

Heat Transfer at the Mold - Metal Interface in Permanent Mold Casting of Aluminum Alloys Project

Quarterly Project Status Report

for the period January 1st, 1998 to March 31st 1998

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Summary:

There have been numerous developments in the current project over the last three months. The most appropriate geometries for performing the interfacial heat transfer studies have been discussed with both of our Industrial Partners. Both companies have molds which may be available for adaptation to record the thermal history during casting required for determining interfacial heat transfer coefficients. The details of what instrumentation would be the most appropriate remain to be worked out, but the instrumentation would likely include thermocoupling in the mold cavity as well as in the mold wall, as well as pressure sensors in the squeeze casting geometry molds and ultrasonic gap monitoring in the low pressure and gravity fed permanent mold geometry molds.

The first advisory committee meeting was held on February 6th, and the steering committee was apprised of the objectives of the program. The capabilities of the Industrial Partners were reviewed, as well as the need for the project to make use of resources from other CMC projects. The second full Advisory Committee Meeting will be held in early May.

1.0 Theoretical Work:

1.1 Sensitivity Analysis:

A brief analysis of the role of size on the temperature and fraction of solid distribution was performed for a geometry approximating that of a wheel casting. This arose from the interest Amcast had expressed in fabricating a new mold, and the need to establish how closely the geometry of the experimental mold has to match the geometry of molds in production. An initial geometry was defined for ProCAST to solve, and then a geometry half the size was defined and solved using the same boundary conditions. A conceptual mold geometry was examined and is represented as an axisymmetric element (along the left hand edge) in Figures 1 and 2. The purpose of this geometry was to provide the significant geometric elements present in wheel castings, without making the geometry excessively complex. The riser would be attached to the central web of the wheel. It is expected that due to thermal contraction following partial solidification, the heat transfer coefficients would vary dramatically depending on the location. Consequently, the outer surfaces would lose contact relatively quickly, while the inner surfaces would maintain good contact throughout the solidification of the component. The differences between the flat sections of the flange and the curved sections of both the flange and the curved web between the upper and lower flanges could be readily determined via this geometry.

The purpose of these calculations was to get a sense of how significant the changes resulting from the change in dimensions would be. For example, could a small mold provide much the same information as a large mold, given appropriate modifications to account for the different scale? As expected, the time scale for solidification was much shorter for the smaller mold geometry. The results of these calculations are shown in Figures 1 and 2.

The major limitation resulting from the difference in the size of the mold is the way in which solidification of the cast metal progressed. In the larger mold, the heavier section meant that there were fewer regions isolated from the liquid metal, while in the smaller mold the thinner section resulted in significantly more isolation of liquefied regions. It would be possible to adjust the parameters of the casting to enable comparable solidification of the cast metal, but the risk is that we would now be moving even further away from the geometry of interest. Given that transferring data from one geometry to another geometry is already expected to be non-trivial, it would be preferable to use a mold geometry which approximates the intended application as closely as possible. Consequently, while a smaller mold will certainly provide

2.56374E+02 Sec

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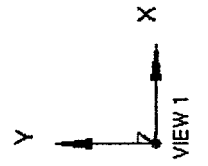
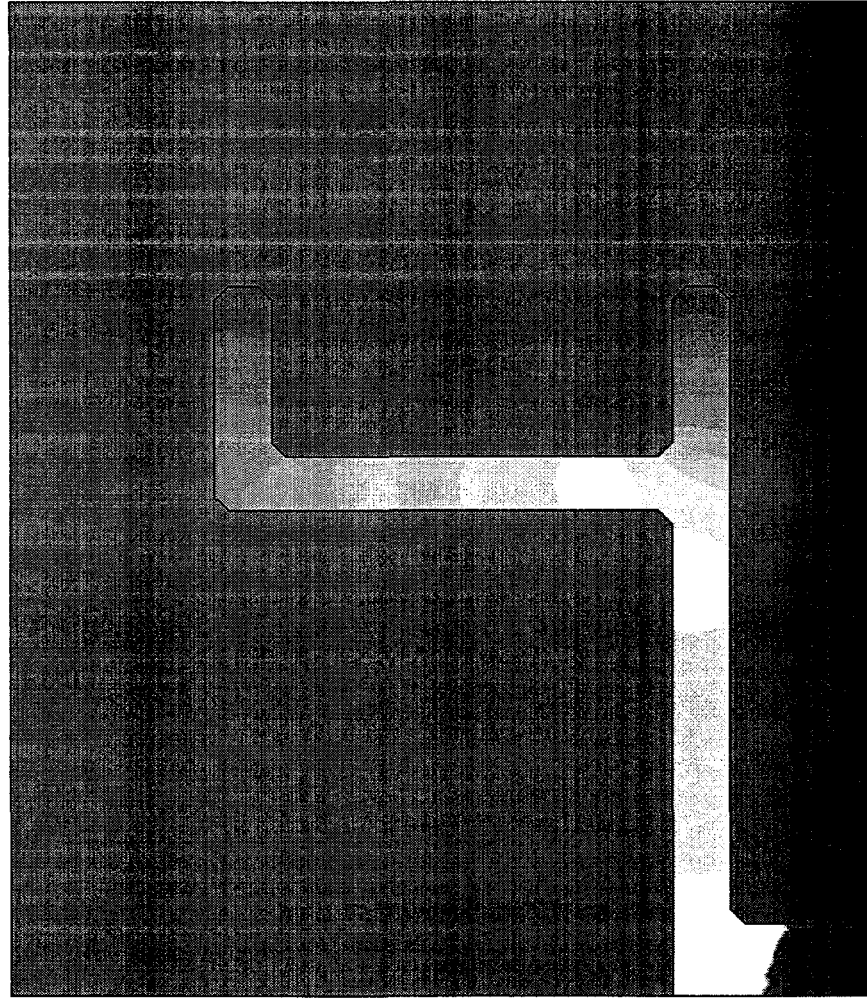
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Figure 1: Solidification time for full size mold

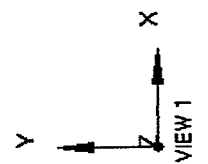
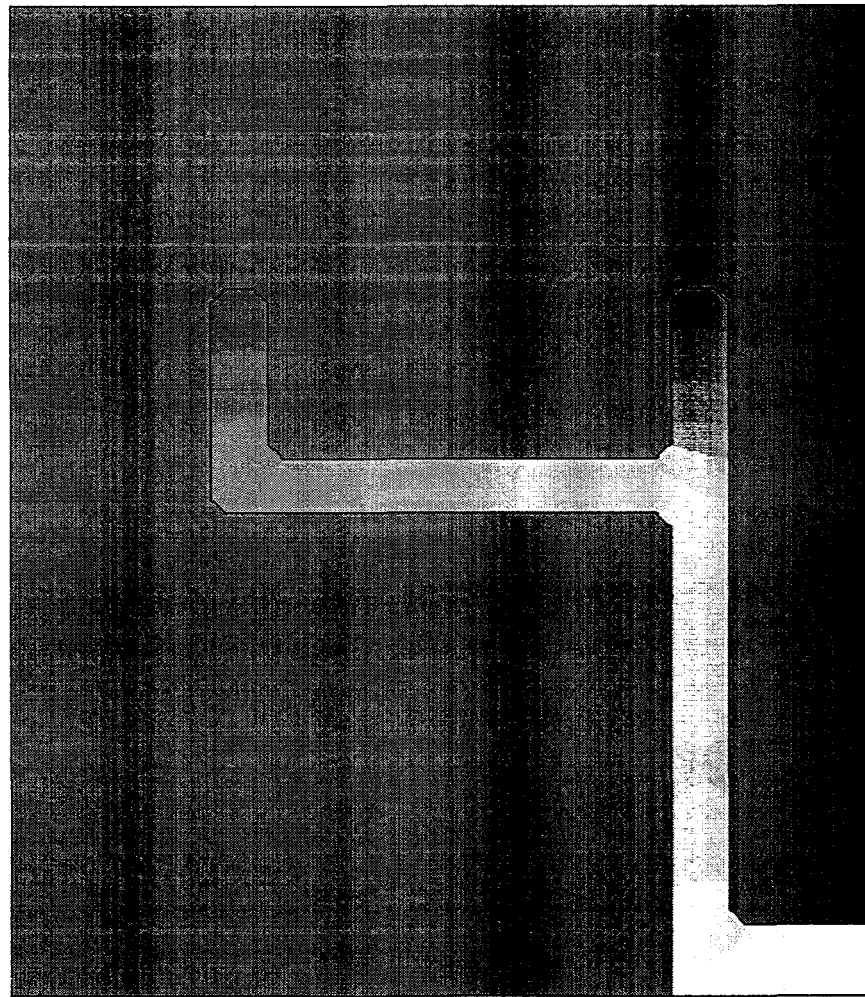


SOLIDIFICATION TIME

ProCAST



Figure 2: Solidification time for half size mold



SOLIDIFICATION TIME

8.85032E+01 Sec

8.26031E+01

7.67029E+01

7.08027E+01

6.49026E+01

5.90024E+01

5.31023E+01

4.72021E+01

4.13020E+01

3.54018E+01

2.95017E+01

2.36015E+01

1.77014E+01

1.18012E+01

5.90105E+00

9.00000E-04

ProCAST



useful information and would also allow geometrical effects to be measured, it may ultimately be more cost effective to use a larger mold which matches the intended application.

1.2 Development of Interfacial Heat Transfer Coefficient Database:

One of the most important aims of the current project is to collect the experimental information from all sources (including the Industrial Partners), and provide a means by which this information can be integrated into simulation models in an effective manner. This will be achieved by 1) performing a comprehensive literature search of all pertinent studies which have reported interfacial heat transfer coefficients, 2) evaluating these studies and digesting the information present and 3) developing a framework whereby these coefficients can be accessed and used in the most efficient manner.

1.2.1 Literature Search:

A comprehensive literature search was performed and is listed as an attachment to this report as Appendix A. The evaluation of this literature shows that almost all of these studies have been conducted in laboratory environments, with simple geometries in gravity fed molds. Most of them were shown to be time-dependent or temperature dependent, and for various reasons the data are scattered quite widely. As a result, transferring these results to a different process in a rather complex geometry is very difficult. Without accurate heat transfer coefficients, obtaining accurate results from simulations is not possible. In practical terms, the best a simulator can do is adjust the IHTCs to match the data empirically.

1.2.2 Framework developed for IHTC Evaluator:

The framework for providing a useful database is beginning to take shape conceptually, with the identification of the following tasks which will be required in an IHTC evaluator:

IHTC Evaluator

1. Definition and Purpose:

- 1.1 To provide guidelines for engineers in the casting industry who need accurate IHTCs quickly.
- 1.2 To accumulate expertise for using IHTCs on a company and industry-wide basis.
- 1.3 To provide a framework for future studies of IHTCs to follow.

2. Features:

- 2.1 PC based with Windows platform.
- 2.2 Codes in C/C++.
- 2.3 User amendable.
- 2.4 Internet accessible for industry wide access (in the final version).

3. Specifications:

- 3.1 Structure - top to bottom, with user input for different parts of the casting.
- 3.2 Processes - includes a selection of the supported casting methods, which can be user extended.

- 3.3 Materials - includes a database which covers the necessary materials, which can be user extended. This would include mold coating materials.
- 3.4 Process parameters - user input of pouring temperature, mold pre-heating, machine type, etc.
- 3.5 Surface conditions - database from which user can select the appropriate surface conditions to use, including dependence on coating.
- 3.6 Geometry Factors - dependence of the IHTC on the geometry of the mold - numerous subfactors (concave vs. convex, cooling channels, etc.)
- 3.7 HTC Evaluator - mathematical model, initially tested with the results from the literature, subsequently tested with the data derived from the geometries of the partner companies. A key difference will be the use of solidification ratio for a given section, as this parameter defines whether sufficient solidification has occurred for a gap to be present, and is therefore more physically meaningful than time or temperature dependent IHTC.

4. Results Output

Four formats for the results will be provided:

- 4.1 The maximum IHTC for a given surface.
- 4.2 The minimum IHTC for a given surface.
- 4.3 Average IHTC for the surface.
- 4.4 Solidification ratio of a section dependent IHTC.

2 Experimental Work:

2.1 Geometry of Molds available

2.1.1 Squeeze Casting Mold at CMI

A plan has recently been presented to CMI for the determination of pressure at various positions in the squeeze cast geometry. Once CMI have had some time to review this plan, it will be brought before the Steering Committee for their input. There are two molds which may be available at CMI, one of which could be used very soon. The first is a "hockey puck" design (formerly a gear blank) and the other is a "scroll" design (inner portion of a coolant pump). Given that the puck design would be available fairly soon, and represents a fairly straightforward geometry, it makes sense to use this design initially in this project. Both the puck and the scroll geometry can be cast at the Ferndale Tech Center using a 350 ton machine.

2.1.2 Low Pressure Permanent Mold at Amcast

A permanent mold may be constructed for this project, but as stated previously, the scaling of the results may introduce complications which would be undesirable at this point. Further, a mold with existing instrumentation may already be available which could be readily adapted.

The benefits of this experiment are considered to be: 1) optimization of mold filling, 2) optimization of cycle time, 3) increase in casting quality, 4) extension of mold life, and 5) optimization of designs. All of these improvements would be made possible if the interfacial heat transfer information available for simulations were more accurate. These benefits are considered to be worth the expense associated with the construction of new molds.

2.2 Instrumentation of Molds

The instrumentation of the various molds will be an important component of this project, and examining the various options has been a major focus in the work this quarter. The use of thermocouples, pressure sensors and ultrasonic probes have been considered, and possible configurations discussed with the Industrial Partners. These are described in more detail in the following paragraphs.

2.2.1 Thermocoupling of Molds

The use of thermocouples will be necessary in all mold geometries, to record the thermal histories of the solidification process. The optimal positions to locate the thermocouples need to be established for each mold geometry, as well as the number of thermocouples which would be required. Initial calculations tend to suggest that the use of more than one thermocouple in a thin walled region of the mold may be of limited value, as the calculated variation in temperature would probably be smaller than the error present in the ultimate thermocouple data. Further, as the algorithms used to determine the IHTCs are based on an ill posed problem, the solutions would probably become unstable even with minimal error in the thermocouple data, such that the use of multiple thermocouples is probably not worthwhile unless there is a significant distance between these thermocouples. There would need to be more thermocouples at different points in the low pressure and gravity fed molds, as the pressure would be insufficient to prevent gaps from forming in more parts of the mold than is the case for squeeze cast components.

Some work has been performed at CMI to record the thermal history of engine cradle castings, to confirm how the metal was being fed into the mold during a tilt pour. However, the focus of this study was to determine the time at which the metal contacted a certain point in the cavity (as indicated by the temperature rise) rather than the variation in interfacial heat transfer.

2.2.2 Pressure Sensors for Squeeze Casting

The high pressures used in squeeze casting ensure that the mold remains filled with liquid metal as well as forcing the solidified portion of the casting against the wall for a greater portion of the solidification time of the casting. As a result the tendency of the casting to form a gap between the mold and the metal can be more than offset during solidification. Unpublished data show that the pressure recorded at the mold wall at several different locations remained high for almost the entire solidification period in the geometry used, which consequently meant that no gap was present. For this reason, the use of pressure sensors is an important part of determining interfacial heat transfer coefficients. The particulars regarding what kind of probes should be used will need to be established prior to these being installed.

2.2.3 Ultrasonic Probe for Gap Formation Detection

The use of ultrasonic probes to determine the formation of a gap between the metal and the mold may be tremendously helpful. Such probes generate an ultrasonic signal which is reflected off regions of different density, especially interfaces, in a given material. The presence of aluminum metal in good contact with the mold wall significantly decreases the intensity of a reflected signal compared to the signal reflected from an empty cavity. Consequently the formation of a mold-metal gap, when the mold has contracted away from

the mold wall, intrinsically generates an interface with quite a different reflection constant, compared with the mold wall in good contact with the cast metal. This means that ultrasonic probes placed appropriately can be used to precisely determine the time at which a gap forms.

The advantage of being able to precisely define the time at which the gap forms is that the temperature history can be correlated to the formation of the gap for a given experiment. Thus, an experimentally determined reference point in time is now available and leads to greater confidence in the data. This provides a substantial benefit as we can now tell the simulation when the gap formed, rather than having to infer it from the inverse calculation based on the thermal history.

The change in intensity is not discrete, but increases from a "good contact" value to an "empty cavity" value over a distance of approx. $0.2\text{ }\mu\text{m}$ as shown in Figure 3. However, this is such a small distance that the resolution of the gap formation event is very good. As shown in Figure 4 the amplitude starts at a high value then suddenly decreases to a lower value once the empty cavity is filled with liquid. The amplitude remains low while there is "good contact" between the metal and the mold, and then begins to rise once the solidified metal pulls away from the wall, returning to the previous "empty cavity" value again, even though only a small gap exists. It is precisely this kind of information which is invaluable to a modeler. These displacements are too small to be determined via extensometers.

As was the case for the pressure sensors, the feasibility of using these probes for the experimental molds remains to be established. However, the prospect of being able to define the time at which a gap has formed is very appealing, and is being investigated further.

3.0 Advisory Committee Input:

Progress has been made in several areas in this start-up phase of the current project. At present, our efforts are directed toward performing the key groundwork required for setting up both the heat transfer calculations as well as the experiments, with a particular emphasis on developing the most useful geometry for calculating the heat transfer coefficients. Consequently, establishing an interaction with the partners as well as external groups was an important component of our progress this quarter. We intend to step up the level of external interaction in the next quarter, with the inclusion of more frequent Advisory Committee meetings. The minutes of the February 6 meeting are attached to this report as Appendix B.

4.0 Personnel Changes:

Dr. Shouwei Hao joined the University of Michigan staff to assume the title of Senior Research Fellow, with the primary focus of his research being this project. John Cookson has accepted a position outside the University. He will remain associated with the project outside regular working hours whenever possible.

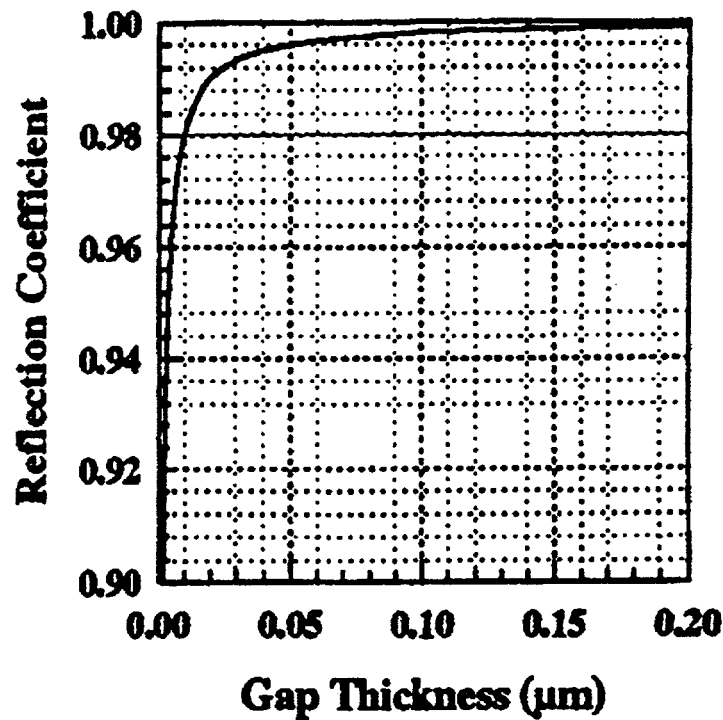


Figure 3: Calculated reflection coefficients for the steel-air-Al combination of materials as a function of gap thickness. From Cao et al, 1996, "Ultrasonic monitoring of injection molding and die casting.

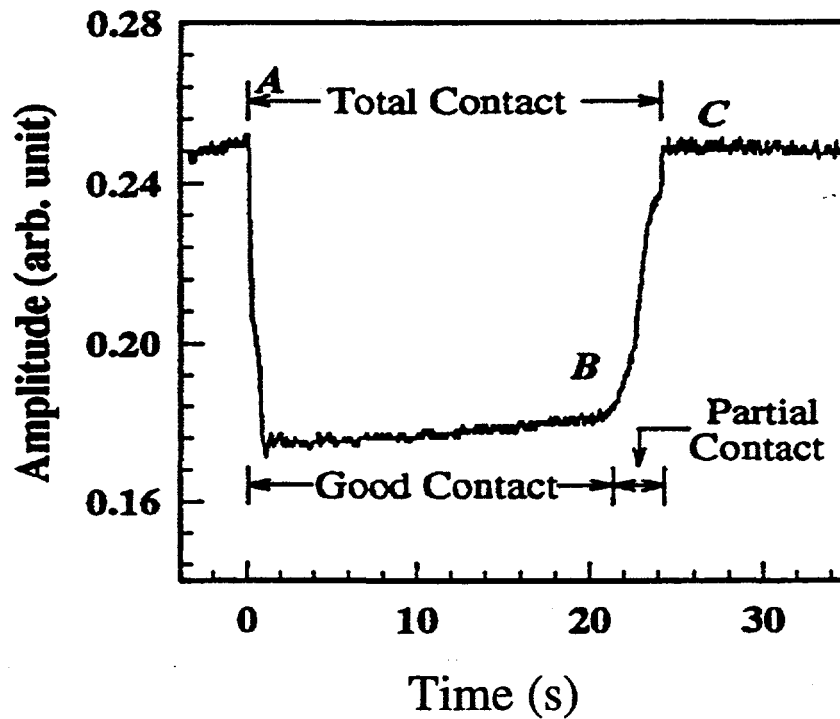


Figure 4: Variation in reflection coefficient vs. time as the initially empty cavity is filled with liquid, which then solidifies, with a brief period of partial contact. From Cao et al. 1996.

Appendix A:

Literature Search

An extensive search of the available literature concerning interfacial heat transfer coefficients (IHTCs) has turned up a sizable number of papers. These papers address either the experimental determination of IHTCs or methods to manipulate the experimental data using various computational methods. The literature found appears in the list below in chronological order. It has been difficult to identify data from both smaller conferences as well as internal documentation, such that the literature may not be complete. However, it seems reasonable to suggest that there are no glaring omissions from this list, as these papers tend to cross reference each other, with no relevant references to work which is not already on this list. The pertinent information will be extracted from these papers and ultimately presented in a descriptive format as well as the tabulated format shown in part below:

Table 1: Heat Transfer Data from the Published Literature

Author(s)	Mold/Metal combination	Geometry	Experimental Interfacial Heat Transfer Coefficient ($\text{W/m}^2/\text{K}$)	Simulation/ Computation Methods used
Ho & Pehlke	Copper chill/ Aluminum	Cylindrical, planar chill	initially... fell to	Finite diff.
Chiesa	Steel/Aluminum	Wheel mold	solidification front plots	Finite diff. (Magma)
Gunasegaram & Nguyen	composite: H13/Aluminum BeCu/Aluminum	Cylindrical with varying diameter	initially fell to	Finite diff. (Magma)

The article by Anderson et al. below represents a very comprehensive treatment, with an attempt made to correlate the geometry of the die with time dependent heat transfer coefficients, as well as the mold coating thickness.

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T.X. Hou & R.D. Pehlke "Determination of Mold - Metal Interfacial Heat Transfer & Simulation of Solidification of an Al 13% Si Casting", *AFS Transactions*, v. 96, (1988), pp. 129.

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Appendix B:

Minutes of the Steering Committee Meeting (by conference call) Friday, February 6th, 1998

Present: Steering Committee: Jiten Shah (K+P Agile), Anand Paul (Concurrent Tech.), Jake Zindel (Ford) & Doug Trinowski (Delta); Joe Santner (AFS), Prof. Robert Pehlke (UM), John Cookson (UM), Sarah Chen (AmCAST) & Karl Voss (CMI).

The call was made at 2:30 p.m. and came to order at that time.

Prof. Pehlke reviewed the program briefly, outlining the objectives and describing the progress made so far. This included the meetings with the industrial partners, the purchase of the HP J282 computer, the literature search performed to date as well as the initiation of sensitivity analyses. The recent publication of the article by Anderson et al. from The University of Swansea, which described the instrumentation of a permanent mold of a wheel was also reviewed.

At this point, the existence and availability of test molds which were extensively instrumented was raised. Karl Voss described a "hockey puck" squeeze cast mold geometry as well as a tensile bar mold geometry, both of which would be available. Joe Santner raised the possibility of using a "Mail Box" casting geometry, and Doug Trinowski confirmed that this had been used for sand casting tests.

Joe Santner encouraged the group to seriously consider using this "Mail Box" geometry as it has been used for sand casting applications. He believes that an appropriately scaled version for permanent mold casting may well be able to take advantage of the understanding which has been developed for this geometry in sand casting. He impressed upon the group that this was a good example of how communication and "cross fertilization" between the different areas of cast metal research could be beneficial, and further encouraged the group to use the pooled information as much as possible. John Cookson asked whether the geometry was representative of parts manufactured by permanent mold casting, and Doug Trinowski responded that there were thin wall sections in the geometry which may make it suitable. However, Karl Voss expressed concern at this point and stated that the design would need to be reviewed for its' suitability prior to a commitment to fabricate a test mold of this geometry.

The reporting requirements were reviewed following an inquiry about the frequency of reporting to both the AFS as well as the DOE. Joe Santner reiterated that monthly reports were to be generated for the AFS, which would in turn be distributed to the Steering Committee. Prof. Pehlke informed the group that the DOE requirement for reporting (DOE F 4600.2 09/92) stipulated quarterly milestone logs and project status reports. These would also be distributed to the Steering Committee.

The meeting was adjourned at 3:00 p.m., to allow a 1-F meeting to take place immediately afterward.