DOE/ID/12869--1

DE91 001348

FINAL REPORT ON EXPENDABLE PATTERN CASTING TECHNOLOGY
Phase I

July 1990

Work Performed Under Contract No. FC07-89ID12869

For
U.S. Department of Energy
Office of Industrial Technologies
Washington, D.C.

By
The American Foundrymen's Society
Des Plaines, Illinois

Technical Information Center
Office of Scientific and Technical Information
United States Department of Energy

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.

This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831; prices available from (615)576-8401, FTS 626-8401.

Available to the public from the National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.

Price: Printed Copy A05
Microfiche A01

FINAL REPORT ON EXPENDABLE PATTERN CASTING
TECHNOLOGY

Phase I

July 1990

Work Performed Under Contract DE-FC07-89ID12869

Prepared for
U. S. Department of Energy
Idaho Operations Office, Idaho Falls, ID
Sponsored by the Office of the Assistant Secretary
for Conservation and Renewable Energy
Office of Industrial Technologies
Washington D.C.

Prepared by
The American Foundrymen's Society
505 State Street
Des Plaines, IL 60016

PRECISION EXPENDABLE PATTERN CASTING TECHNOLOGY

TABLE OF CONTENTS

ABSTRACT	1
1.0 LITERATURE REVIEW SUMMARY	4
1.1 The EPC Process Sequence	4
1.2 EPC Process Advantages over Conventional Casting Process	11
2.0 FACTORS INFLUENCING SAND FLOW AND PERMEABILITY	15
2.1 Sand Characterization Studies	24
2.1.1 Screen Distribution	24
2.1.2 Bulk Density	24
2.1.3 Refractory Density	25
2.1.4 Hall Flow Rate	25
2.1.5 Angle of Repose	25
2.1.6 Sand Permeability	27
2.1.7 Orifice Flow	27
2.2 Sand Characterization Results	30
3.0 EP CASTING DIMENSIONAL PRECISION	36
3.1 Sand Casting Dimensional Analysis	47
3.2 Data Presentation	51
3.3 Casting Results	54
4.0 CASTING DEFECT ANALYSIS	63
4.0.1 Core Shift or Float	63
4.0.2 Erosion	63
4.0.3 Exogenous Inclusions	63
4.0.4 Fins	64
4.0.5 Gas	64
4.0.6 Hot Tears	64
4.0.7 Metal Shot	64
4.0.8 Mold Collapse	65
4.0.9 Penetration	65
4.0.10 Short Pour	65
4.0.11 Shrinkage	65
4.1 Examples of Major Defects Observed in Production Castings	66
4.1.1 Carbonaceous Residue	66
4.1.2 Fluidized Sand Defects	66
4.1.3 Penetration	72
4.1.4 Core Float	72
4.1.5 Burned on Sand	72
4.2 Casting Defects Summary	72
5.0 SUMMARY AND CRITICAL CASTING PARAMETERS	77
REFERENCES	81

LIST OF ILLUSTRATIONS

	<u>DESCRIPTION</u>	<u>PAGE</u>
1	Effect of Vertical Vibration on Sand Density	19
2	Effect of Horizontal Vibration on Sand Density	20
3	Effect of Vibration Direction on 60 Sec. Density	21
4	Schematic of Hall Flow Meter	26
5	Apparatus for Measuring the Permeability of Sand to Gases . . .	28
6	Tubes and Orifices for Conducting Vertical Sand Flowability Studies	29
7	Effect of Orifice Size on Flow Rate of Silica Sands (No Vibration)	32
8	Effect of Sand Flow Rate (No Vibration) on Deposit Density . . .	33
	of Silica Sands	
9	Effect of Density on the Permeability of Silica Sands	35
10	EPC Test Pattern for Dimensional Analysis	37
11	Webbed Test Cube	39
12	Percent Dimensional Changes from Cold Die Dimensions in 17 EPS Test Cubes Molded to a Density of 1.3 lb/ft ³ .	41
13	Percent Dimensional Changes from the Cold Die Dimensions in 17 EPS Test Cubes Molded to a Density of 1.3 lb/ft ³ . Plotted as a Function of Linear Lapsed Time.	43
14	Dimensional Measurements Made to Track Foam Changes	44
15	Average "C" Dimensional Changes in 12 1.3 pcf EPS Cone Test Patterns.	45
16	Foam Pattern after Shading with Dyken Layout Ink (a) Top View and (b) Bottom of Pattern.	48
17	Sand Casting Test Pattern for Dimensional Analysis	49

LIST OF ILLUSTRATIONS

	<u>DESCRIPTION</u>	<u>PAGE</u>
18	Photographs of a Typical Aluminum Test Casting Made from EPS Pattern. (a) Top View and (b) Bottom of Casting.	58
19	Typical EP Foam Cast Gray Iron Casting (a) Top View and (b) Bottom View.	62
20	Carbon Defects in Gray Iron Casting (a) 0.75X (b) 200X	67
21	Carbon Folds in Ductile Iron at Magnifications of (a) 25X and (b) 200X.	68
22	Fluidized Sand Defect Near Glue Line	69
23	Sand Fluidization Defect in Casting Bolt Hole	70
24	Sand Fluidization in Iron Casting Tree	71
25	Penetration Defect in Gray Iron Casting (50X) Sand Density 94.2 lb/ft ³ .	73
26	Core Shift and Sand Flotation in 1.6 EPS Test Cube (a) Corner Containing Blind Hole Sawcut from Cube (b) Cross-Section Showing Coating and Penetration (25X).	74
27	Burn-on from a Gray Iron Test Cube AC4. Sand Density 93.5 lb/ft ³ .	75

LIST OF TABLES

TABLE		PAGE
1	Steps in the EPC Process	5
2	Density of New and Used Sands	31
3	Foam Cone Die Block Dimensions	38
4	CMM Precision Data on Stabilized EPS Webbed Cube	40
5	Mean and Standard Deviation in Foam Cone Dimensions after Aging Approximately 58,000 Minutes	46
6	Match-plate and Cope and Drag Pattern Dimensions	50
7	Dimensional Analysis on 356 Aluminum Cone Castings Made from Experimental Match-plate Pattern (Foundry AE7) (Green Sand)	52
8	Dimensional Analysis on Gray Iron Cone Castings Made from Experimental Foam Patterns (Foundry AC4)	53
9	Dimensional Measurements and Precision on Cast Aluminum Alloy Cones Cast Using Conventional and EPC Methods	55
10	Dimensional Measurements and Precision of Gray and Ductile Iron Cones Cast Using Conventional and EPC Methods	60
11	Summary of Defects Observed in Aluminum and Iron Castings . .	76

PRECISION EXPENDABLE PATTERN CASTING TECHNOLOGY
ABSTRACT

The Expendable Pattern Casting (EPC) process is a potential casting process breakthrough which could dramatically improve the competitiveness of the U.S. foundry industry. Cooperatively supported by U.S. Industry and the Department of Energy and managed by the American Foundrymen's Society, a project was started in May, 1989 to develop and optimize expendable pattern casting technology. Four major tasks were conducted in the first phase of the project. Those tasks involved: 1) reviewing published literature to determine the major problems in the EPC process, 2) evaluating factors influencing sand flow and compaction, 3) evaluating and comparing casting precision obtained in the EPC process with that obtained in other processes, and 4) identifying critical parameters that control dimensional precision and defect formation in EP castings.

The objective of Task 1 in the project was to search the published literature and visit with EP casting producers to identify current technical hurdles in implementing the process. This search included making foundry visits, and compiling, analyzing, and summarizing available technical information about the process. Approximately 350 published papers were obtained from the open literature and participating companies. This information was compiled and summarized.

Task 2 involved evaluating the factors that influence sand flow and compaction in expendable pattern casting. Vibration during densification decreases the angle of sand repose which aids horizontal migration under overhangs and into blind areas. High sand densities are essential for minimizing metal penetration into sand.

Task 3 involved evaluating the factors that influence dimensional precision of EP castings and comparing EP castings with green and no-bake sand casting processes. A cone pattern was selected to evaluate inter-process variations compared to green sand, no-bake, etc. Two patterns, one for use with cope and drag molds and the second for match-plate molds, were precisely machined. A tool for foam patterns of the same design was machined. Foam patterns were prepared and submitted to participants in the study and were poured with iron and aluminum.

All sand casting processes had difficulty with the 0.5° taper on the pattern. After much difficulty drawing the pattern from sand molds, the pattern taper was increased to 1° on the cope and drag pattern. None of the conventional sand casting processes could produce cast-in holes on the flange or top of the cone casting.

EP castings had cast-in holes, almost zero taper, close dimensional tolerances, and a superior surface finish compared to the sand castings. The iron castings produced using the EPC process were acceptable. However, several castings exhibited casting defects, principally metal penetration.

Task 4 involved identifying the critical process parameters and system properties that control dimensional precision and defect formation in evaporative pattern casting. Over 400 commercially produced EP castings were received and representative defects have been analyzed. The major defects were found to be the result of incomplete removal of pyrolysis products, sand fluidization produced by gas evolution during pouring, and sand burn-on/penetration caused largely by inadequate sand compaction. Possible control strategies have been developed and will be tested in future studies.

Special tests also were conducted in Task 4 to study foam pyrolysis under controlled radiant and conductive heating conditions. Permeability measurements were conducted on selected commercial sands and foam pattern coatings. These special tests and modeling efforts have aided in understanding the important mechanisms in the process.

1.0

LITERATURE REVIEW SUMMARY

The use of expendable foam patterns for making metal castings was developed and patented by H. F. Shroyer in 1958.(1) The patterns were initially machined from blocks of expanded polystyrene and molded in bonded sand. The patent was purchased by The Grunzweig & Hartmann Co. of West Germany, and further developed for commercial use by A. Wittmoser.(2,3) The concept of casting into unbonded sand was later patented by Smith in 1964 (4); however, users of the unbonded sand process were required to be licensed by The Full Mold Process, Inc. until the patents expired in 1980.

The most popular current use of the process places patterns in unbonded sand. The patterns are coated with refractory and placed in a flask. Backup sand is added and compacted around the patterns, and liquid metal poured into the mold to replace the foam. This casting technique has been referred to by several generic and proprietary terms including evaporative pattern casting (3), expendable pattern casting, lost foam casting, and full mold casting (5,6), Castral (7), Replicast (8) and Policast (9). The term Expendable Pattern Casting (EPC) will be used throughout this report. As presently practiced, the EPC process uses expanded polystyrene (EPS) or expanded polymethyl methacrylate (EPMMA) patterns that are consumed with each casting poured.

1.1

The EPC Process Sequence

The steps involved in the EPC process are outlined in Table 1. The first step in the process is to design the part. Direct conversion of existing castings without EPC design changes often fails to take advantage of the useful features of the process and the net EP casting cost may be higher than conventional castings.

TABLE 1.

STEPS IN THE EPC PROCESS

1. PART DESIGN
2. DIE DESIGN AND PRODUCTION
3. PREPARE FOAM SECTIONS
 - A. PRE-EXPANDED BEADS
 - B. MOLD BEADS
 - C. EJECT SECTION
4. ASSEMBLE SECTIONS
5. COAT PATTERNS
6. FILL & COMPACT SAND
7. POUR
8. SHAKEOUT & FINISH THE CASTINGS

615-848-tab

After a part has been designed, it is necessary to design tooling to make the sections of foam required for the pattern. Tool design for foam production is important since it fixes the initial foam dimensions and influences the foam pattern quality, surface and internal bead fusion, and production cycle time.

Complex casting designs may require that several foam sections be made separately and glued together to form the pattern. Each foam section requires a tool; and a second tool or fixture may be required to maintain alignment during gluing operations.(2) Tool design and construction may be costly and involve long delivery times.

Prototype parts may be made from foam pieces cut from board stock and assembled by hand gluing. This technique is useful but the resulting patterns have lower surface quality and poor dimensional accuracy. Hand assembly operations may result in excessive glue that can produce unacceptable defects.(2,10)

The production of molded foam sections is a two step process. The foam most commonly used at the present time is polystyrene, containing about 5-8% pentane as an expansion agent.(11) EPMMA currently uses chloro-fluorocarbons (CFC's) as an expanding agent. However, due to the environmental problems caused by CFC's, new hydrocarbon expanding agents are being tested (12) and CFC's will not be used as an expanding agent for EPPMA by the end of 1990.

EPS raw material is received as unexpanded beads with a bulk density of about 40 lb/ft³ (600 g/L), and EPMMA is received at a density of about 60 lb/ft³ (950 g/L). The first step in pattern making is to expand the beads to the desired use density. Iron casting producers prefer a density of 1.0-1.3 lb/ft³ (20.8 g/L).(13) Aluminum casting producers commonly prefer an

EPS density of 1.4-1.5 lb/ft³ (22.4-25.6 g/L). Most EPMMA is expanded to a density of about 1.5-1.8 lb/ft³ (24-29 g/L). Bead expansion is accomplished by rapid steam heating. The resulting beads must be stabilized before use. Expansion takes place in two phases. The initial bead expansion step is called pre-expansion and the resulting product is called prepuff or pre-expanded beads. After stabilization, the pre-expanded beads are ready for molding.

The pre-expanded beads are transported to molding machines for molding into foam patterns. The tool in the molding machine must be preheated to the operating temperature, dried, and closed to start the cycle. If pulls are used, they are normally pushed into their closed position when the tool is closed. The pre-expanded beads are then blown into the empty cavity.

Many quality problems in foam production are a result of a lack of complete pattern fill. Tool venting must be adequate to allow air in the tool cavity to escape. Fill guns also must be properly placed and regulated to assure filling of the cavity and uniform foam density in the pattern.

Once the cavity is filled with beads, the steam cycle is begun. Steam is passed from one side of the tool to the opposite side through vents, and then the steam direction is reversed. The steam causes the beads to soften and expand a second time, thus filling the interparticle voids, and bonding together. After fusion, steam is blown simultaneously from both sides of the die and the pressure raised. This causes the tool surface temperature to rise, the expanding agent to further expand the beads, and the foam surface to fuse. This process step is referred to as the autoclave step. Care must be taken during autoclaving to prevent overheating that can cause surface bead collapse.

After steaming, the foam must be cooled. This is done by spraying either a large volume of water on the back of the die or with a small amount of water followed by the application of a vacuum. Then the tool is opened, the pulls are extracted, and the foam is ejected. At this time, the foam is still warm and soft so care must be taken during ejection and immediate storage to minimize distortion.

After initial foam shrinkage caused by die's cooling, the foam expands briefly as it is infiltrated by air. Then it begins to contract as expanding agent and water vapor diffuse out. This is known as the aging process. Most of the shrinkage occurs within 30 days and amounts to about 0.8% linear contraction in EPS patterns and 0.5% in EPMMA. Control of the aging process is necessary to achieve dimensional consistency and gain the full benefit of the EPC process.

One way to dimensionally stabilize patterns and reduce the 30 day aging process is by artificially aging in an oven. Artificial aging is normally performed at 140-160 °F (60-70 °C) for 2-18 hrs. Unfortunately, artificial aging reduces dimensional precision. Shrinkage of molded foams must be understood to advantageously use the process.

After aging, the foam sections are ready for assembly. Assembly requires the same precision needed in the cast part. Sections are normally glued together on automatic machines using hot melt glue. The glue joint must be sufficiently strong to hold the part together; fast setting to maximize the production rate; seal joints against penetration of the ceramic coating; and have minimum mass to minimize contributions to casting defects.(2) The sprue and gating system may be assembled on automatic machines or hand assembled. The gating system sections may be molded or cut from board stock. Molded sections are preferred to minimize mold wash erosion. Attachment of the

gating system completes the preparation of the foam assembly or cluster for casting. Assembled patterns also may be purchased to minimize the initial difficulties when trying the process. (13)

The foam cluster usually is coated with a ceramic before a casting can be made. Some aluminum castings may not require a coating, but coating is essential for almost all ferrous castings. Even if a coating is not absolutely essential, it still offers advantages by producing a barrier so metal does not penetrate or erode the surrounding sand during pouring. The coating also helps prevent sand from falling into the gap between the advancing liquid metal and the retreating foam. Furthermore, the coating stiffens the pattern to help minimize distortion during compaction.

The coating is usually a slurry of refractory in a water carrier. It is applied to the foam cluster by dipping, spraying, or pouring over the pattern. After the coating has been applied, it must be dried. Careful control is necessary to obtain a uniform coating layer on each cluster because thickness affects coating permeability and performance.

The dried coated cluster is ready to be placed in a flask and backed up with sand. Cluster placement, filling the flask with sand, and sand compaction must be accomplished such that the sand fills all internal cavities and packs tightly around the cluster to provide support. The sand filling and compaction cycle for each cluster design is important. The sand may be rained from above through a screen or supplied through tubes placed around the cluster. The rate of filling and the distribution of sand in the flask can have a significant effect on pattern deformation.

Compaction is usually achieved using a table vibrated with counter-rotating motors having eccentric weights. The flask may be placed on locator pads on the table or clamped to the table. There is considerable

controversy about the utility of vibrating flask in a clamped or unclamped condition. Rigid clamping of flasks to the vibrating table is more likely to produce a repeatable compaction cycle.(14) Compaction is usually done during filling to help sand flow into internal pattern cavities.

The mold is ready to be poured after a cluster is packed in a flask. Pouring consistency is more critical with the EPC process than in conventional foundry practices. Automatic pouring commonly is employed to minimize pour-to-pour variations. If pouring is interrupted, the sand may collapse into the casting cavity. The pouring rate must be high enough to maintain a relatively constant ingate pressure to prevent mold collapse. But the pouring must be sufficiently low to allow the foam pyrolysis products to escape. The gating system, coating properties, sand properties, and pouring practice must operate as a system to allow both liquid and gaseous pyrolysis products to escape from the cavity.(15)

After pouring, the casting cluster is allowed to solidify and cool in the flask prior to being shaken out. Shake out of EP castings is usually a relatively simple matter of dumping the flask and lifting the castings out of the loose sand. Once the sand has cooled it can be reused again with little or no additional preparation.(5) Since there are no fins or parting lines, casting cleaning is normally easy and requires few operations. The loose sand in the internal cavities is more easily removed than the lumps of bonded sand that remain in conventional castings where cores are made with chemical binders.

Eliminating foam pyrolysis products from the casting cavity during pouring is essential to success. Failure to completely eliminate the foam results in carbon defects in iron, laps or folds in aluminum, and porosity in both metals.

1.2

EPC Process Advantages Over Conventional Casting Process

The use of foam patterns allows some design and process flexibility not possible with conventional casting processes. The primary advantages of the EPC process are that bonded sand molds, bonded cores, and parting lines are eliminated, and this may improve casting accuracy and the labor and energy costs associated with cleaning. Some of the conventional operations bypassed with the EPC process include mixing and molding of sand, tucking, ramming, jolting, squeezing, striking off, core making, core setting, pattern drawing, mold closing, sprue cutting, and a shake out.(5,11)

A conventional mold cavity is made with a pattern that must be withdrawn from the mold after the sand has been compacted. Pattern removal requires that the pattern be designed with a sufficient draft angle to allow its removal. The presence of the parting line on conventional patterns often dictates the orientation of the pattern in a mold and restricts the number of castings in a flask. Multiple levels of castings around the sprue are not usually possible. The parting line may limit the placement of gates and risers. This may cause gates or risers to be placed on a surface that must be dimensionally precise. The removal of these gates and risers results in dimensional inaccuracies that must be corrected by machining.

Conventional mold closure also may lead to casting inaccuracies. A typical allowance for a shift between the cope and drag in a conventional mold is 0.030 in (0.75 mm). This allowance also is typical of the inaccuracy expected between molds and cores. The use of foam patterns eliminates shifting and this is one reason the process is more accurate.

Poor joints between cores and mold halves in conventional casting processes allows metal to penetrate joints during pouring. Penetration

produces fins that must be removed during finishing. The removal of fins increases the dimensional variability in the normal casting process.(2,16)

The use of expendable patterns reduces tooling wear, eliminates fins, insures uniform section sizes, and improves dimensional control. The casting is a more perfect reproduction of the pattern, and the superior accuracy of foam patterns translates directly to more accurate castings.(16)

Eliminating bonded cores can be achieved if the unbonded sand can be caused to flow into cavities in the foam pattern and the gases and liquids associated with pattern pyrolysis can be vented properly. Filling internal passages with sand may require the presence of a small hole in the pattern but usually does not require the extensive core access necessary for conventional bonded sand cores.(2) Conventional cores must be supported and positioned with core prints and chaplets and may shift during casting. Shifts result in inaccurate internal passages and wall thickness variations.

The ability of foam patterns to eliminate cores allows complex internal passages and sometimes even multiple passages to be accurately cast. Casting walls can be curved or of variable thickness.(16) Pumps have been cast with sufficiently smooth internal surfaces so that the amount of water pumped increased by 12%. There also was a reduction of about 25% in pump weight and a reduced product cost.(17) Eliminating cores also eliminates separate tooling usually required for core production. The process of mixing core sand, ramming, curing, setting, and removing bonded sand cores is eliminated. Core crush, core damage, core related porosity and other problems that result from setting cores also is eliminated.

Eliminating core prints, chaplets, fins, etc., also reduces the amount of cleaning required on the final casting. Cleaning room cost reductions of up to 80% have been reported.(2,16,18,19)

The improved accuracy of the lost foam process allows machining operations to be reduced. For example, holes that are greater than 1/4 inch (6 mm) in diameter that normally are drilled may be cast with the EPC process. The repeatability of the hole dimensions can be quite good, typically within 0.2%. (16,18)

Design tolerances have been summarized by Troxler as follows: 1.) Linear dimensions between features located on the same piece of foam are normally controllable to $\pm 0.3\%$ in the first inch and $\pm 0.2\%$ for each subsequent inch. 2.) Linear dimensions across glue joints can be expected to have less accuracy. An additional allowance of about 0.02 inches variation in thickness should be made for each glue joint. 3.) Positional accuracy across glue joints is affected by shifting or mismatching foam pattern pieces. An allowance of ± 0.03 inches should be made for each glue joint. 4.) Glue seams typically have an extruded bead of glue around the joint. The glue bead can normally be expected to be +0.04 inches and -0.0 inches. (20)

The RMS values on EP iron castings are typically in the range of 200-250 microinches compared to 250-1000 for green sand and 125-500 for shell sand castings. EP aluminum castings can have a measured RMS value as low as 120 microinches when special precautions are used to optimize the surface finish. (20)

EP iron castings are reported to have more consistent mechanical properties. The elimination of fins eliminates the chill common when parting line fins form in conventional processes. (21,22) The compacted unbonded sand resists mold wall movement during solidification and may reduce the need for risers. Reducing the number and size of risers increases the casting yield and reduces energy costs.

The cost of sand disposal will increase dramatically over the next decade as federal and local regulations for the disposal of used conventional foundry sand become more stringent. The cost of foundry sand, as well as clay and chemical binders, also are expected to increase in the future. Preliminary tests on EPC iron foundry sand indicate that used EPC sand can be used as conventional land fill which will significantly reduce disposal cost. (26)

There are also disadvantages to the EPC process. The lead times and costs of tooling are substantial. Simple tools can be cast to shape, but once the tooling is made, changes are neither easy nor cheap. Gating systems are larger than conventional processes and require more effort to remove. Foam patterns can distort during compaction and this results in distorted castings. (2,18) The most troublesome problem seems to be carbon defects in gray and ductile iron castings and laps and folds in aluminum. These problems are either caused or substantially aggravated by foam pyrolysis residue in the metal.

2.0

FACTORS INFLUENCING SAND FLOW AND PERMEABILITY

Proper sand characteristics are essential in the pouring of quality EP castings. A cluster is ready to be backed up with compacted sand and poured after it has been coated and dried. The sand must flow into internal casting cavities, allow pyrolysis products to escape, provide mechanical support to the cluster during pouring, and prevent metal penetration. The sand selected is normally silica with an AFS GFN of 25-45. Fine grains or an excessive amount of fines in a coarse sand reduces permeability and limits the amount of gas that can escape through the coating into the sand during pouring. However, too coarse a sand may not provide enough mechanical support for the coating, and this can allow metal penetration and cause rough casting surfaces.

Rounded and sub-angular sands are preferred to maximize sand permeability, and normally the sand distribution is narrow with a majority of the sand being retained on a single sieve. A narrow size distribution helps maintain the needed permeability. Coarse round grain sands have the best flowability, but properly compacted finer sands are better at providing mechanical support for the coating. The sand must work with the coating to provide mechanical support for the molten metal.

EPC sands should be handled as gently as possible in the sand transportation system to minimize generation of fines. Generous bend radii are needed in pneumatic transport tubes and the transport air should be dry. A classifier should be used to remove lumps and eliminate fines. Heat exchangers are needed to control sand temperature in higher volume foundries. The sand always should be cooled to less than 120 °F (50 °C) before reuse. Higher sand temperatures soften EPS patterns and increase the likelihood of pattern distortion.

After a casting cluster has been coated and dried, it is ready to be placed in a flask and the flask filled with sand to provide support for the cluster during pouring. The fill and compaction cycle must result in sand filling all internal passages and compacting to a sufficiently high density to provide support during pouring.

Vibration during filling of the flask has two goals. The first goal of this process is to produce local sand migration, i.e., to aid the sand grains so they flow and fill the inner cavities of the pattern. The second goal is to densify the sand sufficiently to produce a rigid sand mass that will resist the metal and gas pressures developed during pouring. This densification process is referred to as compaction. Filling pattern cavities with sand generally takes more time, and sand flowability is important in this context. Vibration to cause sand compaction may reduce the volume of loose sand and increase its density by as much as 15% compared to the uncompacted density.

The vibration parameters of greatest concern are the duration, direction, frequency, and amplitude. A flask of sand may be oscillated back and forth linearly in the vertical and/or horizontal directions. In addition, rotational oscillations can occur around each axis resulting in up to six motions occurring simultaneously. Because of the complexity of directions of vibration, the resultant motions can be quite difficult to characterize, measure, and correlate with sand or casting behavior.

Vibration amplitude can be described as zero-to-peak amplitude or root mean square amplitude. The root mean square amplitude of a sinusoidal signal is $0.707 \times$ the zero-to-peak value.

One of the most comprehensive studies of sand compaction was conducted by Wegscheid at Deere and Company.(24) Wegscheid filled small

flasks and vibrated them in a controlled manner in both horizontal and vertical directions with an electrohydraulic exciter. The electrohydraulic drive device allowed frequency and acceleration to be specified and the resulting vibration cycle electronically monitored. Flasks were clamped to the vibrating table.

In most of the work reported by Wegscheid, the flask was filled prior to the onset of vibration. Flasks were vibrated at a specific amplitude, frequency and direction, and the density of the sand determined before and after vibration. Tubes were placed in the flask and moved with the flask during vibration. The extent of sand flow into a tube during vibration was monitored by an linear variable differential transducer (LVDT) that was periodically slipped inside the tube to measure the sand depth.

The effect of vertical vibration time at a frequency of 31.5 Hz on sand density is illustrated in Figure 1(A). Starting at an initial density of about 96 lbs/ft³, the density rapidly increased during the first 30 seconds of vibration and then leveled off at a maximum density of about 105 lb/ft³. Some continued densification occurred after 30 seconds with 1 G acceleration, but accelerations of 2 and 4 G's did not increase densification. At 125 and 250 Hz, higher acceleration levels gave higher density values.

Similar results are illustrated in Figure 2 with horizontal vibration. In general, higher G forces obtained at high frequencies and low amplitudes resulted in the most rapid compaction of sand.

The effect of the direction of vibration on the density obtained in 60 seconds is illustrated in Figure 3. The density increased with frequency when using horizontal vibration. At vibration levels of 2 and 3 G's, horizontal vibration gave higher densities at a given frequency after 60 seconds of vibration, as illustrated in Figures 3(B) and 3(C). At a constant

615-447

Figure 1. Effect of Vertical Vibration on Sand Density.

Figure 2. Effect of Horizontal Vibration on Sand Density.

615-448

Figure 3. Effect of Vibration Direction on 60 Sec. Density.

615-449

vibration level of 4 G's, horizontal vibration produced the highest densities at each of the frequencies examined. (24)

Both fill and compaction must be accomplished without cluster distortion. Improper equipment or equipment use will result in uncompacted areas or gross pattern distortion. Understanding and controlling sand fill and compaction is essential if dimensional control is to be maintained.

Sand vibration in both the horizontal and vertical planes may be necessary to maximize the rate of sand flow into and around patterns. Most of the sand flow appears to occur in the top few inches of a flask. Deeper in the flask, flowability is reduced because the overburden of sand increases the load and consequently increases the friction between sand grains.

Bulk or long range flow effects also have to be considered in minimizing pattern warpage. If excess sand is added to one side of the flask, the resulting flow across the cluster (shadowing) can cause pattern bending.

The rate of the sand addition must be matched to the sand compaction cycle and to the amount of horizontal sand flow needed to fill internal cavities in particular patterns. The method of pattern insertion and holding of the foam cluster also is important. If the cluster is held and the flask vibrated, flask vibration will elongate the pattern.

The most commonly used vibrational frequency is around 30-50 Hertz, although higher frequencies have been used. The frequency must be chosen as much to avoid flask or table resonance as to achieve sand compaction. Resonance causes nonuniform compaction because it induces long range sand currents. Flask size should be kept to a minimum to reduce the sand required, the energy required for compaction, distortion producing sand currents, and the fill and compaction cycle time.

Flasks are typically made from 5/16-3/8" steel fabricated by welding. Wear plates are used at compaction table contact points. Flasks also commonly contain screened channels in the side to allow gases to escape. If vacuum is used during pouring, a vacuum connection is included on the flask.

Pattern distortion tends to be higher away from the center of the flask. In an unclamped flask, the center of gravity (G/C) in the flask does not experience as much vibrational energy and does not compact as well as locations nearer the wall. The lack of vibration at the C/G tends to reduce distortion at that location. However, there may be insufficient vibration at the center of mass to move sand into the interior cavities of castings.

The compaction table design influences sand compaction and filling the casting cluster. The most common systems used to produce castings use round flasks vibrated unclamped on a compaction table. The flask rests on three posts which transmit vibration energy into the flask. The table is energized by two counter rotating motors. Accelerometers are used to monitor the vibration of the table.

Control of the process requires a rigid flask and a compaction table driven in a controlled manner. Inconsistent motor control results in erratic vibration cycles.

The best direction for vibration to achieve fill and compaction is of some dispute. Most equipment vibrates principally in the vertical direction. However, at least one design vibrates the sand in the horizontal direction, and some equipment has been designed to allow vibration in more than one direction. Acceptable parts have been produced with all the available equipment, and there is no clearly preferred method of compaction at this time.

2.1 Sand Characterization Studies

Several sands used in EP casting production were submitted for examination. Preliminary characterization studies were conducted to determine the sand size distribution, bulk density, material density, Hall flow rate, compacted density, and angle of repose. This report describes the procedures used and presents sample data. Future research will be concerned with relating sand characteristics to sand behavior during compaction, and the effects of these variables on the resulting EP castings.

2.1.1 Screen Distribution

The screen distribution of each type of sand was determined by removing a 60 ± 10 gram sample from the bulk sand using a splitter and vibrating the sample through a series of stacked sieves. The stack used in the sieve analysis consisted of U.S. Sieves #6, #12, #20, #30, #40, #50, #70, #100, #140, #200, #270 and the pan. The entire sand sample was placed in the top sieve and vibrated for 15 minutes. Each sieve was then removed from the stack and the retained sand placed on a balance. The weight of sand retained on each sieve was determined by subtracting the previous cumulative weight from the current cumulative weight. The per cent of the sample retained on each sieve was determined using the total mass of the sample. The AFS grain fineness number was calculated using multipliers related to each sieve, adding the products, and dividing the sum by the cumulative per cent material. The procedure is described in detail in published texts.(25)

2.1.2 Bulk Density

The bulk density of each sand was determined by taking approximately 250 grams of the sand and rapidly dumping it into a 250 ml cylinder. The top surface then was leveled so that the average column height

could be determined, and the volume was divided by the initial weight to calculate the bulk density.

2.1.3 Refractory Density

The sand (material) density was determined by helium pycnometry. Helium pycnometry uses a known sample weight to displace helium in a chamber of known pressure. From the amount of helium displaced (as determined from a pressure rise), the density of the material added to the chamber can be calculated.

2.1.4 Hall Flow Rate

Vertical flow through an orifice of free flowing materials was determined using a Hall Flow Meter illustrated in Figure 4 following the procedures of ASTM-B213-83. The Hall Flow Value was determined by placing ± 0.1 grams of the material of interest into the Hall Flow funnel. When the last material left the funnel, the elapsed time was recorded in seconds as the Hall Flow time. Bulk density also was determined using the Hall Flow device by filling the catch basin with sand, striking it off, determining the weight of sand in the basin, and dividing the volume of the basin by the total weight.

2.1.5 Angle of Repose

The angle of repose was determined by passing 100 grams of sand through a funnel with an opening of 0.25 in. onto a horizontal surface. After all the sand had flowed through the funnel, the height of the deposited sand was determined using a scale calibrated in hundredths of an inch. The internal angle of repose was calculated as the inverse tangent of the deposit height divided by the deposit radius. Typical values of the angle of repose ranged from 32 to 39°.

Figure 4. Schematic of Hall Flow Meter.

2.1.6 Sand Permeability

Sand permeability was determined using 24 inch long tubes containing sand compacted to various densities. The lowest density value was always obtained by filling the cylinder without any vibration (unpacked bulk density). The maximum density was achieved by attaching a vibrator to the cylinder and vibrating the cylinder for about 500 seconds. Intermediate sand density values were obtained by vibrating for shorter periods of time.

The permeability apparatus is illustrated in Figure 5. The height of the sand column was measured prior to and after all permeability measurements, and where the height changed, an average value was used in the calculation. Upstream pressures ranging from 1 to 15 psig were applied to the column of sand while the downstream pressure and flow rate of gas (99.99% pure nitrogen) was measured for each applied pressure. The series was repeated once, and average values were used to calculate the permeability coefficients of the sand.

2.1.7 Orifice Flow

It is recognized that the rate of sand flow through an orifice and the drop height affects the as-deposited sand density. The effect of flow rate on density was determined using the apparatus illustrated in Figure 6. The apparatus consisted of two sections of tubing each 10.875 inches long. A 45° tapered orifice of known diameter was placed between the two sections to provide a controlled orifice area. The orifices had diameters of 5/64, 10/64, 15/64, 20/64, and 25/64 of an inch.

The flow rate of sand through each orifice was determined by dumping a known weight of representative sand into the top sleeve and simultaneously starting a stopwatch. The stopwatch was stopped when all of the sand had flowed through the orifice. The as-deposited sand density was

APPARATUS FOR MEASURING THE PERMEABILITY OF SAND TO GASES

615-509

Figure 5. Apparatus for Measuring the Permeability of Sand to Gases.

Figure 6. Tubes and Orifices for Conducting Vertical Sand Flowability Studies.

determined by removing the top tubing section, carefully smoothing the top of the deposited sand surface, and determining the height of sand with a scale graduated in hundredths of an inch. The volume of sand was calculated from the product of the area times the height, and the total sand weight divided by volume provided the as-deposited density. The volume divided by the time required for the sand to flow through the orifice provided the flow rate.

2.2 Sand Characterization Results

Three new silica sands from a sand supplier, #430, #445, and #460, and a sample of #445 that had been used in a production foundry were examined. The characteristics of each sand are summarized in Table 2. All sands had a true material density of 2.65 g/cc or 165.4 lb/ft³ as determined by helium pycnometry. The angle of repose ranged from 31.5 ° to 33.3° with the smaller sand having the highest angle of repose.

The base (unpacked) permeability ranged from 315 to 430 with the coarser sand having the highest permeability. The used #445 sand had the same permeability as the new #445 sand indicating that no substantial changes had occurred during use.

The flow rate of #430, #445, #460, and Used #445 sands through various static orifices is illustrated in Figure 7. All of the sands had a flow rate of approximately 0.7 in³/sec through the orifice with an area of 0.12 in². The Hall Flowability was 71 and 72 seconds for the #430 and #445 sands and slightly higher for the #460 sand at a value of 78.6 seconds.

The effect of flow rate through the orifice on the as-deposited density of the silica sand is illustrated in Figure 8. The highest as-deposited density of approximately 104 lb/ft³ was obtained at the lowest flow rate. The higher flow rates resulted in lower as-deposited densities until, at a flow rate of approximately 0.7 in³/sec, the as-deposited density was

TABLE 2

DENSITY OF NEW AND USED SANDS

SAND #	CONDITION	SAND DESIGNATION	DENSITY		ANGLE OR REPOSE DEGREES	BASE PERMEABILITY	HALL FLOWABILITY (SEC)
			G/CM ³	LB/FT ³			
1	NEW	# 430	2.65	165.4	33.3	315	71
2	NEW	# 445	2.65	165.4	32.0	345	72
3	USED	# 445	2.65	165.4	33.0	345	--
4	NEW	# 460	2.65	165.4	31.5	430	78.6

615-850.tab

Flow Rate Vs Orifice Area Silica Sands

Figure 7. Effect of Orifice Size on Flow Rate of Silica Sands (No Vibration).

Deposit Density Vs Flow Rate Silica Sands

Figure 8. Effect of Sand Flow Rate (No Vibration) on Deposit Density of Silica Sands.

approximately 96 lb/ft³. The finer grained #430 sand had the lowest as-deposited density.

The influence of sand density on permeability is illustrated in Figure 9. The finer grained #430 had the lowest overall permeability at a given density, and #460 had the highest permeability. #445 was intermediate. At a given density there was approximately 40% difference in permeability between #430 and #460 sands.

The used #445 had a permeability approximately 10% lower than the new #445. Since the appearance and flow characteristics were identical it was concluded that the organic residue on the used sand reduced the permeability.

The permeability of each sand progressively decreased with an increase in density. #430 had a permeability of 12E-7 Darcy at a density of 96 lb/ft³ compared to 6E-7 at a density of 110 lb/ft³. The change in density from 100 to 110 lb/ft³ reduced the permeability by approximately 50%. At the other sand size extreme, #460 had a permeability of approximately 16.5E-7 at a density of 100 lb/ft³. An increase in density to 107 lb/ft³ reduced the permeability to 11E-6 which amounts to a decrease of approximately 35%. #445 was intermediate between these two sands.

It is evident that the permeability varies by at least an order of magnitude at a constant sand density over the range of sands. The highest permeabilities are obtained with larger round grained sands. Intermediate permeability values at intermediate density values were obtained depending on the actual size distribution of these sands.

Future studies will be concerned with relating flowability properties of sands to the ease of compaction in flasks. Similarly, efforts will be made to relate laboratory measurements of permeability to the ease of gas evolution during pouring.

Figure 9. Effect of Density on the Permeability of Silica Sands.

3.0 EP CASTING DIMENSIONAL PRECISION

The objective of this task was to determine the dimensional precision of iron and aluminum castings produced by green sand, no-bake, and EP casting techniques. The highest quality patterns were used in all cases. All patterns were NC machined from 6061 aluminum billets and carefully checked for dimensional precision after machining.

The dimensions of the pattern are illustrated in Figure 10. A variation on this pattern has been shown to be useful in evaluating effects of process variables on casting precision.(23) The foam tool dimensions are presented in Table 3. The table contains the part drawing dimension, the calculated foam dimensions, the calculated tool dimensions, the measured tool dimensions and the tool deviations. The webbed cube test pattern illustrated in Figure 11 was selected to determine the effect of EPC process variations on casting quality.

A coordinate measuring machine was set up in the foam production facility and approximately 6% of the foams produced were carried to a coordinate measuring machine immediately after production for dimensional analysis and tracking of foam dimensional changes during stabilization.

Sample data illustrating measurement precision on a webbed cube casting are presented in Table 4. These measurements were made on a well-stabilized two year old foam pattern. The foam was removed from the machine between each measurement to obtain data on total system precision. The standard deviation in measurements on each face of the cube was approximately 0.0014 inches, and the coefficient of variation was about 0.048% or 0.00048 inch/inch.

The dimensional change data on 17 EPS foam cubes at a density of 1.3 lb/ft³ is illustrated in Figure 12 on a logarithmic time scale. The cubes

Cope	Non Dim (mm.)
VC	100
T	10
A	22
B	10
F	50
P	6

Drag	Non Dim (mm.)
VD	100
TRD	80
DHD	60
E	100
BN	5
PH	50

Note: 'X' and 'Y' are starter
dimples. All
others are 6mm
holes.

Figure 10. EPC Test Pattern for Dimensional Analysis.

615-406

Figure 11. Webbed Test Cube.

TABLE 4.
CMM Precision Data on Stabilized EPS Webbed Cube

Reading Number	<u>Dimensions from Center Line (Inches)</u>				Time
	0°	90°	180°	270°	
1	3.030	3.037	3.054	3.035	13:33:47
2	3.030	3.037	3.056	3.037	13:41:49
3	3.034	3.039	3.053	3.035	13:48:58
4	3.030	3.037	3.053	3.035	13:55:32
5	3.030	3.036	3.054	3.035	14:02:13
6	3.033	3.039	3.053	3.034	14:08:42
7	3.030	3.035	3.052	3.034	14:15:27
8	3.030	3.037	3.052	3.032	14:22:11
9	3.033	3.036	3.051	3.035	14:29:19
<hr/>					
$\bar{x}$ (in)	3.0314	3.0370	3.0531	3.0347	
σ (in)	0.0017	0.0013	0.0014	0.0013	
CV (%)	0.056	0.043	0.047	0.044	

615-631

615-498-R3

Figure 12. Percent Dimensional Changes from Cold Die Block Dimensions in 17 EPS Test Cubes Molded to a Density of 1.3 lb.ft³.

were initially approximately 0.8% under the room temperature die dimension, and gradually expanded until they were approximately 0.4-0.5% undersized. They then began contracting, and after 10,000 minutes (1 week), the patterns were approximately 0.7% under the die block dimension. After 140,000 minutes (14 weeks), the foams were about 1% under the die block centerline to face dimension. This is slightly higher shrinkage than reported in the literature.

The percentage change in foam dimensions from the cold die block dimensions after molding are plotted as a function of linear time in Figure 13. EPS cubes at 1.3 pcf were stable within 0.001 inch/inch after four weeks.

Four dimensions, illustrated in Figure 14, were selected for tracking the dimensional changes of the foam test cones after molding as a function of time after molding. The "A", "B", and "C" dimensions represent cone diameter measurements at progressively greater distances from the fill gun. The "H" dimension is the height of the cone across the parting line from the bottom of the flange to the top of the cone.

Typical "C" dimensional changes (flange width) for 1.3 pcf EPS are illustrated in Figure 15. The "C" dimension was initially about 0.75% under the die block dimension, expanded slightly between 100 minutes and 1,000 minutes after removal from the block, and then began to shrink. After about 5 weeks, the "C" dimension was approximately 1.25% under the die block dimension. The net shrinkage was slightly less nearer to the fill gun on the top of the cone.

The mean and standard deviation in pattern dimensions in EPS foam cones at densities of 1.3 and 1.6 lb/ft³ and EPMMA at a density of 1.5 lb/ft³ after aging about five weeks is presented in Table 5. The coefficient of variation in each measurement was below about 0.3% (0.003 inch/inch) in all

Figure 13. Percent Dimensional Changes from the Cold Die Block Dimensions in 17 EPS Test Cubes Molded to a Density of 1.3 lb/ft³. Plotted as a Function of Linear Lapsed Time.

615-707

Figure 14. Dimensional Measurements Made to Track Foam Changes.

Figure 15. Average "C" Dimensional Changes in 12 1.3 pcf EPS Cone Test Patterns.

MEAN AND STANDARD DEVIATION IN FOAM CONE DIMENSIONS
AFTER AGING APPROXIMATELY 58,000 MINUTES

45

cases except for the "A" dimension on EPMMA foams. This value was about 0.60% or 0.006 in/in.

A typical foam pattern is illustrated in Figure 16. The foam has been lightly sprayed with a commercial layout dye to make it easier to photograph. The cone pattern, as viewed from the top, is illustrated in Figure 16(a). A view from the bottom illustrating the sharp "vee" notch and holes is illustrated in Figure 16(b).

3.1 Sand Casting Dimensional Analysis

A schematic of the sand casting is illustrated in Figure 17. The only differences between the EPC test cone in 10 and the sand cast cone in Figure 17 are the four 6 mm diameter cast-in holes on the flange and the 12 mm diameter center hole on the top of the EPC cone. Both match-plate and cope and drag patterns were machined to produce this casting using a variety of molding techniques. A shrinkage of 1% was assumed from pattern dimensions for the metal being cast. The actual dimensions of both patterns and the expected casting dimensions assuming 1% shrinkage from the pattern are presented in Table 6.

All castings analyzed in this study were produced in commercial foundries. Some were produced from the match-plate pattern; others from the cope and drag pattern and still others were cast from EP foam patterns. All EP aluminum castings were produced from EPS foams with a density of 1.6 lb/ft³.

Iron castings were produced from EPS at a density of 1.3 lb/ft³ and EPMMA at a density of 1.5 lb/ft³. Mold coatings and compaction cycles were based on foundry experience. Future studies will be conducted to optimize the casting parameters and improve dimensional precision.

(a)

(b)

Figure 16. Foam Pattern after Shading with Dykem Layout Ink. (a) Top View and (b) Bottom of Pattern.

Cope	Non Dim (mm)
VC	100
T	10
A	22
B	10
F	50
P	6
Drag	
VD	100
TRD	80
DHD	60
E	100
BN	5
PH	50

Note: 'X' and 'Y' are starter dimples.

Figure 17. Sand Casting Test Pattern for Dimensional Analysis.

5-524

TABLE 6

MATCH-PLATE AND COPE AND DRAG PATTERN DIMENSIONS

<u>DIMENSION</u>	<u>MATCH-PLATE PATTERN MEASUREMENT (INCH)</u>	<u>EXPECTED MEASUREMENT (1% SHRINKAGE) (INCH)</u>
A	0.874	0.865
B	1.751	1.734
C	3.578	3.542
H	4.376	4.332

<u>DIMENSION</u>	<u>COPE & DRAG PATTERNS MEASUREMENT (INCH)</u>	<u>EXPECTED MEASUREMENT (1% SHRINKAGE) (INCH)</u>
A	0.875	0.866
B	1.751	1.734
C	3.571	3.541
H	4.378	4.334

615-748.TAB

3.2 Data Presentation

A total of 22 green sand castings poured at participating foundry AE7 were dimensionally analyzed. Typical dimensional data for a set of sand castings is presented in Table 7. This table presents data on the "B" casting dimension, but other dimensions were similarly analyzed.

The cones were numbered from 1 through 22. The "B" match-plate dimension was 1.752 inches. Each cone was put on the Coordinate Measuring Machine (CMM) and the dimensional analysis performed. Four measurements were made at 90° intervals at "A", "B", "C" and "H" positions as the casting was rotated. The average dimension was then calculated from the four individual readings, and the casting dimensional changes from the pattern dimensions were calculated. This procedure was repeated for each of the 22 castings at each position.

The mean, standard deviation (σ), 3 standard deviations (3σ), and coefficient of variation (CV) was calculated for each of the four columns of data corresponding to casting positions at 0, 90, 180, and 270°. Finally, the entire group mean, standard deviation (σ), 3σ , and CV was calculated for the entire data population. These values are located at the bottom of the "Average" column. Finally, the average change in casting dimension from the pattern dimension was calculated. In this case, the casting change from the pattern dimension averaged 1.22%.

Similar data on 28 1.3 lb/ft³ EPS patterns are presented in Table 8. All cones were serialized during production so dimensional changes with time could be monitored. These cones were about 35000-38000 minutes old (nearly four weeks) when they were shipped to the participating foundry for casting. Prior to shipment, the dimensions were checked at the "A", "B", "C", and "H" positions, and the average dimensions and dimensional precision

TABLE 7.

Dimensional Analysis on 356 Aluminum Cone Castings
Made From Experimental Matchplate Pattern (Foundry AE7)
(Green Sand)

Cone Number	Matchplate Pattern Dia. (in.)	"B" Dimension					Average Change From Pattern (%)
		0° (in.)	90° (in.)	180° (in.)	270° (in.)	Average (in.)	
1	1.752	1.748	1.740	1.718	1.748	1.739	-0.771
2	1.752	1.737	1.713	1.719	1.754	1.731	-1.209
3	1.752	1.737	1.727	1.736	1.746	1.736	-0.910
4	1.752	1.750	1.746	1.717	1.730	1.736	-0.920
5	1.752	1.734	1.739	1.723	1.719	1.729	-1.331
6	1.752	1.749	1.746	1.717	1.731	1.736	-0.928
7	1.752	1.738	1.736	1.717	1.732	1.731	-1.216
8	1.752	1.739	1.717	1.713	1.736	1.726	-1.480
9	1.752	1.736	1.742	1.715	1.714	1.727	-1.452
10	1.752	1.748	1.747	1.722	1.731	1.737	-0.856
11	1.752	1.721	1.731	1.721	1.718	1.722	-1.687
12	1.752	1.737	1.710	1.716	1.752	1.729	-1.323
13	1.752	1.723	1.726	1.735	1.729	1.728	-1.370
14	1.752	1.748	1.703	1.715	1.765	1.733	-1.099
15	1.752	1.724	1.724	1.718	1.713	1.720	-1.848
16	1.752	1.719	1.724	1.733	1.736	1.728	-1.381
17	1.752	1.724	1.720	1.745	1.745	1.734	-1.052
18	1.752	1.729	1.745	1.751	1.733	1.739	-0.717
19	1.752	1.732	1.706	1.722	1.747	1.727	-1.452
20	1.752	1.731	1.717	1.721	1.731	1.725	-1.534
21	1.752	1.728	1.722	1.727	1.731	1.727	-1.434
22	1.752	1.748	1.725	1.730	1.745	1.737	-0.853
Average =		1.735	1.727	1.724	1.736	1.731	-1.219
s =		0.010	0.014	0.010	0.013	0.013	0.312
3s =		0.030	0.041	0.031	0.040	0.038	0.935
C. V. =		0.578	0.787	0.592	0.774	0.738	

615-750

TABLE 8.

Dimensional Analysis on Gray Iron Cone Castings
Made From Experimental Foss Patterns (Foundry AC4)

Core Number	Foss Type	Lapsed Time From Product To Measure (min)	9° Dimension Foss Patterns Distance From Centerline				9° Dimension Foss Castings Distance From Centerline				Average Change Of Foss From Cold Die Dia. (%)	Average Change Of Casting From Foss Dia. (%)	Average Change Of Casting From Cold Die Dia. (%)
			0° (in.)	90° (in.)	180° (in.)	270° (in.)	Average (in.)	0° (in.)	90° (in.)	180° (in.)	270° (in.)	Average (in.)	
190	1.3 EPS	37810	1.765	1.767	1.770	1.769	1.768	1.822	1.741	1.695	1.767	1.756	-0.513
191	1.3 EPS	35935	1.761	1.766	1.772	1.766	1.766	1.744	1.739	1.735	1.747	1.741	-1.353
192	1.3 EPS	35964	1.762	1.762	1.772	1.770	1.767	1.727	1.754	1.752	1.714	1.737	-1.604
193	1.3 EPS	35972	1.765	1.759	1.771	1.773	1.766	1.745	1.741	1.740	1.733	1.739	-1.452
194	1.3 EPS	35982	1.765	1.763	1.774	1.771	1.767	1.766	1.741	1.718	1.726	1.738	-1.547
195	1.3 EPS	35992	1.762	1.767	1.773	1.766	1.767	1.729	1.748	1.749	1.731	1.739	-1.477
196	1.3 EPS	36016	1.765	1.768	1.769	1.764	1.767	1.739	1.761	1.766	1.754	1.753	-0.567
199	1.3 EPS	35838	1.765	1.759	1.774	1.775	1.767	1.748	1.742	1.727	1.741	1.746	-1.445
202	1.3 EPS	35879	1.765	1.765	1.774	1.768	1.767	1.747	1.741	1.733	1.733	1.739	-1.602
203	1.3 EPS	35888	1.765	1.767	1.771	1.765	1.766	1.742	1.724	1.738	1.761	1.741	-1.363
204	1.3 EPS	35898	1.762	1.768	1.770	1.766	1.767	1.742	1.749	1.737	1.729	1.739	-1.455
205	1.3 EPS	35910	1.762	1.760	1.771	1.773	1.767	1.700	1.763	1.778	1.710	1.738	-1.537
206	1.3 EPS	35918	1.765	1.758	1.773	1.775	1.766	1.763	1.746	1.711	1.743	1.741	-1.385
207	1.3 EPS	35846	1.765	1.769	1.772	1.772	1.766	1.714	1.728	1.766	1.749	1.739	-1.448
212	1.3 EPS	35896	1.765	1.762	1.771	1.770	1.766	1.741	1.750	1.736	1.738	1.739	-1.459
219	1.3 EPS	35760	1.765	1.761	1.771	1.771	1.766	1.746	1.747	1.754	1.746	1.748	-0.963
220	1.3 EPS	35769	1.765	1.763	1.769	1.774	1.767	1.747	1.743	1.733	1.736	1.739	-1.448
223	1.3 EPS	35917	1.765	1.762	1.774	1.766	1.767	1.754	1.728	1.738	1.751	1.740	-1.395
224	1.3 EPS	35825	1.765	1.768	1.772	1.765	1.767	1.743	1.748	1.736	1.734	1.740	-1.402
226	1.3 EPS	35818	1.765	1.762	1.772	1.769	1.767	1.752	1.733	1.730	1.753	1.742	-1.307
227	1.3 EPS	35860	1.765	1.764	1.772	1.769	1.766	1.738	1.739	1.739	1.741	1.739	-1.462
228	1.3 EPS	35871	1.765	1.767	1.769	1.765	1.766	1.766	1.734	1.715	1.741	1.739	-1.491
231	1.3 EPS	37742	1.765	1.766	1.774	1.771	1.769	1.724	1.698	1.757	1.773	1.738	-1.516
232	1.3 EPS	37802	1.765	1.765	1.772	1.771	1.768	1.737	1.745	1.740	1.738	1.740	-1.427
233	1.3 EPS	37810	1.765	1.767	1.773	1.770	1.769	1.756	1.750	1.754	1.767	1.757	-0.471
234	1.3 EPS	36280	1.765	1.765	1.772	1.773	1.768	1.711	1.735	1.767	1.741	1.739	-1.686
235	1.3 EPS	36290	1.765	1.767	1.769	1.766	1.768	1.743	1.754	1.737	1.729	1.741	-1.381
236	1.3 EPS	36300	1.765	1.771	1.768	1.767	1.769	1.750	1.744	1.729	1.737	1.740	-1.424
Average =			1.763	1.764	1.772	1.769	1.767	1.744	1.742	1.739	1.741	1.741	-1.440
s			0.003	0.004	0.002	0.003	0.005	0.022	0.013	0.018	0.015	0.017	0.308
3s			0.008	0.011	0.005	0.010	0.014	0.065	0.038	0.055	0.045	0.051	0.925
C.V.			0.144	0.199	0.097	0.187	0.262	1.238	0.722	1.657	0.654	0.979	615-751

calculated as previously described. The average "B" dimension was 1.767 inches with a standard deviation of 0.005 inch and a coefficient of variation of 0.26% or 0.0026 inch/inch.

Similar measurements were made on the castings when they were returned. The mean "B" dimension on 28 cones was 1.741 inches with a standard deviation of 0.017 inch. The coefficient of variation was 0.98% or 0.0098 inch/inch in this diameter.

Finally, this table presents the average change in the foam "B" dimension from the cold tool dimension, the average change in the casting from the foam dimension and the average casting change from the tool dimension.

The average "B" casting dimension was 1.741 in. with a standard deviation of 0.017 in. The average change in the casting dimension from the cold die dimensions was -1.33%.

3.3 Casting Results

Dimensional precision data on cast 356 and 319 aluminum test cones are presented in Table 9. Foundry AE7 produced 356 aluminum test cones from a match-plate pattern in green sand. The sand was prepared using 130 AFS GFN olivine sand with about 6.5% bentonite. Each casting was poured at a temperature of approximately 1375 °F in six seconds from a 15 lb lip pour ladle. The runner on each casting had a 1:4:4 sprue:runner:ingate area.

The expected casting dimensions for the match-plate pattern were 0.866, 1.734, 3.542, and 4.332 inches, respectively, based on 1% metal shrinkage from the mold. The green sand castings had an "A" dimension of 0.874 inches, a "B" dimension of 1.731 inches, a "C" dimension of 3.534 inches, and an "H" dimension of 4.323 inches. The expected casting dimensions for the match-plate pattern were 0.866, 1.734, 3.542, and 4.332 inches, respectively. The standard deviation in all cases was 0.02 inches or less.

TABLE 9

Dimensional Measurements and Precision on Cast Aluminum Alloy Cones
Cast Using Conventional and EPC Methods

Table, Sand & Coating					Compaction (rpm.sec)	Casting Dimension (in)				Surface Finish (rms) σ
Fdry	Metal	Pattern	Sand	Coating		A	B	C	H	
M/P Pattern -1.0%										
AE7	356	MP	Olivine, 130GFN, Green	MP Pattern		0.866	1.734	3.542	4.332	
					x - 0.874	1.731	3.534	4.323	378	
					s - 0.018	0.013	0.011	0.018	45	
					3s - 0.053	0.038	0.033	0.054		
					CV% - 2.030	0.738	0.311	0.419		
						n - 22				
C/D Pattern -1.0%										
AE9	356	C/D	Silica & Zircon 1% Urethane	G/D Pattern		0.867	1.734	3.541	4.334	
					x - 0.862	1.727	3.531	4.335	563	
					s - 0.018	0.011	0.013	0.019	66	
					3s - 0.053	0.032	0.038	0.058		
					CV% - 2.039	0.623	0.358	0.447		
						n - 25				
Foam Tool -0.8% -1.0%										
AC4	319	1.6 EPS 40 AFS, Silica-Alumina Based Coating (Not Blasted)		1800,4 2800,7		0.871	1.734	3.542	4.334	
					x - 0.877	1.743	3.522	4.364	223	
					s - 0.014	0.006	0.004	0.012	32	
					3s - 0.042	0.019	0.012	0.036		
					CV% - 1.597	0.356	0.117	0.272		
						n - 24				
AC4	356	1.6 EPS 40 AFS, Silica-Alumina Based Coating (Not Blasted)		1800,4 2800,7		0.876	1.740	3.518	4.357	181
					x - 0.876	1.740	3.518	4.357	181	
					s - 0.015	0.007	0.004	0.010	12	
					3s - 0.045	0.022	0.013	0.031		
					CV% - 1.695	0.424	0.126	0.236		
						n - 4				
AB9	356	1.6 EPS 31 AFS, Silica-Alumina Based Coating (Blasted)		3100,60		0.874	1.740	3.517	4.349	465
					x - 0.874	1.740	3.517	4.349	465	
					s - 0.031	0.015	0.008	0.025	24	
					3s - 0.093	0.044	0.025	0.074		
					CV% - 3.564	0.852	0.235	0.564		
						n - 30				

The coefficient of variation was 2% on the "A" dimension, 0.74% on the "B" dimension, 0.31 on the "C", and 0.42 on the "H" dimension.

Similar results were obtained on the cope and drag pattern. The anticipated casting dimensions, assuming a 1% shrink of the metal from the pattern dimension, was 0.867, 1.734, 3.541, and 4.334 inches for the "A", "B", "C", and "H" dimensions, respectively. Foundry AE9 cast 356 aluminum test cones using 1% urethane binder in a blended silica + zircon sand from the cope and drag pattern. The average casting dimensions were approximately 0.01 inches below the calculated casting dimensions on the "A", "B", and "C" positions. The "H" dimension was the same as the expected dimension.

The coefficient of variation based on 25 castings was close to that obtained with the green sand molds. The coefficient of variation on the "A" dimension was 2.04% and 0.62, 0.36, and 0.45% on the "B", "C", and "H" dimensions, respectively.

The remaining three entries in Table 9 represent EP castings poured from either 319 or 356 aluminum. Foundry AC4 cast 319 aluminum test cones using EPS patterns at a density of 1.6 lb/ft³. The foam patterns were coated with silica-alumina based coating and backed up with AFS GFN 40 silica sand. Sand was compacted around the patterns for about 4 seconds at 1800 rpm and 7 seconds at 2800 rpm using a single axis vertical unclamped vibration compaction table.

The expected casting dimensions based on -0.8% foam shrinkage from the tool and 1% metal shrinkage from the foam should produce castings with "A", "B", "C", and "H" dimensions of 0.871, 1.734, 3.542, and 4.334 inches, respectively. The "A" and "B" dimensions obtained on the 319 aluminum were approximately as expected. The "C" dimension was 0.02 in undersized and the "H" dimension was 0.03 in oversized. The standard deviation in dimensional

measurements was somewhat smaller than obtained with sand castings. The standard deviation in the "A" dimension was 0.014 inches and standard deviations in the "B", "C", and "H" dimensions were 0.006, 0.004, 0.012 inches, respectively.

The coefficient of variation in the "A" dimension was 1.59%. The coefficient of variation in the "B", "C", and "H" dimensions was 0.36, 0.12, and 0.27 per cent, respectively. These castings had a surface finish of 223 with a standard deviation of 32 microinches.

Similar data on a smaller sample of four 356 aluminum test cones also are presented in Table 9. The 356 castings were produced with the same sand compaction cycle and coating on the foam. The calculated dimension was achieved on the "A" and "B" position. The "C" dimension was 0.02 undersized and the "H" dimension was 0.03 inch oversized.

Thirty test cones made from 356 aluminum were supplied by Foundry AB9. These castings were produced from EPS at a density of 1.6 lb/ft³ and poured into a mold prepared with AFS GFN 31 silica sand. The compaction cycle consisted of vibrating for 60 seconds at 3100 rpm. Almost identical results were obtained in this foundry compared to those produced in Foundry AC4. The "A", "B", "C", and "H" dimensions were 0.874, 1.740, 3.517, and 4.349 inches, respectively. The standard deviation for each of these positions was 0.31, 0.015, 0.008, and 0.025 inches respectively. The coefficient of variation was 3% in the "A" dimension, and somewhat lower at values of 0.85, 0.24, 0.56% in the "B", "C", and "H" positions. These castings after blasting had a surface finish of 465 microinches rms with a standard deviation of 24 microinches rms.

Photographs of a typical aluminum casting made from EPS is illustrated in Figure 18. The ability to cast in holes such as illustrated in this makes EP castings commercially attractive.

(a)

(b)

Figure 18. Photographs of a Typical Aluminum Test Casting Made from EPS Pattern. (a) Top View and (b) Bottom of Casting.

Similar dimensional analyses of iron castings are presented in Table 10. Assuming casting shrinkage from the match-plate pattern of 1%, iron castings are expected to have dimensions of 0.866, 1.734, 3.543, and 4.332 inches in the "A", "B", "C", and "H" positions.

Foundry AE8 produced gray iron castings using AFS GFN 60 silica sand with clay and achieved dimensions 0.870, 1.743, 3.543, and 4.354 inches. The standard deviation in all cases was 0.02 to 0.03 inches. The coefficient of variation based on 29 castings was 3.16% in the "A" dimension, 0.94% in the "B" dimension, and 0.42 and 0.44% in the "C" and "H" dimension.

Foundry AB5 produced ductile iron castings from the cope and drag pattern. The cope and drag pattern was expected to produce dimensions identical to the match-plate pattern. Twenty cope and drag ductile iron castings had average "A", "B", "C", and "H" dimensions of 0.866, 1.732, 3.540, and 4.348 inches, respectively. The "H" dimension was 0.02 inches greater than calculated probably because of the effect of the parting line.

EP castings were produced in two foundries using single axis vertical unclamped tables with silica backing sand. Foundry AC4 used a compaction cycle consisting of vibrating for 20 seconds at 1800 rpm, 15 seconds at 2100 rpm, 30 seconds at 2400 rpm, and 15 seconds at 2150 rpm. Twenty-eight castings were produced with casting dimensions of 0.872, 1.741, 3.525, 4.355 inches, respectively for the "A", "B", "C", and "H" dimensions. The "H" dimension was approximately 0.03 inches greater than expected.

Foundry AC1 produced fourteen castings with a more complicated compaction cycle. Dimensions of 0.882, 1.755, 3.543, and 4.391 inches were obtained for the "A", "B", "C", and "H" dimensions respectively. The coefficient of variation was approximately 4.1% in the "A" dimension, 1.1% in the "B" dimension, 0.36 in the "C" and 0.81% in the "H" dimension. These

TABLE 10
Dimensional Measurements and Precision of Gray and Ductile Iron Cones
Cast Using Conventional and EPC Methods

Table, Sand & Coating					Compaction (rpm,sec)	Casting Dimension (in)				Surface Finish (rms)
Fdry	Metal	Pattern	Sand & Coating			A	B	C	H	
M/P Pattern - 1.0%										
AE8	GI	MP	60 GFN Silica + Clay	MP Pattern		0.866	1.734	3.543	4.332	627
					x -	0.870	1.743	3.543	4.354	76
					s -	0.028	0.016	0.015	0.019	
					3s -	0.083	0.049	0.044	0.057	
					CV% -	3.160	0.940	0.418	0.434	
n - 29										
C/D Pattern - 1.0%										
AB5	DI	C/D Phenolic Urethane	Silica	C/D Pattern		0.867	1.734	3.541	4.334	763
					x -	0.866	1.732	3.540	4.348	40
					s -	0.024	0.012	0.008	0.019	
					3s -	0.072	0.037	0.023	0.057	
					CV% -	2.781	0.705	0.219	0.438	
n - 20										
Foam Tool - 0.8% - 1.0%										
AC4	GI	1.3 EPS	GK 1 Axis 40 GFN 380 PM	1800,20 2100,15 2400,30 2150,15		0.871	1.734	3.542	4.334	410
					x -	0.872	1.741	3.525	4.355	79
					s -	0.038	0.017	0.011	0.037	
					3s -	0.115	0.051	0.032	0.111	
					CV% -	4.384	0.979	0.302	0.849	
n - 28										
AC1	GI	1.5 PMA	GK 1 Axis 34 GFN Mullite-Based Coating	1450,6 1750,6 1900,7 2100,10 2350,31 2650,20		0.882	1.755	3.543	4.391	580
					x -	0.882	1.755	3.543	4.391	109
					s -	0.036	0.019	0.013	0.036	
					3s -	0.108	0.057	0.038	0.107	
					CV% -	4.076	1.088	0.359	0.809	
n - 14										

615-759-CR2

dimanally.tab-pg 13

coefficient of variation values were similar to those obtained in Foundry AC4. The gray iron castings had an average surface finish of 627 rms microinches with a standard deviation of 76 microinches.

The ductile iron castings had an average surface finish of 763 rms microinches with a standard deviation of 40 microinches.

A typical EP cast iron part is illustrated in Figure 19. The surface finish was 410 microinches with a standard deviation of 79 microinches. The EP cast parts had a better surface finish than the sand cast parts.

It is concluded from these dimensional analyses that EP test cone castings have good dimensional precision, but not necessarily better precision when similar sand castings are made from high quality, precisely machined patterns. One of the reasons that the test cone design was selected for dimensional analysis was because it could be cast by both EP and conventional casting techniques. One of the main advantages of EPC is that it provides a method for casting parts not possible with conventional sand casting methods.

(b)

(a)

Figure 19. Typical EP Foam Cast Gray Iron Casting. (a) Top View
(b) Bottom View.

4.0 CASTING DEFECT ANALYSIS

A wide variety of casting defects can be obtained in EP aluminum and iron castings, although a few seem to occur much more frequently than others. The following preliminary definitions are based on appearance and microstructure of a variety of defects submitted. Refinements in some of these definitions will be made as more experience is obtained.

4.0.1 Core Shift or Float

Shifts and core float phenomena in EP castings result when cores have inadequate stiffness to resist the static or dynamic metal pressures exerted during filling and solidification. EPC cores will distort and float much like conventional cores. Flotation resistance is increased by high densification, application of a vacuum, and by keeping cores vertical so the cores are primarily in compression rather than in tension or shear.

4.0.2 Erosion

Erosion results in rough spots and areas of excess metal caused by erosion of the sprue, mold, or core surface by metal flow. Erosion produces objectionable sand inclusions somewhere in the casting.

4.0.3 Exogenous Inclusions

Exogenous inclusions are particles of foreign material embedded in the metal. If these inclusions are at the surface, they may be removed during cleaning, leaving holes.

Typical exogenous inclusions include eroded sand from various parts of a mold or sprue, slag from the melting furnace or pouring ladle, oxidation products formed during turbulent pouring, eroded mold wash, and incompletely eliminated pyrolysis products from foams and glues.

4.0.4 Fins

Fins appear as an irregular line of metal protruding from the surface of a casting. Fins on EP castings result from expansion-contraction forces on the casting or rough mechanical handling. The metal was fluid enough to enter the crack when the fin formed.

4.0.5 Gas

Gas holes usually occur at or near the surface of castings. The holes are caused by localized gas pressure that exceeds the metal pressure. Small gas holes usually are called pinholes and larger ones called blows. Both are manifestations of the same phenomena -- they just differ in size and extent. Gas and shrinkage defects also are sometimes difficult to differentiate. Gas defects usually are thought to be smooth and rounded, and shrinkage defects to be irregular and dendritic. Gas defects often occur in combination with shrinkage defects, and the predominate cause is difficult to determine.

4.0.6 Hot Tears

Hot tears are tensile fractures in metal occurring at elevated temperatures as the sand is heated and expands while the metal cools and contracts. Hot tears usually appear as linear or planar defects. On complete fracture, the tear is usually discolored because of oxidation that occurred at an elevated temperature.

4.0.7 Metal Shot

Shot metal or cold shuts are small globules of metal embedded in, but not entirely fused with, the casting. Metal shot shows as an approximately round ball sometimes coated with carbonaceous pyrolysis products, while a cold shut is a form of misrun and appears as a crack or seam

that also may contain pyrolysis products. Seams, shots, and shuts are related closely in EP castings and result from incomplete bonding at metal surfaces.

4.0.8 Mold Collapse

A mold or core collapse is a casting defect caused by dropping of a portion of sand from the cope, core, or other overhanging section into the casting. Collapse of a mold or core commonly is caused by an interrupted pour. The foam continues to decompose from the radiant heat resulting in an excessively wide gap between the metal and foam. Mold collapse is minimized by the application of a vacuum and rapid and continuous pouring.

4.0.9 Penetration

Metal penetration is a condition in which the metal or metallic oxides penetrate the voids between sand grains without displacing them. Penetration suggests an openness of the mold surface that may be caused by poor sand compaction or by localized gas pressures exceeding the sand head pressure. Penetration is aggravated by low interfacial energies between the metal and the sand.

4.0.10 Short Pour

An incompletely filled casting cavity has been poured short. A short pour may be the result of a gas back pressure caused by inadequate mold permeability or improper gating system design or by attempting to pour cold metal.

4.0.11 Shrinkage

A shrinkage cavity usually consists of a jagged hole or spongy area often lined with dendrites. A shrinkage depression on the surface of a casting is a recession from the true plane or the mold surface. It is characteristic of a shrink to appear in heavier sections, at changes of

section, and or at hot spots. These same locations also are prone to gas defects.

4.1 Examples of Major Defects Observed In Production EP Castings

4.1.1 Carbonaceous Residue

Carbonaceous residue may result from incompletely pyrolyzed foam or glue. The manifestations of carbonaceous residue are usually laps and folds in and on the surface of castings. A black, tar-like residue may be found in iron castings especially on the cope surface.

A carbon residue fold defect in gray iron is illustrated in Figure 20. The folds appear as overgrown carbon flakes, but they are much longer than flakes in the matrix of the iron.

Typical carbon folds in ductile iron are illustrated in Figure 21. Again, the folds appear as long carbon stringers in the ductile iron matrix.

4.1.2 Fluidized Sand Defects

A fluidized sand defect on a 413B aluminum casting is illustrated in Figure 22. The sand was fluidized by escaping pyrolysis gases causing the metal to collapse from one portion of the casting onto the inner casting wall. This type of defect can be eliminated by reducing the gas volume, venting the gas or by applying a vacuum to both stiffen the sand and aid in gas removal.

A similar defect in an iron casting bolt hole is illustrated in Figure 23. Again, gas has forced sand from the cavity allowing metal which penetrated the mold wash to partially fill the bolt hole. Some sand is present, causing the defect to externally appear to be a penetration defect, but very little penetration of the sand by the metal has actually occurred. A rather gross case of sand fluidization is illustrated in Figure 24.

Sufficient gas pressure was developed to cause sand fluidization and lifting of the top casting surface about 6 inches above its proper position. This

Figure 20. Carbon Defects in Gray Iron Casting. (a) 0.75X (b) 200X

(a)

(b)

Figure 21. Carbon Folds in Ductile Iron at Magnifications of
(a) 25X and (b) 200X.

Figure 22. Fluidized Sand Defect Near Glue Line.

Figure 23. Sand Fluidization Defect in Casting Bolt Hole.

Figure 24. Sand Fluidization in Iron Casting Tree.

type of defect can only be cured by reducing the gas volume, increasing the sand head height or by applying a vacuum to remove gas and stiffen the sand.

4.1.3 Penetration

A penetration defect on the interior of a gray iron casting is illustrated in Figure 25. This defect contains the mold coating and locked on sand grains. The sand density in the penetrated area was rather low, approximately 94.2 lb/ft³ as determined by quantitative microscopic analysis.

4.1.4 Core Float

A core float is illustrated in Figure 26. The core had inadequate stiffness to resist the metal head pressure and simply fractured and then "floated" before the metal solidified.

4.1.5 Burned-on Sand

Burned-on sand is considered to be a more severe case of metal penetration resulting in large volumes of sand integrally locked on to the casting. A substantial area of burned on sand on a gray iron casting is illustrated in Figure 27. This sand had an apparent density of about 93.5 lb/ft³ as determined from the area fraction of sand in the cross section.

4.2 Casting Defects Summary

A compilation of the wide variety of defects submitted by program participants is presented in Table 11. Displaced and burned on sand accounted for over 50% of the defects in EP castings. Carbon folds and related defects and gas were the two other major categories. These three defects accounted for approximately 90% of the defects in the gray and ductile iron castings and about 85% of the defects in aluminum castings analyzed.

Figure 25. Penetration Defect in Gray Iron Casting (50X).
Sand Density 94.2 lb/ft³.

Figure 26. Core Shift and Sand Flotation in 1.6 EPS Test Cube.
(a) Corner Containing Blind Hole Sawcut from Cube
(b) Cross-Section Showing Coating and Penetration. (25X)

Figure 27. Burn-on from a Gray Iron Test Cube AC4. Sand Density
93.5 lb/ft₃.

TABLE 11

SUMMARY OF DEFECTS OBSERVED IN IRON AND ALUMINUM CASTINGS

GRAY IRON

<u>FOUNDRY</u>	<u>MOLD TYPE</u>	<u>DISPLACED SAND AND/OR BURN-ON</u>	<u>GAS</u>	<u>CARBON</u>	<u>MOLD</u>	<u>OTHER</u>	<u>NUMBER OF DEFECTS</u>
AE8	GREEN SAND	35	36	3	0	28	102
AC4	NO-BAKE	0	25	16	13	17	71
AC4	1.3 EPS	105	23	24	0	26	178
AC4	1.5 EPMMA	138	21	54	0	7	220
AC1	1.5 EPMMA	32	35	11	0	10	88
TOTAL		310	140	108	13	88	659

DUCTILE IRON

<u>FOUNDRY</u>	<u>MOLD TYPE</u>	<u>DISPLACED SAND AND/OR BURN-ON</u>	<u>GAS</u>	<u>CARBON</u>	<u>MOLD</u>	<u>OTHER</u>	<u>NUMBER OF DEFECTS</u>
AB1	GREEN SAND	0	3	0	0	7	10
AB5	NO-BAKE	0	20	2	0	0	22
AB5	1.3 EPS	10	1	7	0	0	18
AB5	1.5 EPMMA	9	2	3	0	1	15
TOTAL		19	26	12	0	8	65

ALUMINUM

<u>FOUNDRY</u>	<u>MOLD TYPE</u>	<u>DISPLACED SAND AND/OR BURN-ON</u>	<u>GAS</u>	<u>CARBON</u>	<u>MOLD OR CORESHIFT</u>	<u>OTHER</u>	<u>NUMBER OF DEFECTS</u>
AE7	GREEN SAND	14	5	1	14	0	34
AE9	NO-BAKE	25	0	0	0	0	25
AB9	1.6 EPS	138	11	19	0	4	172
AC3	1.6 EPS	56	1	10	22	0	89
AC4	1.6 EPS	9	1	0	0	0	10
TOTAL		242	18	30	36	4	320
TOTALS (ALL METALS)		571	184	150	49	100	1044

615-849.tab

This program was conducted to review and summarize the literature on EP casting, evaluate factors influencing sand flow and compaction, evaluate casting precision using EP and other casting processes, and identify critical parameters controlling dimensional precision and casting defect formation.

The literature search included making foundry visits, and compiling, analyzing, and summarizing available technical information about the process. Approximately 350 published papers were obtained from the open literature and participating companies for analysis.

Sand flow and compaction is a critical area of the process about which much has to be learned. The forces required to overcome friction and cause interparticle rearrangement are not understood, and no model has been found to explain the required events. Compaction of sand on vertical faces is reasonably easy, but fill and compaction under horizontal surfaces and in holes is more difficult and not well understood. Long range sand flow associated with achieving compaction is a major cause of dimensional imprecision.

Factors were evaluated that influence dimensional precision of EP castings, and data on EP castings were compared with data on castings made using green and no-bake sand casting processes. A cone pattern was selected to evaluate effects of inter-process variations. All sand casting processes had difficulty with the 0.5° taper on the pattern. After much difficulty drawing the pattern from sand molds, the cope and drag pattern taper was increased to 1° . None of the conventional sand casting processes could produce cast-in holes on the flange or top of the cone casting.

EP castings had cast-in holes, almost zero taper, close dimensional tolerances, and a superior surface finish compared to the sand

castings. The iron castings produced using the EPC process were acceptable but several castings exhibited casting defects, principally metal penetration.

Future studies will be conducted to optimize casting parameters and improve dimensional precision.

The principal advantage of EP Casting appears to be its ability to cast in special features to reduce or eliminate machining. Simple parts without holes or other special features could be cast equally as precisely with conventional casting processes.

The three major types of defects found in test castings were gas, carbon pyrolysis products, and displaced sand and/or sand burn-on. Many factors influence defect formation including the metal pouring rate, ratio of surface area to cross-sectional area of the pattern, solidification time of the casting, heat transfer rate to the pattern, diffusivity of pattern decomposition products through the pattern wash, polymer melt viscosity, and ease of passage of depolymerization products from the foam into the mold.

There is a great deal of uncertainty about the nature of reactions occurring in the metal-foam interphase region and the effects of metal temperature in this area. This is a critical area that must be better understood if casting defects are to be understood and eliminated. The same is true of glue pyrolysis.

It is apparent from an examination of defects submitted in this study that many defects are a result of inadequate sand compaction. It is essential that a better understanding be gained of sand compaction, and instrumentation is needed that can be used in flasks to periodically measure the extent of in-situ compaction. Better procedures may also be needed to measure sand flowability.

The production of high quality EP castings requires learning how to compact sand without distorting low modulus patterns, learning how to deal with the pyrolysis products from foams and glues, and developing instrumentation to monitor the critical steps in the process.

REFERENCES

1. Shroyer, H.F. (Inventor) "Cavityless Casting Mold and Method of Making Same". U.S. PATENT 2830343. April 15, 1958. 10 p.
2. Gorla, C.A.; G. Del Gaudio "Moulding of Iron Castings with Evaporative Polystyrene Foam Patterns Immersed in Loose Sand: Prospects and Problems". METALLURGICAL SCIENCE AND TECHNOLOGY. No. 1 June, 1983. 14-31 p.
3. Bailey, Robin "Understanding the Evaporative Pattern Casting Process (EPC)". MODERN CASTING. April, 1982. 58-61 p.
4. Smith, T.R. (Inventor) "Method of Casting". U.S. PATENT 3,157,924. 1964. 4 p.
5. Dieter, H.B.; Paoli, A.J. "Sand Without Binder for Making Full Mold Castings". AFS TRANSACTIONS. 1967. 147-160 p.
6. Wittmoser, Adalbert "Full Mold Casting". AFS TRANSACTIONS. 1964. 292-303 p.
7. Thomas, Jacques "Improvement to the Lost Foam Process: Casting--A New Patented Process Developed by Aluminum Pechiney". PRESENTATION MADE AT 4TH ANNUAL EPC CONFERENCE, ROSEMONT, IL. June 6-7, 1989.
8. Ashton, M.C.; Sharman, S.G.; Brookes, A.J. "The Replicast FM (Full Mold) and CS (Ceramic Shell) Process". AFS TRANSACTIONS. No. 22. 1984. 271-280 p.
9. Gorla, C.A.; Remondino, M.; Seli, M. "Developing Equipment for Policast Lost Foam Moulding". FOUNDRY TRADE JOURNAL. September 12, 1985. 188-196 p.
10. Wieser, Peter F. "New Molding Processes-V-Process, Full Mold Process: STEEL FOUNDRY FACTS. January 1978. 14-22 p.
11. "The Evaporative Casting Process Using Expandable Polystyrene Patterns and Unbonded Sand Casting Techniques". ARCO CHEMICAL TECHNICAL DATA. September 24, 1982. 1-8 p.
12. "EPC Demands on Pattern Material". PRIVATE COMMUNICATION WITH NORMAN MOLL, DOW CHEMICAL. June, 1989. 1-9 p.
13. Wessman, Eric "Update: ECP Goes on Line at Ford's Essex Plant". MODERN CASTING. MARCH, 1985. 1-4 p.
14. Burchell, V.H. "Production Systems for Lost Foam Castings". AFS TRANSACTIONS. 1984. 629-636 P.

15. McMellon, B.A. "Design and Operation of Production Lost Foam Casting Systems". AFS TRANSACTIONS 88-09. 1988. 27-36 P.
16. Rodgers, Robert "Automating Lost Foam Casting". FOUNDRY MANAGEMENT & TECH. April, 1988. 1-5 p.
17. Patz, Murray "Unique Casting Applications with Lost Foam ". PRESENTATION MADE AT 4TH EPC CONFERENCE, ROSEMONT, IL. June 6-7, 1989.
18. Hubler, D. "Evaporative Pattern Casting". THE CRUCIBLE. March/April 1987. 2-5 p.
19. Hubler, D. "Evaporative Pattern Casting". THE CRUCIBLE. May/June 1987. 8-11 P.
20. Troxler, John "Design Advantages of the Evaporative Pattern Casting Process". PRIVATE COMMUNICATION WITH JOHN TROXLER. June 1989. 1-8 p.
21. Longnecker, Elmer F.; Kanoah, K.; Fukuya, J.S. "High Production Quality Iron Casting in Japan-Factors for Good Evaporative Foam Process Performance". EFC TECHNOLOGY III. June 7-8, 1988. 5-38 p.
22. Bates, Charles "State of the Art and Five Year Goals". EFC TECHNOLOGY III June 7-8, 1988. 97-118 p.
23. Anderson, G.R. "Casting Tolerance, Foundry Process Precision, and Pattern Tooling Accuracy". AFS TRANSACTIONS. Vol. 30. 1987. 203-210 p.
24. Wegscheid, Edward, "Sand Vibration for the Lost Foam Process," PRESENTATION MADE AT EPC CONFERENCE, ROSEMONT, IL. June 6-7, 1989.
25. Foundry Sand Handbook. American Foundrymen's Society, Seventh Edition, 1963.
26. Troxler, John "The Prospects for Lost Foam in 1995", PRESENTATION MADE AT AFS CAST EXPO, DETROIT, MI., April, 21-24, 1990

6860-v.ref

-END-

DATE FILMED

11 / 28 / 90