ADVANCED LOST FOAM CASTING TECHNOLOGY

PHASE IV

by

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1998 - 2000 SUMMARY REPORT AND
FINAL TECHNICAL REPORT TO

THE DEPARTMENT OF ENERGY

DoE CONTRACT NO. DEFC07-98ID13603
REPORT NO. UAB-MTG-EPC2000SUM

NOVEMBER 2000

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EXECUTIVE SUMMARY AND CONCLUSIONS

Previous research, conducted under DoE Contracts #DE-FC07-89ID12869, DE-FC07-93ID12230 AND DE-FC07-95ID113358 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 six tasks listed as follows:

- Task 1: Pattern Pyrolysis Products and Pattern Properties
- Task 2: Coating Quality Control
- Task 3: Fill and Solidification Code
- Task 4: Alternate Pattern Materials
- Task 5: Casting Distortion
- Task 6: Technology Transfer

This report describes the research done under the current contract in all six tasks in the period of October 1, 1998 through March 31, 2000. A brief summary of this research results is as follows:

Task 1. A summary of the major accomplishments includes the results from research on: 1) pattern pyrolysis 2) mechanisms of defect formation in Lost Foam castings, 3) the effect of pattern material properties on casting quality and 4) vacuum assisted casting.

Pattern Pyrolysis - An experimental technique for studying the process of foam pyrolysis was developed that mimics the conditions present in LF casting of aluminum and provides the data necessary for a computer model. A foam pyrolysis apparatus based on this technique was built. The apparatus allows studying pyrolysis of different foam polymers at temperature up to 1200°C either at controlled pressure or controlled recession velocity. Pyrolysis parameters such as gas fraction, gas temperature, power density, heat transfer coefficient, and energy of degradation can be determined in experiments. The apparatus is described in sections 1.1.1.1 and 1.1.1.2.

Foam pyrolysis experiments were conducted using the apparatus to study the effects of polymer type, pattern density, bead fusion, driving pressure, and recession velocity on pyrolysis parameters and to develop pyrolysis data for future use in a computational model of the LFCP. Three polymer--EPS, copolymer, and PMMA--were studied in experiments. The controlled pressure experiments were conducted in the temperature range of 580-910°C on EPS at driving pressure levels of 10.3 kPa (1.5 psi) and 27.6 kPa (4 psi). The controlled velocity experiments were conducted in the temperature range of 580-1040°C on EPS, copolymer, and PMMA at nominal recession velocities of 1.78 and 3.33 cm/s. The experimental data developed in the experiments include gas fraction, heater power density, and specific energy of degradation. An analysis of the experimental data is presented in sections 1.1.1.3 and 1.1.1.4.

The feasibility of using a 60% platinum/40% rhodium alloy as a heater material to extend the temperature capabilities of the foam pyrolysis apparatus to iron and steel pouring temperatures in LF casting (1600°C) was investigated. The Pt/Rh heater allowed extension of the maximum pyrolysis temperature from ~1050°C, obtainable with the Kanthal heater, to 1200°C. Controlled velocity pyrolysis experiments were conducted on PMMA in the temperature range of 690-1070°C at a nominal recession velocity of 1.78 cm/s and on EPS in the temperature range of 780-1220°C and at nominal recession velocities of 1.78 , 3.33, and 6.96 cm/s. The new data showed good agreement with the existing degradation data for PMMA and EPS developed in constant velocity experiments using the Kanthal heater. These results are presented in section 1.1.1.5.

Pyrolysis temperature for EPS could not be extended above 1200°C due to carbon deposition on the heater front face. The carbon layer acted as a thermal insulator introducing an error in the power density measurements and causing heater overheating. A silicon carbide heater is proposed to develop pyrolysis data in the temperature range of 1200-1600°C.

Temperature of the gaseous degradation products as they leave the kinetic zone was measured using the foam pyrolysis apparatus. This data is necessary in a computer model of the LFCP to calculate pressure in the kinetic zone to predict the metal fill velocity in the mold. The gas temperature was not found to be affected by the bar recession velocity and steadily increased from about 450 to 730°C as the heater temperature increased from 617 to 1040°C. The temperature of the liquid fraction was estimated at 315°C at a heater temperature of 600°C and at 446°C at a heater temperature of 1000°C. The estimates of the temperature of the gaseous fraction made using the heat balance approach showed good agreement with the measured values over the experimental temperature range. These results are presented in section 1.1.1.6.

The development of the pyrolysis apparatus significantly impacts the development of a computational model of the Lost Foam filling process. The data obtained from this apparatus can be used to realistically describe the events occurring at the metal/pattern interface without the excessive computation time required using a more theoretical approach. Hopefully the data available from this apparatus will accelerate the development of a computational model.

Defect Formation - In studies to determine the repeatability of experimental results (section 1.1.2.3), it was determined that although metal velocity during fill may be predictable, the severity of the defects in the flange pattern varied over a wide range. Defects did tend to concentrate in certain areas -- for example, blisters were normally found in a band about halfway around the flange pattern, while folds normally were located where the two main metal streams met. However, other, usually relatively small, folds were somewhat randomly located on the flange. This suggests that there may be two important causes for the fold defects -- the impingement of

metal streams on one another and turbulence either during pouring or at the metal-foam or metal-foam-coating interface. This may also lead to different fold chemistries, as suggested by the Auger analysis, with metal stream impingement leading to a composite carbon-oxide fold surface and turbulence leading to a primarily oxide fold surface.

High sand temperatures (section 1.1.2.4), in addition to or perhaps because of increasing metal velocity, normally increased the incidence of folds and blisters. The higher metal velocity would tend to make the metal front more unstable, leading to entrapped oxides and pyrolysis products.

Although extra glue or use of a foam rather than a hollow ceramic sprue had little effect on metal velocity, they did increase the number of defects (section 1.1.2.5). Thus the amount of organic material introduced through the glue or foam influences the incidence of defects separately from any velocity/turbulence effect.

Using either extruded or reticulated filters at the base of a hollow sprue had little effect on metal velocity and also little effect on the incidence of defects (section 1.1.2.6). However, the hollow sprue, with or without filters, did produce fewer defects than a foam sprue. The tests that showed this effect, however, were unable to indicate whether the filters are effective in eliminating any pyrolysis products or oxides introduced during pouring or displacement of foam sprues. A set of tests to be conducted during Phase V will address this issue.

The gating design influences defect formation (section 1.1.2.7). Bottom gating of a flange pattern produced the fewest defects, while top gating produced the most defects. When the flange pattern was oriented horizontally, the fewest fold defects were found when only a single side gate was used. Additional gates increased the number of locations where metal streams impinged.

High metal velocities are obtained when the coating permeability is high -- this normally leads to more severe defects.

High density EPS foams lead to lower metal velocities, but also provide more pyrolysis products that may be trapped in the casting (section 1.1.2.8). The conflicting influences of velocity and amount of organic material sometimes makes it difficult to predict the effect of foam density on defect formation. However in these tests denser foams resulted in more likelihood of internal porosity and possibly more folds. Blisters tended to decrease in number.

Higher silicon levels in Al-Si alloys, resulting in a narrow solidification temperature range, produced very large folds and numerous internal pores when a high permeability coating permitted rapid fill rates (section 1.1.2.10).

An Al-Cu alloy can produce comparable or even better fillability than conventional Al-Si alloys, with slightly higher metal velocities.

Defect formation is similar in severity to the traditional 319 and 356 alloys (1.1.2.13).

The critical gate area at which fill changes from gate size control to coating control increases with the A/P ratio of the pattern. Even for large A/P ratios, however, the critical gate area is very small (section 1.1.2.14).

These experimental results should serve as guidelines for defect reduction in Lost Foam foundries. High metal velocities, high pattern densities and foam sprues are major contributors to defect formation. It is interesting to observe that coating permeability, and perhaps some other coating parameter, can be used to reduce the effects of these defect contributors.

Pattern Properties - The mystery of 'summer beads' was resolved by developing procedures to determine the effects of polymer molecular weight and blowing agent content on the glass transition temperature of beads. 'Summer beads' resulted from inadequate control of the molecular weight of polystyrene, which caused normal pre-expansion and molding processes to produce overfused patterns. These patterns, in turn, produced castings with high porosity, laps, folds, and misruns. Results of this study revealed that blowing agents plasticise the polymer which reduces the polymer glass transition temperature from 100°C to as low as 60°C, depending on the type of blowing agent, blowing agent content and polymer molecular weight. This study emphasizes the importance of controlling the polymer molecular weight and blowing agent content within limits in order to produce patterns with consistent properties that assure quality castings (section 1.2.1).

A precoat material was discovered that dramatically decreased the incidence of defects in both iron and aluminum castings. This liquid material was applied to the patterns and dried before the normal refractory coating was applied. Laboratory tests provided statistical proof that this material could reduce certain types of casting defects by as much as 50%. Implementation of this precoat would add two additional steps to the Lost Foam process which would probably prohibit it's use; however the discovery paved the way for experimentation of additives to the polymer (section 1.2.2).

A large laboratory experimental matrix was completed to study the effects of pattern density and bead fusion gradients on metal front shapes and defect formation. The results from the instrumented laboratory castings revealed the metal front shape generally followed the density gradient - low densities generated high metal velocities and high densities generated low velocities. In addition two plant trials were completed to verify the laboratory results. Defects were reduced significantly in a cast iron fire plug casting by reducing the EPS pattern density and minimizing the density gradients. The cause of increased scrap for a austempered ductile iron railroad car casting was traced to severe density gradients in patterns which had the same overall density as patterns that produced little scrap (sections 1.2.3

and 1.2.4).

A Pattern Quality Manual was written and released to the sponsors. This manual is similar to the Coating Quality Manual and contains the procedures required to assure consistent pattern quality. The manual is being updated as addition information is available (section 1.2.5).

An experimental test matrix was completed to study the effects of vacuum applied to the flask on Lost Foam Castings poured in iron and aluminum. This study was a range finding study which compared castings poured with no vacuum to those poured with a covered flask vacuum of 10 inches of mercury. The study revealed extremely high metal velocities with the vacuum assist accompanied by the expected defects of burn-on, porosity and folds. The iron castings revealed a significant decrease in surface defects caused by pyrolysis products when using vacuum, indicating the possibility of pouring steel castings with minimum carbon pick-up. A strong interaction between the coating permeability and the vacuum assist provides hope that, with combinations of coating permeability and vacuum assist levels the defects could be controlled (section 1.3).

Task 2. Coating permeability continues to be the dominant control used on the production floor to control casting defects. An additional procedure has surfaced in the form of viscosity control which dictates the deposited coating thickness and hence the effective coating permeability. This procedure includes measuring a viscosity index by comparing viscosities at various shear rates which better represents the coating behavior during pattern dipping and removal (section 2.0). Overall the coatings manufacturers have, over the past few years, significantly improved the consistency of coating properties and continue to be innovative in search for improvements.

Task 3. A computational code that accurately describes the filling process in Lost Foam Casting is rapidly becoming a reality. Both Flow 3D and Procast have made tremendous strides in improving their software. The Flow 3D code can make reasonable predictions of possible defect locations based on free surface tracking of metal fronts, provided the metal velocities are know. Flow 3D does not yet include the parameters that control metal velocity such as coating and sand permeability. Procast has incorporated coating and sand permeability into their code but not in a realistic manner.

Accurate thermal properties of sand and coatings are necessary as inputs to the fill and solidification code. These properties were determined through a joint effort between UAB and Oak Ridge National Laboratory. This data is presented in section 3.1.1.

Task 4. The search for alternate pattern materials for the Lost Foam Casting process has yielded only one possibility - PAC polymer. This polymer produces significantly less liquid by-products during thermal degradation which should improve casting quality; however difficulties in pre-expansion and pattern molding, coupled with a very

unpleasant odor are serious barriers to production. In addition the development time and cost will probably dictate a cost equal to or greater than CoPolymer or PMMA, which currently has limited usage. The approach UAB has taken to accomplish this task is to evaluate EPS pattern materials with additives that alter the pyrolysis process in ways to improve casting quality. Polymer chemist are playing an active role in this effort (section 4.0).

Task 5. The major issues surrounding casting distortion have been identified as flask acceleration levels during filling and compaction, sand angularity and sand thermal expansion. Although these issues have been identified through laboratory experiments, implementation has been slow in the foundries. Production schedules continue to cause excessive acceleration levels that produce warped patterns. Silica sand continues to be the most economical media for casting, hence change to a lower expansion sand has only occurred where casting precision and accuracy is required. Aluminum engine castings were poured using patterns where critical dimensions were recorded, followed by measurement of these dimensions on the castings. The results indicated that the major causes of casting distortion were flask acceleration, sand angularity and sand expansion (section 5.0).

Task 6. Technology transfer between UAB personnel and sponsors occur in the form of meetings held every four months and individual contacts as requested by the sponsors. Five sponsor meetings were held at AFS in Chicago and 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.

Several training courses were taught at participating sponsors' facilities to summarize the research efforts of the past years and to assist in training of plant personnel. This was deemed necessary as Lost Foam continues to grow at a rapid pace. The growth rate of the Lost Foam industry was the subject of a marketing study performed by the University of Wisconsin - Milwaukee and the American Foundrymen's Society, funded by UAB as a part of this research. This survey is included as Appendix B.

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.

DOE CONTRACT NUMBER DEFC07-98ID13603
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- 1.0 Pattern Pyrolysis Products and Pattern Properties
- 1.1 Pyrolysis Products
- 1.1.1 UAB Research
- 1.1.1.1 Experimental Technique

On the basis of the previous path-finding experiments¹ with high watt density round cartridge heaters, an experimental technique that closely mimics the conditions of pattern degradation in LF casting of aluminum and provides data necessary for a computer model of the LFCP was developed. The technique is schematically illustrated in Figure 1.1.1.1.1. A foam bar is pressed against an electric strip heater whose central part (hot zone) is significantly narrower than the bar. The heater is supported by a block of high temperature insulation material. The insulation minimizes any radiation and convection heat transfer from the back side of the heater to the foam. The energy exchange between the heater and the foam bar occurs only at the front side of the heater. The liquid residue flows around the heater and stays on the inner sides of the partially degraded bar. Degradation energy transfer rate Q_{degr} can be calculated from the power balance:

$Q_{degr} = P - Q_{loss}$, where P is the total power generated in the heater and Q_{loss} is the total heat losses (conduction through the ends of the heater and the insulation). The total power is calculated as $P = U \times I$ where U is voltage across the heater hot zone and I is current flowing through heater. The gas fraction F_{gas} can be deduced by the following mass balance:

$$F_{gas} = \frac{M_{gas}}{M_{degraded}}$$

where M_{gas} = mass of gaseous products (g), $M_{degraded}$ = mass of foam

$$M_{gas} = m_{fin} - m_{in}$$

degraded into gas and liquid (g) (shaded volume in Figure 1.1.1.1.1),

$$M_{degraded} = \rho_{pattern} abL$$

m_{in} = initial mass or mass of the bar before the experiment (g), m_{fin} = final mass, or mass of the bar after the experiment (g), a = height of the heater hot zone (cm), b = width of the bar (cm), L = length of the bar (cm), $\rho_{pattern}$ = pattern density (g/cm³).

Pyrolysis experiments can be conducted in two ways. In constant pressure experiments, the foam bar is pushed against the heater with some constant force F which creates pressure in the contact area of the bar with the heater equal $F/(a \times b)$. The driving force is usually chosen to generate pressure equal to the pressure created at the metal front in LF casting, which is approximately equal to the metallostatic pressure. Constant pressure experiments mimic the conditions of pattern replacement with metal except for the coating permeability.

The absence of coating around the kinetic zone creates the conditions of infinite permeability and allows the degradation products to escape the kinetic zone with negligible resistance, which results in the formation of the gap between the heater and the foam bar much smaller than the actual gap between the metal and the pattern in LF casting. A smaller gap allows higher heat transfer rates between the heater and the foam which results in recession rates higher than the metal fill velocities observed in LF casting. Constant pressure experiments can provide data on terminal velocities of metal in the mold.

In constant velocity experiments, the foam bar is pushed against the heater at some constant recession velocity V_{rec} chosen to represent an actual metal filling velocity. The pressure exerted on the foam bar represents the intrinsic pattern degradation pressure and is usually significantly smaller than the total pressure at the metal front in the mold at the same filling velocity because of the conditions of infinite permeability around the kinetic zone. Heat transfer between the heater and the bar is assumed to be closely representative of heat transfer between the metal and foam pattern in LF casting at the same metal temperature and filling velocity. This assumption is based on the idea that heat transfer between the metal and the foam can be treated as a function of only two variables--metal velocity and metal temperature--since for a given metal temperature the metal velocity is determined by coating permeability and metallostatic pressure. The dependence of the physical properties of degradation products on pressure is neglected in this case. The width of the kinetic zone is considered to be uniquely determined for a given metal front velocity and temperature from the requirements of heat transfer across the gap.

Constant velocity experiments better model heat and mass transfer in the kinetic zone in LF casting than the constant pressure experiments. Constant velocity experiments with simultaneous measurement of the driving force on the bar would combine the two experimental techniques and provide complete degradation data needed for better understanding and modeling of the metal/pattern exchange mechanism.

1.1.1.2. Experimental Set-Up

A pyrolysis apparatus using the above principles was built. The design of the apparatus is illustrated in Figures 1.1.1.2.1-1.1.1.2.8. The apparatus allows either constant velocity or constant pressure pyrolysis experiments. A foam bar slides along guides as it is pushed against the heater. The pusher represents a carriage that rolls (to minimize friction) on a rail (see Figures 1.1.1.2.1-1.1.1.2.3) being moved by a cord either with the drive system (in constant velocity experiments) or by a weight (in constant pressure experiments). The drive system allows smooth feed velocity adjustments and consists of a variable speed 25 watt 90 V DC gearmotor with a sheave and an electronic speed control. Two limit switches located at the ends of the rail reverse the direction of the carriage movement at the ends of the rail. A resistance potentiometer is used to record instantaneous carriage position.

The strip heater is made from a high temperature heating alloy. Heaters made from a Fe-Cr-Al heating alloy (Kanthal) have temperature capabilities of about 1050°C; Pt/Rh heaters can be theoretically used at temperatures up to 1600°C, but carbon deposition on the heater face during pyrolysis of EPS (see Section 1.1.1.5.2) limits the practical pyrolysis temperature to about 1200°C.

The central narrow part of the heater can be made either convex or concave to study the effect of the metal front shape on foam degradation. The convex shape facilitates the flow of liquid pyrolysis products around the heater and helps them stay on the sides of the bar. Five 0.23-mm type K thermocouples (TCs) are spot-welded to the heater front surface to determine the temperature profile along the heater and to calculate conduction heat losses. Three TCs are located inside the contact area of the heater with the bar, and the other two are located outside (see Figure 1.1.1.2.4). The space near the heater is purged with nitrogen supplied through 0.64-cm copper tubes to prevent ignition of gaseous degradation products and cool the exposed parts of the heater. Photographs of the front and the rear of the heater assembly are shown in Figures 1.1.1.2.6 and 1.1.1.2.7.

The heater is powered by a 110 V/0-130 V 17.5 kW variable transformer with a phase-angle silicon controlled rectifier (SCR) controller in the primary circuit for smooth power adjustments (see electrical diagram of the apparatus in Figure 1.1.1.2.8). The heater current is measured with a current transformer in the secondary circuit. Voltage is measured across two leads spot-welded to the back side of the heater at the width of the foam bar (see Figure 1.1.1.2.5). A true root-mean-square signal conditioner is used to determine actual current and voltage in the heater circuit.

The apparatus has the following technical capabilities:

1. Foam pyrolysis temperature: up to 1200°C (with a Pt/Rh heater for EPS).
2. Foam bar feed velocity: 1 to 7 cm/s.
3. Foam bars dimensions: 1 to 3 cm wide, up to 6.5 cm tall, up to 127 cm long.

The data acquisition system consists of an analog/digital converter and a laptop computer. The following parameters are recorded during experiments: (a) heater temperature in five locations, (b) instantaneous position of the carriage to calculate recession velocity, (c) heater voltage and amperage to calculate heater power, and (d) initial and final weights of each bar to determine gas fraction.

1.1.1.3. Constant Pressure Foam Pyrolysis Experiments

The constant pressure pyrolysis experiments were intended as preliminary experiments to verify the design of the apparatus and develop pattern degradation data for future use in a computational model of the LFCP. The data developed in the experiments included

recession velocity, gas fraction, power density, and energy of degradation at different driving pressure levels and heater temperatures.

1.1.1.3.1. Experimental Matrix

The pyrolysis experiments were conducted on EPS bars at two nominal pressures of 10.3 kPa (1.5 psi) and 27.6 kPa (4 psi) in the temperature range from 580 to 910°C. The foam bars 1.84 cm wide, 3.2 cm tall, and 54-63.5 cm long were hot wire cut from a 3.2-cm thick, 22.0 kg/m³ (1.37 pcf) bulk density EPS board. The density of the central part of the bar that was in contact with the strip heater was measured at 19.6 kg/m³ (1.22 pcf) using the water immersion technique with oil impregnation of open pores in the samples (see Section 1.2.4.4). The experiments were conducted using a Kanthal heater with the height of the hot zone of 0.952 cm. A total of 12 bars were pyrolyzed at 10.3 kPa (1.5 psi) and 15 bars at 27.6 kPa (4 psi).

1.1.1.3.2. Results

The degradation data, which includes recession velocity, power density, heat transfer coefficient, gas fraction, and specific energy of degradation, are presented as functions of average heater temperature and driving pressure on Figures 1.1.1.3.2.1-1.1.1.3.2.5. In accordance with theory and experimental casting data¹, the recession velocity (Figure 1.1.1.3.2.1) was observed to increase with an increase of heater temperature and driving pressure. This is explained by an increase in heat transfer rate from the heater to the foam at higher heater temperatures and driving pressures, as illustrated in the power density plot in Figure 1.1.1.3.2.2. The recession velocities were higher than the metal front velocities observed in LF casting of Al alloys in the same temperature range due to the condition of infinite permeability around the kinetic zone.

Figure 1.1.1.3.2.3 illustrates that both heater temperature and driving pressure had a significant effect on the heat transfer coefficient h between the heater and the foam calculated as $h = p / (T_h - T_f)$ where p = power density (W/cm²), T_h = heater temperature (EC), T_f = pattern temperature (25°C). The heat transfer coefficient increased 2.3-2.8 times as the heater temperature increased from 600 to 900°C. The h values at 27.6 kPa (4 psi) were about 30-50% higher than those at 10.3 kPa (1.5 psi).

The gas fraction (see Figure 1.1.1.3.2.4) was observed to steadily increase from 20-25% at 600°C to 33-43% at 900°C. The effect of pressure on gas fraction could not be determined due to a significant scatter in the data. Gas fraction is expected to be higher at lower driving pressures due to a longer residence time of the polymer in the kinetic zone at lower recession rates. A longer residence time allows polymer to degrade further and generate more gaseous pyrolysis products. The effect of velocity on gas fraction of EPS was observed in constant velocity experiments described in Section 1.1.1.4.2.1.

Figure 1.1.1.3.2.5 illustrates that specific energy of degradation had a distinct dependance on driving pressure. Degradation energy at 27.6 kPa (4 psi) was 8-12% lower than at 10.3 kPa (1.5 psi) due to the effect of driving pressure on polymer residence time in the kinetic zone described above.

Constant pressure pyrolysis experiments on foam polymers using a different technique were conducted by Walling¹⁵. In his experiments, a preheated steel bar with instrumented TCs was freely lowered onto EPS and PMMA blocks held in a bonded sand mold. TCs readings were used to calculate the bar surface temperature and the heat flux to the foam. While the recession rates observed by Walling (see Figure 1.1.1.3.2.6) were close to those measured in the present work at 10.3 kPa (1.5 psi), the heat flux data is in disagreement. Walling observed two distinct temperature modes in the degradation of EPS and PMMA. For EPS at bar temperatures below approximately 680°C, the relationship between the heat flux and the bar temperature was linear with the heat flux values on the order of 10-20 W/cm² (see Figure 1.1.1.3.2.7). At temperatures between 680 and 900°C, the heat flux-bar temperature line was far steeper. For PMMA, the heat flux followed a similar behavior with the change in the modes occurring at about 550°C (see Figure 1.1.1.3.2.8). The heat flux values measured in the present work for EPS at 10.3 kPa (1.5 psi) are 1.5 to 4 times higher than Walling's, and the mode of heat transfer does not change in the temperature range of 600-860°C. The discrepancy in the results might be explained by the bar lateral heat losses which Walling did not include in the calculations for heat flux.

1.1.1.4 Constant Velocity Foam Pyrolysis Experiments

The objective of the constant velocity pyrolysis experiments was to quantitatively study the effects of polymer type, pattern density, bead fusion, and recession velocity on foam pyrolysis and obtain pyrolysis data for future use in a computational model of the LFCP.

1.1.1.4.1. Experimental Matrix

Three different polymers were selected for experiments: EPS, copolymer with a composition of 70% EPS and 30% PMMA, and PMMA. Since pure PMMA is rarely used as a pattern material in LF casting, the effects of pattern density and bead fusion on degradation parameters were studied only for EPS and copolymer.

1.1.1.4.1.1. EPS and Copolymer Foam Patterns

EPS and copolymer foam bars were cut from the patterns shown in Figure 1.1.1.4.1.1.1. The patterns were molded at two nominal densities--20.8 kg/m³ (1.3 pcf) and 24.0 kg/m³ (1.5 pcf)--and at two bead fusion levels--low fusion and high fusion. The level of fusion was controlled by the duration of the steaming cycle during molding. Low fusion patterns were produced with a steaming cycle of 17 s and the high fusion patterns were produced with 24 s. The patterns were

first machined on a table saw to achieve a rectangular shape and then were hot wire cut to produce bars with dimensions 1.83 cm x 3.18 cm x 43.18 cm.

Pattern local and overall densities and bead fusion were measured. The measurements of density and bead fusion were made using the water immersion technique with oil impregnation of open pores in the samples. Open porosity (OP), or the volume of voids between the beads, was used as a measure of bead fusion. Foam slices 0.95 cm x 0.95 cm x 1.83 cm, to match the size of the heater, were cut with a sharp razor blade from different locations in the patterns to check for density variations. The samples were cut out from pattern locations corresponding to the contact area between the heater and the foam bar (see Figure 1.1.1.4.1.1.2). Normally four samples (from two patterns of the same type, two samples per pattern) were taken from each type of pattern. Five or six samples were used for patterns with a large scatter in the density values.

In another experiment the overall density of the patterns was measured. Pattern sections 10-15 cm long were weighed and measured. The overall density was calculated as

$$\text{overall} \frac{2W_{\text{section}}}{LH(B_1 B_2)}$$

where L = length of the pattern section (cm), H = height of the pattern section (cm), B_1 and B_2 = upper and lower bases of the pattern section (cm), respectively (see Figure 1.1.1.4.1.1.2), W_{section} = weight of the pattern section (g).

The density and bead fusion data presented in Table 1.1.1.4.1.1.1 indicates that the high fusion patterns have a lower density than the low fusion patterns. This observation is explained by the mass transport phenomenon occurring in the pattern molding process. During the steaming cycle the preexpanded beads soften, expand, and fuse. The internal pressure created by bead expansion compresses and densifies the beads on or close to the surface of the pattern, causing the transport of pattern material from the center of the pattern to its periphery. This process continues during the cooling cycle because of the low thermal conductivity of expanded beads which makes it difficult to cool the center of the pattern fast enough. Because the more highly fused patterns required a longer steaming cycle than the low fusion patterns, the core of the high fusion patterns expanded to a lower density than the low fusion patterns.

Bead expansion and mass transport in the pattern during molding produce density gradients in the pattern similar to those shown in Figure 1.1.1.4.1.1.2. Because the foam samples used for density and bead fusion measurements had these gradients, the results of the measurements represent average density and open porosity values for the part of the foam bar that experiences thermal degradation.

The difference between the overall and the average slice

densities is not significant except for the 20.8 kg/m³ (1.3 pcf) nominal density high fusion copolymer and the 24.0 kg/m³ (1.5 pcf) nominal density high fusion EPS. These significant variations are attributed to the pattern molding process conditions.

1.1.1.4.1.2. PMMA Foam Patterns

PMMA foam bars with dimensions 1.78 cm x 3.18 cm x 40.3 cm were used in experiments. The bars were cut with a band saw from 3.18-cm thick PMMA boards. The slice density and bead fusion measurements were made on 17 foam samples using the water immersion technique with oil impregnation of open pores in the samples. The results of density measurements are also presented in Table 1.1.1.4.1.1.1.

1.1.1.4.1.3. Experimental Conditions

Pyrolysis experiments were conducted in the temperature range of 580-1040°C and at two nominal feed (recession) velocities--1.78 and 3.33 cm/s. These velocity values approximately represent the lower and upper limits of filling rates for LF aluminum castings. The actual recession velocities did not differ by more than 2.4% from the nominal velocities. The fluctuations of the heater temperature in individual experiments were within about 50°C. A Kanthal heater with dimensions shown in Figure 1.1.1.4.1.3.1 was used in the experiments.

A total of 8 copolymer, and 12 to 15 EPS bars were pyrolyzed in the experimental temperature range for each combination of nominal density, bead fusion, and recession velocity. A total of 61 copolymer and 109 EPS bars were pyrolyzed. A total of 13 and 22 PMMA bars were pyrolyzed in the experimental temperature range at recession velocities of 1.78 and 3.33 cm/s, respectively.

1.1.1.4.2. Results

Pyrolysis data for the three polymers is presented in the form of effects of pyrolysis variables, such as recession velocity (V_{rec}), pattern density, and polymer type, on pyrolysis parameters, such as gas fraction, power density, heat transfer coefficient, and specific energy of degradation, plotted against the average heater temperature. Bead fusion was excluded from the list of variables because of its small variation and the absence of any theoretical support for the bead fusion having any effect on pyrolysis parameters in controlled velocity experiments. Pyrolysis data for EPS is presented in Figures 1.1.1.4.2.1-1.1.1.4.2.8, in Figures 1.1.1.4.2.9-1.1.1.4.2.20 for the copolymer, and in Figures 1.1.1.4.2.21-1.1.1.4.2.24 for the PMMA. Comparisons of pyrolysis parameters for EPS, copolymer, and PMMA are presented in Figures 1.1.1.4.2.25-1.1.1.4.2.30.

1.1.1.4.2.1. The Effect of Pyrolysis Variables on Gas Fraction

Pattern density appeared to have no effect on gas fraction at either recession velocity for either EPS or copolymer in the pattern density range of 19.4-25.0 kg/m³ (1.21-1.56 pcf) (see Figures

1.1.1.4.2.1, 1.1.1.4.2.2, 1.1.1.4.2.9, and 1.1.1.4.2.10). Pattern densities around 16.0 kg/m^3 (1.00 pcf) may have an effect on gas fraction at $V_{\text{rec}}=3.33 \text{ cm/s}$ as the data for 16.7 kg/m^3 (1.04 pcf) copolymer in Figure 1.1.1.4.2.10 suggests. Additional experiments are needed to verify this observation. Theoretically, pattern density is expected to have no effect on gas fraction.

The data in Figures 1.1.1.4.2.3 and 1.1.1.4.2.21 indicate that the recession velocity had a noticeable effect on gas fraction for EPS and PMMA. The gas fraction for EPS at $V_{\text{rec}}=1.78 \text{ cm/s}$ was 5-10% higher than at $V_{\text{rec}}=3.33 \text{ cm/s}$. For PMMA, the effect of recession velocity on gas fraction was similar with the distinction that the difference in gas fraction gradually decreased from about 10% at 600°C to zero at around 900°C . The effect of recession velocity on gas fraction is explained by the dependence of the fraction of volatile degradation products on not only the heater temperature but also on the residence time of degrading polymer in the kinetic zone. The residence time is inversely proportional to the degradation velocity. Thus, in foam pyrolysis experiments conducted at the lower recession velocity, the polymer was in contact longer with the heater and experienced further degradation which resulted in greater gas fraction than the polymer degraded at the higher recession velocity. Recession velocity was not observed to have an apparent effect on gas fraction for copolymer (see Figure 1.1.1.4.2.11). A more elaborate analysis of the data suggests that the effect of V_{rec} on gas fraction for copolymer is less pronounced than that for EPS and is largely overshadowed by data scatter.

No difference in gas fraction between EPS and copolymer was observed at a recession velocity of 1.78 cm/s (see Figure 1.1.1.4.2.25); at a recession velocity of 3.33 cm/s the gas fraction for $19.4\text{-}23.3 \text{ kg/m}^3$ ($1.21\text{-}1.45 \text{ pcf}$) copolymer was ~10% higher than that for $22.7\text{-}25.0 \text{ kg/m}^3$ ($1.42\text{-}1.56 \text{ pcf}$) EPS (see Figure 1.1.1.4.2.26). 16.7 kg/m^3 (1.04 pcf) copolymer is shown separately from the rest of copolymer gas fraction data in Figure 1.1.1.4.2.26 due to a possible effect of a low pattern density on the gas fraction mentioned above. Gas fraction for PMMA was about 45% higher than that for EPS and reached 100% at around 1000°C . These observations support the use of copolymer and PMMA in LF casting of iron and steel to reduce liquid residue-related defects and is in agreement with the results of foam ablation experiments by Shivkumar¹¹ and Shivkumar and Gallois¹³.

A difference was observed in the appearance of the gaseous degradation products of EPS and PMMA. Pyrolysis of EPS produced a white smoke-like gas fraction. Some pyrolysis products condensed on cold metal parts of the heater assembly to form a yellow oil-like residue with a smell of styrene. The white smoke-like fraction was apparently condensed styrene monomer--the main degradation product of EPS at aluminum pouring temperatures. The gas fraction formed during the pyrolysis of PMMA also appeared white, but was not as thick. No condensation of PMMA gas fraction on the heater assembly parts was noticed. The products of degradation of PMMA at these temperatures consist primarily of methyl methacrylate monomer and light gaseous components, which, due to their lower molecular weight and boiling

temperature, were not likely to produce much condensate.

1.1.1.4.2.2 - The Effect of Pyrolysis Variables on Power Density and Heat Transfer Coefficient

The data presented in Figures 1.1.1.4.2.4, 1.1.1.4.2.12, and 1.1.1.4.2.22 illustrate that recession velocity had a significant effect on power density for the polymers. Power density for patterns pyrolyzed at 3.33 cm/s was up to 1.8 times higher than at 1.78 cm/s. Pattern density also had a pronounced effect on power density. For copolymer this effect appears to be linear as illustrated in Figures 1.1.1.4.2.13 and 1.1.1.4.2.14. Due to a narrow density range for EPS patterns (22.7-25.0 kg/m³ [1.42-1.56 pcf]), the effect of pattern density on power density was overshadowed by data scatter. Nevertheless, the pattern density effect on power density for EPS should be similar to that for copolymer. Theoretically the effect of recession velocity and pattern density on power density is explained on the basis that increasing either the recession rate or the pattern density increases the amount of foam to be degraded per unit time, which in turn requires more power.

The linear appearance of the power versus temperature and power versus density relations for copolymer suggests that an equation of the form

$$p = a_1 T^{a_2} D^{a_3} \quad (1.1.1.4.2.2.1)$$

where p = power density (W/cm²), T = heater temperature (°C), D = pattern density (kg/m³ or pcf), $a_1 \dots a_4$ = coefficients, could be fitted to the data. Figures 1.1.1.4.2.15 and 1.1.1.4.2.16 illustrate 3-D plots of Equation 1.1.1.4.2.2.1 fitted to the power density data for copolymer at recession velocities of 1.78 and 3.33 cm/s, respectively, using a multivariable regression analysis. Equation fitting was not performed on the EPS data due to a narrow pattern density range. Representing pyrolysis data in the form of equations is convenient for analysis and input into computer models.

Figures 1.1.1.4.2.27 and 1.1.1.4.2.28 illustrate that 23.3 kg/m³ (1.45 pcf) copolymer did not significantly differ in power density from the same pattern density EPS at V_{rec} =1.78 cm/s. 21.6 kg/m³ (1.35 pcf) PMMA had up to 12 W/cm² higher power density values than 23.3 kg/m³ (1.45 pcf) copolymer. Valid comparison of power density values for PMMA with those for EPS and copolymer is not possible due to a different density of PMMA.

Figures 1.1.1.4.2.5, 1.1.1.4.2.17, and 1.1.1.4.2.23 illustrate the heat transfer coefficient, h , between the heater and the foam for the three polymers at different pattern densities and recession velocities. Since the heat transfer coefficient is proportional to the power density, the effects of recession velocity and pattern density on h are similar to those for the power density. At a recession rate of 1.78 cm/s the heat transfer coefficient was practically independent of heater temperature and ranged, depending on the pattern density and polymer type, from 0.05 to 0.09 W/(cm²-°K). At a recession rate of 3.33

cm/s the heat transfer coefficient slightly increased with temperature and ranged, depending on the pattern density and polymer type, from 0.08 to 0.16 W/(cm²-°K). These values for h agree well with a heat transfer coefficient of 0.07 W/(cm²-°K) for aluminum LF casting reported by Miller⁷.

The power density and heat transfer coefficient data developed for EPS, copolymer, and PMMA did not show any abrupt change in the heat transfer mode in the temperature range of 620-950°C. Similar results were obtained in constant pressure experiments (see Section 1.1.1.3 and Figures 1.1.1.3.2.2 and 1.1.1.3.2.3). The results of these two works are in disagreement with the results of foam recession experiments by Walling¹⁵ who observed two different modes of heat transfer for EPS and PMMA. The change in the modes occurred at about 680°C for EPS and 550°C for PMMA (see Figures 1.1.1.3.2.7 and 1.1.1.3.2.8). As was mentioned in Section 1.1.1.3.2, the discrepancy in the results might be explained by the bar lateral heat losses which Walling did not include in the calculations for heat flux. However, a change in the heat transfer mode associated, for example, with a transition from nucleate to film boiling, can occur at lower temperatures below 620°C. Additional pyrolysis experiments are needed to verify this hypothesis.

1.1.1.4.2.3. The Effect of Pyrolysis Variables on Specific Energy of Degradation

Pattern density in the range of 22.7-25.0 kg/m³ (1.42-1.56 pcf) for EPS and in the range of 19.4-23.3 kg/m³ (1.21-1.45 pcf) for copolymer was not observed to have an effect on specific energy of degradation for these polymers (see Figures 1.1.1.4.2.6, 1.1.1.4.2.7, 1.1.1.4.2.18, and 1.1.1.4.2.19). 16.7 kg/m³ (1.04 pcf) copolymer may have a lower degradation energy than the higher density copolymer at $V_{rec}=3.33$ cm/s and at heater temperatures above 780°C, as Figure 1.1.1.4.2.19 suggests. This correlates with a lower gas fraction for 16.7 kg/m³ (1.04 pcf) copolymer observed at $V_{rec}=3.33$ cm/s (see Figure 1.1.1.4.2.10).

Figures 1.1.1.4.2.8, 1.1.1.4.2.20, and 1.1.1.4.2.24 illustrate that recession velocity had no effect on specific degradation energy E_{degr} for copolymer, but had a noticeable effect for EPS and PMMA. Degradation energy for EPS at $V_{rec}=1.78$ cm/s was 7-18% higher than at 3.33 cm/s. For PMMA the difference in E_{degr} was 10-18%. Higher degradation energy at the lower recession velocity for EPS and PMMA is explained by a longer residence time of degrading polymer in the kinetic zone and correlates with a higher gas fraction at the lower V_{rec} for these polymers. The independence of gas fraction and specific degradation energy of recession velocity for copolymer in the temperature range of 600-900°C may be explained by the specifics of degradation of copolymer at these temperatures. Recession velocity may have an effect on these two pyrolysis parameters for copolymer at higher temperatures. Additional experiments need to be conducted to verify this hypothesis.

EPS and copolymer did not differ in degradation energy at a recession rate of 1.78 cm/s, as Figure 1.1.1.4.2.29 illustrates; at $V_{rec}=3.33$ cm/s, 19.4-23.3 kg/m³ (1.21-1.45 pcf) copolymer had somewhat higher (up to 10%) energy than 22.7-25.0 kg/m³ (1.42-1.56 pcf) EPS (see Figure 1.1.4.2.30). The latter observation correlates with a higher gas fraction for 19.4-23.3 kg/m³ (1.21-1.45 pcf) copolymer compared to EPS at a recession velocity of 3.33 cm/s (see Figure 1.1.1.4.2.26). Degradation energy for PMMA was 300-500 J/g or about 30% higher than for EPS at a recession rate of 1.78 cm/s and 190-430 J/g or 21-28% higher at a recession rate of 3.33 cm/s. Higher degradation energy for PMMA can be explained by a significantly higher gas fraction for this polymer compared to EPS.

The specific energy of degradation can be estimated using the energy balance approach: $H_{degr} = H_{sens} + H_{depol} + F_{gas} H_{vapor}$, where H_{degr} = specific energy of degradation of polymer to a gas fraction of F_{gas} and a liquid fraction of $1 - F_{gas}$; H_{sens} = sensible heat involved in heating the polymer from room temperature (25°C) to the temperature of liquid residue; H_{depol} = heat of depolymerization of polymer to the main constituent of the liquid residue; H_{vapor} = heat of vaporization of liquid fraction, which includes the heat of depolymerization of the main constituent of the liquid fraction to the main constituent of the gas fraction and heating the gas from liquid fraction temperature to the temperature of the gaseous fraction.

In the case of pyrolysis of EPS at aluminum pouring temperatures, tetramer is assumed to be the main constituent of the liquid residue (Shivkumar,¹²) and styrene monomer is assumed to be the main component of the gas based on analysis of degradation products of PS by Lehman and Brauer⁵ and Straus and Madorsky¹⁴. The temperature of the liquid was estimated at 330°C in another experiment (see Section 1.1.1.6.2). The average specific heat capacity of PS in the temperature range of 25-330°C is about 1.5 J/g (Gaur and Wunderlinch⁴). The heat of depolymerization of PS to monomer has been reported to be 73 kJ/mol (Brandrup and Immergut,²) or 701 J/g. The heat of depolymerization of PS to tetramer would be then $701/4 = 175$ J/g. The heat of depolymerization of tetramer to monomer is equal to (701-175) or 526 J/g.

The temperature of the gaseous fraction in the kinetic zone at heater temperature of 650°C and a recession velocity of 1.78 cm/s was measured to be approximately 440°C (see Section 1.1.1.6.2). The average specific heat capacity of styrene vapor in the temperature range of 330-440°C is 2.3 J/g (Gallant,³). Using the above values the energy of degradation of EPS to a liquid fraction of 65% and a gas fraction of 35% at a heater temperature of 650°C and a recession velocity of 1.78 cm/s would be $1.5(330 - 25) + 175 + 0.35[526 + 2.3(440 - 330)] = 905$ J/g. This estimate is in good agreement with the experimental value for E_{degr} of about 1075 J/g (see Figure 1.1.1.4.2.6). A summary of the effects of experimental variables on pyrolysis parameters discussed above are presented in Table 1.1.1.4.2.3.1.

1.1.1.5. Extension of Pyrolysis Temperature Range

The objective of this work was to extend the temperature capabilities of the foam pyrolysis apparatus from ~1050°C obtainable with the Kanthal heater to iron and steel pouring temperatures in LF casting (1600°C). In this project, the feasibility of using a 60% platinum/40% rhodium alloy as a heater material was investigated. The Pt/Rh alloy was chosen among other high temperature materials due to its high melting point (~1947°C), resistance to oxidation at high temperatures, and good formability at room temperature. The Pt/Rh heater could be used in the pyrolysis apparatus without making any significant modifications to it.

The heater was cut from 0.25-mm thick Pt/Rh foil and had the shape and dimensions similar to those of the Kanthal heater (see Figure 1.1.1.4.1.3.1). The Pt/Rh heater was instrumented with 0.23-mm type B (30%Pt/Rh-6%Pt/Rh) TCs in the same fashion as the Kanthal heater. The space near the heater was also purged with nitrogen to prevent ignition of gaseous degradation products and cool the exposed parts of the heater. The heater was powered by a 208 V/5.5 V 2 kW transformer with an SCR controller in the primary circuit for smooth power adjustments.

1.1.1.5.1. Experimental Matrix

The pyrolysis experiments were conducted at constant recession velocity with two different polymers--PMMA and EPS. The PMMA bars were identical to those used in the constant velocity pyrolysis experiments with the Kanthal heater (see Section 1.1.1.4.1.2) and had dimensions of 1.78 cm H 3.18 cm H 40.3 cm and an average slice density of 21.6 kg/m³ (1.35 pcf). The EPS bars were cut with a band saw from the 20.8 kg/m³ (1.3 pcf) nominal density low fusion patterns used in the constant velocity experiments (see Figure 1.1.1.4.1.1.1). The machined bars were 1.78 cm wide, 3.18 cm tall, and 43.18 to 43.66 cm long. The slice density measurements were made on 14 foam samples using the water immersion technique yielding an average density of 23.5 kg/m³ (1.47 pcf).

Pyrolysis experiments with PMMA bars were conducted in the temperature range of 690-1070°C at a nominal recession velocity of 1.78 cm/s. A total of five bars were pyrolyzed in the experimental temperature range. Pyrolysis experiments with EPS bars were conducted in the temperature range of 780-1220°C and at nominal recession velocities of 1.78, 3.33, and 6.96 cm/s. A total of 11 bars were pyrolyzed at a recession velocity of 1.78 cm/s, 18 bars at 3.33 cm/s, and 6 bars at 6.96 cm/s.

1.1.1.5.2. Results

The power density and specific energy of degradation data for PMMA is presented, respectively, in Figures 1.1.1.5.2.1 and 1.1.1.5.2.2. This data shows good agreement with the existing

degradation data for PMMA developed in constant velocity experiments using the Kanthal heater. The degradation data for EPS including gas fraction, power density, heat transfer coefficient, and specific energy of degradation is presented, respectively, in Figures 1.1.1.5.2.3-1.1.1.5.2.6. The new data for recession velocities of 1.78 and 3.33 cm/s also shows good agreement with the existing degradation data for EPS developed for the same recession rates.

In comparison with degradation data at $V_{rec}=3.33$ cm/s, pyrolysis of EPS at $V_{rec}=6.96$ cm/s was characterized by ~7% lower gas fraction, 260 J/g lower degradation energy and by a factor of 1.8 higher power density and heat transfer coefficient. This effect of recession velocity on degradation parameters is similar to what was observed in the constant pressure and constant velocity experiments (see Sections 1.1.1.3.2 and 1.1.1.4.2).

Pyrolysis of EPS at temperatures higher than 1200°C presented some problems due to carbon deposition on the heater front face (see Figure 1.1.1.5.2.7). The carbon layer acted as a thermal insulator affecting the heat transfer between the heater and the foam bar and introducing an error in the power density measurements. Pyrolysis experiments at temperatures above 1200°C were discontinued after a failure of two Pt/Rh heaters caused by overheating. It is believed at this point that no significant advances in the temperature of pyrolysis are possible with the current Pt/Rh heater. A silicon carbide heater is proposed to develop pyrolysis data in the temperature range of 1200-1600°C.

A phenomenon similar to carbon deposition observed in pyrolysis experiments occurs in LF casting of iron and steel where the free carbon diffuses into the liquid metal increasing the carbon content of the casting surface layer or is trapped between the metal and the coating to form lustrous carbon defects.

1.1.1.6. Measurement of Temperature of Gaseous Degradation Products

Experiments to measure the temperature of the gaseous degradation products leaving the kinetic zone were conducted using the foam pyrolysis apparatus to generate input data for a computer model of the LFCP. Such data is necessary for calculating pressure in the kinetic zone to predict the metal velocity in the mold during filling.

1.1.1.6.1. Experimental Setup and Matrix

The experimental technique used for gas temperature measurements is schematically illustrated in Figure 1.1.1.6.1.1. The gas temperature was measured with 0.076-mm exposed junction type K TCs located at the edges of the kinetic zone inside 3.7 mm wide and 1.9 mm deep grooves machined on both sides of the foam bar. The TCs were attached to the metal guards which directed the gas flow from the kinetic zone into the grooves.

EPS bars with dimensions of 1.78 cm H 3.18 cm H 43.3 cm and an average slice density of 22.9 kg/m³ (1.43 pcf) were used in the

experiments. The bars were cut with a band saw from 20.8 kg/m³ (1.3 pcf) nominal density high fusion patterns used in constant velocity pyrolysis experiments (see Figure 1.1.1.4.1.1.1). The experiments were conducted in the heater temperature range of 600-1040°C at nominal recession velocities of 1.78 and 3.33 cm/s. A total of 11 bars were pyrolyzed at each recession rate.

1.1.1.6.2. Results

Figures 1.1.1.6.2.1-1.1.1.6.2.3 show average gas temperature for each experiment plotted vs. average heater temperature. The plots illustrate that the gas temperature was not affected by recession velocity and it steadily increased from about 450 to 730°C as the heater temperature increased from 617 to 1040°C.

Gas temperature data at $V_{rec}=3.33$ cm/s has more scatter than at $V_{rec}=1.78$ cm/s, with some data points (for example, for bars #12, #13, and #21, Figure 1.1.1.6.2.2) having noticeably lower values than the rest of the data. The scatter is likely attributed to contact of the TCs with molten polystyrene during experiments, which had a lower temperature than the gas. This is illustrated in the gas temperature curves for bars #12, #13, and #21, Figures 1.1.1.6.2.4-1.1.1.6.2.6, where the sections of low gas temperature values (between 300 and 400°C) probably indicate periods of contact of the TCs with liquid polymer. From the gas temperature curves for individual bars the temperature of the liquid fraction was estimated at 315°C at a heater temperature of 600°C and at 446°C at a heater temperature of 1000°C.

The temperature of the gaseous fraction was also estimated using the heat balance approach described in Section 1.1.1.4.2.3. The temperature of the liquid fraction was assumed to vary linearly with the heater temperature. The predicted gas temperature values plotted in Figure 1.1.1.6.2.3 show good agreement with the measured values over the experimental temperature range despite the differences in the shape of the curves.

1.1.1.7. Summary and Conclusions

The significant results obtained in this task are summarized as follows:

1. In the course of this research project, an experimental technique for studying the process of foam pyrolysis was developed that mimics the conditions present in LF casting of aluminum and provides the data necessary for a computer model. A foam pyrolysis apparatus based on this technique was built. The apparatus allows studying pyrolysis of different foam polymers at temperature up to 1200°C either at controlled pressure or controlled recession velocity. Pyrolysis parameters such as gas fraction, gas temperature, power density, heat transfer coefficient, and energy of degradation can be determined in experiments.

2. Foam pyrolysis experiments were conducted using the apparatus to

study the effects of polymer type, pattern density, bead fusion, driving pressure, and recession velocity on pyrolysis parameters and to develop pyrolysis data for future use in a computational model of the LFCP. Three polymer--EPS, copolymer, and PMMA--were studied in experiments. The controlled pressure experiments were conducted in the temperature range of 580-910°C on EPS at driving pressure levels of 10.3 kPa (1.5 psi) and 27.6 kPa (4 psi). The controlled velocity experiments were conducted in the temperature range of 580-1040°C on EPS, copolymer, and PMMA at nominal recession velocities of 1.78 and 3.33 cm/s. The experimental data developed in the experiments include gas fraction, heater power density, and specific energy of degradation. An analysis of the experimental data is presented.

3. The feasibility of using a 60% platinum/40% rhodium alloy as a heater material to extend the temperature capabilities of the foam pyrolysis apparatus to iron and steel pouring temperatures in LF casting (1600°C) was investigated. The Pt/Rh heater allowed extension of the maximum pyrolysis temperature from ~1050°C, obtainable with the Kanthal heater, to 1200°C. Controlled velocity pyrolysis experiments were conducted on PMMA in the temperature range of 690-1070°C at a nominal recession velocity of 1.78 cm/s and on EPS in the temperature range of 780-1220°C and at nominal recession velocities of 1.78 , 3.33, and 6.96 cm/s. The new data showed good agreement with the existing degradation data for PMMA and EPS developed in constant velocity experiments using the Kanthal heater.

Pyrolysis temperature for EPS could not be extended above 1200°C due to carbon deposition on the heater front face. The carbon layer acted as a thermal insulator introducing an error in the power density measurements and causing heater overheating. A silicon carbide heater is proposed to develop pyrolysis data in the temperature range of 1200-1600°C.

4. Temperature of the gaseous degradation products as they leave the kinetic zone was measured using the foam pyrolysis apparatus. This data is necessary in a computer model of the LFCP to calculate pressure in the kinetic zone to predict the metal fill velocity in the mold. The gas temperature was not found to be affected by the bar recession velocity and steadily increased from about 450 to 730°C as the heater temperature increased from 617 to 1040°C. The temperature of the liquid fraction was estimated at 315°C at a heater temperature of 600°C and at 446°C at a heater temperature of 1000°C. The estimates of the temperature of the gaseous fraction made using the heat balance approach showed good agreement with the measured values over the experimental temperature range.

1.1.2 UMR Research

1.1.2.1 Introduction - Model for Pyrolysis Defect Formation

As the relationships between the casting variables, metal velocities, and defect formation have been developed, theories for the formation of pyrolysis-related defects have been refined and verified, although much work remains and fool-proof methods for preventing such

defects have not been identified. We are confident that the three major defects -- internal pores, folds, and blisters -- that are caused by entrapped pyrolysis products are related. Figures 1.1.2.1.1 and 1.1.2.1.2 help illustrate this.

Decomposing polymer can be trapped in the liquid metal due to impinging metal streams or irregular metal fronts, particularly when casting conditions lead to high metal velocities. Bubbles containing polymer pyrolysis products may eventually be produced within the metal stream, Figures 1.1.2.1.1a and 1.1.2.1.2a. The surface of the bubble includes a thin layer of oxide, typically either aluminum oxide or a magnesium-aluminum oxide. The presence of the oxide layer suggests that the trapped polymer is initially either a bubble of air and gaseous pyrolysis products from the kinetic zone, or gap, between the metal front and the solid polymer, or the metal front bounded by a thin layer of oxide envelops liquid polymer in the kinetic zone. The polymer-containing gas bubble floats toward the top surface of the casting, Figures 1.1.2.1.1b and 1.1.2.1.2b. So long as the bubble is floating in just liquid metal, the bubble should be approximately spherical in shape. If the top of the casting solidifies completely before the bubble reaches the casting surface, a round pore will be trapped within the casting. However, if the skin of the casting is not completely solid when the bubble reaches the surface, the bubble can collapse, Figures 1.1.2.1.1c and 1.1.2.1.2c, producing a fold or blister, Figures 1.1.2.1.1d and 1.1.2.1.2d.

Defect maps, which will be described later, have repeatedly shown that blisters tend to concentrate near the first part of the casting to fill, or the last part to solidify, where the liquid metal temperature is high but not too high¹⁶. In the flange castings, for example, there is usually an area near the gate that is free of defects. However, a little bit further from the gate, blisters are often encountered. About halfway between the gate and the far end of the flange, the blisters disappear. When the metal temperature is high enough, i.e. near the gate, bubbles float to the top surface of the casting before solidification begins and all of the gas in the bubble escapes into the coating and surrounding sand -- no pyrolysis defect is formed. However, a little ways from the gate, the surface may begin to solidify, perhaps being fed by tangential flow of a mushy liquid-solid material that forms at the metal front and moves toward the casting surface. The gas in the bubble can escape through the still liquid portions of the surface, perhaps between dendrites, for example. The bubble collapses, but the carbon-oxide layers that originally were inside the bubble and are now collapsed into a single sheet still float toward the casting surface, finally being trapped just beneath the surface due to the partly solidified skin. This results in a blister, which is partly connected to the surface but mostly lying just beneath and parallel to the surface. This configuration permits the blister to be raised during sand blasting or when a knife blade is inserted into it.

Blisters were observed more often in heavy sections in an early test, no blisters were observed in thin sections (0.25-in. or less),

perhaps because of the cooler metal and more rapid solidification.¹ Pores were observed in these castings, however, because there may not have been sufficient time for the bubbles to float to the surface or because a surface skin formed too quickly.

Further from the gate, say more than halfway between the gate and the end of the flange, the temperature of the liquid metal is lower and the solidification times are shorter. The bubble still floats to the surface of the casting and the gas in the bubble may escape through the coating. The bubble then collapses to form the carbon-oxide composite sheet, just as when the blister formed. However in this portion of the casting, solidification is further advanced, with a more extensive dendritic region already formed. The collapsed sheet will not be able to float to just beneath the casting surface but instead remains trapped within the casting, more or less perpendicular to the casting surface. In this case, a fold is formed and the fold is expected to have a carbon core surrounded by oxide. For both blisters and folds, the defect is connected to a surface of the casting.

It should be noted that, in at least one case, an internal pore was found that contained a carbon layer but no oxide layer. Folds have also been found that contain no carbon layer but only an oxide. Therefore there may be more than one mechanism that produces defects in the aluminum lost foam castings.

The following sections describe the experiments performed during Phase IV that have helped in the development of the model for pyrolysis defect formation. The description of other tests and their results are also included.

1.1.2.2 Typical Procedure

Research concentrated on the origin and control of defects in aluminum lost foam castings. Tests were conducted to examine the influence of several variables, including sand temperature, open vs. hollow sprues, gating systems, glue, filters in the gating system, foam type, foam fusion, and foam density. In addition, a set of twelve identical flange castings were poured at various times over a several-month period to determine the repeatability of the experimental procedure and the incidence of defects in the castings. A number of other tests were also performed to determine the critical gate area that divides gating-control and foam/coating-control over metal velocity and to evaluate the feasibility of using Al-Cu alloys rather than Al-Si alloys for lost foam casting.

The flange pattern, shown in Figure 1.1.2.2.1 was used in many of the tests. Two refractory coatings, designated as high and low permeability, were used almost exclusively; their characteristics are listed in Table 1.1.2.2.1. The high permeability coating is normally intended for iron castings, while the low permeability coating is intended for aluminum castings. The experimental procedures and the parameters that were measured and analyzed were similar for nearly all

of the tests. In the case of the flange patterns, a set of twenty wires was inserted into the pattern, using a template to assure that the wire locations were consistent. The wires serve as electrical contacts to determine the location of the liquid metal front as a function of time. The wire probes were in four sets of five probes, each set connected to an electrical circuit which changed voltage as the wires were contacted sequentially by the liquid metal during pouring. From these wire probes, the average circumferential velocities along four radii in the flange were calculated -- these are called the sectional velocities. An overall average circumferential velocity was then found from the four sectional velocities, and in some cases the metal front profile at various times was constructed. This procedure is similar to that described previously.^{16,17}

In addition, up to five chromel-alumel thermocouples sheathed in two-hole ceramic protection tubes were located along the centerline of the flange -- the first thermocouple was located near the gate, and others were located at approximately 45°, 90°, 135°, and 180° from the gate. The thermocouples were used to detect the location of the liquid metal as a function of time, provide an indication of the apparent maximum metal temperature at each location in the casting, and permit the solidification times of the castings to be determined. An example of the temperature response during the mold-filling stage of data acquisition is shown in Figure 1.1.2.2.2.

After velocities were calculated, metal front profiles were constructed, and thermal analysis was completed, the castings were subjected to a detailed defect analysis. First, the castings were examined visually to note any penetration (or burned-on sand) on the bottom surface of the casting or whether there were any carbon defects on the top surface of the casting. Often such defects occur together, with the surface defect directly above the burned-on sand, and these are typically attributed to poor compaction. Next, the castings were sand blasted to remove the coating and some of the pyrolysis product stains on the casting surface. The stains are attributed to liquid pyrolysis products that wetted the coating during fill but did not completely wick into the casting. These pyrolysis products did not create a surface defect that remained after sand blasting. However sand blasting often revealed blisters on the top surface of the casting, Figure 1.1.2.2.3, which sometimes were associated with the stains. The blisters are thin sheets of aluminum parallel and connected to the casting surface and are separated from the bulk of the casting by a thin film of pyrolysis product. The aluminum foil tends to be raised from the surface by sand blasting and could, if one wished, be peeled off the casting with a pair of tweezers. Blisters as small as the diameter of one foam bead to as large as about one inch in diameter were observed. The number of blisters was counted and their locations on the castings were noted by constructing a blister map.

Internal pores caused by entrapped polymer were located by x-ray radiography. The number of pores and their location in the casting, drawn as a pore map, were noted. Often internal pores, sometimes very

large in size, were located at the electrical probes and/or thermocouples. The probes and thermocouples likely were wet by liquid polymer, which eventually pyrolyzed to a gas. These pores were not included in the porosity analysis.

The sand-blasted casting surface was also examined visually to identify potential locations for folds. In some cases, a trace of the fold could be observed -- in the worst case they resembled a lap, while in other cases a thin line cutting through the impression of a foam bead was observed, Figure 1.1.2.2.4a. The castings were then broken with a sledge hammer; the castings typically fractured due to the embrittling effect of the folds. Figure 1.1.2.2.4b shows an example of such a fold. The castings were fractured into a number of pieces until all suspect areas were tested. The number of folds was counted and their locations in the casting, in the form of a fold map, were constructed. Image analysis was used to estimate the exposed surface area of the folds. Figure 1.1.2.2.5 points out the wide variation in fold surface area observed in the fractured castings. In some cases the pores, folds, and blisters were also subjected to SEM (scanning electron microscopy) and AES (Auger emission spectroscopy) analysis.

1.1.2.3 Repeatability of Metal Velocity and Defects

In most of the tests, no replication of the castings was done. At best, only two or three replications were done in some tests. This is not ideal, particularly since the defects occur in a somewhat random fashion and might be expected to vary in number or severity even under ideal conditions. In order to gain some appreciation for the amount of error involved in the experimental procedure, plus some idea of the variability of the results, a set of twelve castings was poured. A set of four flange patterns was poured in April, 1998, with most of the work and analysis done by one student. In June, 1998, a second set of four flange patterns was assembled, poured, and analyzed by another student, who tried to duplicate as closely as possible the conditions that prevailed for the first set. In November, 1998, a third set of four identical castings was produced by yet another student. The data is included in Table 1.1.2.3.1.

In these tests, 1.86 lb/ft³ EPS flange patterns were poured using 356 aluminum alloy. The sand temperature was 26°C and the pouring temperature of the metal was 850°C. A 16-in. tall foam sprue and a 10-in. tall ceramic pouring cup were used, with a simple foam gate connecting the sprue to the flange pattern, Figure 1.1.2.3.1. The high permeability coating, with a screen permeability of 50, was used to coat the patterns. The high density foam, high permeability coating, and foam sprue all contribute to producing many defects, which was intended in this series of tests.

Figure 1.1.2.3.2 shows the sectional velocities for all twelve of the castings. Generally the velocity calculated at the outer radius was lower than that at the inner radius; this will be discussed further in section 1.1.2.8. Figure 1.1.2.3.3 shows just the average

velocity for all twelve of the castings. The average velocities are, for the most part, quite repeatable both within each set of four castings and from one set to another. The average metal velocity measured in all of the castings, including a special flange poured under identical conditions except that a higher viscosity coating (giving 19 screen permeability, $9 \text{ cm}^3/\text{cm}^2\cdot\text{s}$ air flow rate, $0.022 \text{ g}/\text{cm}^3\cdot\text{s}$ liquid infiltration rate) was used, fell within one standard deviation of the average $0.85 \text{ in.}/\text{s}$ velocity.

Figure 1.1.2.3.4 shows the maximum observed temperature of the metal at several locations along the flange castings. Note that these temperatures are not the metal front temperature. The maximum observed temperature is usually obtained some time after the metal front has passed the thermocouple and reflects fresh hot metal flowing along the casting, trailing the colder metal front. Data from some of the castings is not included in this figure. In some cases, the thermocouples failed or the data acquisition did not occur. In other cases, misleading temperatures were observed, perhaps because a bubble of liquid polymer was trapped on the thermocouple. For the castings for which good data was obtained, the maximum temperatures fall within a fairly narrow band.

Figures 1.1.2.3.5 to 1.1.2.3.8 report the defects observed in the castings, showing the large amount of scatter both within sets and from one set to another. For none of the measured defects did all of the data fall within one standard deviation. This can be attributed to several factors. For example, different students performed the analysis on each set of four castings; differences in interpretation from one person to another affect the number of defects recorded. The number of blisters observed may depend on the severity of sand blasting of the castings prior to inspection. The number and area of folds depend on whether the castings were fractured into small enough fragments in order that all might be detected. Slight differences in the amount of glue used to assemble the patterns, or slight differences in the density of the patterns, or differences in the coating properties may lead to differences in the amount of organic material that was created and the efficiency by which that organic material was eliminated through the coating. Finally, not all of the folds are necessarily caused by pyrolysis products; some may simply be oxide films introduced during pouring and trapped in the casting due to a turbulent metal front. A major factor, however, is almost certainly the randomness by which the defects form during fill.

Figures 1.1.2.3.9 to 1.1.2.3.11 are defect maps for the twelve castings. Four maps are shown in each figure -- one composite for each set of four castings and an overall composite for all twelve castings. Note that, in general, pores and folds are located in the last half of the casting to fill, while blisters are located in the first half of the casting to fill. However there is some randomness within this generalization -- a few small pores and folds are occasionally found in the first half of the casting. As has been reported in earlier studies using the flange pattern, the folds tend to be most heavily concentrated where the two streams of metal meet, with additional and smaller folds associated with holes or edges of

the pattern.¹⁷ In all cases, the fold is in contact with a casting surface.

In summary, these tests show that it is possible, with reasonable care, to control the fill time or metal velocity from one casting to another. And, although the location of pyrolysis-related defects follow a pattern, there is still a significant amount of randomness in their formation.

1.1.2.4 Effect of Sand Temperature on Metal Velocity and Defects

It has been suggested that the incidence of some casting defects may be reduced when the sand temperature is above ambient. Based on the physical model for mold filling and defect formation in aluminum castings, a higher sand temperature provides higher velocities during mold filling, which would be expected to encourage more, not fewer, defects. In fact, higher metal velocities were found in previous experiments.^{18,19} However a higher sand (and thus coating and pattern) temperature would also be expected to help transport liquid pyrolysis products away from the liquid metal and into the coating, thus reducing casting defects. Two separate tests were performed to look at the effect of the sand temperature and determine which possibility might be more important.

Test 1: The first set of tests was performed in conjunction with the repeatability tests described in the previous section. Four castings, produced under the same conditions as the twelve repeatability castings, were poured with a sand temperature of about 60°C. Sand at a slightly higher than 60°C temperature was compacted around the pattern, which again contained five thermocouples and twenty electrical probes. The flask was held until all five of the thermocouples in the pattern indicated that the temperature had reached 60°C. At that point, the castings were poured. Data analysis was carried out as described in section 1.1.2.2. Figures 1.1.2.4.1 to 1.1.2.4.6 show the effect of the hot sand on velocity, maximum observed temperatures, solidification times, and defect formation. In this series, the hot sand provided higher metal velocities, although the peak temperatures of the liquid metal and the solidification times were similar to those for the cold sand. The velocities measured for the hot sand were well outside the 1s limits calculated for the cold sand. The higher sand temperature resulted in more blisters but fewer internal pores. The number and area of folds were on the high side compared with the cold sand castings, near or just outside the upper 1s level for the cold sand castings.

The higher sand temperature may have kept the casting surface open enough so that bubbles were able to collapse. This resulted in fewer pores but more folds and blisters.

Test 2: The second set of castings was more extensive. In the second test, the gating system used a hollow sprue with a pouring cup, Figure 1.1.2.4.7, rather than a foam sprue. The 356 aluminum alloy was poured at two temperatures -- 750°C and 850°C. Both the high and

low permeability coatings were used. The high permeability coating had a screen permeability of 44 to 48 and a UAB air flow rate of 21 to 25 cm³/cm²·s. The low permeability coating had a screen permeability of 14.5 and a UAB air flow rate of 5 to 6 cm³/cm²·s. The density of the EPS foam pattern was lower -- nominally 1.45 lb/ft³. Three sand temperatures were selected -- 25°C, 40°C, and 50°C.

Figure 1.1.2.4.8 shows that increasing the pouring temperature had no effect on the average metal velocity, increasing the sand temperature provided only a small increase in velocity, and the coating played the major role in controlling metal velocity. Unlike the first set of tests, very little internal porosity was observed under any conditions -- this may have been a result of the lower pattern density and use of the hollow sprue, both of which would reduce the total amount of polymer material that would accumulate at the metal front. The number of folds observed on the fracture surfaces of the casting did increase substantially when a high permeability coating was used, perhaps because of the higher metal velocities and thus less time for liquid polymer to be removed from the metal front, Figure 1.1.2.4.9. Figure 1.1.2.4.10 again shows the pronounced effect of the coating on folds and suggests that higher pouring temperatures slightly reduce the severity of the fold defects -- there have been indications in previous work²⁰ that a high metal temperature helps increase the rate at which the liquid polymer wets and subsequently infiltrates into the coating. However there was no major effect of sand temperature on the number of folds that were observed. Figure 1.1.2.4.11 shows the fold area, rather than the number of folds; the coating again is an important variable, but neither the sand temperature nor the pouring temperature have a pronounced effect on fold area. The number of blisters observed on the casting surface was higher for the high permeability coating, which gave the highest metal velocities, Figure 1.1.2.4.12. No major effect of either sand temperature or pouring temperature was noted for the low permeability coating, although for the higher permeability coating more blisters were observed when both the sand and pouring temperatures were high, Figure 1.1.2.4.13.

Comparing the two sets of tests, it appears that the sand temperature has little effect when a hollow sprue and a low density foam pattern are used in conjunction with a low permeability coating. The results do suggest, however, that defects become more numerous when the system becomes overloaded with liquid pyrolysis products, which would be the case when a foam sprue and a high density foam pattern are used. For these circumstances, a high sand temperature encourages the formation of folds and blisters. Finally, it should be noted that the effects of metal velocity and coating on defect formation are not necessarily connected.

All of the castings that used the high permeability coating had high velocities -- there is little relationship between velocity and number of defects when we look just at the high permeability coating results. It may well be that some other aspect of the coating is as or more crucial than the permeability.

1.1.2.5 Effect of Glue and Type of Sprue on Metal Velocity and Defects

Not surprisingly, previous tests, including those described above, suggest that increasing the amount of polymer that might melt and be trapped at the metal front will increase the severity of pyrolysis-related defects. A set of four flange castings was poured in which the effects of glue and sprue type were examined. Two castings used a simple gating system -- one casting used a foam sprue and the other used a hollow sprue. For the other two castings, the gating pad, Figure 1.1.2.5.1, was cut at three locations and then reassembled with thermoplastic glue -- again both a foam and a hollow sprue were used. A high permeability coating with a screen permeability of 52 was used. A 1.45 lb/ft³ EPS pattern was poured at 800°C using 356 aluminum alloy. A thin sheet of aluminum was placed at the bottom of the hollow sprue to help assure that the sprue filled completely and rapidly and thus gave a constant pressure head.

The polymer load differed from pattern to pattern. The patterns weighed about 16.8 g. The foam sprues weighed about 9 g. For the hollow sprue casting, an extra 1.48 g of glue was applied, while for the foam sprue casting, an extra 1.73 g of glue was present. Normally about 0.3 g of glue are required for assembly of the pattern to the gating system.

Figure 1.1.2.5.2 shows that there was no appreciable effect of the amount of glue or the type of sprue on the average velocity during fill. However the maximum temperature observed at each location in the pattern decreased when a foam sprue was used or when extra glue was applied, Figure 1.1.2.5.3. The extra temperature loss was due to the consumption of specific heat of the liquid aluminum during melting and pyrolysis of the foam sprue and glue.

The number of internal pores in each casting was determined using radiography. The largest number of pores was observed when the polymer load -- foam sprue with excess glue -- was highest, Figure 1.1.2.5.4. The fewest folds, both by number and area, were observed when the polymer load was smallest -- hollow sprue with no excess glue, Figure 1.1.2.5.5. Introducing additional glue and/or using a foam sprue made the severity of the fold defects much worse. Figure 1.1.2.5.6 shows a map of the location of the pores and folds.

1.1.2.6 Effect of Filters and Type of Sprue on Metal Velocity and Defects

A set of castings was produced with hollow vs. foam sprues with and without ceramic filters in the gating system. One of the reasons for using filters was the idea that the filters might trap some of the oxide in the liquid metal that might contribute to the formation of folds. A typical gating arrangement is shown in Figure 1.1.2.6.1, which also shows the location of the filter. Figure 1.1.2.6.2 shows the types of filters -- extruded and reticulated -- that were used. The filters, which were only used with a hollow sprue, were sanded

into a circular shape and wedged into the bottom of the ceramic fiber sprue.

In these tests, 1.45 lb/ft³ EPS patterns were coated with a high permeability coating having a screen permeability of 45 to 51. The metal was 356 aluminum alloy. The castings were all intended to be poured at 800°C; however one casting was accidentally poured at 850°C instead. Each combination of factors was repeated -- replicas were poured. Two sets of castings used reticulated filters with 15 openings per inch -- one set was 0.5-in. thick and the other set was 0.75-in. thick. The third set of castings used 0.5-in. thick extruded filters with 17 openings per inch. Data from this test is included in Table 1.1.2.6.1.

Figure 1.1.2.6.3 shows the maximum temperatures measured along the length of the patterns. The filters had no discernible effect on the temperatures, although the two castings using a foam sprue suffered a greater temperature loss than the castings that used the hollow sprue. Note the temperature profile for the one casting that was accidentally poured at a higher temperature.

The average metal velocities for the replicate castings gave exceptionally good repeatability, Figure 1.1.2.6.4. All eight of the castings poured using a hollow sprue filled at nearly the same average velocity, regardless of the type of filter or even if a filter was used. Even the casting that was poured at 850°C gave the same approximate velocity. Surprisingly, the highest measured velocities were for the two castings that used a foam sprue.

In general, the most severe pyrolysis defects -- blisters, internal pores, and folds -- were observed in the two castings that used the foam sprue, Figures 1.1.2.6.5 to 1.1.2.6.8. The filters did not appear to help prevent blisters or internal porosity, although the extruded filter, in particular, led to the fewest folds and the least fold area. Figures 1.1.2.6.9 to 1.1.2.6.11 show defect maps for the castings and are similar to those observed in other tests.

1.1.2.7 Effect of Gating System Design on Defects

In most of the tests performed using the flange patterns, the pattern was horizontally oriented and just one gate was used to introduce the molten metal. Typically, the first half of the casting was free of porosity and fold defects. This observation, coupled with work done by Sun²¹ some years ago, suggests that there is a defect-free zone between the gate and the first occurrence of pyrolysis defects. Two sets of flange castings were poured in which the orientation of the pattern as well as the number of gates, glue joints, and overflows were varied to determine their effect on the formation of defects.

Test 1: For the first set of castings, all of the castings were poured in 356 aluminum at 850°C using 1.45 lb/ft³ EPS patterns with a high permeability coating. Six gating systems were used, all with a foam sprue and a ceramic fiber pouring cup. The six castings were:

- Standard single side gate with horizontally-oriented pattern
- Two side gates (from the inside of the flange) to a horizontally-oriented pattern
- Four side gates (from the inside of the flange) to a horizontally-oriented pattern
- Two side gates (from the outside of the flange) to a horizontally-oriented pattern
- One bottom gate to a vertically-oriented pattern
- One top gate to a vertically-oriented pattern

The six gating systems are shown in Figure 1.1.2.7.1. Because of the multiplicity of the gates, instrumentation for data acquisition was more difficult and subject to greater error than when a single gate was used. Data is included in Table 1.1.2.7.1. Figure 1.1.2.7.2 shows the velocities that were measured. The top-gated pattern filled much faster than the bottom-gated pattern, with the conventional single side-gated pattern filling at an intermediate rate. The three castings with two or more gates apparently filled at about the same or higher velocity than the standard system.

Figures 1.1.2.7.3 to 1.1.2.7.6 show the effect of the gating systems on internal porosity and folds as well as the metal front locations at 1 second intervals. Very little internal porosity was observed for the bottom and side-gated castings; however a large number of small pores were scattered throughout the casting when a top gate was used. Folds were observed in all six of the castings. The fewest number and smallest total area of folds were found when the casting was bottom gated, while the largest number of folds was found for the top-gated castings. Using multiple side gates increased the number and severity of the folds compared with the standard single side-gate arrangement. This is likely because multiple gates introduced a large number of locations where two metal streams met.

Test 2: The second set of castings was poured at 800°C using 1.45 lb/ft³ EPS patterns and a high permeability coating. The alloy poured in this set was 319. Variables included hollow versus foam sprue, overflow versus no overflow, single gate versus two gates, and excess glue versus no excess glue. Excess glue was introduced by cutting the pattern, then reassembling the pattern with thermoplastic glue. Figure 1.1.2.7.7 shows some of the gating systems used in the tests. Table 1.1.2.7.2 includes the castings that were poured along with the measured velocities and results of the defect analysis.

Figure 1.1.2.7.8 shows the number of blisters observed for the eleven castings. Using two gates located at the inside diameter of the pattern reduced the number of blister defects. A hollow sprue coupled with the inside gates gave the fewest blisters. Apparently with a shorter distance for the metal to flow, the temperature remained high enough to remain within the defect-free zone that is present before blisters begin to form. Neither excess glue nor use of an overflow had a significant effect on the number of blisters.

Similarly, the use of the two inside gates reduced the number of folds, particularly when a hollow sprue was also used, Figure

1.1.2.7.9. Overflows did not give any noticeable benefit, but the excess glue did produce a larger than usual number of folds. Similar observations were made when fold area rather than number of folds was examined, Figure 1.1.2.7.10.

The average velocity was not measured when the inside gates were used due to difficulty in appropriately locating the probes. However, as described in previous sections, the velocities for castings using just one side gate were similar for both foam and hollow sprues, Figure 1.1.2.7.11.

Figure 1.1.2.7.11 also shows that there was a very large variation in the maximum observed liquid metal temperature at the second thermocouple, located 45° from the gate, but this had no effect on the fold area, Figure 1.1.2.7.12, or the number of blisters, Figure 1.1.2.7.13. Less temperature variation was found at the end of the casting, but again there was no correlation with number of defects, Figures 1.1.2.7.14 and 1.1.2.7.15.

1.1.2.8 Effect of Foam Density and Foam Type on Metal Velocity and Defects

The density of the foam pattern affects metal velocity as well as the amount of liquid polymer that is produced. For a low density foam, less liquid polymer is generated but, because the metal velocity is higher, it is more difficult to transport the liquid polymer from the metal front. In addition, foams produced from terpolymers have also been considered -- these foams behave differently than the standard EPS foams. The terpolymers contained approximately 78% methyl methacrylate, 13 to 18% styrene, and 4 to 7% alpha methyl styrene. Two sets of tests were performed in which different foam densities and foam types were compared.

Test 1: The first test involved a quick survey using six flange patterns. These included standard EPS patterns of four different densities and two terpolymers (trade name Clearpore) patterns of two different densities. All were coated with a high permeability coating with a screen permeability of 50 and were gated from a hollow sprue with a 1/16-in. sheet of aluminum at the base to help fill the sprue before the liquid metal entered the pattern. The castings were produced from 356 aluminum alloy poured at 800°C. Figure 1.1.2.8.1 shows the experimental setup.

The nominal densities of the patterns differed from the actual density. To compensate for this, the 1.86 lb/ft³ pattern was assumed to be correct and, based on weight, the density of the other patterns was normalized to the 1.86 lb/ft³ pattern. Due to some unexpected results, the tests using the terpolymer were repeated at a later time. The coating was thinner for these two check castings and this led to higher velocities than for the first castings using the terpolymer. Data concerning the patterns and coatings are included in Table 1.1.2.8.1.

Table 1.1.2.8.2 includes the results from these tests. The metal velocity measured for the four EPS patterns decreased as the density of the pattern increased -- the higher density foam decomposed more slowly and produced more pyrolysis products that, in turn, reduced the velocity. The velocities observed for the terpolymer were higher and increased with increasing foam density, Figure 1.1.2.8.2. Many blisters were observed in these castings. The number of blisters increased with increasing metal velocity. For the EPS patterns, the blisters also increased with decreasing foam density, Figure 1.1.2.8.3. However the opposite behavior was observed for the terpolymer, and this was also the case for the extra castings produced using the terpolymer. The number of folds increased both with higher metal velocity and with higher foam density for both EPS and terpolymer, Figures 1.1.2.8.4 and 1.1.2.8.5.

The high metal velocities for the terpolymer were not expected. The terpolymer contains a large amount of methyl methacrylate; previous work has shown that patterns containing all methyl methacrylate (PMMA patterns) produced low metal velocities because nearly all of the pyrolysis products are gases.²² This in turn produced large back pressures and low recession rates of the foam. However we have no understanding of how the terpolymer decomposes.

Another unexpected result for the terpolymer was the increase in metal velocity with increasing pattern density. Examination of the thermal analysis indicated that the maximum observed temperature near the gate was nearly 100°C lower than that for the other castings, Figure 1.1.2.8.6. In addition, the metal front profiles were very unusual, which may have led to errors in calculating metal velocity. To check this, the test for the terpolymer was repeated, although with a thinner coating. This led to higher velocities than before, but the velocity still increased with increasing foam density, Table 1.1.2.8.2.

A final anomaly was that the 1.45 lb/ft³ EPS pattern had a lower velocity than expected when compared with the other EPS patterns. The 1.45 lb/ft³ patterns were produced at a different time than most of the other patterns and, as H. Littleton at UAB reported, also had a more uniform cell size inside the expanded beads than did other patterns of about the same density. This may have affected the pyrolysis of the foam pattern, resulting both in a low velocity and fewer pyrolysis defects.

The higher metal velocity along the outer diameter of the flange has been noted in each experiment involving the flange pattern. Other research has shown that the area-to-perimeter (A/P) ratio influences metal velocity²³. The thicker section at the ID of the flange contains a large volume (or large cross-section) of foam that must be decomposed but a large surface area (or large perimeter) through which to remove the pyrolysis products, Figure 1.1.2.8.7. The thinner section of the OD contains a small volume of foam and a large surface area. The middle of the pattern where the two center electrical probe channels are located have the lowest surface area. Consequently the

metal velocity would be expected to be higher at both the OD and ID of the flange. Figure 1.1.2.8.8 shows that this behavior is not quite accurate, particularly for the terpolymer. The velocity is highest at the OD, with the smallest A/P ratio, but tends to be relatively low at the ID, which has the next smaller A/P ratio. However, when plotted versus cross-section area rather than A/P ratio, Figure 1.1.2.8.9, a very consistent pattern of decreasing velocity with decreasing cross-sectional area is observed for all of the foams. Across the cross-section of the flange, apparently mass rather than a combination of mass and transport of pyrolysis products controls the velocity. It should be noted, however, that a high permeability coating was used, which would help to reduce the importance of the transport of pyrolysis products.

The metal front profiles were reconstructed from the times at which the electrical probes were contacted by metal during fill. Figures 1.1.2.8.10 and 1.1.2.8.11 show the profiles for the EPS patterns. Note that the shape of the metal front near the end of fill for the 1.86 lb/ft³ pattern would concentrate liquid pyrolysis products across the entire flange where the two streams meet, leading to a large number of folds, as was observed. Figure 1.1.2.8.12 shows the profile for the first terpolymer patterns. The metal front for the 1.25 lb/ft³ is similar to that for the high density EPS pattern, and again a large number of folds was observed.

It was also noted that severe folds were found underneath the lip of the flange, particularly for the terpolymer casting, Figures 1.1.2.8.13 and 1.1.2.8.14. One possible mechanism for this would be a much different metal velocity along the lip compared with through the bulk of the flange cross-section, permitting two streams of metal to meet at the lip-flange junction. The two check terpolymer patterns included an additional channel of electrical probes located in the lip, permitting the metal profiles shown in Figure 1.1.2.8.15 to be drawn. This shows that the metal front was progressing faster along the lip than through the rest of the pattern, perhaps leading to these defects.

Test 2:

Particularly because of an unusually large number of blisters found on the castings in test 1, some doubt as to the quality of the coating or pouring practice arose. A second set of tests was conducted to check on the preliminary test, using the same set-up shown in Figure 1.1.2.4.7. In this test, 356 aluminum was again poured at 800°C. Two coatings were used. The high permeability coating had a screen permeability of 47 to 48, a UAB air flow rate of 18 to 20 cm³/cm²·s, and a liquid absorption rate of 0.011 g/cm³·s. The low permeability coating had a screen permeability of 12 to 15, a UAB air flow rate of 3.3 to 6 cm³/cm²·s, and a liquid absorption rate of 0.005 g/cm³·s. Three EPS patterns, with nominal densities of 1, 1.5, and 1.86 lb/ft³, and two terpolymer patterns, with nominal densities of 1.25 and 1.5 lb/ft³, were used.

The actual densities of the patterns differed from the nominal

densities. Consequently, each pattern was weighed and the measurements of metal velocity and defect severity were compared with pattern weight, rather than nominal density. This data is included in Table 1.1.2.8.3. Figures 1.1.2.8.16 and 1.1.2.8.17 show how the average velocity varied with nominal pattern density and actual pattern weight. For the EPS patterns with a low permeability coating, the average velocity was nearly independent of pattern weight until the pattern became quite dense; then the velocity dropped off. For the EPS patterns with a high permeability coating, the velocity dropped continuously with increasing pattern weight. The terpolymer patterns gave somewhat inconsistent results. When a high permeability coating was used, the velocities were very high and dropped off with higher density patterns. One of the terpolymer patterns using a low permeability coating also filled very rapidly, but the other three terpolymer patterns filled at the same rate as the EPS patterns and the velocity did not change with pattern weight.

Blisters were observed on the casting surface, with the number of blisters tending to increase with metal velocity, Figure 1.1.2.8.18. For the low permeability coating, few blisters were observed. For the high permeability coating, more blisters were observed, with the defect being particularly pronounced for the EPS patterns. Figure 1.1.2.8.19, which shows the number of blisters versus pattern weight, better illustrates that the low permeability coating leads to virtually no blisters, the terpolymer with a high permeability coating gives more blisters, and the EPS with a high permeability coating gives many blisters. However this figure suggests that the pattern weight (and thus the density) does not affect blisters -- the number of blisters correlates better with the type of polymer and the coating.

Figures 1.1.2.8.20 and 1.1.2.8.21 show the effect of the factors on internal porosity, for both nominal pattern density and actual pattern weight. Particularly severe porosity is evident around a velocity of 0.9 in./s, which has been observed in other tests using the flange pattern. The porosity becomes more severe with increasing pattern weight, particularly when the EPS patterns are used. High permeability coatings also tend to give more internal pores.

There appears to be relatively little effect of average metal velocity on the number or area of folds, Figure 1.1.2.8.22. Figure 1.1.2.8.23 indicates that denser patterns increase the number of folds, which are particularly high when high permeability coatings are used. The type of foam does not have any clear-cut effect.

The higher density EPS patterns do appreciably decrease the maximum observed temperature of the metal during fill, Figure 1.1.2.8.24, particularly when a low permeability coating is used. Maximum temperatures of the metal front are much lower when a low permeability coating is used due at least partly to the slower metal velocity. The data was not as clear-cut for the terpolymer, although it appears that the polymer type had little effect, but, instead, the effect of the type of coating dominated.

1.1.2.9 Correlation of Defects with the Temperature of the Liquid Metal

The various defect maps that have been described suggest that blisters tend to form during the initial stages of the mold filling process, when the temperature of the metal front, as well as the temperature of the metal flowing through that portion of the casting, tend to be high. On the other hand, folds and internal pores are more often found in the last half of the casting, where the temperature of the liquid metal is lower. The maximum observed metal front temperature was correlated to the occurrence of defects in several sets of tests. Figure 1.1.2.9.1 shows the relationship between temperature and casting location for the series of castings using various filters (see section 1.1.2.6). Blisters were observed when the liquid metal was between about 650°C and 750°C, well above the liquidus temperature of 612°C. Folds and pores were found further along the casting, where the metal temperature was between about 650°C and the liquidus of 612°C.

Similarly, for the tests exploring the effect of excess glue and type of sprue (see section 1.1.2.5), folds and pores were observed after the liquid metal dropped below about 675°C, Figure 1.1.2.9.2.

In several cases, the response of the thermocouples at each location in the fold was examined more closely. Figure 1.1.2.9.3 shows the history at five thermocouples in one of the flange castings poured in the repeatability experiment (section 1.1.2.3). Typically the thermocouple heats quickly, but then the temperature rise suddenly changes slope before the maximum observed temperature is attained. The temperature at which the change in slope occurs may be closely related to the actual temperature of the metal front. The dashed line shows that this slope change occurs very near the liquidus temperature of the alloy at all five thermocouple locations and indicates that, during fill, the temperature of the liquid front very quickly drops to the liquidus temperature and some solidified metal may be present at the metal front during most of the fill process. The partially-solidified metal is then presumably pushed toward the coating and fresh metal replaces it, keeping the metal front at a nearly constant temperature.

1.1.2.10 Effect of Alloy Composition on Metal Velocity and Defects

A series of flange patterns was poured using different aluminum alloys, including pure aluminum, 206, 319, 356, and 380. One of the purposes of this test was to determine whether the alloy composition, which in turn influences the solidification process, has a significant effect on the metal velocity and the formation of pyrolysis defects, and to see if the defect analysis would help to explain the mechanism for defect formation. Defects found in the castings produced in this series were also characterized using optical microscopy, SEM analysis, and AES (Auger) analysis. Table 1.1.2.10.1 includes some data for these alloys.

The flange patterns were 1.45 lb/ft³ EPS. Two patterns were used for each alloy -- one pattern was coated with a high permeability coating, while the other was coated with a low permeability coating. Data concerning the coatings is included in Table 1.1.2.10.2. A small gating system cut from a low density foam plank was used along with a hollow, untapered ceramic sprue. Because the five alloys have different liquidus temperatures, a constant superheat of 190°C, rather than a constant pouring temperature, was used. Unfortunately, a lower superheat was inadvertently used for the 380 alloy castings.

Metal velocity, metal front profiles, and temperatures were obtained as described in section 1.1.2.2, and the results are shown in Table 1.1.2.10.3. Figure 1.1.2.10.1 includes all of the velocity data and shows that the calculated velocity increases towards the outer diameter, as has been reported previously.^{16,17} Figure 1.1.2.10.2 compares the average metal velocity for the various combinations of alloy and coating. As expected, the high permeability coating produced a higher average metal velocity for all five of the alloys, although the difference in velocity was comparatively small for the 206 alloy. The effect of the alloy on metal velocity, however, was difficult to interpret for a variety of reasons. For example, based on Sun's research,²¹ we would have expected the high silicon 380 alloy to have a high metal velocity. But the liquidus temperature for 380 is lower than that of the other alloys and, even had we not inadvertently used a low superheat, the pouring temperature and thus recession rate of the foam would have been slower than that for the other alloys. More work needs to be done on alloy effect in the future.

The maximum temperature recorded by each of the thermocouples revealed little helpful information. The maximum observed temperature did decrease between the gate and the far end of the pattern, as has been demonstrated before. The maximum temperatures tended to be unusually low for the 206 alloy, perhaps because of the comparatively slow metal velocity. However, as will be seen in section 1.1.2.14, a later test suggests that temperatures and velocities are actually higher for 206 alloy than for either 319 or 356 alloys.

The number of pyrolysis defects in the castings was counted and is shown in Figure 1.1.2.10.3. Few, if any, folds or blisters were observed when the low permeability coating was used. In addition, few if any blisters were found for the 206 and 380 alloy castings even when a high permeability coating was used. Although fewer folds were observed in the 380 casting than for the 319, 356, and 206 castings, the folds in the 380 casting were huge, giving a much greater surface area than the folds in the other alloys. It appears that problems with folds increase for higher silicon alloys. Most of the castings also contained a few isolated internal pores, Table 1.1.2.10.3. These pores were almost always associated with probes or thermocouples, which likely trapped some liquid polymer which later pyrolyzed to a gas. However the 380 casting that used the high permeability coating contained an enormous number of small pores, particularly near the end of the casting.

Figures 1.1.2.10.4 and 1.1.2.10.5 suggest that there is a relationship between defects and metal velocity. Both figures show that blisters and folds are not observed when the average metal velocity is less than about 1 in./s, while defects are usually observed for higher velocities. However, it should be noted that the higher velocities and defects were all obtained with the high permeability coating, while the low permeability coating produced low velocities and nearly defect-free castings. The high permeability coating was also much thicker than the low permeability coating. It is highly likely that other characteristics of the coating, such as thermal conductivity, wettability, or liquid absorption rate, might be just as important as the permeability/velocity relationship. Figures 1.1.2.10.6 and 1.1.2.10.7 show a composite of where the blisters were located in the castings. The maps are similar to what has been described previously.

1.1.2.11 Surface Characterization of Defects

Specimens of folds, pores, and blisters were removed from a number of castings, including some of those discussed in section 1.1.2.10. The location of some of these specimens are shown in Figure 1.1.2.11.1. Some specimens were mounted in Bakelite, polished, and microstructures were obtained. Others were observed using scanning electron microscopy, and still others were subjected to Auger analysis.

Auger analysis: Auger analysis permits atoms to be sputtered off the surface of a material layer by layer, with the composition of each layer being identified. The results reported here are reported in terms of sputtering time rather than the depth below the initial surface, since no calibration for rate of sputtering of the carbon-oxide layer that comprises the pyrolysis defects was available. In addition, the compositions are not calibrated against any standard, so the weight percentages that are shown in the figures should be considered relative rather than actual. In addition, it is known that carbon atoms from the environment can be adsorbed onto the fracture surfaces as adventitious carbon. In some cases, the bare fracture surface adjacent to a pyrolysis defect was analyzed to determine how much adventitious carbon might have been present. Figures 1.1.2.11.2 to 1.1.2.11.5 show the results from the fracture surface near four defects. Carbon and oxygen are enriched at the fracture surface due to exposure to the environment, but these levels drop off after about 10 minutes of sputtering. It is likely that high carbon and/or oxygen levels after sputtering for 10 minutes reflect the composition of the pyrolysis or oxide defect.

Three pores -- one each from 319, 356, and 380 castings -- were examined, Figures 1.1.2.11.6 to 1.1.2.11.8. Carbon levels at the pore surface were extremely high and were surely the result of pyrolysis of polymer residue inside the bubble. Oxygen levels for the pores found in the 319 and 356 castings were initially very low but then increased when the carbon level dropped. The source of the oxide is not clear, but may be due either to an oxide film trapped with the polymer or trapped bubbles from the kinetic zone containing air and pyrolysis

products. For the pore in the 380 casting, however, no oxygen was observed. The oxide in the pores does not contain magnesium, even for the pore in the 356 casting; the oxide is just aluminum oxide. However high levels of strontium were found in pores obtained from the 319 and 356 castings, although the strontium is associated with carbon rather than with oxygen. Thermodynamically, the oxygen should prefer aluminum to strontium. It is not clear why oxygen is present in the 319 and 356 castings but not in the 380 casting. One reason may be that the pores examined in the 319 and 356 castings were associated with probes, while the pore taken from the 380 casting was not.

Four folds -- from 206, 319, 356, and 380 castings -- were examined, Figures 1.1.2.11.9 to 1.1.2.11.12. The 206 casting was a box pattern, while the others were flange patterns. The carbon at the surface of the 206 fold may be primarily adventitious carbon and the fold consisted primarily of an aluminum-magnesium oxide. The carbon on the surface of the 319 fold also may be adventitious and, since no magnesium is present in the alloy, the oxide was primarily aluminum oxide. The fold obtained from the 356 casting is a composite of carbon over an aluminum-magnesium oxide; the carbon is not adventitious in this case. In the 380 casting, the fold is a composite of both carbon and aluminum oxide. It is interesting to note that the folds in the 356 and 380 castings were obtained at the location where the two metal streams met, while the fold from the 319 casting was not. The fold in the 206 casting also was not at a location where two opposing metal streams met. Folds can form in at least two different ways and the fold composition depends on how it formed.

Two blisters were analyzed, Figures 1.1.2.11.13 and 1.1.2.11.14. The blister found in the 356 casting is a composite of carbon over a primarily aluminum oxide layer, although there may be a very small amount of magnesium associated with the oxide. Carbon and aluminum oxide also are associated with a blister obtained from the pure aluminum casting.

Scanning electron microscopy: A few folds and blisters were examined using the SEM. The folds in 319 and 356 castings, Figures 1.1.2.11.15 and 1.1.2.11.16, revealed a wrinkled surface, with the wrinkles all oriented in the same direction. A blister obtained from a 319 casting, Figure 1.1.2.11.17, has the identical appearance. However a blister obtained from a 356 casting, Figure 1.1.2.11.18, still has a wrinkled surface but the wrinkles are more randomly oriented. The wrinkles may be a result of the different coefficients of thermal expansion and contraction for the metal and the carbon-oxide film on the defect. It is speculated that the randomly-oriented wrinkles may have been caused by turbulence in the liquid metal twisting the oxide before solidification began. Folds often occur when the metal is cool and even partly solidified, so turbulence would not affect the defect. Figures 1.1.2.11.19 and 1.1.2.11.20 also show that porosity can be associated with a blister.

A wrinkled surface was also found on a fold removed from a 206

casting, Figure 1.1.2.11.21. The structure beneath the fold defect reflects the dendrites that formed during solidification. Figure 1.1.2.11.22 shows a fracture surface for a 206 casting without the fold defect and the same dendritic structure is observed.

Optical microscopy: In some cases, defects were observed by visual inspection and were then cut from the casting and mounted so that the microstructure on either side of the defect could be examined. A particularly unusual structure, which has been reported previously, sometimes occurs in both 319 and 356, Figures 1.1.2.11.23 and 1.1.2.11.24. On one side of the fold or blister, the Al-Si eutectic is modified, while the other side is unmodified. The side nearest the casting surface typically is the unmodified material. Silicon also tends to be nucleated at the surface of many defects.

In one casting, a very large pore was found associated with a blister, Figures 1.1.2.11.25 and 1.1.2.11.26. The pore was beneath the surface but connected to the surface by a thin sheet of collapsed bubble. The thin sheet of collapsed bubble then trailed off of the opposite side of the remaining pore into the rest of the casting.

1.1.2.12 Effects of Foam Type, Density, and Degree of Fusion on Velocity and Defects in Thick Castings

Most of the research has involved relatively thin section castings, for which pyrolysis-related defects such as folds and pores are most prevalent. A series of castings was also poured using heavier section patterns cut from an as-blown gating system. The gating system pattern was produced in several ways, giving two degrees of fusion, two densities, and three foam materials (two EPS foams and a copolymer). Three separate designed experiments were performed, with each experiment dedicated to one of the foams. Analysis of Variance was used to statistically compare the effects of the different variables for each experiment. The variables studied in each designed experiment included foam density, degree of fusion, orientation of the pattern, and coating, Table 1.1.2.12.1. The metal velocity, metal front profile, and surface defects were determined. Castings were poured at 750°C using 319 alloy. A hollow, untapered ceramic sprue was used. Pattern weights, coating weights, and amount of glue used to attach the pattern to a short foam gate were recorded, Table 1.1.2.12.2.

The patterns included EPS beads made by two different manufacturers and a 30% PMMA-70% EPS copolymer. The degree of fusion of the beads was varied by changing the steam time for the patterns by 7 seconds (24 seconds vs. 17 seconds). Nominal pattern densities were 1.3 lb/ft³ and 1.5 lb/ft³. Both a high and low permeability coating were used.

T-shaped patterns were cut from the large gating system, Figures 1.1.2.12.1 to 1.1.2.12.4. A total of 18 electrical probes were inserted into the pattern to permit metal velocities to be measured. The patterns were arranged either horizontally, with a side gate, or

vertically, with a bottom gate.

To help characterize the patterns, slices were cut through the foam patterns, Figure 1.1.2.12.5, and densities were measured by Archimede's principle. This permitted density gradients to be determined for all of the various foams. The results are shown in Tables 1.1.2.12.3 and 1.1.2.12.4. In addition, larger cross-sections were cut from each foam to get a bulk density. Because the thin slices were cut using a hot wire, there was some error introduced and the slices had higher than expected densities. However the bulk samples gave densities nearly equal to the nominal density. The density gradients were higher for the high fusion foams, while nominal foam density and the type of foam had relatively little effect.

Velocity: Figure 1.1.2.12.6 includes the velocity results. Velocities were difficult to interpret, particularly for the vertically-oriented patterns, due to the shape of the metal front profile. Consequently average velocities were measured only for the initial few inches of the pattern. Based on the ANOVA results, for EPS-1, the foam density was the major factor influencing the metal velocity; for EPS-2, the coating permeability was most significant; and for the copolymer, degree of fusion had the greatest effect. However other factors and interactions also played a role in controlling velocity. In general, low metal velocities were obtained with a high foam density, a high degree of fusion, a low coating permeability, or a vertical orientation of the pattern.

The effects of foam density, coating permeability, and pattern orientation have been reported and explained in previous tests. A lower degree of fusion resulted in a smaller foam density gradient and more interconnected porosity between the beads. As the metal-foam front moves through the pattern, the gaseous decomposition products that are generated may be able to escape through the interconnected porosity. For most poorly fused patterns, the interconnected porosity ahead of the metal-foam front connects to the pattern surface, allowing the gas to escape through the coating. Since more of these gaseous products can be removed, the back-pressure on the metal front is reduced and the metal velocity is higher.

The effect of the foam type was not determined by the three separate designed experiments. To examine this, the velocities were plotted so that the velocity was examined for each of the three foams plus one of the other variables. Figure 1.1.2.12.7 illustrates again that a higher foam density reduces metal velocity for the EPS patterns; however the density of the copolymer had little if any effect on metal velocity. Figure 1.1.2.12.8 shows that the highly fused patterns reduced metal velocity, especially for the copolymer patterns. Higher coating permeability increased the metal velocity when EPS patterns were used, Figure 1.1.2.12.9, but had virtually no effect for the copolymer patterns. Lower metallostatic pressure caused by the vertical orientation of the pattern reduced the metal velocity about the same amount for all three foam types, Figure 1.1.2.12.10.

Blisters: Results of the defect analysis are shown in Tables 1.1.2.12.5 to 1.1.2.12.7, and the results of the ANOVA analysis for defects are summarized in Table 1.1.2.12.8. In the designed experiments for all three of the foam types, the coating statistically had the most significant effect on the severity of blister defects. All of the castings poured with the high permeability coating contained at least some blisters, while few blisters were found on the castings poured using the low permeability coating. The pattern orientation and interactions between pattern orientation and coating were also significant statistically. Blisters always form at top surfaces of the casting; because of the pattern geometry, there is more top surface when the pattern is oriented horizontally and consequently there is a greater likelihood that blisters will form. Figure 1.1.2.12.11 shows the effect of coating permeability in graphical form. There is no clear-cut correlation of blisters with metal velocity, Figure 1.1.2.12.12 -- thus it would appear that the reason that coating has such a dramatic effect on blisters is related to coating properties other than just permeability.

Polymer burn-on and polymer residue: The surface of an aluminum lost foam casting often contains discolored areas that are likely a result of residue from the decomposing polymer. In some cases, a thin layer of coating adhered rather tightly to the top casting surface as well, probably because of polymer residue that infiltrated the coating and did not completely burn out during solidification and cooling. This also was observed, but less often, on the bottom surface of the T-shaped casting. These surface defects were more prevalent for high degree of fusion patterns, the high permeability coating, and the horizontal orientation (more top casting surface area). The high degree of fusion patterns likely produced a more arrow-shaped metal front, pushing the pyrolysis products to the coating surface and perhaps over-loading the ability of the coating to completely remove the polymer residue, particularly when there was insufficient time available to remove the residue due to the metal velocity caused by high permeability coatings.

Penetration (burn-on) and surface abnormalities: In a number of the castings, the coating at the bottom surface of the casting cracked due to the combination of poor compaction of the sand beneath the pattern, use of the high-expansion silica molding sand, and the higher metal pressure at the bottom surface of the casting. Consequently liquid metal penetrated into the sand. Figure 1.1.2.12.13 illustrate a possible mechanism for the formation of the penetration defect. In some cases, sheets of the coating begin to float towards the top of the casting, while depressions form at the top surface of the casting as liquid metal drains out the bottom. This suggests that the penetration defect and corresponding surface abnormality occur shortly after the castings is filled with liquid metal, but before the surface of the casting solidifies. As a result, there was very little correlation of these defects with the experimental variables, which tend to affect primarily metal fill.

Metal front profiles: Electrical probes were only inserted along

the centerline of the patterns, so there was insufficient data to completely describe the shape of the metal front during fill. However, using a little poetic license, probable profiles were sketched. Figure 1.1.2.12.14 shows the profiles that might ideally be expected, while Figure 1.1.2.12.15 shows examples of profiles that are estimated based on the probe data. Table 1.1.2.12.9 describes the type of profiles found for each of the castings.

When the metal front in a horizontally-oriented pattern reaches the intersection point, the metal front may progress evenly into the end and arms of the casting, or may preferentially flow most rapidly into one or two of the arms. When the pattern is oriented vertically, the metal front also can fill the two arms before progressing towards the far end of the pattern. This last option made it impossible to determine metal velocities after fill reached the intersection point.

For EPS-1 patterns, fill tended to be relatively ideal, while fill using EPS-2 patterns was a little less predictable, and fill for copolymer patterns was even less ideal. Abnormal fill patterns were more likely for high foam densities and vertically-oriented patterns. However no relationship between fill pattern and defects was discerned in the experiments.

1.1.2.13 A Preliminary Evaluation of Al-Cu Casting Alloys

Most aluminum lost foam castings are produced using 319, 356, or similar Al-Si alloys. Their good castability makes production of reasonably sound castings relatively effective. However there is some interest in obtaining higher strength aluminum lost foam castings, and the various 200-series Al-Cu alloys might be a possible solution. For example, 206 in the T4 condition has about 36,000 psi yield strength, 51,000 psi tensile strength, and 7% elongation, while 319 in the T6 condition is about 24,000 psi yield, 36,000 tensile, and only 2% elongation.²⁷ The properties of heat-treated 356 are intermediate between 206 and 319. Alloy 206 is a long freezing range alloy with relatively little eutectic microconstituent forming during solidification -- in most sand and permanent mold casting situations, the long freezing range leads to microporosity and hot tearing. The alloy also has a higher liquidus temperature (650°C) compared with 319 and 356 (about 612°C).

However, the lost foam process inherently tends to produce good directional solidification from the extremities of the casting (where the liquid metal is cold and solidification may even have already begun by the time fill is complete) toward the gates (where the liquid metal is still relatively close to the pouring temperature).²⁸ It is possible that many of the castability problems associated with the Al-Cu alloys may be alleviated by using the lost foam process. Several tests were performed to evaluate whether 206 alloy is a reasonable candidate for the process. Initial tests have compared 206 with 319 and 356 in terms of fillability, metal velocity, and pyrolysis defects. Additional tests to evaluate microshrinkage and hot tearing problems will be performed during Phase V of the research program.

Test 1: An initial series of castings was poured using 10-in. long as-blown EPS patterns having a nominal density of 1.6 lb/ft³, Figure 1.1.2.13.1. Patterns were 0.125-in. x 1.2-in. (A/P = 0.056 in.), 0.25-in. x 1.2-in. (A/P = 0.1034 in.), and 0.1875-in. x 3-in. (A/P = 0.088 in.). The patterns were oriented vertically and bottom gated. The patterns were coated with a high permeability refractory, having a screen permeability of about 60. A hollow, untapered sprue was used. Three alloys -- 206, 319, and 356 -- were poured at both a constant pouring temperature of about 750°C and at a constant superheat of 150°C. Separate green sand castings were simultaneously poured to obtain cooling curves typical of the alloy, while the foam patterns were instrumented with 10 electrical probes to permit metal velocities to be calculated. Whenever possible, duplicate castings were poured for each combination of pattern, alloy, and pouring temperature.

The cooling curves show that the 206 alloy begins to freeze at a higher temperature than the other two alloys, and only a brief eutectic arrest occurs for the 206 alloy, Figure 1.1.2.13.2.

Previous tests²² using these patterns showed that fillability depended on two factors -- the perimeter of the casting (which controlled the rate at which pyrolysis products could be transferred to the coating) and V/A ratio (which controls how quickly the metal cools and begins to solidify). For a constant V/A (or A/P) ratio, the fillability increases almost linearly with increasing perimeter. The fillability also increases when the V/A ratio of the casting increases. Although the data is somewhat limited in this test due to availability of patterns, Figure 1.1.2.13.3 shows that a similar behavior can be described for this test when the alloys were poured at about the same pouring temperature. At the same pouring temperature, the fillability of 356 and 319 is about the same, while the fillability for the 206 alloy is a couple of inches shorter. However when the alloys are poured at the same superheat, the fillability for the three alloys is almost identical, or the 206 alloy may even be slightly higher, Figure 1.1.2.13.4.

Because the patterns were bottom gated, the velocities given are the initial velocity when the metal first enters the pattern (the velocity gradually decreases somewhat during fill due to the decreasing effective metal head). Figure 1.1.2.13.5 shows these velocities when the castings were poured at a constant pouring temperature. The 319 and 356 alloys produced the same velocity, while the 206 alloy gave very similar velocity. When a constant superheat was used, Figure 1.1.2.13.6, the velocity for 206 was higher than for the other alloys for the thinnest patterns (smallest A/P ratio) but identical for the two larger patterns.

Test 2: In a second test, box patterns, Figures 1.1.2.13.7 and 1.1.2.13.8, were poured using the three alloys. This time, a low permeability coating with a screen permeability of about 18 was used to coat the patterns, which had an approximate density of 1.5 lb/ft³. The box pattern was poured in a horizontal position, with two side gates. The pattern has three major section sizes, and a set of five

probes was placed in each section to enable velocities to be calculated.

Figure 1.1.2.13.9 shows the velocities in each section obtained for the four castings that were poured. In the thicker sections of the pattern and for a constant superheat, the velocities obtained using 206 alloy were higher than those obtained for the other alloys. Velocities were similar for all alloys when a constant pouring temperature was used. In the thinnest section, the velocities were particularly high for the 206 alloy, a result consistent with test 1. All of the velocities were higher than normally expected, probably because the beads in the pattern were poorly fused.

For confirmation, one box pattern was gated at the thin end using an overdiluted high permeability coating, which had a screen permeability of about 135. The casting was poured using 356 alloy. Due to the higher permeability, the velocities were high and about the same in all three section sizes, Figure 1.1.2.13.10. However, even with the exceptionally high permeability coating, the velocity in the thin section was still less than that observed in the thin section for the 206 alloy poured at the same temperature.

The castings were visually inspected for blisters, radiographed for porosity, and broken into pieces to locate folds. The observations are included in Table 1.1.2.13.1. No blisters were observed on any of the castings. Internal porosity was only observed in the casting with the overdiluted high permeability coating. Folds were found in all of the castings and typically at about the same locations, Figures 1.1.2.13.11 to 1.1.2.13.15. The 206 alloy did not give an appreciably larger number of folds than the 319 and 356 alloys.

Test 3: A final test compared 356 and 206 alloys in the flange pattern. Three identical castings were poured at 790°C for each alloy, using 1.45 lb/ft³ EPS patterns and a low permeability coating having a screen permeability of 14. A hollow, untapered sprue was used, and 20 probes and 3 thermocouples were embedded in the patterns. The metal was degassed with nitrogen prior to pouring; density measurements using vacuum-solidified coupons indicated 2 to 7% hydrogen.

Figure 1.1.2.13.16 compares the calculated velocities for the six castings. Even though the pouring temperature was the same (i.e. less superheat for the 206 alloy), the velocities were higher for the 206 alloy.

No blisters were observed on visual examination, and no internal pores were observed from radiographs. A few folds were found when the castings were broken into pieces. Folds were slightly more prevalent in the 206 alloy than in the 356 alloy, Figure 1.1.2.13.17. This may have been partly due to the higher metal velocity, Figure 1.1.2.13.18. However other factors, such as the higher liquidus temperature of 206 alloy and the different solidification characteristics of the two alloys, may have been a factor.

The maximum observed temperature at three locations along the flange were also measured, Figure 1.1.2.13.19. Since the pouring temperatures were the same, the temperatures are all about the same near the gate. However the temperature of the 206 alloy drops more slowly than that of the 356 alloy. But, because of the higher liquidus temperature of 206, the temperature for both 206 and 356 are at or close to the liquidus by the time the metal front reaches the end of the casting.

1.1.2.14 Effect of Casting Size and Geometry on the Critical Gate Area

In work done several years ago¹⁴, using 0.5-in. x 4-in. x 8-in. patterns cut from a foam plank, tests showed that for a very high permeability coating, the metal velocity was independent of gate cross-sectional area when the gate was larger than about 0.15 in.¹⁷, Figure 1.1.2.14.1. Instead, the coating permeability and/or foam recession rate acted as the choke governing metal fill. Only for smaller gates did the gate act as the choke. When a very low permeability coating was used, the critical gate size was about 0.1 in.¹⁷. All of this work was done with a single pattern size and with cut patterns. A study was performed in which cut patterns of a variety of sizes, or A/P ratios, were poured using various gate areas in order to determine the effect of casting size and geometry on the critical gate area.

Several sets of castings were poured. One set included 2-in. wide, 10-in. long patterns varying in thickness from 0.25-in. to 4-in. A second set of tests used 4-in. wide, 6-in. long patterns varying in thickness from 0.5 to 4 in. -- unfortunately the gate areas used in the second set were all larger than the critical gate size and little helpful information was obtained from it. All of these patterns were cut from foam plank and had a nominal density of 1.3 lb/ft³. All of the castings were poured at 800°C using 319 alloy and a low permeability coating with a screen permeability of 16. The results were compared to the test run several years ago. Data for the pattern dimensions are included in Table 1.1.2.14.1 and typical gate dimensions are shown in Table 1.1.2.14.2.

Particularly for the thinnest castings, the gate areas needed to be so small that they could not possibly support the cluster during coating and compaction. To get around this problem, holes were drilled through a 0.5-in. thick, 0.5-g/cm³ sheet of insulating refractory, Figure 1.1.2.14.2. The refractory then was glued to both the pattern and the gating system. Ten probes were inserted into each pattern to enable metal velocities to be calculated. A hollow, untapered sprue was used to complete the cluster.

Because the patterns were arranged vertically and bottom-gated, the metal pressure head decreased during fill, which in turn helped decrease the metal velocity. The velocity used to determine the critical gate area was therefore defined as the initial velocity, or the tangent to the distance versus time curve, an example of which is

shown in Figure 1.1.2.14.3.

For each pattern size and geometry, several castings were poured with different gate areas. The velocities were calculated for each and plotted versus gate area. Figure 1.1.2.14.4 shows an example. As the gate area initially increased, the metal velocity increased as well, indicating that the gate served as the choke. Above the critical gate area, the velocity reached a constant value, indicating that the coating or foam was serving as the choke. Similar figures were obtained for each pattern size and geometry.

Additional tests used as-blown rather than cut patterns. In one case, flange patterns with a nominal density of 1.45 lb/ft^3 were poured. Relatively thin pendant patterns with a density of 1.3 lb/ft^3 and chunky T-shaped patterns with a density of 1.3 lb/ft^3 were also poured. Figure 1.1.2.14.5 shows these patterns.

We expected the critical gate area to be related to the geometry of the pattern, and the A/P ratio was expected to provide the best correlation. However, just to be sure, critical gate area was plotted versus perimeter (Figure 1.1.2.14.6), cross-sectional area (Figure 1.1.2.14.7), as well as A/P ratio (Figure 1.1.2.14.8). The best correlation does appear to be the A/P ratio. The data points from the previous test conducted several years ago are also included in these figures and the data point for the low permeability coating fits almost exactly on the new curve for the A/P ratio. The data point for the high permeability coating, as expected, predicts a larger critical gate area. The results from the flange, pendant, and T-shaped patterns are also included; the results for the flange and T-shaped patterns correlate well with the results from the cut pattern. The results for the pendant pattern do not fit as well, but the data for the pendant pattern was not as reliable as that for the other patterns due to fewer castings being poured.

The fact that the data for the as-blown patterns fits well with the data from the cut patterns may indicate that, at least for these castings, the coating rather than the foam recession rate controls the metal velocity when the gate exceeds the critical area.

The velocity, measured when the gate area exceeds the critical size, was plotted versus the A/P ratio for the castings obtained using the cut patterns. Figure 1.1.2.14.9 shows this relationship. The velocity decreased with increasing A/P ratio. This behavior is typical of patterns cut from a foam plank. The opposite behavior has sometimes been observed when as-blown patterns are used.

1.1.2.15. Summary

The major thrust of the research at UMR during Phase IV has been centered on the origin (including mechanism of formation) of pyrolysis-related defects and how different casting variables influence their formation.

- In the repeatability studies, we found that although metal velocity during fill may be predictable, the severity of the defects in the flange pattern varied over a wide range. Defects did tend to concentrate in certain areas -- for example, blisters were normally found in a band about halfway around the pattern, while folds normally were located where the two main metal streams met. However, other, usually relatively small, folds were somewhat randomly located on the flange. This suggests that there may be two important causes for the fold defects -- the impingement of metal streams on one another and turbulence either during pouring or at the metal-foam or metal-foam-coating interface. This may also lead to different fold chemistries, as suggested by the Auger analysis, with metal stream impingement leading to a composite carbon-oxide fold surface and turbulence leading to a primarily oxide fold surface.

- High sand temperatures, in addition to or perhaps because of increasing metal velocity, normally increased the incidence of folds and blisters. The higher metal velocity would tend to make the metal front more unstable, leading to entrapped oxides and pyrolysis products.

- Although extra glue or use of a foam rather than a hollow ceramic sprue had little effect on metal velocity, they did increase the number of defects. Thus the amount of organic material introduced through the glue or foam influences the incidence of defects separately from any velocity/turbulence effect.

- Using either extruded or reticulated filters at the base of a hollow sprue had little effect on metal velocity and also little effect on the incidence of defects. However, the hollow sprue, with or without filters, did produce fewer defects than a foam sprue. The tests that showed this effect, however, were unable to indicate whether the filters are effective in eliminating any pyrolysis products or oxides introduced during pouring or displacement of foam sprues. A set of tests to be conducted during Phase V will address this issue.

- The gating design influences defect formation. Bottom gating of a flange pattern produced the fewest defects, while top gating produced the most defects. When the flange pattern was oriented horizontally, the fewest fold defects were found when only a single side gate was used. Additional gates increased the number of locations where metal streams impinged.

- High metal velocities are obtained when the coating permeability is high -- this normally leads to more severe defects.

- High density EPS foams lead to lower metal velocities, but also provide more pyrolysis products that may be trapped in the casting. The conflicting influences of velocity and amount of

organic material sometimes makes it difficult to predict the effect of foam density on defect formation. However in these tests denser foams resulted in more likelihood of internal porosity and possibly more folds. Blisters tended to decrease in number.

- Higher silicon levels in Al-Si alloys, resulting in a narrow solidification temperature range, produced very large folds and numerous internal pores when a high permeability coating permitted rapid fill rates.

- An Al-Cu alloy can produce comparable or even better fillability than conventional Al-Si alloys, with slightly higher metal velocities. Defect formation is similar in severity to the traditional 319 and 356 alloys.

- The critical gate area at which fill changes from gate size control to coating control increases with the A/P ratio of the pattern. Even for large A/P ratios, however, the critical gate area is very small.

1.2 Pattern Material Properties

1.2.1 Effect of Bead Properties on Casting Quality

During the early phases of this program foundries and pattern blowers have reported increased casting scrap associated with batches of beads used to blow patterns. Historically these batches were labeled 'summer beads' since they tended to appear in the summer months. Due to other pressing technical issues these summer beads have received little attention other than simply replacing the troubled beads with another batch, which, in most cases, corrected the issue. Pattern material properties such as molecular weight, specific heat, thermal conductivity and glass transition temperature have previously received little study during the earlier phases of this program. During the past two years several instances of sudden increases in casting scrap at sponsors' foundries, that could not be attributed to known principles, presented an opportunity to evaluate bead properties and their effect on casting quality. In one case study an aluminum foundry experienced a sudden increase in misruns and porosity. Coating permeability, viscosity, pattern density and metal pouring temperature were within normal operating values. Further investigation revealed that the increased scrap began after changing from one batch of raw pattern beads (37A) to a second batch (31U). Communications with other foundries revealed similar difficulties in making castings using patterns blown from this batch of beads. Even though the pattern densities were within specifications the time required to pre-expand the new batch had increased to 90 seconds from 55 seconds for the previous batch. It was also noted that molding times increased. Castings poured using these patterns experienced a misrun (non-fill) and high levels of porosity. These incidents prompted an intensive study of these two batches of beads along with representative samples

from bead manufacturers and foundries.

Initially raw beads from the two batches of beads were evaluated using TGA and DSC in an effort to detect any differences in specific heat, heat of degradation or glass transition temperature (TG). TGA (Thermogravimetric Analysis) consists of heating a small sample of beads at a constant rate (20 °C per minute) while recording the sample weight. Data from this technique allows calculation of the blowing agent content, the temperature at which blowing agent escapes and the polymer degradation temperatures. DSC (Differential Scanning Calorimetry) also heats a small sample weight at a constant rate while recording any exothermic or endothermic reaction. Data from this technique reveals the temperature at which reactions occur and allows calculation of glass transition temperature (TG), specific heat (J/gm) and total heat of degradation (J/gm). Figure 1.2.1.1 illustrates typical TGA and DSC responses of raw polystyrene beads. The DSC response in this figure reveals that three transitions exist for raw polystyrene beads and that they are endothermic in nature. The first transition (A) occurs at approximately 60 °C and represents the glass transition temperature (TG) of blowing agent softened polystyrene. The TGA response at this temperature reveals little or no weight loss, indicating that the blowing agent is not escaping from the beads. Since the TG of pure polystyrene is 95 to 100 °C, it is obvious that the blowing agent has plasticized (softened) the polystyrene. The second transition (B) occurs at approximately 95 °C and represents the true TG of polystyrene. At this temperature the TGA response shows an appreciable weight loss as the blowing agent begins to escape from the polymer. The third transition (C) occurs at about 125 °C as the beads collapse and almost all of the blowing agent escapes. As the temperature approaches 350 °C the polymer begins to degrade into lower molecular weight components. At temperatures above 450 °C the polymer has fully degraded.

Results of the initial TGA and DSC evaluations on the "well" and "poor" beads showed little or no difference in specific heat or heat of degradation; however the glass transition temperatures (TG) of these two batches of beads appeared to be different (Figure 1.2.1.2). Since the blowing agent in both batches of beads was N-Pentane and the percent weight of Pentane was practically equal it was obvious that another factor was controlling the pre-expansion and blowing process. Further evaluation of these beads included measuring the molecular weights shown in Figure 1.2.1.3. This figure shows the molecular weight of three samples from three batches of beads manufactured by Nova and two samples from Styrochem. The batch identified as 37A was used to cast aluminum parts successfully, batch 31U produced the misruns and porosity and 39S was the batch received to replace the 31U beads. First note the variation in molecular weight within the three samples from each of these batches. Next note that batch 37A had a molecular weight of about 240,000 while batch 31U was about 300,000 and 39S about 275,000. Samples identified as T180 and T170 are shown as a reference to indicate the consistent molecular weight within batches from another manufacturer.

Since the only revealed differences in bead properties of these two batches of beads that performed differently in pre-expansion, pattern blowing and casting were glass transition temperature and molecular weight an explanation was sought in the literature. Two literature sources (x,x) revealed that the escape of blowing agents from high molecular polystyrene requires more energy than from lower molecular weight polystyrene. This is explained by first understanding that the blowing agent molecules are dispersed within the molecular structure of the polystyrene and are trapped within the voids created by the maze of long chains of the polystyrene. Higher molecular weights have longer chains and thus the path of escape for the blowing agent molecules becomes more complex. Coupled with this phenomenon is the fact that the higher molecular weight polystyrenes are stiffer and stronger, causing the glass transition temperature to be higher. This can be clearly seen in Figure 1.2.1.2. Going back to the foundry, it was mentioned that the pre-expansion times increased from 55 to 90 seconds from batch 37A to 31U. This was apparently caused by the higher molecular weight of 31U as more time was required in pre-expansion to heat these beads to a higher TG to attain a target density. Likewise more time was required in the pattern blowing process. The end result was an overfused, high density pattern which produced scrap castings.

A complete study of the effect of polystyrene molecular weight on TG was completed to confirm the literature and document this effect for inclusion in the Pattern Quality Control Manual. Three types of pentane were included in this study. Table 1.2.1.1 lists the values of the variables included in this study. The study was designed to evaluate the TG of polystyrene beads following a simulated pre-expansion exposure. This was accomplished by first heating raw bead samples rapidly to various temperatures followed by cooling the samples rapidly to room temperature and immediately performing the DSC evaluation to 160 C. Figure 1.2.1.4 illustrates the heating programs used. The heating rate used for pre-expansion simulation and cooling was 100 °C/Minute. DSC evaluations were performed at 10 °C/Minute.

Figure 1.2.1.5 reveals the changes in DSC response as the beads are exposed to different temperatures. The top curve (preheat at 40C) is a typical DSC response revealing the three endothermic reactions (see Figure 1.2.1.1) which indicates that preheating to 40 °C has not altered the beads from their virgin state. The second curve reveals that preheating to 80 °C is sufficient to remove the first endothermic reaction, allowing the TG of the plasticized polystyrene to be identified as an inflection point in the response. Without this preheating the TG of the plasticized polystyrene would go undetected. The third curve illustrates that preheating to 120 C is sufficient to remove the second endothermic reaction. Although this second reaction does not mask the TG it is apparent that the TG (inflection point) has shifted to a higher temperature. This occurs as some of the pentane escapes, reducing the plasticizing effect. The fourth curve (160 C) reveals removal of all three endothermic reactions along with further shifting of the TG to the published value of pure polystyrene (95C to 100C). This data indicates that the temperature of the pre-expansion

process cannot be higher than the point that preheating causes the change of the third endotherm. Otherwise the pre-expanded beads will be collapsed.

The values for all glass transition temperatures are shown in Figure 1.2.1.6 as a function of preheat temperature. Several conclusions can be drawn from this figure:

1. Preheating of beads evaporates the blowing agent, revealing the TG that was masked by the first endothermic reaction.
2. Higher molecular weights generally have higher TG's; however the type of blowing agent can alter this trend. For example, the higher molecular weight beads with N-Pentane, Iso-Pentane and Cyclo-Pentane have a lower TG than the lower molecular weight beads. Iso-Pentane appears to increase the TG over N-Pentane.

1.2.2 - Effect of Bead Structure and Pattern Precoat on Casting Quality

During the study of bead properties a separate evaluation of complete polymer degradation was performed using TGA and DSC procedures. These evaluations were prompted by the discovery of a pattern precoat material that dramatically reduced surface defects on iron castings. It was initially thought that this precoat material was an oxidizer, hence TGA and DSC evaluations were performed in air as opposed to nitrogen. All previous TGA and DSC evaluations were performed in nitrogen due to the fact that the environment in the casting cavity is reducing. Figure 1.2.2.1 compares the TGA response of raw polystyrene beads in air and nitrogen and indicates that polystyrene begins to degrade at about 300 C in air compared to 360 C in nitrogen. The degradation rate of the beads evaluated in air is significantly slower due to the complex reactions that occur. This data also indicates incomplete degradation in air as indicated by the insert in this figure and the presence of a dark brown residue remaining in the specimen cup after exposure to elevated temperatures. Figure 1.2.2.2 illustrates the DSC response of polystyrene beads fully degraded in air and nitrogen. This figure indicates that the degradation process in air is exothermic in nature as opposed to the endothermic process in nitrogen. Since exothermic reactions generate heat it seemed logical that the precoat material could possibly provide a higher metal front temperature which would enhance the pattern degradation process. The TGA and DSC data of EPS beads in air explains why PMMA (polymethylmethacrylate), a polymer with attached oxygen molecules, reduces carbon related casting defects.

Two types of precoat material were analyzed to determine their basic structure in an effort to explain the significant decrease in carbon related casting defects when patterns were precoated with these materials prior to the normal refractory coating procedure. Results of these evaluations revealed the precoat materials were emulsions of PMMA, PBA (polybutylacetate) and polystyrene copolymers with a solids content of about 22% and a molecular weight of around 20,000. Although there is some additional oxygen available in these precoats

calculations indicate that only a small percentage of the polystyrene would be oxidized. These calculations are based on an increase in pattern weight of 10 % (typical) through the addition of the precoat. The mechanism of how these precoats reduce the incidence of casting defects remains a mystery yet laboratory tests and plant trials have confirmed the increased performance. The significance of this discovery provides a new path for development of new pattern materials and is discussed in section 4.0 of this report.

Table 1.2.2.1 lists the patterns, precoat and coatings used to evaluate the effects of two types of precoat on EPS pattern. This matrix also includes EPS patterns blown at different time periods and from different raw bead batches. Previous evaluations had indicated a significant difference in the incidence of defects when using these patterns. These two batches of beads produced significantly different expanded bead structures as indicated in Figure 1.2.2.3. The patterns at UMR (University of Missouri - Rolla) have a uniform cell structure within each bead while the UAB patterns have large cells at the center of each bead surrounded by smaller cells. Previous casting evaluations indicated the UAB patterns produced significantly more folds in aluminum castings than the UMR patterns. Evaluations of these two groups of patterns revealed no statistical difference in density and open porosity. The test matrix in Table 1.2.2.1 included these patterns to confirm the previous results. Clusters 1 through 4 used a three-on arrangement while cluster M and 7 through 15 used a two-on arrangement. Each cluster was poured using a 3/2 inch open fiber sprue as illustrated in Figure 1.2.2.4. Flange patterns were instrumented with position probes and thermocouples as illustrated in Figure 1.2.2.5.

Table 1.2.2.2 lists the calculated metal velocities at positions A,B,C and D along with the metal temperatures at locations 1 and 2 where the metal fronts should meet. The data from clusters 1 through 4 (UMR patterns with and without precoat) reveals significantly lower metal velocities for those patterns with precoat. There was no statistical difference in the metal temperatures. Clusters 7 through 15, using both UAB and UMR patterns, with and without precoat, also reveals a significant reduction in metal velocities when the precoat was applied. One possible explanation for this reduction in metal velocity assumes the precoat seals the pattern open porosity at the pattern surface, preventing pyrolysis gases from escaping through the coating until the precoat material has degraded. Figure 1.2.2.6 illustrates how the precoat has sealed the pattern surface. The lower metal velocities should allow more time for patterns to degrade to gaseous products and produce less liquid induced casting defects.

Castings were examined for surface indications of folds and subsequently fractured at the indications. The number of folds and the dimensions of each fold were recorded. Table 1.2.2.3 lists the total number of folds, total area of folds and the total area of small surface cracks for clusters M through 15. These small surface cracks are thought to be folds that almost healed. Figure 1.2.2.7 illustrates a typical fracture surface with folds and Figure 1.2.2.8 illustrates

the distinction between a fold extending to the casting surface and a healed fold. The data in Table 1.2.2.3 indicates that both type S and type F precoat reduced the number of folds and the area of the folds by more than 50 % for both UAB and UMR patterns. Clusters 9, 11 and 12 were poured to compare castings using the UAB and UMR patterns without precoat. The data for Clusters 9, 11 and 12 clearly indicate a significant increase in the number and size of folds for the UAB patterns. These patterns had the large cell structure in the center of each bead. The bead manufacturer attributed this irregular cell structure to a non uniform distribution of blowing agent in the raw beads.

Although these experiments confirmed the benefits of using a precoat on patterns to decrease fold defects, the implementation of this procedure in the foundry would add two additional steps to the Lost Foam Process. The first step would be coating the pattern by dipping followed by a drying step to remove any water or solvent. This drying procedure is necessary since the precoat is typically 78 % water and solvents. The success of using the precoat does offer an opportunity to pursue the possibility of including additives in the raw beads to achieve similar results. This will be discussed in Section 4.0 of this report.

1.2.3 Effect of Pattern Density Gradients on Casting Quality

Earlier research has indicated that pattern cross sectional density gradients can control metal front shape and, in turn, casting quality. Cross sectional density gradients are generated by steep thermal gradients across the pattern thickness during cooling of the pattern. Another type of pattern density gradient exists which is termed location density gradient. This type of density gradient occurs in the pattern blowing process and is typically caused by incomplete filling of beads in isolated areas of the pattern. This phenomenon is best explained by first understanding the various bead packing arrangements and the variation in pattern bulk density resulting from these arrangements. Spherical beads can arrange themselves to achieve a maximum bulk density, a minimum bulk density or some density between these values. Maximum bulk density is achieved through stacking in a pyramidal or face-centered cubic arrangement while minimum bulk density is achieved through a simple cubic arrangement. From geometric considerations of spherical shapes the void fraction (ratio of the void volume to the solid volume) is 0.35 for the pyramidal arrangement and 0.91 for the simple cubic arrangement. This means that a pattern with beads stacked in the pyramidal arrangement and a bulk density of 1.40 pcf would have a bulk density of 1.01 pcf if the beads had stacked in a simple cubic arrangement. These variations in stacking can occur in the pattern pre-expansion and blowing processes in the following way. Bead density at the pre-expander is measured by filling a container with beads while vibrating the container to achieve maximum density (pyramidal stacking). This quality control procedure assures consistent pre-puff bead densities for the blowing

process. There is no assurance that the beads will stack in this pyramidal arrangement during the process of blowing beads into a pattern mold. In fact, densities from 1.8 to 1.0 pcf have been measured in patterns blown from 1.4 pcf pre-puff. This data suggests that beads can be packed to achieve bulk densities higher than theoretical maximum and that minimum densities can be achieved through incomplete filling or minimum packing arrangements. It is probably appropriate at this point to mention that pattern average bulk densities higher than the pre-puff density can also be achieved by failing to achieve pyramidal bead packing (no vibration) of the pre-puffed beads.

Location density gradients can cause metal fronts to increase in velocity in low density areas of a pattern and decrease in high density areas. This causes merging metal fronts downstream, increasing the probability of folds and porosity as the amount of pyrolysis products on the metal fronts increase locally, placing an increased burden on the coating to remove these products. An example of these casting defects, the relationship to pattern densities and the remedy occurred in a Lost Foam iron foundry that produced large water distribution products. This foundry used EPS patterns blown in-house. The casting was a large fire hydrant pictured in Figure 1.2.3.1. The defects were massive areas of porosity, folds and irregular surface blemishes located as described in this figure. Figures 1.2.3.2 through 1.2.3.3 illustrate the severity of these defects and Figures 1.2.3.4 through 1.2.3.5 identifies the source of the defects as carbon, a pyrolysis by-product. Patterns were instrumented with position probes to track the metal filling process. Results of these evaluations indicated multiple fronts merging at the locations of the severe defects. Based on this evidence a major effort was initiated to:

1. Determine the density gradients within the pattern.
2. Minimize the density gradients.
3. Reduce the overall pattern density in an effort to reduce the amount of pyrolysis products (carbon).

Figure 1.2.3.6 illustrates the initial pattern density variations prior to implementing any changes to the pattern blowing process. Densities from 1.13 to 1.72 pcf were measured. Pre-puff density was 1.4 pcf. After investigating the pattern molds it was discovered that the upper section had five (5) fill guns and the lower section had seven (7) guns. In addition a drain valve was partially blocked which restricted the air removal from the cavity during mold filling. The number of fill guns was reduced systematically while measuring the resulting density gradients. The final mold configuration included only two fill guns each on the upper and lower sections. The final density gradients are shown in Figure 1.2.3.7. Note the final density range was 1.23 to 1.45 pcf compared to the initial range of 1.13 to 1.72 pcf. Castings made using these patterns showed a dramatic decrease in the severity of defects.

The next effort to decrease the overall pattern density occurred in steps as the pattern blower adjusted to the new beads. This was necessary since lower density pre-puffs contain less blowing agent and

pattern steam times and steam pressures must be adjusted to achieve good pattern surface fusion. Final pattern densities approached 1.1 pcf with a corresponding decrease in casting defects. These changes to the pattern to reduce density and density gradients made the overall Lost Foam Process more robust (less sensitive to inherent changes in other control parameters). This foundry experience proved that producing iron castings using EPS patterns is possible by reducing pattern densities and density gradients. A secondary finding was that pattern density gradients can be caused by the interaction between multiple fill guns.

Another iron foundry was experiencing similar results on a railroad car support member. This part was cast in austempered ductile iron and periodically suffered significant increases in scrap (porosity and folds) in a critical location. The foundry purchased patterns from a commercial pattern blower and related the sudden changes in casting scrap to different batches of pattern shipments. Patterns were examined from two shipments - shipment 518 yielded 7.5% scrap while shipment 508 yielded 25% scrap. Sections were removed from the selected areas of patterns from each shipment as illustrated in Figure 1.2.3.8. Bulk density and open porosity were evaluated on these specimens using the procedures described in Section 1.2.4.4. In addition, molecular weight and glass transition temperature were measured on samples from each batch. Tables 1.2.3.1 and 1.2.3.2 lists the values of density and open porosity of sections removed from patterns from shipments 518 and 508 respectively. Table 1.2.3.3 lists the molecular weights and glass transition temperatures of both pattern shipments.

Note the density values of samples from both 518 and 508 have the same value of 1.23 pcf. Likewise the values of open porosity are practically the same. The significance of this data is that normal foundry quality control procedures of measuring pattern weights or density would not detect a difference in these two shipments of patterns. Note also the molecular weights and glass transition temperatures are almost identical. The density, open porosity, molecular weight and glass transition temperature data indicates raw bead properties and pre-puff and pattern molding parameters are not the cause of the difference in casting scrap levels. For all practical purposes the conclusion would be that these two pattern shipments are identical.

Note the range of pattern densities for 518 and 508 in Tables 1.2.3.1 and 1.2.3.2. Patterns from shipment 518 has a range of densities from 1.0 to 1.42 pcf while patterns from shipment 508 has a range from 0.98 to 2.02 pcf. These location density gradients are usually caused by the bead filling process as described earlier in this section of the report. These severe location density can cause merging metal fronts that produce laps, folds and porosity.

The two foundry experiences above indicate a need to understand the bead filling process more thoroughly to determine the parameters that can create these location density differences.

1.2.4 - Effects of Pattern Density and Bead Fusion on Casting Quality

1.2.4.1 - Introduction

Lost Foam foundrymen have reported that pattern bead fusion can have a dramatic effect on casting quality in both aluminum and iron. Specifically the reports indicate that patterns with poor bead fusion in the center of a pattern section along with a well fused surface produce castings with fewer defects. The procedure for measuring bead fusion has been to fracture a pattern section and peel beads from the fractured surface. Poor fusion was characterized by beads that were easily removed without fracturing individual beads. Attempts to develop a quantifying measurement technique for this pattern property have been unsuccessful to this point. Current understanding of pattern blowing parameters and bead properties has led to the possibility that the void space between beads may be an indicator of bead fusion. This hypothesis is based on the facts that bead expansion occurs at or above the glass transition temperature of the bead polymer and fusion occurs at or above the bead polymer melting point. Polymer glass transition temperatures are reduced by the plasticising effect of the blowing agent. This issue is addressed in another section of this report. Typically the glass transition temperature of polystyrene is 65 C to 100 C, depending on the blowing agent content. Since polystyrene is an amorphous material a melting point is not defined , therefore the temperature at which fusion occurs is not defined. Typically the 'melting' temperature is given as 160 C for polystyrene. The literature teaches that bead fusion is controlled by both temperature and pressure and this process is currently under study in a continuation of this work. It is increasingly obvious that the void space between beads (porosity) in a pattern may be related to the degree of fusion. With this principle in mind a study was made to investigate the effects of interconnected porosity (open porosity - OP) and pattern density on metal front behavior and ultimately casting quality.

An interconnected porosity evaluation procedure was developed as a part of this study. This test procedure was used to quantify the amount of open porosity and the density of 864 samples. The samples came from an experimental blowing matrix where both the density and steam time were varied. The results showed that within a pattern there exist gradients of both interconnected porosity and density with the pattern center being the least dense and least fused.

An experimental matrix was used to relate pattern properties to casting defects. Both iron and aluminum castings were made from patterns with high and low bead fusion as well as high and low density, coated with high and low permeability coatings. Patterns were arranged in a three-on cluster and instrumented with thermocouples and 72 position probes.

1.2.4.2 - Preliminary Experiments

Two preliminary experiments were conducted. The first

experiments involved coating and drying patterns that were considered normally, highly, and poorly fused. The pattern weights were recorded every half hour after they were dipped in a coating. The results indicated that the highly fused patterns were completely dry thirty minutes before the normally fused pattern and one hour before the poorly fused pattern. This experiment indicated that the bead fusion level was significant in affecting the drying times of patterns. Assuming the open porosity is a measure of bead fusion this experiment also indicates that high open porosity can contain high water contents which requires longer drying times.

The second preliminary experiment involved two iron castings of bars that were 2.54 cm in diameter and approximately 30 cm long. The two bars cast were coated with a low permeability coating and instrumented with position probes, a thermocouple, and a pressure transducer. The pressure transducer was attached to copper tubing that was inserted a few centimeters into the end of the pattern opposite the gate. In the first pour a type K 16 gage wire thermocouple was positioned directly over the copper tube opening. In the second pour, the diameter of the wire was reduced to provide a faster response. Position probes were inserted to track the position of the metal front in relation to the end of the copper tubing. The tests indicated that while a pressure was indicated by the pressure transducer well in front of the metal front, approximately 6 cm, the thermocouple did not register a temperature increase until the metal was in contact. This was true for the thin gage thermocouple also. This suggests that the open porosity of a pattern may be a contributing factor in the escape of gases generated during pouring and that there is no significant preheating of the pattern ahead of the metal front.

1.2.4.3 - Processing Effects on Bead Fusion and Density

The quantity of bead fusion can be controlled directly in the blowing process of patterns. Pattern preparation in LFC involves a pre-expansion process and a molding process. The pre-expansion process expands the raw beads by heating the beads to evaporate the blowing agent, creating an internal pressure in the beads. At temperatures above the glass transition temperature the beads expand to a lower bulk density. In the molding process the amount of bead fusion depends on the amount of heat applied by the steam, the amount of pressure exerted to fuse the beads together, and the time the beads are exposed to these conditions. In general, long steam times and high pressures yield highly fused patterns.

Pattern density is actually controlled by the pre-expansion process. In the pre-expansion process beads are expanded to the nominal bulk density of the desired pattern. Low density patterns are created from low bulk density beads.

Surface interconnected porosity of the foam pattern affects the casting process in interactions with the coating and surface finish. If the surface of a pattern is poorly fused, the refractory coating can penetrate between the beads. The coating can then be entrained in the molten metal stream producing casting defects as liquid by-products attach to the coating particles and generate metal porosity as the liquid degrades. The effect of surface interconnected porosity on coatings is schematically represented in Figure 1.2.4.3.1. The highly porous surface allows for the penetration of coating and water into the pattern, which leads to many defect nucleation points. The highly fused surface is more desirable to minimize defects caused by coating and carrier entering into the molten metal.

The carrier of the refractory suspension, typically water, can also penetrate between poorly fused beads. Carrier pick-up directly effects the amount of time required to dry a pattern and remove the deep-seated carrier. Castings with porosity defects can result from insufficient drying as water is decomposed by the molten metal. Water has a relatively high energy absorption characteristic. This energy absorption can chill the metal and reduce the fluidity of the molten metal. The water is also a source for hydrogen gas, which can create porosity defects in aluminum. Excessive amounts of water vapor can also lead to blow back during pouring.

The quantity of internal interconnected porosity or bead fusion affects metal front shape, coating carrier pick-up, and pattern strength for handling purposes. In the past, little attention has been paid to the bead fusion of patterns by foundries. It is known to experienced LFC foundrymen that a poorly fused center of a pattern generally produces a casting with fewer defects. Miller's⁷ study further indicates that control of the metal front shape is imperative to obtain defect free castings.

High internal interconnected porosity invites wicking of the coating carrier into the center of the pattern through capillary action. This water produces gas, steam, and requires large amounts of energy to remove. This energy consumption reduces the fluidity of the metal and causes misruns. The presence of the gas and steam also contributes to increases in porosity defects.

The most important effect of high internal interconnected porosity is the expected change in shape of the metal front. Figure 1.2.4.3.2 illustrates the expected effect of pattern interconnected porosity on the metal front shape. A non-porous structure has a flat shape with minimal surface area for heat transfer to occur. The preferred pattern with high internal interconnected porosity should produce a pronounced bullet shaped metal front. This more pointed shape increases the area available at the foam/metal interface for heat transfer, and it directs the degradation products to the coating for removal.

1.2.4.4 - Scale Test for Density and Interconnected Porosity Measurements

The scale test was developed to be easy to use and give usable results in a short amount of time. The biggest advantage to the test is the ability to get both the density and interconnected porosity of a foam sample in the same procedure. The largest disadvantage to the test is that each sample can only be used once. The scale test was also conceived to allow foundries to run the tests with supplies and equipment on hand or with minimal acquisition.

Figure 1.2.4.4.1 is a photograph of the overall setup of the scale test, while Figure 1.2.4.4.2 is a drawing of the apparatus mounted to the scale. The balance used was a Mettler AE100 equipped with a computer output option and a density harness. Samples are cut from foam patterns using a razor blade. Generally, sample size is approximately 1/4 to 3/8 inch cubes. Since interconnected porosity levels and density vary in any given part, it is important to cut and test a few small pieces from each section of interest. For example, a surface interconnected porosity test would involve a few pieces from the surface while an internal foam interconnected porosity test sample would be taken from the center of the pattern.

The test procedure begins with placing each sample on the scale and recording the dry weight. Next, each sample is placed on the surface of olive oil in a container. The olive oil is drawn into the pattern samples by capillary action. It is important to allow one side of the pattern not to be covered with oil so displaced air can escape. After sufficient time has been allowed for the oil to penetrate all the pores, the samples are removed. The saturated samples are then blotted to remove any surface oil.

A tare weight in excess of the expected buoyant force is placed on the scale platform and this tare weight is recorded. Each of the saturated samples are then placed on the needle and their saturated weight is recorded to compute the interconnected porosity. With the sample mounted, a container of water is placed so that the sample is totally immersed. The buoyant force is then recorded to compute the density of the sample. The water does not significantly replace the oil during this phase of testing and thus allows for accurate density calculations to be made. Detailed procedures and equipment are described in Appendix A.

1.2.4.5 - Experimental Matrix

The experimental matrix is shown in Table 1.2.4.5.1. This matrix evaluates the effects of pattern density and bead fusion (open porosity) on casting quality. Both pattern density and bead fusion include high and low values based on foundry experience. These values provide four populations of patterns. Each population has 3 pours to obtain a 95% confidence level in the matrix results. Both aluminum and cast iron were used, the two most common LFC metals. The matrix allows for the separation of interconnected porosity effects from density variation effects. The matrix has provisions for a total of 48 pours to test both metals.

The viscosity of each coating was adjusted to bring them into the range of typical lost foam coatings. Samples were prepared and evaluated according to the UAB Coating Quality Control procedures. Table 1.2.4.5.2 shows the air permeability and liquid absorption capacity of each coating.

Each pour was instrumented with thermocouples and velocity probes. The velocity probes work by discharging a specific voltage when in contact with the molten metal front. The probes were inserted at an angle in an effort to reduce the possible premature contact of the metal with the long probe. These voltage spikes are read by a data acquisition system to give metal front position, velocity, and shape. Figure 1.2.4.5.1 illustrates the velocity probe locations. Figure 1.2.4.5.2 illustrates the sprue, metal plug, runner and patterns along with the thermocouple locations. The metal plug delays the pour long enough for the metal head pressure to be established in the down sprue.

After the test sample was poured, each specimen was cleaned and examined for defects. Surface finish defects were tabulated with respect to surface area occupied by the defect. Surface blisters were also tabulated by the amount of area they occupied. Misruns were recorded as the distance filled versus total fill distance available. Laps and folds were measured and recorded as a linear distance. Once visual inspection was completed, the specimens were broken and the internal defects were examined. Finally, each part was scored on a scale of 1 to 5, 5 being best and 1 worst, based on the researcher's opinion of relative quality and the cumulative tally of all the defects present in each casting.

1.2.4.6 - Results and Conclusions

Patterns: The four populations of patterns used in these experiments were blown using two densities and two steaming times for each density. The foam blower varied the steam time from 17 to 24 seconds to produce levels that were considered low and high fusion, respectively, and used two bulk densities of 20.8 and 24.0 kg/m³. From these patterns, six sections were cut from the pattern as shown in Figure 1.2.4.6.1. Each of these sections was then divided into twelve sections for density and open porosity evaluation. Density and open porosity data were recorded on three samples from each population to determine an overall average. These results were extrapolated to the rest of the samples since the test is destructive to the patterns and the whole population was prepared under the same conditions. Averages of the densities and open porosities from the three replications of each of the pattern blowing conditions were calculated and are presented in Figures 1.2.4.6.2 through 1.2.4.6.9. The overall average open porosity measurements from are shown in Table 1.2.4.6.1. The data indicates that the low density patterns have no significant difference in open porosity for the two steaming times while the high density patterns have significant differences. The effect of pattern blowing parameters on density and open porosity is currently under study and will perhaps explain this phenomenon.

The densities indicate that high internal porosity patterns are less organized but more uniform in density. Density values for the high fusion condition were more organized with a less dense structure in the center. Section 2 is the most sporadic because it was taken from a position where side arms of the gating had been removed. These side arms reduced the available area for heat transfer during blowing. Section 4 and 6 were taken from areas that later had 1.9 cm holes removed from. The high fusion condition appears to favor the proposed metal front shape when looking only at density.

The highest levels of open porosity and porosity gradients are observed in the high density low fusion plots. Section 2 showed no real effect from not having two metal interfaces on the side of the pattern tool for heat transfer whereas the density plots showed considerable effect from the lack of heat transfer area. All of the foam blowing conditions had the proposed favorable condition for patterns with poorly fused centers and better fused exteriors.

In the high density patterns, the low fusion had the most favorable open porosity gradients while the high fusion patterns had the least. The low density patterns are almost indistinguishable from each other. The results do show that the tooling had variations in it which did not allow for the fusion of beads in all areas to be accomplished equally. In order to maintain a constant metal front shape, the pattern tooling needs to be developed such that the density and open porosity gradients are constant throughout the length of the pattern. This would minimize the possible effects from momentum changes in the metal flow.

Data was recorded for each pour at 200 samples per channel per second for at least one minute. Most of the iron castings failed to yield usable data for position measurements due to equipment failure. The aluminum castings yielded usable results. Figures 1.2.4.6.10 - 1.2.4.6.17 illustrate the metal front shape and pattern density profile in the horizontal plane for all four pattern types and both high and low permeability coatings. The metal front profiles were generated from the arrival time of the metal at each of the four position probes in the horizontal plane. The density profiles were generated from the sample densities described previously in this section. These figures indicate that the low density patterns with either low or high fusion yielded metal front profiles that closely followed the density profiles. These profiles have the favorable shape to move liquid pyrolysis products to the coating for removal. All high density patterns yielded a more flat profile. Figures 1.2.4.6.18 - 1.2.4.6.25 illustrate the metal front shape and density profile in the vertical plane. The high density patterns produced a more flat metal front shape while the low density patterns produced a more favorable shape for moving liquid by-products to the coating. The effect of gravity on the vertical metal front shape is evident by the skewing of the metal front shape towards the bottom surface. No distinct effect of bead fusion was evident in the metal front profile data. These effects of density on metal front shape confirms the physical model of

pattern replacement by metal proposed by Pears and Littleton earlier in this research.

The number of defects in both the aluminum and iron castings were insufficient to draw any conclusions on the effects of pattern density and bead fusion on defect formation. Perhaps the pattern size (thickness and width) was sufficiently large to provide enough energy from the metal mass to allow sufficient time for liquid pyrolysis products to escape. Typically folds and porosity are more numerous in thin wall castings than thick wall castings.

1.2.5 - Pattern Quality Control

During the past two years the experience gained in Lost Foam foundries indicated that a Pattern Quality Control Manual was needed. Although this manual is incomplete it is included as Appendix A of this report and will be updated periodically as new understanding is achieved. Hopefully this manual will provide some consistency in the procedures for controlling pattern quality.

1.3 - Vacuum Assisted Casting

An experimental matrix was completed to study the effects of vacuum assist on the incidence of defects for aluminum and iron Lost Foam castings. The test matrix included pattern density and coating permeability since previous research has indicated a strong interaction between these variables. Both iron and aluminum lost foam castings were poured using patterns with low density (16 kg/m^3) and high density (24 kg/m^3), high and low coating permeabilities. Table 1.3.1 lists the coating properties.

In theory, the application of vacuum should expedite the removal of the byproducts that are produced from the degradation of foam. This theory was tested by applying vacuum to the flask at the time of casting. The removal of byproducts through the coating and the sand was enhanced by the increased pressure differential. Wedron 445 sand was used for all the experiments in this study, and although the permeability of sand was not considered in this study, the permeability of silica and other specialty sands have been evaluated in other studies. A flask was modified by welding a sheet of porous metal near the bottom of the flask. Vacuum was applied to the flask through a 5.1 cm diameter outlet hole that was placed in the wall of the flask below the sheet of porous metal, as illustrated in Figure 1.3.1.

1.3.1 - Experimental Setup

An experimental matrix was developed to study each of the three parameters: foam density, coating permeability, and vacuum assistance. The experimental matrix was originally designed to provide four

castings for each scenario. Each cluster consisted of two patterns, so two clusters were generated for each combination of parameters to produce four parts. A total of 16 clusters was cast for each metal, for a total of 32 pours. The number of castings for each parameter is better illustrated in a full factorial experimental matrix, shown in Table 1.3.1.1. Vacuum was applied to only half of the experiments, so that a direct comparison between the castings poured with and without the vacuum assistance was possible. The patterns were blown using polystyrene.

1.3.2 - Experimental Procedure

The patterns for this experiment were the flange geometry. Small foam gates (2.54 cm square and 1.25 cm in thickness) were glued to the outside circumference of the pattern. The gating was glued in the middle of the two bead injectors directly next to one of the holes in the flange pattern. The location of this gating was arbitrarily selected, but it was kept consistent throughout the study. The patterns were stamped with a five-digit code that completely identified each casting. The meaning of the code in the order of the digits is revealed in Table 1.3.2.1. The gating system was completed by another piece of foam, which is called the center gating.

Coating. The viscosity of both aluminum coatings was adjusted to 2200 centipoise (2.2 kg/cm.s). The viscosity of iron coatings was adjusted to 2500 centipoise (2.5 kg/cm.s). The two coatings for each metal were adjusted to the same viscosity to eliminate the coating viscosity as a factor in the experimental matrix. The patterns and the gating systems were coated after the viscosity adjustment and the permeability measurements were completed.

The patterns and the small gating were coated as an assembly. The center gating was coated separately. A total of 16 patterns, 8 high density and 8 low density, were coated. After coating the patterns were held in a vertical position, without shaking, for a few seconds to allow the excess coating to drip. The patterns were hung in the same vertical position and allowed to dry at room temperature.

The weight for each pattern and the small gating was measured before the pattern was coated. The patterns were again weighted after they were coated to measure the wet weight. Finally, the dry weight of the pattern was measured after the coating had completely dried. These measurements were taken to reveal any inconsistency in the patterns or the coatings. An example of these measurements is shown in Table 1.3.2.2.

Cluster assembly. The center gating was cut from a wagon wheel gating that was used for other castings and provided a place to attach the hollow sprue. A 61 cm hollow down sprue was used to deliver the metal to the pattern. Each cluster consisted of two patterns that were glued together, one on each side of the center gating. A metal plug was inserted at the bottom of the hollow down sprue to provide a temporary halt of the flow of metal so that the sprue could be filled

before the metal advanced to the patterns. Aluminum plugs with the thickness of 0.48 cm and diameters of 3.2 cm were cut from an aluminum plate. These plugs were used for the first set of aluminum castings. The need for the change in aluminum cluster assembly, explained in the following sections, eliminated the need for this plug in the remaining aluminum castings. Iron plugs were used for all iron castings. The thickness of iron plugs was reduced to 0.3 cm to make sure that the molten iron melted the plug and advanced to the pattern. The iron plugs were cut from 3.2 cm diameter iron rods. This method of pouring helped assure a consistent metal head pressure during casting. A schematic of the complete cluster assembly is shown in Figure 1.3.2.1.

Metal fill rate. The metal fill rate was determined by inserting position probes at measured locations of the pattern. These position probes were connected to an electronic circuit that was developed to generate a 50 millisecond voltage pulse as a probe made contact with the common probe. The electrical circuit for the position probes is shown in Figure 1.3.2.2. This circuit consists of two channels (channel a and channel b), each supporting 12 probes for a total of 24 probes. Probe circuits generated voltage pulses in increments of 0.4 volts. For example, the first probe circuit generated a 0.4 volt pulse, the second probe circuit generated a 0.8 volt pulse, and so on. The probe circuits in channel b were designed to generate negative voltage pulses to distinguish channel b from channel a.

The position probes were placed in only one of the patterns in a cluster. A template for the location of the position probes was created to keep the location of the probes constant for all the experiments. The probe arrangement in the pattern is shown in Figure 1.3.2.3. The common probe for each channel was placed in the gating system. The metal reached the common probe first and closed the circuit when it came in contact with the other probes. The closed circuit caused a capacitor in the circuit to discharge, yielding a voltage pulse which indicated the arrival of the metal to that particular location of the casting. All 24 probes were arranged in one pattern to help generate a rough sketch of the metal front profile. The position probe data was also useful in calculating the metal fill rate. The metal fill rate was calculated by dividing the distance that the metal traveled through the casting by the time that was needed for the metal to travel this distance. The arc lengths between probes 1a and 5b, 2a and 6b, 3a and 7b, and 4a and 8b were used for the fill rate calculations. Table 1.3.2.3 shows the arc lengths for each step in each of the four arcs used for fill rate calculation. The location of the arc lengths is illustrated in Figure 1.3.2.4. The elapsed times for metal to travel these distances were calculated by subtracting the time indicated by the first probe in the arc from the time indicated by subsequent probes in the arc. The final fill rate of the metal for each casting was calculated by averaging these four fill rates. The arc lengths were calculated according to the following equation.

$$AR = A * \text{Pi}/180 * 2r$$

where AR is the arc length between the probes, A is angle between the probes, and r is length between the probe and the center of the pattern. The arc lengths between these probes were selected because they provided the longest distance, and this method agreed with other studies conducted by University of Missouri Rolla. The time each probe triggered versus the distance that the metal traveled is plotted in Figure 1.3.2.5. The last row of probes (9b through 12b) was positioned on the left side of the pattern and could have been triggered by the metal advancing from the left side of the pattern. The last row of probes was not used for the metal fill rate calculations because the path of the metal that triggered these probes was not clear.

Thermocouple and pressure transducer. The temperature of the metal as it entered the pattern and the metal temperature profile was measured with a 30-gage thermocouple. This thermocouple was inserted in a hole that was made in the foam center gating directly below the metal plug. This thermocouple indicated the arrival of the metal and measured the temperature of the metal front as it entered the pattern. The thermocouple was connected to the data acquisition system through an Analog Devices isolated type K thermocouple module.

The instrumentation of the cluster was completed with the insertion of a pressure transducer. An Omega pressure transducer (model number PX302-050AV) was placed in the center of the flange that was instrumented with the position probes via a hollow 0.635 cm copper tube. This pressure transducer was capable of measuring pressures from 0 to 243 kPa. An Analog Devices module (model number 5B38-02) was used to condition the pressure transducer signal. This module provided a 10.0 volt excitation power that was necessary for the pressure transducer. The pressure transducer recorded the pressure in the sand close to the pattern.

Vacuum was applied to the flask through a 5.08 cm pipe at the bottom of the flask through a sheet of porous metal. This setup raised a concern about the uniformity of the vacuum applied. A second pressure transducer was added to a few of the castings poured with the assistance of vacuum. The second pressure transducer had the same setup as the first pressure transducer and was placed in the center of the second flange.

All data was recorded with the use of computer and a data acquisition program (Daqview). The position probes were connected to the computer through an Iotech Daqbook 216, 16-bit data acquisition system. The thermocouple and the pressure transducers were connected to the computer through an Iotech DBK42 signal conditioning chassis and the Daqbook 216. Because the voltage pulse for the position probes had a duration of 50 milliseconds, data was taken at 100 samples per

second and continued for 1 minute. Data was taken in a text format so that it could be imported to other programs for analysis.

Pattern cluster for aluminum castings. All the aluminum castings without the assistance of vacuum were cast using the cluster assembly with a hollow down sprue. These casings were x-rayed to inspect for porosity defects. The x-ray analysis of the first set of aluminum castings revealed only one porosity defect in one of the castings. These casting were then broken to search for fold or lap defects. Again, only one fold was discovered in all of the castings. The hollow sprue apparently caused the almost defect-free castings which is consistent with results from research at UMR. It was decided to change the sprue in hopes of creating castings with more defects since castings with no defects provided no basis for comparison.

The hollow down sprue was replaced with a solid foam sprue. A square piece of foam 0.5 meters in length and 3.2 cm square was cut from a foam board. Aluminum coatings were again adjusted to the correct viscosity. The solid sprues were coated with the appropriate coating and were dried at room temperature. The part in the center gating used for connecting the hollow sprue was cut off, and the solid sprue was glued in this location. The top part of the hollow sprue was cut and was used as a pouring cup. All the instrumentation and the pouring procedures were kept the same. The second half of the aluminum castings were poured with the solid sprue. The aluminum castings poured with the hollow sprue were repeated, but only one casting was poured for each combination of parameters.

Compaction. Approximately 20 cm of sand was added to the flask and compacted manually for approximately 10 seconds at 1.0 acceleration level. This bed of sand provided a firm sand base to place the pattern cluster. The pattern cluster was placed in the flask and oriented so that the vacuum line was directly in between the two patterns. The thermocouple wire and the copper tubing for the pressure transducers were placed in their proper locations, as shown in Figure 1.3.2.6. This figure shows the complete cluster assembly with the instrumentation for aluminum casting with solid sprue. Two pressure transducers were used to measure the pressure at the center of each pattern. A vibrational energy of 0.9 acceleration level was selected for the entire compaction cycle.

Melting and pouring of aluminum. The melting process for the aluminum casting started with 356 aluminum alloy scrap. The molten aluminum was degassed before it was poured. Degassing of aluminum is a procedure used in most aluminum foundries to reduce the hydrogen porosity in aluminum castings. Nitrogen gas was injected into the molten metal via a long graphite rod. Compressed air was used to spin the graphite rod so that nitrogen gas was better dispersed in the metal. The amount of nitrogen injected in the metal was adjusted so that nitrogen would bubble in the metal but not splash the molten metal. Degassing was continued for 3 minutes. After such time the

air and gas were turned off and the graphite rod was removed from the metal. The molten aluminum was removed from the furnace at approximately 825°C and was poured at an average temperature of 788°C.

Melting and Pouring of Iron. A class 35 gray iron was melted in a 45.4 kg capacity induction furnace. This iron was produced from charge consisting of steel scrap, graphite, silicon, and the necessary alloying elements. Silicon and graphite equivalents were checked and adjusted by pouring quick cups. An inoculant of 121.1 grams of Fe-Si was added as the metal was poured in the crucible. Iron was tapped into a silicon-carbide crucible at approximately 1420°C and was poured at approximately 1340°C.

Vacuum. Vacuum was applied to the flask using a 40 horsepower Nash vacuum pump connected to an accumulator tank. The accumulator tank was connected to the bottom of the flask through a 5 cm diameter vacuum hose. A plastic membrane was placed on top of the flask to achieve higher vacuum levels. The pressure in the flask was reduced from atmospheric to an approximate 34 kPa for those castings poured with the assistance of vacuum.

The castings were cooled in the flask. The aluminum castings remained in the flask for a minimum of 1 hour, and iron castings remained for at least 2 hours. The instruments and the gating system were then removed from the casting, and each casting was lightly sand blasted to remove the coating.

1.3.3 - Casting Evaluation

All of the castings were inspected for internal and surface defects. The internal defects of interest included porosity, folds, and laps. Porosity in the casting is generally created by entrapped byproducts that did not have the chance to exit the mold. Byproducts left between the metal fronts create a line defect called folds or laps. These byproducts are sometimes pushed to the surface of the mold but are not always absorbed by the coating. The byproducts that are pushed to the edge of the mold will cause surface defects in the casting if they are not absorbed by the coating in a timely fashion.

Sometimes, changing a parameter results in moving a defect from one location to another location in the casting rather than eliminating the defect. The castings were divided into six sections so that each casting could be evaluated by its sections as well as the whole casting. The division of each casting into its sections is shown in Figure 1.3.3.1. The castings were divided in this manner because of symmetry between the left and right side of the casting. The metal was expected to enter from the gating and travel simultaneously on both sides of the flange. Section 1 was the largest section because porosity and fold defects were expected to form at locations where two metal fronts come together and not around the

gating system. For the same reason, section 6 was the smallest because the metal fronts are expected to meet in this section.

The castings were evaluated on the basis of defects present in each section of the casting. The defects were evaluated individually so that if a set parameter introduced a type of defect, this defect was distinguished from other defects. Since these experiments were designed to be range finding, quantifying the results was neither feasible nor necessary. Instead, a score system was developed to evaluate the casting based on the severity of the defect found. A casting with no defects was given a score of 0, whereas the casting with the most severe defect was given a score of 5. Other castings were given a score between 0 and 5 depending on the severity of the defects found in the casting compared with other castings. Each section of each casting was evaluated based on this system. Aluminum and iron castings required slightly different methods of evaluation.

Aluminum castings. Aluminum castings were first inspected using real-time x-ray capability. A certified x-ray operator with experience in detecting defects in aluminum castings performed the x-ray analysis. It was possible for certain types of defects to go undetected if the x-ray analysis was preformed only from one angle. Each casting was x-rayed at three different angles, as illustrated in Figure 1.3.3.2, to insure that no defect would go unnoticed. First, the casting was inspected in the vertical position. The casting was then rotated 30 degrees in the z-axis direction in a standard xyz coordinate system and was inspected again. The casting was then rotated 30 degrees in the y-axis and was inspected again.

The surface defects of the castings were determined by visual inspection. The surface defects were given a general score depending on the amount or the severity of the defects. The aluminum and iron castings were ranked on the same scale. The scale used to rank the castings was determined from the best and worst case scenario as described early. This means if an iron casting was ranked 1, then an aluminum casting with the same amount or severity of defect was also ranked 1, regardless of how it compared with other aluminum castings. Detecting the fold or lap defects with the x-ray analysis was a difficult task since this type of defect was not usually visible with x-ray. The castings were broken into pieces in search for folds after the x-ray and visual inspections were complete. The castings were placed on top of two metal supports and were struck with a sledgehammer. The theory was that the castings should break at locations where defects exist because the defects weaken the casting by introducing stress concentration areas. According to this theory, fractures should occur at the areas with fold defects. The fold defects should be visible at the fracture surfaces if any such defect was present in the casting.

Iron castings. The real-time x-ray machine available did not have enough energy to penetrate through the iron castings. Performing

the x-ray analysis at another facility would have been both expensive and time consuming. It was decided to forgo the x-ray analysis since breaking the casting and inspecting the fracture surfaces should reveal the same information. The iron castings were broken in the same manner as the aluminum castings. But first, the surfaces of the iron casting were visually inspected.

Initial inspection of the castings revealed a different surface defect in the top and bottom surfaces of the casting. The top surface of the casting was referred to the surface that was facing up toward the opening of flask. Both the top and the bottom surfaces of the castings were inspected individually so that a distinction could be made between the types of defects present in both surfaces.

The two major surface defects found in the castings were sand burn on and entrapped pyrolysis products that were pushed to the surface but were not absorbed by the coating. Metal penetration was also detected on the surfaces of some castings. Each section of both surfaces was given a score based on the sand burn on defect and another score based on pyrolysis defects. The casting with the least severe defect was given a score of 1, and the casting with the most severe defect was given a score of 5. Other castings were given a score based on these two extremes. An example of a casting given a score of 1 for sand burn on defect and a score of 1 for the pyrolysis defect is shown in Figure 1.3.3.3. Examples of a casting receiving a score of 3 and a casting receiving a score of 5 for the two defects are shown in Figures 1.3.3.4 and 1.3.3.5, respectively. It was crucial that the scoring be impartial and free of bias. A colleague was asked to join in the evaluation of the castings to help assure a more impartial scoring. This colleague was informed of the types of defect to look for and the scoring system. Both persons had to agree on a score before a score was given to any section of the casting. The data was analyzed and the level of influence of each parameter was determined.

1.3.4 - Results and Conclusions

The results of the data collected by the data acquisition and the casting evaluation are presented and discussed in this section. Since aluminum and iron castings were poured at significantly different temperatures, a direct comparison between the results of the two metals was impractical. Some of the results can be related for both metals, but for most, cases the results of the iron and aluminum castings are discussed separately.

The thermocouple in the center gating indicated the arrival of metal and tracked the temperature of the metal as it passed through the gating. Typical temperature responses of the metal for both aluminum and iron castings is illustrated in Figure 1.3.4.1. The metal temperature for the aluminum castings always included a dip in temperature as the metal first passed by the thermocouple, indicating

that the temperature of the metal front was always cooler than the temperature of the rest of the metal. A dip in temperature profile was not apparent for the iron castings.

The pressure profile of the flask was also recorded using a pressure transducer. The pressure transducer was positioned in the center of the pattern with the help of a 0.6 cm diameter copper tubing. The pressure in the flask for the aluminum castings poured without vacuum remained constant throughout the casting, as shown in Figure 1.3.4.2a. The pressure profile for the iron casting without the vacuum, however, showed a pressure jump of about 0.6 kPa as the metal entered the pattern (Figure 1.3.4.2b). A second pressure transducer was added to some of the castings poured with vacuum assistance. The second pressure transducer was added to investigate the concern about the consistency of the pressure inside the flask, and it was located in the center of the second pattern. The two pressures for the aluminum and iron castings poured with vacuum assistance are illustrated in Figure 1.3.4.3. The average pressure difference for the aluminum castings was 1.623 kPa, and it was consistent throughout the experiment. The average pressure difference for the iron castings was 0.123 kPa.

Aluminum Castings

The results of the aluminum castings poured with a hollow sprue were not used in studying the effects of vacuum. However, the output of the position probes was used to study the effects of coating permeability and pattern density on the metal fill rate since the coating permeability was the dominant parameter in controlling the metal fill rate. The metal fill rate for all aluminum castings poured is shown in Table 1.3.4.1. The metal fill rate increased an average of 112% when the coating permeability was increased from a low permeability of $1.43 \text{ cm}^3/\text{cm}^2.\text{s}$ to a high permeability of $5.34 \text{ cm}^3/\text{cm}^2.\text{s}$. Pattern density also affected the metal fill rate. The average metal fill rate for castings poured with high density (24 kg/m^3) pattern was 3.94 cm/s ; the average metal fill rate increased to 4.43 cm/s when a low density (16 kg/m^3) pattern was used. The effects of the coating permeability and the pattern density are further illustrated in Figure 1.3.4.4. The means and 95% least square differential (LSD) intervals for the high and the low permeability coatings and the high and low pattern densities are plotted in this figure.

The confidence interval indicates with 95% certainty that the metal fill rate would fall within the range shown in the figure if the experiment was repeated with all the parameters held constant. If the range bars shown in a 95% LSD interval plot do not overlap, it is stated with 95% certainty that the parameter directly affects the results. The metal fill rate was directly affected by the coating permeability since the range bars for the coating permeability did not overlap. The pattern density had little impact on the metal fill rate since the 95% range bars overlapped.

The second set of aluminum castings was poured with a solid foam sprue and no metal plug. Analysis of vacuum effect was possible for this set of aluminum castings because half of these castings were poured with vacuum assistance. The metal fill rate, internal defects, and surface defects were studied for this set of castings. The metal temperature and the pressure inside the flask were also recorded. The coating permeability, foam density, and vacuum affected the metal fill rate.

The coating permeability and the vacuum affected the metal fill rate as expected, but the foam density had an opposite effect on metal fill rate than expected. The metal fill rate increased by an average of 42% with the higher density foam. Possible causes of this behavior are discussed later. Metal fill rate increased by 65% for the casting poured with the high permeability coating. Vacuum had the largest impact on the metal fill rate: the application of vacuum increased the average metal fill rate by 123%. The mean and 95% LSD plots for the coating permeability and the vacuum assistance are illustrated in Figure 1.3.4.5. These plots state with 95% certainty that coating permeability and vacuum both affect the metal fill rate.

Defects. Aluminum castings were inspected for surface defects in the same manner as the iron castings. Surface pyrolysis defects were found in the form of blisters in some of the aluminum castings. The blisters were similar to pyrolysis defects in the iron casting with the exception that in aluminum castings the defect was under a thin skin of metal. The blisters were apparent on the top surfaces of all four castings poured with the combination of vacuum assistance and high permeability coating. Blisters occurred only in the castings where both of these conditions were met; all other aluminum castings were free from this defect. High permeability coating aggravated the pyrolysis defect in both aluminum and iron castings. Vacuum increased the pyrolysis defects in aluminum castings but reduced this defect in iron castings.

Vacuum was responsible for increasing another surface defect (sand burn-on). The sand burn-on defect in aluminum castings was not generally as severe as in the iron casting, but the same scale was used to rate the sand burn-on defect in both iron and aluminum castings. The sand burn-on defect for both surfaces of the aluminum castings was similar in the sense that the intensity of the defect gradually decreased from section 1 to section 6. The sand burn-on defect on the bottom surface of the aluminum castings was nearly twice as severe as the top surface, and for this reason, most of the efforts were concentrated on analyzing this defect on the bottom surface of the castings. Vacuum was the largest cause of this defect. Sand burn-on was increased nearly 16 times for the castings poured with vacuum assistance compared with those poured without the assistance of vacuum. Coating permeability had a very small influence on this defect. The average score for the sand burn on defect for castings

with high and low permeability coating was 1.125 and 0.979, respectively, but the effect of coating permeability was not statistically significant.

X-ray analysis was combined with the visual inspection of the broken surfaces to evaluate the internal defects of the aluminum castings. The aluminum castings were broken into smaller pieces, and the fracture surfaces were inspected for internal porosity or other defects. The x-ray analysis revealed a spongy porosity defect in many castings. This porosity defect was always found in section 1 of the casting, close to the gating system. The severity of this defect was rated on the basis of the area covered by the defect compared with the area covered by this defect in other castings. Analysis of the data revealed that the two dominating parameters controlling the porosity defect were the coating permeability and the vacuum assistance. Application of vacuum increased the severity of the porosity defect by 250% according to the average score recorded for the castings poured with and without the vacuum assistance. High permeability coating caused a 36% increase in the severity of this defect.

The internal defects were further investigated by actually breaking the castings and inspecting the fracture surfaces. The castings were broken in such a way that most of the fractures occurred on the sections that included a hole. For this reason, most of the internal defects were discovered in sections 1, 2, 4, and 6. The results were similar to those found for the porosity defects. The castings poured with vacuum assistance had almost 4.5 times more defects than those castings poured without the vacuum. High coating permeability also increased the internal defect by 2.3 times. Foam density was not statistically significant. These results were based on the average score of each casting poured with the indicated parameters. The evaluation of the internal defects was based on the size of each defect compared with other internal defects found in all of the aluminum castings. The average scores given to each section of the aluminum castings for all the defect analysis are tabulated in Table 1.3.4.2.

Iron Castings

The metal fill rate for the iron castings was also calculated by the use of the position probes. The metal fill rate for each iron castings along with the coating permeability, foam density and the vacuum level is summarized in Table 1.3.4.3. The average metal fill rate of all the iron castings was 20.98 cm/s, with the most dominant controlling factor being the coating permeability.

The effects of coating permeability and vacuum assistance on metal fill rate are illustrated in the means and 95% LSD intervals plotted in Figure 1.3.4.6. These plots are illustrated in the same manner as the plot shown for the aluminum castings. The coating permeability plot indicated with 95% certainty that the high

permeability coating resulted in a higher metal fill rate. The average metal fill rate for the iron castings increased by 47% when the coating permeability was increased from 29.39 cm³/cm².s to 91.84 cm³/cm².s. Application of vacuum also affected the metal fill rate. The pressure inside the flask was decreased from atmospheric to approximately 34 kPa, with a corresponding increase in the metal fill rate of 19%.

Foam density with vacuum assistance had an opposite effect on the metal fill rate than expected. Logic suggests that more energy is needed to decompose a higher density foam because there is more foam to decompose. The higher foam densities also generate more byproducts, which again oppose the advancement of metal. According to this logic, metal fill rate should decrease when higher foam density is used, but the metal fill rate increased by 6% with the higher foam density. Perhaps this can be explained by studying the interactions between the parameters. The interaction between the foam density and the coating permeability and the interaction between the foam density and the vacuum are illustrated in Figure 1.3.4.7. The interaction between the foam density and the coating permeability revealed a sharp drop in metal fill rate for the low density foam as the coating permeability was lowered. The metal fill rate for the high density foam was not as greatly affected by the coating permeability. The interaction between the foam density and the vacuum assistance showed a decrease in metal fill rate when vacuum was applied, and the foam density was changed from high to low. The average metal fill rate increased with the decrease in foam density when vacuum was not applied. Although generally higher metal velocities were achieved with vacuum, the metal fill rate for castings poured with high density foams was affected much more by the vacuum than the metal fill rate of the castings poured with low density foams.

Defects. The surface defects for the iron castings were evaluated as described previously. Two major surface defects were discovered in the iron castings. One was the pyrolysis defect that was created by the byproducts surfacing to the top of the mold but were not removed through the coating. The pyrolysis defect was most severe on the top surfaces of iron casting poured without the assistance of vacuum. The second major surface defect was the sand burn on defect. This defect was most evident on the bottom surfaces of castings poured with vacuum assistance. Metal penetration was another surface defect found in most iron casting poured with high permeability coating. Small beads of metal were discovered on both top and bottom surfaces of these castings. The metal penetration was more pronounced in the casting poured with vacuum. Since metal penetration mostly occurred on the casting poured with high coating permeability, the cause of this defect was that the high permeability coating held many small cavities for the gases to travel through, and these cavities provided spaces for the metal to penetrate. Vacuum aggravated this defect by forcing the metal into these cavities.

The pyrolysis defects were concentrated on the top surface of the casting. Each section of each surface for each casting was given a score between 0 and 5 (scoring system is explained in more detail in chapter 5). The average score for the pyrolysis defect for the bottom surface was only 0.021. This low score indicated that not many pyrolysis defects existed on the bottom surface of the castings. However, the sand burn on defect was mostly concentrated on the bottom surface of the casting. The average surface score for each section of both surfaces is listed in Table 1.3.4.4.

Most of the attention was focused on the top surface of the castings for the pyrolysis defects because pyrolysis defects were almost nonexistent in the bottom surfaces. The pyrolysis defect on the top surface was more concentrated in sections with larger surface areas. Sections 1, 3, and 5 hosted more severe pyrolysis defects than sections 2, 4, and 6. The coating permeability and vacuum assistance were the major contributors affecting the pyrolysis defect, whereas the effect of foam density was negligible. The pyrolysis defect increased by 114% with high permeability coating, but it decreased 43% with the vacuum assistance. The liquid capacity for high permeability iron coating was 15.2 % lower than the liquid capacity of the low permeability iron coating. The increase in the pyrolysis defect caused by the high permeability coating was explained by the fact that the coating simply did not have the capacity to hold all of the pyrolysis byproducts generated from the degradation of foam. The pyrolysis products left in the mold created a surface defect. Vacuum helped reduce the pyrolysis defect by forcing the byproducts through the coating into the sand.

Vacuum was not effective in reducing the sand burn on defects. In fact, vacuum increased the sand burn on defect on both top and bottom surfaces of the castings by an average of 592%. Both top and bottom surfaces of the casting followed the same trend as sections that had more sand burn on defect. Because this defect was more severe on the bottom surface, most of the efforts in analyzing the data were concentrated on the data obtained from the bottom surface. The severity of sand burn on defect was gradually decreased from section 1 to section 6 as the metal entered and traveled through the pattern. This trend is illustrated in the mean and 95% LSD interval plot shown in Figure 1.3.4.8. The two major parameters controlling the sand burn on defect were, again, the coating permeability and vacuum assistance. Foam density was not statistically significant according to the data. The interaction between the coating permeability and the vacuum is also illustrated in Figure 1.3.4.8. This plot showed a drop in sand burn on defect with low permeability coating. The average score was higher for the castings poured with vacuum assistance, but the drop in score was much more significant for the castings poured with low permeability coating. This indicated that the sand burn on defect could be reduced with coating control.

The internal defects for the iron castings were studied by breaking the casting. The castings were broken in the same manner as the aluminum castings, and the fracture surfaces were inspected for any internal porosity or folds. The castings were mostly broken in sections 1, 2, 4, and 6 since these sections were suspected to produce more internal defects. This analysis revealed that, again, high coating permeability and vacuum assistance increased the internal defect. High foam density also had a part in increasing this defect, but the most influential parameter was the vacuum assistance. Castings poured with the assistance of vacuum showed an average of 215% more internal defects than those cast without the vacuum. The castings with high coating permeability had 124% more internal defects.

1.3.5 - Summary

This study was designed to be a range finding experiment to develop a simple understanding of the effects of vacuum on lost foam castings. This study provided a basis for evaluating the effects of vacuum; more studies are needed to further develop a better understanding of the vacuum and to investigate vacuum's potential. Forming an overall opinion about the vacuum solely on the results and conclusions of this study would be premature because only one level of vacuum was used for this study. With that in mind, the following conclusions were drawn.

The metal fill rate for the aluminum castings was not greatly affected by the sprue type. However, vacuum assistance increased the metal fill rate in aluminum castings by more than 123%. Application of vacuum also increased the metal fill rate for iron castings. Metal fill rate for both metals was also directly influenced by the coating permeability. Higher coating permeability always resulted in higher metal velocities. Generally, lower foam densities resulted in a higher metal fill rate, but this increase was minor and was not statistically significant. Coating permeability and the vacuum assistance also influenced most of the defects found in the castings. More defects were found in all of the aluminum and iron castings poured with high coating permeability compared with the castings poured with low permeability coating. Vacuum also increased most of the defects except for the pyrolysis defect in iron castings. Surface pyrolysis defects were greatly reduced with the use of vacuum, whereas all other defects, especially the sand burn on defect, were increased by the application of vacuum. The effect of foam density on the formation of defects for most cases was insignificant. The only time that the foam density showed a significant impact was in the formation of internal defect in iron castings. Low foam density reduced the intensity of internal defects found in the iron castings. Generally, the best castings were achieved with the low permeability coating and without the assistance of vacuum.

The conclusions made from these results may be misleading. The studies conducted at the University of Missouri-Rolla showed that a window of metal fill rate exists for each metal that will generate the least defects in castings. In one study the maximum metal fill rate for aluminum casting was 4.14 cm/s and this metal fill rate generated higher surface and other defects. None of the studies conducted on metal fill take into account the effect of vacuum. The effect of vacuum on the metal fill rate was not known at the beginning of this project. This study was designed as a range finding experiments to determine the effect of vacuum. Because the effect of vacuum on metal fill rate was not known, designing this series of experiments to account for vacuum effects was impossible. The use of vacuum increased the metal fill rate as expected, which pushed the metal fill rate above the desired window. Now that the effect of vacuum on fill rate has been investigated and the surface pyrolysis defect in iron castings was reduced with the use of vacuum, the next set of experiments can be designed to have better control on the metal fill rate and reduce other defects with the use of vacuum.

The fact that the surface pyrolysis defects were reduced with the use of vacuum assistance opens the possibility of producing iron castings with greater quality in lost foam process. The potential of vacuum assistance for producing higher quality casting goes beyond iron. Better controls on parameters such as coating permeability, coating thickness, foam density, and the introduction of vacuum assistance can open the doors of lost foam casting process to other metals such as steel.

These conclusions were based on the data obtained from the experiments conducted in this study. It would be wise to continue this study and gather more data before forming an opinion on the performance of vacuum in lost foam castings. A uniform vacuum of approximately 34 kPa was applied to all the castings poured with the vacuum assistance. It would be beneficial to conduct some experiments with lower levels of vacuum. It is recommended to decrease the vacuum level incrementally and continue this study at vacuum levels of 51 kPa, 68 kPa, and 85 kPa.

2.0 - Coating Quality Control

Coating properties remain as the single most used variable in controlling the Lost Foam Process on the production floor. The dominant coating property in controlling casting quality has been identified as gas permeability. Throughout this report, as well as past reports, the physical model of the metal/pattern replacement mechanisms has stressed the importance of coating permeability in removing the gas and liquid by-products from pattern degradation. It is well known on the production floor that variations in coating permeability can create or eliminate a specific casting defect. UMR has verified these observations by production personnel by compiling

data from past and present laboratory evaluations into a summary chart for aluminum castings. Figure 2.1 illustrates that a 'metal velocity window' exists for a specific pattern geometry that yields a minimum of casting defects. This data reveals that metal velocities below this 'window' tend to produce castings with surface collapse and misruns while metal velocities above the 'window' produce metal porosity, folds, metal penetration and surface defects. There is insufficient data to develop a similar chart for iron castings; however foundry experience indicates the 'window' does exist.

Past research has also shown that the dominant factor in controlling metal velocities in Lost Foam castings is coating gas permeability when casting aluminum and coating and sand permeability when casting iron. This occurs as the pattern degrades into gas and liquid by-products as metal replaces the pattern. The gas/liquid ratio for various pattern materials, pattern densities and metal velocities has been presented in Section 1.1 of this report. The gas produced must exit the mold cavity at the same rate as it is generated in order to maintain a constant metal velocity (steady state condition). If the coating permeability is too low a back pressure will build in the zone between the metal front and the receding pattern, retarding the metal progress. Likewise a high permeability coating will provide a lower pressure in this zone, allowing the metal front velocity to increase - up to the limits of the available heat transfer from the metal front (infinite permeability). UMR research has indicated that metal front velocity control is impractical by adjusting gate sizes; therefore coating permeability must be controlled to maintain metal velocities within a 'window' that produces quality castings.

Coating permeability has received the most attention in previous research and this research has led to procedures to measure this property. Two procedures have been developed - a research procedure and a foundry procedure. These procedures have been outlined in a Coating Quality Control Manual and distributed to all sponsors. These procedures have been used by both coatings manufacturers and foundries for the past five years to improve coating properties as dictated by foundry experience, improve the consistency of coating properties to insure consistent casting quality and to explore new theories for coating development. The Research version of the Coating Quality Control Procedures measures physical properties of a coating and has aided the coating manufacturers in quality control of their coating ingredients, specifically particle size and distribution which controls gas permeability and liquid adsorption. The Foundry version of the Coating Quality Control Procedures was developed for use in the foundry to shorten the test procedure while providing the foundry with accurate coating gas permeability. The need for this procedure became apparent over the past years as UAB personnel visited foundries and found that the test time for coatings must be shortened in order to provide timely data in the production process.

Many questions have surfaced concerning the influence of the shearing action of a drawbar on coating structure and permeability, and the effect of various coating drying procedures. These questions have been addressed, evaluated in the laboratory, and included in the Phase III final report and as an appendix to the Coating Quality Control Manual.

Another coating parameter controlling metal velocity is the deposited thickness. The equation below describes the volume rate of gas flow through a layer of coating of thickness (L). The effect of

$$Q = (Bo * A * (Pu - Pd)) / (u * L)$$

where:

- Q = Flow rate (cm³/sec.)
- Bo = Darcy's constant (cm²)
- A = Area (cm²)
- Pu - Pd = Pressure across coating (Dynes/cm²)
- u = Gas viscosity (Dyne - sec./cm²)
- L = Coating thickness (cm)

coating thickness on the volume rate of flow is non-linear as illustrated in Figure 2.2. Note also in this figure that the knee of the curve falls in the range of 0.005 to 0.015 inches of coating thicknesses. This range coincides with the usual deposited coating thicknesses in foundries. Hence the rate at which gas escapes from the mold cavity through is very sensitive to the deposited coating thickness. For example, changing the coating thickness from 0.012 to 0.010 inches causes the gas flow rate to change from 3 to 4 cm³/cm²-sec. At thinner coating thicknesses the sensitivity of gas flow rate to coating thickness is even greater. This points to the fact that deposited coating thickness must be controlled along with the gas permeability.

Typically coating thickness is controlled by adjusting and maintaining coating viscosity. Viscosity of typical Lost Foam coatings is dictated by the rheology built into the coatings and depends on the refractory particle size and distribution, the binder system and the suspension system. Since coatings are typically thixotropic materials (viscosity depends on shear rate), a procedure for measuring coating viscosities has been developed by coating manufacturers and used throughout the Lost Foam industry. This procedure included measuring the viscosity with a Brookfield viscometer (RVF Model) at a spindle speed of 20 RPM using a #3 size spindle. Both spindle speed and size affect the measured viscosity by changing the shear rate and this speed and spindle have proven to give consistent results on most Lost Foam coatings. A typical coating viscosity response to spindle speed (shear rate) is illustrated in Figure 2.3. This figure reveals that at high shear rates the coating viscosity is low and changes only small amounts with changes in shear rate. This characteristic is utilized in the Lost Foam process through constant stirring of the coating tank to reduce the viscosity in order to facilitate the pattern dipping

process. Without stirring pattern beakage could occur. Figure 2.3 also reveals that the coating viscosity increases rapidly as the shear rate is reduced. Again this characteristic is utilized to allow the coating to 'set' and remain on the pattern after withdrawal from the coating tank. As the pattern is withdrawn the shearing action is reduced, allowing the coating to 'set'.

Experience has taught that coatings can, under certain conditions, lose their initial rheological properties so that the typical viscosity/shear rate curve is altered. This phenomenon is illustrated in Figure 2.4 where two coatings have showed viscosity/shear rate behaviors. In some cases, single viscosity measurements at 20 RPM, did not detect the changes. A revised procedure was developed to detect these changes and to better characterize coatings. This procedure included measurements of viscosity at 20, 10 and 5 RPM to better define the coating response at shear rates that are representative of pattern extraction from the coating and thus the amount of coating retained on the pattern. A coating index was defined as the ratio of viscosity at 20 RPM to the viscosity at 10 RPM. This ratio should be about 1.8. Any significant deviation from this ratio would indicate a change in the coating rheological properties. A higher ratio would be accompanied by an increase in wet coating weights and a lower ratio would produce lower wet coating weights and increased drip losses.

This procedure has not been included in the Coating Quality Manual since data is currently being evaluated to assess the value of this discovery.

3.0 - Fill and Solidification Code

At the present time, a Lost Foam simulation code capable of accurate modeling metal fill and solidification and predicting defect formation in LF casting does not exist, either in commercial or research form. The development of such codes is hindered by a lack of understanding and data on the complex mechanism of metal/pattern exchange. The existing codes implement simplified mechanisms of metal/pattern exchange and account only for those factors that are very important. Filling velocity is usually calculated using the metal/pattern interface heat transfer coefficient or empirical formulas deducted from the data on filling of simple-shaped LF castings. Most codes either do not address or unrealistically model the generation and escape of gaseous and liquid degradation products from the mold cavity. Pattern material degradation properties, such as rates of vaporization and liquid production, gas yield, and energy of degradation, used in the calculations are not accurately known for the actual casting conditions since they are either theoretically calculated or approximately estimated from casting simulation experiments. The existing casting simulation codes have had limited

(mostly for the castings of simple geometry) success in modeling the LFCP.

The original plan for developing an accurate fill and solidification model of the LFCP adopted by UAB in Phase III of the project was to simultaneously work on two modeling approaches which included collaborative work with UES Inc. on ProCAST casting simulation software and the development of an in-house research code based on the 2D fill and solidification code written at the University of Missouri-Rolla (UMR) (Bates et al., 1998). UAB has tested the LF capabilities of the existing ProCAST code. Significant modifications have to be made to the LF module of the software to model escape of the liquid and gaseous degradation products from the mold cavity. Work on the UMR code was suspended due to a lack of data and understanding of the mechanism of metal/pattern exchange.

UAB is currently exploring the possibility of collaborative work with Flow Science, Inc. and UES, Inc. to enhance the LF module of each company's heat transfer and fluid and gas flow software. The current version of Flow-3D models advancement of metal in the mold using the user-defined metal/foam heat transfer coefficient and has the capabilities of tracking the liquid pyrolysis products in the metal. UAB has acquired a copy of Flow-3D and is currently testing the software.

3.1 - ProCast Code

UAB personnel performed a verification of the ProCAST LF module on a simple-shaped axisymmetric part. The tests revealed problems with solution convergence and unrealistically predicted metal filling behavior. The model of metal/pattern interaction currently used in ProCAST does not address or properly describe the physical phenomena associated with production and escape of gaseous and liquid pyrolysis products from the mold cavity through the coating and requires significant modifications.

3.1.1 - Thermal Properties of LF Coatings and Foundry Sands

The knowledge of thermo-physical properties of LF coatings and foundry sands is critical to understanding and correct modeling of heat transfer between the metal and the mold during fill and solidification in LF casting. A literature search indicated that accurate property data on this materials is very limited or nonexistent. Therefore, an effort was made by UAB in cooperation with the High Temperature Materials Laboratory at the Oak Ridge National Laboratory in July-August, 1997 to generate this data. A description of the experiments and the generated data were presented in the Phase III final report (Bates et al., 1998). Some additional experimental work and data analysis on the coatings and sands since then is presented below.

3.1.1.1 - Thermal Properties of LF Coatings

Additional experimental work, which included thermo-gravimetric (TG) analysis and scanning electron microscopy (SEM), was done on the coatings to understand physico-chemical changes occurring in the coatings during exposure to high temperatures and to explain the effect of temperature and coating chemical composition on the thermal conductivity. The TG experiments were conducted in the temperature range of 40-800°C using a Mettler TG 50 analyzer which had an upper temperature limit of 800°C. The experiments were conducted in a nitrogen atmosphere using vented alumina crucibles and a heating rate of 10 C/min. Samples of coatings CERAMCOAT™ EP9 510 and SK27 were the same as those used for the specific heat measurements. Samples of coatings CERAMCOAT™ EP9 533 and SK400 were cut from the layers of coatings prepared for the diffusivity measurements and weighed from 21 to 47 mg. Two samples of each coating were tested. The average of two TG curves was used in thermal conductivity calculations. The results of the TG analysis are presented in Figure 3.1.1.1.1.

The TG data was used to calculate coating density as a function of temperature. Because no shrinkage was observed in coatings during preheating and thermal expansion was negligible, the density of the coatings at different temperatures, ρ , was calculated as $\rho = \rho_0 f_{wt}$ where ρ_0 was initial coating density and f_{wt} was weight fraction of original weight at a specific temperature obtained from TG data.

Coating thermal conductivity was recalculated using the new temperature dependent coating density data and the previously measured diffusivity data and the heat capacity data for the preheated coating samples. The specific heat capacity data in the temperature range of RT-100°C and the diffusivity data in the temperature range of 950-1025°C was obtained by extrapolation. The new thermal conductivity values for the coatings are presented in Figure 3.1.1.1.2.

Coatings SK27 and 533 exhibit higher conductivity values while coatings SK400 and 510 exhibit lower conductivity values. The ~50% difference in conductivity between these low and high conductivity groups is explained by the differences in (1) thermal conductivity of solid phases of the coatings and (2) structure of coating solid phases. Thermal conductivity of coating solid phase depends on the conductivity of coating constituents, their relative amounts in the coating, and interphase bonding mechanism. The primary refractory of insulating coatings 510 and SK400 is mica, which has an order of magnitude lower conductivity than silica and aluminum silicate, the primary refractories of coatings SK27 and 533. The structure of the solid phase, i.e. porosity, pore size and geometry, is determined by refractory particle size, shape, and their volume fraction in the coating. The combined effect of the physical and chemical differences between the coatings on thermal conductivity is complex and difficult to determine.

The increase in coating thermal conductivity at high temperatures can be explained by (1) the increased role of thermal radiation in overall heat transfer through the coating and (2) "bridging" between the coating particles, similar to sintering. SEM photographs of the virgin coatings and the coatings after the second differential scanning calorimeter (was used for heat capacity measurements) heating cycle (i.e. exposed twice to 1025°C) were taken to estimate the degree of bridging. Visual analysis of the photographs presented in Figures 3.1.1.1.3-3.1.1.1.10 suggests that only the mica-based coating SK400 experienced significant bridging between the coating particles. The mica/kyanite-based coating 510 also shows some bridging. Bridging in coatings 533 and SK27 was undetectable.

3.1.1.2 - Thermal Conductivity of LF Foundry Sands

3.1.1.2.1 - Experimental Procedure

The thermal diffusivity of unbonded sands could not be measured with the Laser Flash Diffusivity method used for diffusivity measurements of the LF coatings due to the semi-transparency of loose sand to infrared radiation. A different method called the Hot Disk technique was used for thermal conductivity measurements of sands. The Hot Disk technique, a variation of the transient plane source technique, employs a sensor consisting of a thin (~0.01 mm) nickel foil in the form of a double spiral sandwiched between two sheets of insulating material (mica or kapton), see Figure 3.1.1.2.1.1. The sensor is placed in the material of interest. During the measurement a constant current is passed through the sensor for a short period of time which causes a temperature rise of the sensor within 0.5-5°K. The heat generated in the sensor is dissipated into the surrounding material at a rate dependent on the material thermal diffusivity. Material's thermal properties such as thermal conductivity, thermal diffusivity, and specific heat capacity are calculated from the temperature vs. time response of the sensor recorded by the data acquisition system.

Mica-insulated sensors with nickel spirals with a diameter of 13.34 mm were used in the experiments. The highest nominal working temperature of the sensors was 730°C. Heating the sensors above 730°C caused mica insulation to delaminate and loose its strength. It was found that the sensors could be used for conductivity measurements at temperatures above 730°C if they were not disturbed during the tests. Due to the high cost of sensors the thermal conductivity measurements were performed only on three sands--silica, olivine, and mullite 30/50. The results of a sieve analysis of the sands are presented in Table 3.1.1.2.1.1.

Stainless steel crucibles 5 cm in diameter and 8 cm deep with a volume of 150 cm³ were used for holding sand samples. Thermal conductivity was measured at two sand densities--low and high. The low density was obtained by filling a crucible with sand without any

subsequent densification. The high density was obtained by vibrating a crucible filled with sand with a miniature drill having an eccentric weight in the chuck. The frequency of vibration was approximately 20 Hz. Additional sand was added into the crucible during compaction as the sand level receded. The duration of compaction was approximately 30 s, and it was stopped when no further reduction in sand level was observed. The density values for the sands are presented in Table 3.1.1.2.1.2.

The shape of the sand particles had an effect on the degree of densification of sand. Table 3.1.1.2.1.2 illustrates that mullite sand, which has particles of a spherical shape, increased its density during compaction by 6.9% compared to 9.6% for silica and 9.3% for olivine sands, which have angular particles.

The thermal conductivity measurements were made at nominal temperatures of 25°C, 150°C, 300°C, 450°C, 600°C, 750°C, and 900°C, with two measurements made for each sample at each temperature. The samples were heated to the desired temperature in a resistance furnace. Due to exposure to temperatures above nominal (730°C), the sensors had to be discarded after each experiment.

3.1.1.2.2 - Results

Thermal conductivity of silica, olivine and mullite 30/50 sands as a function of temperature for high and low packing density values is presented in Figures 3.1.1.2.2.1-3.1.1.2.2.5. The data suggests that the sand packing density had a noticeable effect on thermal conductivity. For silica and olivine sands, a 9% increase in density increased thermal conductivity by 14-20%. For mullite 30/50 sand, a 7% increase in density increased thermal conductivity by 8-16%. No significant difference was observed between thermal conductivity values for different sands at a given packing density level, as illustrated in Figures 3.1.1.2.2.4-3.1.1.2.2.5.

Comparison of the measured sands thermal conductivity values with the literature data shows that above room temperature the measured conductivity values are significantly higher than the literature values, see Figures 3.1.1.2.2.2, 3.1.1.2.2.3, and 3.1.1.2.2.6. The source of this discrepancy is not known at the present time. More experimental work may be needed to explain the difference.

3.2 - UMR Code

Work on the UMR code was suspended mainly due to a lack of data and understanding about the mechanism of metal/pattern exchange and difficulty of utilizing the TGA and DSC data on EPS and PMMA in the model. At the present time, the experimental approach #1 based on direct measurement of pattern degradation parameters (see final report

for Phase III (Bates et al., 1998) and Section 1.1) seems to be better suited for modeling the LFCP than approach #2 based on the linear pyrolysis model.

3.3 - Summary and Conclusions

The significant results obtained in this task are summarized as follows:

1. UAB personnel tested the LF module of the ProCAST casting simulation software. The tests revealed problems with solution convergence and unrealistically predicted metal filling behavior. Significant modifications need to be made to the program to model physical phenomena associated with metal/pattern exchange. Work on the UMR code was suspended mainly due to difficulties in implementing the modeling approach based on TGA and DSC data. The alternative approach based on using pattern degradation data developed in pyrolysis experiments with the foam pyrolysis apparatus is currently being pursued.

2. Additional experimental work including the TG analysis and SEM was done on the coatings to understand physico-chemical changes occurring in the coatings during exposure to high temperatures and to explain the effect of temperature and coating chemical composition on the thermal conductivity. Coating thermal conductivity was recalculated using the new temperature dependent coating density data and the previously measured diffusivity and heat capacity data. The difference in conductivity between the coatings was attributed to the differences in (1) thermal conductivity of solid phases of the coatings and (2) structure of coating solid phases.

3. The thermal conductivity of three unbonded LF castings sands-silica, olivine, and mullite 30/50-was measured with the Hot Disk technique in the temperature range of 25-900°C in loose and densified states. Thermal conductivity of densified sands was measured to be 8-20% higher than that of loosely packed sands. No significant difference in thermal conductivity between different sands at the same density level was found. The measured conductivity values were significantly higher than the literature values. More experimental work may be required to explain the difference.

4.0 Alternate Pattern Materials

4.1 Introduction

Throughout this research a major effort has been made to characterize existing pattern materials and to identify alternate pattern materials. The currently used pattern materials (Polystyrene-PS, Polymethylmethacrylate-PMMA and Copolymer-CoP) are materials that have previously established markets other than Lost Foam patterns. These markets are typically the food, building and packaging

industries. Polystyrene (PS) is the most commonly used material, consequently the price has been driven down by a competitive market. PMMA is a specialty material that has attractive properties for Lost Foam patterns but the higher price limits its use. CoPolymer is a chemical blend of PS and PMMA developed for Lost Foam as a compromise in performance and price. Typical prices for these pattern materials are: PS - \$1.25/lb., CoP - \$7.00/lb., PMMA - \$11.00/lb. Based on this pricing the Lost Foam Industry has adopted PS as the most commonly used material. PMMA and CoP are used primarily for iron castings and only when the casting demands improved quality and can absorb the increased pattern cost. Both PMMA and CoP patterns provide improved casting quality due to the lower amounts of liquid pyrolysis products. This data was presented in Section 1.1.1.4.

Only one(1) new pattern material has surfaced in the past ten years - Polyalkyldcarbonate (PAC). This material shows promise as a Lost Foam pattern material due to its high gas to liquid ratio during thermal degradation. This material is in the development stage and is available only in small quantities. Efforts to blow patterns using this material have not been entirely successful, experiencing difficulty in pre-expansion and pattern blowing. Pattern quality is currently significantly less than the quality provided by conventional materials.

One major obstacle in using the PAC material in production would be the objectionable odor released during thermal degradation. Although not considered a health hazard this odor would prevent the use of this material in Lost Foam Foundries. Efforts to eliminate the odor and to improve the pattern quality are continuing; however the development time for this material may be years without an increase in effort through financial support by Lost Foam foundries. Even if the technical issues could be resolved, the predicted cost, based on the small usage by Lost Foam foundries, would be as high or higher than PMMA or CoP.

The approach UAB has taken in developing new pattern materials is through the enhancement of the pyrolysis properties of existing materials, specifically the low cost EPS. The Precoat discovery was an eye opener which paved the way for continuing efforts towards this goal. Simultaneously, bead suppliers have experimented with additions to EPS beads which would improve the degradation properties. Oxidizers have been added along with other chemicals to achieve certain results. Some of these additives show promise and will be addressed in a continuing phase of this research. The bottom line is that because the Lost Foam pattern market is small compared to the markets that currently consume the majority of expandable beads, the development of a new and improved polymer with the desired pyrolysis properties is unlikely due to the high cost of development.

4.2 Laboratory Evaluations

In an effort to determine the usefulness of PAC as a Lost Foam pattern material several laboratory procedures were used to characterize the thermal properties. Table 4.2.1 lists the molecular weights of three batches of PAC polymer beads and a typical EPS bead. This data indicates the PAC polymer has a significantly lower molecular weight (Mw) than the EPS polymer. The significance of this difference is the lower molecular weight polymer should require less energy to degrade. The pattern pyrolysis apparatus described in Section 1.1.1.1 was used to determine the gas fraction of this material. Figure 4.2.1 illustrates the gas fraction of the PAC material compared to EPS. This data indicates that the PAC has a gas fraction of about 58% at a metal front temperature of 640°C while EPS has a gas fraction of about 33%. The density of the PAC material was 3.86 pcf compared to about 1.4pcf for the EPS. The PAC material, with its high gas fraction, would most likely produce castings with less pyrolysis related defects than EPS.

TGA and DSC evaluations were also performed on the PAC polymer to compare the thermal degradation behavior. Figure 4.2.2 illustrates the TGA response of PAC and EPS polymers. A significant weight loss occurs about 90 C which should correspond to bead collapse and loss of blowing agent. This observation is confirmed in Figure 4.2.3 which illustrates the DSC response of PAC and EPS polymers. The PAC polymer exhibits two endothermic peaks, the first about 60°C and the second about 90°C. The first peak is probably the glass transition. Figure 4.2.2 indicates that thermal degradation of the PAC material begins about 260°C and is completely degraded at 320°C while the EPS material begins about 320°C and is completely degraded about 430°C. In Section 1.2.1 the DSC response curve revealed that EPS had three endothermic peaks which were identified as: 1) Plasticized glass transition, 2) True polystyrene glass transition and 3) Bead collapse. The DSC response for PAC (Figure 4.2.3) reveals only two endothermic peaks, indicating that this material may not be plasticized by the blowing agent.

Based on the TGA and DSC responses of PAC polymer a general observation would be that pre-expansion and molding of this material would require temperatures below 90°C to prevent bead collapse. In addition the temperatures used in pre-expansion and molding would need to be between 60°C and 90°C, a significantly smaller temperature range than the range used for processing EPS. This probably explains the difficulty encountered by molders in pre-expanding and blowing of patterns. Another observation would be that the PAC polymer would degrade at a lower temperature than EPS, absorbing less heat which would provide a higher metal front temperature. This is in agreement with the lower molecular weight data presented in Table 4.2.1. The higher metal front temperature should aid in filling thin walled castings.

5.0 Casting Distortion

Casting distortion can be generated during several steps of the Lost Foam Process beginning at the pattern molding operation. Pattern growth and shrinkage has been well documented in previous phases of this research, including the effect of pattern warpage due to density differences in various locations, coupled with geometric shapes. This data has been used to machine accurate pattern molds that produce consistent, predicted pattern dimensions. Pattern dimensions are periodically verified with scheduled measurements using a CMM or air gaging system. Other sources of casting distortion can occur as patterns are extracted from the molding machines, stacked or suspended from racks, the racks moved to the drying-aging oven, moved again to the gluing and clustering operation, coated with refractory by dipping, suspended from racks or a conveyor system, dried at elevated temperatures, placed in flasks where sand is added along with vibrational energy to fill cavities and densify the sand, metal poured to replace the pattern and finally casting shakeout. Historically the sand fill and compaction operation has been blamed for the majority of casting distortion and certainly this is justified for patterns that have geometries conducive to distortion by excessive forces during sand filling and compaction. Sand thermal expansion has also been identified as a major factor in casting distortion, causing castings to deform as a result of large forces created by the expanding sand in a confined area. Silica sand, the most commonly used molding media, exhibits a large increase in thermal expansion at a temperature of about 540 C where a phase transformation occurs. Other sands, such as Olivine and Synthetic Mullite have a linear coefficient of expansion significantly lower than Silica. These sands have been proven in Lost Foam foundries to produce significantly less casting distortion.

During this research a major effort has been expended to identify the effects of sand filling and compaction and sand thermal expansion on pattern and casting distortion. This understanding has been passed along to personnel in Lost Foam foundries. Slowly flask acceleration levels have decreased and a few foundries have replaced Silica sand with Olivine or Synthetic Mullite.

In previous research Sheldon³⁰ concluded that pattern distortion was controlled during filling and compaction by 1) flask acceleration level and 2) sand angularity. High flask accelerations produced large pattern distortions and the more angular sands produced higher pattern distortions at the same flask acceleration. These two parameters are not entirely independent since the acceleration level required to fill pattern cavities is a function of sand angularity. Specifically a more angular sand requires higher flask accelerations to achieve pattern cavity filling in the same elapsed time. Later Vatankhah³¹ concluded that these same parameters (flask acceleration level and sand angularity) controlled the time required to fill pattern cavities. A major conclusion from this research was that lower flask accelerations could be used with rounded sands to achieve pattern cavity filling in the same elapsed time required using higher flask accelerations with

an angular sand. Coupled with Sheldon's conclusions, this would allow patterns to be filled and compacted within a given time window with lower pattern distortion.

Aluminum Engine Block Distortion - An aluminum engine block was chosen to test the theories of distortion caused by compaction acceleration levels and sand thermal expansion. This engine was an overhead cam design with a history of high scrap rates due to a non-cleanup condition in the camshaft bores during machining. Three castings each were poured in 356 aluminum using 1.1 g, 1.7 g, silica sand and synthetic mullite. A vertical compactor was used to fill and compact the sands.

Figure 5.1 illustrates the camshaft bore positions in orthogonal directions. These dimensions were measured on each pattern assembly, the castings made and final dimensions were measured on each casting. Figures 5.2 and 5.3 illustrate the camshaft location dimensions on castings produced in silica sand at 1.1 and 1.7 G, respectively. The circle labeled "target" in these figures represents the range of dimensions that will provide enough metal stock for machining cleanup of the camshaft bores. The rectangle labeled "predicted" represents the range of expected camshaft bore dimensions calculated from actual pattern dimensions, less metal shrinkage. The rectangle labeled "casting" are actual measured dimensions for the camshaft bore locations. Several observations can be made from Figures 5.2 and 5.3. First, the "casting" dimension rectangle does not fall within the "target" dimensions, indicating a large scrap rate. Second the "casting" dimension rectangle is significantly larger than the "predicted" rectangle, indicating distortion of the pattern during filling and compaction or during pouring and solidification.

Comparing Figures 5.2 and 5.3, which compares the castings made in silica sand compacted at 1.1 and 1.7 G respectively, the "casting" rectangle for those castings compacted at 1.7 G is larger than the rectangle for castings compacted at 1.1 G. This indicates that higher flask accelerations have generated larger distortions in the pattern. This is consistent with Sheldon's research on pattern distortion.

Comparing Figures 5.4 and 5.5, which compares the castings made in synthetic mullite sand compacted at 1.1 and 1.7 G respectively, the "casting" dimensions appear to be unaffected by acceleration level. This is also consistent with Sheldon's research which indicated that pattern distortions caused by rounded sands are relatively insensitive to flask acceleration level. Note that the range of casting dimensions is significantly less than the range for castings made in silica sand. Although this reduced range could be attributed entirely to reduced pattern distortion during compaction, other experiences in other foundries indicate at least some portion of this reduction can be attributed to the lower thermal expansion of the synthetic mullite. It is obvious that changing this existing process to synthetic mullite

would cause even higher scrap, compared to the silica sand, since the "casting" dimensions fall outside the "target" dimensions; however it should be recognised that the production system had been tuned for silica sand. Tuning for the synthetic mullite would result in a more robust process with lower scrap rates. Tuning would include changing some pattern mold dimensions or altering some section gluing procedures.

6.0 Technology Transfer

Technology transfer between UAB personnel and sponsors occur in the form of meetings held every four months and individual contacts as requested by the sponsors. Five sponsor meetings were held at AFS in Chicago and 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.

Several training courses were taught at participating sponsors' facilities to summarize the research efforts of the past years and to assist in training of plant personnel. This was deemed necessary as Lost Foam continues to grow at a rapid pace. The growth rate of the Lost Foam industry was the subject of a marketing study performed by the University of Wisconsin - Milwaukee and the American Foundrymen's Society, funded by UAB as a part of this research. This survey is included as Appendix B.

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

ACKNOWLEDGMENTS

We wish to express grateful acknowledgment and deep appreciation to the many companies and individuals who participated in the project by providing advice, descriptions of particular difficulties, defects, and guidance regarding the most fruitful areas for investigation.

A special word of thanks goes to Mr. Joe Santner for guidance throughout the project. We also wish to express our appreciation to the Department of Energy for technical assistance and partial funding of the project. Special thanks go to Mr. Bob Trimberger and Harvey Wong. Matching funds from DoE were provided under Cooperative Agreement DEFC07-98ID13603 with Amendments. Matching funds were also provided to the University of Missouri at Rolla by the Missouri Research and Training Center.

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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