To the Graduate Council:

I am submitting herewith a thesis by Roger Kok Wee Tan entitled "A computer-Aided Design of a Semi-Permanent Mold for the Casting of an Aluminum Spool." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the Master of Science, with a major in Mechanical Engineering.

Rao V. Arimilli, Major Professor

We have read this thesis
and recommend its acceptance:

Accepted for the Council

Associate Vice Chancellor and
Dean of the Graduate School

Computer-Aided Design of a Semi-Permanent Mold for the Casting of an Aluminum Spool

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Roger Kok Wee Tan (陈国威)

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DEDICATION

This thesis is dedicated to my parents

Mr. Tan, Kim Chwee
（陈金水）

and

Mrs. Tan, Chooi Hun
（郭娴翠）

whose support has been invaluable to me.

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ABSTRACT

A semi-permanent mold was designed to improve the quality and increase the production rate of the casting of an aluminum spool used in the textile industry. Presently, the spool is being cast in a sand mold at a rate of 3 castings per hour. The size and shape of the spool requires it be cast with the flanges in the vertical direction and have six risers. This method requires large quantity of green sand for each mold and generates significant amount of scrap metal.

The proposed semi-permanent mold was designed in various stages. First, a preliminary mold was designed using the design practices currently followed in the casting industry. Secondly, PATRAN was used to build the geometrical model of the mold and mesh its surfaces. Thirdly, the meshed geometry of the mold was exported into ProCAST for pre-processing, analysis, and post-processing of the results of the simulation. The results from the casting simulation were evaluated and the design was modified as necessary to remove any problems indicated by the simulation. This redesign-simulation process was repeated until the desired objectives were met. The effect of thermal cycling of the mold was also included. From the results of the simulation of the final design the following conclusions were reached.

In the startup cycle, porosity formed at the top flange and the top section of the barrel. However, in the production cycle the solidification was unidirectional resulting in a stronger part with higher surface hardness and without any porosity.

The results from the cycling simulation indicated that the mold achieved a periodic temperature distribution after the second cycle, and that the first two parts cast from startup will have the porosity problem mentioned above. Several suggestions are made to reduce or eliminate the porosity problem in the first two cast parts.

The semi-permanent mold can be used to cast at a rate of 4 parts per hour, requiring fewer and simpler finishing operations, having much better quality, and at reduced cost.

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1. INTRODUCTION

Metal casting process has gained the reputation as a technique that can be used to create almost any part of any shape the designer can envision. The cost associated with the casting of each object is determined by the method of casting used. There are numerous casting methods currently being used by the foundry industry, namely, sand casting, shell molding, investment castings, permanent mold casting, etc. By far, sand casting offers the most economical method. Nevertheless, sand casting is not suitable for high volume production and achieving superior surface finish. Whenever high volume production and superior surface finish are required, other methods are usually used. Until recent years, mold design has been an art rather than science. Trial and error seems to be the prevalent approach in most smaller foundries. With the rapid advancement in the computer industry to produce faster microprocessors, the development of numerical modeling and simulation of solidification processes has taken a giant leap. Many commercial casting simulation codes are now available such as ProCAST, MAGMASOFT, and MOLD3-D. Most of them can accurately predict the macroscopic features like shrinkage cavities and macrosegregation as well as microscopic features like dendrite radius, dendrite tip composition and secondary dendrite arm spacing.

1.1 Statement of the problem

The objective of this study is to design a semi-permanent mold for an aluminum spool for a foundry located in the state of Tennessee . Presently the spool is being cast in a sand mold and the castings require several finishing operations to remove the risers and

ingates. There are two main reasons for the design of the semi-permanent mold for casting the spool. These are (1) to achieve a better finished cast part to reduce the number of finishing operations on the part, and (2) to reduce the solidification time to increase the rate of production using water-cooled chill. A mold designed to meet these requirements will be geometrically modeled in PATRAN, and the casting process will be simulated using ProCAST. The motivation for using the computer simulation is to evaluate the solidification process within the semi-permanent mold prior to building the prototype for the mold. If defects such as porosity, dross, cold shuts, distortion, misrun and shrinkage problems are found, the mold design can be improved and the updated design could be simulated. This process of design improvement can be continued until no defects are found in the solidification process. The final design should increase the rate of production and require less machining of the cast part relative to the current production based on the sand casting practice.

In summary, the objective for this thesis is to design the semi-permanent mold for the spool to achieve shorter production time for each spool cast as well as to achieve better product finish to reduce the machining required for the cast part to meet the required specification. The following design parameters are critical for achieving the above mentioned objectives:

1. The pouring temperature of the molten aluminum.
2. Placement of insulating materials to the needed section of the mold to ensure that the solidification takes place progressively from the bottom to top and finally toward the risers.
3. The riser design and placement.
4. The ingate design and placement.
5. The heat removal rate of the chills and placement.
6. The kind of mold coating used.

2. REVIEW OF LITERATURE

2.1 Current trends in the casting industry.

The enduring interest in the research of casting and solidification and the associated software technology development has taken a giant leap in the past two decades. This is clearly evident in both the quality and quantity of papers published in the Seventh International Conference In Modeling of Casting and Welding Processes, held in London, England 1995 [1]. This is due to the better understanding of the physics involved in casting process as well as the recent advances in our ability to make more powerful computers. The driving force behind this rapid development was the fact that the key to success in this highly competitive global economy market is to have lean and flexible production lines as well as shorter turn-around time between the design phase and the production phase. Consequently, there is a need to be able to design products that are "fit for the purpose and fit for manufacture the first time" [1]. The recent developments in numerical modeling and simulation of casting processes will be able to meet this challenge of shorter turn-around times from design to production.

2.2 State of the art in the modeling of casting solidification processes.

The state of the art in development of computer modeling in the casting solidification simulation can trace its origin to the first published paper by Henzel and Keverian [2]. This paper described the application of numerical analysis to solve the heat transfer diffusion equation for the study of solidification during casting. Subsequently, the method was further developed by many other numerical approaches.

Stefanescu has reviewed the state of the art in the modeling of casting solidification processes [3]. Stefanescu refers to the computer models based on Henzel and Keverian [2] method as the first generation of computer solidification models. In addition, those computer models "that combine macro-scale description of important properties and features with a micro-scale description (μm) based on phase transformation kinetics" [3] were classified as the second generation in computer modeling. In general, the second generation of computer models consist of the basic approach "in solving the equations for conduction heat transport and diffusive mass transport by numerical methods while using solidification kinetics to calculate heat generation during solidification." [3] Furthermore, Stefanescu speculated that the future (i.e. third) generation of computer models "will solve the heat equation, diffusive mass transport, and fluid flow by numerical methods, including kinetics, and will use an atomistic approach to describe liquid/solid and solid/solid transformations. This will result in a fundamental approach to predicting all the features of interest." [3] In Figure 1, adopted from the paper by Stefanescu [3], compared the prediction capabilities of existing and future computer models for solidification.

The second generation of the computer models have been developed and some codes are commercially available. Among them ProCAST produced by UES and MAGMASOFT produced by MAGMA Gießeritechnologie GmbH have been widely welcome, accepted and used in practice by the casting industry. Both softwares are very

Computer models for solidification			
Predictions	**First generation 1965**	**Second Generation 1966 to 1984**	**Third Generation ?**
Location of shrinkage cavity	Limited	Best	Best
Microporosity	Limited	Yes	Yes
Microsegregation	No	Yes	Yes
Microstructure • Grain number • Interphase spacing • Structural transitions • Phase ratio	 Empiric Empiric No No	 Empiric Fundamental Yes Yes	 Fundamental Fundamental Yes Yes
Mechanical properties	Empiric	Empiric	Empiric
Macrosegregation	Yes	Yes	Yes
Hot- and cold-cracking	Yes	Yes	Yes

Figure. 1 Comparison between prediction capabilities of existing and future computer models for solidification [3].

user-friendly. The user is given a high degree of freedom in specifying process parameters that include temperature, heat transfer coefficients, temperature-dependent thermophysical data, and others. In addition, the users also have the freedom in viewing the results in several ways. In the following two sections, the two softwares are briefly described. The section on MAGMASOFT was based on the review by Hansen, et al., [4] and the section on ProCAST is extracted from the ProCAST user manual [5] For more details the reader is referred to the user manuals.

2.2.1 MAGMASOFT - The MAGMA system of mold filling and solidification modeling

MAGMASOFT is the product of extensive research undertaken by Foundry Institute at the Technical University in Aachen and the Technical University in Copenhagen. MAGMASOFT is written in standard C and is portable on any workstation platforms using the UNIX operating system. MAGMASOFT consists of five main modules, namely, software controller shell, preprocessor, mainprocessor, postprocessor, and database module. Each module performs its designated task to complete the simulation analysis. The software controller shell module provides a user-friendly menu to control those parameters necessary to conduct the solidification simulation. A mini CAD-system and an automatic mesh generator is provided within the preprocessor module to build the geometry of the model. The mainprocessor module will solve the equations of fluid flow, heat transfer and solidification equations based on the formulated problem. 3-D color graphical results can be viewed in the postprocessor module. Some of the results that can be shown are, cooling curves, isotherm plots, criterion function plots, etc. Lastly, the database module allow the user to store and handle thermophysical data for future analysis.

2.2.2 ProCAST - The professional casting simulation system

ProCAST is produced by UES, and a complete ProCAST analysis requires the use of five or six software packages. The flow of information through these software packages is shown in figure 2.

The functionality of each of the software items is described next. PreCAST uses interactive menus to add more specific information to the finite element model to define

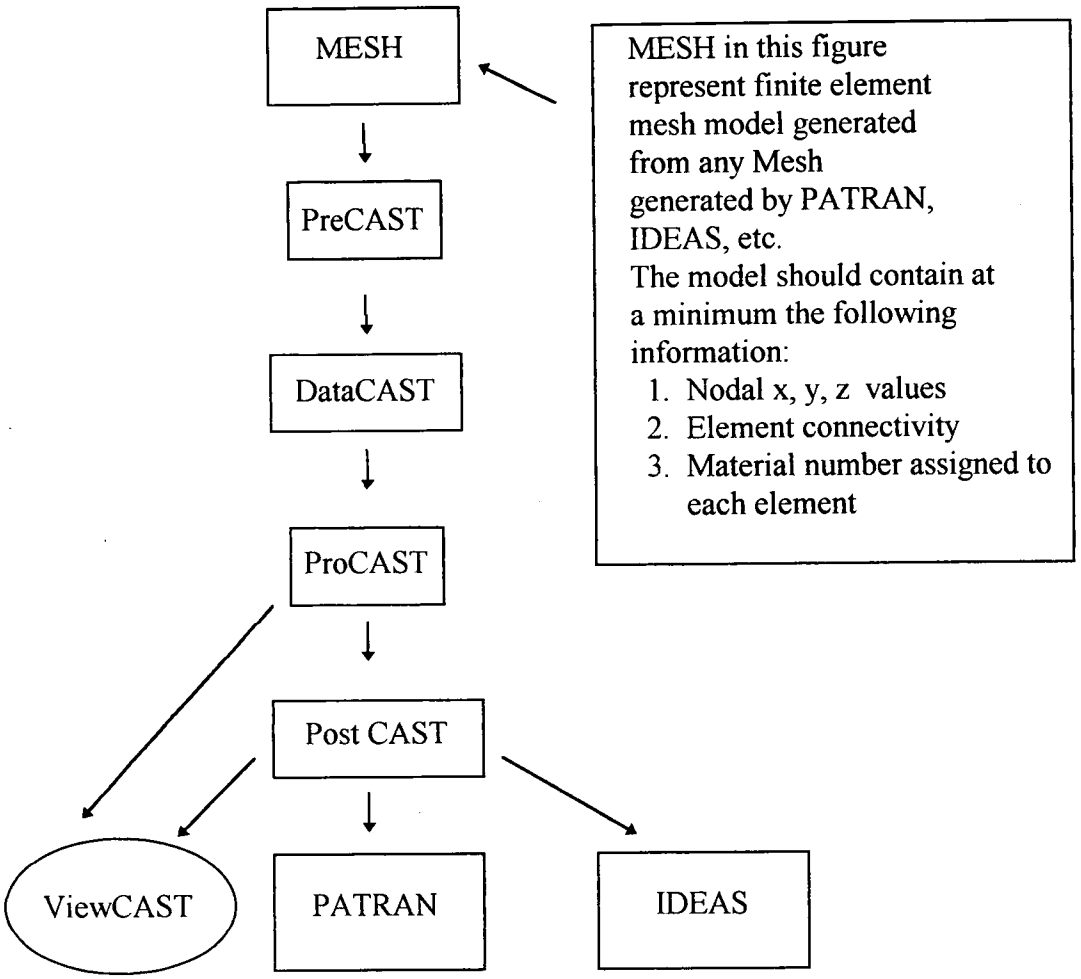


Figure 2. A flowchart of ProCAST Analysis

the boundaries, initial conditions, and others required for analysis. Within PreCAST coincident node interface can be generated between two different material types and the interfacial heat transfer coefficient data are assigned by the user. In addition, the user can specify the slave-master nodes and their associated weights in a multi-point constraint. Temperature dependence material properties can be selected either from the material data base provided within PreCAST or the user can provide the desired material

properties. Boundary conditions and initial conditions as a function of time, temperature and constant value can be defined. Emississivities, temperatures and velocities can be specified as well. Moreover, the user can defined and control the run time options which will be used in ProCAST. The analysis is completely defined upon exiting PreCAST. DataCAST is then used to review the total model and perform extensive error checking and convert all the units into a standard system (cgs). A summary file consisting of a description of the complete model is generated by DataCAST. ProCAST performs the simulation analysis. The results of the simulation are written out to several files. The postprocessing of the output files can be done using PostCAST. PostCAST provides the abilities to view the temperature, pressure, velocity, and heat flux results at each time steps. In addition, temperature versus time, solidification rate, cooling rate, temperature gradient results for various nodes, and other information can also be plotted. Lastly, ViewCAST, PATRAN or IDEAS can be used to graphically display the 3-D results generated by ProCAST.

2.2.3 Utililising the commercially available casting codes to enhance mold design

To take full advantage of the user-friendly commercially-available casting simulation software, the user/designer stills needs a good understanding of the physics of solidification as well as the fundamentals of the casting process. Many technical papers and books [6-15] have been written in this area of solidification and metal casting. Collectively they represent many years of experience and knowledge passed down through the generations. Users of casting simulation codes would find the works of those reseachers [6-15] to be very valuable in their designs. In particular, commercial codes

available such as ProCAST, are setup such that the user has to specify the geometric model, the meshing of the geometry, the casting-mold interfacial heat transfer coefficient, pouring velocity, pouring temperature, initial conditions, the boundary conditions external to the mold, and conditions associated with other solidification control devices such as chills, etc. Consequently, a good background in the area of heat transfer, fluid mechanics, and numerical methods of solution are essential to correctly setup up the model for simulation in ProCAST. In the following section issues pertinent to the heat transfer at casting-mold interface will be discussed.

The rate at which liquid metal loses heat and solidifies is controlled by several thermal resistances to heat transfer. The internal resistances within the molten metal and the mold are fully accounted for by ProCAST. What remains to be specified is the thermal interface between the casting and the mold. This can be specified in the form of an effective heat transfer coefficient at the interface. Clearly, the interfacial heat transfer coefficient will depend upon the nature of contact between the casting and the mold, and their temperatures, thermal radiation, possibly thermal convection, and the complexity of the geometry. The specification of the interfacial heat transfer coefficient, therefore, becomes both mathematically and physically quite complex.

At the casting-mold interface heat transfer by radiation, diffusion and/or convection have to be accounted for. As the casting cools and the mold heats up, the two remain in good thermal contact while the casting interface is still in the liquid phase. When the casting starts to solidify, it contracts away from the mold. Simulteneously, the mold will expand with the increase in its temperature, and begins to move away from the

cast. The movement of the cast and the mold eventually leads to the formation of a gap between the casting part and the mold. Pelke and other researchers [16-26] have studied interfacial heat transfer and indicated in their works that the heat transfer coefficient decreased rapidly from a very high value when the molten metal is in thermal contact with the mold, to a very low value once the gap started to form between the casting and the mold. Nevertheless, the previous studies of interfacial heat transfer were all case-specific [16-26] and, therefore, could not readily be extended for use with other materials or geometries. For these reasons, according to Sholapurwalla [27], most users of ProCAST set a constant value for the interfacial heat transfer coefficient in their model. Clearly, this practice will not yield very accurate results. To enhance the accuracy of specifying the interfacial heat transfer coefficient, a numerical code was developed by Arimilli and Tan [28]. Since this is presently unpublished, the details of their model and results will be briefly discussed in chapter 5

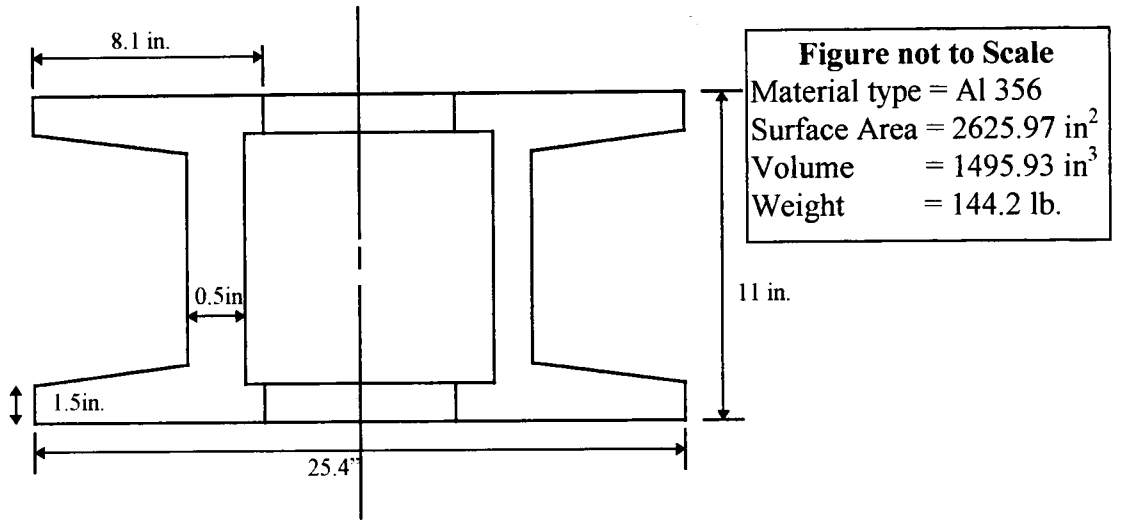
3. THE MOLD DESIGN

The semi-permanent mold to be designed for casting the spool, shown in Figure 3, will consist of two halves with a single vertical parting plane. The vertical mold parting plane is chosen for its ease of operation and often it is the preferred position for mold opening and casting removal [29]. The mold clamps to hold the two halves in place for casting as well as the devices to close and open the mold are outside the scope of this design. The company which proposed this project, as of this writing, has not decided as to which mechanism it would use to operate the mold. Some possible mechanisms are: manually operated device, two-way air, and other hydraulic mechanisms. As such, the objective of this work is to design the mold. In order to protect the proprietary interests of the foundry that casts the spool, detailed dimensions of the spool will be omitted in this thesis. Nevertheless, dimensions of significance are given in Figure 3 to allow the readers to appreciate the physics of the problem, and the steps taken in designing the mold and the casting process.

Gray iron is selected as the material for the construction of the mold. West, et al., [29] recommend that gray iron mold be used for the casting of aluminum parts with a maximum dimension of 36 inches and an expected mold life of about 10,000 pours prior to a complete overhaul and repair. This is definitely within the production requirement of the foundry casting the spool.

An expendable sand core insert will be used and placed at the middle of the mold perpendicular to the parting line for each unit of spool produced. A stationary metal core cannot be used because of the intricate shape inside the core of the spool that does not

(a) A 2-D cross sectional view with selected dimensions



(b) Isometric view showing the plane of symmetry and the vertical parting plane.

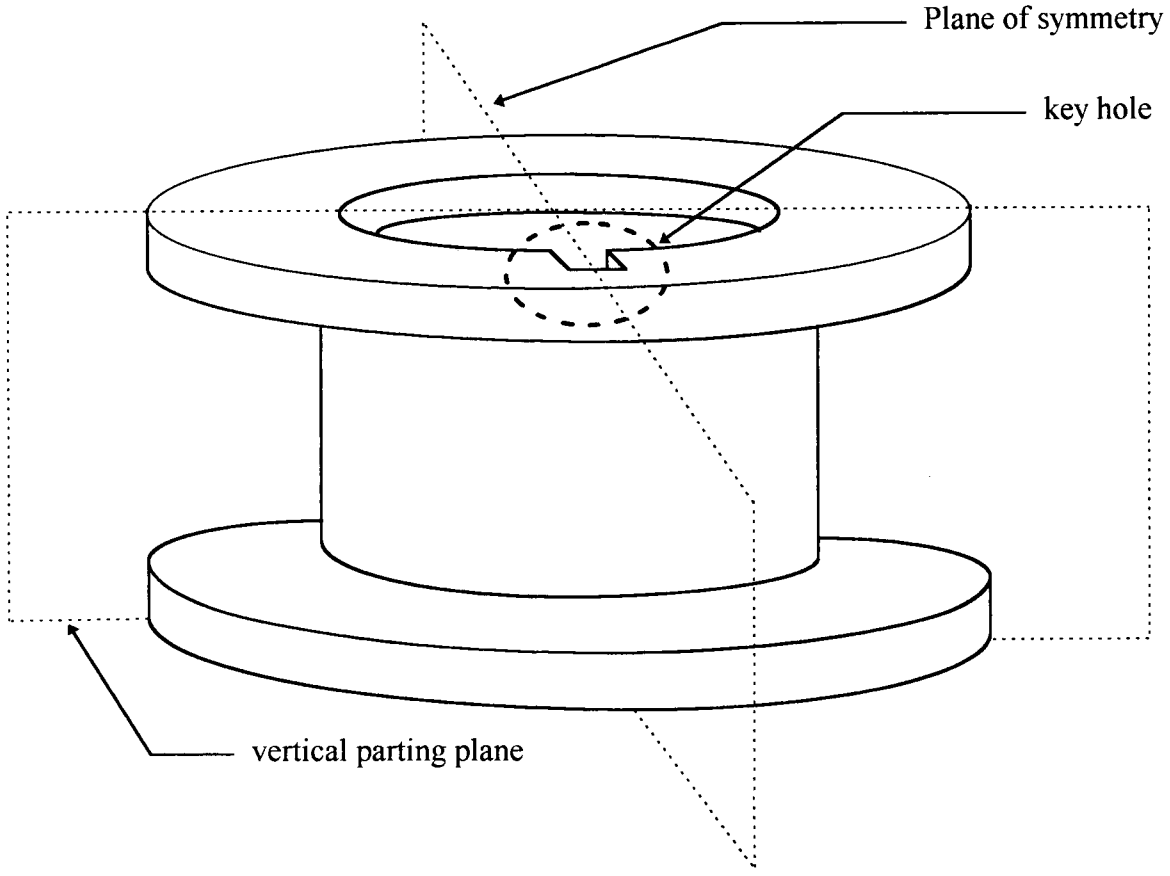


Figure 3. The aluminum spool.

permit the removal of the core once the spool has been cast. The selection of a single vertical parting plane of the mold dictates that the placement of the risers and the ingates has to be along the vertical parting plane of the mold to facilitate the removal of the spool from the mold after each cycle of casting.

In addition, because of the plane of symmetry of the spool about the keyhole normal to the vertical parting plane shown in Figure 3, an even number of risers and ingates will have to be used. Based on preliminary design calculations, two ingates are found to be sufficient to perform the filling task in about 10 to 15 seconds. Therefore, it is decided to use two ingates and two risers for the mold design. In keeping the number of risers and ingates to a minimum, the volume of scrap metal and the number of finishing operations will be significantly reduced. It is estimated that the cost of finishing operations will be reduced to about one fourth of the present sand-cast operation.

3.1 The design of the risers and their placement.

The riser design is based on the modulus method [30]. The freezing time of the riser must be at least as long as the freezing time of the casting. The casting modulus is defined as the ratio of the volume to the surface area. The casting modulus of the riser (M_{riser}) must be greater than the casting modulus of the casting ($M_{casting}$). Introducing a safety factor of 20 % for error in the estimation [8],

$$M_{riser} \geq 1.2\, M_{casting} \qquad (3.1.1)$$

where,

$$M_{riser} = \text{(volume of the riser)/(surface area of the riser)} \quad (3.1.2)$$

and

$$M_{casting} = \text{(volume of the casting)/(surface area of the casting)} \quad (3.1.3)$$

For the geometry under consideration, the volume of the aluminum spool is equal to 1496 cubic inches, and the surface area of the spool is equal to 2626 square inches. In view of the plane of symmetry, only half of the spool and the mold need to be considered. Hence, for half the spool, Eq.(3.1.2), and Eq.(3.1.3), the moduli become:

$$M_{casting} = 748 \text{ inches}^3 / 1313 \text{ inches}^2$$

$$= 0.57 \text{ inches} \quad (3.1.4)$$

$$M_{riser} = 1.2\, M_{casting} = 0.68 \text{ inches} \quad (3.1.5)$$

According to Plutshack, et al.,[30] the characteristic values for a cylinderical riser with the height of the riser equal to the diameter of the cylinder are given as:

$$\text{Volume} = 0.785\, \text{Diameter}^3 = 1.69\, M_{riser}^3 \quad (3.1.6)$$

where

$$M_{riser} = 0.1667 \text{ Diameter}$$

and

$$\text{Diameter} = \text{Height} = 6M_{riser} \quad (3.1.7)$$

Substituting Eq. (3.1.5) into Eq.(3.1.7) produces

$$\text{Diameter} = \text{Height} = 4.1016 \text{ inches} \quad (3.1.8)$$

Therefore, two cylinderical risers of 4 inches in diameter and 4 inches in height are used and they are positioned along the vertical parting plane as shown in Figure 4.

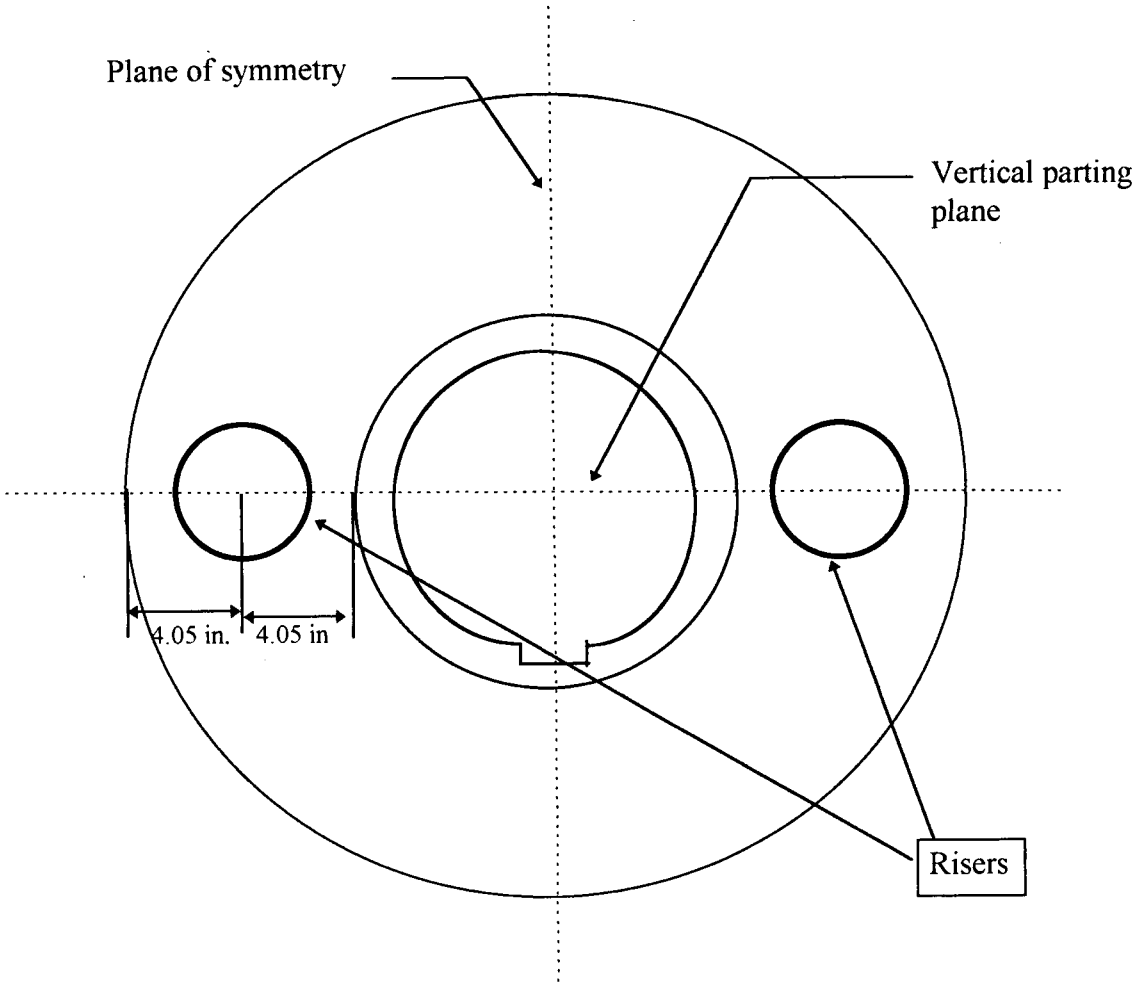


Figure 4. Schematic top view of the spool showing the placement of the risers

3.2 The design of the ingate

A good gating system is very critical in ensuring a sound cast part. A good gating system will be somewhat more tolerant of the wide variations in the pouring practices of different operators. However, the pouring speed will be under the control of the gating system, not the skill of the pouring operator. Campbell [8] states that the elements of a good filling system consists of the economy of size, the filling of the mold at the

required speed, the delivery of only liquid metal into the mold, the elimination of turbulence, and ease of part removal. These elements are incorporated into the design of the gating system of the semi-permanent mold.

An off-set pouring cup is selected for the design as shown in Figure 5. The operator should be instructed to pour the molten metal into the off-set end of the cup, so that the liquid metal will flow smoothly into the down the spruce with minimum entrapment of air and allows slag to float out. The spruce with a well at the base is design using the nomogram given in Campbell [8].

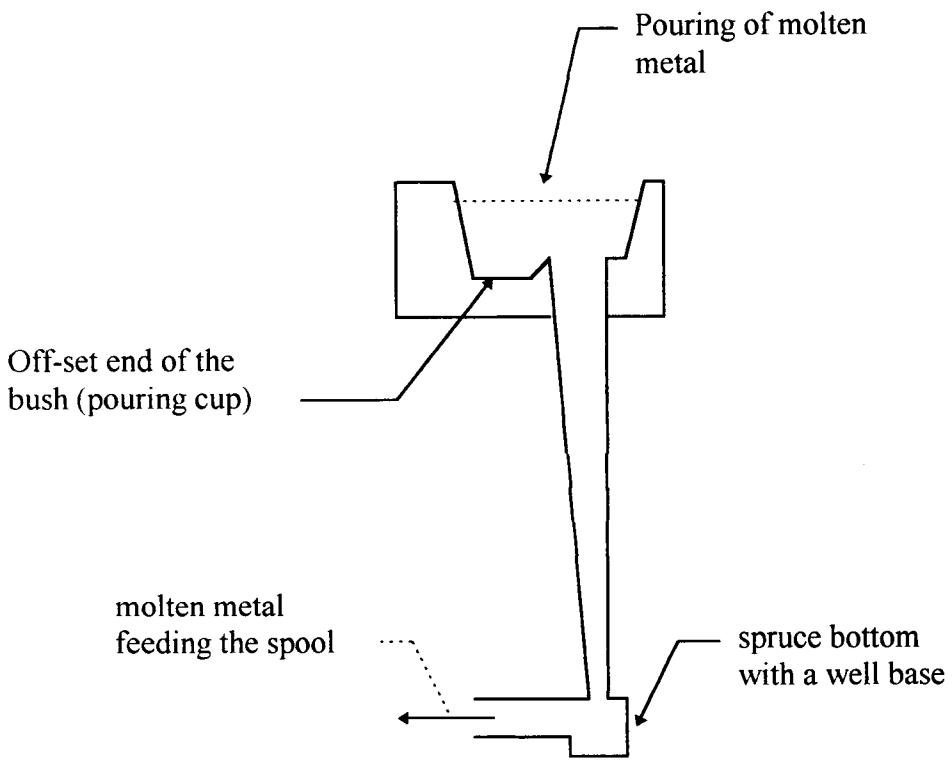


Figure 5. A schematic view of the gating system

3.3 The mold wall thickness

The minimum wall thickness of the mold is taken to be equal to the minimum wall thickness of the casting which is 0.5 inch. Thus the exterior walls of the mold and the walls around the barrel and the flanges of the spool are taken to be 0.5-inch thick. However, at intersection with other surfaces, wall thickness are considerable higher especially around the pouring cup and the section surrounding the risers.

3.4 The complete mold

A geometric model of the mold is built based on the preliminary design. A finite element model is created and a filling and solidification process is simulated and the results are studied to determine if any casting defects are present, and to ensure that the design criteria are met. If not, the mold design is modified to remove any problems indicated by the simulation. The modified design is modeled again and the process is rerun. This process of design modification and simulation is repeated until the mold design satisfied the desired objectives. The final design of the mold is highly three-dimensional and complex. The geometry is shown in several views in Figure 6.

3.5 The design of the chill.

One of the primary objectives of the semi-permanent mold design is to achieve a unidirectional solidification of the spool to ensure a sound cast part. The solidification direction should take place progressively from the bottom of the flange to the risers. To achieve this objective the mold will be placed on a flat table-top chill. The bottom

(a) The isometric view looking at cavity side of mold

1, 2, 3, 4 air cavities; 5, 6 fire-clay

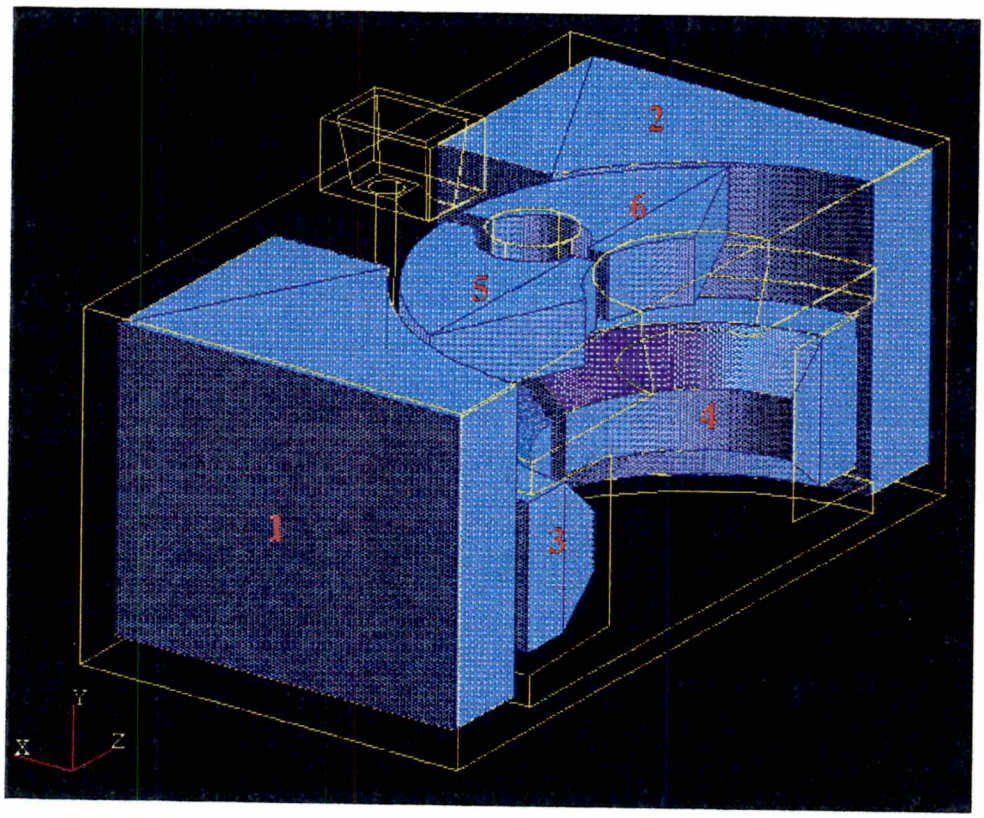


Figure 6. Various views of the wireframe of the mold showing the surfaces of its interior components (sandcore not shown).

(b) The view looking at the ingate–side

1, 2, 3, 4 air cavities; 5, 6 fire–clay

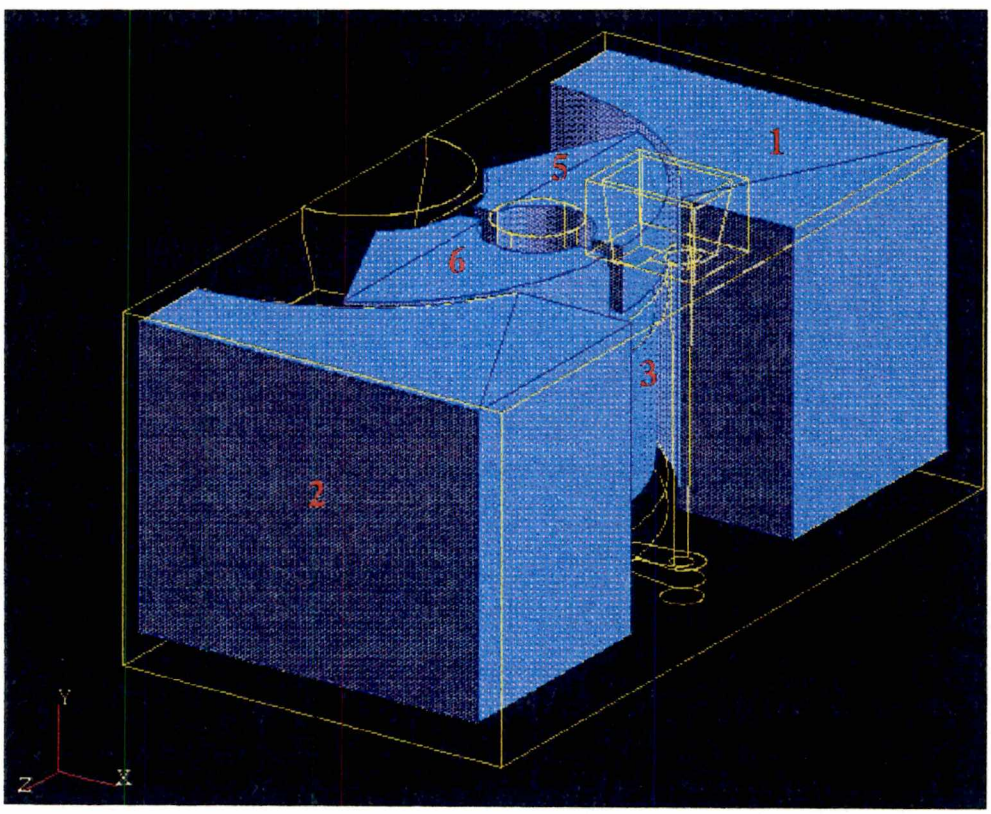


Figure 6. (continued)

(c) The front view of the mold cavity

1, 2, 3, 4 air cavities; 5, 6 fire–clay

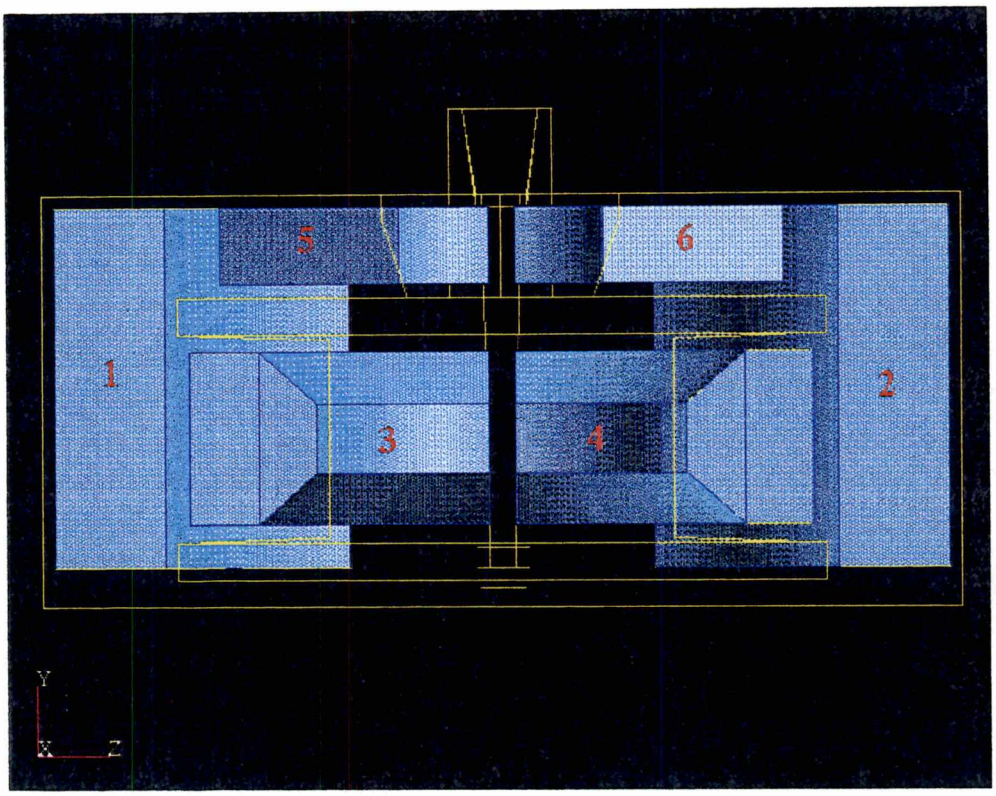


Figure 6. (continued)

(d) The back view showing the ingate

1, 2, 3, 4 air cavities; 5, 6 fire–clay

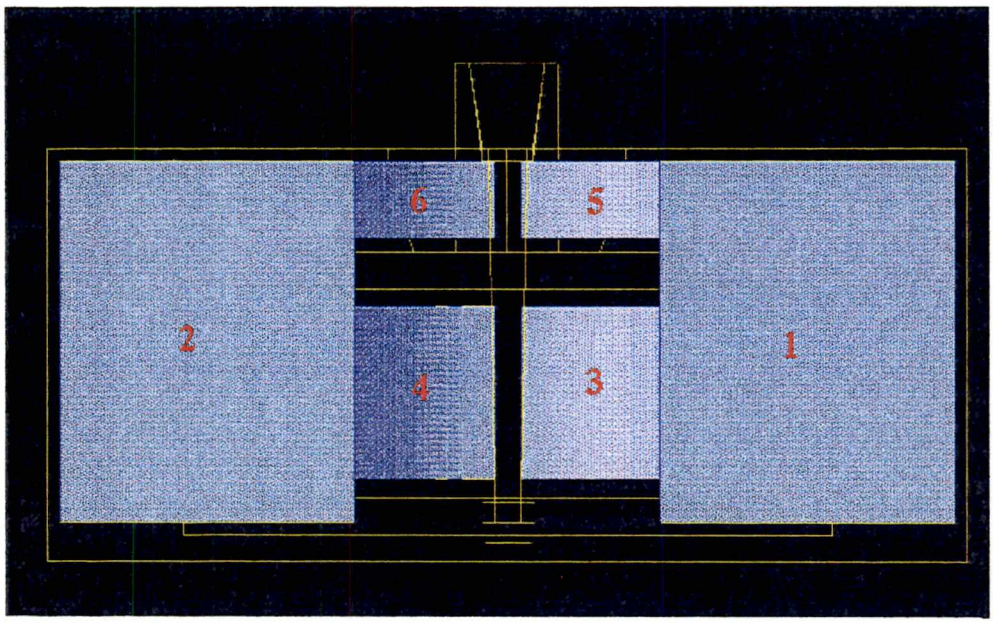


Figure 6. (continued)

(e) The top view of the ingate and the riser, etc.

1, 2, 3, 4 air cavities; 5, 6 fire-clay

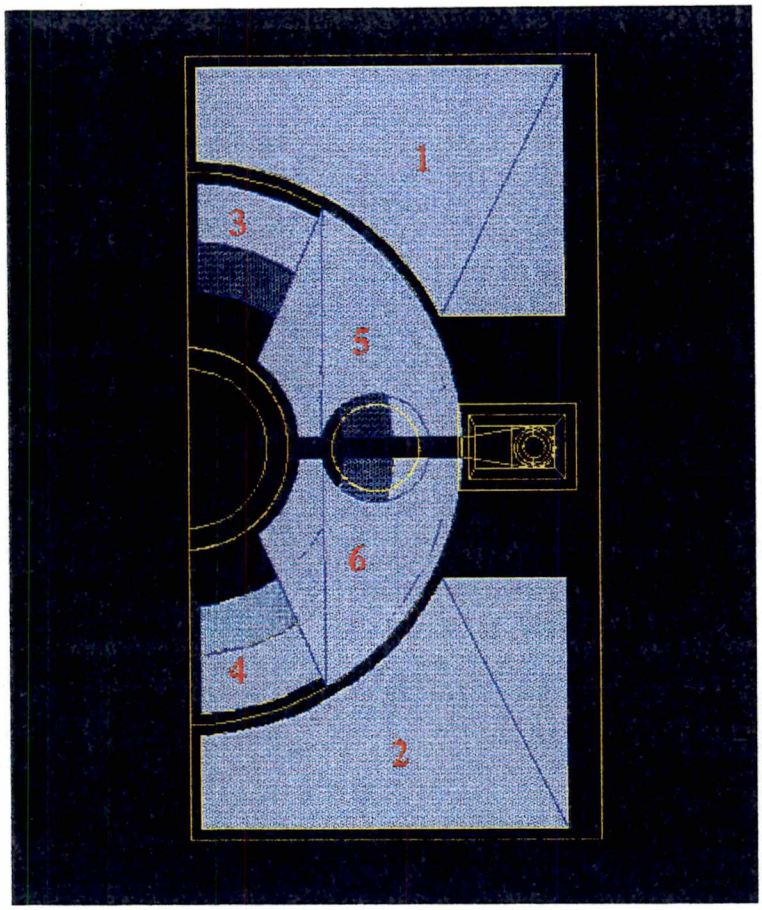


Figure 6. (continued)

surface of the chill will be maintained at a constant temperature of 80° F by the chilled water pipe lines shown in Figure 7a.

The chilled water pipe lines are connected to one side of the plate heat exchanger with a water pump in the process loop. The other side of the plate heat exchanger is connected to an air-cooled chiller to form a water loop. The schematic of the flow chart of the chiller and piping arrangement is shown in figure 7b.

The cooling load for the chilled water table-top will be determined from the results generated from the numerical simulation of the casting process. From the load requirement, the size and length of the pipe for the table-top-chill will be estimated. In addition, the plate heat exchanger and the air-cooled chiller will be sized and selected. The details of the final design are discussed in chapter 6.

(a) Water chilled table-top

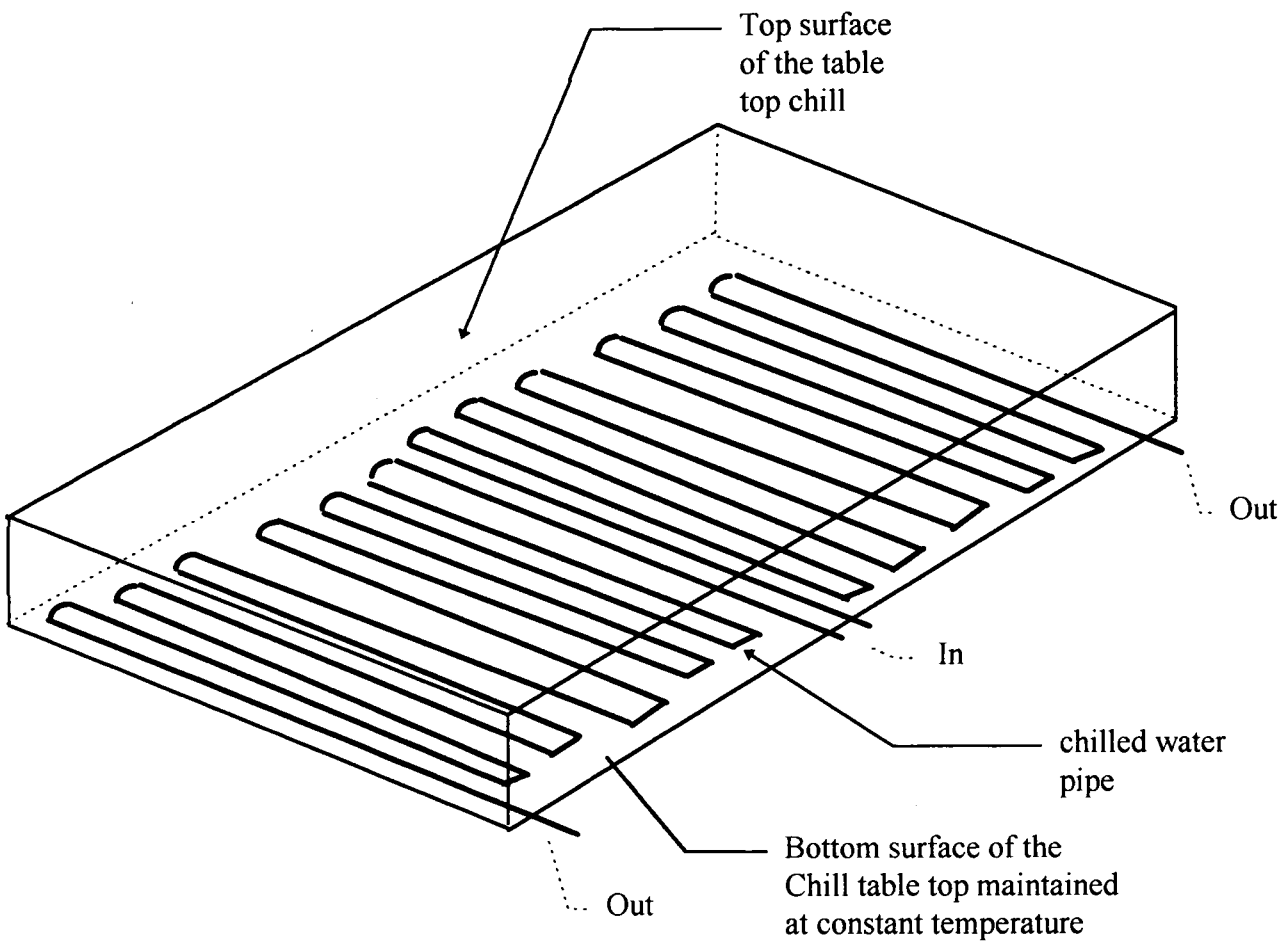


Figure 7. Schematic of water-chilled table-top and layout of the proposed cooling system for the chiller.

(b) Layout of the proposed cooling system for the chiller.

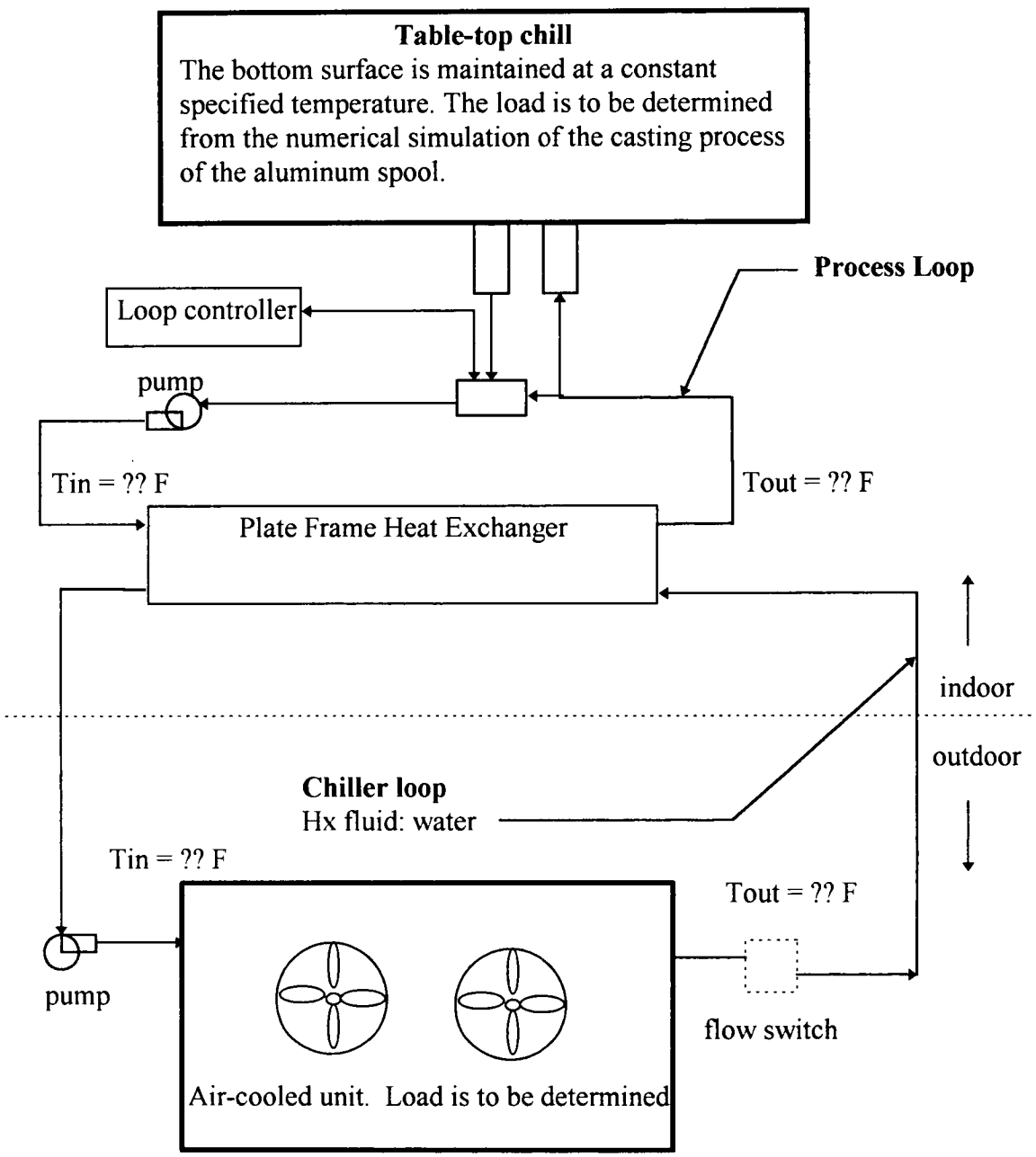


Figure 7. (continued)

4. GEOMETRIC MODEL

4.1 Brief Introduction to PATRAN

PATRAN was used to build and perform the surface meshing of the geometrical model of the casting and the mold. In the following section, PATRAN is briefly described. More details may be found in the PATRAN User Manuals [31].

PATRAN is from MacNeal-Schwendler Corporation(MSC) and has grown from its infancy in the 1970's to the present as one of the leading general purpose 3-D graphics package, widely applied in computer-aided engineering analysis. Originally, PATRAN was developed at PDA Engineering Corporation to provide pre- and post-processors for NASTRAN. Currently, PATRAN has progressed beyond its infant role as a pre- and post-processor for NASTRAN. Both PATRAN and NASTRAN are now owned by MSC. The latest version of PATRAN consists of an advance geometry modeling, finite element modeling, as well as many pre- and post-processing functions for FEM (Finite Element Method) computations.

Any model generated in PATRAN has to undergo two progressive construction phases. In the first phase, the solid geometry is constructed. There are four basic entities available for this task, namely, point (i.e., point in space), curve (i.e., parametric cubic curve in space), surface (i.e., bicubic surface in space), and solid (i.e., tricubic volume). It is possible to build very complex geometrical parts in PATRAN, using the various construction methods available utilizing these four basic entities. In addition, a skeleton geometry from any CAD system saved in IGES format can be imported into PATRAN. Currently, models constructed in Unigraphics, Pro/ENGINEER, Euclid, and others, can be imported into PATRAN readily.

In the second phase, the finite element mesh is generated. In this process, 2-D and 3-D surfaces and solids are paved with nodes and elements. There is a choice of

several meshers available within PATRAN to perform this operation. Within each mesher, there are different element types available for meshing such as, hexahedral, quadrilateral, wedge, and triangle. There is a very close relationship between phases one and two, and a well-constructed model in phase one will normally alleviate the difficulties of the mesh generation in the second phase. Hence, special care must be taken in the construction of phase one of the geometrical model.

A very important feature of PATRAN is the session file. The session file is automatically generated whenever any commands are executed in PATRAN. The session file is a sequential record of all the inputs to PATRAN during the two construction of phases. In other words, PATRAN commands can be regarded as a computer language with the session file as a source code. The session file can be edited as necessary, using any text editor, and can be used to drive the PATRAN system. In the area of computer simulation, this features offered by the session file is very valuable. It enables the technique of connatural modeling to be employed. Connatural modeling is a technique by which design alternatives can be studied by varying key characteristic parameters such as, diameter, length, etc., in the model. In order to meet the design objectives of the mold-design process, it often becomes necessary to vary one or more of the geometric parameters such as the size, shape, and position of the spruce and the gating. In other words, variations of the original geometrical model can be built with relative ease simply by editing the original session file and using the edited session file to drive PATRAN to obtain the updated geometrical model. In this manner, the need for rebuilding an entirely new model, which can be very tedious and time consuming, can be avoided.

4.2 Geometry building and surface meshing

PATRAN version 5 running on a Sparc 5 Sun Workstation located in the Advanced Casting-Simulation and Mold-Design Laboratory at the University of

Tennessee, was used to build and mesh the geometrical model of the casting and the mold. Special care was taken, during the first phase of the construction of the geometric model, to take advantage of the benefits of connatural modeling. This was done prior to building the first geometric model. The key parameters of the geometrical model were the size, shape, and position of the spruce, the gating, the insulator, and the chill.

The Paver surface mesher within PATRAN was used to mesh the geometrical model. The Paver mesher is preferred over the IsoMesh surface mesher due to the complexity of the model surfaces. IsoMesh only maps mesh on regularly shaped geometry and it is not as versatile as the Paver mesher. The Paver mesher is more versatile for creating finite element mesh on any trimmed, uneven, or similar surfaces. Paver can mesh surfaces with an arbitrary numbers of edges and with any number of holes. It is especially good for surfaces requiring "steep" mesh transition, such as going from 4 to 20 elements across. "Tri 3" element was chosen over the rest of element topology for the surface mesh because the current version of MeshCAST [33], which was used to perform the 3-D meshing of the surface mesh, only supports a 3-D tetrahedral mesher.

The mesh density of the model was controlled by the "Global Edge Length" parameter on the mesh form, and additional control was applied by specifying mesh seed to the curves, and/or edges of surfaces. Denser surface mesh density was placed on the spool, ingate, riser, and runner based on the physics of the problem, whereas more coarse mesh density was selected on the rest of the model to save CPU time in the analysis.

The equivalencing of the node feature within PATRAN was executed after the meshing routine was performed on the geometrical model. The meshing creates coincident nodes at the boundaries of adjacent curved surfaces of the geometrical model, and equivalencing is an automated means to eliminate those duplicate nodes.

Next, the optimization feature using two mathematical methods, Cuthill-McKee and Gibbs-Poole-Stockmeyer algorithms within PATRAN, was executed. The purpose of optimization is to renumber the nodes and elements of the model in such a way that the stiffness matrix assembled in the finite element analysis can be solved (inverted) using minimum of CPU time. Lastly, the surface meshed model was exported from PATRAN to a neutral file, which will be used by MeshCAST for 3-D solid meshing.

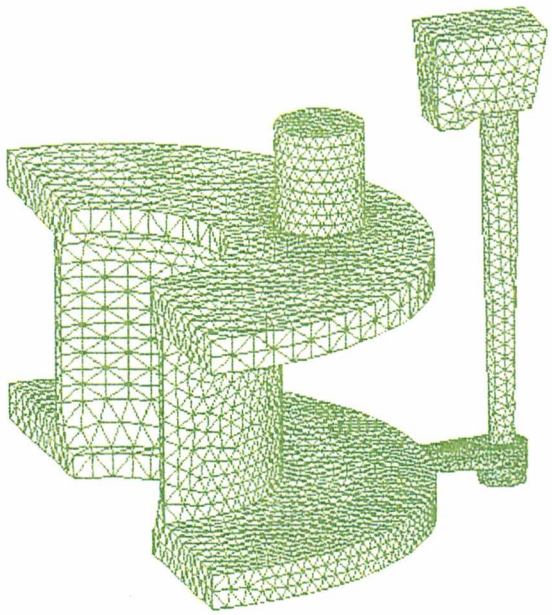
4.3 Solid meshing of the geometric model

MeshCAST is produced by UES. It is developed mainly as an interfacing program between ProCAST and 3-D CAD programs like IDEAS, and PATRAN. The current version of MeshCAST only supports a 3-D tetrahedral mesher. The full layer option was selected for the creation 3-D mesh on the model. This option guarantees the generation of a layer of interior nodes in the Tet Mesh inside a thin-walled region even if the surface mesh at this location has no interior nodes connecting the boundary edges. This option is very important for the analysis of the casting simulation of the aluminum spool because the absence of interior nodes in the thin-walled sections constitutes a 'dead zone' for molten metal to flow. The completed 3-D finite element model is shown in figure 8.

4.4 Symmetry of the casting and the mold geometries

When geometry of a part together with its mold and the associated pouring lines, risers, chills, sandcores, insulators, etc. are symmetric, then the geometry of the model is considered to be symmetric. If the boundary conditions and the initial conditions are also symmetric, then the entire model is considered to be symmetric. These features were completely taken into account in the present work as can be seen figure 3, 4, and 6. The symmetry enabled a 50 per cent reduction in the number of nodes and elements, and considerable reduction in the CPU time for the execution of each simulation. The model has approximately 43, 000 nodes and 250, 000 elements. In typical computation given the required CPU time was 4 days.

(a) The spool with riser and ingate.



(b) The mold with the sandcore in the middle and the chill at the bottom.

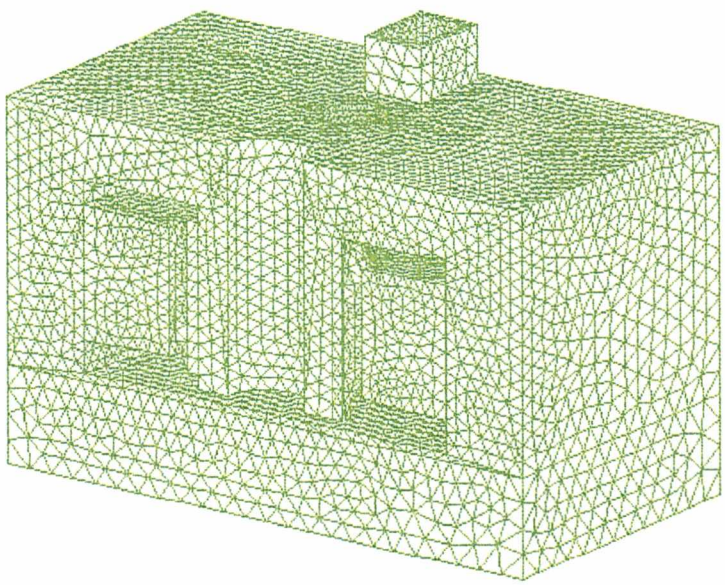


Figure 8. The finite–element meshes of the model.

5. MODEL FOR ANALYSIS AND SIMULATION

In this chapter, a brief explanation of cycling in semi-permanent molds is given, and the start-up and production cycles are defined. The need for a three-stage simulation to determine the details of the casting processes within a production-cycle is explained, and the details pertinent to the implementation in ProCAST are discussed.

5.1 Brief explanation of cycling in semi-permanent molds

At the beginning of each work shift in a semi-permanent-mold casting facility, the mold is preheated (to about 400°F) and the cavity and the contact surfaces are sprayed with a new coating or spot repairs are made on an existing coating with touchups as needed.

The mold is then preheated to a suitable nearly-uniform temperature (to about 600 to 800°F depending upon the type and size of the part) to avoid casting defects associated with cold shuts and misruns which generally result in shrinkage, hot tears, and sticking of the casting to the mold.

The mold halves are then closed and locked. The metal is then poured to fill the gating system and the mold cavity, and allowed to solidify. After the metal has solidified, the mold is opened and the part is removed. The surface of the coating is inspected and cleaned. The mold halves are then closed and locked, and the metal is poured again for the next casting. The sequence of operations described represents one typical casting cycle. On a production line, the cycle is repeated to cast the desired number of parts.

It should be noted that for the first cycle the mold temperature is uniform and during the first few cycles the mold temperature distribution changes from cycle to cycle, resulting in corresponding variation in the quality of the cast parts. Once a periodic temperature distribution is established within the mold, quality of the cast parts will be uniform and do not change with cycle. The mold reaches this state usually after a few casting cycles and all cycles after reaching this state can be called standard or production cycle. For consistency the name *production cycle* will be used throughout this thesis.

In simulating the solidification process within a semi-permanent mold, special care should be taken to include the effects of cycling on the mold temperature distribution. The very first cycle will be called the *startup cycle*. After several cycles, the mold temperature distribution becomes periodic. However, the simulation of filling and solidification of several cycles is prohibitively time consuming. A typical filling-and-solidification simulation takes several days of CPU time. The filling process itself takes up most of the CPU time (80 percent of the total). For the present casting, simulating several cycles will take several weeks of CPU time and require massive disk storage capacity.

The main difference between the startup and the production cycles is the initial temperature distribution of the mold. However, if the temperature distribution of the mold at the beginning of a production cycle is available/known, then it can be used to simulate the production cycle in a single simulation. To determine the periodic temperature distribution achieved by the mold, a simplified model is used. This model

is the same as the original model with the following exception. The cavity is assumed to be filled and simulation is done in a cycling mode. The details of the specification are presented in a later section. Once the mold achieved a periodic temperature distribution, the temperature distribution at the start of the periodic cycle can be extracted and used as the mold initial temperature distribution to rerun the simulation program to determine the results for the production cycle.

In all the simulations used in this study, the pouring velocity and the interfacial heat transfer coefficients were taken to be both functions of time and temperature. The methods developed, as part of this study, for determining these functions are described in the next two sections. The use of such functions is a new contribution to the state-of-the-art in casting process simulation using ProCAST.

5.2 Pouring velocity

In the semi-permanent mold the cavity is fed by gravity. In modeling, the current practice is to specify a constant pouring velocity as determined from the ratio of the volume of the cavity to be filled to the product of the inlet cross sectional area and the filling time[32].

In a gravity fed flow it should be pointed out that the fluid level at the pouring cup is maintained constant by the operator. But the velocity of pouring, and hence the rate of filling, will change with time as the driving hydrostatic head drops progressively as filling continues.

When all other conditions remain the same, a cast part is cooled much faster in semi-permanent mold than in sand mold because the thermal diffusivity of the mold

material is much higher than that of sand. For the present situation, the thermal diffusivity of the gray iron is over two orders of magnitude higher than that of sand. Therefore, in a sand casting process the filling process plays a less significant role on heat transfer and the current practice of using a constant inlet velocity in the model may be acceptable. However, for casting in a semi-permanent mold, the filling and the heat transfer processes are closely coupled and the current practice of using a constant inlet velocity for the model is not acceptable, and the details of heat transfer cannot be captured adequately to identify the presence of cold shuts.

To accurately simulate the filling process with ProCAST for molds fed by gravity, the velocity at the inlet must be specified sufficiently accurately as a function of time. To provide the inlet boundary condition, a separate numerical model was developed[32] to determine the time-dependent pouring velocity for a given complex geometrical casting part and shown in Figure 9.

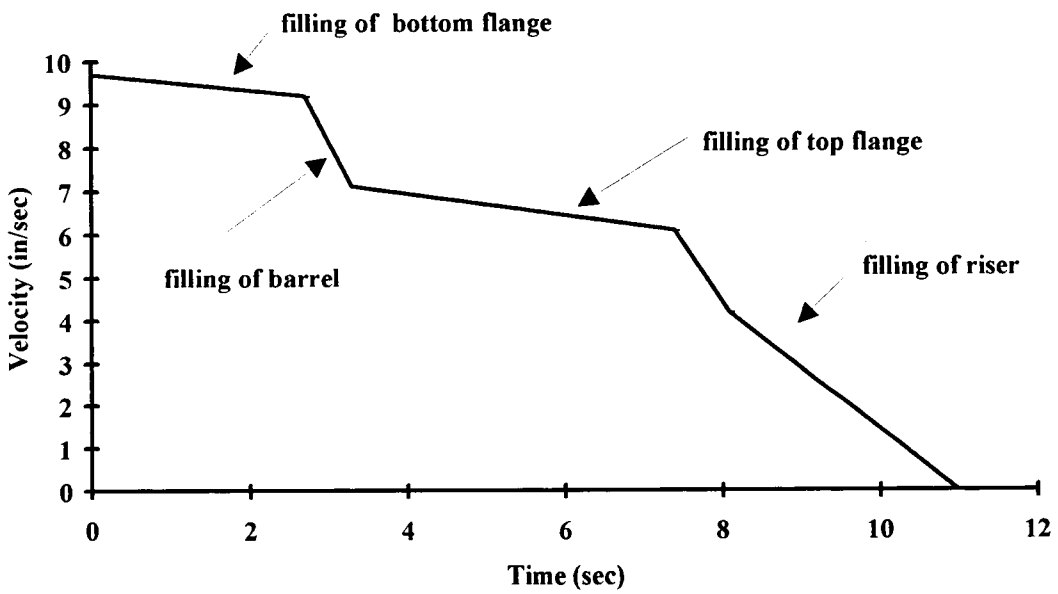


Figure 9. The temporal variation of the inlet velocity to the varying area spool cavity

5.3 The interfacial heat transfer coefficient (h) between the casting and mold

In ProCAST the interfacial heat transfer coefficient can be specified as a constant or a function of surface temperature of either the cast or the mold for a typical simulation, and for cycling simulation as a function of time. It should be pointed out that, when the interfacial heat transfer coefficient is specified as a function of surface temperature of either the cast or the mold, the cooling rate at any interfacial node will depend on its own temperature and, in turn, varies with time. The net result of such a specification is that the cooling around the interface becomes an intrinsic function of position and time. Therefore, it is highly desirable to specify the interfacial heat transfer coefficient as a function of surface temperature. However, the specification of the interfacial heat transfer coefficient as a function of surface temperature has to be done accurately.

As discussed in chapter 2, previous studies of interfacial heat transfer were all case-specific [16-26] and, therefore, could not readily be extended for use with other materials or geometries. In an attempt to bridge this gap and provide a means to improve the accuracy of specifying the interfacial heat transfer coefficient as a function of temperature, Arimilli and Tan [28] have developed a 1-D transient heat transfer model of air gap, coating, cast and the mold boundaries. A schematic of the geometric model is shown in Figure 10.

The 1-D transient model consists of several material layers including an air gap of zero initial width that grows with time as the molten metal solidifies and shrinks. The assumptions made in formulating the problem are (1) the growth of the gap size between the casting and the mold is directly proportional to the coefficient of linear thermal expansion of the casting material and the mold material, (2) air is assumed to be the dominant element in the gap when it forms, (3) the heat transfer is by conduction in the different solid layers, and (4) across the air gap the heat transfer is by conduction,

convection and radiation. The transient problem is solved numerically using a finite-difference method.

The formation of the gap at the bottom surface will not be the same as that of the side and top surfaces. The weight of the casting will cause the casting to rest firmly on the bottom surface of the mold. Consequently, the rate of heat transfer at the bottom of the cast is controlled by the contact resistance at that interface. Therefore, the interface at the bottom surface is handled differently from the case of top and side surfaces.

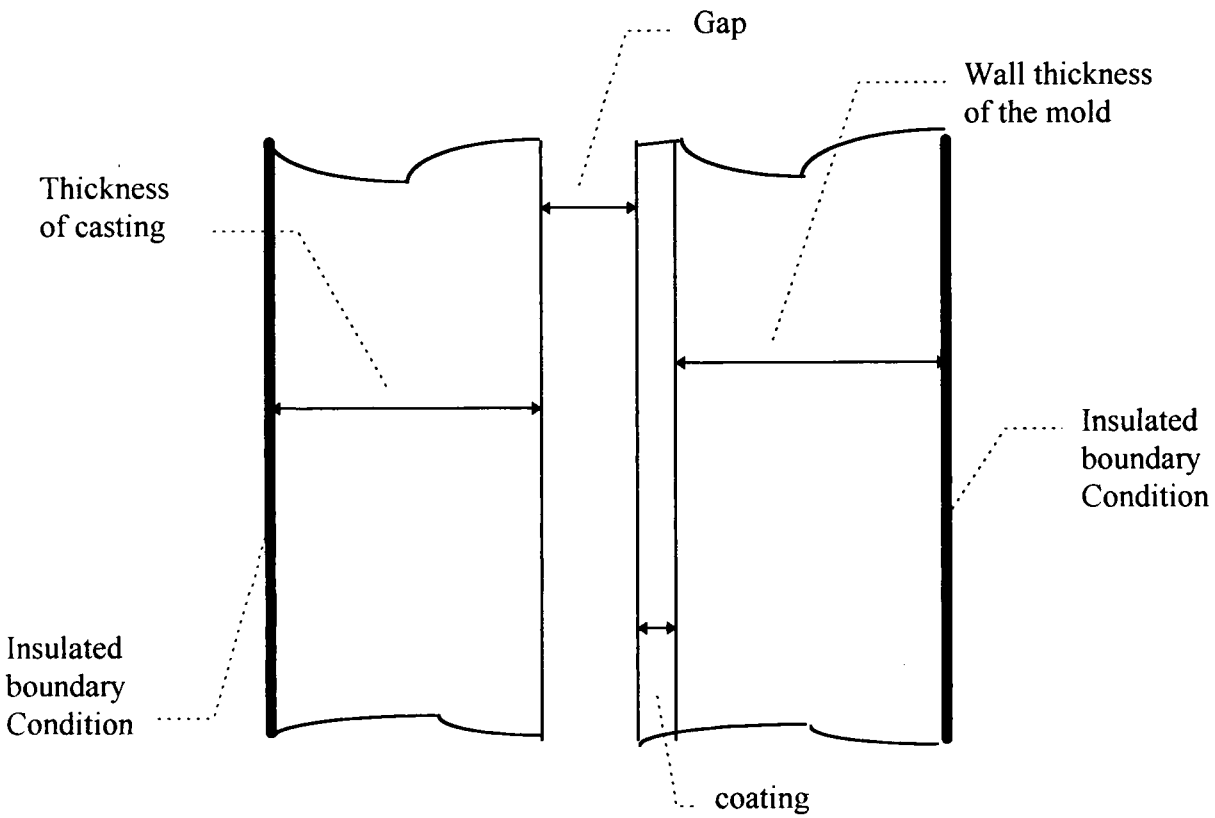


Figure 10. Schematic of the 1-D transient problem involving several layers including an air gap whose width grows in time.

The interfacial heat transfer coefficient computed by the 1-D code and used in the present models are shown in Figures 11a - 11d. In the model for the startup and production cycles, the interfacial heat transfer coefficient is specified as a function of the surface temperature of the casting. The interfacial heat transfer coefficient for the interface between the casting and the mold for the side and top surfaces is shown in Figure 11a, and for the bottom surface is shown in Figure 11b. However, for the cycling simulation, ProCAST requires that the interfacial heat transfer coefficient be specified as function of time. The interfacial heat transfer coefficient for the interface between the casting and the mold for the side and top surfaces is shown in Figure 11c, and for the bottom surface is shown in Figure 11d.

(a) For side and top surfaces as a function of cast surface temperature

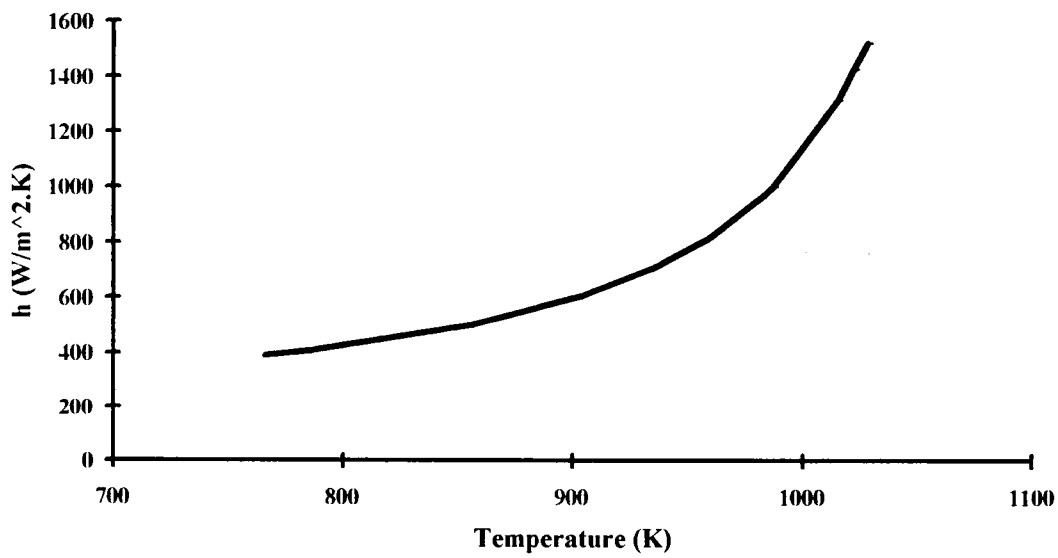
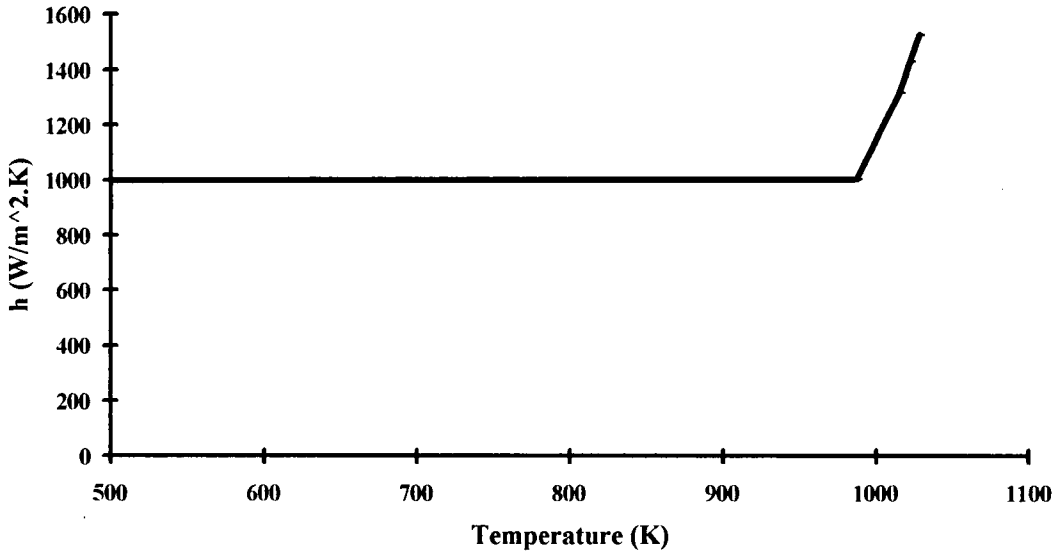


Figure 11. The interfacial heat transfer coefficient between the casting and the mold.

(b) For the bottom surface as a function of temperature



(c) For top and side surfaces as a function of time.

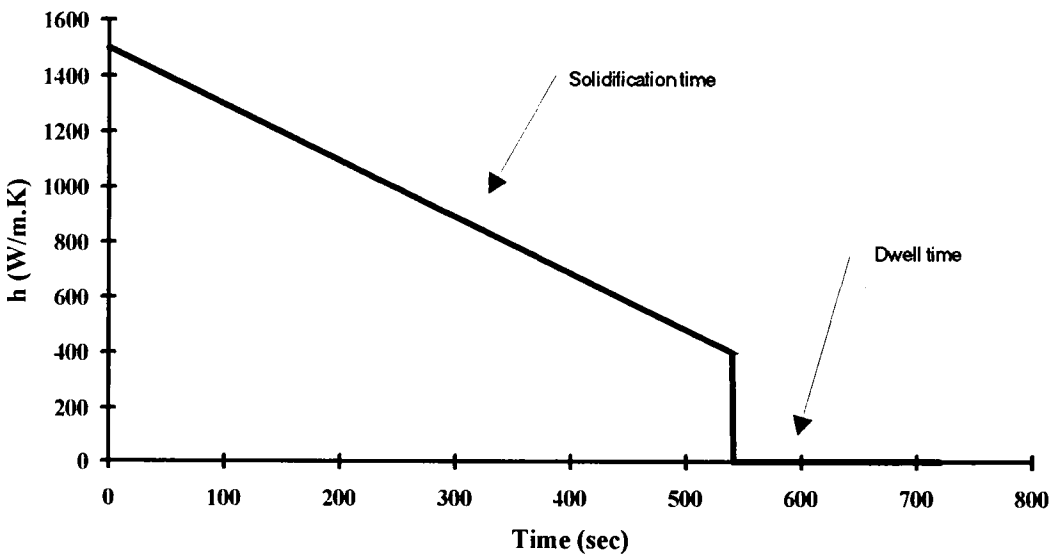


Figure 11. (continue)

(d) For bottom surface of the as a function of time.

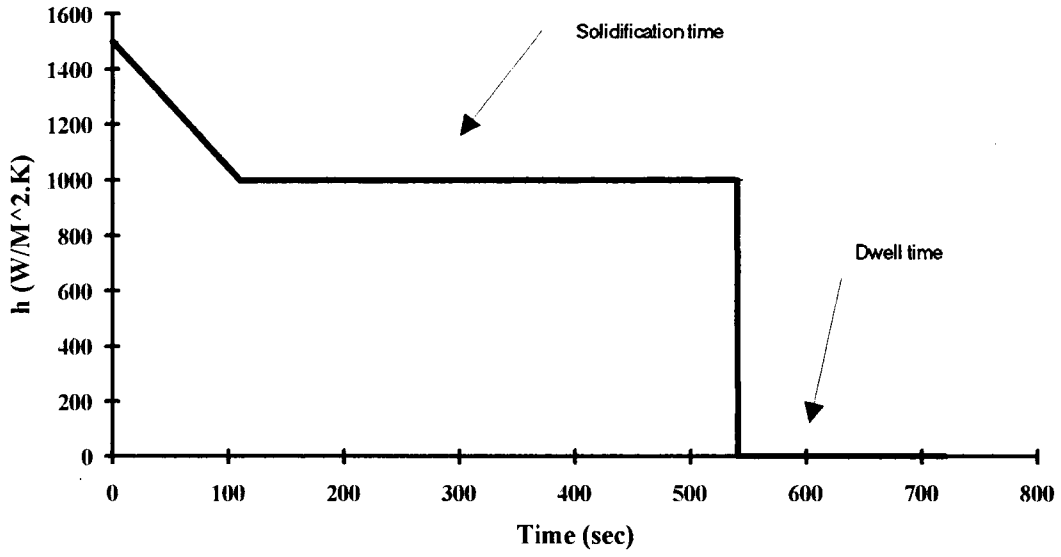


Figure 11. (continued)

5.4 Model setup for simulation in ProCAST

In this section the setup of the boundary conditions for startup, cycling simulation, and production cycle are enumerated.

5.4.1 Model setup for startup cycle

(a) Boundary Conditions

The pouring temperature of the molten metal (AL356) is selected to be 1450 °F.

The inlet velocity is a function of time as shown in Figure 9.

The interfacial heat transfer coefficient between the cast and the mold is a function of temperature. The function for the side and top surfaces is shown in Figure 11a, and for the bottom surface is shown in Figure 11b.

The interfacial heat transfer coefficient between the cast and the 1.5-inch thick sand core and 0.0315-inch thick fireclay coating based on an equivalent thermal resistance calculation by Eq.(5.4.1) is 11 W/(m^2.K).

$$h = (\text{Resistance}_{\text{sandcore}} + \text{Resistance}_{\text{coating}})^{-1} \quad (5.4.1)$$

The interfacial heat transfer coefficient between the riser and the 0.25-inch thick fireclay insulating sleeve based on an equivalent thermal resistance calculation by Eq.(5.4.2) is 178 W/(m^2.K).

$$h = (\text{Resistance}_{\text{coating}})^{-1} \quad (5.4.2)$$

External conditions:

In ProCAST the heat transfer on each external surface by convection and radiation can be modeled through the specification of the convective heat transfer coefficient, the surface emissivity and the ambient temperature.

Top surface of riser:

Temperature (K)	h (W/m^2.K) due to natural convection (Eq. 9.30, Reference [33])
600	9.24
700	9.64
900	10.08
1000	10.20
1060	10.22

Emissivity of 0.06 was used.

Ambient temperature was 80 °F.

Vertical surface of the mold:

Temperature (F)	h ($W/m^2.K$) due to natural convection (Eq. 9.26, Reference [33])
300	0.454
500	0.494
600	0.507
700	0.518
900	0.537

Emissivity of 0.6 was used.

Ambient temperature was 80 °F.

Horizontal surface of the mold:

Temperature (F)	h ($W/m^2.K$) due to natural convection (Eqs. 9.30 & 9.31, Reference [33])
300	1.068
500	1.159
600	1.174
700	1.179
900	1.175

Emissivity of 0.6 was used.

Ambient temperature was 80 °F.

Bottom surface temperature of the table-top-chill was maintained constant at 80 °F.

(b) Initial Temperature Conditions

Mold and associated parts were selected to have an initial temperature of 600 °F.

Table-top-chill temperature was maintained constant at 80 °F

5.4.2 Model setup for the cycling simulation

Cycling simulation was done to determine the initial temperature distribution of mold for the production cycle. In this case, the interfacial heat transfer coefficient is used in its time-dependent form.

(a) Boundary Conditions

All other boundary conditions were selected to be the same as startup case with the following exceptions:

There was no need to specify the pouring temperature of the molten metal (AL356) or the inlet velocity as the mold cavity was assumed to be filled.

The interfacial heat transfer coefficient between the casting and the mold was a function of time. The function for the side and top surfaces is shown in Figure 11c, and for the bottom surface is shown in Figure 11d.

The interfacial heat transfer coefficient between the casting and the sand core, is shown in Figure 12a.

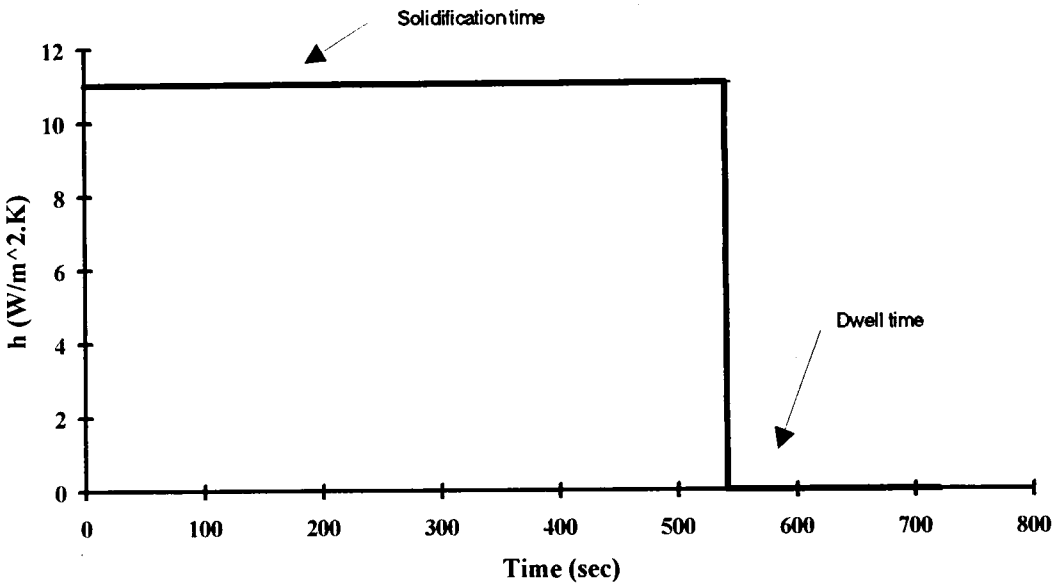
The interfacial heat transfer coefficient between the riser and the insulating sleeve, is shown in Figure 12b.

In addition, another boundary condition was added to simulate the cooling of the mold due to natural convection during the dwell time of the cycle, where h is calculated using Eq. 9.26 Reference [33], as shown in Figure 13.

(b) Initial Conditions

The initial temperature distribution of the table-top-chill, mold and associated parts was taken to be the same as that at the end of the startup cycle. Specifically the temperature distribution of these parts at the end of the startup cycle was extracted for this purpose. The initial temperature distribution of the molten metal in the cavity was taken to be the same as that at the end of the filling process of the startup cycle.

(a) For the interface between the cast and the sandcore.



(b) For the interface between the cast and the insulating sleeve.

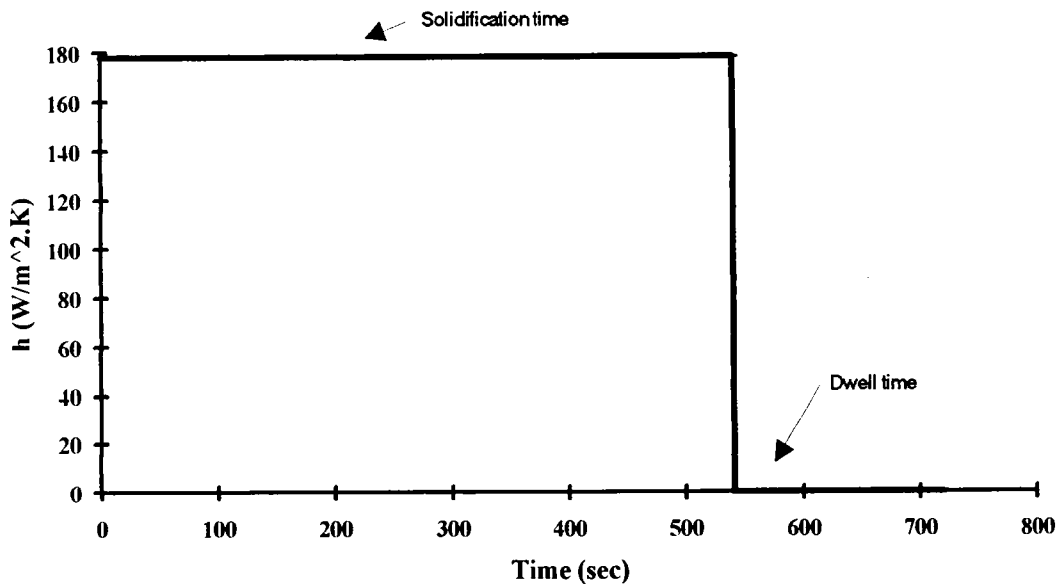


Figure 12. The interfacial heat transfer coefficient between the cast, and the sandcore and insulating sleeve as a function of time.

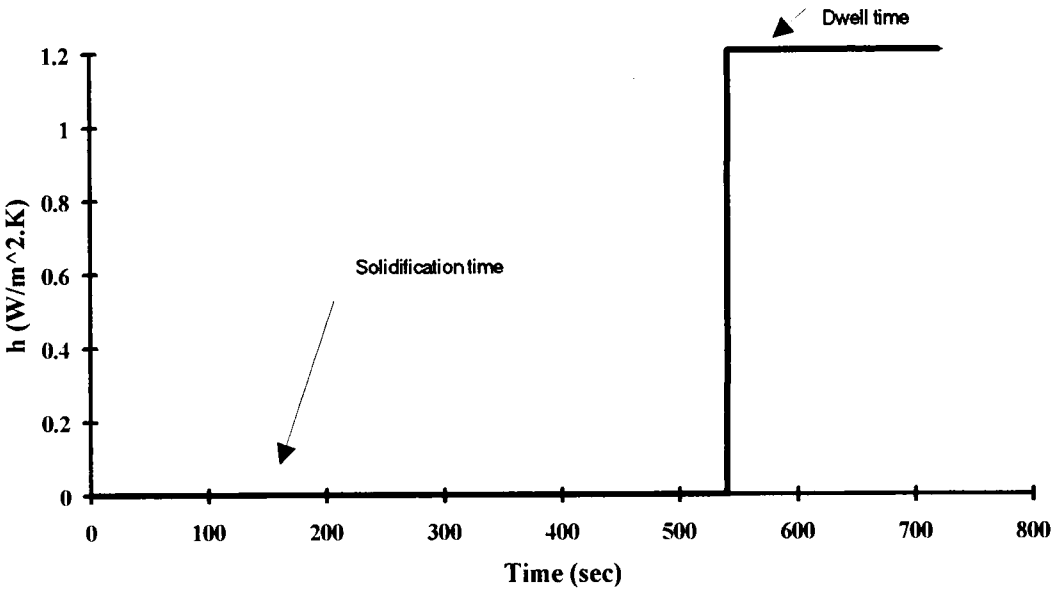


Figure 13. Boundary condition on the cavity as function of time during dwell time between cycle.

5.4.3 Model setup for the production cycle

(a) Boundary Conditions

All boundary conditions are the same as those for startup cycle.

(b) Initial Conditions

The temperature distribution of the table-top-chill, mold and associated parts were extracted from the end of the fourth cycle of the cycling simulation and used as the initial temperature distribution.

6. DICUSSION OF RESULTS

In this chapter the results from the startup cycle, cycling simulation, the production cycle and the sizing of the water chiller are presented and discussed. First, the fraction-solid fringe plot and the temperature fringe plot of the startup cycle are presented at selected values of real time. Next, the periodic temperature distribution of the mold after cycle 3 and cycle 4 are given. Third, the fraction solid fringe plot and the temperature fringe plot of the the production cycle are presented as a function of real time. Lastly, the maximum cooling load of the mold is determined from the heat flux distribution at the bottom surface of the table-top-chill and the water chiller is sized based on this load requirement.

6.1 The startup cycle

The casting process for the startup cycle is simulated using the conditions specified in chapter 5. The fraction-solid fringe plot and the temperature fringe plot are shown in Figures 14 - 18 at selected values of time. All time values indicated in this dicussion are elapsed times from the start of the pouring process. In these figures the details of the casting process within the cavity and the ingate system are shown. In Figure 14 it can be seen that nearly half of the cavity is filled at 3.75 seconds. After 9.77 seconds, Figure 15 show that the cavity is about 95 percent filled. Although not shown in these figures, the complete filling of the mold cavity took 11 seconds and the pouring is stopped when the cavity is filled. At this stage the cavity including the pouring cup are completely full. In Figure 16, at 93.5 seconds, the beginning solidification in the pouring

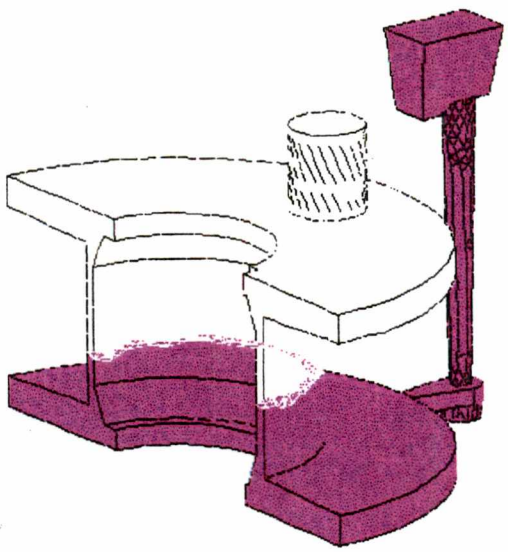
up, the ingate, the outer edge of the two flanges are shown. Because of the metal shrinkage upon solidification, the liquid level in the pouring cup can be seen to drop to account for the shrinkage within the cavity.

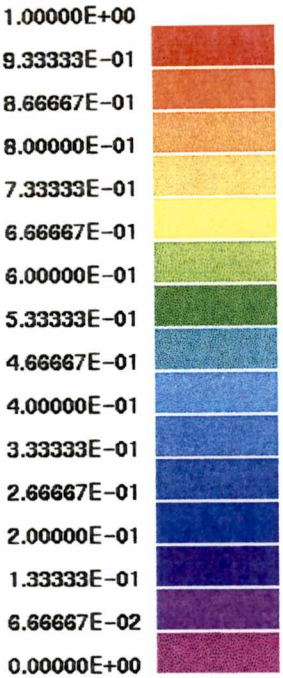
In Figure 17, at 213.5 seconds, about 85 percent of the cavity is solidified except the riser and regions near the junction between the top flange and the top section of the barrel. It should also be noted that the liquid level in the riser has essentially remained constant. Upon a careful review of the progress of solidification, by looking at several cross sections, within the cavity it is found that all paths for the flow of the still molten metal from the riser to the rest of the cavity are blocked because of premature solidification of the region. The details of the blockage are not included because of the large number cross sections and time steps involved. A negative consequence of this blockage is that the molten metal from the riser cannot flow into the barrel and the flange to compensate for the volumetic shrickage of these regions. Hence, these regions are expected to develop porosity. However, in the production cycle the temperature distribution within the mold is generally higher by about 100 °F and it is found that the riser is able to provide the needed molten metal to compensate for the shrinkage. (This can be seen in Figures 24 and 25). In Figure 18, at 538.5 seconds, the cavity is completely solidified and the temperature distribution can be seen.

6.2 The cycling simulation.

As discussed in chapter 5 the complete simulation of the several cycles of filling and solidification of the present casting process will take several weeks of computer

(a) Fraction Solid Fringe Plot





(b) Temperature Fringe Plot

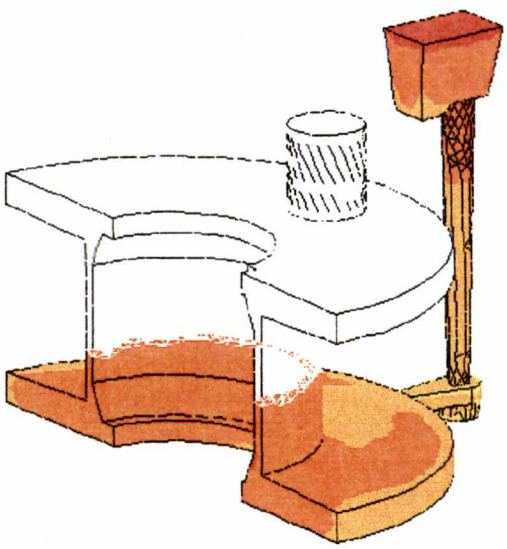
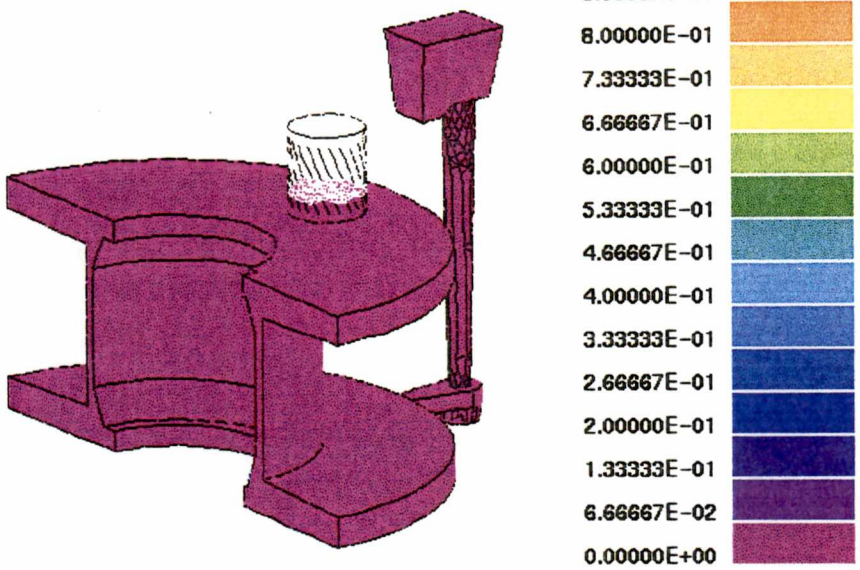




Figure 14. Fraction solid and temperature distribution at time = 3.75 sec.

(a) Fraction Solid Fringe Plot



(b) Temperature Fringe Plot

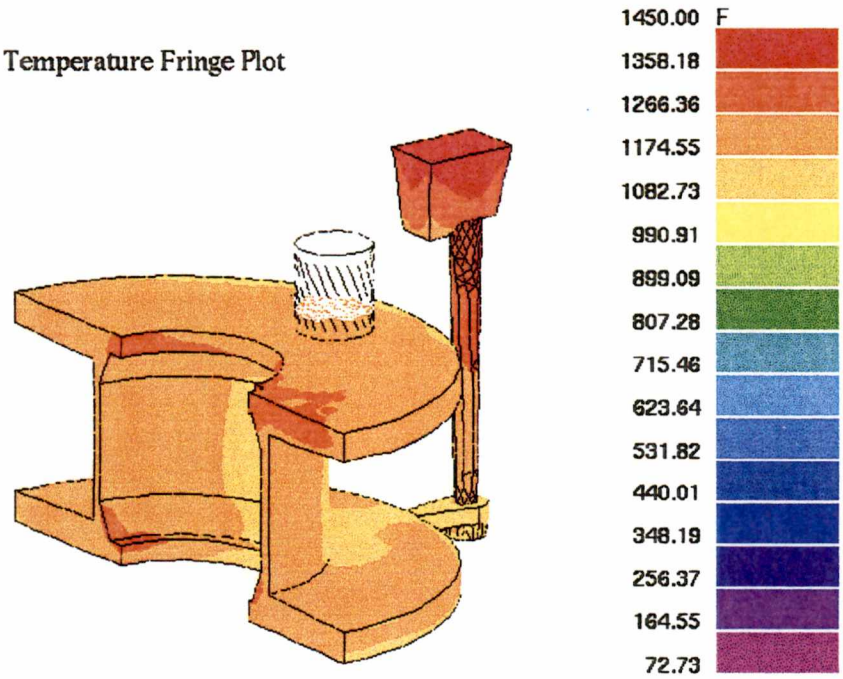
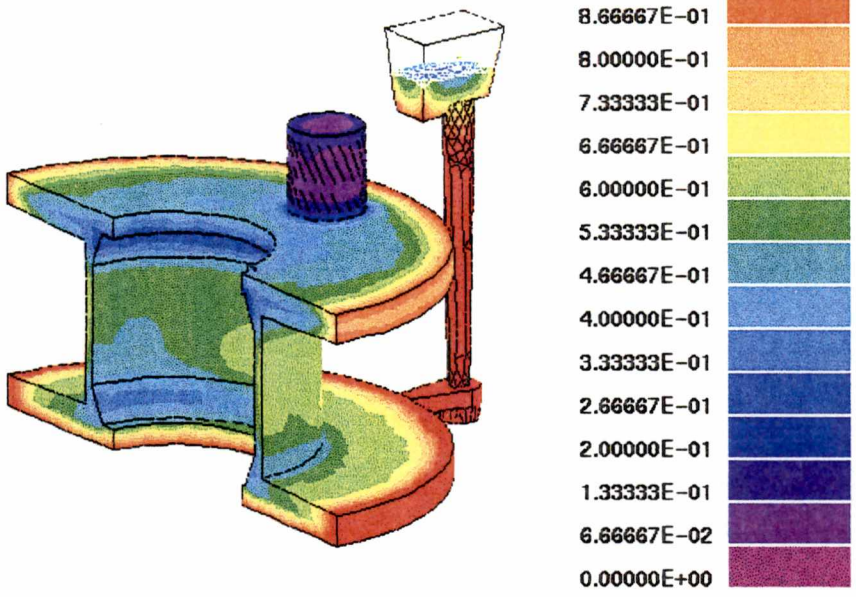


Figure 15. Fraction solid and temperature distribution at time = 9.77 sec.

(a) Fraction Solid Fringe Plot



(b) Temperature Fringe Plot

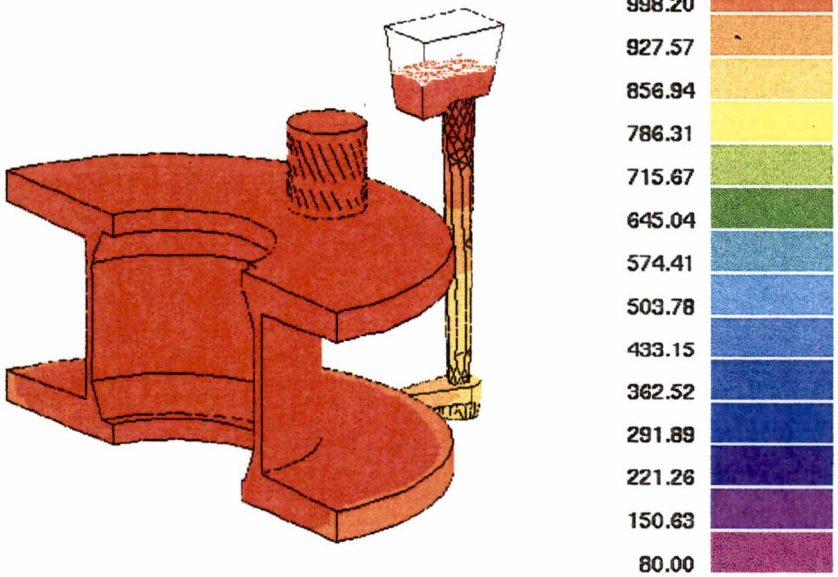
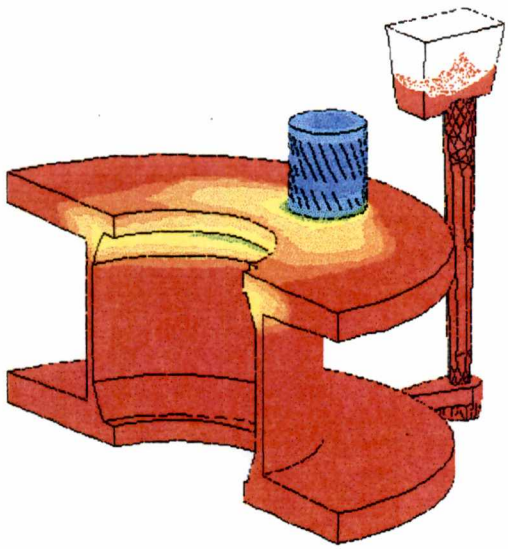
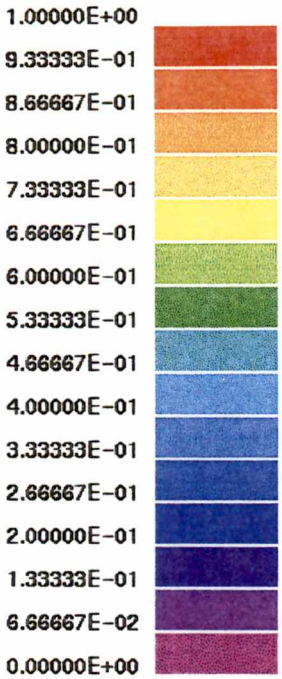


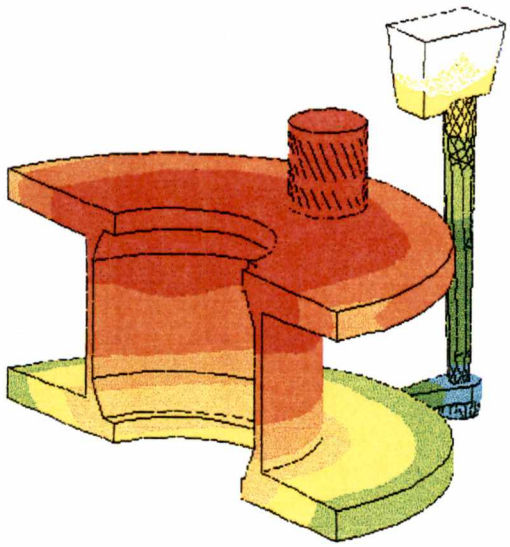
Figure 16. Fraction solid and temperature distribution at time = 93.5 sec

(a) Fraction Solid Fringe Plot





(b) Temperature Fringe Plot



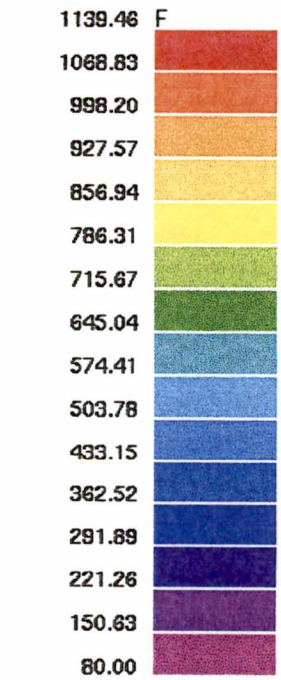
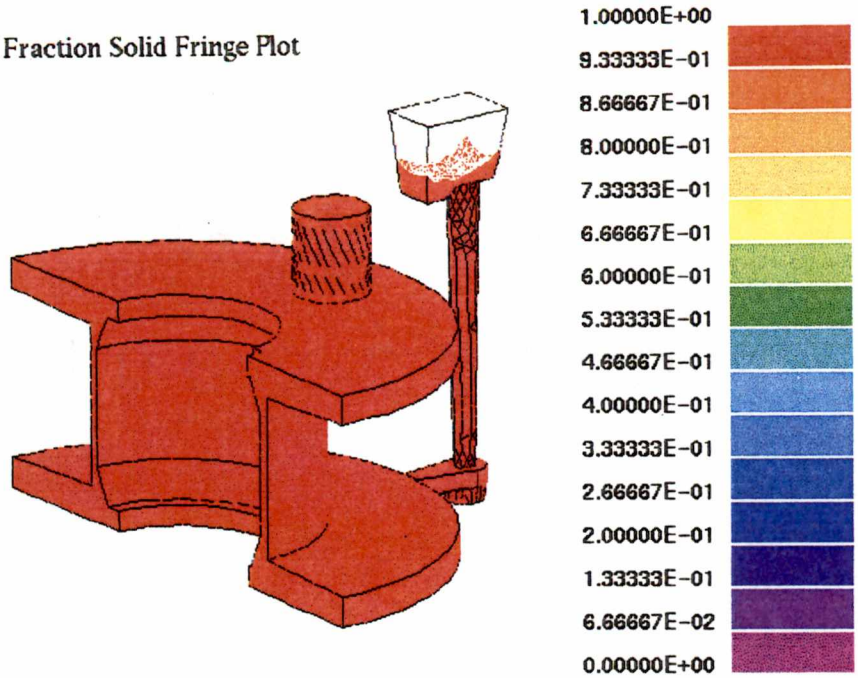


Figure 17. Fraction solid and temperature distribution at time = 213.5 sec.

(a) Fraction Solid Fringe Plot



(b) Temperature Fringe Plot

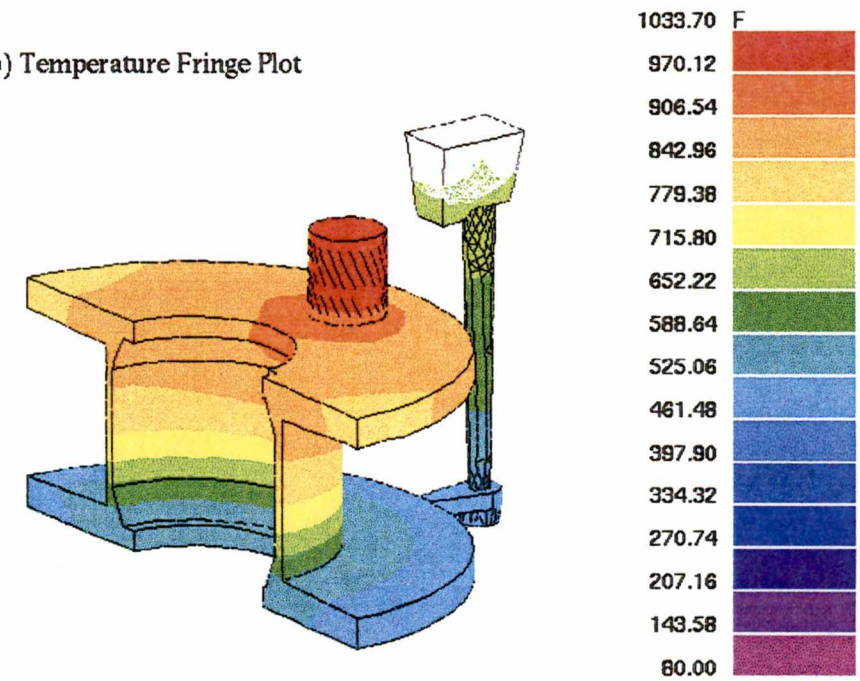


Figure 18. Fraction solid and temperature distribution at time = 538.5 sec.

time. A simplified model of the model used in the startup cycle, with the mold completely filled at the beginning of each cycle, is simulated in a cycling mode. The details of the model setup to perform the cycling simulation are described in chapter 5.

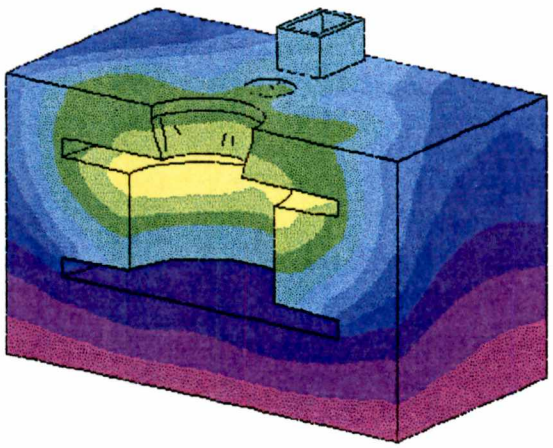
The cycling simulation in ProCAST required an additional boundary condition to be specified as a function of time at the cavity surfaces in order to simulate the heat removal from the mold during the dwell time. This boundary condition is shown in Figure 13. The results indicate that the mold temperature distribution at the start of cycles 3 and 4 are identical as shown in Figure 19. From this it is concluded that the mold has achieved a periodic temperature after the third cycle. Therefore, the mold temperature distribution at the start of cycle 4 is used as the initial temperature distribution of the mold for simulating the production cycle.

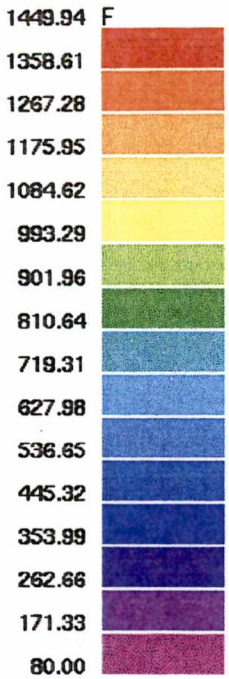
6.3 The production cycle

The casting process for the production cycle is simulated using the conditions specified in chapter 5. The periodic mold temperature distribution at the start of cycle 4 of the cycling simulation is extracted and used as the initial mold temperature distribution for simulating the production cycle. The fraction-solid fringe plot and the temperature fringe plot are shown in Figures 20 - 25 at selected values of time in chronological order. In Figure 20 it can be seen that less than half of the cavity is filled at 3.75 seconds.

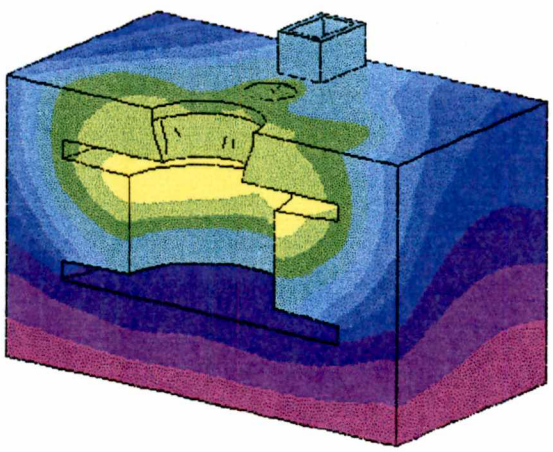
After 9.77 seconds, Figure 21 shows that the cavity is about 95 percent filled. Although not shown in these figures, the complete filling of the mold cavity took 11

(a) Temperature Fringe Plot of Cycle 3





(b) Temperature Fringe Plot of Cycle 4



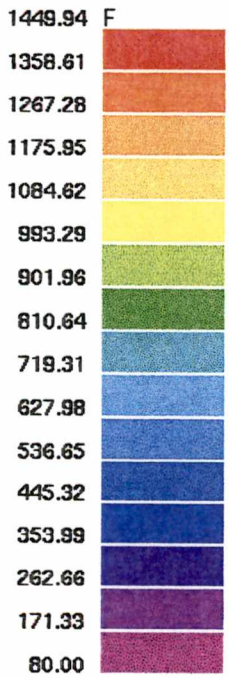


Figure 19. Cycling results showing mold temperature distribution at the start of cycles 3 and 4.

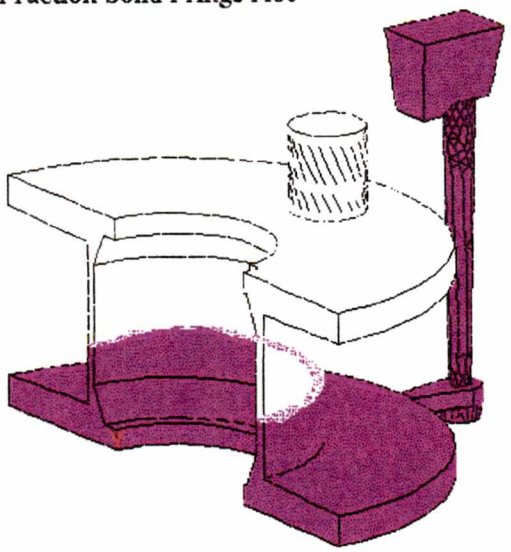
seconds and the pouring is stopped when the cavity is filled. At this stage the cavity including the pouring cup are completely full. It should be noted that in the production cycle the mold temperature distribution around the top flange and the riser are higher by about 100 °F when compared to the startup cycle. These can be seen by comparing Figures 21 and 15.

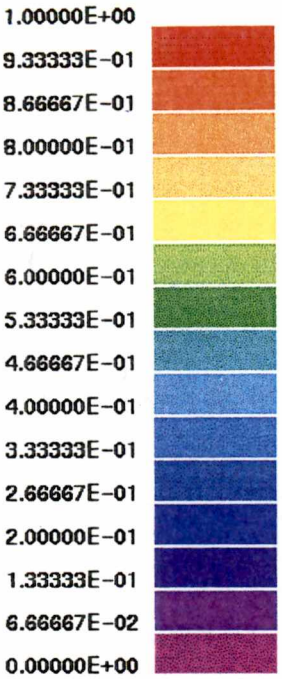
In Figure 22, at 66.6 seconds, solidification begins in the ingate and the outer edge of the bottom flanges. In Figure 23, at 153 seconds, the bottom flange and the ingate are solidified and more importantly the solidification front is nearly planar within the barrel and is seen to progress toward the top.

In Figure 24, at 488 seconds, about 85 percent of the cavity is solidified except the riser and regions near the junction between the top flange and the top section of the barrel. It should also be noted that the liquid level in the riser has dropped to compensate for the volumetric shrinkage in the cavity. Hence, the solidified regions would be free of porosity. In Figure 25, at 938.2 seconds, the cavity is completely solidified. From the temperature distribution it can be seen that the isotherms are planar within the barrel and the grain formation will be unidirectional.

In the production cycle the solidification started at the outer edge of the bottom flange and progressed to the barrel and then up along the barrel to the top flange and finally toward the riser within the top flange. In the production cycle the typical cooling rates for estimating the microstructure are in the range of 35 to 40°C/sec. The typical cooling rates for sand casting are slower at about 0.5 to 12°C/sec. It can be concluded

(a) Fraction Solid Fringe Plot





(b) Temperature Fringe Plot

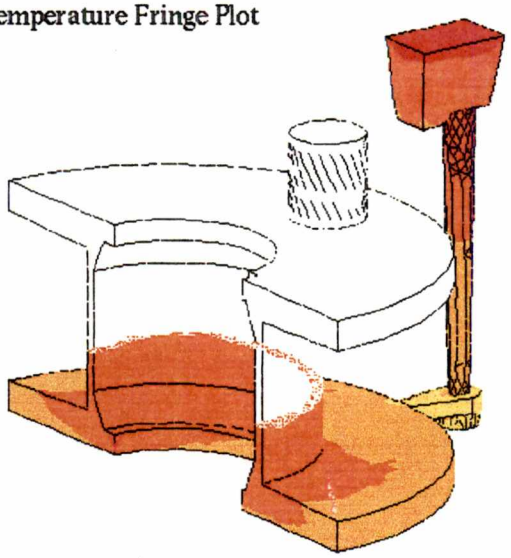
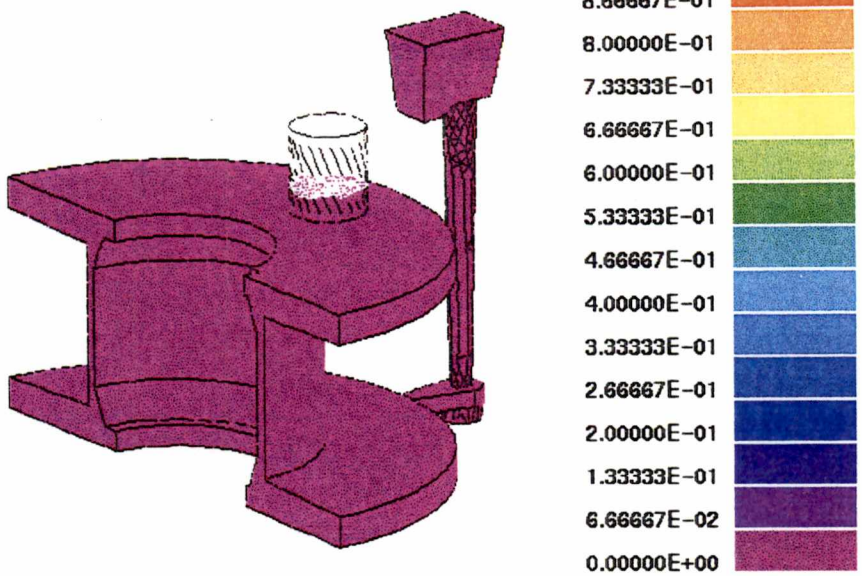




Figure 20. Fraction solid and temperature distribution at time = 3.75 sec.

(a) Fraction Solid Fringe Plot



(b) Temperature Fringe Plot

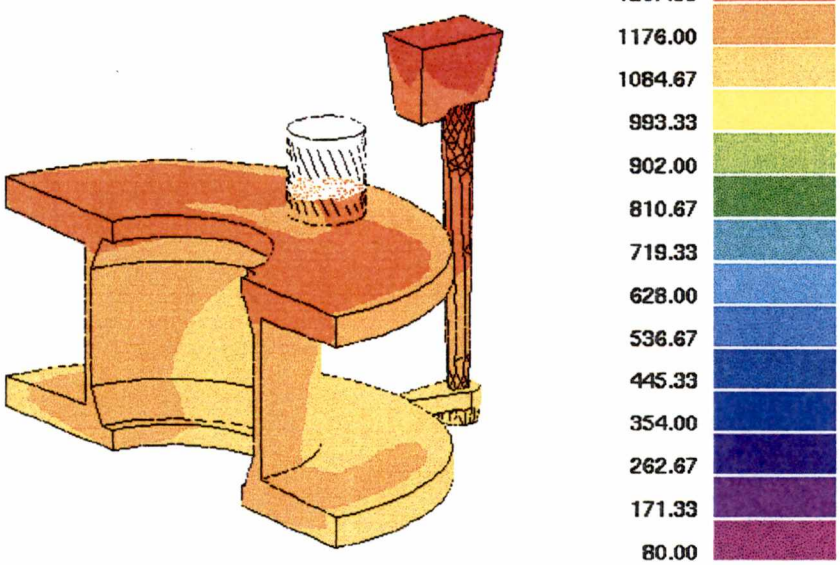
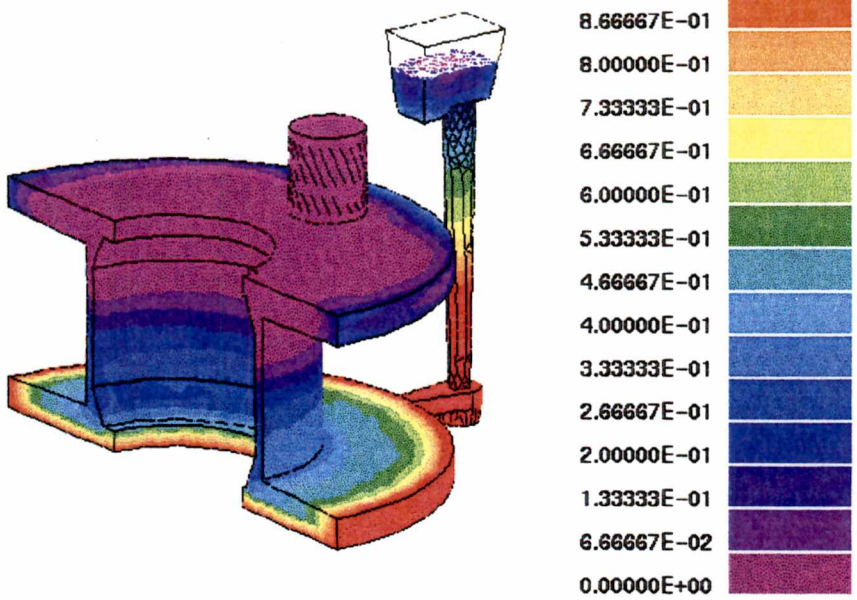


Figure 21. Fraction solid and temperature distribution at time = 9.77 sec.

(a) Fraction Solid Fringe Plot



(b) Temperature Fringe Plot

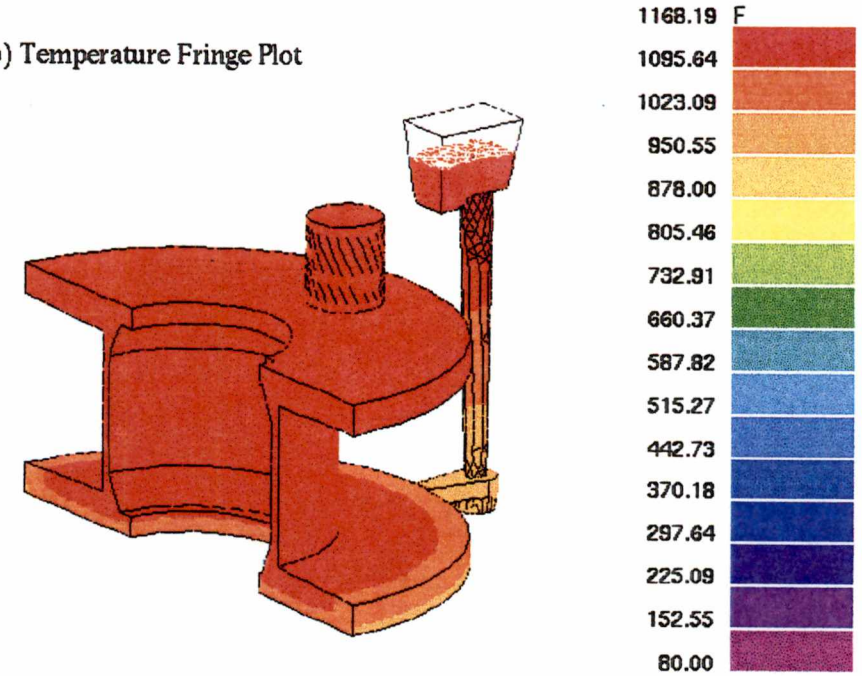
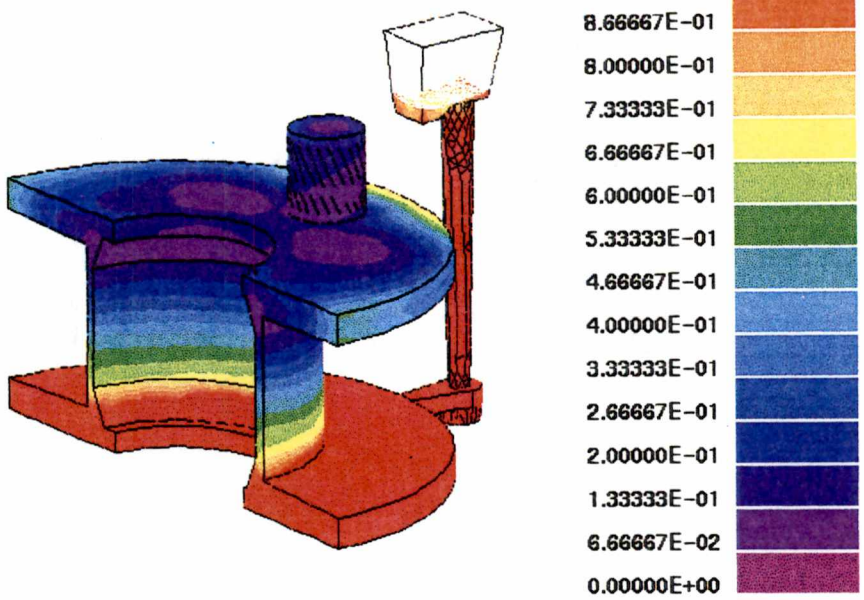


Figure 22. Fraction solid and temperature distribution at time = 66.6 sec.

(a) Fraction Solid Fringe Plot



(b) Temperature Fringe Plot

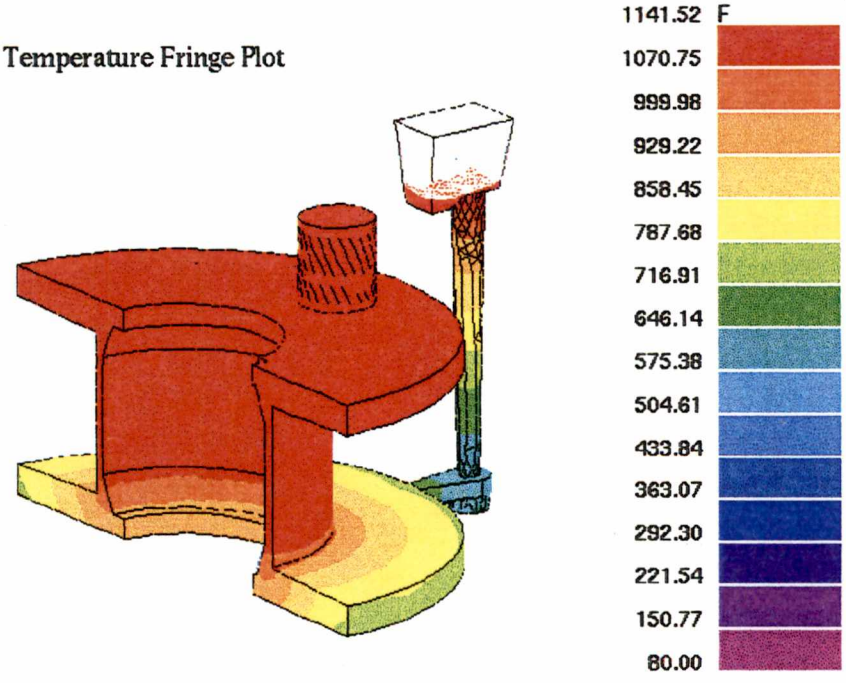
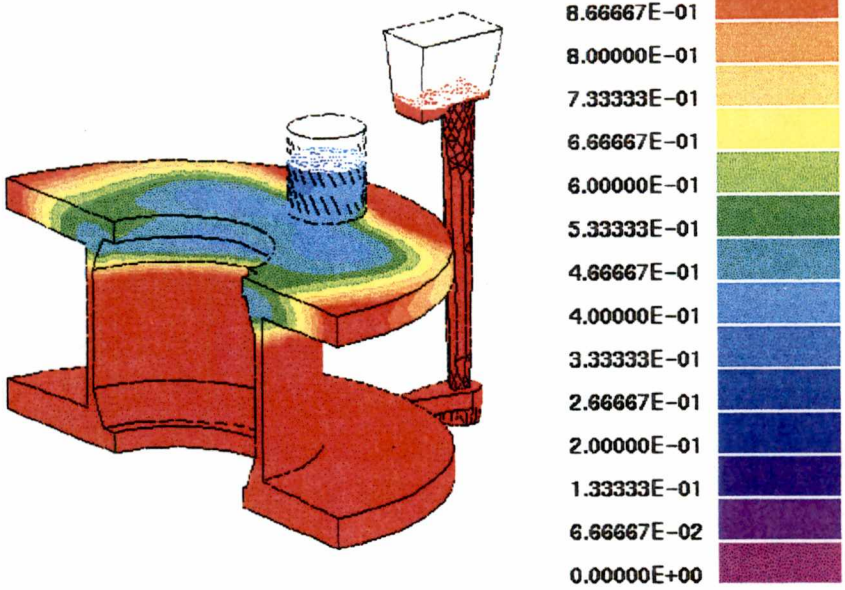


Figure 23. Fraction solid and temperature distribution at time = 153 sec.

(a) Fraction Solid Fringe Plot



(b) Temperature Fringe Plot

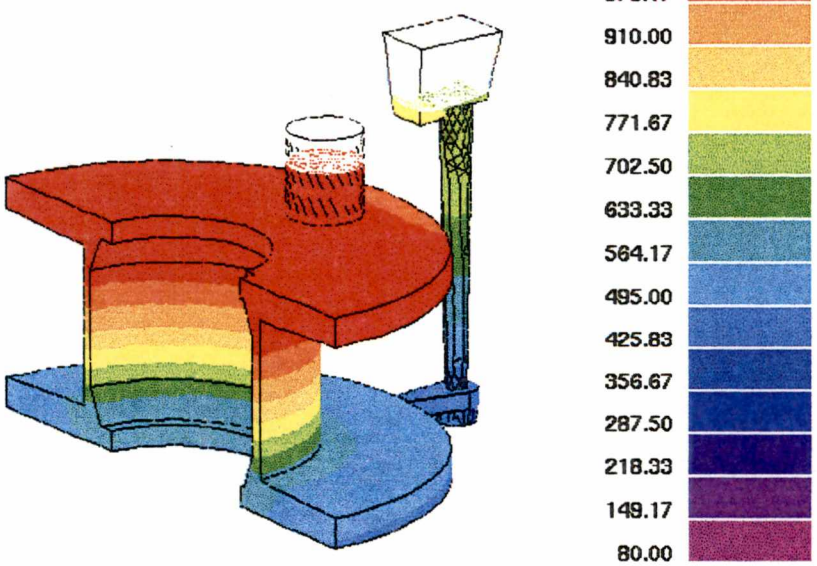
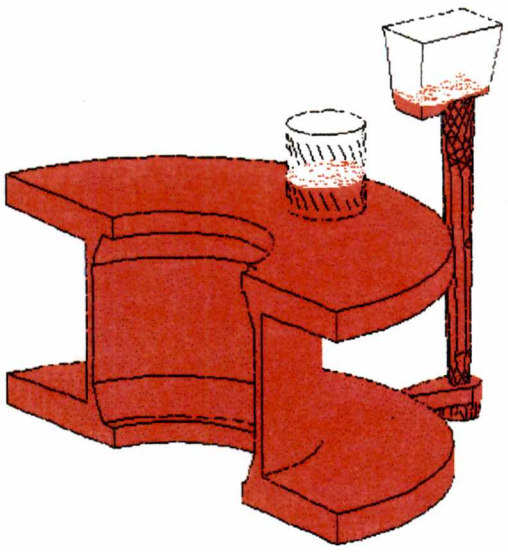
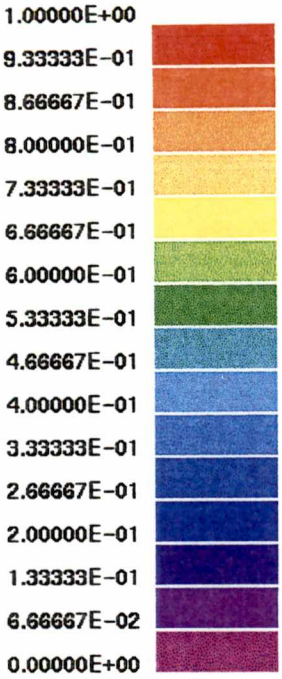


Figure 24. Fraction solid and temperature distribution at time = 488 sec.

(a) Fraction Solid Fringe Plot





(b) Temperature Fringe Plot

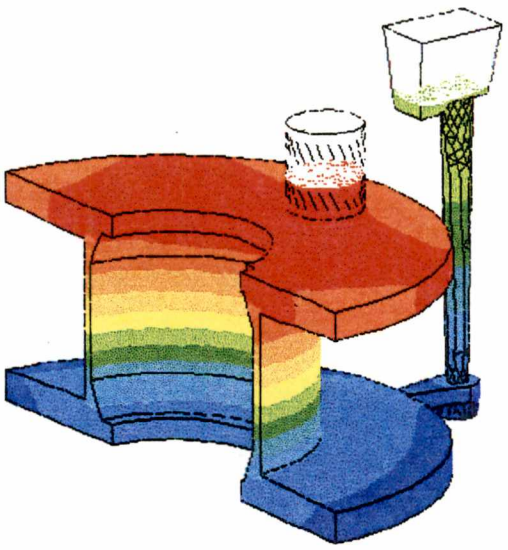




Figure 25. Fraction solid and temperature distribution at time = 938.2 sec.

from metallurgical principles that faster cooling rates with the present mold will yield finer microstructure resulting in stronger parts with higher surface hardness. The improvement in strength and hardness can best be quantified after casting several parts with a prototype of this design.

6.4 Sizing of the chill

As discussed in chapter 3 a flat table-top chill was selected with the bottom surface of the chill maintained at a constant temperature of 80 °F by circulating chilled water through piping at the bottom. The objective for having the table-top chill was to achieve a unidirectional solidification of the spool to ensure a sound cast part. The solidification would proceed progressively from the bottom of the flange to the risers. The chilled water pipeline was connected to a one side of the plate heat exchanger with a water pump in the process loop. The other side of the plate heat exchanger was connected to a air-cooled chiller to form a water loop.

The cooling load for chilled water table-top was determined from the results generated from the numerical simulation of the casting process. The maximum load was found to be 6.34 tons. The pipe diameter and length were estimated. In addition, the plate heat exchanger and the air-cooled chiller were sized and selected. The details of the final design are shown in Figure 26.

The estimated cost of the chiller and the plate heat exchanger are $9500 and $2000, respectively. Cost of installation is not included.

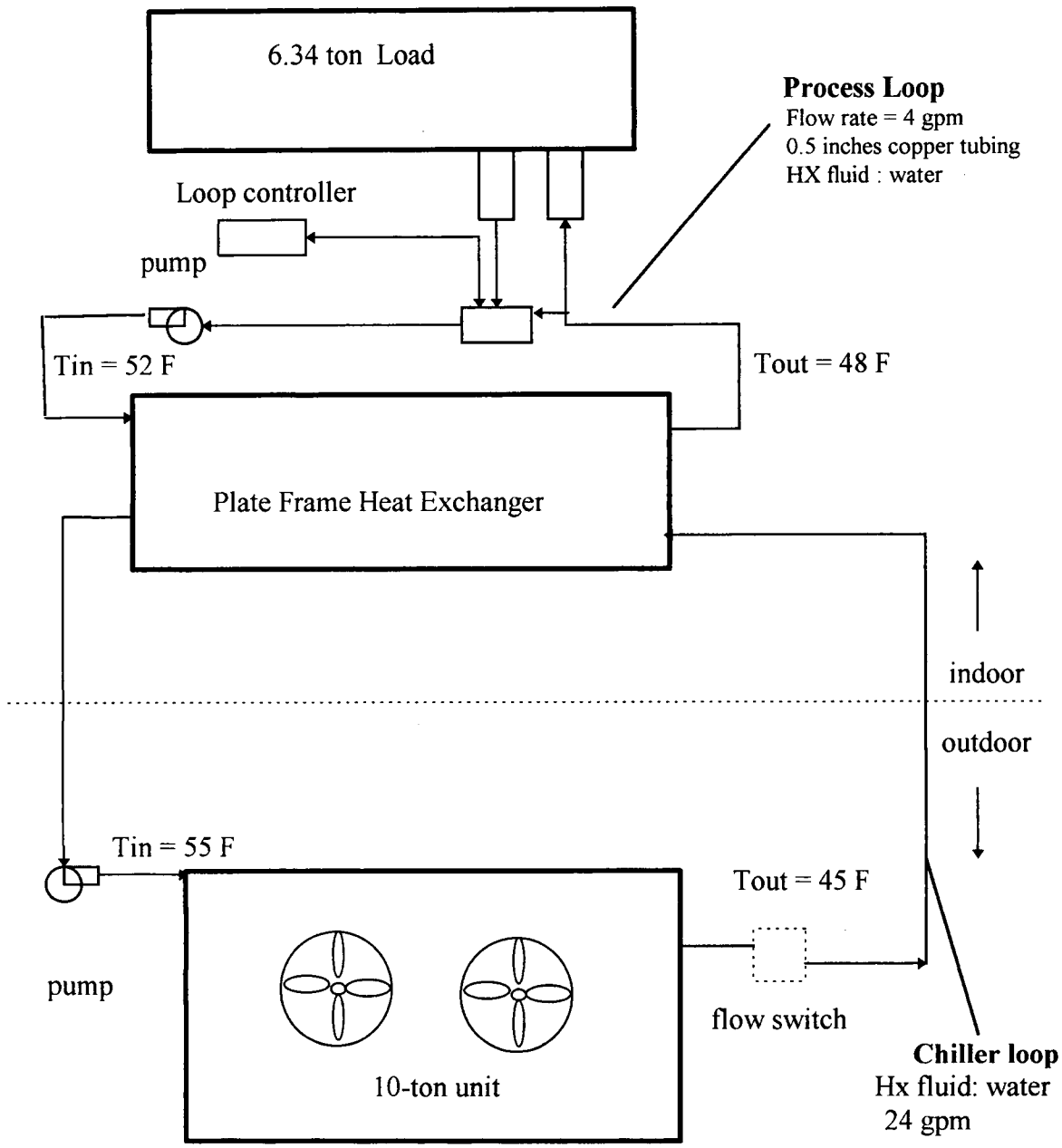


Figure 26. Schematic of the chiller cooling system.

7. Conclusions and Recommendations

7.1 Conclusions

The semi-permanent mold design was completed and the two objectives for the design were met. The following are the specific conclusion reached from this design and simulation study

In the startup cycle, the simulation results showed that there was porosity at the top flange and the top section of the barrel. However, in the production cycle the simulation results showed that the solidification was unidirectional and without any potential for the formation of porosity.

The results from the cycling simulation indicated that the mold achieved a periodic temperature distribution after the second cycle. Therefore, it can be concluded that at the start of each production day/shift, only the first two parts cast from the startup cycle will have the problem of porosity mentioned about . However, it may be possible to salvage the first two cast parts as indicated in the next section.

The present mode of casting this part in a sand mold is done at the rate of 3 parts per hour and requires highly-skilled operators to performed the finishing operations. The production rate of the semi-permanent mold is projected to be 4 parts per hour, requires fewer and simpler finishing operations, and the quality of the part will be significantly better. The need for highly-skilled operator to perform the finishing operations can be eliminated. It is projected by the plant manager of the foundry that cost of the finishing

7.2 Recommendations

7.2.1 Recommendations for software improvements.

The cycling simulation needs to be made more realistic than is possible with the present version of ProCAST.

The need for the user to specify the interfacial heat transfer coefficient should be removed. This can be done by incorporating a routine to calculate the local values of interfacial heat transfer coefficient at any time step based on the temperature distribution at the preceding time step.

7.2.2 Recommendations for salvaging the first two cast parts.

The porosity problem in the first two parts may be eliminated by some ingenious maneuvers. Two possible approaches are: (1) Molten metal can be poured directly into the riser (topping the riser) when the cavity of the spool is about 90 percent full. This action will raise the bulk temperature of the molten metal at the top of the flange thereby delaying solidification of this region and allowing unidirectional solidification to without interruption. (2) Additional heat can be applied to the top surface of the mold, for example, with a blow touch . This action will delay the cooling of the metal from the top wall of the mold.

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VITA

Roger was born in Singapore on the 18 Dec 1967 and lived there for most years of his life. After 6 years of Primary School education, he spent another 4 years at Mount Vernon Secondary School from where he graduated with an GCE "O" level certificate. He then proceeded to Nanyang Junior College for his "A" levels. During his junior college days, he was active in the basketball team as a point guard for 2 years.

In Singapore, it is compulsory for young men to go through their national service in the Singapore Armed Forces (SAF) for two years or more after they turned 18 years old. Roger was no exception. He was enlisted to serve the nation a few months after his "A" level examinations. After 3 months of Basic Military Training at the Infantry Training Depot, he was selected to attend the Officer Cadet School. After 9 months of training at the Officer Cadet School he was commissioned as a 2nd Lieutenant in the Republic of Singapore Air Force. He was put in charge of one platoon of the Rapier surface-to-air missile system. He was promoted to the rank of 1st Lieutenant shortly after one year.

After his active duties in the Air Force, he spent the next 4 years in Knoxville pursuing a further education. During these years, he was very active on campus and at the same time he was also working as a Resident Assistant, Mathematics Grader, Librarian and Research Assistant at the University. Finally in May 1994, he received his Bachelor of Science in Mechanical Engineering at the University of Tennessee, Knoxville.

Following that, he was offered to do the Masters of Science in Mechanical Engineering and also successfully received assistantship from the Department of Residence Halls. Subsequently, he worked for 2 years as the Assistant Hall Director at the Apartment Residence Halls while pursuing his Masters of Science in Mechanical Engineering.