

PREVENTATIVE METAL TREATMENT THROUGH ADVANCED MELTING TECHNOLOGY

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Abstract

Conventional aluminum melting results in a deterioration of metal quality due to in-situ melt oxidation, exposure of molten metal to products of combustion, and from separation of the oxide envelope that surrounds the charge media. Peak melt surface temperatures in reverberatory melting can exceed 2000°F. This results in an increase in oxidation rate by a factor of 64, compared to a bulk temperature of 1350°F. Additionally, the dew point of typical products of combustion is equivalent to saturated air at 75°F, further exacerbating oxidation and establishing a high partial pressure of monatomic hydrogen. Such melting processes depend on downstream *remedial* metal treatment for removal of oxide inclusions and dissolved hydrogen.

An advanced melting process currently being developed under the support of the US Department of Energy Office of Industrial Technology, with the objectives of minimizing specific melting energy and melt loss. The process is now in the early stages of commercialization. During operation of this process, it has been found that dissolved hydrogen levels are maintained at exceptionally low values during melting, with a freedom from visible supernatant oxides, using billet charge material. Importantly, the maximum temperature that the melt is exposed to is under 80°F higher than bulk temperature, and this occurs sub-surface in the absence of oxygen. The melt is not exposed to products of combustion that otherwise results in the generation of oxides and dissolved hydrogen. The melting process includes an integral flotation device to separate surface oxides and remove any dissolved hydrogen introduced by the charge media.

Metal treatment has now become implicitly *preventative* through the use of advanced melting (Isothermal Melting). This paper considers the implication of various melting parameters on molten metal quality, and provides a perspective on cause-effect relationship through phenomenological and quantitative analysis. Source to charge heat transfer and intra-charge secondary heat transfer is considered in the context of impact on metal quality. This analysis clearly demonstrates the detrimental impact that conventional melting methods can have on metal quality. Preventative metal treatment, through advanced melting methods, represents a paradigm shift in aluminum melt preparation methodology.

Introduction

A melting operation is essentially an energetic sink-source balance. Thermal energy is supplied to the solid charge by some means (source), which satiates both the sensible and transformation heat requirements of the melting (sink) process.

Additional heat is required to offset thermal losses that are characteristic of the particular containment system. The sourcing process involves two subsidiary operations, namely, the conversion of either chemical or electrical energy to heat, and the subsequent transfer of this thermal energy to the charge and surrounding containment surfaces. Heat transfer is typically the rate limiting process in melting.

Aluminum and aluminum alloys presents several melting challenges. First, aluminum has a combination of relatively high specific and transformation (melting) heats. Table 1 is an approximate compilation of relevant thermal data for elements of commercial interest, and it can be seen that the specific melting energy of aluminum is positioned well above the mean. Melting heat requirements are therefore quite large.

Table I. Compilation of relevant thermal data

Property	Units	Al	Cu	Fe	Mg	Zn	Source
T_m	°F	1220	1981	2797	1204	787	[1]
ΔH_f	BTU/lb	168	88	106	156	48	[2]
C_p	BTU·lb/F	0.225	0.094	0.14	0.266	0.092	[3]
ρ	lb/ft ³	155.5	536.6	473.3	104.8	427.8	[4]
K (near T_m)	BTU/ft·hr·°F	70	180	25	50	40	A
η	Lb//ft·hr	2.90	10.51	17	3.03	8.47	[5]
ϵ	clean	0.03	0.3	0.15	0.07	–	[1], [6], [7]
ϵ	oxidized	0.2	0.95	0.8	0.25	–	[1], [6], [7]
α	ft ² /hr	2.00	3.57	0.38	1.79	1.02	$A = k/\rho C_p$
Pr	–	0.009	0.005	0.094	0.016	0.019	$Pr = \eta/\rho\alpha$
SME	BTU/lb	449	277	502	484	123	B
SME/T_m	BTU/lb·°F	0.368	0.140	0.179	0.402	0.156	–

- A. Approximate values, some obtained from Lorenz Number ($2.45 \times 10^{-8} W\Omega^2K^{-2}$)
- B. Specific Melting Energy at 70°F incoming charge temperature to $T_m + 150^\circ F$

Second, two properties of aluminum are problematic to the heat sourcing process. Although aluminum melting is conducted at a relatively low temperature, the high solvency of aluminum has traditionally precluded direct contact with materials that can efficiently transfer melting heat by conduction. The majority of commercial aluminum melting operations therefore use radiation as the primary heat transfer mechanism, with the heat source being either a burner flame or an electric resistance “glo-bar”. Moreover, aluminum’s emissivity is exceptionally low. Radiation heat transfer is dependent on emissive power, which is directly proportional to emissivity. Although it is unrealistic to base melting considerations on the emissive power and exceptionally low emissivity of nascent aluminum, even oxidized aluminum has comparatively low emissivity values, as illustrated by Table 1. Emissivity is wavelength dependent, and the values cited for emissivity in Table 1 are polychromatic. They should therefore be used to compare the relative anticipated radiation heat flux of the metals listed, with both clean and oxidized surfaces. They do not allow for radiation heat transfer optimization by the selection of a particular source wavelength.

Finally, unalloyed aluminum oxidizes quite rapidly at elevated temperatures.

Surface oxides produced by alloys of less than 0.5% magnesium are predominantly aluminum oxide. Aluminum oxide is coherent and follows parabolic law oxidation, which ultimately becomes kinetically self-limiting in thickness.

Mechanical disruption of the oxide layer, the addition of magnesium, or presence of certain alkali and alkali earth elements significantly increases oxidation rate. Mechanical agitation and melt turbulence is practically unavoidable in high rate melting operations. Such agitation renews melt surface and the consequential melt oxidation.

Aluminum oxide in all polymorphic forms substantially increases the apparent emissivity of an “aluminum” surface, and in some cases by over an order of magnitude. Such an oxide supernate will be beneficial to radiation heat transfer, but not to the conductive component of heat sourcing. The thermal conductivity ratio of aluminum oxide to aluminum at melt temperature is approximately 0.05 [8]. A typical gas fired reverberatory melter is designed for a firing rate of 115,000 BTU/hr-ft² which results in an area specific melt rate of 60 lb/ft²-hr. At an SME of 449 BTU/lb, the net surface heat flux is 26,940 BTU/hr-ft². Every 5 millimeters of aluminum oxide supernate will result in an 110°F temperature decrease. These thermal conductivity implications dramatically reduces melt rate and increases oxide supernate surface temperatures at a thickness of only several hundred microns. Contributions to bulk heat transfer facilitated by an oxide induced emissivity increase are negated.

Metal Quality Considerations

Heat sourcing and metal quality factors are closely related. Most contemporary aluminum melters use fuel air combustion burners with primary charge coupling by radiation heat transfer. This method of heat sourcing establishes the composition of the furnace atmosphere, as well as determining the surface temperature of the charge. Both influence metal quality.

Hydrogen Uptake

The two metal quality considerations of importance are hydrogen adsorption and oxidation. As discussed, oxides that remain supernatant to the melt are relatively innocuous, and may even be beneficial to radiation heat transfer in the nascent stages of melting. Some investigators have reported, however, that certain oxides promote elevated temperature proton conduction and this can result in an increased hydrogen adsorption rate. A notable example of oxide assisted proton conduction occurs with boron oxide and sodium borate.

Sievert’s Law establishes the relationship between the partial pressure of a diatomic gas and the concentration of the gas as a species in a solvent phase, viz:

$$[H] = S_o \sqrt{P_H} \quad (1)$$

Where: $[H]$ = dissolved hydrogen concentration, S_o = equilibrium hydrogen solubility
 P_H = hydrogen partial pressure

Substitution of a suitable expression for hydrogen equilibrium solubility, S_o [9], yields:

$$[H] = \exp [(-2760/T^\circ K) + 2.796] \sqrt{P_H} \quad (2)$$

Temperature Effects

A graphical representation of this equation results in the familiar exponential rise curve demonstrating the temperature dependence of dissolved hydrogen concentration in pure aluminum. Equation (2) however, indicates that dissolved hydrogen is an explicit function of two processing variables: temperature and hydrogen partial pressure. Since the form of S_0 is essentially Arrhenius, hydrogen solubility and temperature are exponentially related. A 10% increase in melt temperature from 1300°F to 1430°F results in a nearly 22% increase in S_0 . If the surface temperature of the melt reaches 1800°F, S_0 increases by 87%.

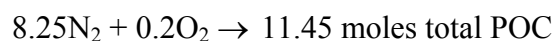
An increase in S_0 enhances the melt's *capacity* for dissolved hydrogen by increasing the value of the equilibrium constant for the serial hydrogen monomerization and dissolution reaction scheme. Importantly, increasing S_0 is a necessary, but alone insufficient, condition for an increased hydrogen activity in the melt. Hydrogen partial pressure has an even greater impact on dissolved hydrogen concentration than changes in equilibrium solubility. The dominant hydrogen source in direct fired reverberatory melting is water from products of combustion.

Hydrogen Partial Pressure Effects

Although only implicit in Sievert's Law, hydrogen dissolves in aluminum as a monotonic (actually ionized species) rather than as molecular hydrogen. Albeit counterintuitive, experiments have demonstrated that sparging with molecular hydrogen can actually decrease the dissolved hydrogen level of an aluminum melt [10]. This is due to the difference in chemical potential between dissolved and molecular hydrogen across the gas/liquid interface. Dissociation reactions and their corresponding free energy change at 1000°K (1341°F) are shown below for molecular hydrogen and water. Absent a reductant, spontaneous dissociation of molecular hydrogen and water does not occur until approximately 6380°F and 7460°F, respectively [11].



Molecular hydrogen has a negligible partial pressure in the atmosphere. The products of combustion from a hydrocarbon fuel do include a significant quantity of water vapor. A natural gas fired melting furnace operating at a burnerhead heat input of 2300 BTU/lb of aluminum melted will require approximately 2.75 moles of methane and produce 5.5 moles (0.22 lb) of water. Such a melting furnace operating at a 10,000lb/hr throughput will generate one metric ton (2200lb) of water per hour. Carbon dioxide is the predominant combustion product gas, and this combines with spectator nitrogen and excess air to dilute this quantity of water. The concentration of water (dew point) in the furnace atmosphere can be determined through a simple stoichiometric calculation and reference to psychrometric charts as shown below. Natural gas combustion with 10% excess air yields 11.45 moles of products of gas phase combustion (POC):



The water vapor fraction of the POC gas is 2/11.45 or 17.5 volume percent.

This concentration is equivalent to saturated air at 80°F. As indicated by equation (4), however, spontaneous dissociation of water vapor is not energetically favorable, and even the high water content of POC gas would not result in melt-accessible hydrogen by dissociation alone. Oxidation reactions supply the thermodynamic driving force for the reduction of water. The role of aluminum as a reductant is illustrated by the following reactions [11]:



Equation (8) makes it apparent that aluminum oxide formation can indeed drive a reaction scheme that avails *monatomic* hydrogen to aluminum for potential dissolution. It was previously stated that a typical gas fired reverberatory melter is capable of producing 0.22 pounds of water per pound of aluminum melted, yielding 0.024 pounds of hydrogen based on a hydrogen/water mass ratio of 1/9. If only 0.01% of this quantity ultimately dissolved in the melt, the resulting hydrogen increase would be 0.3 cm³ H₂ (STP)/100g Al.

Oxidation

It can be readily demonstrated through simple thermodynamic arguments that aluminum oxidation will occur at oxygen partial pressures (P_{O2}) greater than approximately 10⁻⁴⁸ atmospheres. With the exception of specialized oxygen scavenged vacuum furnaces, all commercial aluminum melting furnaces operate using atmospheres with P_{O2} values on the order of 10⁻² to 10⁻¹ atm. Oxides will therefore form regardless of efforts to seal and/or establish inert atmospheres in these furnace. The *rate of oxidation*, however, is dependent on temperature, atmosphere, turbulence, and alloy.

Coherent oxides, such as most forms of aluminum oxides, effectively limit cation (metal) diffusion as thickness builds to the point that the rate of oxidation asymptotically approaches zero. Such oxidation behavior is known as parabolic oxidation, and depicted in Figure 1.

The value for the parabolic oxidation constant, K, is influenced by temperature. Since parabolic oxidation is solid-state diffusion controlled, *temperature* dependence is proportional to e^{-Q/RT}, where Q is the activation energy. A generally accepted empirical relationship is that K doubles for every 60°C increase in temperature. Again, however, parabolic oxidation is kinetically self-

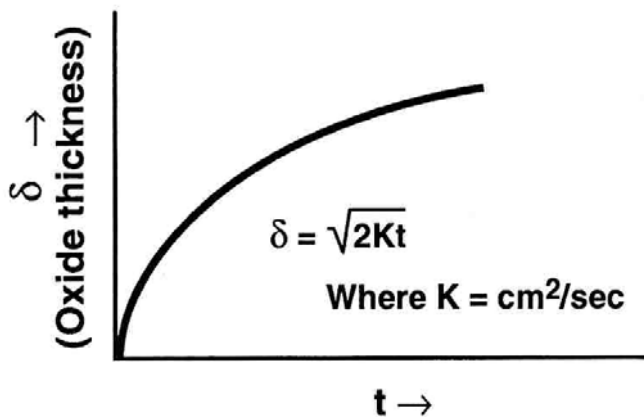


Figure 1. Parabolic oxidation typical of unalloyed aluminum if left undisturbed. Turbulence leads to surface renewal, and the curve essentially regresses in time with an instantaneous increase in K.

limiting and increasing K by several multiples will not necessarily result in “excessive” oxidation. A dramatic increase in the overall oxidation rate will occur if the protective nature of the surface oxide is compromised.

Oxide coherency is affected by two means: oxidization mechanism shift and surface renewal. The oxidation mechanism can shift from parabolic to linear or logarithmic if the nature of the developing oxide is altered.

A good example of a coherent oxide is γ -alumina. This oxide is frequently encountered in aluminum melting situations where the charge media composition does not include significant concentrations of magnesium, alkali or alkali earth elements. Charge consisting of most non-5000 series wrought alloys (ie: 1100, 1350, most 2xxx, etc.), and most non-Mg₂Si strengthened casting alloys are in this category. Figure 2 depicts a γ - alumina film produced in melting 1100 alloy. Such films can form polymorphs at higher temperatures and/or longer residence times. α -alumina is a typical polymorph of alumina that results from a calcining reaction.

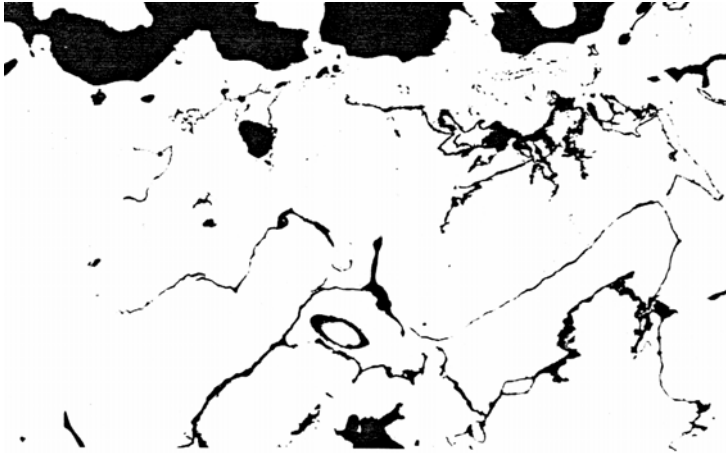


Figure 2. The lacy film morphology oxide shown above is γ -alumina. This desirable oxide, if left undisturbed, is coherent and protective. Melt turbulence or movement that exceeds the film strength of the oxide will result in rupture additional oxidation viz a vi a surface renewal mechanism.

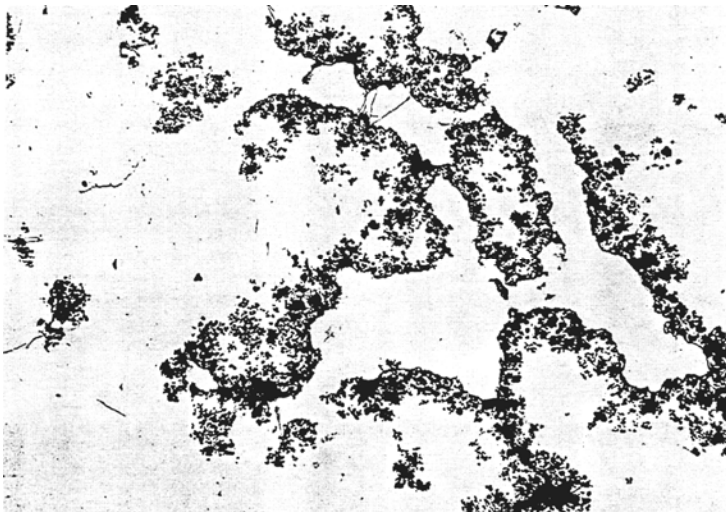


Figure 3. The addition of magnesium to an aluminum melt usually results in the formation of a non-protective oxide, as shown by this evolving magnesium-aluminate spinel.

Solute elements that form oxides with a lower molecular volume than aluminum oxide will reduce the normally protective nature of the oxide layer. Such elements effectively lower the coherency (Pilling-Bedworth ratio) of the oxide layer, and facilitate transport of metal vapor or oxygen to the metal/oxide layer. Oxidation will then begin to occur at the metal/oxide interface rather than the oxide/atmosphere interface alone, as characteristic of parabolic oxidation.

The addition of magnesium to aluminum will result in the formation of an incoherent oxide and subsequent departure from parabolic oxidation. Such oxides are not protective. Figure 3 illustrates the evolution of a magnesium-aluminate spinel (MgAl₂O₄) from an alumina precursor with added MgO “seeding”. Melting operations where MgAl₂O₄ formation occurs are notoriously high in melt loss and potentially compromised metal quality through inclusion formation. Oxidation of such melts is seemingly interminable as a supernatant oxide readily establishes itself and grows following melt skimming. Such a situation is not kinetically self-limiting as is the case with coherent oxides.

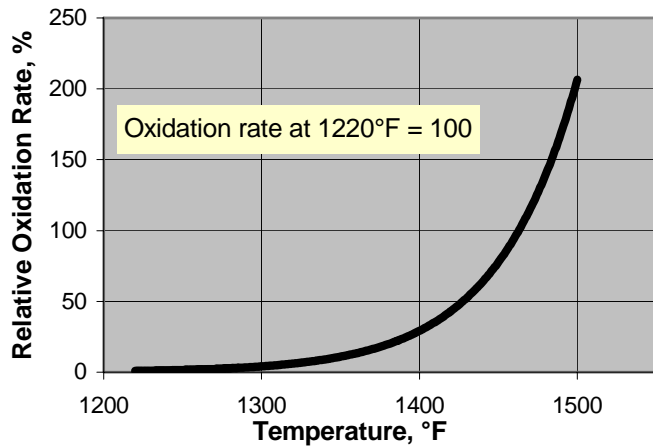


Figure 4. Temperature dependence of oxidation rate for an Al-0.5%Mg alloy (rate; $Ae^{-Q/RT}$ with $A \sim 4 \times 10^{16}$ and $Q \sim 70,300$ cal/mole-°K).

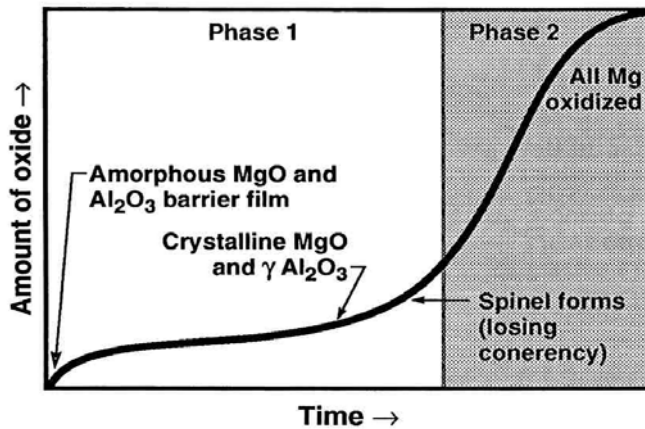


Figure 5. Oxidation of an Al-0.5%Mg melt as influenced by time and the developmental pedigree of the breakaway oxidation product, spinel. MgO formation and entrainment is to be avoided because this oxide is a progenitor for spinel.

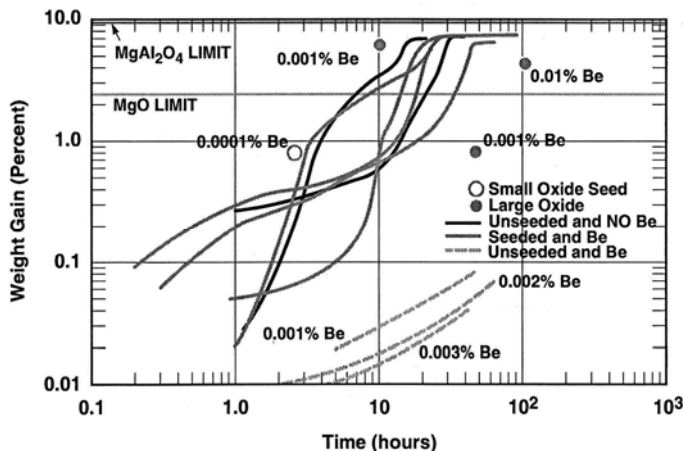


Figure 6. The effect of Be and oxide seeding on an Al-3.5%Mg melt. Prudent melting and atmosphere control are the preferred approaches to reducing oxide generation in such alloys [12].

Temperature will consequentially have an enhanced impact on oxidation rate, as illustrated for aluminum – 0.5% magnesium melt, as shown in Figure 4. Magnesium, lithium, and sodium, for example, are solute elements that will dramatically increase oxidation rate through a parabolic to linear oxidation mechanism shift.

Subsequent to the initial parabolic growth, “break-away oxidation” occurs, Figure 5. The dramatic change in curvature at Phase 2 is coincident with the emergence of incoherent magnesium-aluminate spinel ($MgAl_2O_4$) [12].

A suspension of pre-existing oxides in alloys containing magnesium and the addition of certain alkali elements can stimulate rapid oxide growth through oxide seeding and epitaxial growth mechanisms. Conversely, other elements, such as beryllium, can reduce the observed oxidation rate. This effect is illustrated in Figure 6.

Summary – Metal Quality

Melting methods dramatically influence metal quality factors in aluminum alloys. Heat sources based on direct combustion produce POCs and create a high dew point environment in the furnace atmosphere. A high P_{H_2O} gives rise to monatomic hydrogen production through water reduction by aluminum. Hydrogen adsorption and dissolution is significantly increased with high peak temperatures that occur in melting. High temperature exponentially increases oxidation rate. Further, turbulence that is sufficient to disrupt the melt surface, results in surface renewal.

The renewal of nascent aluminum surface negates any protective benefits of a coherent aluminum oxide supernate. The overall oxidation rate therefore remains high and will emulate linear oxidation. Finally, spinel formation is promoted if melting practices produce magnesium oxide giving rise to break away oxidation.

Low melt temperature, low dew point, and low surface turbulence all promote the preservation of metal quality in aluminum melting operations. The ideal melting process will combine these attributes with a high heat flux to maximize throughput and special efficiency. A high heat flux must result from a favorable heat transfer coefficient (heat source to furnace charge coupling), and not from simply a high temperature differential. High melt rates also minimize holding time and therefore the opportunity for oxides to grow.

Overview of Heat Transfer Mechanisms

Heat sourcing in aluminum melting involves a combination of primary and secondary heat transfer. Induction furnaces notwithstanding, *primary* heat transfer occurs from the heat source to the charge. In essentially all commercial melting operations, this occurs by radiation, from either burner or electric “glo-bar” sources. *Secondary* heat transfer occurs within the charge by conduction, convection, or a combination of both. Convection can either be natural or forced. Forced convection is an important mode of heat transfer in melting process where the charge is submerged and subsequently melted through the sensible heat of recirculating metal.

The rate equations for radiation, conduction, natural convection, and forced convection are very different. Conduction depends on the presence of a conductive material and the resulting heat flux is dependent on the thermal conductivity of this material and the temperature gradient. This gradient is directly proportional to the difference between the first power of source and sink temperatures. Convection is a function of kinematic properties and system parameters, such as velocity. Bulk fluid movement facilitates energy transfer. Convective heat transfer is coupled to momentum transfer in the fluid. Radiation is based on the transfer of electromagnetic energy, and the radiative heat flux is proportional to the difference between the *fourth power* of source and sink temperatures. Flux also depends on view area, view factor, and separation distances.

Dry hearth furnaces melt by ablation. Molten aluminum in such furnaces is allowed to flow into a separate chamber as the melting process progresses, and is kept separate from the melting charge. Since transformation heat requirements of the charge are a powerful sink, melting occurs in a pseudo-isothermal manner in dry hearth furnaces. So-called wet hearth furnaces allow molten metal to collect around the melting charge to significantly augment primary radiation heat transfer by conduction of surplus sensible heat to the melting charge. The increased surface area of the molten bath also improves radiation heat transfer. Wet hearth furnaces use either static baths or a recirculating flow of metal to enhance heat transfer. Static baths depend on conduction and buoyancy force driven natural convection for heat transfer. A melting process known as submerged melting, advantageously uses metal recirculation for secondary heat transfer. Forced convection is also intrinsic to both coreless and channel induction furnaces. The heat sourcing process used in the majority of aluminum melting operations today, however, consists of radiation heat transfer, conduction, and natural convection in serial flow. Top down firing in aluminum melters makes natural convection extremely problematic, as will be shown.

Natural convection is predicated on the density reduction of heated fluid resulting in buoyancy force development. Buoyancy forces are responsible for transport of heated fluid from a geometrically lower heating source to colder regions above this heat source.

Three dimensionless groups are important in considering natural convection heat transfer: Reynolds Number ($Re = \text{inertial/viscous forces}$), Prandtl Number ($Pr = \text{momentum/thermal diffusivity}$), and Grashof Number ($Gr = \text{product of buoyancy and inertial forces/viscous forces}^2$). Each is shown parenthetically indicating their respective physical significance. Re and Gr are functions of both material and system parameters, while Pr is dependent only on material properties. As indicated in Table 1, the value of thermal diffusivity, α , for aluminum is second only to copper. Further, the Prandtl Number, Pr , for aluminum is also quite low as compared to the other metals tabulated. The physical significance of low values for Pr is that the thermal gradient will be negligible relative to the velocity gradient in situations where convection is the dominant mode of heat transfer. Gr is directly proportional to the thermal volume expansion coefficient, β , of the melt, viz: $\beta = (1/\rho) (\Delta\rho/\Delta T)_p$, which is approximately $10^{-3}/K$ for aluminum. Such expansion provides the driving force for natural convection. Using values from Table 1, the value for Gr is calculated for a $100^\circ F$ temperature difference and a 1-inch characteristic dimension. In the case of molten aluminum, $Gr \sim 10^9$, which indicates that natural convection heat transfer could be quite effective from submerged heating surfaces of proper placement and geometry.

An experiment was conducted with an 84-inch deep quantity of aluminum (319 alloy) with heat applied by a *top mounted* burner operating at a heat flux of $83,200 \text{ BTU/hr-ft}^2$. Heat sourcing was therefore unidirectional and intended to emulate the conditions in a reverberatory furnace. Thermocouples were positioned at 5, 35, and 50 inches from the melt surface, and the developing temperature profile was measured. The resulting temperature profiles are provided in Figure 7. This was a holding situation only designed to establish a vertical thermal profile

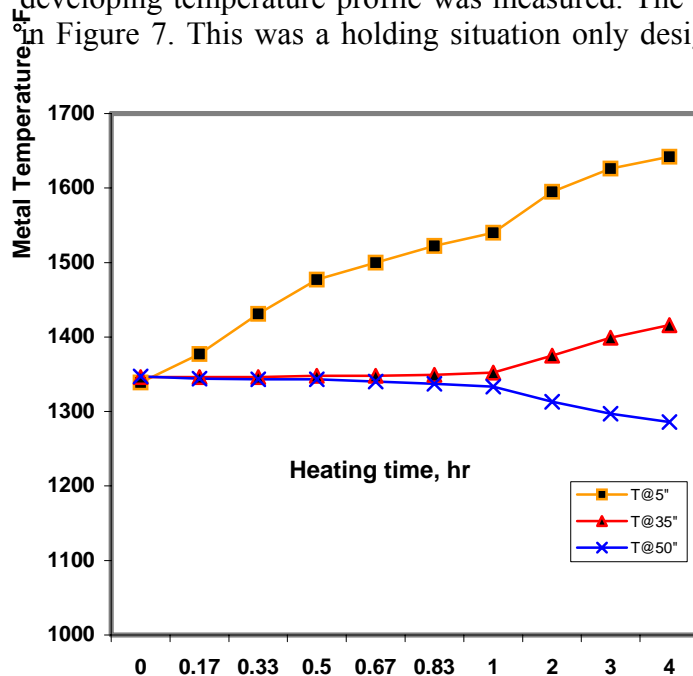


Figure 7. Temperature profiles illustrating inadequacy of top heat sourcing as demonstrated by a temperature differential of almost $400^\circ F$ at only a moderate heat flux ($83,200 \text{ BTU/hr-ft}^2$).

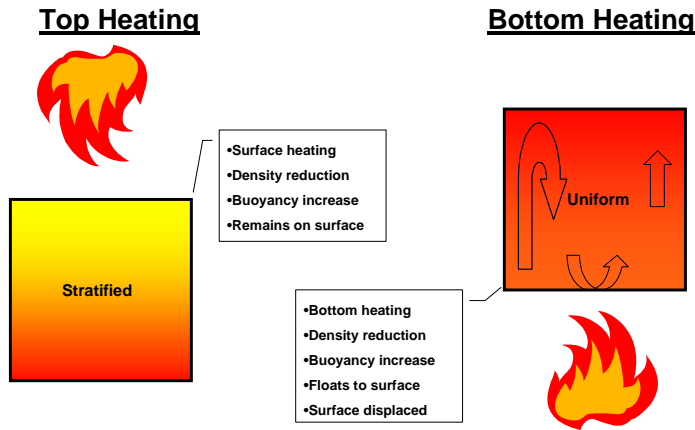
unless a top down flow field is induced. Primary heat transfer (radiation) is also compromised by high metal surface temperature, since heat flux $\propto T^4$. The melt headspace was being controlled at $2300^\circ F$ ($1533^\circ K$). The decrease in primary heat flux from the start of heating at a $1340^\circ F$ ($1000^\circ K$) surface temperature to the developed profile after 4 hours was 19%.

and evaluate the effect of poor secondary heat transfer on primary heat transfer and melt surface temperature. No melting was being performed. The heat sink was exclusively containment loss.

Regardless of favorable values for Pr and Gr that promotes natural convection heat transfer in an aluminum melting situation, unidirectional top-down heat sourcing completely obviates any buoyancy driven heat transfer augmentation.

In contrast to the pot on a stove analogy, a fluid density reduction caused by local heating maintains the highest temperature aluminum at the point where heating occurs, namely, the top. The dominant secondary heat transfer mode is therefore liquid phase conduction,

Clearly the thermal sink imposed by the deep melt bath could no longer be offset by the sourcing rate, and metal temperature at the 50 inch level began markedly decreasing after approximately one hour. Figure 8 provides a pedestrian illustration of top-down heating.



Summary – Heat Transfer

Radiation is the dominant primary (source to sink) heat transfer mode in electric or combustion reverberatory furnaces. Heat flux is proportional to the difference between the source and sink temperatures, and directly proportional to melt emissivity and exposed surface area. A net heat flux of approximately 27,000 BTU/hr-ft² is used in most commercial furnace designs to avoid excess melt surface temperature and optimize thermal efficiency. High surface temperature decreases radiative heat flux and creates metal quality related problems. Secondary heat transfer occurs within the charge and is principally conduction in static furnaces, and a combination of conduction and forced convection in recirculating loop submersion melters. Natural convection cannot occur in a top down heating geometry. Secondary heat transfer is serial to primary heat transfer. Accordingly, the maximum heat flux attainable by primary heat transfer is determined by the secondary heat flux.

Figure 8. Heat transfer with a body of top heated fluid occurs by conduction only-unless forced convection is present. The majority of aluminum furnaces are un-circulated.

Melting Heat Transfer

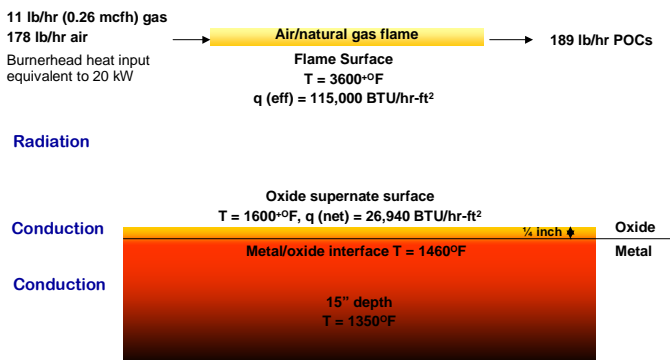


Figure 9. Melting heat transfer consists of serial resistances. The basis for the heat and mass balance calculations shown is 62,000 BTU/hr net heat recovered in the melt, which is thermally equivalent to 20 kW-h.

Figure 9 schematically summarizes source-sink and intra-melt heat transfer in a typical top heated reverberatory furnace. The net heat flux at the surface of the melt results in a melt rate of 60 lb/hr-ft², with a gross energy input to this system of 275,000 BTU/hr (11 lb/hr methane).

Isothermal Melting

In view of the inherent limitations of melt rate and metal quality presented with conventional melting, as well as a desire for significantly higher melter thermal efficiency, a process was developed that uses electric resistance heat sources and conduction/convection for heat transfer. Isothermal Melting embodies an array of direct immersion resistance heaters in a heating bay operating at a surface heat flux as high as 130 w/in², transferring heat by predominantly forced convection to a flowing metal stream, and ultimately sinking this heat by a continuous melter charge feed. The effective melt surface heat flux in the array is at least 385,000 BTU/hr-ft², and heater surface to bulk metal temperature difference is less than 40°F. Sink side heat transfer to the charge is also by predominantly forced convection, and the maximum bulk to charge temperature differential is 34°F. Obviously, low loss heat transfer is germane to the successful operation of an Isothermal Melter.

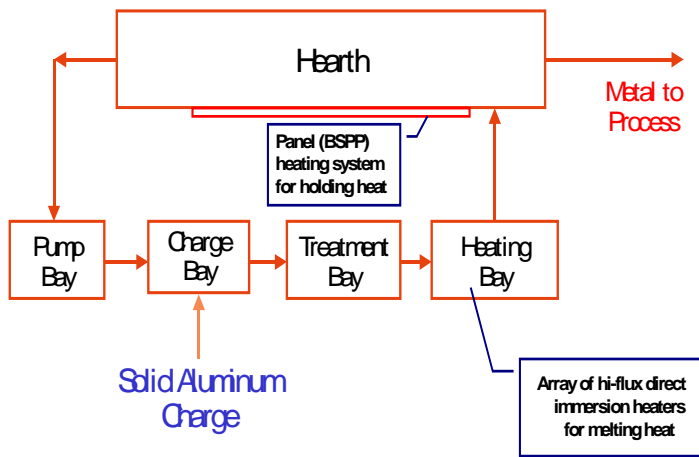


Figure 10. The Isothermal Melting process is a continuous process so named because metal is removed from and returned to the “hearth” at essentially constant temperature.

Conventional melting furnaces are frequently designed to operate in a thermally cycled batch-processing mode. Such operation is discontinuous by nature. Isothermal Melting, however, imparts heat as a continuous process. Figure 10 is a schematic representation of an Isothermal Melter. The particular sequence of operations illustrated (pump-charge-treat-heat) was selected as a design expedience and does not initially appear to exploit the benefits of countercurrent flow relative to charge heat transfer. If the size of the hearth is minimized and internal wall thermal losses

minimized, this flow geometry is not a limitation.

Equation (8) is essentially an elementary energy balance that describes the conditions necessary for “isothermal” operation:

$$W_R/W_C = (\Delta T_C + \Delta H_f/C_p)/\Delta T_R \quad (9)$$

Where: W_R , W_C = recirculating metal flow rate and charge rate, ΔT_R = recirculating temperature differential (source-sink), ΔT_C = charge temperature differential, ΔH_f = heat of fusion (melting), and C_p is heat capacity with the simplifying assumption that it is constant over the temperature range of interest and equal in both solid and liquid states. It can be shown for melting room temperature aluminum using a ΔT_R of 34°F, the recirculating rate to charge rate is approximately 55:1. A charge rate of 5,000 lb/hr therefore requires a recirculation rate of 275,000 lb/hr, which is reasonable. An Isothermal Melter containing 8,500 pounds of internal metal would therefore experience a complete turnover approximately every 2 minutes.

Actual designs of such a melter are depicted in Figures 11 and 12.

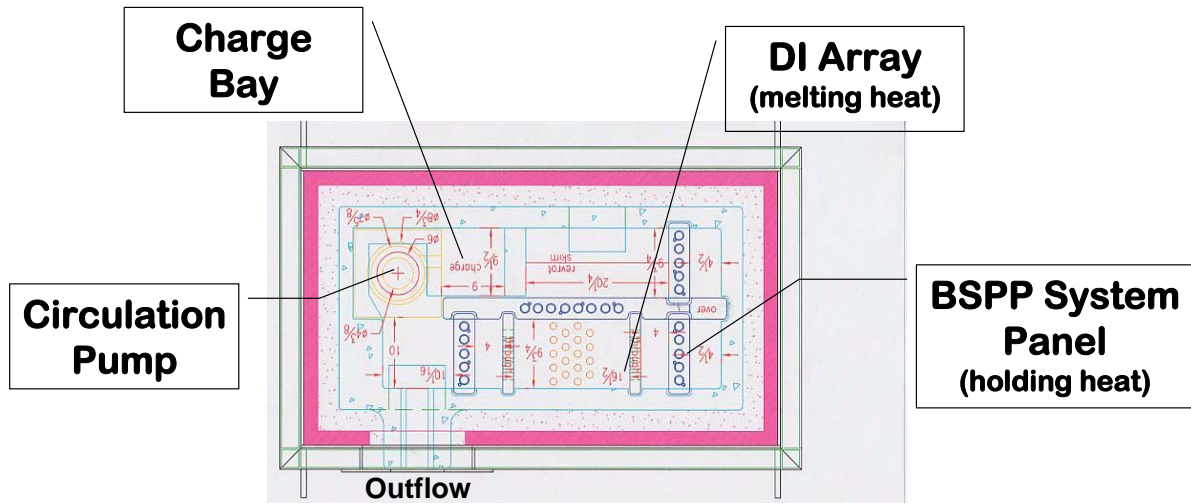


Figure 11. An Isothermal Melter design to handle a charge rate of nearly 1000 lb/hr. The total internal quantity of recirculating aluminum is less than 1500 lb. This unit requires less than 9 kW at idle, and can consume up to 145 kW during maximum rate melting.

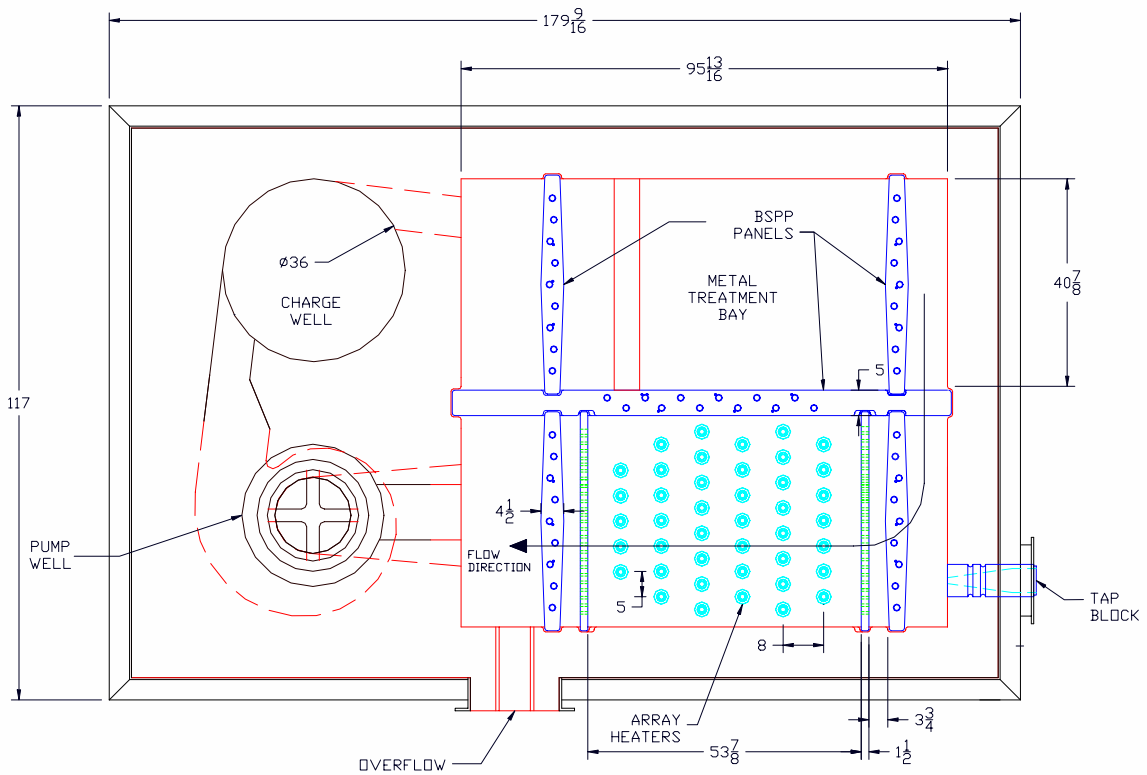


Figure 12. A Isothermal Melter designed for a nominal charge rate of 5,000 lb/hr that can be expanded 40%. The plan dimensions are 10 feet x 15 feet, and the melting power requirement at nominal melt rate is 820 kW. This unit uses 8500 pounds of internal recirculating metal.

Low temperature differential melting, characteristic of Isothermal Melting, has had a substantial impact on thermal efficiency, melt loss, and metal quality. Specific melting energy (SME) for this process has been measured at 614 BTU/lb (with holding losses) and 487 BTU/lb (without holding losses) for an Al-0.5% Mg alloy. Typical reverberatory furnaces operate at an industry average of 2100-2300 BTU/lb. Actual Isothermal Melter melt loss is under 0.5% and holding melt loss is 0.08%/month for a furnace vessel containing 1500 lb of aluminum. No measurable dissolved hydrogen accrual has been measured as a consequence of melting. Although an integral rotary phase contactor type of sparging device has been incorporated to separate surface oxides from the charge, evidence suggests that indigenous inclusions are not formed as a consequence of melting. The approach used by this melting process to attaining and maintaining high metal quality is therefore preventative rather than remedial.

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