The Development of an Innovative Vertical
Floatation Melter and Scrap Dryer for Use in the
Aluminum Processing Industry

Final Report

Robert De Saro
ERCo
Energy Research Co.
2571-A Arthur Kill Road
Staten Island, NY 10309
(718) 608-8788
rdesaro@er-co.com

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Forward

The U.S. Department of Energy (DOE), Industrial Technologies Program, funded the work covered in this report. This report covers the results of a project aimed at the development of a Vertical Floatation Melter, for application to the aluminum industry. This is intended to improve both the energy efficiency and environmental performance of aluminum melting furnaces. Phase I of this project dealt primarily with the initial research effort. Phase II, dealt with pilot-scale testing.

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Robert De Saro - Energy Research Company
Graham Guest - Stein Atkinson Stordy

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Abstract

A problem faced by the primary metal and glass industries is their intense energy usage. The secondary aluminum industry alone, expends about 1,000 Btu per pound of aluminum to remove oil, paint, plastics and other organics from the scrap. Another 3,000 Btu per pound is used in melting the scrap for a total energy use of 4,000 Btu per pound. The glass industry uses about 4 MMBtu per ton of batch and cullet to make glass bottles. Additionally, emissions and generation of waste materials are also industry problems.

For the secondary aluminum industry (our near term market) an innovative melter and dryer is proposed that will reduce this energy use. First the scrap is dried or decoated in a controlled atmosphere, indirect heated, rotating kiln (IDEX) that completely removes the organics. The heat content of the organics drives the process with little or no supplementary fuel required. Second, the preheated scrap from the IDEX is fed to the top of the Vertical Flotation Melter (VFM) where it falls through a melting cone and into the holding furnace. The products of combustion (poc) flow upwards through the cone, counter current and in direct contact with the scrap. The gases impose a variable drag force on the scrap which impedes its descent. For most scrap pieces, an equilibrium is reached in which the scrap weight equals the gas drag force and the scrap is hung-up and does not fall for 15 to 30 seconds. This greatly increases the scrap residence time, allowing the scrap to be melted in the cone. As the scrap reaches a liquid state, it takes on a more aerodynamic drop shape which reduces the drag force and allows it to fall into the holding furnace.

This program has been completed with the following results:

- The VFM concept has been experimentally shown to be feasible.
- The performance of the VFM has been determined.
- The marketing strategy has been devised. The target markets have been identified and the strategic partnerships have been arranged.
- The installed cost and installation geometry has been determined.
- A pilot-scale VFM/VFD was built and operated.
- Pilot testing confirmed the performance of the equipment.

The VFM and IDEX will result in the following:

- Substantial energy reduction. When combined with the IDEX, the VFM has a thermal efficiency of 75%, as compared to a conventional furnace at 19%. This results in an energy savings of 2,250 Btu/lbm. A possible 15.3 trillion Btu per year can be saved with widespread use of this technology.
- Use of waste fuel, the scrap organics occurs during IDEX operation.
- For the IDEX, reduction in emissions of NO_x, SO_x, CO, and VOC which led to measured emission levels to be below 20% of the regulated allowable limits.
- Increase in revenue for the secondary aluminum industry by over \$400 million.

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1. Introduction

1.1. Project Goals

The primary goals were

- Determine the feasibility of the Vertical Floatation Melter (VFM) and metal dryer (IDEX) combination to achieve the target energy and emission reduction, and productivity improvements.
- Assess industry needs and acceptance of the VFM and use industry input to shape the VFM commercial design.

The objectives of the work were:

1. Analytically determine the System's Performance for both the Secondary Aluminum and the container glass markets to assure new designs will meet the target improvements.
2. Evaluate other industry segments that can use the VFM and possibly the IDEX.
3. Develop an optimum VFM design based on industry input and the results of the analytical and experimental development work.
4. Experimentally determine aluminum melting characteristics in the new design
5. Test the Pilot Scale VFM

2. Secondary Aluminum Industry

2.1. Description

Aluminum alloys can be made by primary production, from bauxite, or by secondary production, from scrap aluminum. The major attraction of secondary aluminum production is that it uses only 5% of that from primary since the energy intensive reaction of converting Al_2O_3 to Al has previously occurred. Processors can be classified as primary or secondary aluminum processors depending on their use of bauxite or scrap. However, this distinction becomes a bit blurred since primary producers will also use scrap metal when suitable; mostly used beverage cans (UBC) to make new can stock. Total scrap aluminum consumption in 2003 was over 3 million tons, by 75 secondary and 23 primary refiners (2.1).

Secondary aluminum production consists of the following steps. Most scrap is shredded to a small size and passed by a magnet to remove iron. The scrap then enters a decoating rotary kiln to remove cutting oils, plastic, paint, and other organics. This is done to minimize melt loss in the furnace from unwanted metal oxidation and to minimize the furnace emissions of smoke and fumes. Some high priced scrap is charged directly into the furnace without pre-processing since it is clean and has no oils.

The scrap is melted in a reverberatory furnace, usually of 40,000 to 200,000 pound capacity. The dross** is mechanically skimmed off the top of the furnace. Ingots and sows, the final products are cast and shipped to the customer.

Secondary smelters usually produce ingots and sows that are in turn fabricated into finished products by foundries and die casters. These, in turn, go into the following products:(2.2)

- Automotive and automotive related (66%)
- Small engines (8%)
- Appliances (7%)
- Other (19%)

The furnaces and rotary decoating kilns are usually fossil fired with either gas or oil. Typical energy usage is 3,000 Btu/lbm in the furnace and 1,000 Btu/lbm in the kiln.

** Dross consists of aluminum metal with an oxide coating that floats to the top of the melt.

2.2. Problems

2.2.1. Furnace Energy Use

The energy use for the furnace is high, about 3,000 Btu/lbm. Table 2-1 shows the energy use breakout for a reverberatory furnace. More than half of the total energy expenditure is in the flue gases, due to its high temperature, typically 2200 F. A high flue gas temperature is required since the heat transfer to the charge is predominately radiatively driven.

Table 2-1 - Energy Use for a Conventional Furnace

	Conventional Furnace (Btu/lbm)	Conventional Furnace (%)
Heat into Scrap	560	19%
Flue Gas Losses	1,562	52%
Wall and holding losses	878	29%
Total	3,000	100%

Thermal Efficiency 19%

The wall and holding losses account for 29% of the total energy use. Wall losses are high since a deep molten bath is needed with considerable thermal inertia to assure it doesn't freeze when cold scrap is charged. Since the bath is deep, a large temperature vertical gradient is required to drive enough heat to the bottom of the bath to keep it molten. Hence, the surface temperature is typically 1450 F, to assure that the bottom temperature remains above the aluminum melt temperature of 1250 F. Also, the bath must be held in a molten state while the scrap aluminum is being melted, which can take 4 hours or more for a typical charge. The combination of high melt temperature and long molten metal residence time leads to a large wall and holding loss.

Hence, the thermal efficiency of a conventional furnace is only 19% (defined as the ratio of the heat going into the scrap aluminum to that of the total energy used).

The total amount of energy used in secondary aluminum smelters is 20.4 trillion Btu per year, which is expected to increase to 32.7 trillion Btu per year by 2010.

2.2.2. Dryer Energy Use

Energy use of conventional dryers is typically 1,000 Btu/lbm, which is needed to heat the scrap to about 900 F and drive off the organics. Conventional dryers do not take advantage of the heating content of the organics on the scrap, which typically have a

heating content of 18,000 Btu/lbm. With a scrap aluminum organic loading of 7% by weight, theoretically no additional energy source would be required. However, conventional dryers vaporize the organics and then either vent the gases or destroy the organics in an afterburner. The heat of the organics is not used.

2.2.3. Production loss from Dross and Fines

Melt loss, from dross, in a conventional furnace is typically 8 to 10 % of the total charge. The loss occurs mostly from the aluminum oxidizing to alumina (Al_2O_3). A large amount of aluminum is lost in this fashion due to the high melt temperature and long scrap residence time in the furnace, as mentioned above. Also, the melt is directly exposed to the flame from the furnace burners which also contributes to melt loss.

Further, if the dryer does not completely eliminate the organics from the scrap, additional melt loss occurs. Alternatively, if the dryers overheat the scrap the metal will oxidize, also leading to melt loss. Most conventional dryers cannot adequately control the scrap temperature and will either overheat or underheat the scrap.

In a conventional dryer, fines can be produced due to the direct flame impingement on the scrap aluminum which leads to significant metal thermal shocking. A conventional dryer will produce 6 to 7% dust (defined as -20 mesh particles), or about 700 pph.

2.2.4. Dryer Emissions

The dust mentioned above, leads to an emission problem of fine particulates, which are usually captured in a baghouse. However, the dust represents lost production and must be landfilled.

Volatile organic compounds (VOC) are also released into the atmosphere by the dryers.

2.2.5. Furnace Emissions

The emissions from conventional furnaces can be quite high and consists of particulates, NO_x , VOC, as well as emissions of fluxing agents such as chlorine, potassium, and sodium.

3. Concept Description

3.1. Introduction

Two innovative technologies were addressed in this program to solve these problems. The first, a Vertical Floatation Melter (VFM) is an advanced furnace with a high thermal efficiency and low melt loss. The second technology was an advanced dryer termed IDEX. The IDEX removes the organics from the scrap aluminum prior to melting in the VFM.

Each of these two technologies is described in the following sections.

3.2. VFM Melter

3.2.1. VFM Description

A schematic diagram of the VFM is shown in Figure 3-1. The furnace consists of three major sections:

- (1) Melting Zone
- (2) Recirculation Fan
- (3) Holding Furnace

Figure 3-1 - VFM

Scrap, having been decoated and preheated by the IDEX, is passed to the top of the melting cone where it falls towards the holding furnace. The products of combustion (poc) flow upwards, counter current and in direct contact with the scrap. The gases impose a drag force on the scrap which impedes its descent. Since the furnace is an

inverted truncated cone, the velocity increases as the scrap falls, thus increasing the drag force. For most scrap pieces, an equilibrium is reached in which the scrap weight equals the gas drag force and the scrap is hung-up and does not fall. As the scrap reaches a liquid state, it takes on a more aerodynamic drop shape which reduces the drag force and allows it to fall into the holding furnace.

Different sizes or shapes of scrap will hang up in different elevations of the cone. Compact, heavy scrap will reach a force equilibrium at a lower level (and therefore higher gas velocity) than will lightweight flakes or foil. Also, some scrap will reach the holding furnace without melting either because they are oversized, or because chance collisions with other pieces of scrap impart enough downward momentum to overcome the drag force. These pieces will melt in the holding furnace.

A gas or oil fired burner is positioned in the end wall of the holding furnace to provide the high temperature poc. The fan blows the recirculating poc into the holding furnace and then up through the cone. The poc then enter a settling chamber where any carry over fines settle and melt by running down the sloping floor and returns to the cone.

3.2.2. Target Market

The first primary target market for the VFM is the secondary aluminum market that process used beverage cans (UBC). The reasons, which are detailed in later sections, are:

- The UBC market is the largest segment of the scrap aluminum industry.
- UBC scrap is reasonably uniform in size and weight.

The second primary target market for the VFM is the secondary aluminum market that processes non-UBC scrap, such as aluminum siding, recycled automobiles, etc.

Alternative markets for the VFM that have been studied are:

- Cullet (recycled glass) melting
- Hazardous waste vitrification
- Radioactive waste vitrification.

3.2.3. VFM Advantages

The major advantages of the VFM are reduced energy consumption and reduced dross loss, as compared to conventional furnaces.

Energy Reduction

There is a significant energy reduction from the VFM due to the scrap suspension and low residence time in the furnace. In a conventional furnace, heat transfer to the cold scrap is by conduction form the aluminum bath. If too great a quantity of cold scrap is fed into a conventional melter, the bath may solidify, so a large heel (molten aluminum

inventory) must be maintained. Also, some amount of shredded scrap tends to float to the top of the melter which further impedes the melting process. Mechanical stirring is typically used to limit this problem. Hence the energy use is substantial, due to the large heel required and due to the residence time needed to completely melt the scrap that remains on the melt top. Further, the flue gas losses are quite high in a conventional furnace since wall radiation is the dominant heat transfer mechanism. A 2,200 F flue gas temperature is typical.

The VFM overcomes these problems by direct contact suspension heating of the particles. The heel required is quite small since only a very small fraction of the scrap reaches the melt cold. Also, the residence time is low since the scrap is heated quickly in the vertical furnace. The heat transfer is driven by convective heat flow between the gas and scrap. Since slip velocities between the two are close to the particle's terminal velocity, high heat transfer coefficients are attained. Also, the furnace is a counter flow heat exchanger so the flue gas is cooled to a much lower temperature than possible with a conventional furnace. This greatly reduces the single largest heat loss associated with conventional furnaces.

The VFM has a thermal efficiency of about 57 % which compares to a conventional furnace of only 19 %. The VFM expends about 846 Btu per pound of scrap processed, which compares to 3000 Btu per pound for a conventional furnace.

Dross loss reduction

The VFM meets the three needs for minimum dross production; low temperature, low residence time, and low oxygen content. While in the melter, the metal temperature is between 1,300 F and 1,400 F, the scrap residence time is 5 to 15 seconds, and the oxygen content is between 2 and 5%. Data from SAS show the melt loss to increase markedly beyond 770 C (1418 F). The VFM operates well below this point.

3.3. IDEX Dryer

The IDEX™ is shown in Figure 3-2, and consists of three major components:

- Rotating kilns to process the scrap
- Incinerator to destroy the organics
- Control system and associated hardware

The purpose of the kiln is to completely remove the coatings from the scrap without oxidizing the metal. This is accomplished by fixing the oxygen content at the optimum value to aid in decoating but not so high as to combust the oils. Unlike the conventional kilns, the kiln atmosphere and pressure are controlled to accomplish this.

The scrap enters the rotary kiln through an airlock. The combination of kiln rotation and internal baffles disperses the scrap throughout the kiln volume. Scrap residence time is a few minutes.

Gases at 1500°F enter the center tube, flow parallel to the scrap, and then reverse direction (flowing counter current) after exiting the center tube. The center tube indirectly heats the scrap and the counter flowing gas to avoid downstream condensation.

The organics are vaporized in the kiln and due to the oxygen level (6-9%) 10% of the oil is oxidized, releasing heat. The balance of the oil passes to the incinerator.

The high temperature gas entering the kiln has 5% to 6% O₂ and air leakage raises this to 8 or 9% O₂. A minimum of 4% is needed to oxidize any carbon coating on the scrap and a maximum of 10% to avoid scrap flaming and fire risk.^(3-1, 3-2) At about 10% O₂ content, a blue flame on the scrap is noticed and at 12% O₂ the scrap is enveloped in a yellow flame. This is to be avoided as it leads to excessive scrap oxidation.

The decoating process can be thought to take place in two stages.^(3-1, 3-3) In the first stage, 300°F to 750°F, the water, oil, and other volatiles are vaporized. In the second stage, 900°F to 1000°F, the non-volatile carbon residue on the scrap is removed by oxidation - oxygen combines with the carbon to produce CO₂ and CO. Hence, the need for a minimum 4% O₂ in the kiln.

The gases from the kiln are passed to an incinerator with an oil or natural gas burner. The burner elevates the temperature to 1500°F and additional air flows in. The organic vapors combust in this environment which both release heat and destroys the VOC.

Part of the gases are vented and part are recirculated back to the kiln. The recirculation rate is set by the recirculation fan.

Since the scrap is indirectly heated, dust formation from direct flame impingement does not occur.

Heat is generated in the incinerator by the combustion of the fuel and the vaporized organics. During steady-state operation this heat is carried away in the incinerator exit gas (a small portion is lost through the walls). Heat for the kiln is provided by that portion of the incinerator gas that is not bypassed, and to a lesser degree, by the carbon oxidation. The heat sinks for the kiln are:

- heat up scrap
- driving off the oil and water
- wall losses
- kiln exit gas heat content

IDEX™ DRYER

Figure 3-2 - IDEX Dryer

Figure 3-3 shows the measured specific fuel consumption, as a function of oil content. The fuel consumption continually decreases as the VOC content increase since, unlike conventional equipment, the heating value of the VOC is used in the process. With no VOC, 1,129 Btu/lbm are required, reducing to 330 Btu/hr at 4% VOC (2% moisture).

As the VOC content increases, an auto thermic point is reached in which no natural gas is needed; the oil heat content supplies all the heat needed in the system. The auto thermic point varies depending on system heat losses and oil heating value and generally occurs at an oil content of between 6 and 7%.

Figure 3-3 - IDEX Fuel Use

The IDEX has significant advantages over conventional equipment: energy reduction, emissions reduction, production increase, and baghouse dust reduction. Each is described.

Energy Reduction

Current dryers use 1,000 Btu/lbm. Most or all of this can be eliminated with the IDEX.

Emissions

The Clean Air Act effect on the secondary aluminum industry are now being debated and will be settled shortly with the Best Demonstrable Technologies to be mandated. It is not likely the current dryers will meet the new standards whereas the IDEX might.

IDEX emission measurements made by ERCo have shown low values of NO_x, SO_x, VOC, and CO are achieved. CO₂ emissions would also be reduced in direct proportion to the reduction in firing rate.

Production Increase

Currently, conventional furnaces lose about 8 to 10% of their furnace melt as dross. Some of this loss is attributable to the poor decoating process, though how much is speculative. Further, dust creation in the current kiln of 6 to 7% could be avoided with the IDEX.

Scrap Purchases

Aluminum smelters could possibly process lower grade scrap not possible now. For instance, aluminum foil (such as candy wrappers) will undergo significant oxidation in

their current kiln since the foil is so thin. Testing of the IDEX showed that foil could be readily decoated with no oxidation.

3.4. Combined Performance

The detailed energy usage for a conventional furnace and the VFM combined with an IDEX is shown in Table 3-1.

Table 3-1 - Energy Use of VFM and IDEX Compared to Conventional Furnace

	Conventional Furnace (Btu/lbm)	Conventional Furnace (%)	VFM (Btu/lbm)	VFM (%)
Heat into Scrap	560	19%	320	43%
Flue Gas Losses	1,562	52%	256	34%
Wall and holding losses	878	29%	174	23%
Total	3,000	100%	750	100%

Thermal Efficiency **19%** **75%**

Most of the energy use for a conventional furnace is lost in the flue gases, and the second largest loss is for the wall and holding losses. The amount of energy actually going into the scrap is 560 Btu/lbm for a furnace thermal efficiency of only 19%.

The VFM receives preheated scrap from the IDEX, so only an additional 320 Btu/lbm is needed to melt the scrap. Since the flue gas temperature has dropped to 1400 F and the firing rate has been decreased, the flue losses are only 256 Btu/lbm. Wall and holding losses are also significantly reduced. The thermal efficiency of the VFM, based on a theoretical energy use for scrap melting of 560 Btu/lbm, is 75% (560 Btu/lbm required divided by the actual use of 750 Btu/lbm).

3.5. Combined System Diagrams

A schematic of the VFM system is shown in Figure 3-4. Scrap is first processed in the IDEX to remove the organics. Next, the scrap is fed into the VFM, where it is melted and, if necessary, alloyed. The resulting products are sows or ingots. The recirculation duct and fan is shown, though its use depends on a trade-off of size and installed cost vs. thermal efficiency. This is discussed in Section 5.3.7.

Figure 3-5 shows the VFM using waste heat from either the IDEX or a conventional reverberatory furnace.

Figure 3-4 - System Diagram of VFM

Figure 3-5 - VFM System Diagram Using Waste Heat

4. VFM Experimental Work

4.1. Purpose

The purpose of the experimental work was:

- Prove that the concept of floating and melting large pieces of metal was feasible.
- Provide the necessary experimental correlations needed to construct an accurate analytical model of the VFM (See next chapter). Particularly, the drag and heat transfer attributes of the scrap aluminum needed to be determined experimentally.

4.2. Experimental Description

Two test rigs were used to conduct the experimental work. The first was a small cold flow Plexiglas model shown in Figure 4-1. A rectangular Plexiglas cone is situated on top of a blower. Individual, full-scale aluminum pieces were placed in the model and their floating characteristics were observed.

The second rig was a hot flow unit shown in Figure 4-2. This shows the vertical cylindrical test chamber with a “Y” site port near the engineer, and another site port on top of the chamber. Test pieces are dropped through the top of the test chamber and their descent is observed through the site port. The time to melt is visually observed and timed. Similarly, the test pieces are visually observed when they are floated and the test conditions (gas velocity, temperature, etc.) are then recorded. From these observations, the melt time is determined which provides the heat transfer coefficient. From the floatation tests, the velocity to float is determined which provides the drag coefficient of the pieces.

The following measurements are made during the testing:

- Test piece mass and dimensions
- Gas flow rate through the test chamber
- Gas temperatures at various locations
- Time to melt
- Oxygen content

The burners are located at the inlet of the combustion chamber, to the left in Figure 4.2. Gases flow through the combustion chamber, through the main chamber, vertically through the test chamber, and then to the recirculation duct. Part of the gases are recirculated back to the combustion chamber and part are vented out the top of the test chamber.

Figure 4-1 - Plexiglas Model

Figure 4-2 - Hot Flow Rig

The large main chamber, underneath the vertical test chamber, houses the refractory ramps used to test the wettability of refractories to molten aluminum.

4.3. General Observations

4.3.1. Cold Flow Tests

Using the cold flow test rig, the following observations were made:

- Scrap aluminum is easily floated in the cone.
- The air flow depends on the scrap aluminum's weight. Higher weights require higher air velocities.
- Multiple pieces of different sizes and weights can be floated simultaneously.
- The scrap does not remain stationary in the cone but will hit and bounce off the walls and, at times, will oscillate vertically. In ERCo's cold flow rig, the walls are more closely spaced than would be for a full-scale VFM. Hence, the walls may be affecting the scrap's trajectory more so than would be expected in a full-scale system.
- Similar results were observed in the hot flow rig when run on ambient air.

4.3.2. Hot Flow Tests

The following general observations were made:

- Scrap melting occurs very rapidly.
- Low gas temperatures of 1252 F can be used and still obtain fairly rapid melting.
- At times, the scrap will elongate as it melts.

4.4. Heat Transfer Results

4.4.1. Procedures Used

The average heat transfer coefficient (h), Nusselt Number (Nu), and Reynolds Number (Re) were determined from the experimental data using the following analysis.

The differential equation that governs the scrap heat-up is:

$$dq = Ah(T_g - T)dt = mc_p dT$$

Integrating and solving for t_h (the time to heat up):

$$t_h = \frac{mc_p}{Ah} \ln\left(\frac{T_g - T_i}{T_g - T_m}\right)$$

The equation for the scrap melting is:

$$dq = hA(T_g - T_m)dt$$

or

$$t_m = \frac{h_v m}{hA(T_g - T_m)}$$

The total time (t) is the sum of t_h and t_m . Adding the two and solving for h yields

$$h = \frac{m}{At} \left[c_p \ln \left(\frac{T_g - T_i}{T_g - T_m} \right) + \frac{h_v}{(T_g - T_m)} \right]$$

Where

- h = heat transfer coefficient
- m = scrap mass (measured)
- T_g = gas temperature (measured)
- T_m = scrap melting temperature
- T_i = scrap initial temperature
- A = scrap surface area (measured)
- t = total time for the scrap to heat up and melt (measured)
- h_v = scrap heat of fusion
- c_p = scrap specific heat

Also,

$$Nu = h/kd$$

$$Re = \rho Vd/\mu$$

where

- ρ = gas density (calculated from the gas temperature)
- μ = gas viscosity (calculated from the gas temperature)
- V = gas velocity (measured)
- d = characteristic dimension (measured)
- k = gas thermal conductivity (calculated from the gas temperature)

The following table lists the constants used.

Table 4-1 - Constants

Variable	Value
T _m	1222 F
T _i	75 F
h _v	170 Btu/lbm
c _p	0.25 Btu/(lbm F)

4.4.2. Results

The experimental results for the UBC - Shiny data are plotted as Nusselt Number vs. Reynolds Number in Figure 4-3.

Figure 4-3 - Melt Results

Also shown as solid lines are standard correlations of the form:

$$Nu = CR_e^a Pr^{1/3}$$

where the following values were used.

Table 4-2 - Constants Used in Correlations

Geometry		C	Pr	a
Parallel to Flat Plate	Turbulent	0.037	0.7	0.800
Across a Diamond	Turbulent	0.246	0.7	0.588
Across a Hexagon	Turbulent	0.153	0.7	0.638
Over a Sphere	Turbulent	0.370	0.7	0.600
Perpendicular to Flat Plate	Turbulent	0.228	0.7	0.731
Parallel to Flat Plate	Laminar	0.664	0.7	0.50

The correlation with the flow perpendicular to a flat plate seems to match the data reasonable well. Within the Re range of interest, the correlations having the flow parallel, over, or across the other geometries showed Nu much lower than measured.

There appears to be a discontinuous jump in Nu at a Re of about 8,000 to 10,000. This is likely due to the boundary layer around the scrap transitioning from laminar to turbulent flow.

4.4.3. Conclusions

- Low gas temperatures can be used and relatively quick melting is achieved. This is a major advantage of the VFM.
- High heat transfer coefficients were measured, correlated best with flow perpendicular to a flat plate. This is also a major advantage for the VFM and leads to high throughputs.
- The critical Re occurs at 8,000 to 10,000 beyond which the flow appears to have transitioned to a turbulent boundary layer based on the sudden increase in Nu.

4.5. Drag Coefficient Results

4.5.1. Procedures Used

The drag coefficient (C_d) was determined from the experimental data using the following analysis.

While the scrap is suspended, or floated, its mass equals the drag force or

$$mg = \frac{1}{2} \rho V^2 C_d A_f$$

or

$$C_d = \frac{2mg}{\rho V^2 A_f}$$

where

g = gravitational acceleration

A_f = scrap frontal area

4.5.2. Results

Figure 5-1 shows the C_d vs. Re for UBC. The C_d remains fairly consistent at about 0.8 to 1.2 until a critical Re of about 20,000 is reached, beyond which the C_d is much lower. Similar to flow around a sphere, it is possible that the boundary layer transitions from laminar to turbulent flow resulting in reduced drag. However, the transition occurs at a Re lower than expected. For flow across round bodies, such as spheres and ovals, the transition occurs at a Re of about 500,000.

Figure 4-4 - Cd of UBC

Other data is available which shows similar results to the above, but with considerable scatter. The scatter can be attributed to:

- Each data point represents a different scrap piece, with a different geometry. Since the drag characteristics would be expected to vary among different geometries, scatter results.
- Defining the scrap frontal area is somewhat subjective due to the contorted nature of the scrap.
- Visually determine the point at which the scrap floats is subjective, and can vary among several observers.

4.6. Critical Reynolds Number

On much of the data, a critical Reynolds Number has been observed, suggesting the boundary layer has transitioned from a laminar to a turbulent flow. The critical Re for the heat transfer data is about 8,000 to 10,000 and for the drag data it is about 20,000. It would be expected that the critical Re number would be the same for each. The difference may be attributed to the same issues given above for the scatter in the data.

4.7. Minimum Temperature Tests

It is desired to operate the VFM at a minimum gas temperature to minimize melt loss due to oxidation, to increase thermal efficiency (by having a low flue gas loss), and to minimize refractory costs. Melt tests were conducted at gas temperatures down to 1252 F, just 30 F higher (2.5 %) than the scrap melting temperature. Such low temperature differences can be maintained since high heat transfer coefficients are obtained due to the convective, high velocity environment. It would not be possible to accomplish this low temperature difference with conventional reverbatory furnaces that operate in a radiative heat transfer mode.

5. VFM Analytical Work

5.1. Purpose

ERCo constructed an analytical model to:

- Determine the performance of the VFM
- Design the full-scale VFM
- Determine the feasibility of the VFM
- Explore off-design conditions
- Guide the experimental testing

5.2. Model Description

ERCo constructed a mathematical model that provided the performance of the VFM as it operated and processed aluminum scrap and other materials. This was a full model in the sense that the entire VFM, including recirculation, variable scrap size, blower power, etc. were included. In addition, a two-dimensional transient heat transfer model was constructed that determined the temperature gradients and heat-up time for individual particles. This aided in the selection of a heat transfer model to be used in the VFM full model. For aluminum, the temperature gradient from the surface to the center of the scrap was small due to its high thermal conductivity and high gas heat transfer coefficient. Hence, in the VFM model, scrap particle temperature gradients were ignored for aluminum processing.

Scrap size distributions were initially calculated using statistical routines. However, subsequent calculations used actual measured size distributions provided by Gillespie+Powers and shown in Figure 5-1 for UBC.

Conventional compact heat exchanger analysis is unsuitable for the VFM since the heat transfer occurs over a large number of discrete particles rather than in a continuous fluid. Also, the heat transfer is strongly coupled to the force balance of drag and weight of each particle. The location of the particle in the cone determines the gas velocity and temperature it will experience. Its location is determined at the point that the drag force equals the particle's weight.

Figure 5-2 shows a schematic of the VFM. In the cone, both fluid mechanical forces and heat transfer flows are calculated for each scrap particle. Every particle is individually tracked as it falls through the cone. The geometry and inlet temperatures are specified

Figure 5-1 - Measured Scrap Size Distribution

Figure 5-2 - Schematic of VFM used in Analytical Model

The following analysis is used:

1) The largest particle (and mass fraction) from the particle size distribution is used first. The terminal velocity of the particles are calculated by equating the particle's weight to the drag force from the counter flowing gases. Figure 5-3 shows a schematic of the force balance.

$$V_t = \sqrt{\frac{2 m g}{\rho C_d A_f}}$$

C_d is taken from the experimental data given above.

- 2) From the particle's terminal velocity and from the cone geometry, the particle's position in the cone is determined. The largest particles will equilibrate at the lowest level. This is labeled Level One.
- 3) Next, the Re, Nu, and radiative and convective heat transfer coefficients are calculated. The convective h is calculated using the heat transfer correlations determined in the experimental work.
- 4) The time for the particle to heat up to its melting temperature and the time for it to melt is calculated.
- 5) The total scrap heat gained, and the gas temperature drop is calculated.
- 6) The next largest scrap size is selected and the step 2 through 6 are repeated.
- 7) This continues until the entire scrap size distribution has been exhausted.

Figure 5-3 - Schematic of Force Balance on each Scrap Piece

The calculation results in a series of levels in the VFM, equal to the number of size cuts chosen for the particle size distribution. Each particle populates one of the levels and remains there until it melts at which time its C_d decreases and it falls out of the cone.

Global conditions in the VFM, are determined by summing the effects of all the levels. For instance, the total gas temperature drop is the sum of the drops at each level. The throughput is the sum of the mass of the particles divided by the time it takes to melt at each level.

Mass and energy balances are calculated, as well as the recirculation flow, blower power, specific energy use, thermal efficiency, gas flow rates, VFM diameter and height requirements, flue gas losses, and wall losses.

5.3. Analytical Results

5.3.1. High Convective Heat Transfer Coefficients Drive the Process

A key finding during the analytical development was that the VFM heat transfer process is driven by convective heat transfer. This is in marked contrast to conventional furnaces that transfer the heat to the scrap via radiation heat transfer.

High convective heat loading occurs since the scrap is immersed in the gases at a relatively high velocity (the scrap particle's terminal velocity). Hence, high heat transfer coefficients are achievable, relaxing the need for high temperatures. In fact, the gas temperature need be only slightly higher than the aluminum melting temperature of 1200 F. Inlet temperatures of 1800 F and outlet gas temperatures as low as 1400 F are possible. This contrasts with typical reverberatory furnaces that fire directly into the furnace with little excess air, with gas temperatures ranging from over 3000 F at the burner exit to 2200 F in the flue.

The VFM's low gas temperature results in three major benefits.

1) Low Inlet Gas Temperature Results in Low Refractory Cost

A low inlet gas temperature allows a major reduction in refractory costs, typically the single largest expense for high temperature furnaces. It is likely that a low cement castable, poured in place, can be used instead of a more expensive AZS precast and precured refractory.

2) Low Outlet Temperature Maximizes the VFM's Thermal Efficiency

A low outlet gas temperature maximizes the thermal efficiency of the VFM since it minimizes the flue gas losses, usually the single biggest energy loss for high temperature furnaces. With conventional secondary aluminum smelting reverberatory furnaces, the flue gas temperature is usually 2200 F whereas with the VFM, the flue temperature is about 1400 F to 1600 F. The outlet gas temperature is determined by the inlet gas temperature, heat losses, scrap feed rate, gas flow rate and other factors. The furnace operator can control it by adjusting either the fuel flow or scrap flow rate.

3) Low Melt Loss

As shown in section 5.4, melt loss due to oxidation is dependent on residence time, and gas and scrap temperature. The combination of low gas temperature, low residence time (due to the rapid melting), and low melt temperature leads to a low melt loss.

5.3.2. Melt Times

The VFM is a rapid melter, principally due to the high convective heat transfer achievable, achieving melt times of between 40 to 140 seconds. Larger sized scrap pieces melt longer particularly at lower gas temperatures. For instance, a one inch scrap piece would need between 10 seconds and 100 seconds to melt at a high and low gas temperature respectively. A 4 inch scrap piece would need 50 seconds to 370 seconds to melt for the same gas temperatures.

However, the larger pieces will equilibrate at lower sections in the VFM, and thus would be exposed to higher temperatures than smaller scrap pieces. Hence, the melt time for each is about the same (about 40 seconds or so); that is the larger size is offset by being at a higher gas temperature.

5.3.3. Affect of Particle Size Distribution

The particle size distribution of the scrap is critical in that it determines the size of the VFM. The cross sectional dimensions determine the cross sectional area of the VFM and the size range determines the VFM height. In the subsequent analysis no attempt was made to affect the size distribution. Rather, the measured scrap size distribution for UBC was used. It is possible, however, to use a monoshear (or similar shredder) to reduce the size range. This would result in a more compact VFM.

5.3.4. Affect of Drag Coefficient

The drag coefficient has been measured for UBC to be between about 0.8 and 1.2. Figure 5-4 shows this variation to have a minimal affect on terminal velocity. However, when the scrap is melted, it takes on a teardrop or elongated shape resulting in a Cd of about 0.1 or less. Hence once melted, the VFM gas flow would not be able to support a melted scrap piece as its terminal velocity would be about 3 times higher than it would for solid scrap. This allows the melted scrap to exit the VFM immediately upon melting.

5.3.5. Transient Results

The temperature gradients in both scrap aluminum and glass are given in Figure 5-5. The aluminum gradients are fairly small and nearly isothermal. Hence, in the subsequent analysis, internal temperature gradients are ignored. For glass, gradients can be important, depending on the glass's thickness. For such analysis, the thermal gradients are included in the analysis.

Figure 5-4 - Affect of Cd on Terminal Velocity

5.3.6. Thermal Efficiency

Figure 5-6 shows the specific energy use in total Btu's expended per pound of aluminum processed vs. the outlet gas temperature. Three curves are shown for combined heat losses of 250 Btu/lbm to 1,100 Btu/lbm. The top curve is similar to measurements made on Roth Bros. reverbratory furnace. It has a flue gas temperature of 2200 F and a specific fuel consumption of 3000 Btu/lbm. The bottom curve is similar to data taken from an early version of the VFM operated at Reynolds's in Venefro, Italy.

Figure 5-5 - Aluminum and Glass Temperature Gradients

Figure 5-6 - Specific Energy of VFM

Figure 5-7 - Thermal Efficiency

As the outlet gas temperature is reduced, the specific energy use goes down. For the VFM, an energy use of about 800 Btu/lbm is realizable.

Similarly, Figure 5-7 shows the thermal efficiency, defined as the energy used to preheat and melt the scrap divided by the fuel energy. The affect of the IDEX™ preheating is included. At 1800 F, the VFM has an efficiency of 55%. Lowering the outlet temperature to 1400 results in an efficiency gain to 62%. A conventional reverbratory furnace would have an efficiency of only 15%.

5.3.7. Integrated Analytical Results

Figure 5-8 shows a schematic of the VFM processing UBC with a design inlet temperature of 1800 F. The outlet temperature is 1622 F. A typical production of 5000 pounds per hour is produced. The thermal efficiency is 56 % with a specific energy use of 846 Btu/lbm.

Table 5-1 shows the energy balance associated with Figure 5-9. The furnace firing rate is 4.2 MMBtu/hour. The useful energy going into the scrap is 276 Btu/lbm (the difference between the energy content of the feed scrap and the exiting molten aluminum).

The recirculation fan has a negligible affect on the energy performance of the VFM. For Figure 5-8, the recirculation flow is 23,682 pounds per hour, with a pressure drop through the entire system of 4 inches of water column ("wc). Assuming a 75% motor efficiency, the motor would need to be only 20 hp and the equivalent energy use of the motor is 8.4 Btu/lbm. This represents only 1% of the overall VFM energy use.

Table 5-1 - VFM Energy Balance

	Specific Energy (Btu/lbm)	Power (MMBtu/Hr)
Energy In		
Fuel	846	4.23
Scrap Aluminum	208	1.04
Total Energy In	1,054	5.27
Energy Out		
Molten Aluminum	484	2.42
Flue Gases	320	1.60
Wall Losses	250	1.25
Total Energy Out	1,054	5.27

Figure 5-8 - VFM Processing UBC

Figure 5-9 shows a similar analysis using solid automobile scrap aluminum. The performance is similar to the VFM in the above Figure, but the dimensions of it have been reduced.

The inlet gas temperature has a major affect on both the performance and size of the VFM. The inlet gas temperature can be controlled by adjusting the recirculation flow rate. At higher recirculation rates, the inlet gas temperature is reduced. As the inlet gas temperature is reduced, the outlet gas temperature is also reduced which improves the thermal efficiency since the flue gas losses are corresponding reduced. Figure 5-10 shows this affect. Both the thermal efficiency and outlet gas temperature change modestly until an inlet gas temperature of about 2400 F is exceeded.

Figure 5-9 - VFM Processing Solid Scrap Aluminum

Figure 5-10 - Parametric Study of Inlet Gas Temperature Affect

The forgoing leads to the interesting possibility of eliminating the recirculation fan and duct altogether, thus minimizing the VFM's size and installed cost. However, the thermal efficiency would be adversely affected as would the melt loss due to aluminum oxidation. It would not be helpful to use excess air to reduce the inlet gas temperature as

this would not improve the thermal efficiency and it could also lead to increased melt loss due to the increased oxygen partial pressure in the flue gases.

Nonetheless, the elimination of the recirculation fan and duct could be accomplished by employing heat exchangers before and after the cone, or by using waste heat (from other sources) in place of the burners, as discussed below. The use of heat exchangers would produce the desired outcome of low gas temperature and high thermal efficiency, but would increase the cost of the system and could only be used in those applications that do not flux or chlorinate. Also, the recovered heat would need to be used elsewhere in the plant.

5.4. Melt Loss Results

5.4.1. Introduction and Approach

Melt loss due to oxidation of the scrap aluminum is a serious problem since it reduces the production and revenue of a plant. Typical melt loss for a conventional reverberatory furnace is about 8 to 10 %. In this section, melt loss mechanics are investigated to assess the improvement possible with the VFM. A detailed literature search was conducted and experimental data was located which provided kinetic rate constant data for aluminum oxidation with H_2O , O_2 , and CO_2 in the temperature and pressure range of the VFM.

The literature search was conducted using Dialog, a computer-based commercial search engine. The Chemical Abstracts database was used from 1968 (its earliest entries) to the present. Work prior to 1968 was found from the reference list of the articles. The search was focused on aluminum oxidation chemistry at temperatures from 500 K (441 F) to 1500 K (2241 F). This temperature range adequately covers the actual maximum aluminum melt temperature in the VFM which is 1325 F.

The pressure in the VFM is close to atmospheric so high pressure reaction literature, as would be found in nuclear reactor work, was ignored. The kinetic data used in this report was measured at a fraction of an atmosphere. However, the data from reference 5-3 suggests that within the pressure range of interest (i.e. close to atmospheric) the oxidation dependence on pressure is weak. The reaction rates, R , were fit to the pressure, P , as:

$$R = (\text{constant})P^n$$

where n is a function of temperature and is given in the following table:

Most of the data presented in this report were taken at 10 torrs (0.013 atmospheres). The partial pressure of the various gas species in a typical natural gas combustion process is given in Figure 5-11. At 10% excess air, the correction factor at the higher temperature would be 59%, 40%, and 5% for H_2O , CO_2 , and O_2 respectively.

Table 5-2 - Reaction Rate Pressure Correction

Temperature (K)	Temperature (F)	n
300	80	0.45
400	261	0.40
500	441	0.32
600	621	0.23
670	747	0.18

Figure 5-11 - Partial Pressure of Combustion Products

All subsequent reaction rates given in this report are corrected for pressure using the above equation and Table 5-2. The combustion gas species of interest are oxygen, water vapor, carbon dioxide, organics, and hydrogen.

5.4.2. Results

Most of the kinetic data found in the literature was for temperatures at or below aluminum's melting temperature. This is adequate to address the question at hand since the aluminum in the VFM would be exposed to the oxidizing gases until it melted, at which time it would rapidly exit the system. Four relevant articles were obtained (5-1, 5-2, 5-3, 5-4). Two other references (5-5, 5-6) at temperatures above the melt temperature are available. In references 5-1 through 5-4, kinetic rate constants for oxidation by oxygen, water vapor, and carbon dioxide were measured in the temperature range from 673 K to 923 K (752 F to 1202 F). The rate constants are given in Table 5-3 using the Arrhenius form of the exponential temperature dependence of the rate constant k :

$$k = A \exp(-E/RT)$$

where:

T = Temperature (K),

R = Universal gas constant,

A = Proportionality constant, and

E = Activation energy.

The particle weight gain due to oxidation from each of the gas species is:

$$W = k \cdot t$$

and the % weight change is given as:

$$\Delta W/W = k \cdot t \cdot A_s / (V \cdot \rho)$$

where

t = time,

A_s = surface area,

V = Aluminum volume, and

ρ = aluminum density.

The data supports a linear (rather than a more traditional parabolic) relationship between weight gain and time.

Table 5-3 - Kinetic Rate Constant Data

Gas	Temperature Range (K)	A (kg/m ² hr)	E (kJ/mole)	Pressure (Torr)	Pressure Correction	Saturation Value (10 ⁻⁴ kg/m ²)
O ₂	673-923	13	71.7	10	1.05	3.8
H ₂ O	673-923	6.4	66.9	10	1.59	38.0
CO ₂	673-923	4.8	82.7	10	1.40	5.9
CO ₂	823-923	10 ¹⁰	250	10	1.40	5.9

Typical weight gains are observed to grow linearly for a period of time, followed by a saturation point at which no further gain is measured. The saturation is reached due to a protective oxide film forming on the surface of the aluminum which blocks further oxidation. Since in the VFM there is no mechanism to disrupt the film, oxidation ceases when the saturation value is reached. Table 2 lists the saturation values.

Figure 5-12 shows the percent weight gain for H₂O, the most reactive gas, and O₂, the least reactive gas. CO₂ falls between the two.

Figure 5-12 - Weight Gain from Oxidation

Two important conclusions can be drawn:

- Saturation is reached quickly, after about 2 to 18 minutes depending on the gas species and temperature. The aluminum residence time in the VFM is about a few minutes or less. It is possible that the saturation point for H₂O will be reached, but that of CO₂ and O₂ may not.
- The weight gain is quite marginal, 0.05% at worst. This compares to melt losses of conventional furnaces between 5 and 10%.

There is a significant difference in the way heat is transferred and oxidation occurs in the VFM and conventional furnaces, which would account for the differences in melt loss. In the VFM, heat is conveyed to the aluminum via convective heat transfer from the products of combustion. Since high heat transfer coefficients are achieved, relatively low gas temperatures can be used (1800 F to 1600 F) and therefore low aluminum melt temperatures (1200 F to 1325 F). Melting is rapid, and the aluminum immediately falls out of the VFM cone when melted, ending any further oxidation. The aluminum may be exposed to the gases for a minute or so. Oxidation occurs as a result of the gas species reacting with solid aluminum below its melt temperature. Hence, a protective oxide layer, characteristic of aluminum, is formed which protects it from further attack. This layer is quite small, only a few microns thick, which results in small melt losses.

In conventional furnaces, the heat transfer is by radiation from the furnace walls to the liquid melt. A large surface area of molten aluminum is exposed to both high temperature gases and direct flame impingement. A large vertical temperature gradient exists in the molten pool, requiring the surface layer to be at an elevated temperature well over 1400 F. Rapid increases in oxidation occur at 770 C (1418 F) and above.

Further, the protective oxide layer can dissolve in the liquid melt, thus continually exposing the aluminum to oxidation attack.

Finally, in conventional furnaces the aluminum may have varying amounts of organics in the form of oil, lacquer, paint, or rubber (in the VFM these will have been removed in the IDEX™, a companion technology). Solid aluminum in a conventional furnace must be submerged in the melt and therefore not exposed to the oxidizing products of combustion to minimize melt loss. However, organics present on the scrap will evolve gases either impeding the scrap submergence⁽⁵⁻⁷⁾ or percolating scrap to the surface⁽⁵⁻⁸⁾ thus increasing melt loss and oxidation.

The foregoing was for oxide reactions. Hydride and carbide formations are also possible. There will be little or no hydrocarbons in the VFM gas stream. The aluminum will be decoated of all oils and other hydrocarbons prior to being melted in the VFM in the IDEX™. Further, the VFM burner will produce little excess hydrocarbons since it is a single staged burner, and presumably, furnace operators will keep the burner tuned for optimum fuel economy. However, hydride formation can occur from the water vapor in the products of combustion.

Reference 1 shows that carbides can form when aluminum reacts with carbon monoxide or carbon, with the latter reaction more likely. The reactions are:

However, measurements made show that the carbide formation would be only 10% of the oxide formation, at the temperatures of interest.

5.4.3. Conclusions

- Water vapor will oxidize aluminum, and to a lesser extent so will carbon dioxide and oxygen in the temperature range of interest.
- The oxidation rates will quickly saturate at which point further oxidation will not occur. This is due to a protective oxide film forming on the aluminum surface.
- The melt loss due to oxidation is quite small, about 0.05 % at worst.
- Some limited data from Stein Atkinson Stordy show large increases in oxidation at melt temperatures beyond 770 C (1418 F). The VFM always operates below that temperature whereas, conventional furnaces are usually above it.
- Melt loss from conventional furnaces are much higher than that predicted for the VFM. This is primarily due to the way heat is transferred to the melt in each case. In the VFM, heat transfer is via gas to solid. As soon as the aluminum melts it leaves

the VFM and further oxidation is not possible. In conventional furnaces, heat transfer is radiative from the furnace walls to a molten bath of aluminum. Also flame impingement on the bath occurs. This leads to higher temperatures and corresponding higher oxidation reaction rates. Further, protective oxide layers can dissolve in the molten bath of conventional furnaces, thus exposing the metal to continuous attack. Also, the molten metal must be overheated in conventional furnaces due to its large vertical temperature gradient resulting in melt surface temperatures in excess of 1400 F. Finally, organics on the solid aluminum can impede it from submerging in the melt, thus exposing it to direct flame impingement and accelerated corrosion.

- Carbide formation has been shown to be possible, but it is small, about 10% of that of oxide formation.
- Hydrogen solubility curves have been obtained and can result from the presence of water vapor.
- Fast exothermic reactions have not been reported in the literature or observed by SAS and G+P. Molten aluminum will thermite when exposed to air if at an elevated temperature.
- Organics do not play a role in the VFM since little or no unburned natural gas is present and organic removal from the scrap has been accomplished in the IDEX™.

5.5. VFM Advantages

The advantages of the VFM compared to conventional furnaces are:

- Reduced energy use
- Reduced melt loss
- Low gas temperature operation is possible
- Low installed cost
- Fast melt time
- Can use a wide variety of scrap types
- Low emissions
- Energy efficient even at small sizes
- Will oxidize organics without affecting metal loss

6. Pilot Test Results

6.1. Introduction

The pilot VFM is shown in Figure 6-1. Scrap aluminum is carried by a bucket elevator to the top of the cone and where it is dropped through. The aluminum is floated in the cone by the counter-flowing gases. The combustion chamber provides the hot gases and a recirculation fan (not shown) recirculates the gases to both lower the gas temperature and increase the gas volume flow.

6.2. DECOATING EXPERIMENTAL RESULTS

Decoating tests were conducted using ERCo's pilot-scale VFD as shown in Figure 6-1. Tests were conducted using both UBC (from Alcan) and turnings (from Wabash). Coated or oily scrap was manually loaded in a bucket elevator, and then passed through a screw conveyor at the top of the VFD. The material then fell through the cone.

During the testing, the VFD was first heated without scrap flow. Next, scrap was fed at the desired throughput until the VFD gas temperatures remained approximately constant.

Figure 6-1 - Photograph of Pilot Scale VFD

For the turnings testing, oxygen content was from 8.9% to 12.4%. The cone gas temperature was 493 to 510 °C (920 °F to 951 °F). Figure 6-2 shows a run in which the gas temperature started out at 527 °C (980 °F), dropped and remained at 500 °C (930 °F). Scrap throughput was from 118 to 250 kg/hr (260 lbm/hr to 550 lbm/hr). Scrap residence time was 1 to 2 minutes.

Figure 6-2 - Gas Temperature While Decoating UBC

For the UBC testing, oxygen content in the cone was from 8 to 11.5% with an occasional drop to 4%. Cone gas temperature was 523 to 565 °C (973 °F to 1049 °F). Scrap UBC throughput was from 122 to 239 kg/hr (270 lbm/hr to 528 lbm/hr).

Figure 6-3 shows the oily turnings received from Wabash, and Figure 6-4 shows the turnings after being decoated in the VFD.

Figure 6-3 - Oily Turnings

Figure 6-4 - Turnings Decoated In VFD

The oil has been completely removed and no oxidation is evident.

Figure 6-5 shows the UBC before decoating and Figure 6-6 after decoating. The decoating has completely removed the organics with no visible sign of oxidation.

Figure 6-5 - UBC From Alcan

Figure 6-6 - UBC After Being Decoated in VFD

The advantages of the VFD Decoater are:

- Effective Decoater: completely decoats scrap aluminum without oxidizing the underlying metal.
- Rapid Decoating: scrap aluminum organics are removed in a minute or two, compared with 10 to 20 minutes of conventional equipment.
- Rapid Change Out: can rapidly change the type of scrap type being processed. Emptying the cone of scrap material is instantaneous.
- Small Footprint: being a cone, the VFD Decoater can be retrofitted immediately above a charge well and feed directly into the furnace. Very little horizontal area is required.
- Preheats as well as decoats: the scrap metal exiting the VFD Decoater can be heated to almost any temperature. This greatly increases furnace production and reduces its fuel use.
- Little Fuel Required: since the VFD Decoater uses the energy content of the organics in processing the scrap, very little fuel is needed.
- Meets EPA and Local Emission Regulations
- Can process a wide variety of scrap: UBC, turnings, and frag for instance. This is accomplished by varying the recirculation flow, which allows the floatation of a wide range of scrap sizes and shapes.
- No Moving parts (except for blower)
- Rotary seals not needed as compared to a rotary kiln.
- Less Expensive than a rotary kiln decoater.
- Simple control system

6.3. MELTING EXPERIMENTAL RESULTS

The pilot-scale VFM, shown in Figure 6-1, was used to melt both clean aluminum scrap and also to simultaneously decoat and melt coated and oily scrap. Used beverage cans

(UBC) were manually loaded in a bucket elevator, and then passed through a double dump valve at the top of the VFM. The material falls through the cone.

Two burners, each with a maximum firing rate of 586 kW (2 MMBtu/hr), fired into the VFM. One burner fired into the lower portion of the cone. This provided most of the energy use. The other burner fired into the holding chamber to maintain the melt temperature. This burner was often at its lowest turndown setting and during melting tests it was usually off.

The gases were recirculated from the top of the cone back into the lower portion. This provided a large enough mass flow to achieve the required gas velocities in the cone. Also, it allowed the VFM to operate at a higher thermal efficiency than would otherwise be possible.

UBC was obtained from Wabash's (formally Roth Bros.) East Syracuse plant. The UBC was decoated, through not well shredded. Typical UBC sizes were 8 to 10 cm (3 to 4 inches).

The material feed system limited the throughput, of this large UBC, to about 453 kg/hr (1,000 pph). Going much above 226 kg/hr (500 pph) resulted in the double dump valve jamming. Hence, for higher throughputs the double dump valve was manually held open, resulting in air leakage into the top of the cone.

During the testing, the furnace was first heated without scrap flow. Next, scrap was fed at the desired throughput until the VFM gas temperatures remained approximately constant. This usually took 2 to 3 hours. For the energy use data collection, the firing rates of both burners was recorded and summed. This was then divided by the metal throughput to arrive at the specific energy use.

For the metal yield measurements, after a period of time, the molten metal top layer, in the holding chamber, was skimmed, and the resulting dross weighed. The resulting oxide was compared to the total metal throughput to obtain the metal yield.

Generally, the yield numbers were taken after the VFM had been operating for several weeks, including extended periods in which the molten metal was exposed to the holding chamber burner directly firing onto its surface. In this sense, the yield numbers are conservative and represent a worse case.

Figure 6-7 shows the specific energy use vs. throughput. As the throughput increases, the energy use decreases. At 453 kg/hr (1,000 pph), the energy use varies between 1973 to 3196 joules/gram (849 Btu/lbm and 1,375 Btu/lbm). The energy use test points at 340 kg/hr (750 pph) were higher than desired due to the holding chamber burner's firing rate. It was at its lowest turndown setting, which for these runs was higher than usual due to a malfunction in the mechanical linkage.

The low measured specific energy use is a result of the low flue gas temperature, which is due to the gas recirculation. Additionally, the scrap is floated in the flue gases, which also add to the VFM efficiency since the flue gas energy is being used to heat the scrap. A comparison of a conventional furnace and the VFM is shown in Table 6-1. Essentially the VFM flue gas losses are only 7% of that of the conventional furnace.

The Figure 6-7 energy measurements are conservative since the wall losses were higher than needed for two reasons. First, being a scaled pilot test, the VFM surface area to volume ratio is much higher than would be designed for a full scale VFM that might be processing four times as much aluminum. This leads to a relatively higher surface area, and therefore higher wall heat loss, as compared to a full-scale VFM.

Second, the outside of the pilot VFM wall was too hot to touch, which indicates inadequate insulation. This also contributes to preventable wall losses.

Figure 6-7 - Measured Specific Energy Use

A major advantage of the VFM is that they provide rapid melting which leads to low melt loss. In essence, the VFM does not allow enough time for complete oxidation to take place. As the scrap aluminum is oxidized, it forms a protective layer that prevents further oxidation. This is sometimes termed saturation. Nonetheless, UBC can have a high exposed surface area to volume ratio, which could lead to significant metal loss. Kinetic rate calculations were conducted which determined that the time to reach saturation is about 2 minutes for oxidation from either oxygen or water vapor. The time to melt in the VFM is only about 20 seconds or so, well below the saturation time. Hence, it is possible the VFM will lead to improved metal yield since the scrap aluminum is only exposed to the oxidizing flue gases for a fraction of the time needed to reach saturation.

Table 6-1 - Comparative Energy Use

	Conventional Furnace		VFM	
	(Btu/lbm)	(%)	(Btu/lbm)	(%)
Heat into Scrap	478	18%	478	46%
Flue Gas Losses	1562	62%	112	11%
Wall and Holding Losses	460	18%	460	44%
Total	2500	100%	1050	100%
Thermal Efficiency	18%		45%	

Dross measurements, for both the VFM (melting clean scrap) and the CFM (melting oily or coated scrap) are shown in Figure 6-8. The clean scrap provides the best metal yield, with a dross loss of 2 to 3%. The oily turnings increase the loss to 5 to 6%. The coated UBC has a dross loss of 8%.

These dross measurements are quite encouraging. In addition, it is likely that they can be improved upon by a continually operating VFM or CFM that does not idle and directly fire over the melt surface in the holding chamber as was experimentally necessary in our tests.

Figure 6-8 - Experimental Dross Measurements

7. Advanced Concepts

7.1. Waste Gas Operated

From Section 4.7, Minimum Temperature Tests, it was determined that low gas temperatures can be used and still provide relatively fast melting. In fact, temperatures down to 1252 F have been experimentally shown to adequately melt aluminum scrap. This leads to the possibility of using waste heat from a source within the plant to drive the VFM process. Two sources of waste heat are possible:

- A conventional furnace - The flue gas from a conventional furnace is about 2200 F, more than adequate to process scrap in the VFM. The volume flow rate of the flue gas is also adequate. If a VFM is sited next to an operating conventional furnace, the flue gases can be used.
- The exhaust gas from the IDEX - The IDEX exhaust gas is at about 1500 F. With the use of auxiliary burners, this source of waste heat can also be used.

The use of waste heat has two major advantages:

- Near complete elimination of fuel use.
- Allows the elimination of the recirculation duct and fan thus minimizing the VFM's size and installed cost.

It is possible to use the VFM cone and couple it directly to a conventional furnace. In this process, the scrap would be fed into the VFM and after melting would pass to the open hearth of a conventional furnace. Any required alloying would take place in the conventional furnace which would also act as the holding tank.

The advantages of this process are:

- The installed cost of the VFM would be low since the holding tank, recirculation duct, and fan would be eliminated.
- The production of the combined furnace would be much higher than the original conventional furnace due to the rapid heating of the VFM.
- The fuel use would be reduced since the thermal efficiency of the VFM is high.
- The operation would be minimally impacted. Plant could process scrap through their existing furnace with little change.
- The VFM would have a small footprint since it would mostly be sited above the charge well of the existing furnace.

7.2. Mag-Melter

The addition of magnetic enhancement to the VFM is a recent development. Figure 7-1 shows a schematic of the Mag-Melter. Aluminum is fed from the bottom and entrained by the high velocity gases. Permanent magnets (electromagnets can also be used for

improved performance) are put around the melter resulting in a magnetic field imposed on the aluminum inside. Whenever an electrical conducting object, such as aluminum, passes through a region of a changing magnetic field, currents are induced in the object which give rise to force that opposes the objects direction of motion. This force, known as a Lenz's force, is proportional to, and in a direction opposite to that of, the aluminum's motion.

When the aluminum melts, its drag coefficient goes down, and its resistivity also goes down resulting in reductions in both the drag and Lenz forces. This will allow the melted aluminum to escape the cone and cylinder and fall into the holding chamber. However, there is an advantage to designing the inlet gas velocity to a very high value, such that the melted aluminum may hang up in the cylinder. In that case, the gas will be periodically pulsed (on one half minute cycles or less) to allow the aluminum to be withdrawn from the Mag-Melter.

In the Mag-Melter there are now three forces on the aluminum controlling its acceleration and therefore its velocity and trajectory:

- Gravity, which is proportion to a constant, g, and always act downwards.
- Drag, which is proportional to velocity squared and acts in a direction parallel to the gas flow.
- Lenz force which is proportional to velocity and always acts in a direction opposite to the aluminum scrap's motion.

Figure 7-1 - Schematic of the Mag-Melter

Summing the three forces on the aluminum and dividing by the mass leads to the following differential equation which governs the aluminum scrap's motion:

$$\frac{dV}{dt} = -g + \frac{1}{2m} \rho (V - V_g)^2 A C_d - \frac{B^2 L^2}{Rm} V \quad (1)$$

Where

V = velocity
g = gravitational constant
m = aluminum mass
 ρ = gas density
Vg = gas velocity
A = aluminum's cross-sectional area
Cd = aluminum's drag coefficient
B = magnetic field strength
L = aluminum dimension
R = aluminum's electrical resistance.

The first term on the left is the acceleration of the aluminum. The terms on the right are due to gravity, drag, and Lenz forces respectively.

To probe the concept's feasibility, ERCo conducted cold flow tests in which aluminum pieces were dropped through a chamber with a magnetic field. There was no gas flow, so only the gravitational and Lenz's forces were at work. The time for the aluminum to fall 0.5 feet was measured with and without the magnetic field as shown in the following table.

Table 7-1 - Time for Aluminum Test Pieces to Fall 6 inches

<i>Aluminum square Size</i>	<i>No Field</i>	<i>0.3 Tesla</i>	<i>0.6 Tesla</i>
1"	0.17 sec	0.2 sec	0.33 sec
2"	0.17 sec	0.3 sec	0.77 sec
3"	0.17 sec	0.47 sec	1.57 sec

As can be seen, the affect of the magnetic field was to increase the time for the aluminum to travel the test distance. This offers an advantage - the gas velocity, flowing in opposite direction to the particle's travel, can be greatly increased resulting in much higher heat transfer rates. This leads to:

- Increased throughput,
- Reduced gas temperatures for the same throughput,
- Reduced size, or
- A combination of the above.

Equation (1) was integrated numerically to determine the aluminum's velocity and trajectory. The Lenz constant (B^2L^2/Rm) was taken from the experimental data in the above table. The equation was solved for two geometries; a cylinder in which the gas velocity is constant (simulating the lower portion of the melter), and a cone in which the gas velocity is varying (simulation the upper or VFM portion of the melter).

Figure 7-2 shows the aluminum's trajectory in the cylinder, with and without the magnetic field, with an inlet gas velocity of 200 fps. Distance from the bottom of the Mag-Melt is plotted vs. time. The aluminum is introduced into the bottom of the melter. Presuming a 10 foot high melter, the aluminum would blow out the top in less than a second, if there were no magnetic fields. With the magnetic fields, the aluminum remains in the cylinder for 30 seconds, sufficient time to melt.

Figure 7-2 - Aluminum Trajectory in the Cylinder

Further, since the heat transfer coefficient varies as the gas velocity to the power of 0.8, doubling the gas velocity in the cylinder (over the aluminum's terminal velocity) results in a heat transfer increase of 74 %. Increasing the velocity above the terminal velocity of the aluminum, and still have the aluminum remain in the cylinder for sufficient times to either heat up or melt is easily accomplished due to the magnetic fields.

Figure 7-3 shows the affect of the aluminum in the cone (varying gas velocity) which simulates the upper part of the Mag-Melter. The cone is used to capture any aluminum pieces that are not melted in the cylinder.

With no magnetic field, the aluminum exhibits a stable oscillation that dampens and eventually reaches an equilibrium point at the particle's terminal velocity. While the aluminum is above its equilibrium point, it is in an area of lower gas velocity and temperature, therefore slowing its melt rate. Further the melter must be built tall enough to avoid the aluminum from blowing out when it reaches its high point.

The aluminum trajectory, with the magnetic field, shows it to be non-oscillatory, thus keeping it in the higher heat transfer area and requiring a smaller melter height.

Figure 7-3 - Aluminum Trajectory in the Cone

8. Technology Transfer

The IDEX is being offered by Solios Thermal, Plymouth, IN. Currently 15 units have been installed worldwide with 4 in the US.

The following articles have been published.

- De Saro, “Innovative Equipment to Decoat Scrap Aluminum”, ACEEE 1995 Summer Study on Energy Efficiency in Industry, Grand Island, NY, August 1, 1995
- R. De Saro, “Innovative Equipment to Decoat Scrap Aluminum”, Alumitech '97, Atlanta, GA May 1997
- R. De Saro, W. Bateman, “A Vertical Floatation Melter for Decoating and Melting Scrap Aluminum”, Fourth International Symposium on Recycling of Metals and Engineered Materials, October 22-25, 2000.
- De Saro R., “Four Projects that Reduce Energy in the Metals Industry”, Light Metals, 2003.

In addition, the following patent has been issued to ERCo:

“Heat Treating Apparatus”, Patent number 6447288B1, issued September 2002.

9. Conclusions

1. The VFM heat transfer is dominated by convective heat loading. Radiative heat loading is relatively unimportant.
2. Since convective heat transfer coefficients are high, low operating gas temperatures are possible.
3. Thermal efficiencies of 60% are readily achievable with the VFM due to the low gas temperatures possible.
4. Substantial energy reduction is possible. When combined with the IDEX, the VFM has a thermal efficiency of 75%, as compared to a conventional furnace at 19%. This results in an energy savings of 2,250 Btu/lbm. A possible 15.3 trillion Btu per year can be saved with widespread use of this technology.
5. Low refractory costs are realizable due to the low temperatures, resulting in overall low installed costs for the VFM.
6. Control of both the inlet and outlet gas temperatures is easily accomplished without undue performance penalties.
7. Fan power consumption is low enough that it has only a marginal affect on thermal efficiency.
8. Throughputs, comparable to conventional reverberatory furnaces, of 120,000 pounds per day are achievable with reasonable sizes.
9. For the IDEX, reduction in emissions of NO_x, SO_x, CO, and VOC have been measured to be below 20% of the regulated allowable limits.
10. Rapid melting, even at low gas temperatures, has been experimentally demonstrated.
11. Melt loss from conventional furnaces are much higher than that predicted for the VFM. This is primarily due to the way heat is transferred to the melt in each case. In the VFM, heat transfer is via gas to solid. As soon as the aluminum melts it leaves the VFM and further oxidation is not possible. In conventional furnaces, heat transfer is radiative from the furnace walls to a molten bath of aluminum. Also flame impingement on the bath occurs. This leads to higher temperatures and corresponding higher oxidation reaction rates. Further, protective oxide layers can dissolve in the molten bath of conventional furnaces, thus exposing the metal to continuous attack. Also, the molten metal must be overheated in conventional furnaces due to its large vertical temperature gradient resulting in melt surface temperatures in excess of 1400 F. Finally, organics on the solid aluminum can impede it from submerging in the melt, thus exposing it to direct flame impingement and accelerated corrosion.
12. A Vertical Floatation heat exchanger has been developed that can decoat scrap (Vertical Floatation Dryer or VFD), melt scrap (Vertical Floatation Melter or VFM), or simultaneously decoat and melt scrap (Combined Floatation Melter or CFM). The advantage of these devices relate to their high heat transfer coefficient which provides rapid melting at a relatively low gas temperature and high metal yield. Experimental results show the VFM or CFM to have metal yields of from 92 to 97% and energy use as low as 1975 joules/g (850 Btu/lbm). The VFD has adequately decoated UBC and oily turnings.

10. References

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