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ADVANCED LOST FOAM CASTING TECHNOLOGY

1997 SUMMARY REPORT

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AMERICAN FOUNDRYMEN'S SOCIETY,

and

AFS-DOE-EPC CONSORTIUM MEMBER COMPANIES

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1996-1997 SUMMARY REPORT

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ADVANCED LOST FOAM CASTING TECHNOLOGY EXECUTIVE SUMMARY AND CONCLUSIONS

Previous research conducted under DoE Contracts #DE-FC07-89ID12869 and DE-FC07-93ID12230 made significant advances in understanding the Lost Foam Casting (LFC) Process and clearly identified areas where additional research was needed to improve the process and make it more functional in an industrial environment. The current project focused on eight tasks listed as follows:

- Task 1: Pyrolysis Defects and Sand Distortion
- Task 2: Bronze Casting Technology
- Task 3: Steel Casting Technology
- Task 4: Sand Filling and Compaction
- Task 5: Coating Technology
- Task 6: Precision Pattern Production
- Task 7: Computational Modeling
- Task 8: Project Management and Technology Transfer

This report summarizes the work done under the current contract in all eight tasks in the period of October 1, 1995 through December 31, 1997.

Twenty-seven (27) companies jointly participate in the project. These companies represent a variety of disciplines, including pattern designers, pattern producers, coating manufacturers, plant design companies, compaction equipment manufacturers, casting producers, and casting buyers.

Task 1. - Pyrolysis Defects and Sand Distortion

A large experimental matrix was completed at UAB to study the effects of pattern geometry and coating permeability on metal front shape, metal front velocity, and casting defects. These experiments were performed for both a Class 35 gray iron and 319 alloy aluminum. Six coatings with air permeabilities ranging from $3.5 \text{ cm}^3/(\text{s} \cdot \text{cm}^2)$ to $91.0 \text{ cm}^3/(\text{s} \cdot \text{cm}^2)$ and four pattern geometries with cross-sectional area-to-perimeter ratios (A/P) from 0.26 to 0.76 cm were used in the experiments. It was found that metal front velocity increased with increasing A/P ratio and increasing coating permeability. For the aluminum castings, a maximum velocity of approximately 2.8 cm/s was found for all patterns using the highest coating permeability. A maximum

velocity for the iron casting was not measured due to the limiting coating and sand permeabilities. These maximum velocities are dictated by the rate of heat transfer between the metal and pattern. For this condition the pattern density appears to control the metal velocity. A mathematical expression has been developed to describe the physical events of pattern replacement by the molten metal under conditions of unlimited permeability.

Defects are related to both metal velocity and metal front shape. A parabolic metal front shape appears to minimize internal porosity defects by forcing the pattern pyrolysis products toward the coating in a controlled manner. Non-parabolic shapes tend to trap volumes of the pattern within the molten metal, resulting in porosity as the pattern degrades to gas with no escape route. Surface blisters and "worm tracks" are caused by a combination of high metal velocities and, in the case of aluminum, coatings with low insulating properties.

Task 2. - Bronze Casting Technology

The initial plan to investigate the variables of coating type and permeability, sand type and permeability, and pattern type and density on the casting of bronze were reduced to a minimum effort by choice of the industrial sponsors. This reduced level effort consisted of a minimum of casting trials to determine the feasibility of this casting technology. A water meter housing pattern with a density of 1.3 pcf was coated with a commercial silica-based iron coating. Several castings were poured at 2170°F using brass alloy CA44. These castings were free from visible defects and demonstrated the capability of pouring brass and bronze alloys using the Lost Foam Casting Process.

Task 3. - Steel Casting Technology

This task was also reduced in effort by the industrial sponsors and is limited to casting trials to determine the feasibility of reducing common steel defects through the use of vacuum. This task has been interrupted twice by the unavailability of a sufficiently large vacuum pump. A new pump has been purchased and this effort will continue under Contract DE-FC07-98ID13603.

Task 4. - Sand Filling and Compaction

Often the fill and compaction process results in distortions of the pattern as forces of moving and densifying sand tend to move the pattern, especially in areas where the pattern is not rigid. The casting will then replicate these distortions. Another mechanism that can generate casting distortions is sand expansion. Earlier in this program it was demonstrated that silica sand, through phase transformation at about 1000°F, can generate large forces which distort castings. Separation of these two mechanisms in casting distortion is difficult; however, some success has been achieved through instrumented patterns and castings. The effort described in this task applies only to compaction related pattern distortions.

A large series of experimental trials has been completed to quantify the effects of various process variables on pattern distortion during the fill and compaction process. Previous experimental work indicates that the following process variables may play an important role in the distortion of foam patterns during the sand fill and compaction stage of the lost foam process. These variables were investigated as part of the experimental matrix:

- 1) Pattern position within the flask
- 2) Acceleration levels within the flask
- 3) Angularity of sand
- 4) Fill rate of sand into the flask
- 5) Horizontal or vertical vibration

Previous experiments also seemed to indicate that sand trapped in a confined area in a pattern may cause significant distortion in that pattern. Trials were conducted to determine the distorting behavior of confined sand, both in vertically and horizontally vibrated compaction systems.

Results indicate that the acceleration level of the sand is largely responsible for distortions of the foam bars, while radial position in the flask also plays a large role in casting distortion. The highest distortions for the foam bars were recorded at locations near the flask walls and at high acceleration levels. Also, the more angular sand produced more pattern distortion than rounded angular sand.

Fill time of intricate pattern cavities during compaction is often the limiting factor of casting volume in production

foundries. Production foundries have expressed an interest in rounded synthetic sand since a reduction in cycle time may be possible. A set of experiments was begun to investigate the fill time of pattern cavities when vibrated with sub-angular silica sand, angular olivine sand, and rounded synthetic sand. Results of these experiments indicate up to a 50% reduction in filling time using the rounded synthetic sand at the same acceleration level.

Rounded synthetic sand provides faster filling of internal pattern cavities and lower pattern distortions. This allows faster production cycles with better dimension accuracy of castings. In addition, the low thermal expansion characteristics of the synthetic sand provide additional accuracy by reducing the effect of sand expansion during pouring and solidification. An added feature of significance is the more robust performance of the rounded synthetic sand.

Task 5. - Coating Technology

The Lost Foam Coating Quality Control Manual was revised to include the effects of compressibility. The need for this revision became apparent as sponsors implemented the procedures in their foundries and manufacturing facilities. In most cases, it was desirable to use one flowmeter to cover the range of permeabilities dictated by a variety of coatings. This was accomplished by throttling the flowmeter to decrease the range of air flows at the expense of raising the pressures. This increase in pressure dictated the need for correcting the procedures to account for compressibility.

A study of the data obtained in the coating quality control procedures revealed a significant amount of variability. The sources of variability were identified and the Procedures were revised a second time.

A foundry version of the coating quality control procedures was developed to yield coating air flow rates in a timely fashion for production. This development included a redesigned coating specimen holder utilizing a larger specimen and more robust sealing which accurately defined the air flow area. A third revision of the Coating Quality Control Manual was issued.

UAB has continually provided assistance to sponsors as the quality control procedures were implemented. Both foundries and coating manufacturers implemented the procedures. These procedures provided quality control measurements of air flow through coatings and liquid absorption into coatings. As foundries developed relationships between these coating properties and casting defect occurrence, tighter specifications were requested of the coating manufacturers. Coating manufacturers used these procedures to develop relationships between their coating manufacturing procedures and the coating ingredient properties. Within the last year a dramatic improvement in coating consistency has evolved, resulting in a more consistent casting process with less scrap attributed to the coating properties.

A test matrix was completed using the procedures outlined in the Coating Quality Control Manual to tightly control coating viscosity, air permeability, and liquid absorption rate. Adjustment of coating thickness (controls thermal insulation and air flow rates) was accomplished through dilution while adjustment of air and liquid permeabilities (controls air flow rates and liquid absorption rates) was accomplished through addition of small particle refractories. This tailoring of coating properties is the intended use of the coating quality control procedures.

These coatings were used on rectangular and round patterns representing a range of cross-sectional area-to-perimeter (A/P) ratios. Metal velocity and a metal front profiles were measured. Castings were examined for defects. The defect types were correlated with pattern A/P ratios, coating properties, metal velocities, and metal front shapes. This data was used to select coating properties for a complex pattern shape and pour a defect free casting.

Task 6. - Precision Pattern Production

Bead fusion has been identified by the industrial sponsors as a controlling factor in the metal/pattern exchange process. Foundry experience indicates that fewer casting defects occur when a pattern is poorly fused in the interior. By definition, bead fusion is understood to mean how well pattern beads are attached to neighboring beads. It is unclear, without a technique for measuring bead fusion, the difference between

pattern density and pattern bead fusion. In order to quantify bead fusion and to understand the density/fusion relationship, several techniques were evaluated as candidates for measuring bead fusion. Pattern density evaluation techniques were developed earlier in this program.

Three techniques were evaluated: 1) air flow rate through the pattern; 2) liquid flow rate through the pattern, and 3) liquid absorption. These techniques are discussed in detail later in this report; however, the results from all three techniques were inconsistent. Extreme care in performing these tests made them impractical for normal use.

Alternate pattern materials were procured to evaluate as pattern materials. Polystyrene is currently the material used most frequently; however, lower molecular weight polystyrene should offer an advantage in the amount of energy required to degrade the polymer. Alternate materials such as copolymers, terpolymers, and polyacrylic carbonate (PAC) offer similar advantages along with some added features. Current data on polystyrene of varying molecular weights and copolymers revealed little, if any, differences in energies of degradation. Samples of polyacrylic carbonate (PAC) have not been available due to processing difficulties which preclude their use.

Task 7. - Computational Modeling

Currently a computational model quantifying the events of metal/pattern exchange in lost foam casting does not exist, either in research or commercial form. This task is to build a model that includes the controlling factors of coating and sand gas permeabilities, coating liquid absorption, and heat and mass transfer of energy. The initial plan included the procurement of a commercial fill and solidification code (ProCast). Most of the first year's effort on this task was devoted to making the ProCast software and the Alpha Dec hardware operational. The system is now operable and several open mold casting examples have been simulated. The commercial Lost Foam version of this code is not accurate since it assumes all pattern material deteriorates to gas. A joint venture between UAB and Procast personnel has yielded an area of research that must be addressed before an accurate code can be produced. This area of research concerns a quantitative method for estimating the ratio of gas/liquid products generated at metal pouring temperatures. A

two-fold approach was taken. First, the gas/liquid ratios can be estimated using the Arrhenius relation for polymer degradation. This technique has been used to predict ablation of rocket nozzles and re-entry shields in the aerospace industry with some success. Second, the gas/liquid ratios can be experimentally determined as a function of temperature and this data can be inserted into the thermodynamic model of metal/pattern exchange. Both of these techniques have merits and limitations, consequently, both are being explored. This effort is in the study stage and will be continued under Contract DE-FC07-98ID13603.

As a supporting effort to the modeling and basic understanding of the metal/pattern exchange, instrumented casting trials have been performed at UMR and UAB. Experimental data generated during the past seven years of research has been compiled and reviewed for consistency. In some cases, experiments were repeated to confirm important principles. Results of these experiments confirmed earlier data which revealed that pattern density and coating permeability are the most important factors in controlling the metal/pattern exchange rate (filling), with metal pouring temperature being next in order of importance. These results also indicate that a particular pattern has a critical metal velocity that should be 'windowed' to produce defect free castings.

An experimental procedure was developed to identify the 'window' of coating permeability to produce minimum casting defects. This procedure was used in a production aluminum foundry to identify the coating permeability 'window' for an automotive engine casting. The procedure was also used to 'window' the coating in a production iron foundry for a marine exhaust manifold. These procedures were transferred to the production foundries for further use on other products.

Task 8. - Project Management and Technology Transfer

Technology transfer between UAB personnel and sponsors occur in the form of quarterly meetings and individual contacts as requested by the sponsors. Four sponsor meetings were held at AFS in Chicago and four at UAB in Birmingham. These meetings provide opportunity for UAB personnel to review the achievements

in the previous quarter and to receive comments and direction from the sponsors. This procedure has served this project well in the past.

Project management is dictated by Charles E. Bates, Ph.D.

ADVANCED LOST FOAM CASTING TECHNOLOGY

1996-1997 Summary Report

1.0 Pyrolysis Defects and Sand Distortion

1.1 UAB Research

In the lost foam casting process, molten metal is used to pyrolyze and replace a foam pattern, leaving a metal replica of the part of interest. To allow the molten metal to fill the cavity, the gaseous products formed from degradation (pyrolysis) of the foam pattern must have a means of escape from the mold cavity. Past research has shown this escape mechanism to be controlled by the coating gas permeability and the pattern area/perimeter ratio. The coating must have sufficient gas permeability to allow these pyrolysis products to escape the mold and move out into the sand in a timely fashion. Insufficient gas permeability, along with poor insulating properties, promotes misruns (incomplete fill). The most persistent problems in the lost foam casting process are defects related to incomplete removal of the liquid foam pyrolysis products. These liquid products can become trapped within an unstable metal front or be pushed to the metal/coating interface for removal after the metal front has passed. Trapped liquid products within the advancing metal front promote the formation of porosity and laps/folds while liquid products trapped at the metal/coating interface promote surface carbon defects sometimes called "worm tracks" or "orange peel." The refractory coating plays the most important role in allowing a controlled metal/pattern exchange process. When the metal/pattern exchange process is too slow, misruns are produced - when the process is too fast, porosity and laps/folds are produced. This suggests that a 'window' of permeability exists for a given pattern, assuming a reasonable range of pattern area/perimeter ratios. At the start of the past two years of research, there were no rules for selecting the best coating for a particular casting. Efforts in the past two years have been directed at verifying that a coating permeability 'window' exists and procedures to identify this 'window' have been developed at UAB. These procedures have been verified within both aluminum and iron foundries.

1.1.1 Pattern Pyrolysis Defect Reduction

Coating gas permeability and liquid absorption test procedures have been developed at the University of Alabama at Birmingham. These test procedures (Coating Quality Control

Manual) have been issued to the LFC industry to monitor and control coating properties and help reduce the number of defects formed during pouring. Figures 1.1.1.1 and 1.1.1.2 illustrate reductions in scrap rate for an aluminum intake manifold and an aluminum engine cylinder head. The objective of this study was to develop a method for selecting, measuring, and modifying a coating to produce a defect free casting. This procedure was designed to extend the utility of the coating test procedures and reduce the time required to bring new castings to market. The validity of this method was verified through a series of experiments using test patterns with varying geometries and coatings with varying permeabilities. Determining the air permeability and liquid absorption capabilities of refractory coatings using the coating test procedures played a central role in these experiments.

1.1.1.1 Experimental Procedures

Several polystyrene bar patterns with known dimensions were cast in 319 aluminum and gray iron. The aluminum castings were poured at a temperature of 788°C and the iron castings were poured at a temperature of 1400°C. The test bars had cross-sectional area-to-perimeter (A/P) ratios between 0.14 cm and 0.76 cm. These bars were coated with six different refractory coatings, including both mica-based and silica-based coatings. These coatings covered a large portion of the permeability range currently used in the foundry industry. The air permeability of these coatings ranged from 3.69 cm³/s-cm² to 90.75 cm³/s-cm² for the aluminum castings and 6.26 cm³/s-cm² to 126.58 cm³/s-cm² for the iron casting. The metal front velocity and metal front shape was measured in each of these casting trials. Each casting was examined to determine the type, extent, and location of several different types of casting defects. Typical casting defects are shown in Figures 1.1.1.1.1 through 1.1.1.1.5.

The six coatings were labeled A, B, C, D, E, and F and were used in both aluminum and iron casting trials. These coatings were chosen to represent the most popular coatings currently used in iron and aluminum lost foam foundries. The viscosity, dried thickness, air permeability, and liquid absorption capability of each coating are listed in Table 1.1.1.1.1. These values were obtained using the measurement procedures described in the Coating Quality Control Manual.

Coatings C and D contain mica as their primary refractory material and are typically used in aluminum lost foam casting foundries. The presence of mica platelets reduces the coating permeability yet increases the insulating ability of the coating,

Figure 1.1.1.1 Scrap reduction for an aluminum intake manifold after introduction of the coating control procedures

Figure 1.1.1.2 Correlation of aluminum cylinder head blown gate scrap to air flow through the coating

(a)

(b)

Figure 1.1.1.1.1. Examples of misrun defects on aluminum test bars

(a)

(b)

Figure 1.1.1.1.2. Burn-on defect present in aluminum castings

(a)

(b)

Figure 1.1.1.1.3. Aluminum castings showing (a) blistered surface and (b) residue under the blister.

(a)

(b)

Figure 1.1.1.1.4. Iron casting showing extreme burn-on defect.

(a)

(b)

Figure 1.1.1.1.5. Iron casting showing (a) carbon defects on top surface of the casting and (b) defect free surface on the bottom.

TABLE 1.1.1.1.1
COATING PROPERTIES

Coating ¹	Viscosity (cp)	Dried Thickness (cm)	Air Flow Rate ² (cm ³ /(s·cm ²))		Liquid Absorption ² Rate @ 0.5 s (g/(s·cm ²))	
			16.7 kPa Pressure for Al	28.7 kPa Pressure for Fe	16.7 kPa Pressure for Al	28.7 kPa Pressure for Fe
A (silica)	2425	0.025	53.85	76.46	0.0156	0.0205
B (silica)	1600	0.025	54.73	77.16	0.0160	0.0210
C (mica)	1725	0.030	6.16	10.16	0.0046	0.0060
D (mica)	2075	0.038	3.69	6.26	0.0036	0.0048
E (silica)	2700	0.043	31.78	46.64	0.0136	0.0178
F (silica)	1275	0.013	90.75	126.58	0.0155	0.0203

Notes: 1. Primary refractory is listed in parentheses next to the coating designation.
2. Results are average of three measurements.

allowing molten metal to fill thin pattern sections. Coatings A, B, E, and F are typically used when pouring castings in iron. The primary refractory in coatings A, B, E, and F is silica. Due to the granular nature of this refractory, these coatings have a higher permeability than coatings C and D.

The measurements listed in Table 1.1.1.1.1 are the average results of three measurements made on each coating as it was used in the casting trials. The coating permeability and liquid absorption capability were calculated at the actual dried coating thickness and at two pressures, 16.7 kPa (2.42 psi) for aluminum castings and 28.7 kPa (4.16 psi) for iron castings. The original bulk coatings received from the manufacturers were modified to achieve the permeability and dried thickness values listed in Table 1.1.1.1.1.

Several test bar clusters with pattern densities of 20.8 kg/m³ and 25.6 kg/m³ (1.6 lb/ft³ and 1.3 lb/ft³) were coated using each of the six coatings described above. After coating, the clusters were dried for 2 hours in a forced air convection oven at 50°C. After drying, the pattern clusters were completed by attaching pouring sprues to the gating systems using hot melt adhesive.

Each cluster was placed in a flask which was vibrated on a compaction table while sand was rained into the flask. A low vibration level of approximately 0.5 g and a slow sand fill rate were used in all casting trials to ensure that the sand did not distort the patterns during compaction and to ensure the sand was completely densified around the patterns. The sand used in all casting trials was a Wedron 445 silica sand with an AFS grain fineness number of 39.4. The permeability of the Wedron 445 silica sand used in the experimental casting trials is shown in Figure 1.1.1.1.6.

The aluminum used in this study was a degassed 319 alloy poured at 788°C. The liquidus temperature of this alloy was 605°C and the solidus temperature was 520°C.

A class 30 gray iron poured at 1400°C was used in these experiments. This iron was inoculated with 75% Fe-Si before pouring. The liquidus temperature of the gray iron was 1172°C and the solidus temperature was 1115°C.

To maintain a constant metallostatic pressure head in each casting trial, a thin, round metal plug was wedged into the bottom of the sprue before each casting trial. The aluminum plugs were 0.43 cm thick and the iron plugs were 0.25 cm thick.

Figure 1.1.1.1.6. Air flow rate through 23 cm of Wedron 445 silica sand.

These plugs allowed the sprue to be completely filled for a few seconds before melting away and permitting the molten metal to enter the mold cavity. When the sprue was full of liquid metal, the metallostatic pressure in the horizontal patterns was approximately 16.7 kPa (2.42 psi) for aluminum and 28.7 kPa (4.16 psi) for iron.

1.1.1.2. Casting Trials

Thirty-six casting trials were poured using the 319 aluminum alloy. The coating type and bar type used in each trial are listed in Table 1.1.1.2.1. This test matrix covered a wide range of pattern cross-sectional area to perimeter ratios and coating permeability values. The temperatures at various points in the castings were measured and recorded in casting trials 34, 35, and 36. The metal front sensors were placed in the patterns to measure metal velocity and velocity profile, depending on the bar geometry.

Twenty-two casting trials were made using class 30 gray iron. The coating type and pattern geometry used in each trial are listed in Table 1.1.1.2.2. The temperature at various points in the castings was measured and recorded in casting trials 54 and 56.

Both the iron and aluminum castings were poured and examined to determine the presence of defect types such as burned-on sand, porosity, misruns, and surface carbon. The metal front velocities and profiles were measured in each casting except those noted in Tables 1.1.1.2.1 and 1.1.1.2.2.

1.1.1.3 Aluminum Casting Results

The castings were analyzed to determine the types of casting defects present. The data obtained using the metal front sensors were used to obtain the metal front velocity through each casting and to construct a metal front profile at each measurement section. Temperature measurements were also plotted and compared to metal front location in select castings. The results of the defect analysis on all aluminum bar castings are shown in Table 1.1.1.3.1. This table contains the type, extent, and location of defects found in and on the castings.

1.1.1.4 Iron Casting Results

All gray iron bar castings were analyzed to determine the types of casting defects present. The data obtained using the

TABLE 1.1.1.2.1

ALUMINUM CASTING TRIALS

Casting Number	Bar Pattern	Coating	Casting Number	Bar Pattern	Coating
1	4	A	18	3	A
2	2	A	19	5	D
3	4	B	20	5	A
4	3	B	23	4	F
5	4	C	24	6	F
6	3	C	25	3	E
7	4	D	26	5	E
8	3	D	27	5	F
9	6	A	28	3	F
10	7	A	29	4	E
11	6	B	30	6	E
12	7	B	31	6	None
13	6	C	33	4	None
14	7	C	34*	6	E
15	6	D	35*	4	E
16	7	D	36*	3	E
17	2	D			

*Temperature and Pressure Data also Recorded

TABLE 1.1.1.2.2
GRAY IRON CASTING TRIALS

Casting Number	Bar Pattern	Coating	Casting Number	Bar Pattern	Coating
37	6	F	47	6	D
39	4	F	48	4	D
40	6	E	49	6	F
41	3	E	50	2	E
42	6	A	52	3	D
43	3	F	54*	4	E
44	7	E	55	5	E
45	3	A	56*	6	E
46	4	A	58*	4	F

*Temperature and/or Pressure Data also Recorded

Table 1.1.1.3.1. Aluminum Bar Casting Defects

Casting	Bar #	Coating	Porosity Defects ¹ Extent and Location along bar	Misrun Defects Length Filled (cm)	Burn-on Defects Location	Brown Splashes ² Extent	Blister Defects ³ Extent and Location
17	2	D	None	11.9	None	None	None
2	2	A	None	12.7	None	Light	None
8	3	D	None	18.3	None	Light	None
6	3	C	None	19.1	None	Light on top and bottom	None
25	3	E	None	19.6	None	Light on top and bottom	None
36	3	E	None	17.8	None	Light	Very light, from 2.5 to 5 cm
18	3	A	Very small, at 23 cm	17.5	None	Light	Very light, from 5 to 7.5 cm
4	3	B	Very small, from 18 to 20 cm	19.8	None	Medium	Light in center, from 2.5 to 5 cm
28	3	F	Medium size, at 20 cm	17.5	From 0 to 5 cm on bottom	Light	Light, from 5 to 7.5 cm
7	4	D	None	Partial Tips	None	Medium to heavy	None
5	4	C	None	25.4	None	Light	None
29	4	E	None	Partial Tips	None	Heavy	Light to medium from 0 to 7 cm
35	4	E	None	Partial Tips	None	Light to medium	Light, from 5 to 10 cm
1	4	A	Very small, after 23 cm	Partial Tips	None	Medium	Light, from 0 to 5 cm
3	4	B	Very small, at 23 cm	Partial Tips	None	Medium	Medium after 18 cm
23	4	F	Large size, from 18 to 20 cm	Partial Tips	Bottom and Sides, full length	Very light	Light to medium from 0 to 10 cm
33	4	None	Medium size, at 18 cm	20.3	All over, mostly on bottom	None	Light, from 0 to 5 cm
19	5	D	None	Complete Fill	None	Medium to light	None
26	5	E	None	Complete Fill	None	Heavy on top, some on bottom	Medium to light, from 8 to 10 cm
20	5	A	None	Complete Fill	None	Medium to light	Heavy, from 10 to 13 cm
27	5	F	Medium size, at 20 cm	Complete Fill	Bottom and Sides	Medium	Medium from 0 to 5 cm
15	6	D	None	Complete Fill	None	Light	None
13	6	C	None	Complete Fill	None	None	None
30	6	E	None	Complete Fill	None	Heavy	Medium to heavy, from 0 to 20 cm
34	6	E	None	Complete Fill	None	Heavy	Light to medium from 0 to 18 cm
9	6	A	Medium size, from 18 to 20 cm	Complete Fill	None	Medium	Medium from 0 to 13 cm
11	6	B	Medium to large size, at 23 cm	Complete Fill	None	Medium	Medium from 0 to 8 cm
24	6	F	Medium size, at 18 cm	Complete Fill	Bottom and Sides	Medium	Heavy, from 0 to 15 cm
31	6	None	Large size, after 15 cm	Complete Fill	All over, mostly on gate end	None	None
16	7	D	None	Complete Fill	None	Light	None
14	7	C	None	Complete Fill	None	Light	None
10	7	A	Small size, after 23 cm	Complete Fill	None	Medium	Heavy, from 0 to 13 cm
12	7	B	Medium size, at 23 cm	Complete Fill	None	Heavy	Medium from 0 to 13 cm

¹Note: Porosity defects always occurred near the edges of the castings, never in the center.²Note: Brown splashes were evenly distributed along top surface of castings except where noted.³Note: All blisters occurred on the top surface of the castings.

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metal front sensors were used to obtain the metal front velocity through each casting and to construct a metal front profile at each measurement section. Temperature measurements were also recorded for select castings.

The results of the defect analysis on all gray iron bar castings are presented in Table 1.1.1.4.1. This table contains the type and location of defects found in and on the castings.

1.1.1.5 Aluminum Casting Data

The metal front velocities for all rectangular aluminum bar castings are shown in Figure 1.1.1.5.1 as a function of coating air permeability. For #3, #4, and #5 bar castings, the metal front velocity increased with increasing coating air permeability. In general, the metal front velocity increased slightly with increasing pattern cross-sectional area-to-perimeter (A/P) ratio. For the low permeability coatings C and D on #3, #4, and #5 bar patterns, the velocity was approximately 1.4 cm/s. When coated with the high permeability coating (F), these bar castings had a metal front velocity in the range of 2.5 cm/s to 2.8 cm/s.

When the pattern A/P ratio increased to 0.76 cm (#6 bar), the average velocity was 2.92 cm/s throughout the coating permeability range used in these trials. When castings 31 (#6 bar) and 33 (#4 bar) were poured without a refractory coating, the metal front velocities were 3.03 cm/s and 3.01 cm/s, respectively. An air permeability value of $130 \text{ cm}^3/\text{s}\cdot\text{cm}^2$ was used when plotting the velocity points for these two castings. This value was the permeability of the silica sand used in these casting trials at maximum compacted density and with a pressure gradient of 16.7 kPa (2.42 psi).

The data presented in Figure 1.1.1.5.1 suggests that the metal front velocity through bars with A/P ratios up to 0.59 cm (#5 bar) increased with increasing coating air permeability up to approximately $100 \text{ cm}^3/\text{s}\cdot\text{cm}^2$. Beyond this point, the metal front velocity in these bars leveled out at approximately 3.0 cm/s with increasing coating air permeability, as evidenced by casting 33. Although the coating permeability had an effect on the metal front velocity through the #3, #4, and #5 bars, it had no effect on the metal front velocity in the thick #6 bars. The constant velocity characteristics of the thick #6 bars and the high permeability coated thinner bars appeared to be independent of coating air permeability and must have been controlled by a different parameter. The constant velocity characteristic of these bars can be best explained by a thermal analysis of the metal front.

Table 1.1.1.4.1 Iron Bar Casting Defects

Casting	Bar #	Coating	Burn-on Defects Extent and Location	Surface Carbon Defects ¹ Extent and Location	Porosity Defects
50	2	E	Light to medium, from 0 to 8 cm, corners	None	None
52	3	D	None	None	None
41	3	E	Light to medium, from 0 to 10 cm, corners	None	None
45	3	A	None	None	None
43	3	F	Light, from 0 to 15 cm, corners	Light	None
48	4	D	None	Light to medium, from 0 to 10 cm	None
54	4	E	None	None	None
46	4	A	None	Light to medium, down center, mostly 10 to 15 cm	None
39	4	F	Very light, random on sides and bottom	Medium, full length down center	None
58	4	F	Medium, from 0 to 4 cm, corners	Medium, from 10 cm to end	None
55	5	E	None	Medium from 0 to 10 cm, light from 10 cm to end	None
47	6	D	None	Very heavy, full length	None
56	6	E	Light on one top corner only, full length	Medium from 0 to 10 cm, also light on bottom after 20 cm	None
40	6	E	None	Heavy, full length, also light on bottom from 20 to 23 cm	None
42	6	A	Heavy on corners, full length	Heavy, full length, also light on bottom from 10 to 15 cm	None
49	6	F	Medium on corners, full length, random on top	Heavy, full length	None
37	6	F	Light on corners, full length, random on all sides	Heavy, full length	None
44	7	E	Extreme veining, full length	Light, from 0 to 10 cm	One very large pore

¹Note: Surface carbon defects occurred on the top surface of the castings only, except where noted.

Figure 1.1.1.5.1. Effect of coating air permeability on aluminum metal front velocity in rectangular bar castings.

One would normally assume that as the pattern A/P ratio increased while maintaining a constant coating air permeability, the metal front velocity must decrease. An increasing A/P ratio means that there are increasing amounts of foam pattern pyrolysis products to be removed from the mold cavity with decreasing perimeter per unit cross-sectional area for these products to be transported through. This would be true if the pyrolysis products always consisted of a constant ratio of liquid to gaseous products. The independence between the metal front velocity and coating permeability could then be explained by differences in the gap thickness as a function of pattern geometry. Unfortunately, the analysis is not that simple. The ratio of liquid to gaseous pyrolysis products is dependent on metal front temperature.

The peak metal front temperatures obtained from each of the thermocouples used in castings 34, 35, and 36 are plotted in Figure 1.1.1.5.2 as a function of length along the 25.4 cm long bars. All three of these castings were poured at 788°C using coating E which had an air permeability of 31.78 cm³/(s·cm²). The metal front velocity through these bars was 3.05 cm/s for casting 34 (#6 bar), 2.14 cm/s for casting 35 (#4 bar), and 2.06 cm/s for casting 36 (#3 bar). The metal front temperature increased with A/P ratio at a constant position along the length of the castings as shown in Figure 1.1.1.5.2. For each bar, the metal front temperature decreased linearly along the length of the mold cavity.

Walling (1992) demonstrated that a phase transformation takes place in expanded polystyrene at approximately 680°C. At this transition point, the majority of the pyrolysis products turn from liquid to gaseous products. As shown in Figure 1.1.1.5.2, the metal front temperature in the first half of the #6 bar casting was above this phase transformation temperature. Therefore, the pyrolysis products in the #6 bar castings were primarily hot gases while the pyrolysis products in the thinner (#3 and #4) bar castings contained more liquid. Hot gases were more easily and quickly removed from the mold cavity than dense liquid pyrolysis products. Therefore, the metal front velocity in the #6 bar castings was controlled by the rate at which the foam pattern material vaporized and not by the rate at which the pyrolysis products were removed from the mold cavity. This was confirmed by the results obtained when #4 and #6 bar castings were poured without using a refractory coating. The metal front velocities were 3.0 cm/s despite the very high permeability condition obtained when not using a refractory coating.

Figure 1.1.1.5.2. Metal front temperature in aluminum bar castings during mold filling.

A schematic illustrating several important thermal properties at the metal-foam-coating interface is shown in Figure 1.1.1.5.3. For a very high permeability coating or non-existent coating, all foam pyrolysis products can be removed from the mold cavity through the gap between the molten metal front and the foam pattern (kinetic zone) at the rate at which they are produced. This rate is determined by how fast the foam reaches the temperature at which it melts and decomposes. Consequently, this rate sets an upper limit on the metal front velocity. Using the notation shown in Figure 1.1.1.5.3, the heat transfer rate from the molten metal front to the kinetic zone (Q_1) can be expressed as

$$(1.1.1.5.1) \quad Q_1 = h_z A_{cs} (T_m - T_z)$$

where

h_z = the heat transfer coefficient at the metal/foam interface [$J/(s \cdot cm^2 \cdot K)$],

A_{cs} = cross-sectional area of foam pattern at the metal/foam interface [cm^2],

T_m = metal front temperature [K], and

T_z = temperature in the kinetic zone [K].

The heat transfer rate required to heat the products in the kinetic zone from the initial foam pattern temperature to the kinetic zone temperature (Q_2) can be written as

$$(1.1.1.5.2) \quad Q_2 = C_{p,z} \rho_z A_{cs} V (T_z - T_f)$$

where

$C_{p,z}$ = specific heat of the products in the kinetic zone (foam pattern) [$J/(g \cdot K)$],

ρ_z = average density of products in the kinetic zone (foam pattern) [g/cm^3],

V = velocity of the molten metal front [cm/s], and

T_f = initial temperature of the foam pattern [K].

By assuming a steady state condition and neglecting heat lost to the coating, Q_1 and Q_2 should be equal. After setting Equations

1.1.1.5.1 and 1.1.1.5.2 equal to each other, the velocity of the molten metal front can be expressed as

$$(1.1.1.5.3) \quad V = \frac{h_z(T_m - T_z)}{C_{p,z}\rho_z(T_z - T_f)}.$$

This is the maximum metal front velocity obtainable for a very high or infinitely permeable coating.

Although all aluminum bar castings were poured at 788°C, the actual metal front temperature in the mold cavity was lower. The metal front temperature at the midpoint in the #6 bar casting was approximately 680°C as shown in Figure 1.1.1.5.2. This value was used as the average metal front temperature, T_m , in Equation 1.1.1.5.3. The average initial foam pattern temperature, T_f , was 18.5°C. Littleton (Final Report, 1993) has shown the temperature at the edge of the kinetic zone to be approximately 300°C and the heat transfer coefficient at the metal/foam interface to be 0.070 J/(s·cm²·K) under similar casting conditions. Walling (1992) has determined the temperature at the foam surface in the kinetic zone to be approximately 200°C. An average value of 250°C was used as the kinetic zone temperature T_z to calculate the maximum metal front velocity in Equation 1.1.1.5.3. The specific heat of the foam pattern material was 1.6 J/(g·K) (Tadmor and Gogos, 1979). The average density of the pattern was 25.6 kg/m³. When these values were substituted into Equation 1.1.1.5.3, the maximum metal front velocity was found to be 3.17 cm/s.

This calculated velocity agreed very well with the average experimental velocity found in the #6 bar aluminum castings. It also agreed well with the velocity obtained when #4 and #6 bars were cast without using a refractory coating (very high permeability). Although the argument leading to Equation 1.1.1.5.3 explained the maximum velocity of 3.0 cm/s measured in the castings poured with no coating, it did not explain why all #6 bar aluminum castings exhibited similar metal front velocities. This includes #6 bar castings coated with the very low permeability mica coatings, C and D.

As previously mentioned, a phase transformation takes place in the kinetic zone at a metal front temperature of approximately 680°C. At this point, significant depolymerization of the polystyrene pattern begins to occur and large amounts of gases are formed in place of the liquid pyrolysis products. As shown in Figure 1.1.1.5.2, the metal front temperature in the #6 bar castings was above this transition temperature as it traveled through the first half of the casting. This high temperature not

Figure 1.1.1.5.3. Schematic illustrating important thermal properties at the metal/foam/coating interface.

only increased the ratio of gases to liquids present in the kinetic zone, but also acted to widen this zone. Therefore, there was more coating surface area available for pyrolysis product transport between the molten metal front and the foam pattern. This large gap thickness increased the effective coating permeability to the point that the foam pattern pyrolysis rate remained the dominant factor controlling metal front velocity through the mold cavity.

A refractory coating must allow finite amounts of liquid and gaseous products to escape the mold cavity before the molten metal begins to solidify. A given pattern geometry, foam density, pouring temperature, and metal front velocity will determine the permeability and liquid absorption requirements for the coating. A mass analysis of the polystyrene bar patterns should provide the amount of liquid products and air produced during mold filling. The total pattern volume-to-surface area ratio can be used to find the liquid removal requirements of the coating. For example, when pouring aluminum in EPS patterns, the pattern simply melts and the foam pyrolysis products are primarily liquid. The remainder of the mold cavity is assumed to be occupied by air. For a given aluminum metal front velocity, foam density, and foam pattern geometry, the required liquid removal and air removal flow rates can be calculated.

Liquid polystyrene has a density of 900 kg/m^3 at 25°C . At the temperature when it actually wets and wicks into the coating, 300°C , the liquid polystyrene has a density of 600 kg/m^3 . The total mass of liquid in the mold cavity can be calculated using these values and the geometry of the foam pattern. The remaining volume of the mold cavity is filled with air. Using an average temperature of 250°C in the kinetic zone when pouring aluminum, the required amount of air and liquid polystyrene to be absorbed through the coating during mold filling can be calculated. The required air and liquid removal rates for several test bar patterns are presented in Table 1.1.1.5.1. This table was prepared assuming aluminum pouring temperatures and an EPS pattern density of 25.6 kg/m^3 (1.6 lb/ft^3). The required liquid removal rate was calculated for several metal front velocities: 1.4 cm/s , 2.3 cm/s , and 3.0 cm/s . The air and liquid production rates for each bar geometry used in the casting trials are illustrated graphically in Figure 1.1.1.5.4 as a function of metal front velocity. This figure shows that air and liquid production rates increase with increasing metal front velocity and pattern A/P ratio.

Metal front profiles measured during mold filling also appeared to be a function of metal front velocity. The metal

Table 1.1.1.5.1. Product evolution rates for aluminum bar castings when all pyrolysis products are in liquid form
(EPS foam pattern density = 25.6 kg/m³)

Pattern Bar #	Pattern Height (cm)	Pattern Width (cm)	Pattern Diameter (cm)	Pattern Perimeter (cm)	Pattern C-S Area (cm ²)	A/P Ratio (cm)	Metal Front Velocity (cm/s)	Total Liquid Evolution Rate (g/s)	Total Air Evolution Rate (cm ³ /s)	Product Evolution Rates Per Unit Surface Area	
										Liquid Product Evolution Rate (g/s·cm ²)	Air Evolution Rate (cm ³ /s·cm ²)
2	0.32	3.05		6.73	0.97	0.14	1.40	0.03	2.53	0.005	0.376
2	0.32	3.05		6.73	0.97	0.14	2.30	0.06	4.16	0.008	0.618
2	0.32	3.05		6.73	0.97	0.14	3.00	0.07	5.42	0.011	0.806
3	0.64	3.05		7.37	1.94	0.26	1.40	0.07	5.06	0.009	0.687
3	0.64	3.05		7.37	1.94	0.26	2.30	0.11	8.31	0.015	1.129
3	0.64	3.05		7.37	1.94	0.26	3.00	0.15	10.84	0.020	1.472
4	1.27	3.05		8.64	3.87	0.45	1.40	0.14	10.12	0.016	1.172
4	1.27	3.05		8.64	3.87	0.45	2.30	0.23	16.63	0.026	1.925
4	1.27	3.05		8.64	3.87	0.45	3.00	0.30	21.69	0.034	2.511
5	1.91	3.05		9.91	5.81	0.59	1.40	0.21	15.18	0.021	1.533
5	1.91	3.05		9.91	5.81	0.59	2.30	0.34	24.94	0.035	2.518
5	1.91	3.05		9.91	5.81	0.59	3.00	0.45	32.53	0.045	3.284
6	3.05	3.05		12.19	9.29	0.76	1.40	0.33	24.29	0.027	1.992
6	3.05	3.05		12.19	9.29	0.76	2.30	0.55	39.91	0.045	3.273
6	3.05	3.05		12.19	9.29	0.76	3.00	0.71	52.05	0.059	4.269
7			3.05	9.58	7.30	0.76	1.40	0.26	19.08	0.027	1.992
7			3.05	9.58	7.30	0.76	2.30	0.43	31.34	0.045	3.273
7			3.05	9.58	7.30	0.76	3.00	0.56	40.88	0.059	4.269

Figure 1.1.1.5.4. Liquid polystyrene and air evolution in aluminum lost foam bar castings.

front profile for the #4 and #5 bar aluminum castings became increasingly concave with increasing metal front velocity and coating permeability. The metal front profiles characteristic of the thicker #6 bar castings were always convex and the metal front velocity was always near 3.0 cm/s, regardless of coating permeability. A convex metal front may be more desirable in the LFC process since it pushes the foam pyrolysis products toward the coating surface where they can be removed from the mold cavity.

1.1.1.6. Formation of Aluminum Casting Defects

This section will explain the analysis of each defect type found in the aluminum bar castings and how these defects relate to various casting variables. The formation of each type of casting defect will also be discussed.

1.1.1.6.1. Misruns

Misruns were created in the aluminum bar castings when the metal front temperature dropped below the liquidus temperature before the mold cavity was completely filled. As discussed previously, this occurred in all #2 and #3 bar aluminum castings, and in some #4 bar castings. Each of the #3 bars filled approximately 19 cm before freezing. The #3 bars coated with higher permeability coatings filled to the same length as #3 bars coated with lower permeability coatings. However, the higher permeability coated #3 bars filled at a faster rate than the lower permeability coated #3 bars. The same was true for the #2 and #4 bar aluminum castings. The metal front temperature dropped linearly along the length of the casting as illustrated in Figure 1.1.1.5.2. Mold filling occurred until the aluminum cooled to the liquidus temperature and the metal front began to freeze. The metal front traveled a shorter length before freezing in thinner bars (lower A/P ratio) than for thicker bars (higher A/P ratio).

Misrun defects were quantified by measuring the length of each bar casting and tabulating and analyzing the results. Since all #5, #6, and #7 bar castings filled completely, the lengths of these castings were recorded as 30 cm, which was the combined length of the bar pattern section and the reservoir tip section.

The length measurements for all aluminum bar castings were compared to several casting variables including pattern A/P ratio, coating permeability, liquid absorption capability, dried coating thickness, coating liquid viscosity, and primary

refractory. The results from this comparison showed that fill distance in the aluminum bar castings was largely a function of pattern geometry. The filled length of aluminum bar castings is illustrated in Figure 1.1.1.6.1.1 as a function of foam pattern A/P ratio. The values graphed in this figure are the average fill lengths for each bar geometry. A measurement of 30 cm is shown in Figure 1.1.1.6.1.1 for the #5, #6, and #7 bar castings since these castings and their tips filled completely. This figure shows that filled casting length increased steadily with increasing pattern A/P ratio. As a result, a mathematical explanation was sought to help explain why misrun defects appear to be a function of pattern geometry while being independent of coating permeability and metal front velocity.

The thermal analysis performed earlier on the metal/foam interface was extended to include the heat transfer through the coating along the entire length of the bar casting. To achieve this, an energy balance was applied to the entire volume of metal present in the mold cavity. This energy balance included the metal/foam interface and the metal/coating/sand interface and was used to find an expression for the bar pattern length that aluminum would fill before freezing off and creating a misrun.

(1.1.1.6.1.5)

$$L_c = \left(\frac{A_{cs}}{P} \right) \left(\frac{h_z(T_m - T_z)}{h_c(T_m - T_s)C_{p,z}\rho_z(T_z - T_f)} \right) (H_L\rho_m + C_{p,m}\rho_m(T_m - T_L) - C_{p,z}\rho_z(T_m - T_z))$$

This equation expresses the length of a foam bar pattern that will fill with metal as a function of the pattern cross-sectional area to perimeter ratio, A/P, and the thermal properties of the foam pattern, metal, and sand. It is noted that this equation is not a function of the metal front velocity or coating permeability.

The thermal properties of the foam, metal, and sand were acquired and used to calculate bar length results using Equation 1.1.1.6.1.5. The results for several A/P ratios were plotted against the actual results obtained for the #2, #3, and #4 bar lengths filled. The results are shown in Figure 1.1.1.6.1.2. The actual filled lengths of #5, #6, and #7 bars were not plotted since these bars did not fill completely. The patterns used in the casting trials were not long enough to evaluate the potential length filled. Equation 1.1.1.6.1.5 was used to calculate the potential casting fill length for #5 bars as 41.3 cm. A potential fill length of 53.7 cm was calculated for #6 and #7

Figure 1.1.1.6.1.1.1. Length of aluminum bar castings filled as a function of pattern A/P ratio

Figure 1.1.1.6.1.2. Length of aluminum bar pattern filled as a function of pattern A/P ratio

aluminum bars. The lengths calculated using Equation 1.1.1.6.1.5 compare very well to the actual average measured lengths of the aluminum bars cast in this study. Even though some bars filled faster than others with the same A/P ratio, all bars with the same A/P ratio filled to approximately the same length. This analysis indicates that the length of bar filled is primarily a function of the pattern A/P ratio.

1.1.1.6.2 Burned-on Sand

Burned-on sand defects occurred only when using coating F or when there was no coating applied to the pattern. Burned-on sand was probably the result of the very thin dried thickness characteristic of coating F. Most of the burned-on sand defects were near the gated end of the castings because the molten metal was hotter there, providing more erosion of the coating, and had longer to penetrate through the thin coating before it solidified. Burned-on sand defects present on aluminum castings poured with the high permeability coating F make this coating unsuitable for use with aluminum lost foam castings.

Burned-on sand defects were quantified by using a severity scale. A value of 1 was assigned to castings with no burned-on sand defects and a value of 5 was assigned to castings with extensive defects. Increasing values between 1 and 5 indicated increasing defect severity. These values were used to compare burned-on sand defects in aluminum castings to several casting variables including pattern A/P ratio, coating air permeability and liquid absorption capability, dried coating thickness, coating liquid viscosity, and primary refractory. The results from this comparison showed that burned-on sand defects in the aluminum bar castings were a function of coating dried thickness or coating air permeability. No correlations were found between burned-on sand defects and other measured properties. Average burned-on sand defect severity values for the aluminum bar castings are shown in Figure 1.1.1.6.2.1 as a function of coating dried thickness. This figure shows that burned-on sand defect severity decreased with increasing coating thickness.

The average burned-on sand defect severity value also increased with increasing coating air permeability. Castings made with coating F (air permeability = $90.75 \text{ cm}^3/\text{s}\cdot\text{cm}^2$) had an average defect value of 3 and castings made with no coating (air permeability = $130 \text{ cm}^3/\text{s}\cdot\text{cm}^2$) had an average defect value of 5. Burned-on sand defects in aluminum lost foam castings are reduced when using low permeability refractory coatings or thick, higher permeability coatings.

Figure 1.1.1.6.2.1. Average burned on sand severity in aluminum bars as a function of coating thickness

1.1.1.6.3 Surface blisters

Brown splotches found on the surfaces of the aluminum bar castings were formed from deposits of liquid pyrolysis products left on the casting surface when the metal solidified. The splotches were formed because the coating did not have enough liquid absorption capability to remove the liquid from the mold cavity in a timely manner. The spots were concentrated on the upper surface of all the castings poured because the liquid pyrolysis products floated to the top of the molten metal front during mold filling. The presence, location, and extent of the brown splotches appeared to be independent of the bar geometry and coating type. Although unsightly, the splotches were easily removed by sandblasting so they did not represent a true casting defect. They were, however, related to the presence of objectionable blister defects found on several aluminum bar castings poured using high permeability coatings.

During sandblasting, blisters were found on some aluminum bars beneath the darkest brown spots. However, this occurred only on castings poured using the higher permeability coatings such as E, A, B, and F. Except in the case of the constant velocity metal fronts in the #6 bars, these castings also exhibited a higher metal front velocity than castings poured using the low permeability coatings C and D. The presence of the blisters is therefore more likely explained by the differences in coating air permeability and thermal conductivity. The low permeability coatings (C and D) are made with mica which is in the form of platelets. These platelets arrange themselves parallel to each other in the dried coating. This layering effect not only gives the mica-based coatings a low permeability, but also a very low thermal conductivity and thus, an insulating characteristic.

The surface blisters were formed when liquid pyrolysis products were engulfed by a fast moving molten metal front as it filled the mold cavity. These products floated to the top of the casting where they should have wicked into and through the refractory coating. In the case of the high thermal conductivity coatings, however, a thin layer of metal present at the coating surface had already cooled and solidified, thereby blocking the liquid products from escaping the mold cavity. This was confirmed by the presence of a brown residue found under the blister defects. The insulating nature of the mica coating kept the casting surface molten long enough to allow the liquid pyrolysis products to escape without creating defects. The low permeability of these coatings also slowed the metal front, thereby reducing the amount of liquid foam that is trapped by the

metal front. In the case of the #6 bars where the metal front velocity was high regardless of the coating permeability, the insulating effect of the mica coatings and the larger mass of molten metal present in the mold cavity allowed the casting to remain above freezing temperatures for a longer period of time.

As with burned-on sand defects, surface blister defects on the aluminum bar castings were also quantified by using a severity scale. Increasing values between 1 and 5 indicate increasing defect severity. These values were used to compare aluminum casting surface blister defects to measured casting variables including pattern A/P ratio, coating permeability, liquid absorption capability, dried coating thickness, coating liquid viscosity, and primary refractory. The results from this comparison showed that surface blister defects in the aluminum bar castings were a function of coating air permeability and primary refractory.

Coatings C and D contained mica as the primary refractory, and the remaining coatings contained silica as the primary refractory. The thermal conductivity of mica is $0.004 \text{ J}/(\text{s}\cdot\text{cm}\cdot\text{K})$ and the thermal conductivity of silica is $0.014 \text{ J}/(\text{s}\cdot\text{cm}\cdot\text{K})$. The overall heat transfer coefficient through each coating was calculated by dividing the thermal conductivity of the primary coating refractory by the dried coating thickness. The thermal properties and dried coating thickness of each coating are presented in Table 1.1.1.6.3.1.

The average blister defect severity for the mica coatings was 1 (no defects) while the average rating for the silica coatings was 2.95 (medium defects). The two castings poured with no coating had a severity rating of 1.5. Blister defects were hard to detect on these castings because the blisters were covered with severe burned-on sand defects. Figure 1.1.1.6.3.1 shows the average blister defect severity as a function of coating air permeability, coating type, and heat transfer coefficient. The data indicates that surface blister defects increased when pouring aluminum castings using coatings having high heat transfer characteristics.

1.1.1.6.4. Porosity

The blister defects usually occurred near the gated end of the aluminum bar castings. All porosity found in these castings, however, occurred at the end opposite the ingate. Both defect types appear to be related and were probably produced in the same manner. When the molten metal front trapped a foam particle near the gated end of the mold cavity, the liquid pyrolysis products

TABLE 1.1.1.6.3.1

COATING THERMAL PROPERTIES

Coating	Dried Coating Thickness (cm)	Refractory Thermal Conductivity (J/(s·cm·K))	Heat Transfer Coefficient (J/(s·cm ² ·K))
A	0.025	0.014	0.56
B	0.025	0.014	0.56
C	0.030	0.004	0.13
D	0.038	0.004	0.11
E	0.043	0.014	0.33
F	0.013	0.014	1.08

Figure 1.1.1.6.3.1. Average blister severity as a function of coating permeability, coating type and coating heat transfer coefficient in aluminum lost foam castings.

had a longer time to float to the top of the cavity since the metal temperature in the gated end was much higher than the metal temperature in the far end of the cavity. Surface blister defects can be thought of as porosity defects that had time to float to the surface. Porosity defects were also formed when the molten metal front trapped some of the foam pattern. However, in these cases the molten metal solidified around the foam particle before it could rise to the surface. The hot metal eventually caused the foam to vaporize and form a void in the solid casting. Porosity defects were found in castings poured using the high permeability coatings A, B, and F and in the two castings poured using no coating. No porosity defects were found in castings poured using coatings D, C, or E.

As with burned-on sand and surface blister defects, porosity defects in the aluminum bar castings were also quantified by using a severity scale. Increasing values between 1 and 5 indicated increasing defect severity. These values were used to compare aluminum casting porosity to pattern A/P ratio, coating permeability, liquid absorption capability, liquid coating viscosity, dried coating thickness, and primary refractory. The results from this comparison show that porosity defects in the aluminum castings were primarily a function of coating air permeability but may also have been related to coating thickness.

Figure 1.1.1.6.4.1. shows the average porosity defect severity as a function of coating permeability, coating type, and coating heat transfer coefficient. Porosity defects increased in severity with air permeability. Castings poured using coatings D, C, and E received a severity rating of 1 since they did not contain any porosity defects. An increase in air permeability increased the metal front velocity which allowed the metal front to trap foam pattern particles and produce porosity defects.

In general, porosity defects also increased with increasing heat transfer coefficient through the coating. Castings poured with coatings A, B, and F and those poured with no coating contained porosity defects. No porosity defects were found in castings poured with coatings C, D, and E. Coatings C and D contained mica as their primary refractory and were considered to be insulating coatings. Coating E was silica based and had a dried thickness of 0.043 cm which acted to increase its insulating characteristics. The insulating properties of these coatings appeared to help reduce porosity defects in aluminum.

1.1.1.7. Summary of Aluminum Casting Defects

An analysis of the data obtained in this experiment indicates that low permeability mica coatings produced the fewest defects of any coating in the current investigation. These coatings have a low air permeability and a low thermal conductivity because of the layering effect of mica platelets. The low coating permeability produced a low velocity, parabolic metal front which reduced porosity. The low thermal conductivity of the coating allowed the liquid pyrolysis products to escape the mold cavity in a timely manner, thus avoiding surface blisters. These coatings also had sufficient dried thickness and strength to prevent the formation of burned-on sand defects. Both surface blisters and porosity defects were associated with castings coated with high thermal conductivity and high permeability silica coatings. Burned-on sand defects also developed when using very thin, high permeability silica-based coatings.

1.1.1.8. Defect Reduction in Complex Aluminum Lost Foam Castings

A methodology was proposed for reducing defects in new lost foam aluminum castings. The previous discussion has shown that coating selection is extremely important in lost foam casting. Coating properties are related to such defects as porosity, burned-on sand, and surface blister defects. A low thermal conductivity coating should always be selected when pouring lost foam aluminum castings. The following methodology applies to aluminum castings poured at approximately 750 - 800°C where the average pressure head height is 50 to 70 cm.

As an example of how a more complex new lost foam pattern might be poured using this methodology, a standard hat-shaped pattern was selected. This pattern has been used by Askeland (Sponsor Meeting Handout 1995) in studies on mold filling and by Griffin (Final Report 1993) in studies on lost foam casting precision. Based on the dimensions of this casting, the total area-to-perimeter ratio (A/P) of this pattern was found to be 0.61 cm. The A/P ratio of the hat-shaped pattern was very close to the A/P ratio of the #5 bar (0.59 cm).

A hat-shaped pattern with an expanded polystyrene foam density of 25.6 kg/m³ (1.6 lb/ft³) was gated at two locations. These locations were near the inside diameter of the flange part of the pattern on the side of the pattern opposite the cone. The runner used to gate the hat-shaped pattern was very similar to that used for the test bar patterns. Coating D was used to coat the pattern assembly. This coating was chosen since it gave

excellent results in the test bar casting trials on patterns with similar A/P ratios. After coating, the pattern was dried and attached to a 61 cm long hollow sprue. The hat-shaped pattern cluster was then compacted in silica sand and poured using an 319 aluminum alloy at 788°C.

Pictures of the sandblasted casting are illustrated in Figure 1.1.1.8.1. No surface blisters developed on the surface of the hat-shaped casting, even where the brown surface splotches appeared. There were no burned-on sand defects present anywhere on the surface of this casting, even in the small 6 mm diameter holes on the flange portion of the casting. The hat-shaped casting was cut into several small pieces to find any porosity that may have developed. No porosity was found.

The metal front velocity through the cone portion of the pattern was approximately 1.6 cm/s. The metal front velocity in the outward radial direction in the flat flange portion of the casting was approximately 1.3 cm/s. These velocities agreed with the velocities measured in test bar pattern #5.

1.1.1.9. Formation of Iron Casting Defects

The metal front velocities for all iron bar castings are illustrated in Figure 1.1.1.9.1. as a function of coating air permeability. In general, the metal front velocity increased with increasing air permeability and pattern cross-sectional area-to-perimeter (A/P) ratio. The metal front velocity for all bars ranged from 4.2 cm/s to 5.4 cm/s when using the low permeability coating D. The high permeability coating F resulted in a metal front velocity of 7.8 cm/s in the #3 bar and a metal front velocity of 14.9 cm/s in the #6 bar.

The increasing velocity characteristic of these bars was apparently not limited by the rate at which the foam pattern could degrade. The velocity in the iron bar castings was controlled by the coating air permeability in the range of permeabilities used in this study. As stated earlier, the ratio of liquid to gaseous pyrolysis products is dependent on metal front temperature. The high pouring temperatures used in iron castings reduced the expanded polystyrene patterns to primarily gaseous pyrolysis products. These hot gases escaped easily from the mold cavity through the refractory coating. As the coating permeability increased, the gases were removed from the mold cavity more quickly, thus increasing metal front velocity. For a constant coating air permeability, the metal front velocity also increased with increasing pattern A/P ratio. Thick bar patterns having large A/P ratios retained heat in the molten metal for a

longer period of time. A hotter metal front degrades the foam pattern quicker and allows a faster moving metal front than that allowed by a cooler metal front.

To calculate the maximum metal front velocity in the iron bar castings, the average metal front temperature at the midpoint in the iron bar castings was estimated to be 1300°C. This value was used as the average metal front temperature, T_m , in Equation 1.1.1.5.3. The average density of the gas/liquid mixture of products in the kinetic zone was assumed to be 20.8 kg/m³ when casting iron bars. The remaining values in Equation 1.1.1.5.3 were not changed from the aluminum velocity calculation performed earlier. When these values were substituted into Equation 1.1.1.5.3, the maximum metal front velocity was found to be 9.5 cm/s. This velocity was well below the maximum velocity of 14.9 cm/s obtained in the iron casting trials. The large discrepancy between the experimental and calculated velocity results can probably be attributed to a higher heat transfer coefficient between the metal and pattern.

Metal front profiles measured during mold filling did not appear to be a function of metal front velocity in the iron casting trials. Unlike the aluminum bar castings where metal front profiles became increasingly concave with increasing metal front velocity, the metal front profiles in iron castings did not exhibit discernible trends.

1.1.1.10. Summary of Iron Casting Defects

The most prevalent defects occurring in iron lost foam castings were the surface carbon defects or "worm-tracks". These defects occurred more frequently on thicker pattern sections having high A/P ratios. To alleviate these defects, the metal pouring temperature should be increased. Burned-on sand defects in the iron castings were found to increase with increasing coating permeability and heat transfer coefficient through the coating. High permeability silica-based coatings are normally used when making iron castings in industrial foundries. In recent years, the use of less permeable coatings in iron casting has increased. In the iron casting trials performed in this study, less defects were formed when using the low permeability mica-based coating and the thick, medium permeability silica-based coating. These coatings provided more insulation and support to the molten metal while still allowing the pyrolysis products to escape the mold cavity. No misruns and only one porosity defect were formed in the iron casting portion of this study.

1.1.1.11. Defect Reduction in Complex Iron Lost Foam Castings

A methodology was proposed for reducing defects in new lost foam iron castings. The previous discussion has shown that coating selection is important in lost foam casting. A low thermal conductivity, mica-based coating or medium permeability silica-based coating should be selected for pouring lost foam iron castings. The proposed methodology applies to iron castings poured near 1400°C where the average pressure head height is 30 to 50 cm.

As an example of how a more complex new lost foam pattern might be poured using this methodology, a standard hat-shaped pattern was used. This is the same hat-shaped pattern used above to pour an aluminum casting. The A/P ratio of this pattern was found to be 0.61 cm which was very close to the A/P ratio of the #5 bar (0.59 cm).

A hat-shaped pattern with an expanded polystyrene foam density of 20.8 kg/m³ (1.3 lb/ft³) was gated in the same manner as the previous aluminum casting. Coating E was chosen and used to coat the pattern assembly. This coating was used since it gave good results in the test bar casting trials on the #5 bar pattern. After coating, the pattern was dried and attached to a 40.6 cm long hollow sprue. The hat-shaped pattern cluster was then compacted in silica sand and poured using a class 30 gray iron at 1400°C.

The metal front velocity through the cone portion of the pattern was approximately 7.2 cm/s. The metal front velocity in the outward radial direction in the flange portion of the casting was approximately 6.9 cm/s. These velocities agreed well with the velocities measured in the #5 bar iron casting.

Pictures of the sandblasted casting are illustrated in Figure 1.1.1.11.1. No burned-on sand defects were present on the surface of this casting, even in the small 6 mm diameter holes on the flange portion of the casting. There was, however, an area containing surface carbon defects on the upper surface of this casting. The hat-shaped casting was then cut into several small pieces to find any porosity that may have developed. No porosity could be found in any portion of this casting.

The surface carbon defects present on the hat-shaped casting also occurred on the #5 iron bar casting which had a similar A/P ratio. These defects could be eliminated by pouring at a higher metal temperature. The higher metal pouring temperature would

give the liquid pyrolysis products sufficient time to escape the mold cavity before solidification occurred.

1.1.2. Aluminum Coating Trials

A coating study was launched to determine the best coating for one particular part in the foundry atmosphere. Research has shown that for every casting in the lost foam process, there is a coating permeability window that results in the lowest scrap rate. The goals of this study were to determine the coating permeability window that results in the lowest scrap rate for a particular part in a sponsor's foundry and provide this information to the foundries so that the procedure could be followed to determine the best coating permeability window for other castings.

The test procedure began with the identification of a part. The parts were assembled on a cluster. The dry weight of the cluster was recorded. Two coatings were used and they were identified as normal production and high permeability coating. The clusters were each coated using one of these coatings. The wet and dry weights of the clusters were recorded. The clusters were cast after the coating had dried and the pouring time and temperature were also recorded. The castings were first visually inspected and the ones that passed this inspection were sent to x-ray inspection.

Each casting was given a score based on the number and severity of the defects. The castings were divided into sections based on area/perimeter ratio and each section received a score based on the defects presented in that section. The castings with zero or very few defects were given a score of 0 while the castings with a large number of defects were given a score of 5.

The average total of the score and the 95 % confidence interval for both the high permeability and the production coating is illustrated in Figure 1.1.2.1. This figure does not show a severe change in the average casting score between the production and the high permeability coating, but a closer, detailed inspection of the results revealed an interesting fact. The area-to-perimeter ratio of each section was calculated. These results show the high air permeability coating is associated with fewer defects in sections of low area-to-perimeter ratio while the low permeability coating is associated with fewer defects in sections of high area-to-perimeter ratio. The production coating produced fewer defects for sections of the casting with high area to perimeter ratios. Figure 1.1.2.2 summarizes the average score for each section of the casting.

Average score for the two Air permeabilities

{0=best 5=worst}

Means and 95.0 Percent LSD Intervals

Figure 1.1.2.1 - Average Defect Score for all Casting Sections

Figure 1.1.2.2 - Average Defect Score for Sections with Different Area/Perimeter Ratios

Some interesting conclusions can be made from these results. Since most parts cast in the lost foam process have more than one area-to-perimeter ratio, each part has a coating air permeability window that results in the lowest scrap rate. This coating air permeability window must be established for each part and satisfy all sections of the part. This coating air permeability window must be established and maintained for each individual part cast in the lost foam process. The final conclusion is that some parts may be impossible to cast in the lost foam process if they consist of a wide range of area to perimeter ratios.

1.1.3. Foundry Iron Coating Trials

The coating trials were continued for iron casings in a sponsor's foundry. Iron castings, like aluminum castings, have a coating air permeability window that results in the lowest scrap rate for each part. A similar set of experiments was conducted at an iron lost foam foundry to find the coating permeability that produced fewest defects in a particular part. The secondary goal of this experiment was to establish a test method to find the best coating for other parts. The test procedure began with the identification of a part.

Four different coatings were under study. One was identified as low permeability coating, one was a modified coating with an air permeability close to the production coating, production coating, and a high permeability coating. The parts were individually weighed and coated. The parts were dried and glued to the gating system to make clusters. The clusters were coated and dried. The clusters were randomly cast. After shakeout, the parts were visually inspected. The parts that did not pass the visual inspection were scraped; the parts that passed the visual inspection were sent for leak test. The percent parts that failed the visual and the leak test is shown in Figure 1.1.3.1.

The results indicate that the coating with the lowest permeability has only 25% scrap rate as compared to the modified coating with 60% scrap and the production costing with 53.3% scrap rate. It was concluded that the coating with the lowest air permeability resulted in the lowest scrap rate. This test will be continued for this part to further reduce the coating permeability window.

1.2 UMR Research

The major goals of the research at the University of Missouri-Rolla during the last two years were (a) continue to

% Total Scrap vs. Air Permeability

Figure 1.1.3.1 - Effect of Coating Air Permeability on Total Scrap for Iron Castings

understand the relationships between casting parameters and mold filling (including metal velocity and metal front profile) and (b) continue to develop the relationships between mold filling, pattern pyrolysis, transport of pyrolysis products through the coating, and casting defects. While most of the research has involved producing and analyzing a variety of castings made using both "synthetic" and "commercial" EPS patterns, some time has been spent reviewing and further analyzing results obtained earlier in the research in the context of what we have since learned.

1.2.1. Historical Data and Comparisons

A large number of individual sets of experiments have been performed, both at UMR and UAB, since the inception of the lost foam research. Data from these tests were correlated to determine the reproducibility between experiments over time, between various investigators at UMR, and between UMR and UAB.

One of the key observations in earlier tests was that internal porosity in aluminum castings, formed as a consequence of entrapped liquid pyrolysis products, was created when the velocity of the metal front exceed a "critical" velocity. Data were correlated from eight tests in which the critical velocity was determined. The critical velocity tended to increase with increasing area-to-perimeter ratio of the casting as shown in Figure 1.2.1.1. For thick (high A/P ratio) castings, internal porosity due to entrapped liquid polymer was not observed. This trend appears to be similar for both 319 and 356 aluminum alloys poured into several casting shapes. A high A/P ratio indicates a large amount of foam to be decomposed and a small area of coating through which the pyrolysis products can be transported - this would suggest that pyrolysis-related defects would be more likely to occur! However the shape of the metal front also changes, particularly as the thickness increases. In thick sections, a pronounced arrow-shaped metal front can develop, helping to transport pyrolysis products toward the coating where they can be safely removed. In thin castings, surface energy effects keep the metal front profile flatter; increasing the velocity of the flat metal front may make the metal front unstable, or cause turbulence, thereby trapping liquid polymer in the metal stream.

The metal velocity has been measured for both 319 and 356 aluminum alloys in several experiments, both at UMR and UAB. When only as-blown patterns are considered, the data from all of these sources appear to be very similar as shown in Figure 1.2.1.2, provided that processing variables such as coating permeability and pouring temperature are also similar. The

Figure 1.2.1.1. The critical velocity above which internal porosity is observed in aluminum castings (solid squares) tends to increase with increasing A/P ratio of the pattern. The open squares indicate that no porosity was observed. Porosity was not observed in thick castings, having a large A/P ratio.

scatter of points in Figure 1.2.1.2 is likely a consequence of other variables, such as coating thickness or metallostatic pressure head, which did vary from test to test. The good correlation between these several sets of data does lend confidence that the metal velocities are quite reproducible, not only at UMR but also between UMR and UAB. In addition, both the 319 and 356 alloys behaved similarly. Finally, Figure 1.2.1.2 shows that, when a high permeability coating was used, increasing the A/P ratio of the pattern increased the metal velocity only a small amount, suggesting that the velocity is controlled more by the metal-foam interface (foam decomposition) than by the metal-foam-coating interface (transport of foam decomposition products). Earlier results showed that fillability (or the likelihood of casting misruns) depended on both metal-foam and metal-foam-coating interfaces.

However, when the metal velocities obtained in as-blown patterns are compared with velocities obtained in patterns cut from thick planks, a large difference is observed as in Figure 1.2.1.3. The cut patterns typically give much higher metal velocities, indicating that much faster rates of foam recession occur. In addition, the metal velocity may decrease at larger A/P ratios — the much more rapid recession rates increase the decomposition product formation so much that the small perimeter (compared to the area, or volume, of foam patterns) begins to restrict foam recession. Clearly, the structures of the foam, such as foam density gradients, foam bead size, and degree of bead fusion, play a role in foam decomposition and transport, and thus on metal velocity.

Reproducibility of metal velocities in gray iron castings within UMR and between UMR and UAB was not as good as that for aluminum as shown in Figure 1.2.1.4. The metal velocity does increase somewhat with increasing A/P ratio. However differences in iron composition, pouring temperature, foam patterns, and other processing variables likely have a large effect on the results and thus the correlation of velocities.

1.2.2 Metal Flow and Gating Effect in Pendant Patterns

In a prior report, the effect of gating design on metal flow in a "pendant" pattern was described. This work showed that, by designing the gating so that metal flowed through the pattern and back into runner, internal porosity in the castings could be prevented. Based on our experience in understanding metal front profiles gained since that report, the metal front profiles in these castings have been revised to better illustrate the gating system effect.

Figure 1.2.1.2. Good reproducibility for metal velocity versus A/P ratio is obtained both within UMR and between UMR and UAB. Data is for a high permeability coating. The metal velocity increases slightly with increasing A/P ratio when blown patterns are used.

Figure 1.2.1.3. The type of foam pattern has a significant effect on metal velocity in aluminum. Normally a maximum velocity of near 1 in./s is observed in blown patterns, but much higher velocities are obtained in patterns cut from thick plank, and the usual observation that velocity increases with A/P ratio may be reversed.

Figure 1.2.1.4. Reproducibility of metal velocity for gray iron castings using data within UMR and between UMR and UAB is not as good as that observed for aluminum castings, likely because of differences in composition, pouring temperature, and foams. The velocity does increase with increasing A/P, just as for aluminum.

A number of studies have shown that, at least for relatively small lost foam castings, the fillability, fill times, and metal velocities are virtually unaffected by gate size¹⁻⁷. Gate location (top vs. side vs. bottom) affects metal velocity by changing metallostatic pressure. Gate location does, however, influence the formation of certain types of casting defects and is still an important consideration for the process.

Defects in aluminum lost foam castings are often caused by entrapped polymer residues, either internally or on the surface. It might be possible to facilitate removal of the decomposition products by an appropriately-designed gating system. A "pendant" pattern (a portion of a tube holder for a heat exchanger) was used as the pattern to test this hypothesis. The metal front was controlled by the number and placement of gates, the placement of the pattern on the cluster, and the permeability of the coating. The goal was to produce a gating system and cluster arrangement that forced the runner to fill at a slower rate than the pattern, resulting in a molten metal front that pushed the decomposition products into the runner, thus removing the main source of defects -- trapped liquid pyrolysis products -- from the actual casting.

The patterns were as-blown 1.3 lb/ft³ industrial patterns with the gating system attached. The down sprues were industrial blown foam having a X-shaped cross-section and a nominal density of 1.6 lb/ft³. Extra gating stock was cut from 1.3 lb/ft³ EPS sheets. The pendant patterns were cut to a length of approximately 22 in. (56 cm), leaving five curved sections and four gates into the pattern. The patterns and their gating systems were attached to the down sprues by 1.5-in. (3.81 cm) wide, 1-in. (2.54 cm) thick, 6-in. (15.2 cm) long runners with hot melt glue as shown in Figure 1.2.2.1. Both a high permeability alumina coating and a low permeability silica coating were used. The aluminum castings were poured using Sr-modified A356 alloy.

Data was acquired using 20 electrical probes inserted into the pattern. Isochronal diagrams showing the metal position and the shape of the molten metal front were constructed based on the time at which the metal reached each probe. Several sets of pendant castings were produced; as each set was analyzed, suggestions for changes in the processing variables were made.

Figure 1.2.2.1 A typical cluster used in producing castings with the pendant pattern. The height of the pendant pattern (on the left) is approximately 22 in. A fiber pouring cup on top of the X-shaped sprue is not shown. The cluster shown here was used for one of the “modified” gating systems.

1.2.2.1 Base-line tests

Castings were poured with the original pattern, with no alterations. In the base-line castings, the molten metal front progressed faster up the runner than the pattern. The metal front in the pattern itself was not "level", i.e. the pattern foam was displaced more rapidly near the gates than opposite the gates. Decomposition products were pushed away from the runner and gates and were trapped in the casting as internal porosity.

1.2.2.2 Redesigned Gating Systems

The goal of redesigning the gating system was to force the molten metal front to progress up the pattern first, pushing the decomposition products into the runner. The first change was to remove the lowest side gate and replace it with a bottom gate of the same cross-sectional area as the gate that was removed. Castings were poured with high and low permeability coatings. The bottom gate did allow the molten metal to enter the pattern before the runner filled to the side gate, and the lower section of the pattern filled in a more level fashion. But the redesigned gating system did not alter the fill pattern after the first side gate was reached; the molten metal still progressed faster in the runner than in the pattern and internal porosity was again observed.

In a second approach, castings used the bottom gate; however, the pattern was coated with a high permeability coating while the down sprue and runners were coated with a low permeability coating. This dual-coating design was intended to decrease the ability to transfer decomposition products from the runner, thus slowing the metal front in the runner. In addition, the pressure head was increased by approximately 12 inches. The dual-coating patterns changed the fill pattern only slightly. The runner still led the pattern, the metal front was not level after the first side gate, and porosity was observed.

1.2.2.3 Redesign of the Cluster

The pattern was reversed on the horizontal runner so that the pattern was closest to the sprue. The molten metal reached the base of the bottom gate before the base of the up-runner, forcing the metal front in the pattern to lead that of the front in the runner. For the casting poured with the high permeability coating the molten metal front in the pattern was much flatter but the front in the runner still reached the side gates first. Some porosity was still observed.

An up-runner with a smaller cross-sectional area was also employed. The metal front in the pattern did appear to be slightly flatter than in the previous castings and reached the first side gate sooner than did the metal in the runner. The internal porosity was much less than in the previous castings, but also the pouring temperature was higher by 25°C. Introducing a small choke in the base of the up-runner was not any more effective in promoting the desired metal front.

1.2.2.4 Straight Pattern

The final redesign in the pendant study was to produce a cluster with a straight pattern instead of the curved pattern. The pattern was cut from 1.3 lb/ft³ EPS foam to the same dimensions as the pendant pattern. The only difference is that the length was approximately 6 inches shorter due to the lack of curvature inherent in the pendant pattern. The straight plate was attached to a runner system taken from a pendant casting so as to be sure that the cluster closely represented the original bottom gated cluster.

The molten metal successfully filled the pattern faster than the runner. Also, the flow was skewed toward the gates, allowing metal to flow from the pattern into the runner. That the pattern filled faster than the runner suggests that the curvature of the pattern in previous experiments was the primary culprit in causing the runners to fill faster. The straight plate pattern was the only casting where the molten metal front in the pattern led the front progression in the runner during the entire fill.

1.2.2.5 Analysis of Defects

Radiographic inspection of the castings revealed large internal pores in each of the castings except the straight plate. The pores tended to concentrate in three areas: in association with the holes in the pattern, at the far side from the gate where liquid pyrolysis products might accumulate, and immediately after the gate where the metal front turned a corner.

By producing a front that was skewed towards the gates as the metal front in the pattern led that of the runner, the foam decomposition products were pushed into the runner and internal porosity in the casting was eliminated. This was proved by the success in producing a sound casting with the desired metal front progression when a straight plate pattern was used. But the curvature of the pendant pattern, with its increased length, made the control of the metal front by the gating and coating modifications difficult.

In previous work^{3,4,7}, it was found that a maximum metal velocity of about 1 in./s. is required to produce a sound casting. All of the castings, including those with low permeability coatings, exceeded this upper limit. Only the straight plate casting was sound, without internal pores. Control of the molten metal front did allow for the decomposition products to be pushed into the gating system. This suggests that control of the molten metal front is essential in producing quality castings in the lost foam process.

1.2.3 Metal Velocity and Defect Formation in Aluminum Flange Patterns

Associated with the introduction of the lost foam casting process are new classes of casting defects. Some of these are related to problems encountered in producing the foam pattern or arise due to inadequate compaction of the sand. Another source of defects is related to phenomena occurring during mold filling, when the foam pattern is displaced by molten metal. One of the mold filling defects is metal penetration (or burned-on sand) caused by fracture of the refractory coating. A second class is made up of surface and internal defects related to the pyrolysis products from the foam pattern.

Using a statistically-designed experiment for which five casting parameters were systematically varied, a set of flange patterns was poured,. The effects of these five parameters on the metal velocity during fill, the shape of the metal front, and a variety of casting defects were measured. The tests revealed a narrow "window" of allowable metal velocities within which a defect-free aluminum casting can be produced. The entire casting process, and in particular the properties of the refractory coating, must be designed to assure that fill occurs within this window.

1.2.3.1 Procedure

A set of sixteen flange patterns was poured using 356 aluminum alloy. A half-factorial statistically-designed experiment was used to determine the relative significance of five casting variables on metal velocity and casting defects. One casting was poured for each set of factor levels.

The pattern, shown in Figure 1.2.3.1.1, was poured horizontally through one gate. Electrical probes were arranged on one side of the pattern; the probes were connected to a voltage supply and then through a data acquisition system to a computer. When liquid metal reached each electrical probe, the

Figure 1.2.3.1.1. The flange patterns used in a number of the tests described in this report. A gated flange pattern, using a foam down sprue and a short foam gate, was assembled using thermoplastic adhesive. A fiber pouring cup was placed on top of the sprue. The cross-section through the flange shows the geometry and dimensions.

voltage in the circuit changed, permitting the location of the metal front to be monitored. The arrangement of the probes is shown in Figure 1.2.3.1.2.

Five factors were studied, each at two levels, and shown in Table 1.2.3.1.1. The patterns were as-blown using polystyrene beads. Half of the patterns were produced by autoclave (A) in which steam was introduced from both sides of the pattern, and the other half by cross-steam (C); in the cross-steamed patterns, steam was first introduced from one side of the tool, then from the other side, and finally from both sides. Half of the patterns were produced with a nominal density of 1.35 lb/ft³, the others of 1.85 lb/ft³. Patterns were gated in two different locations -- half were gated near a blow hole so that the nominal density of the pattern decreased away from the gate ("decreasing foam density gradient"); the other half were gated so that the nominal density of the pattern increased away from the gate ("increasing foam density gradient"). Both a high permeability alumina coating and a low permeability silica coating, representing extremes in permeability for standard commercial coatings, were used. Finally, castings were poured at either 750°C or 850°C.

The foam beads were originally expanded to a density of either 1.35 or 1.85 lb/ft³. After the patterns were blown, the density at the centerline of the patterns was close to the nominal density. However the density was higher at the pattern surface, where the degree of bead fusion was better. The two blowing methods gave little difference in the density gradient and, as will be shown later, no effect on metal velocity and incidence of defects was found. Comparison of the densities at the centerline of the pattern near the blow holes (12 o'clock position) and between blow holes (4 o'clock position) revealed a small density gradient, but no effect of blowing method was observed.

1.2.3.2 Metal Velocities

Metal velocities were measured in a circumferential direction for each of the four sets of probes, as indicated in Figure 1.2.3.1.2. The results are included in Table 1.2.3.2.1. For purposes of data analysis, an overall average velocity was calculated from the velocities obtained for each channel.

A statistical analysis was performed using the overall average velocity data. By far the most important factor influencing metal velocity was the coating. The nominal foam

Figure 1.2.3.1.2. Arrangement of the electrical probes in the flange items used for many of the tests described in this report. Four channels of five probes each were used to provide information on when the liquid metal front reached 20 locations in the casting.

density and the pouring temperature played a minor role, and neither the blowing method nor the location of the gate were statistically significant. The highest metal velocities were observed for the low density (1.35 lb/ft³) foams, the high permeability coating, and a high (850°C) pouring temperature.

The results for the metal velocity were expected. With a low density foam, there is less polymer to decompose and fewer pyrolysis products to transport out of the system. Both a higher foam recession rate and more rapid transport of air and gaseous products lead to faster metal velocities. The higher permeability coating permits more rapid wicking of liquid polymer away from the foam/coating/metal interface and more rapid transport of air and gases through the coating. The higher pouring temperature increases the foam recession rate, increases the amount of gaseous pyrolysis product, and speeds wicking by heating the coating and liquid polymer to a high temperature more rapidly.

1.2.3.3 Defect Analysis

The quality of the castings was judged in several ways and the defects observed in each casting are summarized in Table 1.2.3.2.1. Visual examination revealed misruns, metal penetration, and surface defects. X-ray radiography revealed internal porosity. Dye penetrant inspection located some fold defects and the castings were then broken to reveal additional folds. The defects were quantified as much as possible; for example, internal pores in the half of each casting that did not contain the electrical probes were subjected to image analysis, which provided the approximate percentage of the plan casting area containing pores. The total number of pores was counted from radiographs. The number and approximate total area of folds were determined using photographic and image analysis methods. The percentage of the misrun casting that did not fill was calculated. To quantify surface defects and surface collapse, the included angle (measured from the center of the casting) that contained the defect was measured and expressed as a percentage. No quantitative measurement was given for penetration.

The severity of each defect was plotted versus the overall average metal velocity. Figure 1.2.3.3.1 shows internal pores caused by entrapped foam pyrolysis products and shows that the amount of internal porosity becomes appreciable only when the average metal velocity exceeds about 0.7 in./s (1.8 cm/s). Figure 1.2.3.3.2 shows typical folds, both at the fracture surface and in a polished cross-section. Figure 1.2.3.3.3 shows

TABLE 1.2.3.2.1.

THE METAL VELOCITIES AND TYPES AND AMOUNTS OF CASTING DEFECTS FOR THE ALUMINUM FLANGE STUDY

<-----Average Metal Velocities (in./s)----->							<----- Defect Analysis ----->							
Casting ID	Casting Number	INNER	Channel 2	Channel 3	OUTER	AVERAGE	Number of Pores	Area % Pores	Surface Defects	Misruns % Unfilled	Surface Collapse	Number of Folds	Fold Area (in ²)	Penetration Severity
A3PHTHGI	1	1.226	1.914	1.685	1.682	1.63	2	0.00	44	0	0	5	0.42	1
A3PHTLGD	2	0.916	0.802	0.698	0.653	0.77	18	0.62	1	0	0	5	1.39	0
A3PLTHGD	3	0.497	0.592	0.625	0.665	0.59	3	0.04	0	0	0	2	0.05	0
A3PLTLGI	4	0.436	0.504	0.503	0.532	0.49	1	0.00	0	0	8	0	0	0
A8PHTHGD	5	0.657	0.850	0.908	0.973	0.85	23	0.25	0	0	0	15	1.135	1
A8PHTLGI	6	0.728	0.788	0.790	0.870	0.79	33	0.60	0	0	0	7	1.09	0
A8PLTHGI	7	0.373	0.414	0.418	0.446	0.41	3	0.00	3	0	0	0	0	0
A8PLTLGD	8	0.362	0.474	0.511	0.540	0.47	3	0.00	0	0	13	0	0	0
C3PHTHGD	9	0.849	1.001	1.114	1.200	1.04	3	0.00	0	0	0	8	1.44	0
C3PHTLGI	10	0.800	0.950	1.050	1.152	0.99	20	0.21	28	0	0	5	0.29	1
C3PLTHGI	11	0.488	0.555	0.591	0.630	0.57	0	0.00	0	0	0	0	0	0
C3PLTLGD	12	0.429	-	0.553	0.592	0.52	4	0.00	0	0	24	0	0	0
C8PHTHGI	13	0.751	0.987	1.279	1.294	1.08	6	0.25	58	0	0	5	0.35	1
C8PHTLGD	14	0.766	0.830	0.854	0.921	0.84	32	0.68	0	0	0	2	0.03	0
C8PLTHGD	15	0.362	0.425	0.471	0.496	0.44	0	0.00	0	0	17	0	0	0
C8PLTLGI	16	0.272	0.350	-	-	0.31	0	0.00	0	28	-	0	0	0

Figure 1.2.3.3.1. The photograph of a fracture surface from a flange casting shows a large internal pore caused by entrapped liquid polymer. Both the number of internal pores and the area percent of internal porosity are significant when the average metal velocity is above about 0.7 in./s. Note that a combination of a high pouring temperature and a low density foam prevented pores in two of the castings that filled rapidly.

Figure 1.2.3.3.2. Folds in an aluminum flange. (a) A fold at the end of a casting where two liquid metal streams met, (b) a small fold near the edge of a casting, and (c) photomicrograph of the cross-section of a fold. The wall thickness of the castings is 0.56 in.

Figure 1.2.3.3.3. Both the number of folds and the surface area of the folds are large when the average metal velocity is above about 0.7 in./s.

that folds appear when the velocity is greater than about 0.7 in./s (1.8 cm/s).

In a few castings, a rough surface (orange peel, or carbon, defect) was observed in isolated areas of the casting as in Figure 1.2.3.3.4. Figure 1.2.3.3.4 also shows that the surface defect tended to be most severe when the metal velocity was higher than about 0.95 in./s (2.4 cm/s).

Two types of penetration defects were observed. One type formed on the drag side of the casting, typically between the holes in the flange, and occurred for velocities higher than about 0.8 in./s (2.0 cm/s) as in Figure 1.2.3.3.5. In Figure 1.2.3.3.5, a "1" indicates that severe penetration was observed, while a "0" indicates that no penetration was observed. Severe penetration was tightly adherent to the casting and could not be chipped off. Examination of the cross-section of the casting indicates nearly complete metal fusion between the penetration defect and the casting. Only a small amount of coating remained at the edge of the penetration defect, and a few sand grains were engulfed by the metal. The top surface of the casting, however, appeared to be unaffected -- it was still smooth and intact. This severe penetration occurred between holes in the flange, where sand compaction is expected to be poorest and the surface area is large. Figure 1.2.3.3.5 includes not only the penetration defect but pieces of the coating that broke off and floated to near the cope surface of the casting. This suggests that the penetration defect occurred after the entire casting was filled.

The second type of penetration defect was also found on the drag side of the casting but was accompanied by depressions on the cope surface directly opposite the penetration as shown in Figure 1.2.3.3.6. This penetration typically was connected to the casting in only a few locations. Coating remained between most of the burned-on material and the casting, and the defect was easily removed by chipping. This defect occurred when the metal velocity was lower than about 0.55 in./s (1.4 cm/s).

Finally, one of the castings did not fill completely as illustrated in Figure 1.2.3.3.7. The misrun occurred for the lowest metal velocity, about 0.31 in./s (0.8 cm/s).

Based on these observations, it is apparent that there is a metal velocity "window" within which casting defects can be minimized or prevented. If the velocity is too low, misruns and surface collapse/mild penetration may occur. If the velocity is too high, porosity, folds, surface defects, and even severe

Figure 1.2.3.3.4. The photograph shows pyrolysis-product surface defects on the cope surface of the flange. Surface defects became particularly severe when the average metal velocity exceeded about 0.95 in./s.

Figure 1.2.3.3.5. Cross-section through a severe penetration defect, showing the continuity of the metal across the original interface between the drag surface of the casting and the sand. Coating fragments that were detached and floated into the casting are also shown. Severe penetration was observed when the metal velocity exceeded about 0.8 in./s.

Figure 1.2.3.3.6. Photograph of the cope surface near the end of a casting, showing collapse of the cope surface. Penetration defects, which were easily chipped off, were present on the drag immediately beneath the surface collapse. Cope surface collapse accompanied by the less severe penetration occurred for metal velocities below about 0.55 in./s.

Figure 1.2.3.3.7. Casting 16, which was poured at a low temperature with a low permeability coating and a high density foam pattern, did not fill completely, resulting in a misrun. The misrun was observed at a low metal velocity.

penetration may occur. Figure 1.2.3.3.8 illustrates the typical velocity ranges for each of these defects and shows that there is a narrow velocity window, between about 0.55 and 0.7 in./s (1.4 and 1.8 cm/s), where no defects are observed.

1.2.3.4 Metal Front Profiles

To help understand the origin of casting defects, the times at which the metal front reached each of the twenty electrical probes were used to construct a picture of the shape of the metal front during filling of one side of the flange. Figures 1.2.3.4.1 and 1.2.3.4.2 provide additional clues; these figures are "maps" of the locations of the internal porosity and folds in all of the castings and suggest the most likely locations at which these defects occur.

Internal pores are concentrated in three general areas. First, a significant number of pores are found at the end of the casting where two streams of metal meet. This is not surprising, since this area of the casting should be "overloaded" with liquid pyrolysis products pushed ahead of the metal front, particularly when the metal velocity is high and there isn't sufficient time for the liquid polymer to be removed from the system. Second, pores are located near the inner and outer diameters of the flange; in these areas, the liquid polymer is pushed to the sides of the pattern and liquid polymer transport may not be rapid enough to eliminate the pyrolysis products. Third, porosity occurs in the thinner (outer) section of the casting and is associated with the holes in the flange.

Similarly, folds form most frequently in three general areas. First, large folds are found at the end of the casting -- the junction between the two streams of metal. Second, small folds are found near the inner and outer diameter of the flange and suggest that the metal front may become unstable and "turn over" due to the influence of the sides of the pattern. Third, large folds were observed between holes in the flange; these folds are oriented perpendicular to the metal front.

Figure 1.2.3.4.3 shows a metal front profile. The metal front divides as it flows around a hole in the flange. The holes and the inner and outer diameters of the pattern/coating interface slow up the metal front at those locations with the front in between bowing out ahead. When the two metal fronts rejoin, a film of oxide and liquid polymer may be trapped between the two streams, producing a fold parallel to the direction of the metal flow. Often one of the two streams undercuts the other, producing a fold with a large surface area parallel to and

Figure 1.2.3.3.8. Summary of all of the various defects versus average metal velocity. Only within a narrow velocity window of about 0.5 to 0.7 in./s were no defects observed.

Figure 1.2.3.4.1. A summary plot showing the location of the internal pores in all sixteen flange castings as observed from inspection of radiographs. Pores tend to be concentrated where the two metal streams met at the end of the casting, near holes in the flange, and along the edges of the casting at the inner and outer diameters.

Figure 1.2.3.4.2. Density profiles circumferentially along flange patterns of two nominal densities. In each case, patterns were produced by a normal amount of fusion and by deliberate over-fusion. Over-fused patterns had slightly lower densities than the patterns fused normally. Locations of highest density are near blow holes.

Figure 1.2.3.4.3. The metal front profiles for Casting 5; each line represents the probable location of the metal front at one second intervals. These metal front positions are derived based on the time required for the front to reach the twenty electrical probes as well as the locations of defects such as porosity and folds found in the casting. The shaded areas represent folds and the open round areas represent internal pores. The approximate location of the folds with respect to the cope and drag surfaces are also shown.

just below the top surface of the casting. Similarly, when the two metal fronts progressing in opposite directions from the gate meet, the oxide and polymer residue may be trapped. Finally, small folds are often observed near the holes and near the inner and outer diameters of the casting. These folds suggest that there is some local turbulence during filling that cannot be accounted for by our rendering of the metal profiles.

1.2.3.5 Internal Porosity

A statistical analysis was performed to determine the relative significance of the five casting factors on both the area percent internal porosity and the number of pores. By far the most significant variable affecting the amount of internal porosity was the coating permeability. Pouring temperature and, to a lesser extent, nominal density of the pattern played a small role. Neither blowing method nor gate location affected the amount of porosity. To minimize porosity, a low density foam, a low permeability coating, and a high pouring temperature are desirable.

1.2.3.6 Folds

The statistical analysis also showed that coating permeability most influenced the number and area of the folds observed in the castings; pouring temperature and gate location were less significant, while the blowing method and the nominal foam density were not significant. Folds were least likely to occur for a low permeability coating. Folds are similar in some respects to the internal porosity, with the most severe fold defects occurring at high metal velocities caused by the high permeability coating.

Below some critical velocity, the combination of temperature, time, amount and type of pyrolysis products, recession rate, wetting and wicking rates, and fraction of the metal solidified permit the film of oxide and pyrolysis products to be pushed to the coating and removed. But for higher metal velocity, there is less time for pyrolysis products to be transported; a greater percentage of the pyrolysis products are liquid; the recession rate of the foam increases faster than the rate of transport of liquid pyrolysis products; and the metal front may be turbulent or even pulsing.

1.2.3.7 Surface Defects

Rough surfaces were found on most of the castings that filled at a high velocity. They are likely caused by liquid

polymer that was pushed to the top surface of the casting but did not have time to wet and wick into the coating. Instead the liquid polymer trapped between the metal casting and the coating eventually pyrolyzed, causing the rough surface.

1.2.3.8 Penetration

Very severe penetration was observed in most of the castings that filled at a high velocity. The penetration defect was observed only on the drag surface, suggesting that relatively poor compaction, or low density sand, contributed to the defect. The large volume expansion of silica sand may also encourage fracture of the coating. The high metal velocities cause the liquid metal to remain at a higher temperature for a longer time, thus causing the sand to heat to a higher temperature and further increase the amount of expansion of the silica sand. Finally, only the high permeability coating led to the penetration defect -- the strength of the coating may also play a role.

1.2.3.9 Surface Collapse / Mild Penetration

At low metal velocities, a different type of penetration defect was observed. This penetration, which was easy to remove due to the weak attachment, was observed near the "end" of the flange, where the two metal streams met, and occurred only for the low permeability silica coating and thus low metal velocity.

The slow metal velocity caused the foam to soften and begin decomposing further ahead of the metal front -- sand at the cope surface then collapsed the coating to produce the cope surface depressions, while forcing displaced liquid metal through the drag coating. The sand also likely is hotter further ahead of the metal front, causing the entire pattern to collapse.

1.2.3.10 Misruns

Very slow fill causes the metal to cool and solidify to a sufficient degree that a misrun occurs. This occurred in only one of the castings, when a low permeability coating, a low pouring temperature, and a high density foam were used. A low pouring temperature in and of itself is not entirely to blame for the misrun. Instead, the low recession rate of the foam pattern and the slow rate of transport of the foam pyrolysis products cause a low metal velocity; the slow velocity in turn permits more of the heat content of the liquid metal to be lost to the surroundings, causing the casting to solidify prematurely.

1.2.3.11 Summary

The velocity and/or shape of the metal front represent the major "symptom" for understanding defect formation in aluminum lost foam castings. Low metal velocities may lead to surface collapse/minor penetration and misruns. High metal velocities lead to internal porosity, folds, surface defects, and possibly serious penetration. Velocity and metal front profile are controlled by the casting parameters. The coating is by far the most crucial casting variable that affected metal velocity and the type and severity of casting defects. The density of the foam pattern and the pouring temperature play a secondary role. The presence or absence of holes and major changes in section size influence the metal profile and thus defect formation.

This study reaffirms the importance of casting variables, particularly coating properties on the velocity of the liquid metal front, and demonstrates the relationship between metal velocity and casting defects. In addition, the morphology of the metal front is important, particularly in controlling defects such as folds. In complex castings such as those containing holes, changes in cross-section, or changes in direction; in castings in which the metal flow is turbulent; and in castings having multiple gates, defects can be introduced when two streams of liquid metal meet. A critical metal velocity window exists for a particular casting, and the casting variables must be adjusted to provide actual metal velocities within this velocity range.

1.2.4 Additional Work on Aluminum Flange Castings

The initial work using the flange pattern for producing aluminum castings suggested that high pouring temperatures may help to eliminate some pyrolysis-related casting defects. Partly in an effort to verify this, an additional set of flange patterns was poured using A356 aluminum and the same gating as described in Figure 1.2.3.1.1 was used. The castings produced in this series are described in Table 1.2.4.1. In this set of castings, a single relatively high permeability aluminum silicate coating was used and the flanges were poured at temperatures ranging from 750°C to 900°C. The patterns themselves were somewhat different — two foam densities (1.35 and 1.85 lb/ft³), two blowing methods (autoclaved and cross-steamed), and two curing times (regular and overfused) were used. The castings were radiographed to check for internal porosity and, after visual and dye penetrant inspection, were fractured to reveal folds. Average metal velocities were measured from the gate toward the end of the casting opposite the gate along four radii (from near the inside diameter to near the

TABLE 1.2.4.1.
CASTINGS POURED IN THE SPECIAL SERIES OF ALUMINUM FLANGES

Casting Designation	Nominal Foam Density lb/ft ³	Pattern Blowing Method	Degree of Fusion	Pouring Temperature °C
M1	1.85	Cross-steamed	Regular	775
M2	1.85	Cross-steamed	Regular	800
M4	1.85	Cross-steamed	Regular	875
M5	1.85	Cross-steamed	Regular	900
M6	1.85	Autoclaved	Regular	850
M7	1.85	Autoclaved	Regular	850
A2	1.85	Autoclaved	Over-fused	850
A3	1.85	Autoclaved	Over-fused	800
MO1	1.35	Cross-steamed	Over-fused	775
A1	1.35	Autoclaved	Over-fused	850
N1	1.35	Cross-steamed	Regular	750
N2	1.35	Cross-steamed	Regular	900
N3	1.35	Cross-steamed	Regular	850
NO1	1.35	Cross-steamed	Over-fused	875
N4	1.35	Autoclaved	Regular	850
PO1	1.35	Autoclaved	Over-fused	875

outside diameter). These four velocities were then averaged for correlation with casting defects and casting parameters.

Increasing the pouring temperature from 750 to 900°C increased the metal velocity by nearly 50% when a low density (1.35 lb/ft³) pattern was used. A similar increase in metal velocity was observed when the nominal density of the pattern decreased from 1.85 to 1.35 lb/ft³. However the average velocity was nearly independent of pouring temperature for the high density foam. Average velocities for all of the castings were greater than 0.7 in./s, at or above the critical velocity found earlier for formation of internal porosity and folds in the flange pattern when other coatings were used.

The number of folds was estimated by breaking the casting into small pieces, often with surface imperfections serving as guides. Folds were almost always located at the end of the casting, where the two metal streams met. Folds were also found between holes in the flange, as well as at seemingly random locations in the casting. Figure 1.2.4.1 summarizes the locations of all of the folds observed in the 14 castings in this series. Folds normally were not observed until the pattern was at least 50% replaced by the molten metal.

The number and surface area of the folds were determined for each casting. The folds were divided into two categories -- folds occurring at the end of the casting where the two streams met and "miscellaneous" folds. The total fold area and the number of folds followed a pattern similar to that observed in the first aluminum flange series. Folds seldom occurred in the flange pattern for velocities less than 0.7 in./s and appear to be particularly severe and numerous just above this critical velocity.

The number and area of folds were also plotted versus the pouring temperature and are illustrated in Figure 1.2.4.2. The fold area may have decreased slightly as the pouring temperature increased but no influence of pouring temperature on the total number of folds was evident.

The density of the patterns would be expected to have two counterbalanced effects on the severity of fold defects. The low density foams lead to higher metal velocities, which might increase defects because there is less time for the pyrolysis products to be removed into the coating. However, fewer pyrolysis products will form from the low density foams, thus reducing defect severity. There is little substantial effect of the foam density on the severity of the total amount of folds.

Figure 1.2.4.1. Approximate location of fold defects in the sixteen flange castings in the special (Jackson) series of castings.

Figure 1.2.4.2. The total number of folds observed in the special (Jackson) series of flange patterns does not appear to depend on the pouring temperature.

Based on the observations from this set of castings, there appears to be little effect of either foam density or pouring temperature on fold defects – if there is any trend, low density foams and higher pouring temperatures provide only slightly better chances of minimizing folds.

1.2.5 Metal Velocity and Defect Formation in Iron Flange Patterns

As a complement to the research done producing aluminum flange castings, 26 gray iron castings were poured, using as variables four coatings, two pouring temperatures, two carbon equivalents, two foam densities, and different coating thicknesses. Two small designed experiments were performed – in one, coatings of two very different permeabilities were used. In the second, two similar coatings were used. In a final test, the effect of increasing the coating thickness to significantly reduce permeability was determined. A summary of the castings is given in Table 1.2.5.1.

The patterns, gating systems, and probe arrangements were identical to those used in the aluminum flange studies as shown in Figures 1.2.3.1.1 and 1.2.3.1.2. Iron was melted to produce carbon equivalents of either 3.9% or 4.3% and was poured at either 2450°F or 2650°F. Patterns were 1.35 or 1.85 lb/ft³ density. Several coatings were used; their properties are given in Table 1.2.5.2.

The results of the statistical analysis are given in Table 1.2.5.3. For the casting series that used coatings of very different permeability, the statistical analysis indicated that the coating permeability was the only significant factor affecting metal velocity. Both the coating permeability and the carbon equivalent of the iron were significant factors for carbon defects, while the interaction between coating permeability and foam density was significant for burned-on sand.

The second designed experiment used two coatings of similar permeabilities. Both higher pouring temperature and lower carbon equivalent tended to reduce the carbon defects but the severity of the burned-on sand was not influenced by any of the factors.

Since the designed experiments suggested that improved casting quality could be obtained with low permeability coatings, a special set of castings was poured using patterns with multiple layers of coating. As the number of coating layers increased from 1 to 4, the permeability of the coating and the metal

Table 1.2.5.1. Experimental set-up for two designed experiments and the special series with multiple dipped coatings.

Casting Number	Coating	Pouring Temperature	Foam Density (lb/ft ³)	Carbon Equivalent	Coating Layers
Designed Experiment with S-Series of Coatings					
1	S-High Permeability	Low (2450F)	High (1.85)	Low (3.9)	1
2	S-High Permeability	High (2650F)	Low (1.35)	Low (3.9)	1
3	S-High Permeability	Low (2450F)	Low (1.35)	High (4.3)	1
4	S-High Permeability	High (2650F)	High (1.85)	High (4.3)	1
5	S-Low Permeability	High (2650F)	High (1.85)	Low (3.9)	1
6	S-Low Permeability	Low (2450F)	Low (1.35)	Low (3.9)	1
7	S-Low Permeability	High (2650F)	Low (1.35)	High (4.3)	1
8	S-Low Permeability	Low (2450F)	High (1.85)	High (4.3)	1
Designed Experiment with E-Series of Coatings					
9	E-High Permeability	Low (2450F)	High (1.85)	Low (3.9)	1
10	E-High Permeability	High (2650F)	Low (1.35)	Low (3.9)	1
11	E-High Permeability	Low (2450F)	Low (1.35)	High (4.3)	1
12	E-High Permeability	High (2650F)	High (1.85)	High (4.3)	1
13	E-Low Permeability	High (2650F)	High (1.85)	Low (3.9)	1
14	E-Low Permeability	Low (2450F)	Low (1.35)	Low (3.9)	1
15	E-Low Permeability	High (2650F)	Low (1.35)	High (4.3)	1
16	E-Low Permeability	Low (2450F)	High (1.85)	High (4.3)	1
Special Experiment (Multiple Dipped Coatings) with E-Series of Coatings					
17	E-Low Permeability	High (2650F)	Low (1.35)	Low (3.9)	1
18	E-High Permeability	High (2650F)	Low (1.35)	Low (3.9)	1
19	E-Low Permeability	High (2650F)	High (1.85)	Low (3.9)	1
20	E-High Permeability	High (2650F)	High (1.85)	Low (3.9)	1
21	E-Low Permeability	High (2650F)	High (1.85)	Low (3.9)	2
22	E-High Permeability	High (2650F)	High (1.85)	Low (3.9)	2
23	E-Low Permeability	High (2650F)	Low (1.35)	Low (3.9)	4
24	E-High Permeability	High (2650F)	Low (1.35)	Low (3.9)	4
25	E-Low Permeability	High (2650F)	High (1.85)	Low* (3.9)	4
26	E-High Permeability	High (2650F)	High (1.85)	Low (3.9)	4

* Actually lower than expected because casting 25 was not inoculated

Table 1.2.5.2. Selected coating properties used for the two designed experiments and the special series with multiple dipped coatings.

Coating	Coating Layers	Baume	Coating Thickness (plastic or steel sheet)	Coating Thickness (from sprue)	Normalized Air Flow (cm ³ /cm ² -s)	Actual Air Flow (cm ³ /cm ² -s)	Liquid Absorption Rate (g/cm ² s)	Liquid Capacity (g ml/cm ²)
E-Low	1	33.5	0.0254 cm (0.010 in.)	-	80.0	118	Medium ~0.0173	0.0298
E-Low	2	33.5	0.0508 cm (0.019 in.)	0.0762 cm (0.030 in.)	19.2	14		0.0270
E-Low	4	33.5	0.1219 cm (0.047 in.)	0.1549 cm (0.061 in.)	10.2	3.2		-
E-High	1	37	0.0330 cm (0.013 in.)	-	88.6	102	Medium ~0.0185	0.0334
E-High	2	37	0.0610 cm (0.025 in.)	0.1041 cm (0.041 in.)	11.6	7.2		0.0335
E-High	4	37	0.1778 cm (0.070 in.)	0.1930 cm (0.076 in.)	5.8	1.2		-
S-Low	1	55	0.0254 cm (0.010 in.)	-	37.4	56	Low ~0.006	0.0375
S-High	1	56	0.0178 cm (0.007 in.)	-	135	289	High ~0.0428	0.0405

Table 1.2.5.3. Statistical analysis giving the "p" values from the analysis of variance. A "p" value less than about 0.05 indicates that the factor or interaction is significant. The confounding interactions are also included. For example, the main effect of the coating (A) is confounded by the three-factor interaction (BCD) of the other three variables.

Factors and Interactions	"p" value		
	Velocity	Carbon Defect	Penetration
For the S-Series Coatings			
A: Coating = BCD	0.0174	0.0525	0.0313
B: Temperature = ACD	0.0728	>0.4026	0.1486
C: Foam Density = ABD	0.1031	0.1195	0.0299
D: C.E. = ABC	0.0845	0.0345	0.0885
AB = CD	>0.1468	0.1848	>0.1486
AC = BD	0.0876	0.4026	0.0200
AD = BC	0.1468	>0.4026	0.1486
For the E-Series Coatings			
A: Coating = BCD	0.0230	0.0671	0.0703
B: Temperature = ACD	0.0333	0.0272	0.0811
C: Foam Density = ABD	0.0492	0.0614	0.1107
D: C.E. = ABC	>0.0505	0.0201	0.1473
AB = CD	0.0298	>0.0716	>0.1473
AC = BD	0.5050	>0.0716	0.0842
AD = BC	0.5050	>0.0716	0.1124

velocity decreased dramatically. The carbon defect and burned-on sand defect both decreased with decreasing permeability.

The quality of the casting is best if the metal velocity is low. In these tests, the coating permeability was reduced to a very low level, producing the least amount of carbon defect, yet the casting still filled completely. Low carbon equivalents, which also reduced metal velocity slightly, and high pouring temperatures also helped minimize carbon defects. The higher pouring temperature might be expected to increase velocity somewhat by causing more complete pyrolyzation of the foam, producing more but smaller gaseous products; these products would be more easily transported through the coating, although this effect might be offset by higher gas back pressures. The net result of increasing the pouring temperature could, if the gas back pressure dominates, actually decrease metal velocity, as was observed by Liu¹⁰ and Fu¹. The effect of carbon equivalent has not been reported before. The higher carbon equivalent iron solidifies at a lower temperature and over a narrower temperature range. The difference in solidification range, leading to higher superheat, better fluidity, and longer solidification time, might explain the carbon equivalent effect, although more evidence is required.

The carbon defects in iron castings are clearly related to the metal velocity and the factors that increase metal velocity. These defects are likely caused by the accumulation of liquid polymer or other high molecular weight pyrolysis products at the metal/foam/coating interface. A low metal velocity, particularly caused by a coating with a low permeability, appears to be essential in minimizing these defects.

No effect of foam density on surface defects was observed; a low foam density is expected to be helpful in minimizing carbon defects by reducing the amount of pyrolysis products that must be removed, but a slight increase in metal velocity would also be expected and perhaps provides an offsetting effect. Higher pouring temperatures, although again tending to increase metal velocity, also increase the rate at which pyrolysis products are transferred into the coating. A hypoeutectic carbon equivalent composition decreased carbon defects, partly due to the lower metal velocity but also the solidification mechanism may provide some benefit. These results appear to be consistent with the model proposed for controlling defects such as internal porosity and folds in aluminum casting.¹²

The other major defect observed in the research was penetration, or burned-on sand. The effects of the four

variables on penetration were not consistent from test to test. Overall, reducing the air flow rate or metal velocity appears to be beneficial. Penetration is generally expected to be appreciably influenced by the degree of compaction and by the thermal expansion of the silica sand. In addition, the strength and perhaps the thickness of the coating itself should be important. These factors were not controlled in the test and, consequently, any effect of the four tested parameters might be masked by the uncontrolled variables.

1.2.6. Structure and Composition of Folds

The folds observed in the aluminum castings were always connected to a surface of the casting. In most of the flange castings, the folds were connected to the cope surface. However a few folds were connected to the drag surface and a number of folds were connected to the inside of the holes in the flanges. Often folds went completely through the casting, connecting the cope to the drag or connecting a hole to the outside flange diameter. Similar observations were made for tests using other types of patterns. Some folds might be related to the collapse of internally-generated bubbles.

1.2.6.1 Metallography

Metallographic examination of the folds suggests that cold metal is not necessarily the cause for the defect (as contrasted to cold shuts sometimes found in traditional casting processes). The folds are exceptionally thin and require significant magnification to be observed. Several folds were found by dye penetrant inspection and samples containing the fold were removed for metallographic examination. A typical fold from a pendant casting poured in modified 356 aluminum is shown in Figure 1.2.6.1.1.

The microstructure is discontinuous across the fold. For example, Figure 1.2.6.1.2 shows that the primary dendrites do not appear to cut across the fold; instead the eutectic microconstituent typically is in contact with the folds. Although in some cases the microstructure appears similar (same dendrite arm spacing, for example) on both sides of the fold (Figure 1.2.6.1.3), in other cases the microstructure is quite different (Figure 1.2.6.1.4). In some areas, there appears to be some degree of continuity of microstructure across the fold (Figure 1.2.6.1.5), perhaps at regions where the fold was disrupted. Often, relatively large silicon precipitates appear to nucleate at or near the fold, even though the 356 alloy is hypoeutectic (Figure 1.2.6.1.6).

Figure 1.2.6.1.1. Severe fold at the junction of two metal streams in the pendant casting.

Figure 1.2.6.1.2. Photomicrograph of a fold in a flange casting.

Figure 1.2.6.1.3. Photomicrograph of a fold in a flange casting. The microstructure of the alloy is similar on both sides of the defect.

Figure 1.2.6.1.4. Photomicrograph of a fold in a flange casting. The microstructure of the alloy is quite different across the fold.

Figure 1.2.6.1.5. Photomicrograph of a fold in a flange casting. The microstructure of the alloy appears almost continuous across the fold.

Figure 1.2.6.1.6. Photomicrograph of a fold in a 356 alloy flange casting. Silicon appears to have nucleated at the surface of the fold.

It is certainly obvious that the folds are a consequence of incomplete fusion of two streams of molten aluminum during the fill process. However this could conceivably occur in several ways, all of which would be consistent with a lack of continuity of the microstructure through the fold. First, it is possible that a fold is nothing more than a cold shut caused by one stream of metal freezing and remaining unfused when the second stream impinges on it. This does not seem likely, particularly since the folds are most likely to occur when the metal velocity is highest. Second, folds may simply be caused by oxide films that prevent fusion of the two metal streams, and a high metal velocity might magnify this problem. Third, folds may be a consequence of thin films of foam pyrolysis products on the surface of the metal stream. If the pyrolysis products were liquid polystyrene, the film would be expected to decompose to gaseous products and produce pores rather than a thin film -- in fact some small pores were associated with some of the folds. If the fold is due to pyrolysis products, the products must be primarily carbon rather than an organic residue. Metallographic examination of the microstructure near the fold was not helpful in conclusively determining which one of the three possible causes was at work.

1.2.6.2 Auger Analysis

Auger analysis was used in an attempt to determine the chemistry of the shiny surface of the fold. In the first try, a fold found at the end of a 356 alloy flange casting where the two metal fronts presumably met was examined. Three spots were analyzed by sputtering off a few nanometers of the film at a time and, based on electron energies, the elements and an approximation of their amounts was found. The five major elements on the fold surface were carbon, oxygen, aluminum, magnesium, and silicon. Small amounts of sodium and calcium, as well as trace amounts of sulfur and chlorine, were also detected. Figure 1.2.6.2.1 shows the carbon content for the three spots as a function of distance from the fold surface and indicate that the composition of the film on the fold is quite uniform. For Figure 1.2.6.2.2, the average compositions from the three spots are plotted. The results suggest that there is a significant amount of carbon at the very surface of the fold, suggesting the presence of pyrolysis products from the foam -- this carbon-rich layer appears to be less than about 7 nm (7×10^{-7} cm) thick. There also appears to be an enrichment of aluminum, magnesium, and oxygen just beneath the carbon-rich surface of the fold, suggesting that oxides also contribute to fold formation. Based on the rise of the silicon percentage, the half of the fold on the specimen that was examined is about 15 nm (1.5×10^{-6} cm)

thick, or perhaps the total width of the fold before the casting was fractured was about 30 nm. The Auger analysis suggests that the folds are a combination of pyrolysis products and oxidation.

A fold that formed immediately after a hole in a 356 flange casting was also analyzed as shown in Figure 1.2.6.2.3. In this case, the metal stream separated as it moved around the hole and the fold formed when the two streams recombined. The analysis was very similar to that of the fold that occurred where two streams met at the end of the casting – the carbon content was very high at the surface of the fold, dropping off rapidly to an Al-Mg oxide layer before the base metal was encountered. It is likely that the mechanism of the fold formation is the same between the holes in the flange and at the end of the flange.

Finally, an isolated fold near the edge of a 356 flange casting was analyzed as shown in Figure 1.2.6.2.4. The carbon layer on this fold was much smaller and less carbon was observed compared with the other two folds. The fold was comprised primarily of Al-Mg oxide, even at the fold surface. This suggests that there are at least two important mechanisms for fold formation in aluminum castings.

1.2.7 Temperature Gradients in Lost Foam Castings

For most conventional casting processes, a risering system is typically required to compensate for solidification shrinkage and thus to produce a sound casting. In the lost foam casting process, however, risers are seldom used because the smooth, progressive movement of the liquid metal front, which is restrained by the solid expendable foam pattern, encourages directional solidification from the extremities of the casting toward the gating system.

Liu¹⁰ poured 1.2-in. x 1.2-in. x 10-in. as-blown 1.6 lb/ft³ polystyrene patterns with thermocouples located 1 in. from the gate and 1 in. from the end of the pattern. A Zn-Al alloy, 319 aluminum, aluminum bronze, and gray iron castings were produced. Complete cooling curves were obtained as the casting solidified, and the end of the casting solidified much more quickly than the gate-end of the casting. The liquid metal at the first thermocouple still retained superheat, with a greater superheat for higher pouring temperatures. The superheat was much smaller at the second thermocouple. In fact for low permeability coatings, the metal temperature detected by the second thermocouple was at or even below the liquidus. The longitudinal temperature gradient between the two thermocouples was lower when

high permeability coatings were used. This behavior, which is expected, helps lead to directional solidification and feeding, even without risers.

Both Sun² and Miller⁹ measured the metal front temperature in as-blown polystyrene patterns and found the temperature decreased linearly along the length of the pattern for 319 aluminum alloy.

In this set of tests, the temperature distribution in simple patterns during mold filling and subsequent solidification was measured for several aluminum alloys, refractory coatings, and pouring temperatures. This research more fully illustrates the directionality of the solidification process in terms of solidification times and temperature gradients. In addition, it is shown that the liquid metal flows a significant distance even after solidification begins and a critical fraction solid is found at which the metal front ceases to advance.

1.2.7.1 Empty Mold Casting

For a comparison to lost foam casting, a 0.5-in. thick bar was produced in green sand using 356 alloy. The velocity of the metal stream was high, approximately 6.8 in./s. The solidification times increased only slightly toward the gate and, as expected, were considerably longer than when a foam pattern was used as illustrated in Figure 1.2.7.1.1.

The data and relationships described in these tests demonstrate the directional solidification inherent in the lost foam process (Figure 1.2.7.1.1). Because the temperature of the metal front continually cools during fill, positive temperature gradients are achieved from the end of the casting toward the gate, permitting the gating system to provide any feed metal that may be required. The solidification times increase significantly from the end of the casting toward the gates, again indicating pronounced directional solidification. The effect of the fill behavior in LFC is particularly evident when compared with the empty mold casting.

The maximum temperature of the liquid metal shows that, in both hypoeutectic and hypereutectic Al-Si alloys, fill continues after solidification begins and a proeutectic phase forms. The metal front does not stop until the temperature of the metal nearly reaches the eutectic temperature, at which time a significant fraction of total solidification has occurred. Higher pouring temperatures produce longer solidification times

Figure 1.2.7.1.1. Comparison of solidification times for 356, 319, 380, and a hypereutectic alloy poured in lost foam with the solidification times for 356 poured into an empty mold. The solidification times for the empty mold were nearly constant along the length of the casting, while LFC castings all displayed a pronounced solidification time gradient.

and higher temperature gradients, suggesting that increasing pouring temperature may also help to reduce any problems with solidification shrinkage that might be encountered.

1.2.8 Use of Filters in the Lost Foam Process

Folds are a composite material composed of a thin layer of carbon surrounded by layers of oxide. The oxides may be introduced from several sources, including air aspirated into the gating system during pouring, reaction of the liquid aluminum with air in the foam beads, turbulent metal flow, and oxides already in the liquid metal prior to pouring. Various methods might be used to reduce the sources of the oxides that appear to be associated with folds. For example, assuring good gating design and pouring practice to quickly fill the sprue and avoid aspiration of air into the metal stream may be helpful. Low metal velocities that produce a more stable metal-foam interface may be effective. Perhaps appropriate additives to the foam that tie up oxygen harmlessly would be of benefit. Finally, good melting practice and filtration of the liquid metal might exclude oxides from the casting. Two preliminary sets of tests were performed to determine whether filtration of the liquid metal in the gating system might help reduce folds in aluminum.

Flange patterns were poured with and without a 0.75-in. thick foamed ceramic filter having about 10 openings per in. In this case, an empty ceramic sprue was used and only a small low-density foam gating system was required to connect the base of the sprue to the pattern. The 2-in. diameter filter was wedged tightly into the base of the hollow sprue. Only one glue joint was required - to assemble the gate to the flange pattern. This arrangement was expected to minimize the introduction of pyrolysis products from both glue and gating system foam from the casting. A high density 1.86 lb/ft³ EPS pattern coated with a medium permeability coating was used; the casting was poured at 800°C using 356 aluminum alloy. Electrical probes permitted the velocity and metal front profile to be determined. Thermocouples located at the gate, 90° from the gate, and 180° from the gate were also inserted into the pattern. After casting, the castings were visually inspected and then fractured to reveal folds.

The filter had no significant effect on metal velocity. The cope surface of the patterns still showed discolored streaks which were easily removed by sand blasting. However, no blisters were observed. Although the total number of folds was higher when the filter was used, the folds were all very tiny and were randomly located near either an inside or outside diameter surface or at one of the holes in the flange; all of these appear

to be a consequence of turbulent flow. The number of folds was less for the unfiltered casting; however, one of the folds was located where the two liquid streams met at the end of the casting and two other folds were located between holes where two metal streams separated by the hole recombine. It is too early at this point to draw any significant conclusions concerning the ability of the filters to minimize one or the other of the types of folds.

2.0 Bronze Casting Technology

The initial plan to investigate the variables of coating type and permeability, sand type and permeability, and pattern type and density on the casting of bronze was reduced to a minimum effort by choice of the industrial sponsors. The feasibility of pouring a bronze casting using the Lost Foam Casting Process was explored jointly with a participating sponsor by selecting a water meter housing pattern with a density of 1.3 pcf. This pattern was coated with a commercial silica based iron coating. Several castings were poured using brass alloy CA44 at a pouring temperature of 2150°F. These castings were free from visible defects and clearly demonstrated the feasibility of producing brass/bronze castings using the Lost Foam Casting Process.

3.0 Steel Casting Technology

This task was also reduced in effort level by the industrial sponsors and will be limited to casting trials to determine the feasibility of reducing common steel defects through the use of vacuum. This task has been interrupted twice by the unavailability of a sufficiently large vacuum pump. A new pump has been purchased and this effort will continue in the continuation of this project.

The increased pouring temperature of steel castings dictates a more rapid pattern degradation rate with increased volumes of gaseous by-products, compared to aluminum and iron castings. This increase in generated gas volumes has dictated coatings with increased gas permeability; causing high velocity, unstable metal front velocities. Within the past few years the trend has been towards using lower permeability coatings for iron and steel castings in an effort to slow the metal front velocity. This trend has resulted in significant reduction in surface defects caused by liquid byproducts trapped between the metal and coating. This trapped liquid causes surface defects such as 'orange peel' and carbon pick-up by the metal. In order to remove this trapped liquid in a timely manner it is felt that a low

pressure area in the sand induced by a high volume vacuum pump, will assist in more rapid removal of the trapped liquid. An additional advantage will also include the reduction of available oxygen in the mold cavity that produces oxidation of the molten steel.

4.0 Sand Filling and Compaction

4.1 Statement of Problem

The fill and compaction stage, like other steps of the Lost Foam process, is much more complex than initial observations would lead one to believe and can lead to a great deal of inaccuracies and variability in final castings. The stated objectives of the fill and compaction cycle are relatively simple: to completely surround a pattern with sand and densify the sand without distorting the original pattern and minimize cycle times. Consistently accomplishing these goals is not so simple. Many different dynamic interactions occur during sand fill and compaction which can affect the final outcome of the process, and understanding these interactions and their impact on the compaction cycle is critical for the production of dimensionally accurate castings.

Dynamic interactions between a casting flask and a compaction table affect the nature of mechanical energy transfer from the table to the flask. These vibrational interactions between the table and the flask are simple to analyze, as long as the flask remains in constant contact with the table. In the case of the vertical compaction table, the actions of the eccentric motors apply a sinusoidal forcing to the compaction table. Above a certain motor speed, the force of gravity is not sufficient to hold the flask on the compaction table and the table will become uncoupled from the flask.

A horizontally operated compaction table operates similarly to a vertical compaction table, since forcing vibrations are generated with the use of dual eccentric weights. A key difference in the operating characteristics of the two types of tables is that a horizontal table operates in one principal mode with the casting flask remaining rigidly clamped to the compaction table. In some cases, the hydraulic fluid pressures required for clamping cannot be fully developed, causing impact loads to be transferred to the flask.

Fill and compaction procedures in production foundries are more often than not the cumulative collection of operator experience and observations. Adjustments to sand compaction

procedures are typically based on the subjective judgements of plant personnel, rather than on knowledge gained from experimental investigations of the sand compaction process. A limitation and barrier to the future growth of the Lost Foam process is that supple or delicate patterns are difficult to cast since they are distorted beyond acceptable limits during sand fill and compaction. Many patterns must be stiffened with additional gating structures or supports to ensure that distortions of the pattern are held within acceptable limits. These additional gating and stiffening arrangements create extra labor costs and decreased casting yields on production run castings.

One of the significant accomplishments of this project is the development of diagnostic instrumentation to investigate the events occurring during the sand fill and compaction process. Compaction diagnostics in a production foundry are often performed by varying compaction parameters and then observing differences in the final castings coming off the line. These techniques certainly have merit, but also have drawbacks in that events which occurred during compaction cannot be discerned from events which occurred in other portions of the process.

Process instrumentation developed at the University of Alabama at Birmingham addresses three significant areas. Instruments have been developed to measure the accelerations of compaction tables, casting flasks, and the sand contained within the casting flask. Devices to indirectly measure sand density in a flask have been developed as diagnostic tools. Several methods of measurement of distortion of patterns during the sand fill and compaction cycle have also been developed.

4.2 Previous Experimental Efforts

Instrumentation was developed to help discern the physical events occurring during the sand fill and compaction process. Sand density gages were developed which used a variable capacitance measurement method for determining the density of sand which was confined between two parallel plates. This capacitor is wired to an amplifier circuit which provided a direct current voltage output proportional to the gage capacitance. The parallel plate sand density gage is shown schematically in Figure 4.2.1. Voltage gain and offset adjustments allow fine tuning of the amplifier characteristics to provide for "fine tuning" of the circuit so that a maximum sand density would produce a minimum amplifier output, and an empty gage would provide a maximum amplifier output. The manufacturer of the amplifier system developed an improvement to the density

Figure 4.2.1.1 - Schematic of variable capacitance density gage

gage which was smaller and did not restrict the flow of sand to the gage in any way. These sensors relied on the same physical principles as the parallel plate gages but used a toroidal field to gage density. A schematic of the improved density gages is shown in Figure 4.2.1.

Another significant use of compaction instrumentation developed as part of the Lost Foam technology project was the use of vibration monitoring equipment to monitor the accelerations of the compaction table, the casting flask, and sand contained within the flask. Reasonable deductions could be made about the behavior of the flask and the sand contained within by monitoring the accelerations recorded by accelerometers. Areas within the flask prone to pattern deformation and lack of sand densification could be identified within the flask by the presence of unusually high accelerations. This "flask mapping" technique was successfully used in several production foundries to diagnose difficulties in compaction operations.

Previous research also included some significant efforts to determine the cause of casting distortions occurring on a casting line producing automotive ductile iron crankshafts. The crankshafts from this line were deflected in the center of the crankshaft, often causing them to be scrapped due to excessive total indicated runout on the main bearing journals. In a two part study of the sand compaction operation, vibration analysis technology was utilized to record acceleration wave forms in the sand. Areas of the flask were identified where high accelerations were present in the sand. Also a crankshaft pattern was instrumented with a stainless steel "distortion strip", a thin strip of steel equipped with strain gages. These experiments pinpointed several causes of distortion in the compaction procedures used. Most notably, a very significant distortion was occurring in the pattern as sand densified underneath the pattern and the pattern was deflected downward in the center by the sand above. Also, these trials led to the revelation that a significant deflection of patterns can occur at the end of a compaction cycle when a cessation of vibrations can cause a sudden densification of sand in a casting flask.

4.3 Static and Dynamic Properties of Bulk and Granular Materials

A granular material is one which can be defined as a collection of loose particles of material combined together in a somewhat uniform state of matter. Under different circumstances, granular materials such as sand can exhibit properties of both liquids as well as solids (Jaeger, 1992). A bed of granular material can support an applied load, such as car tires driving

along the beach, but granular flows are typically characterized as shear driven flows, such as in a Newtonian fluid.

The properties of a granular material are a function of the base material the particles are composed of, the size distribution of the particles, the particle shape, and the surface friction characteristics of the individual particles. Two approaches can be taken when analyzing the characteristics of a granular material. Using a microscopic approach, the interactions of individual particles are analyzed as to how they react with the particles surrounding them. In a macroscopic approach, the material is treated as a continuous medium. This literature review provides some background on both types of analyses, both from a theoretical as well as a experimental approach.

The static strength of a granular material is most commonly described by the Coulomb failure criteria for granular materials (Bosscher, 1989 and Pitman, 1994). This criteria describes the static failure criteria for a mass of granular material. The Coulomb failure criteria of a granular material can be described by the equation

$$\tau = (\tan \Phi) \cdot \sigma + c \quad (1)$$

where τ = the shear stress at a point in the material
 Φ = the internal friction angle of the material
 σ = the normal stress applied to the sample
 c = the cohesiveness of the material

This approach to granular material strength is derived from soil mechanics, and states that the shear strength of a material is a function of both the properties of the material and the external compressive stresses applied to the sample. This relationship between applied stress and shear strength is illustrated in Figure 4.3.1. A state of stress relating normal and shear stresses at a point in a sample can be described by Mohr's circle for a state of biaxial shear stress. Should any point on the Mohr's circle cross the Coulomb yield line, shear failure will occur in the sample. The behavior of material according to the Coulomb yield criterion predicts that the more normal stress is applied to the material, the higher its shear strength becomes. In a casting flask full of sand, the sand at the top of the container is more prone to shear failure than that at the bottom due to the weight of sand.

The shear angle, Φ , of a granular material is principally affected by the size, shape, and surface friction characteristics

Figure 4.3.1 - Schematic of Coulomb shear failure criteria.

of its particles. Research has also concluded that the density of a material can also be a determining factor of the materials shear angle (Bosscher, 1989). As the density of a granular material increases, so does its friction angle. This statement agrees with an earlier statement that attainment of high density in an unbonded casting sand is one of the keys to successful production of Lost Foam castings since high sand strengths produce sound castings. The higher the shear angle of a granular material is, the more resistant that granular material is to shear failure.

4.4 Pattern Distortion

There were two principal goals of this research. The first goal was to conduct an intensive set of designed experiments to better understand the mechanisms of distortion in both vertically and horizontally vibrated Lost Foam casting flasks. In addition, several sets of compaction process diagnostic tools were used to gain a better understanding of the physical events occurring during the compaction cycle. The second goal was to develop a theoretical explanation of the pattern distortions observed based on experimental results and the known properties of granular materials.

The first designed experiment was an investigation of the causes of distortion of rectangular foam bar patterns in a vertical compaction system. Using a technique developed as part of this research project, strain gage circuits were affixed to the foam bars to gage the bar distortions during the actual compaction cycle. The test bar configuration is illustrated in Figures 4.4.1 and 4.4.2. The pattern deflection for a single bar, along with the sand density, is recorded in real time and is reproduced in Figure 4.4.3.

A full statistical analysis was conducted on the distortion data at the conclusion of the experiments revealing that the most influential single factor effects were the acceleration level of the flask and the sand angularity. Figures 4.4.4 and 4.4.5 illustrate these factors. High acceleration levels in the vertically vibrated flask tended to distort the bar patterns towards the center of the compaction flask. This implied that the physics of the compaction system above 1G vertical acceleration level created forces which deflected the bar patterns towards the center of the flask.

The other single factor effect which was found to be significant was the angularity of the sand used for compaction. Although both types of sand produced the inward distortions seen in the vertical flask, the bars were distorted remarkably less

Figure 4.4.1 - Rectangular test bar for pattern distortion trials

Figure 4.4.2 - Schematic of experimental pattern cluster for vertical compaction trials with single bar distortion patterns

Figure 4.4.3 - Deflections for bar 5 superimposed on sand densities

Figure 4.4.4 - Effects of Sand Type on the Distortion of Single Vertical Patterns for Vertical Compaction

Equivalent Deflection with 95% Confidence Intervals (in.)

Figure 4.4.5 - Effects of Acceleration Level on the Distortion of Single Vertical Patterns for Vertical Compaction

when the more rounded synthetic mullite sand was used. A set of tests by a local soil laboratory revealed that shear static properties of both sands were nearly identical, but some differences between the two must account for the differences in the compaction behavior between the two sands. The difference lies in the rounded shape of the synthetic sand. The round grain structure of the sand means that any contact between two grains produces a very efficient collision, and hence a more effective way of transmitting energy between the grains.

Accelerometers and signal analysis equipment were used to investigate the dynamic behavior of a vertical compaction table. The first set of tests simultaneously measured vertical acceleration on both the table and the flask at different compaction table motor speeds. At lower acceleration levels, sinusoidal accelerations were present on both the compaction table and the flask. However, at acceleration levels high enough to cause levitation of the flask, very short impulses of extremely high acceleration were transmitted to the flask, while the accelerations of the compaction table were still fairly close to a sinusoidal acceleration. The second set of trials measured horizontal wall accelerations at various speeds. These tests revealed that the walls undergo little or no horizontal accelerations at low speeds but are subject to large magnitude accelerations at high compaction table motor speeds.

In a final set of dynamic analysis trials, accelerations of the flask walls and the sand within were investigated by placing accelerometers in the sand itself with a lightweight positioning fixture. At low motor speeds, the accelerations of the flask and the sand within the flask were observed to be nearly identical, indicating that both were moving as one unit. However, it was clear that at high table speeds, the walls were moving independently of the sand and were repeatedly impacting the sand.

Several conclusions can be stated based on the results of the dynamic analysis experiments and the designed experiments. It is clear that the conditions which promote the inward distortions of the foam bars are most prevalent when high accelerations are used and when the bars are positioned near the walls of the compaction flask. The dynamic analysis experiments indicated that significant horizontal movements of the flask walls only occur at high compaction table speeds, and that these horizontal movements cause sand impacting and compression. Together, these two results indicate that the dynamic actions of the walls of the flask and the sand directly adjacent to those walls at high acceleration levels cause the inward distortion of the foam bars.

The results of the horizontal compaction trials were remarkably similar to those of the vertical compaction trials. In the designed experiments investigating horizontal compaction, the three experimental factors which were investigated were the sand type, the peak horizontal accelerations of the flask, and the distance of the patterns from the side walls of the flask. The distance from the walls was practically equivalent to the radial position factor in the vertical compaction trials. In the horizontal compaction trials, the vast majority of the distortions of the foam bars were distortions inward towards the flask center and aligned with the direction of vibration.

All three of the main factor effects in the designed experiment were significant contributors to the distortions of the foam patterns. This is illustrated in Figures 4.4.6 through 4.4.8. It was experimentally determined that the bar patterns which were compacted in silica sand had distortions significantly higher than those compacted in the synthetic mullite sand. An increase in the peak horizontal acceleration of the table also resulted in substantially increased inward distortions of the pattern. The effects of the distance of the patterns from the flask wall were predictable. The patterns placed closest to the flask walls were distorted inward significantly more than the patterns placed in the center of the flask.

A series of dynamic analysis experiments confirmed that the horizontal table was performing as designed and was vibrating in a smooth sinusoidal motion in the horizontal direction. Further tests which observed the vibrations transmitted by sand inside the flask revealed a pattern of accelerations similar to those occurring in the vertical compaction table. At low flask accelerations, the sand and the flask moved as one unit. At higher accelerations however, noticeable movement of the sand within the flask could be detected. This inferred that some compression of the sand was occurring within the flask at high accelerations due to high accelerations of the flask walls.

From an observational standpoint, the vertical and horizontal compaction tables could not be more different. One transmits energy to a cylindrical flask in the vertical direction primarily through repeated impact loading. The other transmits vibrational energy in the horizontal direction primarily through smooth sinusoidal motion. The remarkable thing that was observed time and time again throughout all of these experiments was how strikingly similar the two types of tables were in all types of behavior, from pattern distortion to the dynamic behavior of sand under high accelerations. However, there was one key contrast in the behavior of the two types of tables. The vertical table operates in two principal modes of vibration; it either transmits

Figure 4.4.6 - Effects of Sand Type on Distortion of Single Vertical Patterns for Horizontal Compaction

Figure 4.4.7 - Effects of Acceleration Level on Distortion of Single Vertical Patterns for Horizontal Compaction

Figure 4.4.8 - Effects of Radial Position on Distortion of Single Vertical Patterns for Horizontal Compaction

a smooth sinusoidal acceleration or it repeatedly impacts the flask. There is no "transition zone" between these two types of behavior, only a cut-off speed above which the table impacts the flask. The horizontal table however, does not make such a clear cut change in behavior. Instead, the horizontal table makes a smooth transition to a state where there are differences in flask and sand movement.

An analytical model was developed for both horizontal and vertical compaction procedures to help substantiate the experimental results of the compaction trials. These models were based on the Coulomb shear failure criteria for granular materials and predict material yield based on which locations in the flask will produce stresses which exceed a critical stress ratio. The model for the horizontal compaction system predicts that the area most affected by acceleration of the table is the region directly adjacent to the flask wall. The boundary of this region is the solution of a linear equation and intersects the far upper corner of the sand contained in the flask. The model for the vertical compaction table predicts a similar area of active sand compression, also with a boundary intersecting the far upper corner of the sand. However, the vertical compaction model predicted a multiple order solution to the boundary of the compressed sand region, which can be described as an asymptotic curve whose slope approaches zero as it goes across the flask.

This research has determined some of the primary causes of pattern distortions in both types of sand compaction systems for the Lost Foam process. Based on the results of this research, the following recommendations can be suggested: Foam patterns will be more susceptible to distortion as their distance from the walls of the flask is reduced. The desire to maximize casting output of a flask must be balanced against the tendency to warp and distort patterns which are placed too close to the walls of the flask. Also, high accelerations in both vertically and horizontally vibrated flasks have been proven beyond any doubt to cause significantly higher distortions in patterns. Compaction procedures should be developed to use the minimum amount of compaction energy necessary to fill of the cavities of a pattern, while at the same time satisfying process throughput requirements.

One of the more interesting results of this research was the realization of the possible benefits of using a more rounded sand or casting media. The rounded sand greatly reduced the incidence of distortions experimentally, most likely because of the grain to grain dynamics inherent to its rounded shape. This experimental evidence adds to previous production studies which

cited low thermal expansion properties of synthetic mullite sand as beneficial to the Lost Foam casting process.

4.5 Sand Filling

One goal of the fill and compaction cycle is to cause sand to flow into and around the foam pattern. This is necessary to provide support for the thin coating during pouring and solidification. It is important that internal pattern cavities be filled completely before sand densification can be fully achieved. Since sand densification can be achieved in a short time period (usually less than 10 seconds) the total fill and compaction time cycle is dictated by filling. Incomplete sand fill results in metal penetration through the coating and into the sand, creating burned-on sand which is often difficult to remove in clean-up. Historically, this condition was remedied by increasing the cycle acceleration level to fill the troubled cavities within the time allotted for the fill and compaction cycle. Previously in this report, high acceleration levels have been shown to be a major cause of pattern distortion.

Since the rounded sand had produced less pattern distortion than angular sand at equal acceleration levels, a series of evaluations were performed to determine comparative sand fill rates for these two types of sand. The test matrix was designed to compare the flowability of synthetic mullite (rounded), Wedron 445 Silica (angular), and Olivine (angular) sands into pattern cavities and determine the parameters that have the greatest impact on phlebolith. The parameters investigated were acceleration level, overburden height, angular position, and radial position. A Plexiglas box, shown in Figure 4.5.1, was instrumented with parallel plate full/compaction gages. The output from these gages was recorded by a data acquisition system. All fill tests were performed on a vertical compactor.

The flask was pre-filled with eight inches of sand and was compacted for approximately 10 seconds at 1.0 acceleration level to assure a firm ground to place the plexiglass box. The plexiglass box was then placed in various radial and angular positions. The density gages were connected to a computer which was set to take data at one second intervals. The flask was filled with sand to the proper level (either 3" or 11" above the top of the box). The sand was then compacted at either 0.8 or 1.5 acceleration level as indicated by the matrix. The compaction was continued for as long as it took the cavities to fill or for 900 seconds, whichever came first. The placement of the plexiglass box in the flask is demonstrated in Figure 4.5.2.

Figure 4.5.1 - Plexiglas Fill Box With Gages

Figure 4.5.2 - Placement of Plexiglass Fill Box

Results of these evaluations indicate a significant reduction in fill times for the rounded sand, for both the vertical and horizontal cavities. Filling of the vertical cavity was accomplished in much less time than for the horizontal cavity. This is to be expected as the sand had to move only a short distance through a 3/4 inch diameter hole and then fall into the vertical cavity. In order to fill the horizontal cavity sand had to move horizontally a considerable distance into confined passage. Comparing the fill rates of the three sands in Figure 4.5.3 reveals that the rounded sand fills the vertical cavity in 20% of the time required for the silica sand and 28% of the time for Olivine sand at a low acceleration level of 0.8G. At 1.5G the differences are much less -- 40% for rounded/silica and 37% for rounded/Olivine. It is obvious from Figure 4.5.3 why compactor acceleration levels are increased to reduce cavity fill times. The silica sand fills the vertical cavity in 13% of the time when the acceleration level is increased from 0.8G to 1.5G.

Overburden height (Figure 4.5.3) had less effect on fill times than the acceleration levels. The 11-inch sand overburden caused the vertical cavity to fill in 66% of the time required for the 3-inch overburden for the rounded sand, and 94% for the silica, and 64% for the olivine.

Angular position (Figure 4.5.4) between the compaction posts provided slightly lower fill times for the rounded and Olivine sands (76% and 89%, respectively). A much lower fill time was recorded for the silica sand with the fill box placed between the compactor posts (44%). This agrees with previous data generated in this project.

Fill times increased for the vertical cavity when the cavity opening was oriented towards the center of the flask. The increase was 105% for rounded sand, 132% for silica, and 117% for olivine. This data supports the observations where it was determined that sand movement originates at the flask walls and moves horizontally inward towards the flask center.

Results of filling the horizontal cavity were similar to filling of the vertical cavity with the horizontal cavity fill times being longer in time. As with the vertical cavity, the acceleration level had the most dramatic effect (Figure 4.5.5) filling the cavity at 1.5G in about 18% of the time required at 0.8G. Overburden height did not appear to be a factor (Figure 4.5.5). Angular position between the post provided a slight reduction in fill times for silica and olivine sands (Figure 4.5.6). This figure also indicates a significant increase in fill times for the horizontal cavity when the opening faces the flask center for the rounded sand. There appeared to be much

Vertical cavity (ch.3)

Figure 4.5.3 - Effect of Acceleration and Overburden Height on Fill Times for the Vertical Cavity

Vertical cavity (ch.3)

Figure 4.5.4 - Effect of Angular and Radial Position on Fill Times for the Vertical Cavity

Horizontal cavity (ch.2)

Figure 4.5.5 - Effect of Acceleration and Overburden Height on Fill Times for the Horizontal Cavity

Horizontal cavity (ch.2)

Figure 4.5.6 - Effect of Angular and Radial Position on Fill Times for the Horizontal Cavity

less of an effect for the silica and olivine sands both of which are angular. Apparently, the acceleration levels used were not large enough to overcome the frictional and mechanical bonds of these angular sands and cause horizontal sand movement.

A second set of experiments was conducted to investigate the possibility of lowering the acceleration level of the compaction table without increasing the time of the compaction cycle. Previous experiments showed that the mullite sand filled the cavities in shorter amount of time. This set of experiments was designed to see how much the acceleration of the table could be lowered with the use of mullite sand. The same experiment setup was used with only the mullite sand. Mullite sand was accelerated at 0.9, 1.0, 1.1., and 1.2 acceleration level with the sand gate open 30% or 60%. It was shown that using mullite sand the acceleration could be lowered to 1.1G-level from 1.5G-level. The cavities filled in less time with mullite sand accelerated at 1.1 G-level than with silica or olivine sands accelerated at 1.5G-level.

Another set of experiments was conducted to mimic the everyday practice of the foundries. For this set of experiments the effects of angular position, radial position and the overburden height were ignored. Using the same procedure, sand was compacted in the flask to create a firm ground for the plexiglass box. The box was placed between the pedestals with the vertical cavity opening to the wall of the flask. A holding device was fabricated with foam isolators to keep the box in place (Figure 4.5.7). The flask was placed under the sand gate and sand rained in during the compaction cycle. Acceleration levels of 0.8 and 1.5G's were used. A low sand rain level of 30% and a high sand rain level of 60% were used. The results of these experiments agreed with the results found by the first set of experiments. Fill time for the vertical and the horizontal cavities are shown in Figures 4.5.8 and 4.5.9. The time needed for sand level to reach the opening of the cavity was subtracted so that the time recorded is the actual fill time of the cavities.

5.0 Coating Technology

The pattern assembly operation is complete when the patterns are attached to a gating system to form a complete cluster. This cluster is then dipped in a refractory slurry or coating, removed and rotated slowly to ensure the coating covers all foam surfaces, and allowed to dry. The coating is a thixotropic liquid mixture of refractory particles, dispersants, and binders in a water carrier. When dry, the coating forms a hard, porous

Figure 4.5.7 - Placement of Plexiglas Fill Box

raining sand while compacting experiments
vertical cavity (ch.3)

Figure 4.5.8 - Effect of Acceleration Level and Rain Gate Opening on Fill Times for the Vertical Cavity

raining sand while compacting experiments
horizontal cavity (ch.2)

Figure 4.5.9 - Effect of Acceleration Level and Rain Gate Opening on Fill Times for the Horizontal Cavity

refractory shell on the pattern cluster surface. The pore size and number of pores in the dried coating are principally controlled by the size, size distribution, and shape of the primary refractory used in the coating. Common primary refractories used in coatings include silica, alumina, mica, and alumino-silicates such as mullite and pyrophyllite. The refractory particles are typically held together with one binder to provide adhesion and cohesion before drying and a second binder to provide strength after drying and during pouring. The mixture may also include suspension agents to separate the refractory particles and surfactants to insure that the coating will wet and coat the pattern.

Lost foam castings are formed when molten metal is poured into the gating system. The metal degrades and displaces the foam pattern while filling the mold cavity. For the molten metal to fill the mold cavity, air in the pattern and the liquid and gaseous products formed from degradation (pyrolysis) of the pattern must have a means of escape from the mold cavity. The only means of escape is through the refractory coating. When pouring molten aluminum into an EPS pattern, the pyrolysis products are primarily liquid polystyrene. Molten iron produces more gaseous decomposition products due to the higher temperatures involved. The density of foam patterns is relatively low, typically 20.8 kg/m^3 to 25.6 kg/m^3 (1.3 lb/ft^3 to 1.6 lb/ft^3), and most of the mold cavity is occupied by air. Therefore, a refractory coating must be permeable to air as well as the liquid and gaseous decomposition products produced in the LFC process.

Most defects in lost foam castings are caused by liquid pyrolysis products. To avoid forming casting defects, the coating must allow all of the pyrolysis products to escape the mold and move into either the coating or the sand in a timely manner. The coating property which controls the metal fill process is called its permeability. If the coating permeability is too low, a large gap between the metal front and the pattern may develop and allow the mold wall to collapse, thereby producing an incomplete casting. If the coating permeability is too high, porosity may develop due to foam being trapped in the metal by rapid, turbulent filling of the mold cavity. If the foam pyrolysis products cannot escape the mold cavity before the metal solidifies, a variety of surface and internal defects can be formed. The most common defects found in lost foam castings are porosity, misruns, folds, and surface carbon defects sometimes called "worm tracks" or "orange-peel" defects. These defects are all caused by the incomplete removal of foam pyrolysis products, both gaseous and liquid, from the mold cavity. Another common defect, commonly called metal penetration

or "burned-on sand," can occur when a thin or cracked coating allows molten metal to penetrate and solidify outside of the mold cavity.

The refractory coating plays the most important role in the removal of air and pattern pyrolysis products from the mold cavity. However, the rule for selecting the best coating for a particular casting is a trial and error process based on past experience. Once a basic formulation has been tried, minor variations in the mixture may be made to modify or optimize the coating viscosity and application thickness for specific castings. The final control of the selected coating is usually solution Baumé, solids content, and application weight.

A wide variety of coating formulations have been developed in the past 10 years for use in making iron and aluminum castings. The coatings are usually described in terms of their heat transfer characteristics (insulating, high conductivity, etc.) and gas flow characteristics (low, medium, or high permeability). These coatings have been developed with years of effort and experience. Much effort has been required because there are no accepted laboratory methods for describing and quantifying the properties of interest. New casting developments generally require repetitive plant trials, correlating casting defects with coating formulations.

Coating permeability test procedures have been developed at the University of Alabama at Birmingham (UAB). These procedures were developed to fill the need for measurement of the permeability properties which control the metal/pattern exchange. In February, 1995, a Coating Quality Control Manual incorporating these procedures was issued to participating sponsors. These test procedures have been used by the LFC industry to monitor and control coating properties and reduce variations in the casting process. Over the past two years dramatic reductions in casting scrap rates have resulted as foundries explored the cause/effect relationships between coating permeability properties and types of defects. It is also interesting to note the reduction in permeability used in producing iron castings over the past two years. The philosophy of 'slower is better' as applied to metal velocities has proven to be accurate.

Several revisions to the Coating Quality Manual have been issued to either improve the accuracy of the procedures or to facilitate the use of the procedures on the foundry. In November 1995, a revision was issued to include the effect of gas compressibility. This revision was necessary to accommodate the use of one flowmeter for a wide range of coating permeabilities. A second revision was issued in January 1996 to incorporate

procedural changes which reduced the variability of the normalized air flow rate calculations. The root causes of the normalized air flow rate calculation variabilities were isolated in a critical study of 1) the effect of drawbar thickness and dipped coating samples; 2) effect of various drying techniques; and 3) effect of various flowmeter calibrations.

5.1 Effects of Drawbar Thickness and Dipped Samples

Using one master batch of mixed coating, samples were prepared with thicknesses from 1.010 inches to 0.035 inches. In addition, samples were prepared with a thickness of approximately 0.015 inches by dipping a double layer of viewgraph film into the coating and then separating the two pieces of film. These samples were dried at 150°F for 3 hours in a convection oven. Sample discs were removed from each sample using a 0.625 inch diameter cutter. A minimum of three discs was removed from each sample and evaluated according to the procedures outlined in the Coating Quality Control Manual. Figure 5.1.1 illustrates the normalized air flow rates of the drawbar samples. Although the data has considerable scatter (which is addressed later) the specimen thickness does not have a significant effect on the normalized air flow rates. This eliminated the concern that the shearing forces caused by the drawbar could affect the coating structure and the air permeability. Figure 5.1.2 compares some of the drawbar samples to the dipped samples. Again significant data scatter exists however reasonable agreement is evident between the drawbar samples and the dipped samples. This comparison was made to compare the drawbar technique to the dipping technique which is more representative of the pattern dipping process.

A major source of air flow rate variability was traced to the plastic specimen holder. The rubber washers deformed considerably when the holder was tightened, causing the effective flow area to change which resulted in erratic air flow rate measurements. To correct this variability, a new specimen holder was designed and produced. Along with this holder a new procedure was incorporated into the Coating Quality Control Manual which simplified and expedited the testing of coatings on the foundry floor. This procedure measured the 'standardized air flow rate' directly, yielding the same value as the more intensive former procedure. Since the liquid absorption rate values had yielded little value to the foundry in reducing defects, this measurement was not included in the new procedure. The former procedure was labeled 'Research and Development Procedures' and has served the coatings manufacturers in their efforts to control the coating ingredient properties which affect coating permeability. The second procedure was labeled 'Foundry Test Procedures' and is

Figure 5.1.1.1. Effect of Drawbar Thickness on Coating Permeability

Figure 5.1.2. Effect of Drawbar Thickness on Coating Permeability

intended to serve as a quick response test to assist in controlling coating air flow rates. The third revision of the Coating Quality Control Manual was issued in February, 1998. Figure 5.1.3 illustrates the standard deviation of normalized air flow rates from 7 samples was reduced from 0.596 cm³/cm²-sec to 0.149 cm³/cm²-sec for a typical aluminum coating. A similar reduction in standard deviation for a typical iron coating is evident.

5.2 Effects of Drying Techniques on Coating Permeability

Samples were prepared from a master batch of aluminum coating using the drawbar technique and then dried with various techniques. The samples were dried by 1) air drying at room temperature overnight; 2) convection oven at 150°F for four hours; 3) microwave drying; and 4) heat lamps. Three coating discs were cut from each sample and normalized air flow rates were determined using the Coating Quality Control Procedures. Figure 5.2.1. illustrates that air drying overnight and convection oven drying yields consistent results with a minimum of variation. In contrast, microwave and heat lamp drying caused a significant increase in the normalized air flow rates accompanied with more variation from sample to sample. The probable cause is that both of these techniques generate high water evaporation rates which tend to increase the coating pore sizes. Some foundries were using these techniques to decrease the response time for coating data which was used to control the pattern dipping process. It is recommended that these techniques not be used.

5.3 Effect of Flowmeter Calibration on Coating Permeability

The Coating Quality Control Manual data reduction procedures utilized a linear regression equation to convert the observed flowmeter readings into flow rates. This data is furnished by the flowmeter manufacturer in tabular form. Table 5.3.1. illustrates a typical data table. Various techniques were used to regress this tabular data to obtain the 'best fit' and these regressions were used to reduce the experimental data on three coating discs. Results are shown in Table 5.3.2. These results indicate that a Quadratic(second order) regression that is not forced through 'best fits' the flowmeter data and produces an error in the normalized flow rate calculations of less than 1%. The original linear regression(forced through zero) caused an error of over 11%. These changes in procedure have been incorporated into the Coating Quality Control Manual and furnished to the sponsors.

Aluminum Coating Results

Sample	Thickness	Large Holder - R&D Test*	R & D Test	Foundry Test
1	0.0437	4.18	4.01	4.326
2	0.0513	4.04	4.56	4.276
3	0.0493	4.06	5.03	4.274
4	0.0413	4.29	4.3	4.552
5	0.0477	3.77	4.72	4.082
6	0.0495	3.81	3.39	4.181
7	0.0525	3.99	3.61	4.376
Standard Deviation:		0.186	0.596	0.149

Cast Iron Coating Results

Sample	Thickness	Large Holder - R&D Test*	R & D Test	Foundry Test
1	0.0547	25.3	26.03	29.268
2	0.0571	25.48	25.48	28.431
3	0.0623	7.57	21.07	27.167
4	0.0502	18.89	24.44	28.727
5	0.0569	30.04	24.65	29.036
6	0.0631	22.56	27.3	31.419
7	0.0625	19.3	24.76	31.120
Standard Deviation:		7.185	1.927	1.500

* The large holder was placed in the R&D test.

Figure 5.1.3. Comparison of Normalized Air Flow Rates Measured Using the Old and New Specimen Holders

Figure 5.2.1. Effect of Drying Technique on Coating Permeability

Table 5.3.1. Typical Flowmeter Data
(SUPPLIED BY MANUFACTURER)

Ball Reading	Predicted Flow (ML/MIN.)	Predicted Flow (cm ³ /sec.)
10	480	8.00
20	868	14.47
30	1145	19.08
40	1500	25.00
50	1780	29.67
60	2117	35.28
70	2400	40.00
80	2708	45.13
90	2990	49.83
100	3256	54.27
110	3520	58.67
120	3780	63.00
130	4040	67.33
140	4295	71.58
150	4562	76.03

Table 5.3.2. Effect of Flowmeter Calibration on Data

	A	B	C	D	E
Standardized Air Flow (percent error)	12.61	11.16	11.79	12.65	12.62
		0.1147	0.0645	-0.0037	-0.0012
B0	6.04406E-10	5.3284E-10	5.78E-10	6.48E-10	6.45E-10
(percent error)		0.1727	0.1022	-0.00056	-0.0016
Absorption Rate	0.005012	0.004559	0.004749	0.005026	0.005016
(percent error)		0.0904	0.0525	-0.0028	-0.0008

<p>A Manostat Data</p> <p>B linear regression through zero</p> <p>C linear regression with a constant</p> <p>D quadratic regression through zero</p> <p>E quadratic regression with a constant</p>
--

5.4 Role of Coatings in Lost Foam Castings

The objective of the study discussed in Section 1.1 of this report was to develop a method for selecting, measuring, and modifying a refractory coating to produce a defect-free casting. This procedure extends the utility of the coating test procedures and can reduce the time required to bring new castings to market. The validity of this method was verified through a series of experiments using test patterns with varying geometries and coatings with varying permeabilities and constituents. The defects present in the castings were then related to the physical conditions present during the casting process to determine what caused each type of casting defect and how each was formed. The results from this analysis were used to formulate a methodology and an example of how to choose and modify a refractory coating to reduce defects in new lost foam castings.

The coating permeability test procedures played a central role in these experiments. They were used to determine the air permeability and liquid absorption capability of refractory coatings. For a given pattern geometry and coating combination, a coating permeability range exists for which a quality casting can be produced. The coating selection method provides the foundry engineer with guidance in selecting the proper coating for use on a given casting. The coating permeability test procedures can then be used to further optimize the permeability of the coating to reduce or eliminate defects present in the castings.

A discussion of the metal/pattern/coating interface is needed to understand mold filling in lost foam casting. A model of the foam pattern displacement process is illustrated in Figure 5.4.1. (AFS 1994 Summary Report 1995). This model illustrates a coated foam pattern section surrounded by unbonded sand as a molten metal front moves through the mold cavity. As molten metal fills the mold cavity, a gap is formed between the advancing metal front and the receding foam pattern. This gap, or "kinetic zone," contains a mixture of air and foam pyrolysis products. The foam pyrolysis products can consist of liquid and/or gaseous hydrocarbons produced by melting and decomposition of the pattern. When molten aluminum is poured onto an EPS pattern, the pyrolysis products are primarily liquid and the gap is rather small. When iron is poured, the gap is larger and contains more gaseous decomposition products because of the higher pouring temperature.

As molten metal fills the mold cavity, the air, gas, and liquid must escape at a rate determined by pattern geometry, foam density, and metal front velocity. The air and gaseous decomposition products escape through the coated surface area between the metal front and the solid foam pattern. This must be

Figure 5.4.1. Physical Model of Metal/Pattern Interface

accomplished before the liquid pyrolysis products reach the temperature at which they wet and wick into the coating. Askeland (Final Report 1993) has shown that liquid polystyrene wets the refractory coating at a temperature of approximately 300°C. When this occurs, the coating pores become clogged. Liu (1995) has shown that no further transport of air and gaseous products through the coating can occur after this event.

During mold filling, the liquid pyrolysis products become trapped at the inner coating surface and may not wet and wick into the coating until after the metal front has passed. As molten metal passes over the coating surface, the liquid pyrolysis products present in the coating pores experience further heating and subsequently are forced into the coating pores. The liquid soon degrades into gaseous decomposition products which move out into the sand where they cool and condense. If the liquid pyrolysis products are not removed from the metal surface before the metal solidifies, the liquid is heated further and decomposes into gaseous products and carbon residue. Surface carbon defects or "worm tracks" are formed at these locations. In addition, if the absorption rate of the coating is incapable of removing all the liquid pyrolysis products as they are produced, these products stack up on the metal front. This results in internal folds along a line where two metal fronts meet or surface carbon defects in the portion of the casting filled last.

Several variables such as the foam pattern density, foam density gradients within the pattern, metal pouring temperature, metallostatic head height, and pattern geometry are known to influence metal fill rate and defect formation. However, Lawrence (1995) and Wang et al. (1994) have shown that the permeability of the refractory coating is the dominant variable controlling the metal fill velocity and metal front shape. These two factors control most defect formation in lost foam casting.

High metal velocities in the mold cavity cause porosity in both iron and aluminum castings and carbon defects in iron castings by entrapping liquid pyrolysis products which are further degraded upon heating to form gas pockets in the casting. Excessively low fill velocities can cause misruns and folds in aluminum castings and mold collapse in iron castings. To control the metal fill rate and thus minimize defect formation in lost foam castings, the permeability of the refractory coating to air, gas, and liquid must be accurately measured and controlled.

Coatings used for the UAB casting trials described in Section 1.1 of this report were controlled through the use of coating property measurements. These properties are air flow

rate, liquid absorption rate, and viscosity. Coating dried thickness was changed by varying the viscosity. Coating thickness controls the air flow rate, hence the metal velocity and the thermal insulation properties. Air flow rates and liquid absorption rates are normally fixed for a given coating; however, these properties were changed by the addition of small amounts of very small particle size refractory. The significance of this "customizing" of air flow rates and liquid absorption rates is that the procedure can be used on the production floor for changing a particular coating where several pattern shapes demand different coating properties.

An overall analysis of the data obtained in this experiment shows that low permeability mica coatings should be used when pouring aluminum lost foam castings. These coatings have a low air permeability and a low thermal conductivity due to the layering effect of mica platelets. The low permeability of the coating allows a low velocity, parabolic metal front which pushes pyrolysis products toward the mold walls. The low thermal conductivity of the coating allows the liquid pyrolysis products to remain molten for a longer period of time and escape the mold cavity in a timely manner, thus avoiding surface blisters. These coatings also had sufficient dried thickness and strength to prevent the formation of burned-on sand defects.

An overall analysis of the data obtained in this experiment showed that iron lost foam castings also benefit from the same coating characteristics as aluminum castings. Mica-based coatings or low permeability, thick, silica-based coatings helped to reduce defects found in iron castings. This result is in contrast to the popular usage of high permeability silica-based coatings for iron castings in the foundry industry; however, the trend in recent years is in this direction.

6.0 Precision Pattern Production

Bead fusion has been identified by the industrial sponsors as a controlling factor in the metal/pattern exchange process. Foundry experience indicates that fewer casting defects occur when a pattern is poorly fused in the interior. By definition, bead fusion is understood to mean how well pattern beads are attached to neighboring beads. It is unclear, without a technique for measuring bead fusion, the difference between pattern density and pattern bead fusion. Based on a glass transition temperature (G.T.T.) of 100°C for polystyrene and a melting temperature of 164°C, it is entirely possible to form pattern beads into a tightly spaced structure with little or no space between individual beads while not allowing melting between beads. The advantage of this bead structure would be maximum surface area

contact with molten metal as individual beads are easily dislodged from neighboring beads and surrounded by metal. This would allow a more rapidly advancing metal front in the area of the poor bead fusion. Since the thermodynamic pattern blowing process dictates the location of the poor bead fusion to be at the center of a section, the metal velocity would tend to be higher in the center forming a parabolic metal profile. Research has shown that a parabolic metal profile is desirable to push liquid and gaseous by-products to the coating for removal.

Quantifying the degree of bead fusion presents a unique set of issues to be resolved. For example, the degree of bead fusion varies from a maximum to a minimum from the surface to the center. In thin pattern sections, this fusion gradient is less significant than in thicker sections. It then becomes a choice of whether a specific test evaluates the entire cross section or a slice from the section. The test of choice would be a tensile test which would evaluate the strength of the bead bonds. Implementation of the tensile test, whether from slices or the entire cross section, is not suitable for foundry environment.

Three techniques for measuring bead fusion were evaluated: 1) air flow rate through the pattern; 2) liquid flow rate through the pattern; and 3) liquid absorption. The air flow rate and liquid flow rate techniques were unsuccessful due to practical measures such as sealing the pattern ends to the inlet and outlet flow device. A small leak, coupled with the very small flow rates, dramatically affected the measured flow. This produced variable flow rate values. The liquid absorption technique produced the most consistent result. This technique used both cut strips and entire cross sections. The technique consisted of hanging a pre-weighed specimen with one end touching the surface of a liquid (water or olive oil) for a specified time interval. The specimen was removed, wiped dry, and weighed again. The weight gain was a measure of the open porosity of the specimen. These results tended to follow the pattern density value; hence, no conclusions could be made.

At this point in time there is little or no data supporting the hypothesis that fusion, as opposed to pattern density, affects the metal/pattern exchange rate. A thermodynamic heat balance presented earlier in this report indicates that pattern density has a strong influence on the metal/pattern exchange rate. The computational model will use this heat balance. Results from the model will be compared to experimental results to verify the model. Agreement between the model and experimental casting data would indicate that bead fusion is a minor contribution.

Development of alternate pattern materials has been limited during this period of research. Polystyrene is currently the material used most frequently; however, lower molecular weight polystyrene should offer an advantage in the amount of energy required to degrade the polymer. Alternate materials such as copolymers, terpolymers, and polyacrylic carbonate (PAC) offer similar advantages along with some added features. Copolymers and terpolymers are currently being used in production patterns and offer some reduction in defects for specific castings. Patterns using the PAC material are not yet in production due to difficulties in consistent pre-expansion and molding. The objective in the development of alternate pattern materials has been to produce less liquid by-products during pattern degradation(casting) and/or to produce less pattern shrinkage after molding. Copolymers are either chemical blends or mixtures of EPS and PMMA. Patterns blown from a copolymer have been shown to have similar shrinkage characteristics to EPS, hence little dimensional precision advantage is achieved. There should be some decrease in the amount of liquids produced during casting since PMMA produces less liquid; however, no test technique is available at this point to evaluate this property. In Section 7 of this report a newly developed technique is discussed.

Lower molecular weight polymers should offer some advantage in casting thin sections since less heat energy(enthalpy) should be required to degrade the polymer. This should allow metal to fill longer distances in thin sections without freezing. Currently no experimental data is available on the degradation energy of EPS or PMMA. A new procedure is currently under study at UAB and will be continued under Contract DE-FC07-98ID13603.

7.0 Computational Model

Currently a computational model quantifying the events of metal/pattern exchange in lost foam casting does not exist, either in research or commercial form. It is essential that an accurate model be developed to assist in the initial introduction of new production castings into the LFC process to minimize the trial and error procedure now used based on experience. This task is to build a model that includes the controlling factors of coating and sand gas permeabilities, coating liquid absorption, and heat and mass transfer of energy. The initial plan included the procurement of a commercial fill and solidification code (ProCast). This plan included the procurement of the source code which was to be modified by UAB/ProCast personnel to include the mechanisms that control the metal/pattern exchange. Most of the first year's efforts on this task was devoted to making the ProCast software and the Alpha Dec hardware operational. The system is now operable; however, several technical limitations of the ProCast software may eliminate this program. The source code for ProCast has not been made available. An alternate plan was to allow ProCast personnel to insert the control mechanisms into their software

with technical input from UAB personnel. A meeting between UAB and ProCast personnel resulted in the following strategy.

7.1. Modeling Approaches to the LFC Process

The process of thermal degradation of the foam pattern and its replacement with liquid metal in the LF casting process is very complex. The kinetic zone (see Fig. 7.1.1) represents a three-phase system (solid polymer {foam}), liquid polymer in the form of droplets, and gaseous products of polymer pyrolysis) in which gas and liquid mass transfer and chemical reactions occur at the same time. Because of the complexity of the events happening in the kinetic zone, the direct computer modeling of the process of foam pyrolysis and foam replacement with liquid metal is impracticable due to the limitations in computational power of today's computers. The complexity of computer modeling of the LF casting process can be greatly simplified by utilizing some experimental data in the model.

To understand the experimental data requirements and how they can be used in the computer model it is necessary to identify the processes occurring in the kinetic zone. These processes are:

1. The process of thermal degradation of the polymer into gas and liquid at the metal-foam interface.
2. The process of escape of the degradation products through the coating and sand.

Accurate computational modeling of the LF casting process must provide the following data as a minimum:

1. Amounts of gas and liquid generated at metal pouring and solidification temperatures.
2. Heat flux from the metal to the foam.
3. Foam recession rates at expected metal temperatures.

Depending on the type of experimental data used, two approaches to modeling the process of foam replacement in the LF casting process are identified (see Fig. 7.1.2).

The foundation of approach #1 is foam recession experiments whose conditions closely mimic the real LF casting process. This is usually done by pushing a block of foam against a hot wall with instrumented thermocouples and collecting the liquid residue and/or measuring the amount of gas generated. The data obtained in these experiments are (1) gas-to-liquid ratio as a function of metal temperature and head pressure, (2) heat transfer rate from the metal to the foam as a function of metal temperature and head pressure, and (3) recession rate as a function of metal temperature and head pressure. This information is then used by a computer program (modified empty mold filling and solidification software) to find the solution at each time

Figure 7.1.1. Physical Model of Metal/Pattern Interface

step for casting conditions. The advantages of this approach are that (1) it does not require a lot of computational power, (2) it could be fairly accurate and easy to implement because of its reliance mostly on the experimental data. The disadvantage of this method is the necessity to run a great number of complex experiments to study the effects of metal temperature, head pressure, foam density, etc.

Approach #2 is based on Thermo-Gravimetric Analysis (TGA). TGA data can provide constants which allow estimations of the rate of polymer degradation. This technique has been used in a Linear Pyrolysis (LP) model developed for a theoretical analysis of solid rocket propellant combustion and ablation of re-entry vehicles with limited success. The limiting factor is the assumption that the constants obtained from relatively slow heating rates used in TGA remain constant at the higher heating rates experienced in the events of interest. The literature reveals that empirical techniques are necessary to make this extrapolation from slow heating rates to high heating rates at conditions of rocket nozzles and re-entry shields. It is unclear at this point whether the constants can be extrapolated to heating rates in the LFC process.

7.1.1 Progress in Approach #1

The following is a list of minimum data to be determined from the experimental technique for Approach #1:

1. Gas-to-Liquid Ratio as a function of heater temperature and back pressure.
2. Heat Transfer Rate as a function of heater temperature and back pressure.
3. Recession Velocity as a function of heater temperature and back pressure.

A new technique that is able to address the above objectives has been developed at UAB. This technique uses an electric heater (shape of the heater is not specified) that is smaller than the foam bar. It has been confirmed experimentally that in this case the liquid residue does not build up on the heater but rather stays on the internal sides of the strips. The heat flux to the foam can be calculated from the power balance: (Heater Voltage)*(Amps)-Losses. The gas fraction (F_{gas}) can be found from the following balance:

$$F_{gas} = M_{gas} / M_{reacted}. \quad (\text{Eq. 7.1.1.1})$$

Where:

$$M_{reacted} = a * b * L * D$$

a = width of heater (cm.)
 b = width of foam bar (cm.)
 L = length of foam bar (cm.)

Figure 7.1.2. Approaches to Modeling the Lost Foam Process

D = foam density (gm/cm^3)
 $M_{\text{gas}} = M_i - M_f$
 M_i = initial mass of foam (gm)
 M_f = final mas of foam (gm)

The technique was first implemented using high watt density round cartridge heaters. Fig. 7.1.1.1 illustrates the experimental setup. The cartridge heaters were supported by a water-cooled copper block whose purpose was also to serve as a heat sink for the lower part of the cartridge. A type K thermocouple was spot-welded on the top surface of the heater using 30 gauge wire. The bars used in the experiments were 2.4 cm x 1.7 cm x 52 cm and had a density of 23.9 kg/m^3 . Fig. 7.1.1.2 and Fig. 7.1.1.3 show the data obtained in the experiments. The velocity data corresponds well with the velocities observed in aluminum LF castings using high permeability coatings. These path finding experiments revealed several shortcomings of the technique and directed the development of a refined apparatus.

7.1.2. Progress in Approach #2

The development of the LF modeling software was based on the 2D heat transfer and solidification code written at the University of Missouri-Rolla. This software implements the Finite Difference Method. Initially, an extensive verification of the code was done. The purpose was to find the source of discrepancy in solidification curves for iron predicted by this program and the ProCAST software. A few errors that caused the discrepancy were identified and corrected.

As a first effort in modeling, a "solid plug flow" model was developed using the UMR code (see Fig. 7.1.2.1). Inputs for the program were the thermal properties of metal and foam (thermal conductivity, specific heat capacity, and enthalpy) and the kinetic zone parameters (the metal-foam heat transfer coefficient and the gas-to-liquid ratio). Foam collapsing is modeled by solving unsteady heat conduction in the foam region affected by the metal front using a heat transfer coefficient between the metal and the foam of 0.07 $\text{W}/\text{cm}^2\text{-K}$ and the polymer surface temperature of 270°C. These values were previously determined in the experiments conducted at UAT. At the present time, the program does not model the fluid flow of molten polystyrene out of the reaction zone or the back pressure generated by the escaping gases. This means that realistic metal front velocity and foam temperature values cannot be determined in the kinetic zone. Fig. 7.1.2.2 shows predicted metal front velocity vs. distance for this model. The velocity values are somewhat lower than velocities measured in actual castings using high permeability coatings. This exercise pointed out the need for more accurate data on the heat transfer coefficient and the temperature at which the pattern collapses.

Simultaneously with our effort, and using UAB technical direction, ProCast is developing a code based on approach #1 which will be added to its ProCAST software. Although ProCAST has a commercial code for modeling the LF casting process, this code assumes

Figure 7.1.1.1. Schematic of Cartridge Heater Apparatus

Figure 7.1.1.1.2. Average Recession Velocity of Pattern for Cartridge Heater

Figure 7.1.1.1.3. Gas Fraction of Degraded Pattern Using Cartridge Heater

Coating of Infinite
Permeability

Velocity
Profile

Figure 7.1.2.1. Schematic of 'Plug Flow' Model

**Figure 7.1.2.2. Metal Front Velocity as a Function of Distance,
"Solid Plug Flow" Model**

complete pattern degradation into gas and does not include the mechanisms of by-product removal through the coating. UAB discussed its collaborative work with UES, Inc in this area at a meeting in June 1996 at Des Plains, IL. UAB transferred necessary technical knowledge in LF casting to UES, Inc to assist in a more comprehensive code development.

Currently UAB personnel are writing the mechanism code for the 3 dimensional fill and solidification code developed by UMR earlier in this program. The first step will be a plug flow model to evaluate the validity of the heat balance equation and the moving boundary necessary to track the metal front.

Both UMR and UAB have developed a vast amount of casting data on metal velocity, metal front profiles, defect formation. This data is based on varying coating and sand permeability, coating thermal conductivity, coating thickness, and pattern density. This data bank is the basis from which the computational model will be judged for accuracy.

7.2 Thermal Properties of LFC Coatings and Foundry Sands

A sensitivity analysis of the thermal events occurring in the metal casting process revealed that metal cooling rates are strongly dependent on the thermal properties of the coatings and sands. Accurate data on these materials is limited; therefore, an effort was necessary to generate this data. The experiments for determining the thermo-physical properties of coatings used in LF casting process and foundry sands were conducted at the High Temperature Materials Laboratory (HTML) at the Oak Ridge National Laboratory in July-August, 1997. The objectives of this effort were:

1. Evaluate the specific heat and thermal conductivity for typical LF coatings in the temperature range of RT-1000°C.
2. Evaluate the specific heat and thermal conductivity for typical LF sands (loose and compacted) in the temperature range of RT-1000°C.
3. Develop test techniques for measuring thermal conductivity of unbonded sand.

Four coatings were selected as typical for both the iron and aluminum casting processes and were obtained from two coatings manufacturers. The coatings studied were 510, 533, StyroCoat 27, and StyroCoat 400. Silica and Olivine sands were selected to represent currently used sands. Two grades of synthetic Mullite, a low expansion sand described previously, were selected. The chemical composition of the coatings and sands are presented in Tables 7.2.1 - 7.2.2.

The thermal properties evaluated were thermal diffusivity and specific heat. Thermal conductivity values were later calculated as:

$$k = C_p * d * a$$

$$\text{Eq. (7.2.1)}$$

Table 7.2.1. Chemical Composition of Coatings

Coating	Refractory
510	Aluminum Silicate
533	Aluminum Silicate
STY27	Silica
STY400	Mica

Table 7.2.2. Chemical Composition of Sands.

Sand	Composition
Mullite 30/50	49 % aluminum oxide 47 % silicon dioxide 2 % titanium oxide 1 % iron
Mullite 30/60	72 % aluminum oxide 13 % silicon dioxide 3.7 % titanium oxide 9.9 % iron
Olivine	$(\text{Mg, Fe})_2\text{SiO}_4$
Silica	Silica

Figure 7.2.1. Laser Flash Diffusivity Apparatus

where:

C_p = specific heat capacity, J/gm-K

d = material density, gm/cm³

a = thermal diffusivity, cm²/s

The diffusivity measurements were conducted on a Laser Flash Diffusivity (LFD) apparatus. In the LFD method, one side of the sample, which is placed in the heating chamber, is heated up with a short impulse of infrared laser light (see Fig. 7.2.1). An IR detector located on the back side records the temperature rise of the sample. The diffusivity is calculated as $bL^2/t_{1/2}$ where b is a coefficient, L is the sample thickness, and $t_{1/2}$ is the half-rise time.

Specific heat measurements were done with the use of a Differential Scanning Calorimeter (DSC). In the DCS, there are two crucibles (see Fig. 7.2.2.). One contains the sample and the other the reference. Two thermocouples under the crucibles measure the temperature difference between the reference and the sample during heating. The temperature differential can be translated into heat fluxes into the sample and the reference. Knowing the heat fluxes, the masses of the sample and the reference, and the heat capacity of the reference, the specific heat capacity of the sample can be determined.

7.2.1. Diffusivity Measurements of Coatings

The diffusivity measurements were conducted in the temperature range RT-950°C. Samples were 12 mm in diameter and 0.6 mm thick. To prevent laser light penetration through the coatings, samples were coated with a gold-palladium alloy. Two samples of each coating were evaluated using three laser exposures at each temperature. In the six slot carousel, three coatings were tested simultaneously. No significant difficulties were encountered during the measurements. The plots of the thermal diffusivity of the four coatings vs. temperature are shown in Fig. 7.2.1.1.

7.2.2. Specific Heat Measurements of Coatings

Diffusivity measurements were conducted in the temperature range 100-1000°C. Samples were 3 mm in diameter and 2 mm thick. One sample of each coating was used. To determine the influence of the binder burn-out on specific heat, two separate runs for each sample were made. Fig. 7.2.2.1 illustrates the specific heat of both a 'virgin' and preheated sample of Coating 400. The upper curve represents the specific heat of a 'virgin' sample containing an organic binder. The lower curve describes the specific heat of the same sample after exposure to 1000°C during the first run. Since the process of binder burnout is endothermic, a 'virgin' sample will absorb more energy than a preheated sample. This explains the offset of the "virgin" curve and the presence of the endothermic peak in the upper curve in the temperature range 450-550°C. The second peak may be attributed to

Figure 7.2.2. Differential Scanning Calorimeter (DSC) Apparatus

Figure 7.2.1.1. Thermal Diffusivity of Selected Coatings

Figure 7.2.2.1. Specific Heat Response of Virgin and Preheated Coated

some phase changes in the components of the coating occurring in the range 750-950°C. Since the 'virgin' sample is representative of the events occurring in the LFC Process these specific heat values should be used in the computational model. The plots of the specific heat values for the four coatings vs. temperature are shown in Fig.

7.2.2.2. The specific heat capacities of coatings differ no more than ~5%. The accuracy of the DSC measurements is ~3%.

7.2.3. Diffusivity Measurements of Sands

The diffusivity of sands could not be measured by the Laser Flash Diffusivity method due to the semi-transparency of sand and small size of the samples. A new technique called "the probe method" was proposed to measure the diffusivity/conductivity of sands. Preliminary results are expected by the middle of the second quarter of 1998.

7.2.4. Conductivity of Coatings

Thermal conductivity values of coatings were calculated using Eq. 7.2.1 and these results are shown in Fig. 7.2.4.1. Coatings STY27 and 533 tend to group together at a higher conductivity value while coatings STY400 and 510 tend to group together at a lower conductivity. The difference in conductivity between these low and high conductivity groups is about 50%. All coatings exhibit similar behavior where conductivity values initially increase slightly from room temperature to about 200°C and then decrease as the binders burn out between temperatures of 200°C to 500°C. With the binder between refractory particles gone the mode of heat transfer is primarily governed by particle-to-particle contact. Above 600°C all coatings increase in conductivity with increasing temperature as thermal radiation starts to influence the process of heat conduction.

7.2.5. Specific Heat of Sands

Diffusivity measurements on sands were conducted in the temperature range 100-1000°C. Two separate evaluations were made on 50 mg samples of loose sand to check the reproducibility of the measurement technique. No significant difference in the values was detected. The plots of the specific heat values for the four sands vs. temperature are shown in Fig. 7.2.5.1. This data indicates that (1) the specific heat capacities of these sands differ by less than 10%, (2) Silica and Olivine sands undergo phase changes during heating.

8.0 Project Management and Technology Transfer

Technology transfer between UAB personnel and sponsors occur in the form of quarterly meetings and individual contacts as requested by the sponsors. Four sponsor meetings were held at AFS in Chicago and at UAB in Birmingham. These meetings provide opportunity for UAB

Figure 7.2.2.2. Specific Heat of Selected Coatings

Figure 7.2.4.1. Thermal Conductivity of Selected Coatings

Figure 7.2.5.1. Specific Heat of Selected Sands

personnel to review the achievements in the previous quarter and to receive comments and direction from the sponsors. This procedure has served this project well in the past.

Project management is dictated by Charles E. Bates, Ph.D.

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Our hope is that the information contained in this report will be of assistance to companies throughout the United States in advancing the technology of Lost Foam Casting.

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