR AND OXYGEN TO FORM DROSS AND HYDROGEN POROSITY, MAJOR CONTRIBUTORS TO CASTING DEFECTS.

take into consideration the additional exposed surface area caused by the inevitable turbulence which could easily multiply this result by a factor of 10 or more. Thus the water vapor and oxygen in the atmosphere have at the very least an unparalleled 49 to 1 opportunity to do their worst damage, particularly since there is no protective thin film of aluminum oxide to guard the moving, turbulent molten metal stream. The results are nearly instantaneous and predictably dramatic. By how much? Let’s look at the literature.

In his article entitled *Calculating Furnace ROI* in the August, 2013 issue of *Modern Casting* magazine, author Richard Schaefer, President of The Schaefer Group, Inc. (one of Rayteq's competitors), writes that,

> *"An efficient aluminum casting facility will deliver the right quantity, quality and temperature of metal as flawlessly as possible. Eliminating the transfer ladle between the melting and holding furnaces is one way to achieve this. Turbulent transfers are detrimental to casting quality and melt efficiency*."

He goes on to state that,

> *"Every time metal is transferred turbulently, approximately half a percent of it is lost. So if you tap or pump molten aluminum out of a central furnace into a transfer ladle, then pour the metal from the ladle to the holding furnace, you have lost 1% of all the metal you have purchased. You have also deteriorated the quality of the metal through added oxides and gas."*

In the same article, Mr. Schaefer also gives a nod to electric melting when he states,

> *"Aluminum casters can gain efficiency by switching from gas to electric. While the majority of furnaces sold today are gas-fired, the most energy efficient (and more expensive in up-front purchase price) are electric."*

Unfortunately, Mr. Schaefer was apparently unaware of how well Rayteq electric furnaces compete price-wise with gas-fired furnaces; in some cases, they're actually *lower* in up-front capital cost! Citing electric furnace efficiency, he concludes,

> *"With a large range of available electric furnaces achieving 70% efficiency, aluminum metalcasters may find that switching to a more efficient furnace is worth the investment, but proper calculation of total costs will prevent overspending."*

Again, Mr. Schaefer is unaware that Rayteq's electric furnace efficiencies run from 75% to nearly 80% in continuous melting applications.

Finally, Mr. Schaefer takes a page out of Rayteq's play book when he opines,

> "*Another progressive way to avoid transfer troubles is to eliminate the large central melting furnace and instead operate a smaller electric melting and holding furnace at each casting cell. Eliminating a central gas-fired melting furnace eliminates transfer ladles, the ladle preheat station, fork trucks and the danger of hauling molten metal around the casting facility, as well as emissions associated with a large furnace. The only molten metal transfer required is from the furnace to the mold."*

Since Mr. Schaefer operates a company that manufactures both gas-fired and electric central melting furnaces, he should be commended for his honesty and integrity in making these statements. For our part, to a respected competitor we've known for many years, we simply say, "Amen!"

Melting Right at the Casting Cell – After reading both Mr. Schaefer's and our recommendations to avoid metal transfers and central melting furnaces, including both stationary and tilting types that require them, one might reasonably ask what should the metal caster do instead? And the answer is to use highly efficient, stationary electric melting furnaces to melt as close as possible to the die casting machine, molding line, permanent mold machine, etc., and bring metal to these furnaces in solid ingot form.

This means that the electric furnaces must have adequate melting capacity to meet the melt rates required. Rayteq currently manufactures a line of electric resistance crucible furnaces with both the highest melting rates per square foot of occupied floor space *and* the highest overall melting efficiency that take advantage of Rayteq's new high power density heating elements and unique hybrid digital/analog power controls. If needed, multiple stationary furnaces can be installed at the casting

RAYTEQ MODEL R-475 ELECTRIC RESISTANCE FURNACE MELTS 475 LBS/HR OF ALUMINUM ALLOY RIGHT AT THE MOLDING LINE, PERMANENT MOLD MACHINE, OR DIE CASTING MACHINE

cell to meet production requirements, including melting furnaces linked together in a "piggyback" configuration where metal is transferred from one melting furnace to the next with minimal turbulence to meet the production requirements. In addition, Rayteq is currently leading the development of larger electric resistance melting furnaces with higher capacity crucibles designed to meet the needs of high volume casting producers.

Use of Robotic Ladles – Molten metal can then be carefully delivered without turbulence and excessive exposure from the stationary electric furnaces to the casting cell either by hand ladle or automatic machine ladle. Today, automatic robotic ladles are available from several sources that can be programmed or "taught" to dip out and pour smoothly and evenly, and many are capable of changing the rate of pour during the pouring operation to accommodate special mold requirements. Such robotic ladles are available in very large sizes for handling large mold requirements.

Taking Advantage of North America's Reliable Electrical System – Today North American metal casters are competing with offshore casting producers who cannot melt electrically because their electrical distribution grids are overloaded and unreliable, leading to scheduled and unscheduled blackouts. Instead, they must melt using natural gas, town gas, or oil, which makes them less competitive against North American metal casters who produce higher quality castings by melting their metal electrically.

The author's electric furnace company manufactured electric furnaces for several Asian joint ventures where the American partners bought and shipped electric furnaces to Asia to produce premium quality castings. However, the electric furnaces had to be replaced with fossil fuel-fired furnaces due to the unreliability of the electrical grid.

At the same time, some North American metal casters who melt electrically had lost work to Asian suppliers but are now getting some of that work back due to unacceptable Asian casting quality. While electric melting wasn't the only factor, it certainly contributed in many cases. This begs the question: Why would North American metal casters switch to gas-fired melting when electric melting offers them a significant competitive edge?

Comparison Cost Studies – In the end, it is the economics of metal melting that most heavily influence the decision whether to use natural gas or electricity to melt aluminum alloys. But metal casters must look beyond fuel costs alone and not let temporary low gas prices obscure the focus on the total picture which must also include metal losses, scrap castings, and overall casting quality.

In an effort to help metal casters determine the relative costs of melting aluminum in their own shops using their gas and electric utility suppliers, aluminum alloy vendors, etc., Rayteq produces a comprehensive, complimentary executive report that transparently shows all the calculations that go into determining summary cost-per-pound figures and investment payback periods while taking new technology like Rayteq's *Fleet Commander*™ interactive demand management system into consideration. For details contact Rayteq by email at Information@Rayteq.com, or by phone at 510-638-2000, or visit www.Rayteq.com.

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