"Improving Energy Efficiency in Aluminum Melting "
Annual Report – 2001
(DE-FC07-01ID14023)

Prepared by

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ANNUAL REPORT

Project Title: Improving Energy Efficiency in Aluminum Melting

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Lexington, KY 40511

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Subcontractors: University of Kentucky
Argonne National Laboratory
Oak Ridge National Laboratory
Albany Research Center

Other Partners: ALCAN Aluminum Corporation
Arco Aluminum
Commonwealth Aluminum
Hydro Aluminum Louisville
Imco Recycling
Logan Aluminum
NSA Division of Southwire
Mccook Metals
Ohio Valley Aluminum Company Inc

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Rich Henderson, Metaullics, Inc.

Background:

The kickoff meeting was held in mid-January, 2001 with the official project start date the 1st of February 2001. At the kickoff meeting, the coordination of the project, infrastructure and technical oversight were detailed. Figure 1 depicts the program structure. Secat, Inc. heads the project with director Dr. Subodh Das. The industrial members on the "*Improving Energy Efficiency in Aluminum Melting*" include Alcan Aluminum, ARCO Aluminum, Century Aluminum, Commonwealth Aluminum, Hydro Aluminum, IMCO Recycling, Logan Aluminum, McCook Metals and Ohio Valley Aluminum where a technical member of each of these companies make up the project steering committee.

A research team was formulated comprised of staff from the national labs, university scientists and participating manufacturing companies. This research team reports directly to the member companies through Secat, Inc. where the industrial partners comprise a steering committee. A thorough analysis of the types of secondary melting technologies utilized by the member companies has yielded a research plan that is progressive, cross-cutting and has a high potential to reach the stated goals of the program. To this end, the research has been divided into 4 separate but intimately coupled parts with the goal of overall increased efficiency in secondary aluminum melting. These four sub-parts are a) computational modeling of the combustion space for each of the furnace types, b) measurement and analysis of current steady state melting practices utilized by the member companies, c) synthesis of the measurements and the combustion space modeling into a detailed furnace model and d) experimentation. Substantial effort has gone into each of these categories with the results presented in this report.

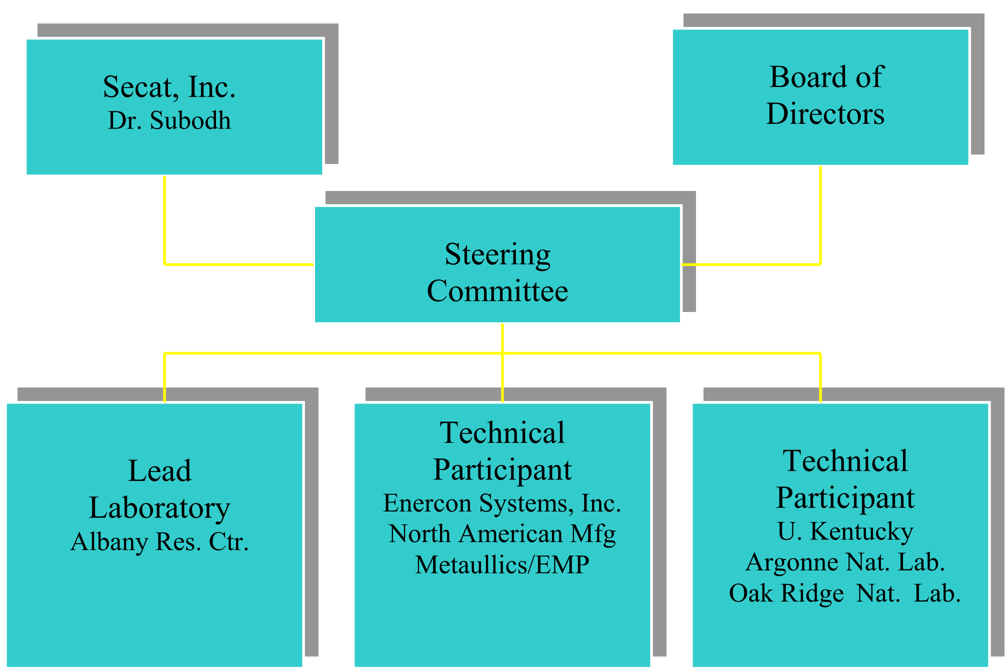

Figure 1 – Improving Energy Efficiency in Aluminum Melting program structure

Project Objectives:

The research objectives of "*Improving Energy Efficiency in Aluminum Melting*" address the specific need for improvements in melting efficiency in the aluminum industry. The proposed project is a multi-company, multi-laboratory project to improve the efficiency of energy use in the aluminum industry. The research team of the three laboratories, the Albany Research Center (ARC), the Oak Ridge National Lab. (ORNL), the Argonne National Lab. (ANL), along with Secat, Inc., the University of Kentucky (UK) and the nine participating aluminum companies is exceptionally strong with a total of several hundred years of experience in aluminum melting technologies. With the addition of three industrial manufacturers as research members, Enercon Systems, North American Manufacturing and Metaullics, Inc., the research team is well grounded in the furnace technologies. Successful introduction of the technologies developed by this research will improve energy use in aluminum melting by 25%. In addition, the incorporation of these technologies will significantly reduce emissions of GHG and $NO_{x.}$ Estimates show that the transfer of technologies developed during this project to the aluminum industry has the potential to save approximately $57 million dollars/year in natural gas fuel costs (~13 trillion Btu/year energy savings) when fully implemented by the year 2015.

The project has been divided into four intimately coupled sub-categories and each of these parts delegated to one of the research partners based upon their expertise. Close contact between the team members is maintained in order to ensure that each of the sub-parts remains on track. These sub-parts are a) computational modeling of the combustion space for each of the furnace types which is being performed at Argonne National Lab (ANL), b) measurement and analysis of current steady state melting practices utilized by the member companies, by the University of Kentucky (UK) c) synthesis of the measurements and the combustion space modeling into a detailed furnace model at Oak Ridge National Lab (ORNL) and d) design, construction and experimentation on a research scale reveberatory furnace at the Albany Research Center (ALRC). In particular, each of these subtasks includes major efforts in their own right and as such possesses many parts that need addressing. These are:

a) Computational modeling of the combustion space, Argonne National Lab.

- Assess the current state of Argonne in-house combustion space model.
- Modify the existing code to include specifics for the aluminum reveberatory furnace.
- Include combustion sub-species such as NO_x and soot.
- Include heat flux and radiation from sidewalls and roof.
- Introduce reveberatory furnace geometry supplied by member companies and run the program.
- Modify as necessary.

b) Measurement and analysis of current steady state melting practices, University of Kentucky.

- Obtain the necessary equipment to perform on-site energy audits of the reveberatory furnace. This includes infrared cameras, stack gas analysis equipment (e.g. gas chromatographs) and temperature measuring devices (thermo-couple probes).

- Design a test plan detailing the on-site measurement, indicating the level of access required, access points, equipment necessary supplied by the member company, personnel requirements and any safety issues.
- Analyze the data and produce a report for each of the companies.

c) Synthesis of the measurements and the combustion space modeling, Oak Ridge National Lab.

- Obtain combustion space information from ANL including heat flux, radiation, hot surface temperatures, etc., and obtain shell temperature, flue gas compositions and temperatures etc from UK.
- Synthesize these values into a unified furnace model to look at all aspects of the furnace, from heat loss through the walls, energy imparted to the load, molten metal flows etc.

d) Experimentation, Albany Research Center

- Obtain industrial support for experimental furnace design.
- Produce preliminary design and final designs for constructing a research scale reveberatory furnace.
- Conduct experiments.
- Coordinate with the other research parts.

As part of the effort to include industrial partners in the research program, the ARC staff has contacted suppliers from the burner manufacturing community, molten metal pumping and stirring, energy conservation industries and the refractory industry. Partnerships have been formed with a burner manufacturer (North American Manufacturing), a molten metal pumping company (Metaullics) and an energy conservation company (Enercon Systems). The search for a refractory partner is still underway. Table 1 lists the research members and their commensurate sub-tasks, although it is kept in mind that since each of these tasks requires information from the others, there is a substantial amount of cross-fertilization and coordination between the different entities, with all coordination being done through the ARC.

Group A Combustion Space Modeling	**Group B** In-Situ Energy Balance	**Group C** Modeling Synthesis	**Group D** Experimentation
S.L. Chang (ANL)	T. Li (UK) M. Hassan (UK) K. Saito (UK) Q. Han (ORNL)	S. Viswanathan (ORNL) Q. Han (ORNL) S.-L. Chang (ANL)	P. King (ALRC) D. Hoecke (Enercon) J. Newby (NAMfg) D. Whipple (NAMfg) R. Henderson (Metaullics)

Table 1 - Research areas and responsible personnel for the "*Improving Energy Efficiency in Aluminum Melting*" program.

Task 1 includes an independent assessment of the current state of the melting technology and an indication of the current state of efficiency for the industry. This task is to be done via a series of onsite visits, which include interviews, surveys, and audits of the current melting practices. Task 4 includes numerical modeling of the furnaces to identify potential areas of improvement. Task 2, 3, 5 and 6 are not slated to begin until the second year of the program and hence won't be discussed in any detail here.

Status

This section will detail the technical progress of each of the tasks and the effort being utilized by each of the project personnel towards those ends. In general, all personnel were involved with the preliminary site visits while the UK staff performed the audits. Meanwhile, ANL and ORNL are performing the modeling. ARC, Enercon, Metaullics and North American Mfg are performing furnace design and construction. Technical meetings are held quarterly in Lexington, KY, which includes project updates and program direction. Direction and guidance are given by the steering committee at this time as well.

1. Assessment of Melting Procedures

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 reveberatory 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 reveberatory 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.

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 2, which plots the number of furnaces, by type. It was found that within the 9 member companies there exist 79 reveberatory 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 reveberatory 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 the melting technology point to the fact that no two furnaces are alike, within a furnace class or across the class lines. Certainly a round top melting operates in a very different fashion then a front charge or side well furnace, and so on.

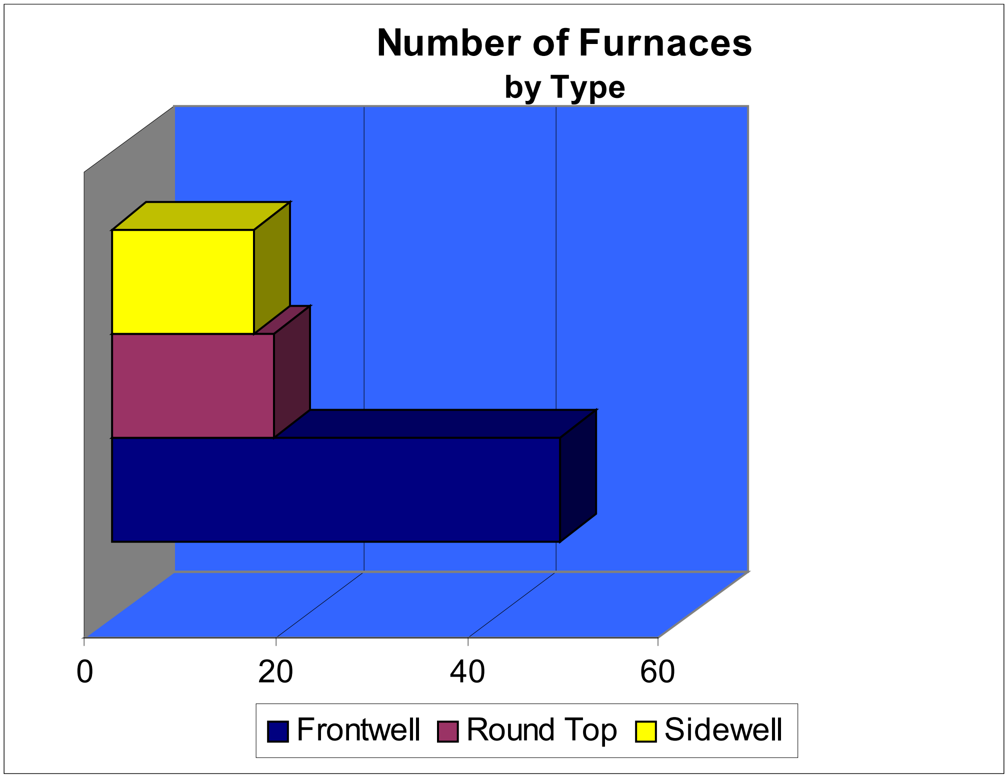

Figure 2 - Number of reveberatory furnaces by type represented within the research consortium.

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 gad 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. As of the end of the first year, 3 plants have had a complete audit of their melting practices. Table 3 indicates the results of these audits while Figure 3 indicates the methodology for determining heat loss and useful head values.

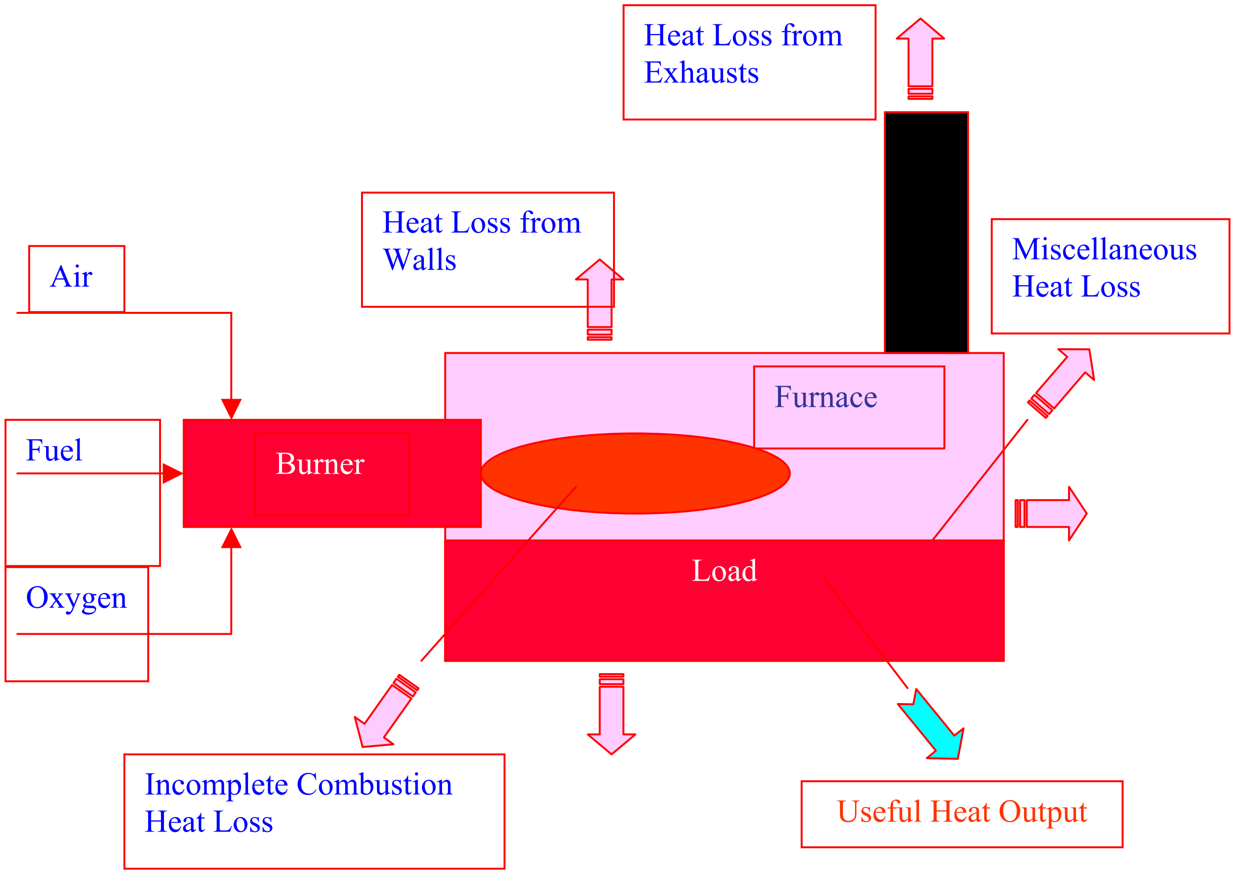

Figure 3 – Heat loss analysis in a model reveberatory furnace.

Case No.	Furnace Capacity (lbs)	Burner Rating (MMBtu/hr)	Melt Rate (lbs/hr)	Direct Method	Indirect Method
1	210,000	20	17,000	26.76	24.13
2	240,000	42	24,000	11.16	10.34
3	180,000	34	18,500	20.76	19.89

Table2 – Efficiency analysis indicating direct and indirect methods of 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.

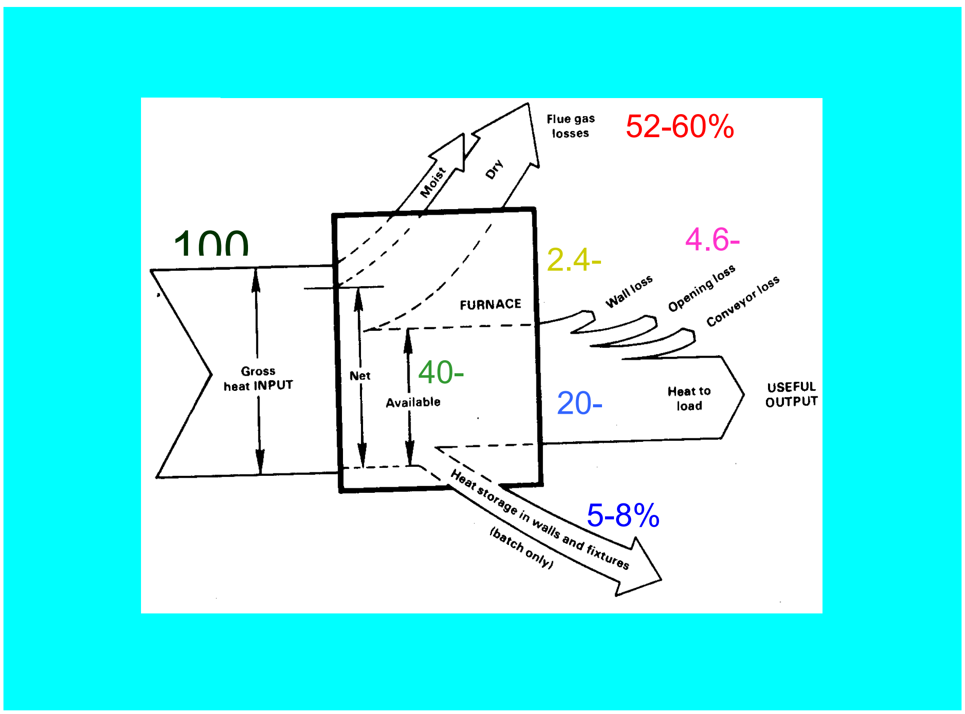

Figure 4 – Energy balance indicating the major sources of heat loss.

Figure 4 indicates the major sources of heat loss and the useful heat utilized by the load. Although the industry reports an overall 30% energy efficiency, this study appears to indicate that a more realistic value is around 24-25%. It is important to note that this study is not complete as of yet and these values are bound to change during the progress of the project. Also interesting, but not surprising, is the amount of heat lost to the flue gas. A full 50-60% of the heat loss is through the flue. This is valuable energy that should be able to be recovered and some of the programs studies will look into this aspect of the energy loss. For example, this heat can be used to preheat the combustion air. Preliminary studies have indicated that for every 100^{o} C the combustion air is increased in temperature, the efficiency of the overall system raises by an amount of 4-7%. This indicates a source of substantial savings.

2. Furnace Mass, Heat and Flow Modeling

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 an aluminum reveberatory furnace. Therefore, it was deemed a fairly straightforward job of revamping the glass furnace code to model the reveberatory 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 5 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 primarily directed towards modeling one of the member company's furnaces. This has been done for two reasons, first, a design for an experimental furnace has not been finalized and second, the company 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, NO_x generation and heat flux calculations.

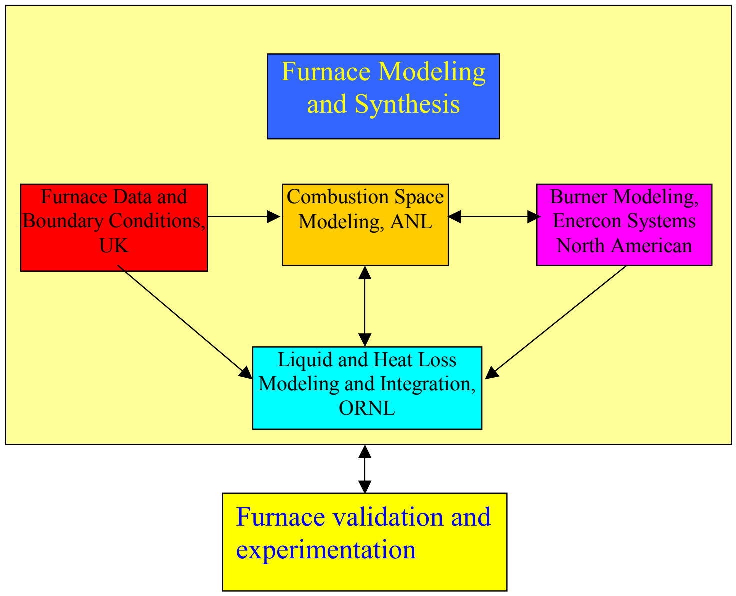

Figure 5 - Furnace modeling and synthesis.

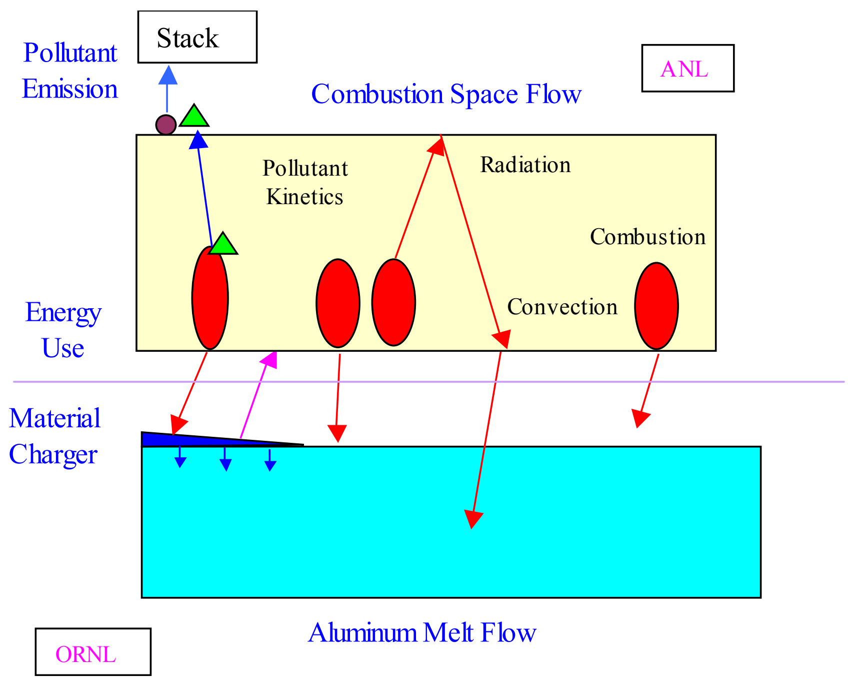

Figure 6 Modeling of a reveberatory furnace is broken down into two problem domains; the combustion space domain is modeled by ANL while the synthesis of this data is incorporated into a system model by ORNL

Figure 6 is a diagram indicating all of the sub-elements in the modeling program. Essentially what we see is that ANL is modeling the top half of the furnace, everything above the melt line, while ORNL is modeling everything below the melt line and including heat balance and heat loss calculations as well.

Some interesting results are plotted in Figure 7. Here we see the temperature distribution of the furnace overlaid with the velocity field. This particular 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 has how quickly the energy is lost through the flue, which is located directly between the two hi-ram fire burners.

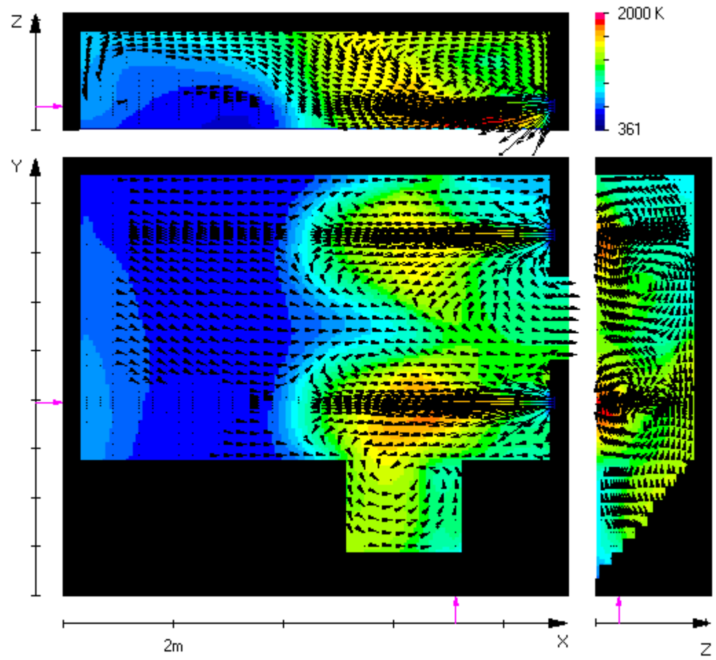

Figure 7 - Furnace temperature and velocity profiles for one of the member company's reveberatory furnaces.

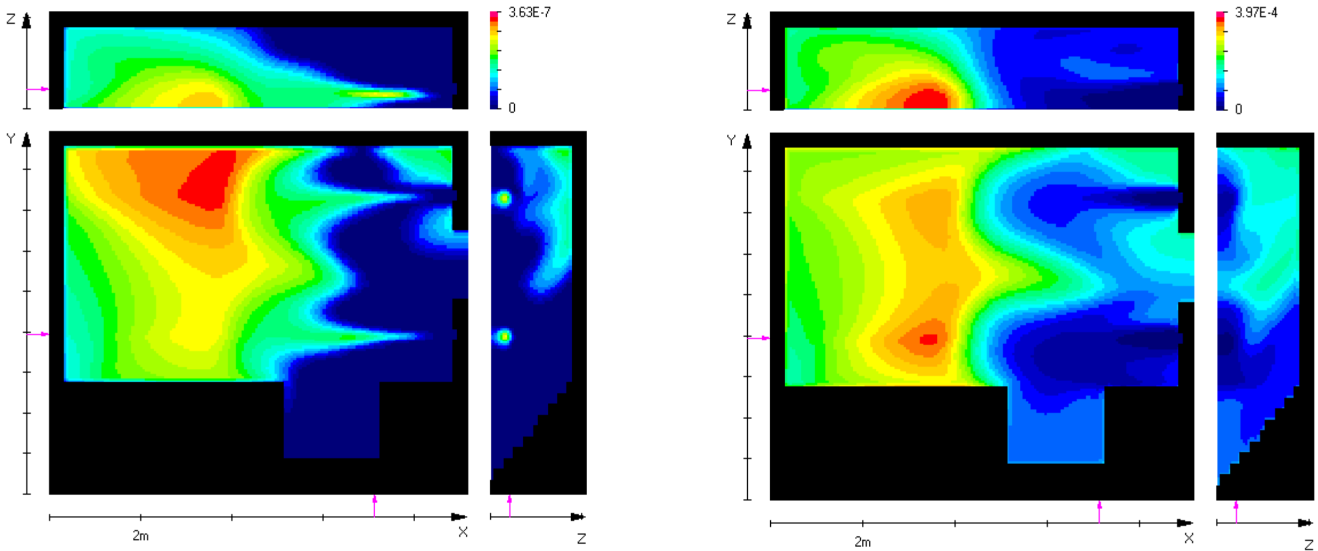

Figure 8 - a) Soot distribution and b) NO_x distribution in the reveberatory furnace.

Figure 8 plots the soot distribution and the NO_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 which 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_x levels. Although this furnace has NO_x levels below air quality standards (i.e. it meets current air quality standards for NO_x emissions), the ability to predict NO_x levels in conjunction with burner replacement and furnace geometry changes will also prove useful.

Because this is preliminary data, the heat flux information has not been sent to ORNL for their complete analysis of the system. A 3-D CAD model of the system has been implemented and all that is required is the heat flux data. Figure 9 shows the furnace as a 3-D CAD drawing.

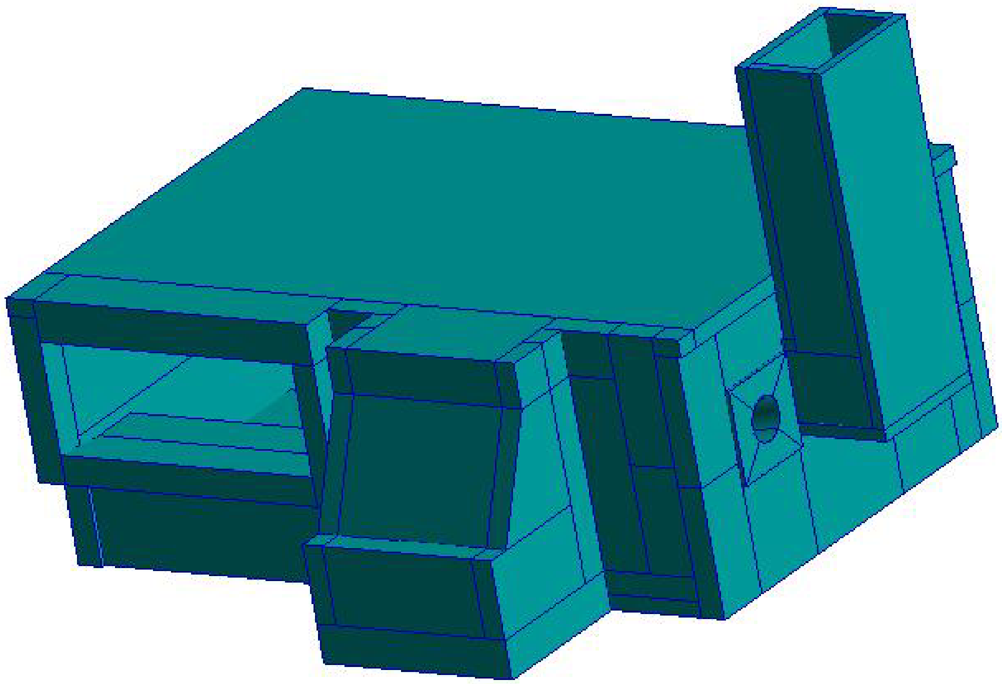

Figure 9 - 3-D CAD drawing of the furnace being modeled jointly by ANL and ORNL

3. Experimental Furnace Design

As partial fulfillment of the funded program, two separate furnaces are to be designed and built for 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. Because of this fact, the project team went straight to designing the EMU. 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 Metaullics.

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 raised or lowered in order to investigate the effects of the size of the combustion space versus combustion apparatus. For example, 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.

This design was submitted to the steering committee members for input and comment. The steering committee members were very helpful in pointing out several flaws in the current design as well as being instrumental in driving the design towards a better, more robust test-bed furnace. North American Mfg is putting a second-generation furnace design together with input from Metaullics and Enercon. The expected time of completion for these drawings is March 2002. Construction should begin shortly thereafter.

4. Miscellaneous Tasks

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 should be performed during the summer of 2002 when the professors and students from the participating IAC facility have time. It is expected that the remaining 4 facilities will produce similar results.

A complete literature search regarding burner technology has been completed. There are apparently a wide variety of burners utilized for a wide variety of applications. Currently there are no less then a dozen research programs in process or recently completed that has been studying such aspects ad flame shaping for low No_x production and high radiation transfer, flame emissivity, oxy-fuel configurations and air-oxy-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.

Plans for Next Year:

The first year of the program on *Improving Energy Efficiency in Aluminum Melting* has been completed. The project is on schedule and advances towards identifying methodology for improving the overall efficiency have been identified. In particular, utilization of the lost heat through the flue gases shows promise. These hot gases can be used in a number of ways, including preheat of combustion air; preheat charge material or co-generation to turn the lost heat into electrical energy. A number of avenues for utilizing this lost energy source are currently being investigated.

Because of the existence of a small, experimental reveberatory furnace located at the Albany Research Center, it was decided that a second furnace would not be designed and built. Instead, all efforts towards installing a new furnace have gone into the laboratory-melting unit. Based upon comments from the steering committee, a second go-around on the engineering of the laboratory-melting unit is underway with construction dates to be set as soon as the plans are finalized, most likely by the end of March 2002.

Energy audits have been performed at 3 of the 9 companies. These audits have yielded a direct and an indirect method of obtaining the efficiency of the furnaces. The direct method utilizes historical data to determine a long-term average of the furnaces. The indirect method utilizes a series of measurements to estimate such quantities as combustion efficiency, sidewall losses and losses due to events as door openings. It was discovered that the major means of energy loss is through the flue gas; nearly 50% of the available heat is loss through the flue gas. It was also discovered by this method that the reported efficiency's are higher, sometimes substantially higher, then actual operational efficiency. Thus, this audit series not only yielded a picture of each facilities melting efficiency, but it also laid a solid, unbiased and uniform method of comparing efficiencies in the furnaces.

Numerical modeling of the combustion space in member companies' furnaces has begun. The modeling will include an analysis of the combustion space, which is then coupled with the fluid flow and subsequent heat balance calculations. Once completed and verified, this will produce a robust platform for studying cause and effect in the furnace environment. Initial investigations have indicated hot and cold spots within the combustion space. However, emissive radiation from the furnace walls and the flame were not included in these preliminary runs. Current work is aimed at including these secondary heat effects.

Patents: No patents have been applied for or have resulted from the award.

Milestone chart:

Task			**Year 1**			
1	Assessment of Melting Procedures					
	A	Plant Visits				
	B	Status Report				
4	Furnace Mass, Heat and Flow Modeling					
	A	LMU Results and Evaluation				
	B	EMR Results and Evaluation				
	C	Industrial Furnace Design				

Milestone chart - 1st Year - "*Improving Energy Efficiency in Aluminum Melting*"

Budget Data:

Excel spreadsheet enclosed.