ADVANCED PRECISION EXPENDABLE
PATTERN CASTING TECHNOLOGY

1994 SUMMARY REPORT

REPORT TO

THE DEPARTMENT OF ENERGY,

AMERICAN FOUNDRYMEN'S SOCIETY,

and

AFS-DOE-EPC CONSORTIUM MEMBER COMPANIES

DOE CONTRACT NO. DE-FC07-93ID13230

REPORT NO. UAB-MTG-EPC94DOE.SUM

UAB THE UNIVERSITY OF
ALABAMA AT BIRMINGHAM

RECEIVED

MAY 31 1995

OSTI

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

1994 SUMMARY REPORT TO

THE DEPARTMENT OF ENERGY
AMERICAN FOUNDRYMEN'S SOCIETY
AND
AFS-DOE-EPC CONSORTIUM MEMBER COMPANIES

ON

ADVANCED PRECISION EXPENDABLE PATTERN CASTING TECHNOLOGY

University of Alabama at Birmingham
Materials Science and Engineering Department
Metals Technology Group
1016 15th Street South
Birmingham, Alabama 35294-4552

MAY 1995

Report No. UAB-MTG-EPC94DOE.SUM

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ha
MASTER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ADVANCED PRECISION EXPENDABLE PATTERN CASTING TECHNOLOGY

TABLE OF CONTENTS

	<u>Page</u>
Acknowledgements	iv
Summary	1
Task 1. Precision Pattern Production	1
Task 2: Pattern Coating Consistency	2
Task 3: Sand Fill & Compaction Effects	3
Task 4: Pattern Gating	6
Task 5: Mechanical Properties	7
Task 6: Technology Transfer	7
1.0 Precision Pattern Production Gauging (Task 1)	9
1.1 Experimental Materials & Procedures	9
1.1.1. Dimensional Changes During Aging	9
1.1.2. Dimensional Measurements	10
1.1.3. Air Gauge Calibration on Commercial Shaped Parts	11
1.1.4. Test Patterns	11
1.1.5. Pattern Density Measurements	11
1.2 Flange Pattern Production and Aging	12
1.2.1. Natural and Artificial Aging of EPS and Copolymer Flange Patterns	12
1.2.2. Air Gauge R & R on the Flange Pattern	12
1.2.3. Flange Pattern Processing	12
1.2.4. O.D. Shrinkage Summary on EPS and Copolymer Flanges	13
1.2.5. Density Variations in Copolymer Patterns	14
1.2.6. Molding Variable Effects on Pattern Density Gradients	14
1.3 Intercooler Pattern Production and Aging	15
1.3.1. Intercooler Gauge R & R	18
1.3.2. Intercooler Pattern Aging	18
1.3.2.1. Intercooler Length Changes	18
1.3.2.2. O.D. and I.D. Dimensional Changes	21

TABLE OF CONTENTS CONTINUED

	<u>Page</u>
1.4 Iron and Aluminum Intercooler Casting	22
1.5 Conclusions and Recommendations	22
References	24
2.0 Pattern Coating Consistency (Task 2)	25
2.1 Air Flow Apparatus	27
2.2 Liquid Flow Apparatus	27
2.3 Summary and Conclusions	31
3.0 Sand and Compaction Effects	
3.1 Introduction	33
3.2 Basic Fill and Compaction Parameters	34
3.2.1. Clamped and Unclamped Flasks	34
3.2.2. Horizontal and Vertical Compactors	39
3.2.3. Sand Filling and Densification Requirements	42
3.3 Guidelines for Fill and Compaction	47
4.0 Metal Flow and Gating	
4.1 Introduction	67
4.2 Definition of Gating	68
4.3 Reconsideration of Previous Data	68
4.4 Completed Tasks	69
4.4.1. Task 1: Pouring Temperature and Fill Rate	69
4.4.2. Task 2: Effect of Gate Size and Other Process Parameters on Fill in Cast Iron	70
4.4.3. Task 3: Effect of Gating and Other Process Parameters on Fill in Aluminum	70
4.4.4. Task 4: Making the Gating System the Choke	70
4.5 Current Tasks	71
5.0 Mechanical Properties	71
6.0 Technology Transfer	71
LIMITATION OF LIABILITY	73

ACKNOWLEDGEMENTS

We wish to express grateful acknowledgement 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. Dan Twarog 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 Mr. Manohar Sohal. Matching funds from DoE were provided under Cooperative Agreement DEFC0793ID13230 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 EP casting.

Harry E. Littleton
Engineering Manager
University of Alabama
at Birmingham

John Griffin
Associate Engineer
University of Alabama at Birmingham

Don Askeland
Professor
Metallurgical Engineering
University of Missouri at
Rolla

Charles E. Bates
Research Professor
University of Alabama at Birmingham

ADVANCED LOST FOAM CASTING TECHNOLOGY

SUMMARY

Previous research, conducted under DOE Contract #DE-FC07-89ID12869, made significant advances in understanding the Lost Foam Process and clearly identified the areas of research needed to improve the process. This led to the current project focusing on the following areas:

- Task 1: Precision Pattern Production
- Task 2: Pattern Coating Consistency
- Task 3: Sand Fill and Compaction Effects
- Task 4: Pattern Gating
- Task 5: Mechanical Properties of Castings
- Task 6: Technology Transfer and Utilization

This report deals principally with precision pattern production, coating consistency, sand compaction, and gating.

Twenty-eight (28) companies are jointly participating in the current 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. This section of the report summarizes the work done in the past year and the conclusions drawn from the work.

Task 1. Precision Pattern Production

The objective of the precision pattern production task was to determine the parameters that control the precision of foam patterns used in the lost foam process. Casting accuracy is dependent on producing dimensionally accurate patterns and maintaining consistent shrinkage during the aging period.

Pattern dimensional precision is directly related to the bead blowing and curing techniques. Although there appears to be some advantage in initial dimensional stability of patterns produced from copolymer beads over EPS beads, the long-term stability of patterns from all bead types was similar.

The discovery of large density variations within patterns is significant. At least two casting defects in sponsor foundries have been related to extremes in foam pattern density. In both cases,

density gradients were minimized by changing the foam blowing variables, and the casting defects were eliminated.

Density gradients were also found to cause pattern warpage. The effects of pattern blowing variables on density gradients and warpage were examined in several carefully conducted experiments. The results are summarized as follows.

- For dimensional consistency, it is imperative that consistent and reproducible foams and blowing conditions be used.
- Variations in blowing cycle can substantially alter pattern dimensions.
- Demolding after short cooling cycle can produce
 - a. O.D. growth above tool dimensions
 - b. I.D. growth below tool dimensions
 - c. Both
- Density variations were found to be a direct function of the tool temperature variations.
- It is recommended that patterns from each batch be dimensionally analyzed using a calibrated CMM or air gauging system in order to assure dimensional consistency. Only dimensional checks will assure that repeatable dimensions are being achieved.

Details of the experimental procedures used and a more complete description of the observations made regarding the pattern stabilization and distortion are presented in Chapter 1.

Task 2: Pattern Coating Consistency

Several conclusions have been drawn concerning coating properties that control the metal/pattern exchange during pouring. These effects are summarized as follows.

- The coating permeability for gas, especially air, is a major factor controlling the pattern replacement rate by molten metal.
- Air and gas removal from the mold cavity must occur prior to the time that the liquid wets the coating. Wetting the coating by pyrolysis products closes the coating pores.

- Room temperature permeability measurements of coatings are reasonably good measures of permeability. The pores are open until moderately elevated temperatures are reached when liquid pyrolysis products soak into and close the pores.
- Liquid pyrolysis products must be removed at a rate equal to their rate of generation to prevent accumulation at the metal/pattern interface.
- Air/gas flow rates and liquid absorption rates largely control coating performance during pouring.

Based on the understanding of the events occurring during pattern replacement, two apparatuses were developed to measure coating properties that are related to coating performance. These are referred to as the "air flow apparatus" and the "liquid flow apparatus". The air flow apparatus measures the flow of air through a coating of known thickness under a known pressure to determine the characteristic gas flow properties. Similarly, the liquid flow apparatus measures properties related to the ability of the coating to absorb liquid pyrolysis products produced during pattern pyrolysis. The use of these two apparatuses resulted in the following:

- A correlation was found between coating properties and causes of casting scrap in one aluminum foundry. Excessively high permeability was associated with short pour times and porosity in the resulting aluminum castings. Excessively low permeability was associated with long pouring times and laps and misruns in the castings.
- Careful quality control to maintain consistency in the coating resulted in a scrap reduction in one aluminum foundry from seven percent to under one percent.
- Careful tracking of scrap rates in additional aluminum and iron foundries is underway to verify the utility of the coating performance Q.C. procedures.

Details of the experimental procedures and results are presented in Chapter 2 of this report.

Task 3: Sand Fill and Compaction Effects

Both sand fill and sand compaction in pattern cavities must be accomplished without pattern distortion. Improper equipment or equipment use can result in pattern distortion and/or poorly compacted areas (areas of low sand density) that result in metal penetration during pouring. Understanding, controlling, and maintaining

reproducible sand fill and compaction is essential if dimensionally accurate castings with a good surface finish are to be produced. The significant results obtained in this area of study are summarized as follows:

- Flask response to external forces is dependent on its physical structure, geometry, and the amount of sand in the flask and is largely independent of the mode of force input (sine wave or impact).
- The flask serves as the energy transport medium between the compactor table and sand. Even though the drive table may have principally a horizontal or vertical direction of motion, other vibrational modes are introduced into the sand because of flask wall deformation.
- Flasks that are vibrated principally by vertical forces have both horizontal and vertical components introduced by flask wall deformation. The ratio of horizontal to vertical acceleration depends on the ratio of vertical to horizontal flask stiffness, sand density, and the amount of off-axis loading.
- Horizontally vibrated flasks similarly develop vertical vibrational components because of off-axis loading and flask deformation.
- Horizontal vibration moves sand into cavities more quickly than vertical vibration in flasks at equivalent vibrational amplitudes with accelerations above one G .
- Certain operational features are required of both vertical and horizontal compactors employing either clamped or unclamped flasks. Sand densification in the flask and pattern cavities must progress in a systematic manner beginning at the bottom of the flask and moving toward the top. It is generally desirable to have a 2 to 3 inch layer of fluidized sand at the top sand surface, with densified sand below the fluidized layer. Cavity filling occurs from and within the fluidized layer. Densification occurs below the fluidized layer as sand moves downward to decrease the void volume.
- Establishing and maintaining the fluidized layer and densified underlayer requires that the table acceleration be increased as the sand weight in the flask increases. Accelerations must be greater than 1.0 G but not high enough to fluidize the entire sand mass.

- Achieving the proper pattern position and orientation can provide generous rewards in compaction time savings. Since each compactor/flask/sand combination is somewhat different, acceleration maps within representative flasks should be developed.
- Additional gates are sometimes added to patterns to serve as supports to help resist high accelerations. These gates sometimes introduce casting defects such as folds which develop when two metal fronts meet. They sometimes aggravate porosity which can develop in turbulent metal flow fronts that engulf a part of the foam pattern. The root cause of the difficulty may lie in the sand delivery system which has caused the compaction procedure to be in a confused state.
- Procedures have been developed to map accelerations that cause sand flow in flasks. The mapping procedure provides options for pattern placement within flasks to maximize the fill rate of pattern cavities.
- Compaction wave patterns in vertically driven round flasks can be quite complex since force inputs occur at three locations 120° apart. The waves originate at different times because the three input points seldom contact at the same instant in time.
- Filling of pattern cavities and densification within the cavities must be achieved to prevent sand collapse defects at the top cavity surface during pouring. Sand collapse can be minimized or avoided by filling the flask sufficiently slow to allow complete sand migration and compaction before the depth of sand above the cavity becomes too great.
- The discovery of casting distortion caused by sand expansion is significant. Sand expansion not only distorts castings but is thought to be the root cause of most forms of metal penetration defects. Alternate low expansion materials are currently being evaluated for physical and thermal properties which will yield dimensionally accurate castings.

More details of the compaction research are presented in Chapter

3.

Task 4: Pattern Gating

In conventional casting processes, the gating system is designed to control liquid metal flow, and the principles of fluid dynamics are employed to control the metal velocity, mold filling time, and the path taken by the molten metal. By careful engineering of the "plumbing" system, casting defects can be controlled and minimized. Gating system design in these processes typically begins with selecting the choke area to govern the rate of mold filling (metal velocity and filling time), using a gating ratio that is appropriate for the metal being poured, and locating the gates to assure complete filling, minimum erosion, and proper temperature gradients. In these processes, the choke is defined as the smallest cross-sectional area in the gating system and, therefore, it is the choke that controls the rate of metal flow. Generally the risering system must also be designed, in concert with the gating system, to assure a sound casting with a maximum yield.

In the lost foam process, the usual definition of the choke as the region having the smallest cross-sectional area and one controlling metal flow is not appropriate. Instead, the rate of decomposition of the polymer foam and the rate of removal of the pyrolysis products, both liquid and gaseous, control the rate of metal flow into the casting. In lost foam, the "choke" may be either the metal-foam interface (if decomposition of the foam is the limiting step) or the metal-foam-coating interface (if removal of the decomposition products is the limiting step).

The objective of the gating research is to devise a set of principles that can be used to locate and size gates for pouring both aluminum and iron castings. The significant conclusions from this work are summarized as follows:

- There is little or no effect of gate size on pattern fillability or fill time. However, the gate location (top versus side versus bottom) and number of gates (particularly when streams of metal are allowed to impinge) may influence fillability, fill time, and defect formation.
- Fill times and metal velocities were obtained from test castings poured over a wide range of alloys, pouring temperatures, and pattern thicknesses. Statistically designed experiments showed that the coating, the type of foam, the pressure head, and interactions between these parameters are most significant.
- Pattern coating properties that allowed or produced high fill rates typically caused internal defects, or voids, attributed to entrapped foam decomposition products. The shape and progress of the metal front during filling was examined and, while the shape depended to a limited extent on the fill rate, no correlation with defects was found.

- For aluminum poured using a high permeability coating, a critical gate area was found that permits the gate, rather than the foam or coating, to act as the choke. However, the gate could not be made small enough to function as the choke when a low permeability coating was used, and the gate was unreasonably small when a high permeability coating was used. The critical gate size for iron poured using a high permeability coating approached 0.5 in².
- Initial results obtained when pouring aluminum castings indicated that the metal front becomes more uniform when the density gradient in the foam is small, particularly when high permeability coatings are used.
- Higher pouring temperatures and higher permeability coatings permit decomposition products to rapidly pass through the coating into the sand. High loss on ignition values were found in, and when using, low permeability coatings.
- As a by-product of other tests, some information has been gathered on the apparent "thermal gap" or "kinetic zone" at the metal-foam interface. The gap, which includes softening, melting, and decomposing foam is relatively independent of aluminum pouring temperature but is somewhat larger when low permeability coatings are used. The apparent gap is much larger for cast iron. Observations of factors influencing the gap and the significance of the gap will continue to be made as by-products of other tests.

Task 5: Mechanical Properties

Axial fatigue data obtained lost foam cast ductile iron has shown that fracture can initiate at bead intersections on poorly fused patterns. In order to reduce the possibility of this stress concentration point affecting the fatigue data on 356-T6 aluminum and Class 35 Gray Iron, the pattern tool was modified to produce better bead fusion. All test patterns for the current project have been produced with the revised tool.

Class 35 gray iron and 356-T6 aluminum have been selected as materials of greatest interest and specimens have been cast. Axial tensile and fatigue properties and fatigue properties are now being determined.

Task 6: Technology Transfer

Process and product development represents about 65% of the current research on lost foam casting. About 35% of the effort in the last year has involved technology transfer to participants in the consortium project.

Seven meetings were held with individual participants to discuss research applicability to particular company needs. Approximately 32 man days were spent in plants conducting experiments to demonstrate and verify laboratory data in an operating foundry environment. Approximately 144 man days were spent with sponsor groups to present and discuss research results and applicability.

Work is currently underway with seven sponsors to implement coating quality control procedures in plants. While the coating control procedures are being implemented, we are providing independent coating analysis. Scrap costs are decreasing, and companies actively participating in the consortium are financially benefiting from the Advanced EPC (Lost Foam) Technology program.

1.0 PRECISION PATTERN PRODUCTION AND GAUGING (TASK 1)

The first objective of the precision pattern production task was to determine the parameters that control the precision of foam patterns used in the lost foam process. Casting accuracy is dependent on producing dimensionally accurate patterns and maintaining consistent shrinkage during the aging period.

The second objective of this task is to determine the precision of the casting process by measuring the dimensions of castings made from the patterns on various molding systems. The precision of the casting process will be addressed in the next year of the program.

1.1 Experimental Materials and Procedures

1.1.1. Dimensional Changes During Aging. Polystyrene beads contain many small individual cells, and each cell in the raw bead stock contains both liquid and gaseous pentane. During preexpansion, the liquid pentane is flashed to a vapor, and the polymer membranes are heated above the glass transition temperature, softened, and plasticized by the heat. The conversion of liquid pentane to gas causes pentane expansion which causes beads to enlarge. After a short stabilization period, the beads are blown into a tool and reheated with steam. The beads again soften, the gases expand, the liquid pentane present flashes back to a gas, and the beads fuse together. The tool is then flushed with cold water which causes steam condensation in the beads, and the part is cooled prior to ejection from the molding machine.

Foam patterns are almost always "aged" for a period after molding. Part dimensions change rapidly after removal from the molding tool, and aging, which may range from a few hours to several weeks, allows some dimensional stabilization to occur prior to use in making castings.

Two theories have been proposed to explain dimensional changes occurring in parts during aging. The first is that equalization of gas pressure in the beads causes pattern expansion and contraction. The second attributes some of the shrinkage to stress relaxation in the polymer cell structure. Stress relaxation in the cell walls occurs during aging and is accelerated by artificially aging patterns at slightly elevated temperatures.

In addition to pattern deformation associated with molding, ejection, and pattern aging, patterns sometimes warp during and after ejection from the tool. The warpage phenomena has been studied in the past year, and results are described in subsequent sections of this report.

1.1.2. Dimensional Measurements. Making systematic foam pattern processing variations and tracking part dimensions was difficult prior to the development of air gauging systems. Freshly blown foams are soft and easily deformed by the stylus on coordinate measuring machines. Coordinate measuring machines are also relatively slow and require substantial amounts of time to make multiple measurements on multiple foams.

All dimension measurements made on foam patterns in the current project were made with an air gauge system marketed by Matrix Technologies in Muncie, Indiana. The Matrix Technologies' system incorporates primary and secondary air chambers and two critical flow orifices to make dimensional measurements. The primary pressure chamber, referred to as the manifold, is the larger of the two chambers and is located before the first orifice. The primary chamber pressure is controlled by an external regulator set to a predetermined pressure. This chamber pressure stays relatively constant (± 0.05 PSI) during operation.

The secondary pressure chamber is created by the gas volume in the air line between the first and second orifice. The secondary chamber pressure varies according to the amount of air leaving the second orifice.

When the gap between the second orifice and a part is zero, the air flow is shut off. This makes the pressure in the secondary chamber equal the pressure in the primary chamber. When the gap is opened, air flow begins and the pressure in the secondary chamber drops to produce a pressure ratio greater than one.

The system is calibrated by measuring pressure ratios as a function of gap opening. A computer is used to curve fit the data with a polynomial expression. The calibration curve is then divided into segments, and a "look-up" data table prepared that relates gap opening to the measured pressure ratio. The "look-up" table allows quick determinations of the gap opening from the pressure ratio.

Two opposing sensors can be placed a known distance apart to allow a part thickness or length to be measured. When a pattern is placed between the sensors, two gaps are measured. The formula (part thickness = $X - A - B$) applies where X is the total distance between the two sensors, A is the gap between the part and first sensor gap, and B is the second sensor gap. The total distance between the sensors, X , is usually measured during setup with a coordinate measuring machine. If the part moves toward the first sensor, that gap becomes smaller but the second gap becomes larger by the exact amount. This allows part thickness measurements to be made using two transducers independent of the position of the pattern between the transducers.

1.1.3. Air Gauge Calibration on Commercial Shaped Parts. The calibration process used to develop the polynomial that relates the pressure ratio to the gap width is usually developed by mounting a flat smooth plate on a stand in front of an orifice. The plate is backed away from the orifice with a micrometer in carefully measured steps to develop a series of pressure ratios as a function of known gap width.

In practice, foam patterns are usually smooth but the areas of interest do not present flat surfaces perpendicular to the orifices. The lack of flatness may allow air from an orifice to flow by a part with less resistance than provided by a flat plate, and this can cause some deviation in the pressure ratio from the calibration curve. The variance can make it more difficult to establish true part dimensions from the pressure ratios.

In the current study, precise "standards" with known dimensions having the pattern shape and contours were machined from graphite. Graphite was chosen as the standard material since it has a low coefficient of thermal expansion and is unaffected by normal variations in atmospheric humidity. Calibration curves for the foam patterns in this study were developed using the flat plate method. These curves were then verified by making measurements on precisely machined graphite shapes with contoured surfaces.

1.1.4. Test Patterns. Two foam patterns were used in the current study. These patterns are referred to as the flange pattern and the intercooler pattern.

1.1.5. Pattern Density Measurements. During the course of the study, density differences were found within foam parts, and some pattern distortion was attributed to the density differences. In order to study the distortion phenomena, techniques were developed to make accurate density measurements on cut pattern sections.

Density determinations involve measuring the weight and volume of an object. In the current program, all weight measurements were made with a Mettler AE200 analytical balance. When placed on a stable surface in a temperature controlled room, the Mettler has a repeatability of 0.0001 grams and is self-calibrating to ASTM class 1 standards.

Since obtaining uniformly shaped sections of a foam pattern with smooth surfaces is difficult, an immersion technique was needed for determining the volume. The liquid used in the immersion test should be stable, have minimum volumetric expansion as a function of temperature, and have a sufficiently high contact angle that the liquid does not wet and run into small pores on the cut pattern surface. The specimen volume is determined by dividing the buoyant weight of the sample after immersion in the test liquid by the density

of the liquid. This measurement is easily accomplished in practice by suspending a specimen from a harness attached to the balance. The buoyant weight is read directly from the balance, and the liquid density is known from pycnometer measurements made on the liquid.

1.2 Flange Pattern Production and Aging

1.2.1. Natural and Artificial Aging of EPS and Copolymer Flange Patterns. A flange pattern was used to examine the effects of natural and artificial pattern aging. The pattern was a ring which consisted of a 11.30 inch outside diameter (O.D.) with a 6.14 inch inside diameter (I.D.) bore. In addition, eight bolt holes were equally spaced around the flange. Two fill guns were used to fill the pattern tool at the locations indicated. The inside diameter of the pattern tool ranged from 6.140 inches in the 0° - 180° direction to 6.142 inches in the 90° - 270° orientation. The outside diameter was 11.300 inches in both orientations.

1.2.2. Air Gauge R & R on the Flange Pattern. A gauge reproducibility and repeatability (R & R) study was performed on the air gauge used to measure the flange foam patterns. Reproducibility reflects the measurement variation introduced by multiple machine operators and repeatability reflects the measurement variations associated with the machine and one operator. In order to perform an R & R study, multiple machine operators must measure the same dimensions on the same parts at least two times.

Gauge R & R was determined using two different procedures. The first procedure consisted of using three operators who measured ten foam patterns two times each. The gauge R & R ranged from 0.00081 to 0.0024 inches. The total gauge R & R is the spread that covers 99% of the measurement variation due to the combination of operator and machine.¹

In order to remove any variations that might be caused by part-to-part variations, another gauge R & R was calculated. A single part was measured two times by three different machine operators. The gauge R & R measured using this procedure ranged from 0.0010 to 0.0028 inches.

1.2.3. Flange Pattern Processing. The purpose of the experimental series on the flange pattern was to establish the effect of natural and artificial aging on the aging shrinkage of EPS and copolymer patterns. A target shrinkage of 0.3% from cold tool dimensions was sought. All patterns were blown on a machine which used vacuum to assist in cooling and water removal from the patterns.

The volatiles content (in both the raw beads and the preexpanded beads), fill pressure, fill time, blow-back time, chest-purge time, cross-steaming time and pressure, autoclaving time and pressure, dwell

time, duration of the water spray, duration of vacuum application, and the demolding temperature for both types of beads were considered in the experiment.

Approximately 80 parts were blown in each group of patterns. Each part was serialized and time stamped as it was extracted from the blowing machine. Parts were delivered to the dimensional analysis laboratory as soon as possible after production. A time lapse of about two hours occurred between blowing and the first dimensional measurements.

After the first dimensional measurements, the batch of foams was broken down into groups of ten parts each, and each group was either naturally aged at room temperature or artificially aged at 125°F or 150°F. The artificial aging periods were 2, 4, 6, 7, 8, 9, and 10 hours in a recirculating air furnace. After a group of parts had been artificially aged for a particular time at the elevated temperature, they were removed from the furnace, cooled to room temperature (80°F) and measured. Subsequent dimensional measurements were made after additional aging at room temperature. Parts were not returned to the furnace for further artificial aging after the initial elevated temperature aging period.

Dimensional measurements were made on both the inside diameter (I.D.) and outside diameter (O.D.) in the 0° - 180° direction and the 90° - 270° direction. The O.D. and I.D. percentage difference from the cold tool dimension in both directions was plotted as a function of time after ejection from the mold.

1.2.4. O.D. Shrinkage Summary on EPS and Copolymer Flanges.

Observations made regarding the outside diameter shrinkage occurring during natural and artificial aging of flange foam patterns at 125 or 150°F, are summarized as follows:

1. Very little change was seen in the copolymer flange O.D. dimension during aging at an elevated temperature.
2. Increased time at artificial aging temperatures progressively decreased the EPS flange O.D.
3. The shrinkage from the tool dimensions associated with artificial aging of EPS foams was higher for any given aging time than the shrinkage observed at room temperature.
4. The outside diameter shrinkage of the flange patterns was uniform in both the 0 to 180° direction and the 90 to 270° direction.

1.2.5. Density Variations in Copolymer Patterns. There was a difference in I.D. dimensions in the copolymer patterns between the 0 - 180° and the 90 - 270° directions. This difference suggested some internal nonuniformity in the material. Systematic studies were undertaken to determine the cause of these differences. The focus of these studies centered on density variations in the pattern that could account for differences in shrinkage behavior. Density measurements were made using the immersion technique described in Section 1.1.5. Density data was obtained as a function of circumferential and radial position in copolymer patterns. Fill guns were located at 0° and 225° orientation.

Observations regarding the I.D. shrinkage associated with aging of copolymer patterns are summarized as follows:

1. The I.D. shrinkage from the tool dimension was never as great as the O.D. shrinkage.
2. The I.D. of the pattern always had a higher density than the O.D., and this higher density was associated with less pattern shrinkage.
3. The shrinkage was not symmetrical on the I.D. circumference. The initial pattern shrinkage was always greater in the 0 to 180° direction which had a lower pattern density. The shrinkage was lower in the 90 to 270° direction where pattern material generally had a higher density.
4. A through-thickness density gradient existed in the flanges.

1.2.6. Molding Variable Effects on Pattern Density Gradients

The following general concepts can be used to explain the density gradients observed in both the copolymer and EPS flange patterns. The bottom half of the mold was fixed and cooled with water sprays. The cores used to form the flange bolt holes were a part of the bottom press-fit ring that formed the flange center cavity. The tool operation consisted of filling the tool, cross-steaming the cavity, autoclaving, spraying water on the bottom tool, applying vacuum to the chest for 25 seconds, and demolding.

The I.D. bore of the flange pattern had the highest density because of the thermal mass of the ring that formed the flange center hole. This ring had no direct cooling; and hence, when heated, it stayed hot and allowed bead compression and densification to occur for a relatively long period during the molding and cooling cycle.

The bottom of the tool stayed hot for an intermediate time because it was cooled for only six seconds with a water spray. Since the water ran off the tool, residual water was unavailable to aid

adiabatic cooling that otherwise would have occurred when the vacuum was applied.

The top of the tool cooled more quickly than either the ring insert or the bottom because condensed water was present on top of the tool that began to boil and cause evaporative cooling when a vacuum was applied. This water would boil at a temperature of 160°F under the applied vacuum of 5 psia.

The density variations in both the EPS and copolymer patterns are in direct relation to the times that the tool temperature was above the pattern glass transition temperature. The center core was hot for the longest time, followed by the bottom tool half and finally by the top tool half. The densities were highest on the flange I.D. followed by the flange bottom, the flange top, and finally, by the midwall except under the fill guns. These density gradients result in distortion gradients as parts were demolded and cooled to room temperature.

1.3. Intercooler Pattern Production and Aging.

The foam patterns for this portion of the study were oil intercoolers which consisted of a barrel-shaped part with parallel-end flanges and two side flanges to allow injection and extraction of the oil and the coolant. The objectives of the intercooler experimental matrix were (1) to determine the dimensional aging response of EPS having different raw bead sizes and expanding agents and (2) produce test castings with these patterns in different compactors in order to correlate distortion with compactor operation.

The experimental bead matrix is illustrated in Table 1.1, and the machine operating conditions used during blowing are given in Table 1.2. The desired process variables included the bead type, bead size distribution, and degree of surface fusion. The air gaging system previously described was used to track the dimensional changes of selected patterns as a function of time after foam blowing.

All of the materials were expanded in a pre-expander using steam. After ejection of the beads from the pre-expander, they were screened, blown into a bag and aged, and then transferred through the plant bead distribution system to the machine set up to blow intercooler patterns.

As each part was blown, a unique label was applied indicating the foam batch number, individual part number in the batch, and the time the part was blown. Dimensional changes were measured and reported as a function of lapsed time after blowing.

Three bead types were used: 1) EPS, 2) Copolymer, 3) a special EPS bead. Patterns were produced using the EPS beads and blown to

TABLE 1.1

BEAD BLOWING MATRIX OIL INTERCOOLER

<u>Batch Number</u>	<u>Bead Description</u>	<u>Pattern Density (pcf)</u>	<u>Surface Description</u>
1	EPS	1.3	Normal Surface
2	EPS	1.3	Highly Fused Surface
3	EPS	1.6	Normal Surface
4	EPS	1.6	Highly Fused Surface
6	Copolymer	1.45	Normal Surface
7	Special EPS Unscreened	1.3	Normal Surface
8	Special EPS Unscreened	1.6	Normal Surface
9	Special EPS -35+40 mesh	1.3	Normal Surface
11	Special EPS -35+45 mesh	1.3	Normal Surface
13	Special EPS -40+45 mesh	1.3	Normal Surface
14	Special EPS -40+45 mesh	1.6	Normal Surface

TABLE 1.2

INTERCOOLER CYCLE SEQUENCING

<u>Cycle Sequence</u>	<u>Duration</u>	<u>Pressures</u>	<u>Utility</u>
1) Press in open position	N/A	N/A	N/A
2) Preheat cavity	4 seconds	18 psig	Steam
3) Manual blow out	10 seconds	35 lbs.	Air
4) Press close	N/A	N/A	N/A
5) Pulls extend (Upper & Lower)	2 seconds	100 lbs	Air
6) Pulls extend (Sides)	1 second	40 lbs	Air
7) Filling with beads	8 seconds	45 lbs	Air
8) Mold Purge	3 seconds	18 lbs	Steam
9) Cross Steam (Upper and lower pulls and moving side chest)	6 seconds	18 lbs	Steam
10) Fusion steam (All chest and pulls)	12 seconds	18 lbs	Steam
11) Pause (Hot)	2 seconds	N/A	N/A
12) Cooling	12 seconds	80 lbs	Water
13) Aging	25 seconds	N/A	N/A
14) Transfer	1 second	30 lbs	Air
15) Pull retract (Sides)	1 second	40 lbs	Air
16) Pulls retract (Top & Bottom)	2 seconds	100 lbs	Air
17) Transfer (2)	1 second	30 lbs	Air
18) Press open (slow with air)	1 second	30 lbs	Air
19) Press open (Fast)	N/A	N/A	N/A
20) Part eject with Air (Stationary side)	2 seconds	25 lbs	Air
21) Cycle Complete	N/A	N/A	N/A

densities of 1.3 and 1.6 pcf. Patterns were blown with both normal and, in some cases, well-fused surfaces. The change in surface fusion was accomplished by changing the steam dwell time.

Copolymer beads were used to blow patterns to a density of 1.45 pcf with a normal fused surface. Four different special EPS raw bead size distributions were used including an unsieved bead similar in size to EPS beads. Patterns were produced with a normal fused surface using the special beads with densities of 1.3 pcf and 1.6 pcf.

Measurements on the patterns consisted of O.D. and I.D. measurement at 90° intervals around the circumference at two positions along the length. In addition, the length was measured in four places at 90° intervals. The inlet flange flatness was measured at four positions.

1.3.1. Intercooler Gauge R & R. The gauge repeatability and reproducibility was determined using two techniques. The first procedure consisted of taking ten foams and measuring each foam three times using three different machine operators. The results are presented in Table 1.3 for the dimensions of interest. For these dimensions, the gauge R & R ranged from 0.024 to 0.034 mm. The percent tolerance consumed (PTC) for these dimensions ranged from 1.2 to 1.7% where the tooling tolerance was 2.0 mm for diameter dimensions and 8.0 mm for length dimensions. The gauge R & R defines the spread that covers 99% of the measurement variation due to the combination of machine (repeatability) and operator (reproducibility).

Again, in an attempt to remove any measurement variation introduced by part-to-part variations, a gauge R & R study was conducted. One part was measured two times by three different operators. The gauge R & R ranged from 0.013 to 0.022 mm as shown in Table 1.4. PTC for these dimensions ranged from 1.0 to 5.7.

1.3.2. Intercooler Pattern Aging. Dimensional changes in these patterns over about ten weeks of natural aging at room temperature were measured. In general, the patterns were extracted from the tool with a shrinkage about 0.1% to 0.2% below the tool dimension. Initially, the patterns expanded to about 0.5 to 1.5% larger than the tool dimension, then they began to contract.

1.3.2.1. Intercooler Length Changes. After aging for 100 hours (6000 minutes), the patterns blown with 1.3 pcf EPS beads having a normal surface fusion were approximately 0.1% under the tool dimension. The patterns blown with 1.3 pcf EPS beads having a more highly fused surface and the 1.6 pcf EPS beads with both normal and highly fused surfaces were about 0.2% beneath the cold tool dimensions when extracted from the tool.

TABLE 1.3

GAUGE R & R ON SELECTED INTERCOOLER PATTERN DIMENSIONS

	<u>OD LEFT X</u>	<u>ID LEFT X</u>	<u>1:00 LENGTH</u>
Reproducibility (mm)	0.0053	0.0042	0.012
Repeatability (mm)	0.024	0.030	0.032
Gauge R & R (mm)	0.024	0.031	0.034
61 PTC* (%)	6.2	7.9	2.2

*percent tolerance consumed

TABLE 1.4

GAUGE R & R ON SELECTED INTERCOOLER PATTERN DIMENSIONS

	<u>OD LEFT X</u>	<u>ID LEFT X</u>	<u>1:00 LENGTH</u>
Reproducibility (mm)	0.005	0.0010	0.012
Repeatability (mm)	0.012	0.020	0.008
Gauge R & R (mm)	0.013	0.022	0.015
20 PTC* (%)	5.7	3.3	1.0

*percent tolerance consumed

A slightly different behavior was observed in the aging of the patterns blown with both the copolymer and special EPS beads. Most of these patterns were demolded with a length dimension about 0.1 to 0.2% below the mold tool dimension. During aging at room temperature, the patterns blown with the special EPS beads expanded to approximately 0.2% above the cold tool dimension, and then began to shrink to a value near the cold dimension over a four day period. However, the patterns blown with copolymer beads only expanded to approximately the cold tool dimension.

The dimensional data obtained for the intercooler pattern also indicate some variations in both the demolded pattern dimensions and initial pattern growth. The patterns produced with a highly fused surface blown from EPS 1.3 pcf beads had a much narrower dimensional spread. Similarly, the patterns blown with the higher density 1.6 EPS beads exhibited a much narrower dimensional spread with both normal and highly fused surface conditions. The higher density EPS patterns had a short plateau of dimensional stability after demolding.

The length dimension of all patterns blown with special EPS beads was very consistent and exhibited less spread than observed in EPS 1.3 pcf patterns.

Although the initial portions of these growth/shrinkage curves were quite different, all of the bead types exhibited quite small dimensional differences after 3000 hours (18 weeks), with the exception of the EPS patterns molded with the higher density of 1.6 pcf. Beads with both normally and highly fused surfaces exhibited considerably more shrinkage. The implication is that foundries purchasing patterns from foam molders must allow for aging to fit the casting dimensional requirements.

1.3.2.2. O.D. and I.D. Dimensional Changes. The growth and shrinkage behavior of intercoolers was examined in the radial direction using the same procedure used for axial dimensional changes. Significant differences were found in the aging behavior between the barrel I.D. and O.D. for EPS 1.3 pcf beads having a normal surface fusion. The O.D. dimension behaved in a manner similar to the length in that it came out of the tool with an O.D. approximately equal to the tool, expanded to a diameter above the tool diameter and then began to shrink. The pattern I.D. came from the tool about 0.8% below the tool diameter, expanded slightly, and finally shrunk to a diameter about 1.2% beneath the tool core diameter after about a week.

Similar results were obtained on the O.D. left x and I.D. left x positions of more highly fused EPS intercooler patterns. Again the O.D. expanded to values above the tool O.D. before beginning to contract. The I.D. was about 1% beneath the tool bore when ejected, expanded some and then contracted to a value about 1% beneath the tool bore in about a day and stayed at that value for about 10 weeks.

A summary of the average dimensional changes on the intercooler at the I.D. Left X and O.D. Left X positions for each of the experimental beads after two, four, and six weeks aging time is presented in Table 1.5. In general, the I.D. dimension was about 0.8 to 1% smaller than the tool dimension while the O.D. was about 0.1 to 0.2% smaller than the tool after four to six weeks aging.

The fact that the I.D. of the pattern is so much smaller than the I.D. of the tool is thought to be a result of the fact that there is no cooling on the tool I.D. In the absence of tool I.D. cooling, the pattern I.D. may be still hot and capable of expanding inward when it is ejected off of the I.D. mandrel. The addition of cooling water to the tool I.D. should eliminate the excess shrinkage and produce an I.D. with much more consistent measurements.

1.4. Iron and Aluminum Intercooler Castings.

Castings will be poured using the intercooler patterns using a compaction cycle suggested by UAB personnel. Dimensional accuracy of these castings will reflect the overall process accuracy.

1.5. Conclusions and Recommendations

Pattern dimensional precision appears to be directly related to the bead blowing and curing techniques. Although there appears to be some advantage in initial dimensional stability of the copolymer bead over EPS, the long-term stability of all bead types is similar. Bead curing dramatically affects dimensional accuracy.

The discovery of density variations within a pattern is significant. At least two casting defects in sponsor's foundries have been related to extremes in density within foam patterns. In both cases, density gradients in the foams were corrected by processing changes on the foam blowing machine, and the casting defects were eliminated.

TABLE 1.5

DIFFERENCES BETWEEN INTERCOOLER PATTERN DIMENSIONS
AND TOOL DIMENSIONS AT SELECTED POSITIONS
AFTER 2, 4, AND 6 WEEKS AGING

Pattern Material	Pattern Difference From Tool Dimensions (%)					
	2 weeks		4 weeks		6 weeks	
	ID L.X.	OD L.X.	ID L.X.	OD L.X.	ID L.X.	OD L.X.
EPS (1.3 pcf) normal	-1.10	-0.05	-1.15	-0.20	-1.20	-0.30
EPS (1.3 pcf) fused	-0.90	-0.05	-1.00	-0.20	-1.05	-0.30
EPS (1.6 pcf) normal	-0.90	0	-0.95	-0.15	-1.00	-0.20
EPS (1.6 pcf) fused	-0.85	0.10	-0.90	-0.10	-0.90	-0.20
Copolymer (1.45 pcf) normal	-0.75	0.20	-0.80	0.05	-0.85	-0.05
Special EPS(1.3 pcf) normal	-0.75	0.10	-0.80	-0.10	-0.85	-0.30
Special EPS(1.6 pcf) normal	-0.80	0.10	-0.85	-0.10	-0.90	-0.20
Special EPS(1.3 pcf) normal	-0.80	0.10	-0.90	-0.10	-0.95	-0.20
Special EPS(1.3 pcf) normal	-0.80	0.10	-0.85	-0.10	-0.90	-0.20
Special EPS(1.3 pcf) normal	-0.80	0.10	-0.85	-0.10	-0.90	-0.20
Special EPS(1.6 pcf) normal	-0.80	0.10	0	-0.10	-0.90	-0.10
Special EPS(1.3 pcf)	-0.95	-0.55	-1.10	-0.60	-1.15	-0.65

REFERENCES

1. Barrentine, Larry B. Concepts for R & R Studies. Milwaukee:

2.0. PATTERN COATING CONSISTENCY (TASK 2)

The pattern assembly operation is complete when the pattern is attached to the sprue and gating system to form a complete cluster. Before the cluster can be poured with liquid metal, however, it must be coated to develop a refractory shell, the shell dried, the assembly placed in a flask and surrounded with sand, and the sand compacted to provide support during pouring.

Pattern coatings contain several ingredients including the refractory filler, dispersant, binder, thixotropic agent, and carrier. Coatings are liquid thixotropic mixtures of components usually suspended in a water carrier with refractory being the primary constituent. The permeability of the coating is principally controlled by the size, size distribution, and shape of the refractory used in the coating. The refractories commonly used are silica, alumina, zircon, chromite, and aluminosilicates such as mullite and pyrophyllite.

The refractory particles are typically held together with one binder to provide adhesion and cohesion before drying and a second binder to provide strength after drying and during pouring. In addition to the binders, the system may also include suspension agents for the refractory and surfactants to insure that the coating will wet and coat the pattern. Coating formulation, application, and control are important in the success of the EPC process.

The coating and surrounding sand can be considered as the mold which contains the casting during and after pouring. Several requirements are placed on the coating and sand under these conditions. The coating must have sufficient bond strength when dried to withstand abrasion by the sand during the compaction process. Coatings in general do not have sufficient mechanical strength to withstand the hydrostatic forces of the liquid metal, and consequently the compacted sand must support the coating. Inadequately compacted sand and/or insufficiently filled and compacted pattern cavities lead to mold wall collapse followed by metal penetration into the sand. Inward mold wall collapse can also occur when excessive coating permeability allows a large gap to form between the advancing metal and the pattern. Other casting defects such as laps, folds, and metal porosity can occur if the coating has insufficient capacity to remove the liquid degradation products from the pattern prior to solidification. The coating must be carefully formulated and controlled in order to achieve these requirements.

The ability of a coating to allow pyrolysis products to escape is generally referred to as its permeability. Iron castings are poured at temperatures of about 2500°F, and permeability to gases and liquids is quite important. Aluminum castings are poured at about 1400°F, and

the coating may need to provide more liquid permeability to allow high molecular weight liquid products to be absorbed.

Coatings for aluminum castings have a different formulation from those used for iron castings. The decomposition of the foam during pouring of aluminum is the dominant source of heat loss to the advancing metal front. Coatings for aluminum castings must be thermal insulators to minimize the second major source of heat loss which is conduction through the coating into the sand. Without sufficient insulating characteristics of coatings, the metal along thin walled aluminum castings freezes before the pattern cavity can be filled with molten metal. Inadequate surface insulation often results in laps, folds, and incomplete fill as the metal is depleted of sufficient heat to allow fill and fusion with metal in other portions of the mold.

There are presently no rules for selecting the best coating for a particular casting. Coating selection is a trial and error process sometimes based on past experience. Once a basic formulation has been tried, minor variations in the mixture may be made to modify or optimize the coating viscosity and application thickness for specific products. The final control on the selected coating is usually solution Baumé, solids content, and application weight. Variations in coating density are included in most coating evaluations to insure the results obtained relate to the conditions likely to be encountered during use.

The target coating thickness is typically in the range of 0.010-0.020 inch (0.25-0.50 mm). Higher pouring temperatures and higher metal head pressures make the thicker coatings more appropriate. Permeability for liquids and gases must be maintained even in thick coatings. Weighing clusters before and after the coating is dry allows a determination of the dry coating weight. This is one of the more informative measurements of coating uniformity and consistency.

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

The objective of the coating consistency task in the current project is to develop procedures for monitoring coating properties that control the metal/pattern exchange and to determine the variability of some existing commercial coatings. Coatings for aluminum and iron casting are of primary interest. Ultimately the

objective is to provide operating foundries with measurement procedures that can be used to monitor and control coating properties. In addition, these procedures are intended to assist the coating manufacturers in developing and maintaining consistent properties in products supplied to the industry.

The kinetic events of the metal/pattern exchange process have been examined in previous studies. The resulting physical model is illustrated in Figure 2.1.

Certain conclusions have been drawn concerning the properties of coatings that control the metal/pattern exchange, and these are summarized as follows.

1. The coating permeability for gas, especially air, is a major factor controlling the pattern replacement rate by molten metal.
2. Air and gas removal from the mold cavity must occur prior to the time that the liquid wets the coating. Wetting the coating by pyrolysis products closes the coating pores.
3. Room temperature permeability measurements of coatings are reasonably good measures of permeability because the pores are closed at moderately evaluated temperatures when the liquid pyrolysis products soak into the pores.
4. Liquid pyrolysis products must be removed at a rate equal to their rate of generation to prevent accumulation at the metal/pattern interface.
5. Air/gas flow rates and liquid absorption rates are properties that control the coating performance during pouring.

Based on this understanding of the events occurring during pattern replacement, two apparatuses were developed to provide coating property measurements. These are referred to as the "air flow apparatus" and the "liquid flow apparatus".

2.1 Air Flow Apparatus

The air flow apparatus was developed to measure gas flow rates at various pressures. The resulting data is used to calculate two physical constants, A_0 , the tortuosity coefficient, and B_0 , the viscous coefficient. These coefficients are used in classical flow equations to calculate the gas and air flow rates at various pressures through coatings of various thickness.

2.2 Liquid Flow Apparatus

FIGURE 2.1 – PHYSICAL MODEL OF METAL/PATTERN INTERFACE

A liquid flow apparatus was developed which records the real time weight of liquid absorbed into a coating, driven by external pressure and capillary pressure. In practice, the external pressure is produced by the head pressure of the metal during pouring. Capillary pressure is always present as a naturally occurring phenomenon. Typical pressures during the aluminum casting process range from 1 to 3 psig and typical measurements during iron casting process range from 1 to 5 psig. Capillary pressures are dependent on pores sizes and are typically 0.5 psig to 2.5 psig.

A typical coating response is illustrated in Figure 2.2. The non-linear portion of this curve is a result of capillary and pressure driven flow of liquid into the coating pores. When the coating pores are filled, the curve becomes linear as flow is controlled by the rate of liquid flowing through the coating. The important feature of the weight/time response in Figure 2.2 is the initial slope. This slope provides a measure of the rate at which liquid pyrolysis products (LPP) can be removed from the mold cavity during the metal-pattern exchange.

A study of coating variability was conducted over a four-month period using weekly samples from six foundries. Data on coating property variability was collected. Significant variations in air flow rates and liquid absorption rates were seen in each coating. These variations are related to the incidence of casting defects including laps, folds, and porosity. In general, low gas permeability leads to laps, folds, and misruns because low permeability causes slow mold fill. High permeability leads to gas defects because the associated rapid metal fill rates cause LPP entrapment and pyrolysis to gas products which produce gas defects in castings.

The coating and liquid permeability procedures were applied in an extensive series of experiments in one aluminum foundry. Increased coating consistency resulted in reducing casting defects from 7% to a consistent 1%. These techniques were also used to isolate the coating as the cause of a sudden scrap increase in an iron foundry.

The research version liquid absorption rate apparatus is very sensitive to vibration and cleanliness and is probably not suitable for use in most foundry laboratories.

As a consequence, a simpler apparatus and procedure was developed that consists of placing a disk of the coating of known thickness on the surface of a container of olive oil. Olive oil has approximately the same viscosity and density as the LPP. The dry weight and saturated weight of the disc provide a measure of open porosity and total LPP absorptive capacity. The time required to achieve saturation provides a measure of the rate of LPP absorption by the coating.

FIGURE 2.2 - TYPICAL WEIGHT/TIME RESPONSE FOR A COATING

FILE: HEL - 123R4W/FILES/COATINGS/MKMILIQ1.WK4

These data can be used in conjunction with the physical constants determined in the air flow apparatus to calculate the liquid absorption rate caused by both capillary and pressure driven flow. These calculations are based on coating model with all pores having the same length and radius. Although this model does not represent a real coating, the results of the analysis agree quite well with measured coating response as illustrated in Figure 2.3. The calculated pore size, pore length, and number of pores represent an ideal coating that produces the same air flow and liquid absorption response as the coating being evaluated.

2.3 Summary and Conclusions

1. Procedures have been developed to accurately measure the rate of air flow (permeability) through coatings used to produce both aluminum and iron castings.
2. A correlation was developed between coating properties and causes of casting scrap in one aluminum foundry. Excessively high permeability was associated with short pour times and excessive porosity in the resulting aluminum castings. Excessively low permeability was associated with long pouring times and laps and misruns in the castings.
3. Careful quality control to maintain consistency in an aluminum coating resulted in a scrap reduction in one aluminum foundry from seven percent to under one percent.
4. The coating quality control procedures have been extended to coatings used on iron castings.
5. Careful tracking of scrap rates in additional aluminum and iron foundries is being done at present to verify the utility of the coating performance Q.C. procedures.

FIGURE 2.3 - COMPARISON OF MEASURED LIQUID ABSORPTION AND CALCULATED LIQUID ABSORPTION IN A COATING MATERIAL

FILE: HEL - 123R4W/FILES/COATINGS/MKMILIQ1.WK4

3.0 SAND AND COMPACTION EFFECTS

3.1. Introduction

A cluster or tree of foam patterns is ready to be backed up with sand in a flask after it has been coated with a thin layer of refractory and thoroughly dried. The sand fill and compaction cycle must result in filling all pattern passages and compacting this sand in all positions inside and outside the pattern to provide support and rigidity during pouring.

Vibration during flask filling has two specific objectives. The first is to cause sand flow into pattern cavities, and the second is to compact the sand in all areas of the flask and pattern to produce a rigid mass with sufficient stiffness and density to resist the metal and gas pressures developed during pouring. During cavity filling, the fluidized and flowing sand has a density in the range of 93-98 pounds per cubic foot (pcf). During densification, it is desirable to increase the sand density to a value in the range of 103-108 pcf depending on the exact sand being used. Sand must continually migrate from upper regions of the flask into cavities as densification occurs.

Both fill and compaction must be accomplished without pattern distortion. Improper equipment or equipment use can result in pattern distortion and/or poorly compacted areas (areas of low sand density) that result in metal penetration during pouring. Understanding, controlling, and maintaining reproducible sand fill and compaction is essential if dimensionally accurate castings with a good surface finish are to be produced.

The duration of the sand fill and compaction cycle is principally controlled by the time required to fill internal pattern cavities. Sand densification occurs rapidly inside these cavities, but considerable amounts of time may be required to get sand to flow into the cavities. There is always a desire to minimize fill and compaction time to maximize the number of flasks that can be filled and poured each hour. This sometimes causes operators to use fast fill cycles with high table accelerations which cause rapid sand migration at the expense of inadequate compaction.

High accelerations cause sand fluidization and migration but do not produce sand compaction except perhaps near the bottom of a flask or in certain cavities. The use of high accelerations to achieve rapid migration and fill of cavities must be tempered with the need for lower accelerations after cavity filling is complete to densify pattern cavities.

Historically, developing the fill and compaction cycle for each new pattern cluster was based on cumulative employee experience and trial and error. Castings are typically poured after compacting patterns with various rates of fill, table accelerations, acceleration dwell times in certain flask sections, etc. When castings with acceptable accuracies, precisions, and surface conditions are achieved, the cycle for that part and cluster configuration is recorded for future use. This process works and continues to be used, but it often requires considerable amounts of time to develop the correct cycle, analyze and qualify the castings produced, and make changes in the tree arrangement or cycle to achieve consistent and acceptable results.

The objective of this task of the Lost Foam Project is to extend the understanding of sand fill and compaction to minimize pattern and casting distortion. In achieving this objective, a need developed for some instrumentation and methodology that could be used to advance the understanding and reduce the time and cost of qualifying new parts for production. This report outlines some approaches to filling these needs. This will be done in the context of the operation of the two major types of compaction equipment.

This discussion is divided into two main sections. The first deals with basic fill and compaction parameters in clamped and unclamped flasks including:

1. sand motion in flasks during vibration,
2. forces involved in horizontally and vertically vibrated flasks, and
3. requirements for achieving sand migration and densification.

The second section provides guidelines for controlling the important fill and compaction variables.

3.2. Basic Fill and Compaction Parameters

3.2.1. Clamped and Unclamped Flasks. All horizontal compactors operate with clamped flasks, and most vertical compactors operate with unclamped flasks. The availability of different flask and compactor designs has raised questions about which design provides the most rapid and efficient sand migration and compaction. The basic question to be answered is not whether the flask is clamped or unclamped, but how does the sand respond to the cyclic loading in the two types of flasks. Since the flask is the structure through which input forces are transmitted to the sand, it is desirable to understand the flask response to externally applied forces before dealing with sand migration within the flask.

Flask response to external forces is dependent on its physical structure, geometry, and the amount of sand in the flask and is largely independent of the mode of force input (sine wave or impact). A flask deforms during vibration in many directions, but the deformation is greatest in the low stiffness direction. This principle is mathematically stated in Equation 1 which describes natural vibration of elastic bodies.

$$f = N^2 \times (EI/W)^{1/2} \quad (1)$$

where: f = Flask natural frequency (Hz)
 N = Boundary conditions of body
 EI = Flexural rigidity (lb-in²)
 W = Weight per unit length (lb/in)

This equation indicates that the natural or resonant frequency (f) of a structure increases as the square root of the flexural rigidity (EI) increases and implies that any structure will vibrate under the influence of a suddenly applied force.

The amplitude of vibration is described by Equation 2.

$$A = Gg/(2\pi f)^2 \quad (2)$$

where: A = Amplitude (in.)
 G = Number of g's acceleration
 g = Acceleration of gravity (in/sec²)
 f = Frequency (Hz)

Combining Equations 1 and 2 yields Equation 3 which describes the vibrational amplitude in terms of the physical structure:

$$A = GgW/(4\pi^2 N^4 EI) \quad (3)$$

This equation predicts that a body with a suddenly applied external force will vibrate at an amplitude proportional to the inverse of its stiffness. In the case of a structure with an unsymmetrical geometry, the direction of maximum vibrational amplitude is the direction of least stiffness. Vibrations at lower amplitudes will occur in other directions having higher stiffness values.

Equation 3 predicts that a cylindrical flask will vibrate with a larger amplitude across its diameter compared to a direction along its vertical axis. A square flask similarly vibrates with a larger amplitude across the top compared to a direction along its vertical axis. In both cases, the transverse vibrational amplitude is greater near the open top compared to the flask bottom because of the lower flexural rigidity near the top.

These vibrational predictions have been confirmed by measurements made on both bench scale and commercial round and square flasks. The maximum flask deformation occurred horizontally as illustrated in Figures 3.1 and 3.2 for round and rectangular flasks, respectively. The flask deformation pattern was independent of the type of force input, i.e., the applied forces could be a result of either impact or sine wave loading. More importantly, the flask deformation pattern did not change with the direction or the location of the input force.

The importance of this vibrational phenomena is that vertically and horizontally driven compactors have both horizontal and vertical vibrational components introduced by flask wall deformation. These vibrational components are superimposed on the compactor table motions. One table may be more efficient than another in fluidizing and compacting sand, but the direction of flask vibration is largely controlled by flask geometry and stiffness in particular directions.

Vertical compactors produce high vertical accelerations in the sand, but associated horizontal accelerations may be much higher. The ratio of horizontal to vertical accelerations depends on the ratio of vertical to horizontal flask stiffness, sand density, and the amount of off-axis loading. Off-axis loading occurs as the table pedestals contact the flask at positions remote from the axis of symmetry. Typical natural frequencies are in the range of 1500 Hz in the vertical direction and 300 Hz in the horizontal direction in commercial round flasks. Higher natural frequencies imply higher flask stiffness.

The addition of sand to a flask has a significant damping effect on vibration. As sand is added, the flask vibrational frequency approaches the frequency of the input force, but the pattern of flask deformation does not change, i.e., the vibrational amplitude is still highest in the low stiffness direction.

The significance of the flask wall deformation can be seen in both round and square flasks during vibration. Sand movement in a round flask on a vertical compactor occurs upward along the flask centerline and downward at the flask walls while the sand is fluidized. Sand movement in horizontal compactors similarly occurs upward along the flask centerline and perpendicular to the direction of vibration.

These phenomena are a result of the flask wall deformation patterns illustrated in Figures 3.1 and 3.2. The inward deformation of opposite walls transfers compression waves into the sand which travel toward the flask center. When these compression waves meet, the sand moves in the least restricted direction, which is upward toward the free sand surface. At 90° to the compression wave, the flask walls move outward creating areas of lower sand density near the flask wall at that location. Hence sand flow occurs toward the walls,

Figure 3.1. Deformation of Empty Flask Walls from Impact Loading on a Round Flask.

616-189a

Figure 3.2. Deformation of Empty Flask Walls from Impact Loading on a Square Flask.

but the velocity is not as high as the vertical velocity because the side walls produce some restraint to the flow.

3.2.2. Horizontal and Vertical Compactors. The flask serves as the energy transport medium between the compactor table and the sand and transfers energy from the table into the sand in a predictable manner. Even though the drive table may have principally a horizontal or vertical direction of motion, other vibrational modes are introduced into the sand because of flask wall deformation.

Flask deformation can be amplified beyond normal ringing when vertical accelerations above 1.0 G are used, because the impact loading on the pedestals produces rotational moments on the flask. This occurs as the flask impacts the table at a point off of the combined flask plus sand center of gravity.

Horizontal flask accelerations of 20 G have been measured in flasks vibrated on vertical tables operated with vertical accelerations of 2.0 G. These high horizontal accelerations create compression waves in the sand and produce the sand flow patterns illustrated in Figure 3.3.

A horizontally vibrated square flask produces elliptical flow patterns as illustrated in Figure 3.4. Sand flow occurs upward along the flask centerline as the compression waves converge along a plane perpendicular to the direction of table vibration.

Both square and round flasks have some areas where local sand acceleration values are low. Such areas have been mapped inside flasks with accelerometers. Cavities in foam patterns in the dead zones were found to fill quite slowly.

Foam pattern cavities in a round flask on a vertical compactor fill considerably faster when:

- (1) the cavity openings are positioned near the flask wall,
- (2) the cavity openings face the wall; and
- (3) the openings are positioned halfway between the pedestals.

Cavities filled about twice as fast on horizontal compactors as on vertical compactors when the same frequencies, orientations, and accelerations were used so long as the accelerations were above 1.0 G. In both vertical and horizontal compactors, the pattern cavities filled more slowly when located in the dead zones, and when oriented such that cavity openings were not perpendicular to the direction of high amplitude flask wall movement.

616-189b

Figure 3.3. Flow Pattern in a Vertical Unclamped Flask.

616-189c

Figure 3.4. Flow Pattern in a Horizontal Clamped Flask.

Horizontal vibration moves sand into cavities more quickly than vertical vibration in flasks vibrated above 1.0 G. On a vertical table, sand is accelerated upward by the table but accelerated downward by gravity (1.0 G). The downward motion of the sand is controlled entirely by gravity while the upward motion is controlled by the acceleration imparted by the table. The upward acceleration tends to compact the sand, but the downward free fall motion may result in some loss of density. If the vertical displacement is too high, the sand may not recompact under the influence of gravity.

During horizontal vibration, sand grain movement occurs as a rubbing, tumbling action in both directions of motion. Gravity assists the nesting of sand grains, and nesting occurs as the table moves in both vibration directions. Less time is required to migrate, fill, and densify the sand at equivalent frequencies and flask amplitudes.

Although horizontal vibration would appear to be more efficient in filling and compacting sand, the flask geometry, pattern geometry, and sand flow patterns must also be considered. Horizontally vibrated flasks are typically rectangular which places some restrictions on pattern placement. Patterns with internal cavities must be placed with cavity openings facing the active flask walls to minimize the filling times. More pattern placement options exist in round, vertically vibrated flasks since there are three active flask walls.

3.2.3. Sand Filling and Densification Requirements. Sand densification has been studied in vertically and horizontally vibrated flasks using both bench scale and commercial compactors. Fill and compaction gauges, schematically illustrated in Figure 3.5, were used to measure the rate of sand flow and compaction. This gauge produces a voltage output proportional to sand density and can be used to determine when a pattern cavity is filled with sand and when sand has been densified. A typical calibration curve is illustrated in Figure 3.6.

The output voltage from the density gauge decreases from about five volts when the gauge contains no sand, to a value of about 1.5 volts when the cavity is filled with sand at a density of about 95 pcf. The voltage output further decreases to about 1.25 volts as the sand density increases to about 108 pcf. With these gauges, the rate of sand movement and densification inside pattern cavities can be examined in response to various compactor frequencies, accelerations, acceleration directions, and durations.

Compaction gauges have been placed inside cavities of a foam pattern as schematically illustrated in Figure 3.7. This pattern has a vertical cavity with one vertical opening and two horizontal cavities. One horizontal cavity is near the pattern bottom, and the second is near the top with openings oriented 90° apart. These patterns have

Figure 3.5. Sand Fill and Compaction Gauge.

HL74

616-080

Gauge Calibration

616-109

+ Gauge #3 Predict. — Gauge #3 Actual * Gauge #5 Predict.
 Gauge #5 Actual □ Gauge #2 Predict. — Gauge #2 Actual

Gage

Figure 3.6. Calibration of Density Gauge.

616-186

Figure 3.7. Top View of Flask with Fill Gauges and Deflection Strips.

been placed in flasks, the flasks filled, and the sand compacted using vertically and horizontally clamped compactor tables schematically illustrated in Figures 3.8 and 3.9. Typical sand densification curves obtained using vertical and horizontal vibration at a frequency of 50 Hz and an acceleration of 1.0 G are illustrated in Figures 3.10 and 3.11, respectively.

Sand density in all three pattern cavities as a function of time during vertical compaction is illustrated in Figure 3.10. The top vertical cavity was filled during rain-in and compacted to a density of 110 pcf almost immediately. Neither the top horizontal nor the bottom horizontal cavity filled with sand using 50 Hz, 1.0 G, vertical vibration.

The densification of sand in the same pattern using horizontal vibration is illustrated in Figure 3.11. The top vertical cavity was filled during rain-in and immediately compacted to a terminal density of about 112 pcf. The bottom horizontal cavity started filling after about 7 seconds of vibration and was completely densified after about 75 seconds. The top horizontal cavity never completely filled under these conditions because it was oriented 90° to the direction of vibration.

The rate of densification at 50 Hz and 2.0 G acceleration in vertically and horizontally vibrated flasks is illustrated in Figures 3.12 and 3.13. Again, the horizontal cavities filled more quickly with horizontal vibration than with vertical vibration. This data helps support an earlier statement that horizontal vibration is more efficient in achieving sand movement than vertical compaction at a given frequency and acceleration.

It was observed that the bottom horizontal cavity (oriented in the direction of table motion) filled more quickly than the top horizontal cavity. This was a result of the flow of sand toward the flask center from the excited flask wall. The bottom horizontal cavity was oriented to take advantage of this directional flow. This data also supports previous comments about active and dead areas in the flask and indicates that pattern orientation and position can be quite important in achieving cavity fill and compaction.

The rate of fill and sand densification in the same pattern cavities at a frequency of 50 Hz and an acceleration of 3 G is illustrated in Figures 3.14 and 3.15. The trends are the same as previously described, but the cavity fill and densification rates were higher at the higher acceleration value.

An important observation can be made by comparing the horizontal compaction data in Figures 3.13 and 3.15. The sand, accelerated at 2.0 and 3.0 G, caused sand to migrate into the pattern cavities and be densified. Sand densification occurred only after the cavities were

filled and the vibrational amplitudes within the cavities were restricted or modulated by the cavity walls. This suggests that fluidized sand surrounding the pattern cavity may not be densified. Some densification of the surrounding sand may occur as the compactor is shutdown at the end of the compaction cycle. This occurs as the frequency and amplitude of the drive table decreased. This late stage compaction is usually undesirable because directional sand motion associated with settling can cause pattern distortion.

Figure 3.16 illustrates the density of sand as a function of time after being quickly added to a flask. Densification occurred from bottom to top of the flask. Sand had to flow downward toward the bottom of the flask to fill the reduced void space as the sand toward the bottom was densified. This process can result in considerable sand motion and has been observed to cause pattern distortion.

The distortion of a crankshaft during compaction is illustrated in Figure 3.17. These distortion curves, obtained at three locations along the shaft length, were obtained by placing an instrumented strip on the crankshaft centerline, bonding the two pattern halves together over the strip, coating the pattern, placing it in a flask, and running a normal fill and compaction cycle.

A significant amount of distortion occurred shortly after the compaction process began and again as the compactor table was shutdown. The initial distortion was a result of initial stages of sand migration as densification began. The final distortion occurred during compactor shutdown as the sand above the pattern settled as the table ramped down.

3.3. Guidelines for Fill and Compaction

Certain operational features are required of both vertical and horizontal compactors employing either clamped or unclamped flasks. Sand densification in the flask and pattern cavities must progress in a systematic, controlled manner beginning at the bottom of the flask and moving toward the top. This requirement is schematically illustrated in Figure 3.18. It is generally desirable to have a 2 to 3 inch layer of fluidized sand at the top sand surface, with densified sand below the fluidized layer, and have these layers move in a controlled manner from flask bottom to top to facilitate cavity filling. Cavity filling occurs from and within the fluidized layer. Densification occurs below the fluidized layer as sand moves downward to decrease the void volume.

Establishing and maintaining the fluidized layer and densified underlayer requires that the table acceleration be increased as the sand plus flask weight increases. Accelerations must be greater than 1.0 G but not high enough to fluidize the entire sand mass.

616-189

Figure 3.8. Schematic Bench Scale Vertical Compaction Apparatus.

616-188

Figure 3.9. Schematic Bench Scale Horizontal Compaction Apparatus.

Figure 3.10. Vertical Vibration-Sine Wave-50 Hz-1 G.

616-189d
F50HVS1D

Figure 3.11. Horizontal Vibration-Sine Wave-50 Hz-1 G.

616-189e
F50HHS1

Figure 3.12. Vertical Vibration-Sine Wave-50 Hz-2 G.

616-189f
F50HVS2

Figure 3.13. Horizontal Vibration-Sine Wave-50 Hz-2 G.

616-189g
F50HHS2

Figure 3.14. Vertical Vibration-Sine Wave-50 Hz-3 G.

Time (seconds)

616-189h

F50HVS3D

Figure 3.15. Horizontal Vibration-Sine Wave-50 Hz-3 G.

The sand addition should be controlled by a raingate that can deliver sand to produce flask fill rates not exceeding about 1.5 inches/second if maximum surface fluidity and in-depth densification are to be achieved. For patterns with large cavities that must be filled through relatively small openings, the sand addition must be halted when the sand level is 2 to 3 inches above the opening. This can be accomplished through sand weighing systems built into the compactor and the use of programmed raingates.

Achieving the proper pattern position and orientation can provide generous rewards in time savings. Since each compactor/flask/sand combination is somewhat different, acceleration maps within representative flasks should be developed.

Most sand delivery systems deposit sand into a flask at relatively high rates, without providing sufficient time for cavity filling and densification. Once the sand is in the flask, cavity filling deep in the sand can only be accomplished with relatively high accelerations, typically 3 to 4 G. Although high G levels aid sand migration and cavity filling, sand may not be adequately densified in and around the pattern. Low density regions allow casting mold wall movement and loss of dimensional accuracy.

Additional gates are sometimes added to patterns to serve as supports to help resist high accelerations. These gates sometimes introduce casting defects such as folds which develop when two metal fronts meet. They also sometimes aggravate porosity which can develop in turbulent metal flow fronts that engulf a part of the foam pattern. The root cause of the difficulty may lie in sand delivery system which has driven compaction procedures into a confused state.

The understanding of sand flow and densification has resulted in procedures to map the accelerations that cause sand flow in flasks. The mapping procedure provides options for pattern placement within flasks to maximize the fill rate of pattern cavities. During this process of flask mapping, a variety of natural frequencies were encountered. This data provided a perspective of compaction modes and improved the understanding of the compaction process.

There are two basic modes of vibration. The first mode consists of almost total sand fluidization accompanied by mounding of sand at the flask centerline. In round flasks, the mounding was produced as sand flowed upwards along the centerline, outward on the free surface, and down along the flask wall. In the square flask, the mounding occurred on a line across the flask perpendicular to the direction of forced vibration. In all cases, the round flasks were unclamped and vertically driven, and the square flasks were clamped and horizontally driven.

Figure 3.16. Sand Densification From Top to Bottom of Flask.

Figure 3.17. Crankshaft Distortion During Compaction

616-189j

Figure 3.18. Fluidized Layer Filling of Cavities.

The sand addition should be controlled by a raingate that can deliver sand to produce flask fill rates not exceeding about 1.5 inches/second if maximum surface fluidity and in-depth densification are to be achieved. For patterns with large cavities that must be filled through relatively small openings, the sand addition must be halted when the sand level is 2 to 3 inches above the opening. This can be accomplished through sand weighing systems built into the compactor and the use of programmed raingates.

Achieving the proper pattern position and orientation can provide generous rewards in time savings. Since each compactor/flask/sand combination is somewhat different, acceleration maps within representative flasks should be developed.

Most sand delivery systems deposit sand into a flask at relatively high rates, without providing sufficient time for cavity filling and densification. Once the sand is in the flask, cavity filling deep in the sand can only be accomplished with relatively high accelerations, typically 3 to 4 G. Although high G levels aid sand migration and cavity filling, sand may not be adequately densified in and around the pattern. Low density regions allow casting mold wall movement and loss of dimensional accuracy.

Additional gates are sometimes added to patterns to serve as supports to help resist high accelerations. These gates sometimes introduce casting defects such as folds which develop when two metal fronts meet. They also sometimes aggravate porosity which can develop in turbulent metal flow fronts that engulf a part of the foam pattern. The root cause of the difficulty may lie in sand delivery system which has driven compaction procedures into a confused state.

The understanding of sand flow and densification has resulted in procedures to map the accelerations that cause sand flow in flasks. The mapping procedure provides options for pattern placement within flasks to maximize the fill rate of pattern cavities. During this process of flask mapping, a variety of natural frequencies were encountered. This data provided a perspective of compaction modes and improved the understanding of the compaction process.

There are two basic modes of vibration. The first mode consists of almost total sand fluidization accompanied by mounding of sand at the flask centerline. In round flasks, the mounding was produced as sand flowed upwards along the centerline, outward on the free surface, and down along the flask wall. In the square flask, the mounding occurred on a line across the flask perpendicular to the direction of forced vibration. In all cases, the round flasks were unclamped and vertically driven, and the square flasks were clamped and horizontally driven.

FLASK WITH HIGH
NATURAL FREQUENCY

Vibration Input

(A)

FLASK WITH LOW NATURAL
FREQUENCY (FLEXIBLE)

Vibration Input

(B)

Figure 3.19 Basic Modes of Vibration in (A) Stiff and (B) Flexible Horizontally Driven Rectangular Flasks.

Figure 3.20. Accelerometer Placement in Horizontally Vibrated Square Flasks.

SETUP
01:57:22

GRP TIME
4 CH TIME

QUAD
INP

VW 80DB
DG X1

CH ABCD
WTG H

FR 2KHZ

H

4

V

-4

LIN

4

-4

4

V_F

-4

4

-4

A

2

B

2

C

2

D

2

0
.021875 SEC

NORM

A:

LNK1

-.509 V

BASE

ΔT .195m SEC

.20000
SPEC EXP N 0

VIB
↑
↓

H
F

Figure 3.21.

Compressive Wave Propagation through Sand inside a
Stiff, Horizontally Driven Flask.

H

Figure 3.22. Compressive Wave Propagation through Sand inside an Unstiff Horizontally, Driven Flask.

Figure 3.23. Deformation of a Cylindrical Flask with Low Natural Frequency (Flexible).

and compaction before the depth of sand above the cavity becomes too great.

4.0 METAL FLOW AND GATING

4.1 Introduction.

Ray Monroe, in his book, Expendable Pattern Casting, describes several design considerations for an effective gating system in lost foam casting. These include:

- assure no damage to the mold during filling
- assure no damage to the metal during filling
- permit the polymer decomposition products to escape in a timely manner
- assure that the cavity fills completely
- serve as a riser to assure a sound casting
- support the casting cluster, including providing proper orientation in the flask, minimizing distortion of the pattern, and helping to handle the cluster during the overall process

The decomposition of the polymer and removal of its decomposition products are particularly influential in assuring complete filling and the production of sound, defect-free castings.

In conventional casting processes, the gating system is designed to control the flow of the liquid; the principles of fluid dynamics are employed to control the metal velocity, the mold filling time, and the path taken by the molten metal. Consequently, by careful engineering of the "plumbing" system, casting defects can be controlled. Gating system design in these processes typically begins with selecting the choke area to govern the rate of mold filling (metal velocity and filling time), using a gating ratio that is appropriate for the metal being poured, and locating the gates to assure complete filling, minimum erosion, and proper temperature gradients. In these processes, the choke is defined as the smallest cross-sectional area within the gating system and, therefore, it is the choke that controls the rate of metal flow. Generally the risering system must also be designed, in concert with the gating system, to assure a sound casting with a maximum yield.

In the lost foam process, however, engineering of a suitable gating system must consider different factors; the principles of fluid dynamics are no longer as critical. In fact, the usual definition of the choke as the smallest cross-sectional area and as the controlling factor in metal flow may not be appropriate. Instead, the rate of decomposition of the polymer foam and the rate of removal of its decomposition products, both liquid and gaseous, control the rate of metal flow. In lost foam, the "choke" may be either the metal-foam interface (if decomposition of the foam is the limiting step) or the

metal-foam-coating interface (if removal of the decomposition products is most critical).

In addition to controlling the rate of filling in conventional processes, the gating system is intended to properly distribute liquid metal into a mold cavity, assuring low turbulence and preventing impingement of metal streams. In lost foam, the gating system must still satisfy these requirements. For example, multiple gates and impinging streams increase the likelihood that foam decomposition products may be trapped within the casting. Furthermore, decomposition products may be directed by a well-controlled metal stream into the least harmful locations. For example, the path of the metal front may be designed by an appropriate gating system, to direct residual decomposition products that cannot be absorbed by the coating into the gating system, rather than allow them to be trapped in the casting.

The emphasis of the current research in mold filling is to continue to develop an understanding of how the processing variables influence the disposition of decomposition products and result in a clean, sound casting. This requires an understanding of the mechanisms by which decomposition products are eliminated from the system, how the metal flow (including metal front velocity, fill time, and metal front profile) assists or detracts from transfer of decomposition products, and finally how gating systems can be designed to achieve the appropriate metal flow.

4.2 Definition of Gating.

"Gating provides for the efficient flow of the molten metal into the mold cavity". Therefore the gating system must deliver metal at an optimum rate that will assure complete filling of the mold without causing damage to the metal by turbulence. If this definition for gating in the lost foam process is accepted, gating requires a careful design not just of the traditional sprue, runners, and gates, but also, matching of the rate and mechanisms of foam decomposition and residue transfer with the profile of the liquid metal front. Gating in lost foam becomes an exercise not just in fluid dynamics, but also in heat and mass transfer.

4.3 Reconsideration of Previous Data.

In previous research supported by the Department of Energy, the American Foundrymen's Society, and the industrial consortium, a considerable effort was made to develop a physical model to explain how the foam pattern decomposes and the decomposition products are transported through the coating into the molding sand. Many of the process parameters that are inherent to the lost foam process were deliberately varied to determine their effects on fillability (the

ability of the molten metal to completely displace the foam pattern), fill time, and metal front velocity. Some work was also done to relate the model to the formation of casting defects, particularly in a series of aluminum alloys. In some cases, the gating system was selected as one of these process variables; however relatively little emphasis was given to gating in these earlier tests.

Based on a variety of experiments, for both aluminum and cast iron, it was apparent that the filling time, metal velocity, and fillability are nearly independent of the size of the gates. The number of gates may not significantly affect filling time or metal velocity unless other variables are properly controlled. Multiple gates can lead to defects, such as laps, where two metal streams meet.

Fill times, metal velocities, fillability, and many casting defects are more closely related to the mechanism and rate at which the foam decomposes and the decomposition products are removed from the system. Consequently, the type of foam, size and geometry of the pattern, nature of the coating, pouring temperature, metallostatic pressure, and other casting variables exert a more profound effect on mold filling than does gate size. More recent research, to be discussed next, confirms these observations.

4.4 Completed Tasks

Several tasks have been completed and a number of others initiated. Completed projects include (1) a survey of metal velocities over a very broad temperature range, with variations in coating and pattern size, (2) a statistically designed experiment to determine fill times and metal velocities in cast iron as a function of gating and variables using simple patterns, (3) two statistically designed experiments to determine fill times, metal velocities, and metal profiles in aluminum as a function of gating and coating variables using a hat-shaped pattern, and (4) a determination of the critical gate size that will act as a choke for both aluminum and cast iron using different coatings.

4.4.1. Task 1: Pouring Temperature and Fill Rate. The fill times and metal velocities for a variety of alloys (zinc, aluminum, copper-base, and cast iron) were measured over a wide range of pouring temperatures. The purpose was to resolve conflicting observations concerning the effect of pouring temperature on metal velocity. In very thin sectioned castings, the metal velocity reached a peak with aluminum alloys but decreased continuously with increasing iron pouring temperature. In thicker sections, increasing the pouring temperature usually increased the metal velocity.

The velocity also increased with higher permeability coatings. These effects can be explained by the effect of temperature on the rate of foam decomposition and the transport of the decomposition products from the casting cavity. However, for very high pouring temperatures, the foam may be decomposed faster than the gaseous products can be transferred through the coating, and the metal velocity may actually be reduced. Higher temperatures are required to reach this stage when a high permeability coating or a thick pattern is used.

4.4.2. Task 2: Effect of Gate Size and Other Process Parameters on Fill in Cast Iron. A statistically designed screening experiment and a full factorial designed experiment were performed, in which the gating system design was varied to determine its effect on mold filling time and cast iron fill velocity. The designed experiments showed that, for iron, the fill times and metal velocities depended primarily on the type of foam and the type of coating. Gating provided an effect only by changing the metallostatic pressure head (i.e. side versus bottom filling).

4.4.3. Task 3: Effect of Gating and Other Process Parameters on Fill in Aluminum. Both statistically designed screening and partial factorial experiments were used to determine fill rates of aluminum in a hat-shaped pattern. The variables included gate area, number of gates, and bottom vs. top gating. The total fill time, the horizontal (or circumferential) metal velocity, the vertical velocity, and the casting quality, as determined radiographically, were measured. The main effects and interactions of process variables on fill times and metal velocities were determined statistically, and a critical metal velocity and fill time required to prevent entrapped foam decomposition products in the casting were found.

The traditional "gating design" parameters, including the number and size of gates, played virtually no role in mold filling and aluminum casting quality. Instead, the shape of the metal-foam interface and its velocity, dictated by the rate at which the foam decomposition products could accumulate and be transferred from the metal-coating interface, were the predominant factors. In fact, a minimum fill time must be maintained. This in turn means that the properties of the coating are the controlling features determining casting quality, not the gating design.

4.4.4. Task 4: Making the Gating System the Choke. Virtually all of the tests indicated that the size of the gates played little or no role in controlling fillability, fill time, or metal velocities. However, there must be some critical gate size below which restricting

of fluid flow becomes more important than foam decomposition or transport of foam decomposition products. A series of bottom-gated, 0.5-in. thick plates were poured in both A356 aluminum and a 4.0% CE gray iron.

In these preliminary tests, a single pattern type (foam composition and density, pattern volume and geometry) was used. The dimensions of the pattern were such that the volume-to-surface area ratio was about 0.22. The casting had a relatively large perimeter -- 8.875 in. These parameters are indicative of a "sprawly" casting, for which there is relatively little volume of foam to decompose compared to the coating surface through which the decomposition products can be removed. The combination of low density EPS and pattern geometry provided a good opportunity for the gate to serve as the choke. Chunkier patterns or PMMA foam might require even smaller areas for the gate to serve as the choke.

4.5. Current Tasks

Several tasks are currently underway. These tasks are intended to determine the influence of casting variables on the rate at which the mold fills, the influence of gate position on pattern filling, and the nature of the metal front profile. The results are expected to help explain how the overall gating design influences foam decomposition and transfer of foam decomposition products and produces an optimum metal front profile and velocity.

5.0 MECHANICAL PROPERTIES

Axial fatigue data obtained lost foam cast ductile iron has shown that fracture can initiate at bead intersections on poorly fused patterns. In order to reduce the possibility of this stress concentration point affecting the fatigue data on 356-T6 aluminum and Class 35 Gray Iron, the pattern tool was modified to produce better bead fusion. All test patterns for the current project have been produced with the revised tool.

Class 35 gray iron and 356-T6 aluminum have been selected as materials of greatest interest and specimens have been cast. Axial tensile and fatigue properties and fatigue properties are now being determined.

6.0 TECHNOLOGY TRANSFER

Process and product development represents about 65% of the current research on lost foam casting. About 35% of the effort in the last year has involved technology transfer to participants in the consortium project.

Seven meetings were held with individual participants to discuss research applicability to particular company needs. Approximately 32 man days were spent in plants conducting experiments to demonstrate and verify laboratory data in an operating foundry environment. Approximately 144 man days were spent with sponsor groups to present and discuss research results and applicability.

Work is currently underway with seven sponsors to implement coating quality control procedures in plants. While the coating control procedures are being implemented, we are providing independent coating analysis. Scrap costs are decreasing, and companies actively participating in the consortium are financially benefiting from the Advanced EPC (Lost Foam) Technology program.

USE OF THIS REPORT AND INFORMATION
CONTAINED THEREIN

Publicity

This report and the information contained therein is the property of the individual or organization named on the face hereof and may be freely distributed in its present form. However, the University of Alabama at Birmingham (UAB) hereby reminds Sponsor that no advertising or publicity matter, having or containing any reference to the University of Alabama at Birmingham, shall be made use of by anyone, unless and until such matter shall have first been submitted to and received the approval in writing of UAB. (UAB does not usually approve any type of endorsement advertising.)

Limitation of Liability

The faculty and staff of UAB associated with this project have used their professional experience and best professional efforts in performing this work. However, UAB does not represent, warrant or guarantee that its research results, or product produced therefrom, are merchantable or satisfactory for any particular purpose, and there are no warranties, express or implied, to such effect. Acceptance, reliance on, or use of such results shall be at the sole risk of Sponsor. In connection with this work, UAB shall in no event be responsible or liable in contract or in tort for any special, indirect, incidental or consequential damages, such as, but not limited to, loss of product, profits or revenues, damage or loss from operation or nonoperation of plant, or claims of customers of Sponsor.

Report No.: UAB-MTG-EPC 1994 Summary

To: Department of Energy

Date: April 25, 1995

UAB Account No. 527963 and 634943

E-File: EPCDOE94.SUM