Final Technical Report

Improving Energy Efficiency in Aluminum Melting
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Secat, Inc.
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Arco Aluminum
Aleris International
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Hydro Aluminum Louisville
Logan Aluminum
Century Aluminum (Formerly NSA Division of Southwire)
McCook Metals (No longer in operation)
Ohio Valley Aluminum Company Inc
Improving Energy Efficiency in Aluminum Melting

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Acknowledgments and Disclaimer

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<tr>
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<th>Description</th>
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<tr>
<td>ANL</td>
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<tr>
<td>ASM</td>
<td>The American Society of Metals</td>
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<tr>
<td>ORNL</td>
<td>Oak Ridge National Laboratory</td>
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<tr>
<td>DC</td>
<td>Direct Chill</td>
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<tr>
<td>DOE</td>
<td>Department of Energy</td>
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<td>UK</td>
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| ARC          | The Albany Research Center  
|              | (Presently National Energy Research Laboratory – Albany) |
| HTC          | Heat Transfer Coefficient |
| IOF          | Industry of the Future |
| ITP          | Industrial Technologies Program |
| IR           | Infrared |
| SEM          | Scanning electron microscopy |
| TMS          | The Minerals, Metals, and Materials Society |
| AES          | Auger electron spectroscopy |
| RCM          | Reheating-cooling method |
1. Executive Summary

1.1 Research and Development

Primary or secondary aluminum is first melted, alloyed and treated in large gas-fired furnaces, transferred to holding furnaces for additional processing and casting into large D.C. ingots. Although the gas furnaces have different geometries, they all work in a similar manner; heat is transferred to the metal charge primarily by convection from the high velocity burner gases, and by radiation from the roof and the sidewalls of the furnace. Typically it takes $2.5 - 5.0 \times 10^6$ Btu/ton to melt/process aluminum and much of that energy is lost as flue gas (~50%) and a smaller amount (~20%) is lost through the furnace walls. It has been shown that gas fired aluminum melting/holding furnaces operate at approximately 30% thermal efficiency. Aluminum melting is also a source of greenhouse gas (GHG), nitrogen and sulfur oxides. The “Energy and Environmental profile of the U.S. Aluminum Industry” estimates that emissions from current aluminum melting and casting practices are ~0.9 lbs/ton for SO$_x$, ~0.8 lbs/ton for NO$_x$, and ~430 lbs/ton for CO$_2$. Clearly, improvements in aluminum melting practices can offer the industry and the nation significant energy savings as well as reduced emissions.

The goal of this jointly funded, multi-partner research program is to improve the energy efficiency of aluminum melting practices by 25%. Full-scale implementation of the results of the proposed research by the year 2015 could lead to yearly energy savings of 13 trillion Btu and related energy cost savings of 57 million per year for the U.S. aluminum industry.

The research team for this proposal included an industry cooperative, Secat, Inc. (Secat), three national laboratories, Albany Research Center (ARC), Argonne National Laboratory (ANL), and Oak Ridge National Laboratory (ORNL), eight participating aluminum companies, and the University of Kentucky - Center for Aluminum Technology (UK-CAT). Several furnace manufacturers and refractory suppliers also participated in this project. The companies in the team used all of the key furnace types, melting practices, and feedstocks used by the aluminum industry. Furnace types include rondtops, sidewells, and conventional reverberatory furnaces ranging in capacity from 70,000 to 250,000 lb with energy consumption from 1500-2500 Btu/lb.

The partnership came together due to the understanding that melting/holding furnace inefficiency is a problem generic to the industry and a successful program could increase the efficiency of furnaces by 25% thereby offering the partners a significant opportunity to save energy and reduce environmental emissions from their melting lines.

During the project time frame quarterly meetings were held that brought the industrial partners and the research team together for discussing research results and research direction. The industrial partners provided guidance, facilities, and experience to the research team. The research team went to representative facilities of each industrial partner to understand the existing operational conditions and energy usage/lb of metal produced.

The project focused on achieving the targeted energy savings by dividing the research work into 4 separate but intimately coupled parts with the goal of overall increased efficiency in secondary aluminum melting. These four sub-parts are a) measurement and analysis of current steady state melting practices utilized by the member companies b) computational modeling of the combustion space for each of the furnace types, c) synthesis of the measurements and the combustion space modeling into a detailed furnace model and d) experimentation in a research scale reverberatory furnace. Carefully designed experiments were carried out at national laboratory and the university facilities as well as the industrial locations using the industrial production facilities. Advanced computational capabilities at national labs were used for...
thermodynamic and kinetic simulations of phase transformation, heat transfer and fluid flow, solidification, and strain/stress evolution during DC casting. The following achievements have been made:

**Assessment of industrial melting practices:** During this first phase, data was gathered on the number of furnaces, size of the furnaces, size of the burners, type of burners (e.g. twin bed regenerating burners, high ram fire burners, etc.), burner rating, melt rates, air to fuel ratio, furnace control parameters and any other information that was deemed essential to a better understanding of operation of a particular plant. Such information as furnace geometry (where actual engineering drawings were provided by the member companies) the high and low heating value of the natural gas utilized, air flow rates, turn down ratios, flue dimensions and exhaust gas velocities and temperatures (if known), stack gas analysis, stack gas temperature, stack gas velocity, historical gas usage, current gas usage, interior and exterior temperatures (taken by infrared camera), and an assortment of other variables required to estimate the efficiency of the furnace. Figure 1.1 is a schematic indicating the findings from these studies, accounting for heat losses within reverberatory furnaces. From this assessment, it was found that the industry standard for re-melt efficiency was between 11-37% with the average being about 25%. This is in comparison with a much higher reported value by the industry.

**Figure 1.1 – Heat loss analysis in industrial aluminum reverberatory furnaces.**

**Furnace Mass, Heat and Flow Modeling:** Furnace mass, heat and flow modeling was conducted jointly by staff at the Argonne National Lab. (ANL) and the Oak Ridge National Lab. (ORNL). ANL worked for a number of years on a combustion space model, primarily for glass furnaces. However, the nature of a gas fired glass furnace is very similar to that of an aluminum reverberatory furnace. Therefore, it was found to be a straight-forward job of revamping the glass furnace code to model the reverberatory furnace. Once this was done and simulations run on the combustion space, the heat flux and heat distribution data was transferred to ORNL in order to implement the data into a furnace model. This unified furnace model is then used to look at areas of heat loss, molten metal flows (through natural convection as well as forced convection if a pumping device exists) and overall energy balance. In order to accomplish this task, the data taken by the UK staff in the plant audits and data obtained from the experimental furnace at Albany is utilized for model validation.
The models were validated using experimental data generated from the Albany Research Center experimental reverberatory furnace as well as trials at industry partner sites. The combined model using the AFMVIEW (Argonne Furnace Model) and the modified ProCAST model utilized at ORNL are currently resident at Secat, Inc for use by the aluminum industry.

**Experimental Furnace:** During the course of the project two experimental furnaces were designed and fabricated at the Albany Research Center. The first is a nominal 200 lb furnace while the second has a 2000 lb capacity. These experimental reverberatory furnaces are ideal for experimentation and model validation.

The 200 lb laboratory scale reverberatory furnace (LSRF, Figure 1.2) is not intended to be a scale model of an industrial furnace, rather it is a test bed to evaluate the intimate contact between combustion atmosphere and the charge material (aluminum) and the dross (waste oxides) produced during melting of certain alloys. The furnace is modular in nature, increasing its flexibility and ease of use and repair, has full accountability of all process parameters and includes close-coupled scales for accurate measurements of weight changes during melting and holding processes. Tests from this furnace include the verification of the reduction of dross generation utilizing novel covering agents.

The 2000 lb experimental reverberatory furnace (ERF, Figure 1.3) consists of two 800,000 Btu/hr burners mounted anti-symmetrically, is connected to a state of the art air pollution system and an advanced data acquisition system. This system was utilized to carry out “what if” scenarios as requested by industry participants as well as a series of planned experiments that was used to check and validate the findings of the modeling effort. The furnaces are resident at the Albany Research Center and available for use by the industry.

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**Figure 1.2** – The Albany Research Center LSRF furnace.

**Figure 1.3** – The Albany Research Center ERF test furnace.
1.2 Technology Transfer

Intellectual property has been generated from this significant research effort. The intellectual property includes: (1) the AFM view modeling software that is currently available at Secat which is used to run “what if” scenarios for aluminum companies in order to enable them to understand the operations of their furnace prior to making changes. (2) ProCast solidification model is available at Secat with the capability to carry metal related studies including the effect of stirring, configuration of side wells and transfer of heat from the combustion zone. (3) The furnaces fabricated during the course of the project are available at the Albany Research Center for use by the industry. The 2000lb reverberatory furnace is modular to enable modification of furnace volume, burners, refractory lining, etc permitting a wide variety of trials to be carried out.

To facilitate the technology transfer of the project results, Secat research staff members were actively participating in the effort throughout the project period. A multiprocessor computer has been purchased for using the models. As a result, Secat, a consortium of aluminum users and producers, has the required capabilities and expertise for transferring the developed technologies to the entire aluminum industry.

1.3 Commercialization

Project participants have used several mechanisms to inform industries of the research results and advance commercialization: (1) incorporating the results into the software resident at Secat, Inc and making it available to the aluminum industry, (2) launching Aluminum Answers, a Secat website, partly for disseminating the latest research results into the aluminum industry, and (3) making presentations at national meetings organized by the Minerals, Metals, and Materials Society (TMS), and the American Society of Metals (ASM), and at industrial locations including Logan Aluminum and Commonwealth Aluminum. Companies are using the computational tools located at Secat in understanding base furnace operations, trying out “what if” scenarios before spending on capital projects. Companies who have expressed interest in the research endeavor include the industrial partners of this project as well as Alcan and Alcoa.

1.4 Recommendations

This research project has successfully demonstrated that the use of the experimental furnace and the modeling tools can help industry participants to understand the behavior of their furnace, select appropriate design changes and optimize their operations resulting in a successful reduction in BTU/lb. The project serves as a starting point for even more sophisticated models for the prediction of crack formation.

One of the issues identified in this project is that the use of stirring devices has a strong effect in equalizing the temperature across the depth of the furnace resulting in rapid heat transfer and hence improving energy efficiencies. Further the use of localized immersion heaters in combination with burners or independent of burners have great potential to improve energy efficiencies. One recommendation of the project team is that the above models can be further developed for understanding the impact of stirring and immersion heaters based on their location within the furnace as well as the capacity selected.
2. Introduction

The Aluminum Industry Technology Roadmap envisions a Government/Industry/University partnership that will conduct medium to long-term research programs that will allow for the modification of existing melting/holding furnace infrastructure to improve fuel efficiency and reduce emissions.

The industrial partners participating in this proposal have melting/holding infrastructures that include every type of furnace, age, and melt practice (Round-tops, sidewells, sideloading reverberatory furnaces ranging from 70,000 to 250,000 lb in capacity with efficiencies ranging from 1500 – 2500 Btu/lb). Secat, and the industry partners will actively participate in the proposed research by providing access to their melting facilities, melting and efficiency data, conducting test data gathering runs in various melting facilities, providing assistance in data reduction, providing consultation and engineering services for both the laboratory melting unit (LMU) and the experimental reverberatory furnace (ERF), and participating as part of the joint team that will direct the research efforts and plan and conduct larger scale demonstrations, etc.

A typical conventional direct-fired reverberatory furnace with no modifications operates at about 30% thermal efficiency. Typically, 50% of the input is lost as flue gas, while the balance is lost through the walls. Other designs such as round tops and side-wells have similar loss patterns. Because of the differences in design and operational characteristics for each type of furnace, Secat and the industrial partners held several meetings to identify areas of commonality between each type of furnace. The important technology drivers identified by the partners for furnacing in general, and retrofitted equipment in particular, are: maintenance, reliability, melt rate and productivity, energy efficiency, environmental impact, ease of use, and cost.

The consortium has identified the need to undertake a systematic program of research and development for improving melting furnace operations. The program intends to incorporate state-of-the-art developments in computational modeling, burner design concepts, refractory materials, sensor and control systems, and melting furnace design concepts to reach the above goals.

However, full-scale trials of either single or multiple technologies for improved melting efficiency suffer from a fundamental disadvantage. If the results from the initial evaluation were to be marginal or neutral, any iterative optimization would be near impossible. Any iterative optimization of these technologies is best done on an experimental-scale furnace. Based on the guidelines developed from laboratory screening tests, we propose to build an experimental reverberatory furnace (ERF) with the ability to easily vary burner design and its physical parameters, the ability to sample the atmosphere in the furnace, and make various measurements on the flue gases and the molten metal. Results obtained from the ERF will be confirmed by modeling studies and then extended to full-scale furnaces. A cost/benefit analysis of the chosen methodologies will be conducted and recommendations for full-scale implementation will be developed. Secat industrial partners will assist in all aspects of project implementation and assessment.

Principal elements of the research proposal include:

1. Evaluation of current melting practices and operational procedures. The consortium members want to identify those (often with minimal or no capital cost) operational changes that can lead to increased efficiency.
2. A research program using the ERF to evaluate a retrofitted system consisting of new
refractory/insulation packages, oxy-enriched fuel burners and robust, intelligent sensor and control systems based on studies in the laboratory melting unit (LMU).

3. Conduct modeling studies using the massively parallel super-computer resources of the national laboratories to evaluate the results from the LMU and ERF studies, and to develop detailed design recommendations for full-scale demonstrations.

4. Validation of the technologies and design recommendations on selected industrial-scale furnaces

The key targets of this program are: 1) reduce the current energy requirements of conventional furnaces used for melting/holding aluminum by 25%; 2) reduce the generation of GHG, and NOx emissions from the melting of aluminum
3. Background

3.1 Project Goal and Scope

The goal of this program is to improve the efficiency of Aluminum melting furnaces by 25%. This reduction in fuel use will also serve to reduce GHG and NOx emissions. The partnership will accomplish this goal by: 1) evaluating melt/holding practices by furnace type, control system, feedstock, to identify best practices; 2) designing, building, and operating an experimental reverberatory furnace (ERF) to conduct trials on combinations of oxy-fuel, staged combustion, and new refractory/insulation; 3) assess new intelligent and robust control systems for the above combinations; 4) developing/demonstrating furnace modifications that satisfy the requirements identified by the partners; 5) conducting economic/technical/barrier evaluations for implementation of the combinations identified above; and 6) demonstrating the most effective technologies in cooperation with the industry.

The proposed research plan is to achieve these objectives by leveraging industry practice and experience with the expertise of the national laboratories (ARC, ORNL, and ARL), and University of Kentucky (UK) personnel. This project will apply and build on the substantial efforts and capabilities of the team members in the understanding of furnace operations, modeling of heat transfer and fluid flow, materials performance, and access to other on-going DOE sponsored research.

This collaboration between industrial, national laboratory and university researchers will also provide a fertile and modern environment for education. Researchers from the industry and the national labs will act as on-site advisors when the students visit these facilities. This project will help develop students who have worked on fundamental research grounded in industrial problems, with first-hand experience of the capabilities of the national laboratories, and a practical knowledge of aluminum industry processes and products. The Secat industrial sponsors are keenly interested in developing a pool of highly educated students and hiring them to improve their global competitiveness.

3.2 Statement of Objectives

The objectives of this program are to improve the efficiency of melting in the aluminum industry by; 1) reducing the current energy requirements for melting aluminum by 25%; 2) reducing the generation of GHG, and NOx emissions from the melting of aluminum; and 3) evaluating alternate metal melting technologies used in other industries that may have application to further efficiency improvements and emission reductions for the aluminum industry.

3.3 Work Breakdown Structure

The objective of this project involved completion of the following tasks:

The proposed research will achieve its objectives through collaboration among Secat, industry participants, national laboratories, and the UK-CAT. The research program will follow the general outline shown below:

Task 1. Evaluation of Current Melt Practices - Conduct a furnace-specific evaluation of melting practices currently employed by the aluminum industry. This study will include melting
practices by furnace type (i.e., round top, reverberatory furnace, side-well reverberatory furnace, single and double chamber, etc.), control system, and feedstock
A. Plant Visits, Data Gathering and Analysis. (Secat/UK-CAT/ARC/ORNL/Industry Partners)
B. Prepare a Summary Document on Melting Practices (Secat/UK-CAT)

**Task 2.** Design and Operation of the Laboratory Melting Unit (LMU)
A. Select LMU Materials, Burner Designs, and Controls (ARC/ANL/ORNL/Secat/Industry Partners)
B. Design and Build LMU (ARC/ANL/ORNL)
C. LMU Experiments
   1. Burner Parameters (ARC/Industry Partners)
   2. Furnace Atmosphere Evaluations (ARC/ORNL/Secat/UK-CAT/Industry Partners)
   3. Refractory Wear/Insulative Properties (ARC/ANL/ORNL/Industry Partners)
D. LMU Summary Report (ARL/ANL/ORNL)

**Task 3.** Experimental Reverberatory Furnace (ERF)
A. Select ERF Materials, Burner Designs, Instrumentation, and Controls (ARC/ANL/ORNL)
B. Finalize ERF Design (ARC/ANL/ORNL)
C. Procure, Build, Install ERF (ARC/Secat)
D. ERF Experiments
   1. Burner Performance Evaluations (ARC/ANL/ORNL/Industry Partners)
   2. Furnace Atmosphere Evaluations (ARC/ORNL/Secat/UK-CAT/Industry Partners)
   4. Melt Loss Effects/Metal Quality (ARC/ANL/ORNL/Industry Partners)
E. ERF Cost/Benefit Analysis (ARC/Secat/Industry Partners)
F. ERF Summary Report (All)

**Task 4.** Furnace Mass, Heat and Fluid Flow Modeling
A. LMU Results/Evaluation (ARC/ORNL/ANL)
B. ERF Results/Evaluation (ARC/ORNL/ANL/Industry Partners)
C. Industrial Furnace Design Development for Retrofits (ORNL/ARC/ANL/Secat/Industry Partners)

**Task 5.** Validation of Design Recommendations on Selected Industrial Furnaces (Team)

**Task 6.** Final Report (Team)
4. Evaluation of Current Melt Practices

The goal of assessing the melting procedures was to familiarize the research staff with the current melting practices utilized in secondary aluminum melting, to familiarize the staff with the various types of reverberatory furnaces, and then to obtain a detailed and scientific measure of the current state of that technology. This task was performed in several phases. The first phase was intended to familiarize all of the research staff with the different types of reverberatory furnaces while the second phase included a more in depth audit of the melters themselves in order to place reported efficiency numbers onto a common scale and to indicate the major mechanisms for energy loss.

4.1 Plant Assessments

Phase one of the assessment required the staff to visit at least one furnace from each of the member companies. This task was completed by August, 2001. The findings from these can be viewed in Figure 4.1, which plots the number of furnaces, by type. It was found that within the 9 member companies there exist 79 reverberatory melting furnaces distributed among the three major types of furnaces, side well, front charge and round top. 60% of these furnaces are side well furnaces, 22% round top and 18% front charge furnaces. In addition to these furnaces, many of the companies operate several other natural gas fired furnaces that are not being considered within this project but which may warrant further work in the future. These furnaces include rotary furnaces and holding furnaces, which is essentially a reverberatory furnace that is utilized solely for staging liquid aluminum prior to casting.

A second item of interest that was learned through this process was the fact that even though there are a proportionate number of furnaces for each type, within a type of furnace there exists a wide variation in the furnace design, operating characteristics and charge material. For example, the front charge furnaces range in size from 90,000 lbs to 210,000 lbs, moreover some of the companies charge all solid scrap while some charge up to 90% liquid. These disparities in melting technology point out that no two furnaces are alike within a given furnace class or across class lines. Certainly a round top melting operates in a very different fashion then a front charge or side well furnace, and so on.

![Number of Furnaces by Type](image)

**Figure 4.1** Number of reverberatory furnaces by type represented within the research consortium.
During this first phase, data was gathered on not only the number of furnaces, but the size of the furnaces, the size of the burners, type of burners (e.g. twin bed regenerating burners, high ram fire burners, etc.), burner rating, melt rates, air to fuel ratio, furnace control parameters and any other information that was deemed essential to a better understanding of operation of a particular plant. During the second phase of the plant audits, additional information was gathered in order to clarify the picture of the state of the melting technology. Such information as furnace geometry (where actual engineering drawings were provided by the member companies) the high and low heating value of the natural gas utilized, air flow rates, turn down ratios, flue dimensions and exhaust gas velocities and temperatures (if known), etc. These data provided a critical review of the furnaces being considered. However, in order to evaluate the state of the industry based upon this random sample, a second on site visit was required in which specific data was to be collected. This data included stack gas analysis, stack gas temperature, stack gas velocity, historical gas usage, current gas usage, interior and exterior temperatures (taken by infrared camera), and an assortment of other variables required to estimate the efficiency of the furnace.

During the measurements, flue gases were sampled from the chimney either near the furnace exit (if an access hole was available) or at the chimney exit through a 6.35 mm stainless steel sampling probe to the EMS 4001 portable 5-gas analyzer. The analyzer was calibrated before each use. The accuracy and measurement range are listed in table 4.1.

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<td>± 25 ppm</td>
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</table>

Table 4.1 Accuracy and measurement range of EMS 5-gas analyzer

The gas analyzer provides the dry-based molar concentrations of combustion species including CO₂, CO, O₂, NO, and unburned hydrocarbons from which the wet-based species concentrations were calculated according to the known fuel and air flow rates.

The flue gas temperature was measured using a conventional K-type thermocouple with 6.35 mm sheath diameter and grounded junction, at the same location as for the flue gas sampling. The temperature was recorded with a hand-held thermometer. The accuracy of the thermocouple in the service range is within 0.75%. The measured flue gas temperature and wet-based species concentrations were used to calculate the heat loss through flue gas.

The refractory temperature of inside and outside furnace walls including roof were measured by using a ThermaCAM PM695 infrared (IR) camera in the 7.5 - 13 m wavelength range. During the measurements, IR thermograph images on the furnace hot face were taken immediately after the furnace door was lifted. The emissivity of hot refractory was assumed in the range of 0.9 - 0.95. The recorded temperature maps were processed with the computer software for color display which could indicate possible hot spots. For the heat loss analysis, temperature map on each wall was taken an average. Temperature, geometry and thermal conductivity of each wall material were used to calculate thermal conduction heat loss.

4.2 Evaluation of Plant Data

As of the end of the first year, 3 plants have had a complete audit of their melting practices while at the end of the second year 10 plants had been visited. Table 4.2 indicates the results of these audits while Figure 4.2 indicates the methodology for determining heat loss and useful head values.
Figure 3 – Heat loss analysis in a model reverberatory furnace

<table>
<thead>
<tr>
<th>Case Number</th>
<th>Furnace Size (x1000)</th>
<th>Gas Flow Rate (ft^3/hr)</th>
<th>Air Flow Rate (ft^3/hr)</th>
<th>Melt Rate (x1000)</th>
<th>Effective Efficiency</th>
<th>Measured Efficiency</th>
<th>Flue Gas Temp (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>210</td>
<td>15,000</td>
<td>188,540</td>
<td>8.7</td>
<td>28.43</td>
<td>28.83</td>
<td>1690</td>
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<tr>
<td>2</td>
<td>240</td>
<td>31,500</td>
<td>315,790</td>
<td>24</td>
<td>11.84</td>
<td>11.72</td>
<td>1630</td>
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<tr>
<td>3</td>
<td>180</td>
<td>33,200</td>
<td>360,000</td>
<td>18.5</td>
<td>26.4</td>
<td>25.99</td>
<td>1860</td>
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<tr>
<td>4</td>
<td>205</td>
<td>85,000</td>
<td>892,000</td>
<td>63.4</td>
<td>35.89</td>
<td>38.52</td>
<td>1990</td>
</tr>
<tr>
<td>5</td>
<td>90</td>
<td>13,365</td>
<td>134,560</td>
<td>18</td>
<td>11.64</td>
<td>11.5</td>
<td>1480</td>
</tr>
<tr>
<td>6</td>
<td>160</td>
<td>28,800</td>
<td>344,590</td>
<td>27</td>
<td>43.82</td>
<td>27.2</td>
<td>160</td>
</tr>
<tr>
<td>7</td>
<td>210</td>
<td>13,730</td>
<td>169,950</td>
<td>8.7</td>
<td>30.67</td>
<td>28.83</td>
<td>1575</td>
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<td>147,860</td>
<td>7.1</td>
<td>27.38</td>
<td>26.60</td>
<td>1900</td>
</tr>
<tr>
<td>9</td>
<td>240</td>
<td>11,575</td>
<td>116,040</td>
<td>16.4</td>
<td>20.76</td>
<td>22.29</td>
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<td>18.1</td>
<td>28.07</td>
<td>27.82</td>
<td>1860</td>
</tr>
</tbody>
</table>

Table 4.2 – Efficiency analysis indicating direct and indirect methods for determining proportion of useful heat to the load.
The direct method of obtaining melt efficiency is obtained by examining the amount of gas used over a period of time versus the amount of metal melted during that same time. This gives an overall average of the efficiency over a period of time. The problem with this method is that it does not detail where the lost energy may be going and does not take into account such factors as down time, holding time, periods of time when the door is held open or the fluctuation in low and high heat values for the supplied natural gas.

The indirect method, on the other hand, has no such flaws. This method utilizes not only the heat values of the gas utilized on that day, but also takes into account combustion efficiency (by measuring the stack gas composition), heat loss through furnace walls and roof, door openings, long holding times etc. As can be seen in Table 3, the indirect method will necessarily give a slightly lower value for efficiency. This is due to the fact that it is a more robust method of obtaining the instantaneous efficiency during a measurement cycle. Some of these issues come to light if we examine case 2, for example. This case indicates a rather low efficiency. However, by taking into account the fact that this furnace is charged with 70% or more liquid aluminum and consequently operates more like a holding furnace, we begin to see why the melting efficiency drops. Although the industry reports overall 30% energy efficiency, this study appears to indicate that a more realistic value is around 24-25%.

In a cold charge at the start of melting the initial temperature of Aluminum scrap was assumed 25 °C and the final temperature varied according to the melting purposes and operational processes. We plot in Fig. 104 the analytical and measured energy efficiency as a function of energy consumption on these furnaces, showing energy utilization in melting furnaces we measured. Figure 104 shows that the energy efficiency is not linearly decreased with increase of energy consumptions. Squared symbols in Figure 4.3 are the measured energy efficiency without air preheating, which was between 26% -29%. The circle symbol is the efficiency with air preheating applied, about 10 % higher than those without air preheating. It is clear that there is a big room for the effort to improving energy efficiency. We did not plot the measurements for holding furnaces because of different purposes.

![Figure 4.3 Comparison of analytic and measured energy efficiency as a function of energy consumption in Aluminum melting](image-url)

**Figure 4.3** Comparison of analytic and measured energy efficiency as a function of energy consumption in Aluminum melting [1].
Figure 4.4 – Energy balance indicating the major sources of heat loss.

Figure 4.4 indicates the major sources of heat loss and the useful heat utilized by the load. The pie plot displays the current energy utilization in our measured industrial furnaces. The major heat loss is through flue gas (35 - 50 %). Thermal conduction heat loss through furnace walls accounts for 2 -12 % depending on the furnace conditions. The heat loss due to dross production is small (1 - 2 %). Other heat loss includes immeasurable heat loss such as those through radiant and heat convection in the door opening and idle operation.

Figure 4.5 – Theoretical and measured energy efficiency at metal temperature of 1350°C.

In fact, Figure 4.5 shows that even the most efficient furnaces are melting at less than a 30% efficiency rating.
The flue gas heat loss, which directly reflects the heat transfer rate from combustion flame to the Aluminum load, is the major concern in improving energy efficiency, because it is the main source of heat loss in Aluminum melting. In almost all cases, the amount of heat loss through the flue exceeds the theoretical limits, and in some cases substantially. This is valuable energy that should be able to be recovered.

Figure 4.6 – Heat loss through the flue as a function of temperature including experimental data taken from industrial cooperators.

Figure 4.6 plots the heat loss through flue gas under industrial operational conditions as a function of flue gas temperature with different excess air in combustion, and compares with the data we measured. The analytical solution shows that the flue gas heat loss increases linearly with the flue gas temperature, and it also depends on the molar fraction of combustion products and the total moles of flue gas, because more heat will be lost by heating nitrogen in air. The typical heat loss through flue gas is between 35 % and 50 %. Some data points are far away from the solid lines, implying high excess air occurring during melting process.

Air preheating and scrap preheating can save large amount energy from waste, hot flue gas, thus improving energy efficiency. In order to determine the amount of energy savings that could be obtained, several example systems were calculated utilizing only the waste heat in the flue. Figure 4.7 plots the analytic (line plots) and measured (data points) results of energy saving and efficiency improvement by air preheating. As can be seen, practical energy efficiency increases on the order of 10-15% can be achieved by utilizing the waste heat to preheat the combustion air alone. It was found, for example, that this heat technique can improve the practical efficiency by 4-7% for every 100° C the combustion air is increased in temperature. This indicates a source of substantial savings. In one case study, it was found that the practical efficiency of the furnace could be increased by as much as 17.5. However, this technology is not widespread in our measured Aluminum furnaces.
A second means of utilizing the waste heat through the flue is by using it to preheat the scrap. There are various methods of doing this, and in fact one industry partner is utilizing all of their hot flue gases as a heat source for melting. This company reports a net efficiency of 43%, however by analyzing the combustion efficiency it is seen that that figure is more on the order of 27%. But, the fact remains that overall their gas bills are substantially less, per pound of aluminum melted because they have found a novel way of utilizing the waste heat in their furnace.

Figure 4.7 Analysis of energy savings by preheating combustion air.

Figure 4.8 – Analysis of energy savings by charge preheating.

Figure 4.8 plots the effective energy improvement by utilizing the flue gases to preheat the charge. In one case study for a member company, this increased the effective efficiency by nearly 7%. These two methods alone indicate a large area for improvement and a means for implementation by utilizing the waste heat in the flue gases.

This was a major benefit of performing the onsite analysis that the project undertook since it not only gave an effective, non-biased picture of the efficiency of the furnace, but it identified means for improving the efficiency directly.
5. Design and operation of Experimental Furnace

As partial fulfillment of the funded program, two separate furnaces are to be designed and built for scoping studies on furnace operational characteristics. The first of these furnaces, designated the Laboratory Melting Unit (LMU) is to be a small, “bench-scale” furnace while the second, the Experimental Melting Unit (EMU) is to be somewhat larger.

Because a small, laboratory-melting unit already resides at the ARC, it was decided that the resources for building such a furnace were better spent elsewhere. It was further decided that based on the comments received from industry partners that all trials should be done using the Experimental Melting Unit since it is of direct relevance to the industry and data obtained could be related and compared with industry practice. Because of this fact, the project team went straight to designing the EMU. Hence, Task 2 and 3 were combined into one task.

5.1 Design Criteria

Several criteria were identified within the team with the help of the steering committee. These criteria include:

1. The furnace must be large enough to represent actual, working industrial furnaces.
2. The furnace must be small enough that it would be useful as a research tool.
3. The furnace must be modular in nature.
4. The furnace must be able to be equipped with off-the-shelf equipment as well as any custom equipment designed through the course of the project.
5. A full compliment of thermo-couples, flow sensors, pressure sensors, etc must be included for a complete picture of the operational characteristics of the furnace. Data acquisition is of paramount importance to the project.

Based upon these criteria, an initial design was obtained with the aid of Enercon Systems, North American Mfg., and Metallics, Inc. After some deliberations and input from the member companies, a second design was obtained through the interaction of North American Mfg. This design took into account more practical experience, included such aspects as molten metal pumping, sidewell or front charging technology, as well as including modern regenerative burners performing at low NOx levels. Moreover, the ability to go with oxygen enriched and air-oxy-fuel burners was included in one design. Operational aspects of the furnace included the ability to perform tests such as what happens to the overall furnace efficiency, refractory life, burner longevity and melt rate values if you decrease the combustion space size. This study could be done with respect to cold fired, hot fired (through the regenerative burners), oxy-fuel fired or air-oxy-fuel fired burner configurations in order to set standards for the optimization of furnace geometries with respect to burner and combustion space configurations. Figure 5.1 is a plan view of this furnace indicating the location of the sidewell, exhaust stack, sample port, hearth and molten metal pump location.

Fluid flow simulations brought concerns to light on the ability for the sample well to be utilized in a sound manner. Figure 5.2 shows the steady-state fluid flow in this furnace with the electromagnetic or a mechanical pump installed. Notice the “dead” spot in the sample well in either case. These simulations indicated that the metal in the sample well would freeze prior to it being useful. For this reason, the sample well was removed. This second generation furnace is...
depicted in Figure 5.3. Here, not only is the side well location visible, but so too are the regenerative burner locations.

Figure 5.1 A schematic of the 12,000lb experimental furnace design for Albany Research Center

Figure 5.2 - Simulations of the proposed furnace indicating a dead zone in the sample well when a) electro-magnetic pump or b) mechanical pump is used.
Moreover, the first design was submitted to the steering committee members for input and comment. The steering committee members were very helpful in pointing out several other flaws in the current design as well as being instrumental in driving the design towards a better, more robust test-bed furnace. The second-generation furnace design was then arrived at with the cooperation of North American Mfg and Metaullcics with input from Enercon.

In either case, the hearth dimensions for the furnace are 5 feet by 6 feet which yields a holding capacity of approximately 9-10,000 lbs of molten aluminum without the addition of the metal circulation device. The furnace design includes the ability to run regenerative burners, oxy-fuel burners or standard ram-fire burners. Moreover, because of the flexibility required in burner usage, the roof was designed to be able to be easily raised or lowered in order to investigate the effects of the size of the combustion space versus combustion apparatus. For example, (as indicated before), while running oxy-fuel burners, there may not be a need for the increased combustion space volume because there is no added nitrogen being introduced through the combustion air. Therefore, it may make sense to decrease the combustion space volume, placing the refractory that is radiating a major portion of the heat to the bath in closer proximity to the bath. Thus, the potential for increased efficiency exists on several levels in this scenario and the whole furnace becomes more closely coupled with the metal load.

Unfortunately, funding that was identified in order to install this furnace quickly vanished and a secondary plan was needed. This short fall occurred a little more than half way through the project year and after many months of deliberations, designs, design changes and more deliberations. However, with the same process in mind, a modification to the plan was obtained and a 2000 lb furnace re-entered. This furnace, although not as flexible or as scalable, was determined to be a good, robust test bed to meet many of the projects need. Figure 5.4 is a schematic of this furnace.
Figure 5.4 2000 lb experimental furnace nearing completion at the Albany Research Center

This furnace runs twin cold fired 800,000 Btu burners manufactured by North American Mfg. and will be capable of melting on the order of 650 lbs per hour. Bath dimensions are approximately 3 feet by 3½ feet and the bath depth 14 inches. The furnace will utilize front charging with a side tap. Full instrumentation is being implemented as well.

Figure 5.5 is a sample of the data acquisition and control interface being developed. The furnace is outfitted with an array of thermocouples placed near the inside surface of the refractory as well as on the shell surface. Mass flow meters measure gas and air rates to the furnace as well as exhaust flow rates. Exhaust compositions will be obtained through the use of infrared meters and a gas chromatograph. Combustion air can either be supplied cold or hot with the addition of an existing air pre-heater at Albany. This pre-heater is capable of pre-heating the air to 1000°F for studies on air preheating with respect to efficiency and NOₓ generation.
5.2 Experimental Trials

Based on discussions with the industry partners the ARF Experimental Furnace was utilized to carry out a series of “what if” scenarios in order to understand the issues related to various aspects of furnace performance as related to furnace design and process parameters. The results of the “what if” scenarios were compared with computational results from the modeling software developed during the course of the projection order to validate the model.

First simple exercise was conducted by placing thermocouples within the charge material and comparing the temperature with that of the instantaneous energy efficiency. This is shown in figure 5.6 below relating instantaneous energy efficiency with melt progression time. It can be seen that as the charge temperature increases the energy efficiency drop slightly as the heat input is transferred to the solid charge. At a certain stage of the heat up process, approximately after 1.25hrs there is a sudden increase in energy efficiency indicating that the material is melting; this continues till the charge is molten after which the energy efficiency drops as the charge is superheated. This clearly shows how energy is transferred to charge from the cold state to superheated liquid metal.

Figure 5.6 Instantaneous Energy Efficiency vs. melt time
A series of tests were run to determine the effective efficiency of the ARC furnace over a range of power inputs ensuring that the following input parameters were maintained.

- Each test maintained constant power input for the duration and the test was terminated when the tap temperature was reached.
- Comparison of the tests indicates the overall efficiency as a function of power input normalized to bath area.
- The combustion space was changed and then all tests repeated.
- Effective efficiency data was utilized for model validation.
- Each test utilized standardized operational techniques, i.e.,
  - The charge time was held constant
  - The power input held constant during a particular test
  - The tap temperature the same in each test

The figure 5.7 below shows the configuration of the furnace for different combustion space volumes; it can be seen that besides the base case the combustion volume was decreased and increased proportionately.

**Figure 5.7** Furnace Combustion Space Volumes

Figure 5.8 plots the efficiency of the ARC ERF as a function of combustion space volume. Note that in Figure 5.8, an increase in combustion space volume increases efficiency during low and high fire times while decreases efficiency near the optimal operating conditions. Also notice that with the lowered combustion space volume (S-3-AB), the furnace has a very high maximum efficiency at a much lower firing rate but that this efficiency drops off dramatically with increase firing rate. This is due to the fact, and shows quite effectively, that it is easy to over fire the furnaces causing large losses in efficiency.
Furnace efficiency as a function of bath area in the Albany ERF

**Figure 5.8** Furnace Efficiency with Different Combustion Volume

The experimental results on the ERF furnace at normal and elevated roof heights and the comparison of experimental results with model predictions are shown in Figures 5.9 to 5.11. The optimum operational conditions for these experiments were predicted and plotted in the same figures.

The measured energy efficiency plotted as a function of melting rate is shown in Figure 5.9 for normal and elevated roof heights in ERF furnace.

**Figure 5.9** Comparison of experimental data at normal and elevated roof heights.

The model prediction provides the optimum melting rate where the maximum energy efficiency can be achieved.

The data points are the experimental results and the curves are the model prediction with optimum operating conditions to be calculated. It can be seen in Figure 5.9 that the measured energy efficiency increases, then decreases as the melting rate increases. In most tests the energy efficiency is around 40% for the ERF furnace, which were much higher than those industrial furnaces we have measured on the (around 30%) [9]. Model prediction demonstrates that the
optimum melting rate was 183 kg/hr·m² for normal roof height and 191 kg/hr·m² for elevated roof height where the maximum energy efficiency calculated from Eq. (113) was 44.8 % and 41.7 %, respectively. The maximum energy efficiency for normal roof height was 3 % higher than that for elevated roof height.

Figure 5.10 presents the measured energy efficiency plotted as a function of heat absorption rate for normal and elevated roof heights and compares the experimental results with model predictions.

![Figure 5.10](image)

**Figure 5.10** Comparison of data at normal and elevated roof heights. The model predicted optimum heat absorption rates & maximum energy efficiency for both cases.

It shows that the energy efficiency increases, reaches a maximum value, then decreases as the heat absorption rate increases, a similar trend as shown in Figure 5.9. The optimum heat absorption rate at maximum energy efficiency was 58.4 kw/m² for normal roof height and 61.6 kw/m² for elevated roof height.

It is known that a fast melting rate can be achieved with a high firing rate. However, a high firing rate may result in short residence time of combustion products in the furnace, resulting in high flue gas temperature and large amount of flue gases produced. Consequently, the energy efficiency would be reduced because a large amount of energy is lost through flue gas.

Figure 5.11 predicts these experimental data and compares with model prediction to show the relationship between energy efficiency and firing rate for both normal and elevated roof heights. Similar to what is shown in Figures 5.8 & 5.9, the energy efficiency increases, then decreases as the firing rate increases. The optimum firing rate at which the maximum energy efficiency can be reached was 130.2 kw/m² for normal roof height and 147.7 kw/m² for elevated roof height.
Figure 5.11 Comparison of measured data for the cases of normal and elevated roof height. The model prediction provides optimum firing rate when maximum energy efficiency is reached.

To better understand the effect of firing rate on the heat absorption rate, and thus the melting rate, Figure 5.12 plots the heat absorption rate as a function of firing rate from experimental results and model predictions.

![Graph showing comparison of experimental data with model prediction for normal and high roof cases.]

Figure 5.12 Comparison of experimental data with model prediction- normal & high roof

It is clearly displayed that the heat absorption rate increases when the firing rate increases. However, the increase in the heat absorption rate slows down at the high firing rate. Slowdown of the increase in heat absorption is caused by a phenomenon called “heat transfer bottleneck” [103]. At a low fuel flow rate, the heat absorption rate increases almost linearly with the
increases of firing rate. However, the linear relation is expected to become non-linear at high firing rate because the heat transfer rate does not increase as fast as the firing rate, resulting in an increased flame temperature in the combustion space, thus an increased flue gas temperature. More energy is lost from the chimney as flue gas. Because the heat absorption rate is directly proportional to the melting rate, the Aluminum melting wouldn’t be fast enough as expected at higher firing rate. Low heat absorption rate and high firing rate result in low energy efficiency, as shown in Figures 5.8 to 5.11.

The table below shows a comparison of experimental data with that of the model with respect to flue gas temperature as well as flue gases CO₂, CO, O₂ and N₂. The concentration calculations are wet hence they were adjusted for dry conditions. The results compare well with each other.

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<th></th>
<th>Meas.</th>
<th>Calc.</th>
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<td>1080</td>
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<td>CO (ppm) flue</td>
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<td>N₂ (%) flue</td>
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</tr>
<tr>
<td>CO2 (%) flue</td>
<td>9%</td>
<td>11%</td>
</tr>
</tbody>
</table>

Table 5.1 Comparison of experimental data with that of the model
Flue gas temperature as well as flue gases CO₂, CO, O₂ and N₂

Base Case Comparison

The figure 5.13 below shows a comparison of the measured and calculated data of the relationship between flue gas temperatures with that of average surface heat flux in BTU/hr/in². The comparison of the measured trends is in very close agreement with the computed trend and the majority of the calculations are well within an order of magnitude of the measurements.

Figure 5.13 Comparison of the measured and calculated data
Flue gas temperatures with that of average surface heat flux in BTU/hr/in²
Figure 5.14 below plots surface heat flux with gas/hr; the graph shows excellent agreement between the computational approach and that found with practical experience.

Figure 5.14: Surface heat fluxes as a function of natural gas flow rate

5.3 Parametric Trials

The Albany experimental furnace was utilized to carry out furnace parametric studies with an extensive series of computations (over twenty cases) performed to determine the operating conditions that maximize heat transfer to the melt. The parameters of the burners as given below were varied with injection angles varied in the same and opposite directions:

- Vertical injection angle
- Horizontal injection angle
- Flow rates through the burners

The effect of vertical injection angle on the energy in BTU/hr transmitted to the furnace is shown in figure 5.15. The injection angle is varied from a downward tilt to an upward tilt from the horizontal as you move from the left. It is noted that maximum heat transfer occurs when the burner is tilted at an angle of 10 degree downward from the horizontal. The optimum angle improves heat transfer as well as residence time of combustion air within the combustion volume.

Figure 5.15: Vertical injection angle of burner vs. BTU/hr transferred to melt
Figure 5.16 below shows the variation in BTU/hr to the melt when the distribution of gas through the two burners in the experimental furnace is varied from a ratio of 100%/0% to 0%/100%. The data clearly indicates that an approximate 70/30 ratio of fuel distribution between the two burners ensures the maximum BTU/hr to the melt compared to a 50/50 ratio as is used conventionally.

**Figure 5.16** Change in BTU/hr to melt when gas distribution between 2 burners are varied

These experimental trials clearly indicate that running “what if scenarios” enable one to understand the functioning of furnaces of different configurations. At the same time it has enabled the validation of the software developed; this would in future enable the use of the software by industry participants to understand the functioning of their furnaces and review potential changes before capital investments.


6.1 Theoretical Analysis of Energy Utilization in Aluminum Furnaces

Analyses of energy utilization and major heat losses in an Aluminum melting furnace are based on the energy balance between energy input and output. Figure 6.1 is the schematic of energy balance in a typical natural-gas fired, reverberatory furnace.

**Figure 6.1** Schematic of energy balance in an Aluminum melting furnace.
The analysis has following assumptions. The furnaces operate under nearly isobaric conditions. Fuel and air flow rates, melting rate, flue gas thermal properties, and thermal conduction through furnace walls are at steady states in continuous furnace operations. For batch furnace operations, these parameters are obtained as average values in a melting cycle. Specific heat capacity of liquid Aluminum is constant due to its weak dependence on temperature. Thermal conductivity of wall materials is stepped-dependent on temperature. In the melting processes, dross is produced on the surface of liquid Aluminum by oxidation reaction. The dross compositions are considered as alumina, whose sensible enthalpy depends on temperature, in that the amount of dross produced is small as compared with the melting rate. For simplicity, natural gas is considered pure methane. The methane-air combustion is complete in that the melting furnaces operate in fuel-lean combustion, and in our plant-site measurements no significant amount of CO in flue gases was measured. Combustion products include only major species including CO₂, CO, H₂O, O₂, and N₂. Their sensible enthalpy is a function of temperature. The heat losses are those measurable heat losses including heat loss through flue gas, thermal conduction heat loss, and heat loss due to dross production, as well as those immeasurable heat losses such as those lost by radiation and heat convection in door opening for Aluminum charging.

Due to nearly isobaric combustion processes in Aluminum furnaces, an energy balance can be obtained directly from the law of energy conservation; the total enthalpy of reactants at the initial state equals the sum of total enthalpy in combustion products at the final state plus the useful energy output for Aluminum melting and all types of heat losses. For practical interpretation, using the (low) heating value is more convenient than using enthalpy of formation for complete combustion so that the total fuel energy input can be represented by the product of molar number of fuel, \( N_f \), and its (low) heating value, \( Q_c \). The energy efficiency may be obtained directly from the measurements of useful energy output, \( Q_{Al} \), to the total fuel energy input as
\[
\eta = \frac{Q_{Al}}{N_f Q_c}.
\]

Indirect assessment of energy utilization obtains energy efficiency by counting all types of energy output. Starting with energy balance in a furnace, and introducing the expressions \( N_i = \sum N_i \) for total molar number of species and \( X_i = N_i / N_t \) for molar fraction of species \( i \) appearing in the reaction, the energy efficiency by indirect assessment can be derived as [1]
\[
\eta = 1 - \frac{\sum N_{i,p} X_p H_p^s(T_2) - \sum N_{i,a} X_a H_a^s(T_1) + Q_{L,w} + Q_{L,d} + Q_{L,m}}{N_f Q_c}
\]

where \( Q_{L,w} \) is the thermal conduction loss through furnace walls and roof, \( Q_{L,d} \) the heat loss due to dross production during melting, and \( Q_{L,a} \) the miscellaneous, immeasurable heat losses. \( H_i^s(T) \) is the sensible enthalpy of species \( i \) at temperature \( T \) with respect to the reference temperature \( T_0 \) at standard temperature and pressure (STP). The subscription “a” represents air, “p” the species in combustion products, “1” the initial state, and “2” the final state. In Eq. (1), the first term in numerator is the heat loss through flue gas, and the second term is the heat recovery from hot flue gas if air preheating is applied. If Aluminum load is preheated, the total fuel consumption will be reduced. The energy saving by Aluminum preheating is concealed in the terms of energy input and heat loss through flue gas.

Incomplete combustion may produce CO and other minor species by major species dissociation, the energy efficiency will be reduced. As concerns the incomplete combustion, the total energy input shown in the denominator in Eq. (1) has to be replaced by the standard enthalpy of formation for all species including reactants and combustion products.

The furnace walls and roof were usually covered by two or three layers of refractory and heat insulator materials. The thermal conduction heat loss can be obtained by measuring temperature...
of hot interior wall surfaces, $T_h$, and cold exterior surface, $T_c$, for each furnace wall including roof, and using the Fourier’s Law of heat conduction,

$$Q_{L,w} = \sum_i \sum_j d_{i,j} A_{i,j} k_{i,j} \frac{T_{h,j} - T_{c,j}}{A_{i,j} k_{i,j}},$$

(2)

where $d_{i,j}$, $A_{i,j}$ and $k_{i,j}$ are the thickness, surface area, and thermal conductivity of the insulation materials covered on the furnace walls and roof, respectively. The subscriptions “$i$” and “$j$” represent different walls and different insulation materials on each wall.

The heat loss due to dross production is evaluated by the law of heat capacity,

$$Q_{L,dross} = m_{dross} C_{P,dross} \Delta T,$$

(3)

where $m_{dross}$ is the dross mass-production rate, $C_{P,dross}$ is the dross specific heat, and $\Delta T$ the temperature difference between dross and environment.

The analytical furnace model was originally established by Essenhigh and Tsai [2, 3] for analysis of glass furnaces. It was used as a tool in diagnostic and monitoring the performance of Aluminum furnaces because the functions and melting practices of both furnaces are very similar, although a modification is necessary for the model to be appropriately used in Aluminum furnaces. Yu [4] first applied the Essenhigh/Tsia model to analyze continuous and batch Aluminum furnaces. Both air and oxy-air combustions were studied to verify model’s capability to apply in Aluminum melting furnaces. The model predicted the performance of the existing furnaces. However, in these studies, the flue gas temperature was not experimentally determined, instead, it was obtained by adding 200 ºF (93.3 ºC) to the refractory temperature [5]. Furnace load was simulated with a water-cooled heat exchanger. Because furnace operations at a wide range of firing rates were impractical in this study, the crowded data points were analyzed by a trial and error approach.

We have developed the modified Essenhigh/Tsai model applying to Aluminum melting furnaces. The modified Essenhigh/Tsai model was based on the experimental data from detailed measurements conducted on the experimental research furnace (ERF) at the Albany Research Center. The objective of using modified analytical model is to find relationships between firing rate, heat absorption rate, melting rate, and energy efficiency in the ERF melting furnace, from which the optimum operational conditions can be predicted.

Before expressing our development, it should note that the ERF furnace was built for research purpose and its dimension was 1:100 scaled-down from typical industrial reverberatory furnaces. This scaled-down option raises a question if experimental data obtained from the tests on a small-sized furnace would validate to those obtained from large industrial furnaces. To assist answering the question, we applied scale modeling concepts to build a model furnace even smaller than the ERF furnace. The purpose to conduct modeling experiments is so called “commit your blunders on a small scale and make your profits on a large scale” [6], that is, we conduct model experiments and applied scaling laws to validate the test results. If the scaling laws are obeyed in the model experiments, the results obtained from the model experiments could apply to the prototype [7]. The law approach and partial modeling relaxation technique were applied in the model experiments. Since nothing in the literature has reported using scale modeling on an Aluminum melting furnace, we have chosen only limit our first effort on the thermal conduction loss instead to scale whole prototype. The detail scaling laws and model experiments can be found in the Ref. 8.

Back to the subject, the bases of the modified Essenhigh/Tsai model is the energy balance in the furnace to be analyzed. The model development requires a limited melting and holding tests with two main assumptions that the thermal conduction loss across furnace walls and roof for the Aluminum melting is the same as for the holding processes, as are the miscellaneous heat losses, and that the heat loss through flue gas is linearly proportional to the melting rate. The first
assumption is reasonable because the thermal conduction loss is small as compared with firing rate, and the miscellaneous heat losses such as heat loss due to door opening are immeasurable and should be eliminated for model simplicity. Thus, we can express the energy balance in the melting processes that the energy charged into the furnace in terms of firing rate, $q_e$, equals the sum of heat absorption rate, $q_{Al}$, heat loss through flue gas, $q_p$, thermal conduction heat loss, $q_w$, and miscellaneous heat losses, $q_m$. The unit of these parameters is kw/m$^2$, which is based on the surface area of melting bath in the furnace.

$$q_e = q_{Al} + q_p + q_w + q_m.$$  \hspace{1cm} (4)

For holding process, the energy charged into the furnace is only for keeping constant temperature for molten Aluminum. If we use the symbols with superscript “’” for the holding process, the energy balance for holding process is,

$$q_e = q_{p}' + q_{w}' + q_m'.$$  \hspace{1cm} (5)

Subtracting Eq. (5) from Eq. (4) yields the relations between differences in firing rates of melting and holding, heat absorption rate, and the differences in heat loss through flue gas for the melting and holding processes.

$$q_e - q_e' = q_{Al} + (q_p - q_p').$$  \hspace{1cm} (6)

The second assumption can be written as the linear equation,

$$h_p = h_p' + (h_c - h_p')m_{Al},$$  \hspace{1cm} (7)

where $h_p$ is the heat loss density of flue gas and $h_c$ the firing rate density with the unit of kj/m$^3$ in the basis of flue gas volume. $m_{Al}$ is the dimensionless melting rate, defined as the melting rate $m_{Al}$ (kg/hr-m$^2$ of the bath area) normalized by its asymptote, $m_{Al,max}$; the latter is a theoretical melting limit at which the heat loss through flue gas is balanced by the firing rate. For the holding process, no Aluminum is melted so that the value of melting rate is zero.

The second assumption is quite accurate, as we show in Figure 6.2 as the evidence, which plots the heat loss density of flue gas as a function of melting rate for a typical melting process from our measurements on the ERF furnace. The correlation coefficient in this plot is over 94%.

![Figure 6.2](image)

Figure 6.2 typical plot show a nearly linear relationship between the heat loss through flue gas and the melting rate in Aluminum melting furnaces.
Realizing the facts that the ratio of $q_p$ and $h_p$ for heat loss through flue gas is equal to the ratio of $q_c$ and $h_c$ for firing rate in both melting and holding cases, and that the heat absorbed by Aluminum load is only for Aluminum heating and melting such that the dimensionless heat absorption rate, $\bar{q}_{Al}$, defined as the ratio of heat absorption rate, $q_{Al}$, normalized by maximum heat absorption rate $q_{Al,max}$, is equal to the dimensionless melting rate, $\bar{m}_{Al}$, defined as the ratio of melting rate, $m_{Al}$, normalized by maximum melting rate $m_{Al,max}$, we can derive the linear equation from Eqs. (6) and (7),

$$\alpha = \alpha_0 (1 - \bar{q}_{Al}),$$  \hspace{1cm} (8)

where $\alpha_0$ is called the intrinsic factor or the energy utilization factor, expressed as $\alpha_0 = q_{Al} / (q_c - q_c')$, because it indicates the usefulness of energy input. The value of $\alpha_0$ can be determined by a few of melting and holding tests. $\bar{q}_{Al}$ is a constant that is an implicit function of the internal heat transfer characteristics between fuel combustion, furnace enclosure, and Aluminum load. It is derived to be the form,

$$\alpha_0 = (1 - \frac{h_c'}{h_c})/[1 + (1 - \frac{h_c'}{h_c} - \frac{q_c'}{q_{Al,max}})].$$  \hspace{1cm} (9)

Equation (108) is an essential one in the modified Essenhigh/Tsai model. Using Eq. (8) based on the results from a limited melting and holding tests, and plotting intrinsic factor as a function of heat absorption rate, the constant value of $\alpha_0$ and the maximum melting rate $q_{Al,max}$ can be determined. Application of Eq. (8) to determine the constant values of $\alpha_0$ and $q_{Al,max}$ for a certain furnace performance is shown in Figure 6.3, which plots $\alpha$ as a function of $\bar{q}_{Al}$ for the ERF furnace operation at normal roof height. The solid line is the linear fitting of the data points from which the values of $\alpha_0$ and $q_{Al,max}$ were 1.53 and 127.5 kw/m$^2$, respectively.

![Figure 6.3](image)

**Figure 6.3** Linear relation of energy utilization factor $\alpha$ and the rate of heat absorption determines the value of $\alpha_0$ and $q_{Al,max}$.

From Eq. (8), the energy efficiency of a melting furnace can be obtained,

$$\eta = \frac{q_{Al}}{q_c} = \frac{\alpha_0 (1 - \bar{q}_{Al} \bar{q}_{Al})}{\beta + (1 - \beta) \bar{q}_{Al}},$$  \hspace{1cm} (10)
where $\eta = \eta_c/q_{Al,max}$ is a constant. The dimensionless firing rate, $\tilde{q}_c$, defined as the firing rate, $q_c$, normalized by maximum heat absorption rate, $q_{Al,max}$, can be derived from Eq. (10)

$$\tilde{q}_c = \frac{q_c}{q_{Al,max}} = \frac{\beta + (1 - \beta)\tilde{q}_{Al}}{\alpha_0 (1 - q_{Al})}.$$  

(11)

The optimum dimensionless heat absorption rate can be obtained by differentiating in Eq. (10) with respect to $\tilde{q}_{Al}$ and setting it to zero,

$$\frac{\partial \tilde{q}_{Al}}{\partial \eta} \eta_{max} = 0$$  

(12)

which yields

$$\tilde{q}_{Al,opt} = m_{Al,opt} = \frac{\sqrt{\beta}}{1 + \sqrt{\beta}}.$$  

(13)

Note that the dimensionless optimum melting rate is the same as the heat absorption rate, Eq. (13) can determine either dimensionless parameters. Substituting Eq. (13) into Eqs. (11) and (10) obtains the optimum firing rate, and the maximum energy efficiency,

$$\tilde{q}_{c,opt} = \tilde{q}_{Al,opt} \frac{\beta + \sqrt{\beta}}{\alpha_0} \eta_{max} = \frac{\beta}{\alpha_0 (1 + \sqrt{\beta})}.$$  

(14)

$$\eta_{max} = \frac{\alpha_0}{(1 + \sqrt{\beta})^2}.$$  

(15)

Thus Eqs. (13) and (14) are used to determine optimum operation conditions (heat absorption rate, melting rate, and firing rate), while the maximum energy efficiency is determined by Eq. (15). Equations (13) to (15) are advantageous in monitoring melting practice because they can be obtained only with a few melting and holding tests on the tested furnace, and provide optimized operating conditions, that is, if the firing rate is set at optimum parameter, the melting furnace would work under the best conditions with the maximum energy efficiency is achieved.

6.2 Numerical Simulation of Aluminum Furnace Combustion Space

Furnace mass, heat and flow modeling is being conducted jointly by staff at the Argonne National Lab and the Oak Ridge National Lab. ANL has been working for a number of years on a combustion space model, primarily for glass furnaces. However, the nature of a gas fired glass furnace is very similar to that of aluminum reverberatory furnace. Therefore, it was deemed a fairly straightforward job of revamping the glass furnace code to model the reverberatory furnace. Once this is done and simulations run on the combustion space, the heat flux and heat distribution data is transferred from ANL to staff at ORNL so that they can implement these data in the furnace model. This unified furnace model will then be used to look at areas of heat loss, molten metal flows (through natural convection as well as forced convection if a pumping device exists) and overall energy balance. In order to accomplish this task, the data taken by the UK staff in their audits is utilized for model verification and model adjustment, if necessary. This iterative process yields a robust, full furnace model capable of modeling the current state of the furnace as well as being extremely valuable in playing what-if scenarios. For example, what if a particular company wanted to reorient their burners, what impact would this have on the overall melting efficiency of the furnace?
Figure 6.4 Modeling of a reverberatory furnace is broken down into two problem domains; The combustion space domain is modeled by ANL while the synthesis of this data is incorporated into a system model by ORNL.

Figure 6.4 is a diagram indicating the interaction between the principles in the modeling effort. Again, notice how information is passed from one member of the team to the next. Because of the cross-fertilization of ideas and information between the principles, it has become imperative to maintain a standard of excellence in modeling and communication. At the end of the first year of the program, the modeling effort has been split between two primary areas, the first directed towards modeling 3 of the furnaces at different member company plants and second to focus on modeling differing aspects of combustion as well as geometry changes in furnace configurations.

This has been done for two reasons, first, a design for an experimental furnace had not yet been finalized and second, the companies that owns the furnace chosen has produced a tremendous amount of information and data regarding their furnace and it’s operation and they have spent many hours with the staff to help the scientists better understand the modeling domain and the interactions between various components. An added benefit of approaching the modeling effort in this manner is that it has proven to be fairly easy to include such furnace and heat characteristics as radiation effects, soot generation, NOx generation and heat flux calculations.

Aluminum melting furnaces are mainly used to produce molten Aluminum from ingots and/or scraps and subsequently make final Aluminum products. In such a melting process, heat release from the combustion of hydrocarbon fuels (usually natural gas) is transferred to metal by thermal radiation and convection. Both modes depend strongly on local flow properties (i.e., pressure, temperature, and velocities) and local species concentrations. The heat flux distribution on the metal surface directly affects the rate at which melting occurs and thus Aluminum production rate. Additionally, gas temperature and local heat flux distribution in the furnace combustion space also affects production of nitric oxides and other pollutants. An understanding
of the fundamentals and interactions of flow and heat transfer in the furnace combustion space plays key roles in improving energy use, increasing production rates, and reducing pollutants formation. A state of the art computational fluid dynamics (CFD) code developed at Argonne National Laboratory (ANL) was used to simulate turbulent mixing, combustion heat release, radiation heat transfer, and pollutant formation and transport in the furnace combustion space. The complicated simulation processes are divided into two major steps: (1) combustion flow calculation and (2) radiation calculation. In the combustion calculation step, a local net radiation heat flux distribution is assumed. Using the assumed heat flux distribution, a combustion flow calculation is performed to predict local radiative properties, including pressure, temperature, and species concentration. In the radiation calculation step, the calculated local radiative properties are used in radiation heat transfer calculation to improve the local net heat flux distribution. The above iteration cycles continue until a pre-set convergence criterion is satisfied.

The combustion of hydrocarbon fuels converts chemical energy into heat by breaking hydrogen carbon bounds in hydrocarbon fuels. The process is complicated and numerous product species can be formed. The major species in combustion of natural gas include methane (CH₄), air (O₂ and N₂), CO₂, and H₂O, and minor species include CO, NO, soot particles. In principal, one can include as many species as one desires. But including every details of chemical reactions and accounting for each species in the reactions would require unduly large amount of computer resources and computational time. The approach adopted here accounts for the most important physics in combustion process while keeping the number of chemical equations as small as possible so that the modeling can be completed in the order of hours on a typical PC. Integral lumped combustion model is used to describe the species reaction and heat release rates. This approach effectively overcomes the severe numerical stiff problem frequently arising in reacting flow problems because of the markedly disparate reaction and flow time scales.

The flow, transport, or generation of species can be described by governing equations. These equations are mathematical expression of conservation physical laws (i.e., conservation of mass, momentum, and energy). These equations are commonly called continuity, momentum, energy, and species concentration equations. The flow properties that have to be solved include velocity components in x-, y-, and z-directions, pressure, enthalpy, temperature, density, and conservation of chemical species. We also have to include ideal gas equation of state in our equation set. For simplicity, we will list governing equations in two dimensions.

State equation of perfect gas:

$$p = \rho RT \sum_i \left( \frac{f_i}{w_i} \right)$$

(1)

Gas continuity equation:

$$\frac{\partial}{\partial t}(\rho u) + \frac{\partial}{\partial x}(\rho v) = \frac{dm}{dt}$$

(2)

Gas x-momentum equation:

$$\frac{\partial}{\partial x}(\rho uu - \mu_e \frac{\partial u}{\partial x}) + \frac{\partial}{\partial y}(\rho vv - \mu_e \frac{\partial v}{\partial y}) = \rho g_x - \theta \frac{\partial p}{\partial x} + \frac{\partial}{\partial x}(\mu_e \frac{\partial u}{\partial x}) + \frac{\partial}{\partial y}(\mu_e \frac{\partial v}{\partial x})$$

(3)

in which,

$$\mu_e = \mu_t + \mu$$

(3a)

$$\mu_t = C_{\mu} \rho \kappa^2 / \varepsilon$$

(3b)

Gas y-momentum equation:

$$\frac{\partial}{\partial x}(\rho uv - \mu_e \frac{\partial v}{\partial x}) + \frac{\partial}{\partial y}(\rho vv - \mu_e \frac{\partial v}{\partial y}) = \rho g_y - \theta \frac{\partial p}{\partial y} + \frac{\partial}{\partial x}(\mu_e \frac{\partial u}{\partial y}) + \frac{\partial}{\partial y}(\mu_e \frac{\partial v}{\partial y})$$

(4)

Gas enthalpy equation:
Improving Energy Efficiency in Aluminum Melting DE-FC07-01ID14023

\[
\frac{\partial}{\partial x} \left( \theta \rho \mu - \frac{\mu_x}{\sigma_h} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( \theta \rho \mu - \frac{\mu_y}{\sigma_h} \frac{\partial h}{\partial y} \right) = S_h
\]  
(5)

Turbulence transport equation of \( k \) (multi-phase):

\[
\frac{\partial}{\partial x} \left( \theta \rho \mu - \frac{\mu_x}{\sigma_k} \frac{\partial k}{\partial x} \right) + \frac{\partial}{\partial y} \left( \theta \rho \mu - \frac{\mu_y}{\sigma_k} \frac{\partial k}{\partial y} \right) = \theta \rho \mu_1 G_\mu - \theta \rho \varepsilon - S_{k,s}
\]  
(6)

in which,

\[
G_\mu = 2 \left[ \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 \right] + \left[ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right]^2
\]  
(6a)

and

\[
S_{k,s} = \int_0^\infty 4 \pi r^2 \left[ \frac{\partial}{\partial x} (g u_x k / \varphi^2) + \frac{\partial}{\partial y} (g v_y k / \varphi^2) \right] dr
\]  
(6b)

\[
\varphi(r) = 1 + 2r + 0.06r^2
\]  
(6b1)

Turbulence transport equation of \( \varepsilon \) (multi-phase):

\[
\frac{\partial}{\partial x} \left( \theta \rho \varepsilon - \frac{\mu_x}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x} \right) + \frac{\partial}{\partial y} \left( \theta \rho \varepsilon - \frac{\mu_y}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial y} \right) = C_1 \mu_1 \frac{\varepsilon}{k} G_\mu - C_2 \theta \rho \varepsilon^2/k
\]  
(7)

Empirical Turbulent Constants

<table>
<thead>
<tr>
<th>( C_\mu )</th>
<th>( C_1 )</th>
<th>( C_2 )</th>
<th>( \sigma_k )</th>
<th>( \sigma_\varepsilon )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.09</td>
<td>1.44</td>
<td>1.92</td>
<td>1.0</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Radiation is the important heat transfer mode for transferring heat from combustion space to melt. Heat is emitted, absorbed, and scattered in the form of waves at different wavelength. Assuming the scattering effect is negligible, the radiative heat transfer becomes the balance of emissive and absorption power. At each wavelength, the local net radiative power is obtained by integrating the absorbed energy coming from all other locations and subtracting locally emitted energy. A radiative transport equation is obtained by integrating net radiation power power all wavelengths.

\[
q_r(x, y, z) = \int_0^\infty \left[ \int \kappa_\lambda e_{b\lambda}(T') e^{-\kappa_\lambda dl'} dv' \right] - \kappa_\lambda e_{b\lambda}(T) d\lambda
\]  
(8)

where \( \lambda, \kappa, \) and \( l \) are wavelength, volumetric absorptivity, and optical length, respectively. \( e_{b\lambda}(T) \) is the blackbody spectral emissive power.

6.2.1 Combustion flow calculation

Combustion flow calculation is very sensitive to pressure and density fluctuations. To alleviate this numerical stiffness problem caused by the largely disparate chemical reaction and flow time scales, a two-step decoupled scheme is adopted. The scheme divides species into two groups and performs flow calculations into two steps. The species that have strong effect on gas density are grouped as major species and the rest are lumped as minor species (or subspecies). The two flow calculation steps are 1) calculation of gas velocities, enthalpy (or temperature), turbulent properties, and major species transport using reduced global reaction, and 2) subspecies transport calculation using more detailed kinetics and the calculated flow and temperature fields from step 1).
**6.2.2 Radiation calculation**

Heat is emitted, absorbed, and scattered by hot combustion species in waves of different wavelengths. Metal and furnace walls also absorb and emit energy. Neglecting radiation scattering, radiation heat transfer becomes the balance between emission and absorption powers. For each wavelength, local net radiation power is obtained by integrating the absorbed power from all other locations and subtracting the emitted power by the local computational cell. For hydrocarbon fuel combustions, the active radiation participating media are the combustion product species carbon dioxide (CO$_2$), steam (H$_2$O), and soot, which is an important radiation contributor. Steam has five strong absorption bands and carbon dioxide has six bands. Soot radiation is proportional to its local volume fraction and inversely proportional to wavelength. Soot is formed in the fuel rich regions due to fuel cracking and is burned by oxygen. The simulation of the furnace can be summarized in the flowing diagram in Fig 6.5

**Figure 6.5** Overall iteration diagram for furnace modeling

The modeling effort has included such combustion species as NO$_x$, soot, CO, CO$_2$, H$_2$O. Moreover, analysis of different furnace geometries, burner placements, combustion velocities, burner types (e.g. cold fired versus regenerative burners), combustion space volumes (i.e. what happens if we raise or lower the furnace roof?) and many more scenarios have been investigated. Some interesting results are plotted in Figure 6.6. Here we see the temperature distribution of the furnace overlaid with the velocity field. This particular member company furnace has a side door utilized for charging liquid, as seen by the small box area on the bottom of the X-Y plot. It is interesting to note the circulation pattern here, as well how quickly the energy is lost through the flue, which is located directly between the two hi-ram fire burners.
Figure 6.6 Furnace temperature and velocity profiles for one of the member companies reverberatory furnaces.

Figure 6.7 a) Soot distribution and b) NO\textsubscript{x} distribution in the reverberatory furnace.

Figure 6.7 plots the soot distribution and the NO\textsubscript{x} distribution in the furnace as well. It turns out that the soot is an important factor in transferring energy from the flame to the metal load. When the carbon molecules in the soot “crack” during combustion, radiation (heat) is emitted; this is then directly transferred to the bath as an energy source. Knowing the distribution
of this energy source may prove to be useful in tuning the furnace for efficiency. Also interesting is the calculated NO\textsubscript{x} levels. Although this furnace has NO\textsubscript{x} levels below air quality standards (i.e. it meets current air quality standards for NO\textsubscript{x} emissions), the ability to predict NO\textsubscript{x} levels in conjunction with burner replacement and furnace geometry changes will also prove useful.

In a more general setting, a “representative” furnace was designed in order to study “what-if” scenarios. Then, different aspects of furnace geometry were tweaked in order to determine the effects of these changes. Figure 6.8 plots the effect of changing the combustion air on the heat transfer to the metal bath. Figure 6.9 through 6.-11 plots the results of the same representative furnace when the turn-down ratio of the burners is altered.

**Figure 6.8** Comparison of effects of changing the combustion air temperature from (a) 80° C to (b) 200° C

**Figure 6.9** Temperature contours with turn down ratios of a) 75 and b) 60%.
Figure 6.10 Soot concentration contours with turn down ratios of a) 75 and b) 60%.

Figure 6.11 Emissive power contours with turn down ratios of a) 75 and b) 60%.

Regenerative furnaces are used to recover some energy from combustion. As shown in Figure 6.12, there are two openings in the furnace. During operation, one opening is used as a burner and the other is used as an exhaust. After a while, the exhaust is switched to the other burner while the first burner becomes the exhaust. In the simulation, a quasi-steady state is assumed. Two calculations are performed and then averaged for overall flow properties.

Figure 6.12 Temperature and velocity profiles a) Left Burner and b) Right Burner Operation.
In order to verify the results obtained so far, comparisons with the simulated bath temperature and the measured bath temperature for this system were carried out. Figure 6.13 plots these values. As can be seen, there is good agreement between the measured value and the calculated value and hence the model is deemed to be accurate within the ranges being studied.

The final aspect of the modeling effort has been to perform a series of studies to identify such parameter changes as turn-down ratios, burner angles, bath stirring and mixtures, to name a few, in an industrial furnace. This has been accomplished in the “representative” furnace.

Recall that the modeling of the combustion chamber is only half of the complete modeling problem. The second half is to investigate the heat transfer to the metal bath and to identify the heat loss through the furnace shell. The heat flux information obtained through this verified model are transferred to Oak Ridge and then included in a 3-D model of the system in question.
Figure 6.14 plots the surface radiation as seen by the bath. Similar plots are available for the heat flux from the walls, roof etc. A 3-D CAD model of the system has been implemented and all that is required is the heat flux data. Figure 16.15 shows the furnace as a 3-D CAD drawing.

**Figure 6.15** 3-D CAD drawing of the furnace modeled jointly by ANL and ORNL

**Figure 6.16** Heat loss simulations of an industrial furnace.

**Figure 6.17** – Infrared photos of furnace in Figures 6.15 & 6.16 indicating areas of high heat loss
For example, Figure 6.17 is an infrared photo of the furnace shown. This photo is taken of the left side burner as shown in Figure 6.16 and indicates the heat loss in this region due to the conductive losses through the shell at high fire. The maximum furnace shell temperature seen in this photo is nearly 400°F while the minimum temperature is less than 200°F. This information can be used to determine life cycles of refractories just as easily as it can be used to determine heat loss values based upon the overall heat loss characteristics of the furnace at a given time.

6.3 Modeling Results

6.3.1 Code validation

Before the modeling code can be used to conduct numerical studies, it has to be validated using measurement data. A pilot scale Aluminum melting furnace has been designed and constructed at Albany Research Center and an extensive experiment program has been designed to provide data that can be used to validate the code. Experimental data that can be used to validate code include flue gas temperature, velocity, gas species concentration, and furnace wall temperatures. For a given operation condition, a simulation run was conducted and its result was compared to measurement to determine the validity of simulation.

Figure 6.18 shows the predicted flue gas temperatures as a function of burner power inputs (presented as power per melt surface area (Btu/hr/in²)).

![Flue gas temperature graph](image)

**Figure 6.18** Comparison of model predicted and measured flue gas temperatures for a range of operation conditions

It can be seen that except for the two data points at the ends of the data series, the simulation results correlate well with experiment data. Note that the experiment flue gas temperatures were the thermocouple readings when all Aluminum ingots were melted, the CFD model prediction,
however, is a steady state one which should be interpreted as thermocouple readings when experiment was run for a long period of time. It is generally believed that if the experiment were run for a long period of time the measured temperature should increase slightly. Figure 6.19 shows the comparison of predicted and measured furnace efficiency as a function of burner power inputs. The predicted furnace efficiency was calculated as the ratio of the net radiation power into melt to the total burner power input. The measured furnace efficiency was calculated as the ratio of actual Btu value per pound Aluminum melted to the theoretical Btu value per pound Aluminum melted. As can be seen, the model predictions match the general trend as well as magnitude of furnace efficiency quite well as burner power increases.

Figure 6.19 Comparison-model predicted furnace efficiency & actual furnace effective efficiency

6.3.2 Combustion space temperature and flow field

Figure 6.20 a) shows the temperature field inside the furnace. Blue and read colors represent low and high ends of gas temperatures, respectively. Temperature variations are three dimensional inside furnace combustion space. The post-processor of the model represents a 3D field by displaying temperature variations in three mutually perpendicular planes (i.e., x-y plane, y-z plane, and z-x planes.) The horizontal plane (x-y plane) was chosen to cut through the furnace at the two burners elevation so that the two approximate flame shape can be seen clearly. As is expected, gas temperature is higher in the flame zone than in other regions. However, except the flame region, the gas temperature is quite uniform inside the furnace. In figure 6.20 b), the gas velocity vector was superimposed on temperature field. The arrow indicates the direction of the gas flow and the length of arrow gives graphically the magnitude of gas velocity. The vector plots clearly show that near the burner gas velocity is high, after it impinges on the opposite wall of the furnace, gas flows in all directions creating multiple toroidal cells and complicated glow patterns in the furnace. Vector plot also shows that burner has a downward injection angle. Near the melt surface (not shown) the two jet streams form a large clockwise cyclone type flow pattern before gas leaves the flue exit.
a) Gas temperature distributions

b) Gas temperature and velocity fields.
Figure 6.20 Model calculated gas temperature and flow field in the furnace combustion space
6.3.3 Oxygen and fuel field
Figure 6.21 shows oxygen and fuel mass fraction inside the furnace. It can be seen that fuel is concentrated in the flame zone, it decreases rapidly towards outside the flame region where it is consumed, and very little or virtually zero in other areas of the furnace since the furnace is operated on fuel lean side (equivalence ration is about 0.89). The oxygen distribution shows a high oxygen concentration near burner inlets, low in the flame region. An oxygen-depleted zone together with gas temperature field helps locate the approximate shape of the flame. Since the combustion is on the fuel lean side, there exists a small amount of oxygen in the furnace and the flue gas.

![Figure 6.21 Oxygen and fuel mass fraction inside the furnace](image)

a) Oxygen concentration.

b) Fuel concentration

**Figure 6.21 Oxygen and fuel mass fraction inside the furnace**
6.3.4 Nitric Oxide and soot

Figure 6.22 shows the nitric oxide (NO) and soot distribution. Nitric oxide is generated mainly near flame region where the gas temperature is high. Note that in the flame zone there is little oxygen and therefore the NO production is actually low. There highest NO production is just outside the flame zone where the gas temperature is high and there is some oxygen. In this furnace, however, the average gas temperature is not extremely high, so the NO concentration in the furnace and at flue exit is generally low. Figure 6.22 b) shows the soot concentration (volume fraction). Soot volume fraction is high in the flame zone due to the fact the soot is generated from fuel cracking. After its production, soot is transported to other areas of the furnace. On its way of being transported, soot is burned (oxidized) by the excess oxygen in the gas. This leads to a soot volume fraction distribution high near the flame zone and low other places.

![Nitric Oxide concentration](image1)

![Soot volume fraction](image2)

**Figure 6.22** Nitric oxide (NO) and soot distribution
Figure 6.23 shows the gas emissive power which has close correlation with soot distribution. As can be seen that the highest gas emissive power comes from flame region where the gas temperature is usually and soot volume fraction is high. Part of energy emitted by gas is absorbed by gas itself, others go to melt and furnace wall. Part of energy reaching furnace wall will be absorbed by wall and the remaining is reflected back into and lost through wall conduction. After receiving radiation energy from gas emission, furnace wall temperature increases and it emits energy too. For this particular furnace, over 70% of energy absorbed by melt coming from wall radiation/reflection.

The modeling demonstrated that a validated CFD code is an important tool in studying fluid flow, heat transfer, and combustion in furnace operations. It is especially useful when one wishes to see the trend of changes as one varies geometrical and/or operational parameters. The model predictions give detailed information inside furnace so that a furnace operator can gain deeper understandings of complicated interactions so as to optimize the operation or improve the furnace performance.

7. Validation of Design Recommendations on Industrial Furnace

7.1 Studies- Effects of Fuel Loading

A systematic analysis (approximately 40 cases) of an existing industrial furnace was performed to determine operating conditions that improve furnace efficiency with the following parameters being varied.

- Flue size and location
- Fuel loading
- Fuel partitioning
The flue height and width was varied to determine optimum dimensions and location of the flue with respect to the furnace. These parameters impact on the total residence time of the hot gases within the furnace thereby controlling the heat transfer to the walls and melt. Flue Height & Width

The graphs in figure 7.1 below show the effect on changing the vertical flue height with respect to the hearth keeping the width constant as well as the effect of changing the width and keeping the vertical height of the hearth constant on the BTU/hr transferred to the melt.

It can be clearly seen that there is an optimum vertical height and flue width at which you obtain maximum heat transfer.

It has to be kept in mind that these calculations will have to be done for each specific industrial furnace as it depends on furnace configuration and location and size of burners.

- Keeping the flue width at the maximum found from the previous calculations, the vertical location of the flue was changed
- Location of the bottom of the flue is kept at the original depth and the flue is gradually made wider
- An optimal flue width of 5.5 feet was found

**Figure 7.1** Effect of flue dimensions and location on heat transfer to melt

The second stage was to control the fuel input with the total fuel loading to the furnace being systematically reduced with the production rate held constant. The table 7.1 below shows the savings obtained under different scenarios with the savings indicating that the industrial practice to “over-fire” furnaces does not generally result in reduced energy consumption.

<table>
<thead>
<tr>
<th>Furnace</th>
<th>Start Input</th>
<th>Finish Input</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting Furnace</td>
<td>517</td>
<td>466</td>
<td>9%</td>
</tr>
<tr>
<td>Melting / Holding Furnace</td>
<td>608</td>
<td>456</td>
<td>13%</td>
</tr>
<tr>
<td>Holding Furnace</td>
<td>501</td>
<td>436</td>
<td>7%</td>
</tr>
</tbody>
</table>

**Table 7.1** Fuel Loading

The asymmetrical loading of the burners was simulated using the software and the results are shown in figure 7.2 below. The results show the same trend as the experimental results thereby
validating the software and indicating that the software can be utilized to predict successfully “what if” scenarios. The simulations indicate a 7.6% savings with asymmetrical fuel loading between burners with industrial practice exhibiting a 5.5 – 6.8% fuel savings.

Figure 7.2 Asymmetrical fuel loading between burners

An industrial partner carried out a series of tests based on software studies on a specific furnace configuration to confirm and maintain the savings indicated in the software. The table 7.2 hows the comparison of the various changes to the base settings

Table 7.2 Comparison of the various process changes based on modeling results to base settings
It can be seen that a reduction in total fuel rate as well as dropping the control setting for roof temperature results in a significant decrease in energy consumption.

The main savings are detailed below.

- Gas efficiency improvement - ~25%
- Est. annual gas savings > $450,000
- Reduction in greenhouse gases

The industrial partner is in the process of implementation of these findings on all of their furnaces.

8. Miscellaneous Tasks

8.1 Industrial Assessment Center (IAC) of Dept. of Energy on-site, industrial energy audits

Several other tasks not specifically outlined in the proposal were identified and undertaken. First, the Industrial Assessment Center (IAC) of the Dept. of Energy was contacted to perform on-site, industrial energy audits. The purpose of these audits is to gauge the overall performance of a specific plant by identifying potential areas of waste and including recommendations on how to make the process more efficient or how to utilize the waste heat.

In August of 2001, IAC staff from the Univ. of Michigan visited three of the plants. The audits performed included a complete plant tour with special attention paid to motors, generators, compressed air, heating, ventilation, and all aspects of energy usage at the plant. The findings from these audits resulted in 21 recommendations for energy savings, an average of 7 recommendations per facility. The primary recommendation for all three of the facilities was to investigate means of utilizing the waste heat in the flue gas. This independent evaluation of the melting capabilities at the three member companies has helped to direct part of the research, some of which is already reported. The remainder of the audits was called off because it was determined that this service was not providing any useful information.

8.2 Evaluation of Energy Optimization Technologies

A complete literature search regarding burner technology has been completed. There is apparently a wide variety of burners utilized for a wide variety of applications. Currently there are no less than a dozen research programs in process or recently completed that has been studying such aspects ad flame shaping for low Nox production and high radiation transfer, flame emissivity, oxy-fuel configurations and air-oxo-fuel configurations. Currently and evaluation of these separate technologies is under way to try and identify the best and most useful technology for the aluminum secondary remelting technology.

Other technologies investigated for the beneficial use of the waste heat include combustion turbines for aiding in heating the furnace, co-generation, operational adjustments to meet current needs and absorption chillers (using the waste heat in a heat transfer mode for air conditioning mode). Co-generation utilizes the waste heat in order to generate electricity. This can be done in a number of ways, but a typical configuration is utilizing steam generators to turn turbines. Figure 8.1 shows a possible layout for a reverberatory or holding furnace where the exhaust from a combustion turbine serves as the primary heat source.
In this case, the combustion turbine can be sized for the specific heat output of a single holding furnace (which would use a relatively small combustion turbine) or it could be ducted to more than one furnace (which would allow it to be larger). The combustion turbine would be a simple-cycle turbine running a generator to produce electricity. A duct burner would be in-line with the combustion turbine to increase and control the temperature into the holding furnace. The output exhaust from a typical combustion turbine would be at a lower temperature than is needed for the holding furnace. If the turbine is used to heat more than one holding furnace it would probably be best to have the duct burner directly in front of the hot exhaust entrance to the holding furnace to better control the temperature of the individual furnaces. The hot exhaust would be used to keep the aluminum in a molten state. Magnetically stirring the molten metal will help with heat transfer in the system.

The hot exhaust will still have a lot of energy when it exits the holding furnace and can then be sent to a heat recovery steam generator (HRSG) for the recovery of the remaining energy by boiling water and superheating steam for use in a steam turbine. The steam turbine will also produce electricity for use in the plant or for export to the grid for revenue production.

There will be two water streams necessary in this system. The first stream is the condenser cooling water which will have to be near ambient temperature and available in sufficient quantity to effectively cool the steam leaving the low-pressure stage of the turbine. This cooling water stream is a large quantity of water and could either be a recirculation system with a cooling tower or, if the system is situated near a body of water, it could be a once through system. There are only minimal treatment concerns for this water stream.
The second water stream is the condensate/steam stream. This is high purity water and there is relatively little make-up water needed for this stream. However, there is a need for some makeup and there will need to be water treatment facilities on-site to maintain water quality for the steam loop.

Analysis of the lost heat in the member companies furnaces indicates that a substantial savings in energy costs can be made utilizing this technique. By performing a heat recovery analysis on individual furnaces, this technology was seen to be able to recover between 9-16% of the lost heat, depending on flue gas temperature and volume. Table 8.1 outlines these findings for 6 of the furnaces investigated.

<table>
<thead>
<tr>
<th>Case Number</th>
<th>Furnace Capacity (x1000)</th>
<th>Burner Rating (MMBtu/hr)</th>
<th>Measured Efficiency</th>
<th>Flue Gas Temp (F)</th>
<th>Savings from Air or Charge Preheat</th>
<th>Savings from Co-generation (MMBtu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>210</td>
<td>20</td>
<td>26.76</td>
<td>1690</td>
<td>~25%</td>
<td>2.29 (11.5%)</td>
</tr>
<tr>
<td>2</td>
<td>240</td>
<td>42</td>
<td>11.16</td>
<td>1630</td>
<td>~25%</td>
<td>3.6 (8.6%)</td>
</tr>
<tr>
<td>3</td>
<td>180</td>
<td>34</td>
<td>20.76</td>
<td>1860</td>
<td>~25%</td>
<td>5.1 (15%)</td>
</tr>
<tr>
<td>4</td>
<td>205</td>
<td>90</td>
<td>35.89</td>
<td>1990</td>
<td>~25%</td>
<td>14.3 (15.9%)</td>
</tr>
<tr>
<td>5</td>
<td>90</td>
<td>10</td>
<td>11.64</td>
<td>1480</td>
<td>~25%</td>
<td>1.1 (11%)</td>
</tr>
<tr>
<td>6</td>
<td>160</td>
<td>16</td>
<td>43.82</td>
<td>320</td>
<td>~25%</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 8.1 – Calculated energy savings and efficiency increase via co-generation.

Another methodology utilized to investigate increasing the efficiency of the furnaces is through online operational adjustments; the idea being that past practices is not necessarily optimal for current practices. In one plant, it was noticed that their operational practices were maintaining a wasteful operating mode. This plant consequently began a study of online adjustments in order to streamline their process.

Through this process, and over a several month period, the gas usage was decreased with little or no effect on the operating characteristics of the furnace. Figure 8.2 plots the gas usage as a function of pounds of aluminum produced. As the operational characteristics were changed via decreasing the furnace temperature set point, the pounds per unit energy input dropped proportionately.
Figure 8.2 – Gas usage as a function of aluminum produced while decreasing the furnace temperature set point.

Figure 8.3 plots the energy savings achieved through this study where it is seen that an across the board 25% increase in efficiency was achieved by operational adjustments alone. This is an encouraging note since, even though not all situations warrant such measures, it does give more information in building expertise towards the overall efficiency ratings of a given furnace.
9. Accomplishments

9.1 Technical Accomplishments

All the objectives for this project were accomplished. Twelve papers have been published and a number of presentations including three at the TMS sessions have been made in national conferences, industrial companies, and universities.

The major technical accomplishments include the followings:

**Designed and developed scaled down industrial furnaces for practical experimentation.**

The furnaces available at the Albany Research Center include the (200 lb experimental crucible furnace and the 2000 lb reverberatory furnace. The latter is modular in design permitting an industrial participant to run “what if” scenarios of design modifications or process improvements and review the results prior to making any capital investments.

**Furnace Model developed at Argonne National Laboratory**

A combustion space model is available to study changes in geometry and heat transfer. The model based on the work done on glass melting simulations has been verified based on experimental data from industrial partners as well as experiments at Albany Research Center. This is resident at Secat, Inc and is available for industry participants.

**ProCAST model to study transfer of combustion model data to liquid metal**

This model software was utilized at Oak Ridge National Laboratory during the course of the project and the concepts and findings have been validated using experimental data from industrial partners as well as experiments at Albany Research Center.

**Process and Design Changes**

The experimental data and modeling results have clearly shown how the aluminum industry can achieve improvements in furnace efficiency by low cost investments including burner operation, burner location and angle, flue gas opening design and controlling melt and roof temperatures.

**Identification of New Technology**

A detailed survey was done of new and available technology and an assessment was done of their potential to reduce energy consumption including air pre-heat and charge pre-heat using flue gases by various methods. Besides reduction in energy consumption this will also result in less waste gases as the heat from waste gases are utilized for preheating.
9.2 Technology Transfer

This project was funded in response to call for proposals under the Aluminum Industry of the Future, Industrial Technologies Program (ITP) of the U.S. Department of Energy (DOE). The objectives of this program are to improve the efficiency of melting in the aluminum industry by: 1) reducing the current energy requirements for melting aluminum by 25%; 2) reducing the generation of GHG, and NOx emissions from the melting of aluminum; and 3) evaluating alternate metal melting technologies used in other industries that may have application to further efficiency improvements and emission reductions for the aluminum industry.

Intellectual property has been generated from this significant research effort. The intellectual property includes: (1) the AFM view modeling software that is currently available at Secat which is used to run “what if” scenarios for aluminum companies in order to enable them to understand the operations of their furnace prior to making changes. (2) ProCast solidification model is available at Secat with the capability to carry metal related studies including the effect of stirring, configuration of side wells and transfer of heat from the combustion zone. (3) The furnaces fabricated during the course of the project are available at the Albany Research Center for use by the industry.

The 2000lb reverberatory furnace is modular to enable modification of furnace volume, burners, refractory lining, etc permitting a wide variety of trials to be carried out.

To facilitate the technology transfer of the project results, Secat research staff members were actively participating in the effort throughout the project period. A multiprocessor computer has been purchased for using the models. As a result, Secat, a consortium of aluminum users and producers, has the required capabilities and expertise for transferring the developed technologies to the entire aluminum industry.
9.3 Publications

The following publications resulted from this project:

Publications:


9.4 Presentations

- TMS 2003 Annual Meeting (3 papers)
- TMS 2005 Annual Meeting (4 papers)
- TMS 2006 Annual Meeting (2 papers)
- 9th Australasian Cast House Conference

The details of the papers published are given under publications

9.5 Students/Degrees

- 3 students (2 – Univ. Kentucky, 1 – Oregon State University)
- 1 Masters Degree (UK)
10. Summary and Conclusions

A successful six year project on Improving Energy Efficiency in Aluminum Melting has been completed. The project was carried out in close collaboration among private industries, national laboratories, and universities. During the four year project, quarterly meetings were held that brought the industrial partners and the research team together for discussing research results and research direction. The Industrial partners provided guidance, facilities, and experience to the research team. The research team went to ten industrial plants to carry out energy audits to understand the current status of energy consumption at the various industry partner sites.

The collaborative research resulted in a few major achievements including the followings:

All the objectives for this project were accomplished.
Twelve papers have been published and a number of presentations including three at the TMS sessions have been made in national conferences, industrial companies, and universities.

The major technical accomplishments include the followings:

1. Designed and developed scaled down industrial furnaces for practical experimentation. Furnaces of 200 lb (crucible furnace) and 2000 lb (reverberatory furnace) are available at the Albany Research Center for industry partners to utilize. The latter is modular in design permitting an industrial participant to run “what if” scenarios of design modifications or process improvements and review the results prior to making any capital investments.

2. Furnace Model developed at Argonne National Laboratory. A combustion space model has been developed and is available to study changes in geometry and heat transfer. This model is resident at Secat, Inc and is available for industry participants.

3. ProCAST model to study transfer of combustion model data to liquid metal. This model was utilized at Oak Ridge National Laboratory during the project and has been validated. This model is resident at Secat, Inc and is available for industry participants.

4. Process and Design Changes. The experimental data and modeling results have shown the aluminum industry how they can achieve improvements in furnace efficiency by low cost investments including burner operation, burner location and angle, flue gas opening design and controlling melt and roof temperatures.

5. Identification of New Technology. A review was done of new technology and their potential to reduce energy consumption including air pre-heat and charge pre-heat using flue gases by various methods. Besides reduction in energy consumption this will also result in less waste gases as the heat from waste gases are utilized for preheating.

The goal of this Aluminum Industry of the Future (IOF) project was to assist the aluminum industry in reducing the incidence of stress cracks in DC castings from a current level of 5% down to 2%. This would lead to energy savings in excess of 6 trillion Btu by the year 2020 for a full scale industrial implementation of the results. The project indicates that ingot cracking can be minimized by reducing the casting speed, or by controlling the composition of the alloy. These results can be incorporated into industrial applications for achieving significant energy savings.
11. Recommendations

This research project has successfully demonstrated that the use of the experimental furnace and the modeling tools can help industry participants to understand the behavior of their furnace, select appropriate design changes and optimize their operations resulting in a successful reduction in BTU/lb. The project serves as a starting point for even more sophisticated models for the prediction of crack formation.

One of the issues identified in this project is that the use of stirring devices has a strong effect in equalizing the temperature across the depth of the furnace resulting in rapid heat transfer and hence improving energy efficiencies. Further the use of localized immersion heaters in combination with burners or independent of burners have great potential to improve energy efficiencies. One recommendation of the project team is that the above models can be further developed for understanding the impact of stirring and immersion heaters based on their location within the furnace as well as the capacity selected.
References