THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF SCHOOL OF ENGINEERING

DEVELOPMENT AND ANALYSIS OF AN INTERNAL GATING SYSTEM FOR METAL CASTINGS

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of the requirements
for a baccalaureate degree
in Mechanical Engineering Technology
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ABSTRACT

The goal of this thesis is to develop a method to gate castings that will increase yield rates compared to tradition gating systems. To achieve increased yield rates, the gating system will become part of the final casting. The gating system will be manufactured out of a metal, similar to that of the casting being poured, and will be placed inside the casting cavity. Liquid metal will be poured into the gating system and exit the gating system into the casting cavity; as the metal fills the mold, the gating system will be surrounded by liquid metal. The gating system will then be heated by the liquid metal until it reaches the melting temperature and becomes part of the casting. To predict the time when the gating system will melt, hand calculations will be used in combination with casting process simulation software. The gating system should stay below the solidus temperature for the majority of the pour to control the flow of the metal, and reach a maximum temperature, above the liquidus temperature, just after the pour ends.

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I would like to thank everyone who helped me as I was writing this thesis.

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Shannon Sweeney, my thesis advisor and faculty reader.

Chapter 1 : Introduction

Introduction

The intent of this thesis is to develop an alternative method to gate castings; the research completed was specific to large gray iron castings. The alternative gating method developed in this research is a gating system manufactured from schedule 40 steel pipes and placed inside the casting cavity. When the casting is poured the liquid metal will travel through the gating system and exit into the mold cavity where the gating system will then be surrounded by the liquid metal. The gating system will consequently be melted by the casting and become a portion of the final part. This gating system will be referred to as an internal gating system or internal gating from here forward. Other methods of gating will be referred to as traditional gating, or traditional gating systems.

Motivation

The primary motivation for this work is to increase yield rates when manufacturing a casting. The yield rate is measured by dividing the casting weight by the total pour weight and is usually increased using one of two methods. The first method is to optimize the riser and chill set-up, allowing for the smallest possible feed volume. The second method is to minimize the size of the gating system; which forms the basis for this thesis. To reduce the size of the gating system, this thesis evaluates the possibility of placing the gating system inside the casting cavity so the gating system liquefies and becomes part of the final casting.

A secondary source of motivation is to provide an alternative option for gating castings. Using an internal gating system will have more strict geometric requirements for the casting than a traditional gating system. Therefore, an internal method of gating does not have the potential to be used on every casting, but could be an option when traditional gating methods are not favorable.

A final source of motivation is to decrease the sand to metal ratio. Often, the casting geometry requires the runner to surround the casting, shown in Figure 1-1. When the gating system surrounds the casting the size of the mold must be increased. Using an internal gating system will allow the mold to be smaller, thus reducing the sand to metal ratio.

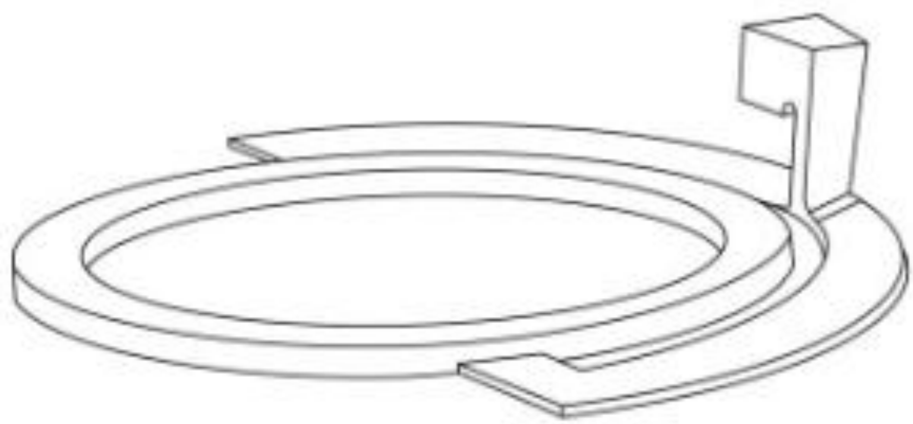


Figure 1-1: Ring casting surrounded by the gating system (1)

Background

The exact origin of the casting process is unknown but it is estimated that the art of metal casting began in ancient Mesopotamia between 5000-6000 years ago. The origin of castings cannot be traced for two main reasons. Firstly, the casting process was developed before written records were kept; and secondly, most of the earliest castings are assumed to have been re-melted. The first iron casting is credited to the Chinese and dated to have been made around 1000 B.C. Despite the fact that castings have been around for thousands of years, the process of casting did not become a common form of manufacturing until the 1800s; with the majority of the advancements in the foundry industry having taken place in the last 60 years (2). These advancements have led to the manufacturing practices used today.

Currently, part of the manufacturing process is to design the gating system, which is used to direct and control the flow of the metal through the mold into the casting cavity. Figure 1-2 shows an example of a bottom fill gating system; bottom fill gating systems introduce the metal into the bottom of the casting cavity and allow the mold to fill from the bottom to the top. The three main components of a bottom fill gating system are the sprue, runner, and ingates. Before entering the gating system, the metal is first poured into the pouring basin (also referred to as a pouring cup or gate box). The pouring basin is a container that sits on top of the mold which holds a portion of the metal being poured. Allowing the metal to be held in the pouring basin ensures that the gating system has a constant pool of metal to draw from. After the pouring basin, the metal enters the gating system. First, the metal falls down the sprue, the vertical portion of the gating system, relocating the metal to the correct elevation in the mold. At the bottom of the sprue there is usually a sprue well or sump. The sprue well is slightly larger than the sprue and stops the vertical fall of the metal, helping to dissipate the kinetic energy before the metal enters the casting cavity. The metal then flows into the runner, the horizontal portion of the gating system. The runner guides the metal to different areas in the mold, allowing the metal to enter the casting cavity from multiple, strategically located channels called ingates. The ingates not only transfer the metal from the runner to the casting cavity but also act as the choke of the system (3).

One of the advancements that has allowed for significant progress in the casting industry is the development of casting process simulation software. Using this software allows foundry engineers to predict the outcome of a mold design without running a sample casting. The casting process simulation software that will be used in this thesis is MagmaSoft ®. Founded in 1988, MagmaSoft® has developed into a world-wide company headquartered in Aachen, Germany. MagmaSoft® is designed to assist foundry engineers in predicting the quality of castings while reducing the cost of manufacture. The functionalities of MagmaSoft® that will be used for this thesis are simulations of the filing and solidification processes (4).

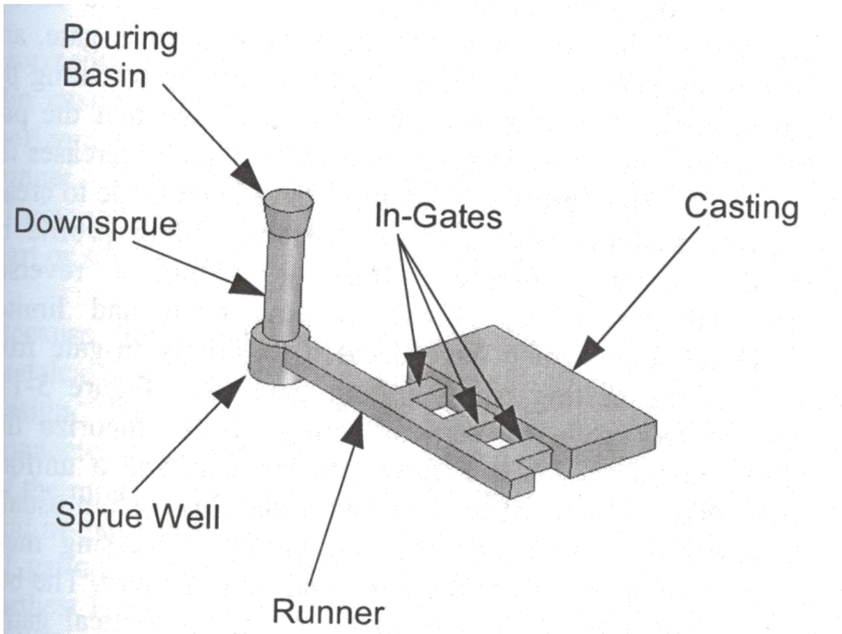


Figure 1-2: Example of a bottom fill gating system (5)

Internal Gating System Concept

The concept of internal gating is to put the gating system inside the casting cavity; the gating system will then become part of the final casting. Figure 1-3 shows an example of an internal gating system designed for a rectangular casting. The vertical pipe is acting as a sprue, the horizontal pipe is acting as a runner, and holes have been drilled through the horizontal pipe to act as ingates.

When using an internal gating system the goal is to melt the gating system so there is no boundary between the casting and the gating once the casting has solidified. Ideally, the gating system will reach the solidus temperature at the end of the pour, thus allowing the gating system to begin melting as soon as the pour is finished. If the system works correctly, the gating system will control the flow of the metal for the duration of the pour and the likelihood that the gating system melts will be maximized. If the gating system reaches the liquidus temperature, in theory, it will completely melt and become part of the final casting.

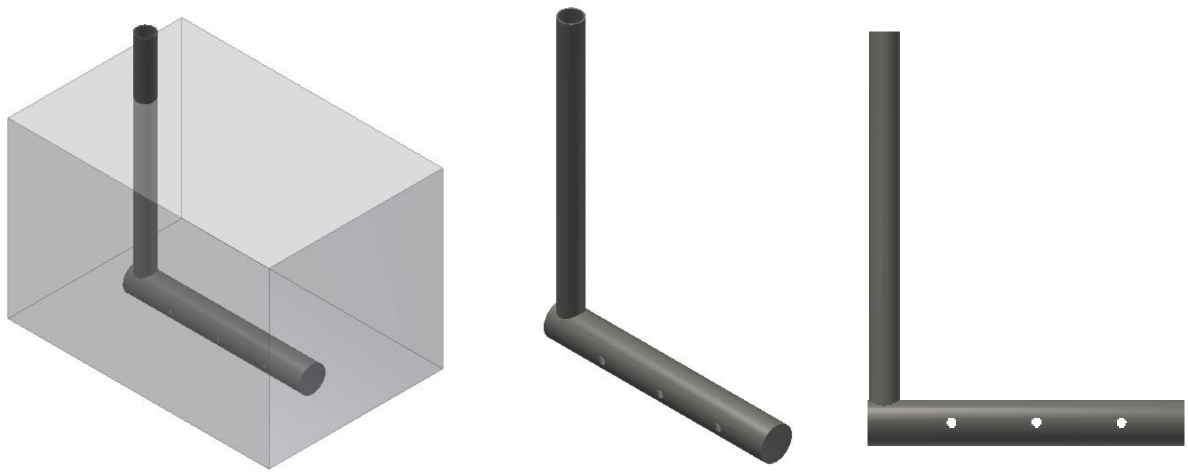


Figure 1-3: Left: Internal gating within a rectangular casting. Center: Isometric view of the internal gating system. Right: Front view of internal gating, displaying the drilled holes acting as ingates.

Chapter 2 : Internal Gating System

Advantages, Disadvantages, and Risks

Using an internal gating system has perceived advantages, disadvantages, and risks compared to a traditional gating system. When considering the advantages, disadvantages, and risks one must acknowledge that this is a matter of perspective. Some of the advantages can also be seen as disadvantages and some of the disadvantages can be considered risks. Risks represent factors that have the potential to cause the casting to be scrapped.

As with any change, the goal is to improve the current situation by introducing advantages. The main advantage of using an internal gating system is increasing yield rates. Increasing yield rates allows castings to be made more efficiently by requiring less metal to be tapped, or taken, out of the furnace. Tapping less metal from the furnace also reduces the amount of alloys needed to reach the material specifications of the casting. Another big advantage of an internal gating system is decreasing the sand to metal ratio of the mold. If an internal gating system is used, extra room is not needed in the mold to accommodate the gating, minimizing the amount of sand in the mold. This reduces the amount of chemical binder used, requires less clean up time, and reduces the total amount of mold material running through the reclaim system after the casting is shaken out, or removed from the mold. A final advantage of this system is that there is only one contact point between the gating system and the casting, which will hopefully reduce the finishing time.

After examining the advantages of the internal gating system the disadvantages must be looked at as well. The first disadvantage is brought about by one of the advantages, the single contact point between the internal gating system and the casting. The vertical pipe leaves a solid cylinder of metal that needs to be removed from the casting; this will be more difficult to remove than ingates, as is necessary when using traditional gating systems. The disadvantage of the single contact point is not a major problem but one of the many minor disadvantages. A second less significant disadvantage is the increased manufacturing time needed to produce the gating system; gating systems are typically made from wood or foam, materials that usually require less manufacturing time than metal. The third minor disadvantage of this system is that the casting will probably have less homogenous material properties than a casting made with a traditional gating system. The significance of this disadvantage will depend on the application of the casting. In addition to these minor disadvantages some larger disadvantages are introduced as well. One of the biggest disadvantages of an internal gating system is that it cannot be used to catch slag as a traditional gating system does. Since the gating system becomes part of the casting, anything that goes down the sprue will also become part of the casting; this makes the functionality of other slag catching techniques critical to the quality of the part. Another significant disadvantage is that the process of making the mold will require an additional step and time because the gating must be placed inside the casting cavity. Standard practices allow the gating system to be rammed during the same step as the pattern.

Final considerations which cannot be ignored are the risks which could scrap the part. Some of the risks that are attributed with using internal gating cross with the disadvantages. One of the biggest disadvantages is also one of the biggest risks; the gating system cannot be used to catch slag. To minimize this risk special consideration will need to be given to the gate box design, as well as metal cleanliness. The biggest risk introduced with an internal gating system would be that the gating system may not completely melt and portions of the system would then remain in the final casting. Some less significant risks include the chance of condensation forming on the gating system between the time the mold is closed and the casting is poured. If condensation forms, a safety hazard is created by increasing the likelihood of a blow back; measures need to be taken to ensure that any condensation is evaporated before the casting is poured.

Technical Information

The research for this thesis was completed for grey iron castings. To achieve the most homogeneous casting possible the internal gating system was originally designed to be manufactured from grey iron. Hand calculations and MagmaSoft ® simulations shown in this thesis were completed using grey iron as the material for the gating system. In later iterations the internal gating system was converted to be manufactured from schedule 40 steel pipes. Changing the material of the gating system will significantly decrease the time and cost to manufacture the system. The gating system represents a small percentage of the total casting weight therefore it was assumed that the disadvantages of using steel compared to iron would be negligible compared to the advantages gained. The material properties and composition of both metals are listed in Appendix A. Some material information has been omitted for confidentiality reasons; calculations involving this data show only the formula and final value calculated from the formula.

While designing the concept of an internal gating system, the components were kept as similar to those of a traditional gating system as possible. Figure 2-1 shows the components of an internal gating system. The metal will first flow into the sprue and at the bottom of the sprue is a cap, a disk of steel, which will close off the bottom of the sprue so the metal can only leave the sprue through the runner. The cap also prevents the falling metal from eroding the mold sand. Calculations for the stress on the mold from the falling metal are shown in Appendix C; drawings of the model used for calculations are shown in Appendix B. Once the metal is in the runner, it will exit into the casting cavity through drilled holes acting as ingates. Caps are placing on the ends of the runner to force the metal to leave the gating system through the ingates thus controlling the flow of the metal during the pour.

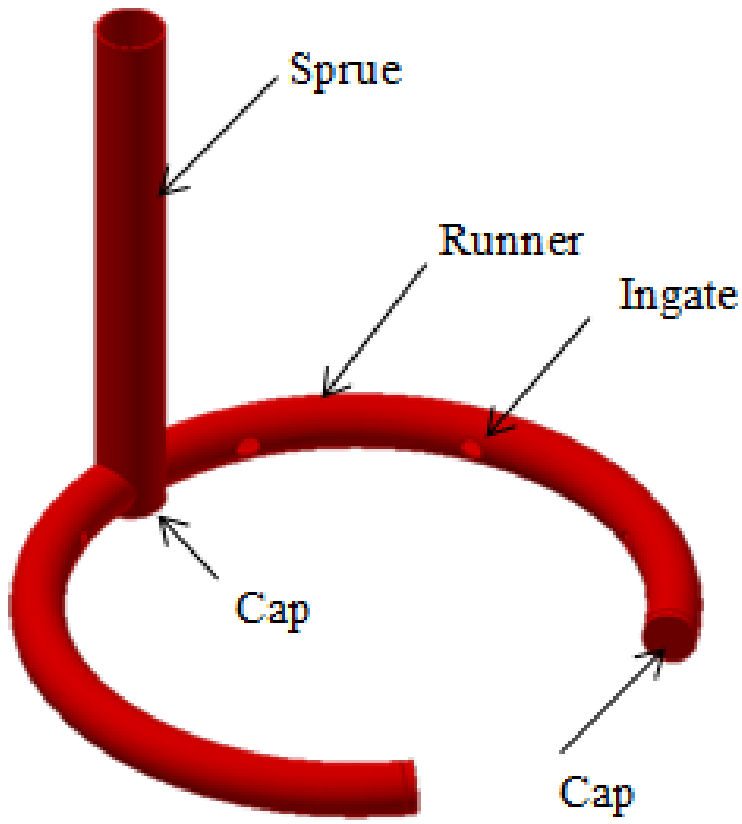


Figure 2-1: Components of an Internal Gating System.

Chapter 3 : Calculations

Calculations

Hand calculations and MagmaSoft® were used to determine if an internal gating system could be used to manufacture a casting, the MagmaSoft® inputs are shown in Appendix D. The main determining factor as to if an internal gating system could successfully be used to manufacture a casting was if the gating system reached the liquidus temperature before the casting solidified. A secondary consideration was the temperature of the gating system at the end of the pour. To simplify the hand calculations temperature gradients were ignored.

To determine the temperature of the gating system at the end of the pour the amount of energy the gating system absorbs during the pour was calculated. The energy absorbed was then converted into a change in temperature; these calculations are shown in Appendix E. The goal was for the gating system to be just below the solidus temperature (2055°F) at the end of the pour. The solidus temperature was determined using an iron/carbon phase diagram, shown in Appendix F. Using the same method, the liquidus temperature can be found. The equilibrium temperature of the mold is the maximum temperature the gating system will reach, this needs to be above the liquidus temperature, calculations are in Appendix G.

The gating system must reach the equilibrium temperature before the casting becomes a solid. To find the time when the gating system reaches the equilibrium temperature lumped system analysis was used, shown in Appendix G. The time when the casting solidifies according to MagmaSoft ® must be compared to the results of the lumped system analysis. To find the solidification time the energy released from the liquid metal before cooling to the solidus temperature was found. The energy released from the liquid metal is absorbed by the gating system and the mold sand. Calculations that show the amount and rate of energy transferred out of the liquid metal are in Appendix H.

Chapter 4 : Conclusions

Discussion

The hand calculations completed for this thesis can be applied to other internal gating systems/castings systems by changing appropriate the material and geometric inputs. To allow for more efficient analysis a spreadsheet was created, displayed in Appendix J. The spreadsheet has a section for all the needed inputs which will produce the necessary outputs. The calculations do not give a definite answer as to if the gating system will work or not, but provide an indication as to the maximum temperature the gating system will reach. The initial calculations for a casting and gating system may show that the internal gating system does not reach a temperature close to the melting temperature, in this situation the geometry of the gating system can be altered and the necessary iterative calculations can be completed. Once the calculations show that the gating system has an acceptable maximum temperature the model can be simulated in casting process simulation software to more accurately predict the outcome of the casting.

After completing the calculations on the initial model a second model was developed, drawings for the second model are in Appendix K. The second model incorporated a steel gating system and iterations on the calculations were completed until the calculations showed that the gating system reached an acceptable maximum temperature. The model was then simulated in MagmaSoft ®; the inputs used for this model are shown in Appendix D. The first simulation of this model showed the maximum temperature of the gating system was reached at the end of the pour, with a maximum temperature being 2297°F. Using an iron/carbon phase diagram the liquidus temperature of the gating system was determined to be about 2400°F. It was assumed that as the liquid iron surrounds the steel gating system the gating system will absorb some of the carbon from the iron and the percent weight of carbon would reach equilibrium between the casting and the gating system. The assumed equilibrium percent weight of carbon was then used to find the liquidus temperature from the iron/carbon phase diagram. After the first simulation, the maximum temperature of the gating system was 103°F below the assumed liquidus temperature. Since the temperature was close to the goal another simulation was run to simulate preheating the gating system to 500°F, all other inputs remained the same. The results from the second simulation showed a maximum temperature of 2328°F, still below the liquidus temperature. The significant results of both simulations for this model are shown in Appendix L. Further simulations were not completed.

Conclusion

For the systems analyzed, the hand calculations and simulations do not show that a casting can be manufactured using an internal gating system. It might be possible, if some of the variables were changed, that this method to gate a casting could be used. The use of this gating system may or may not be practical, each situation would need to be considered individually. The outcome of using this type of gating system cannot be accurately predicted due to the large number of unknowns and variables that are involved. Estimations of the results can be made, but unless experimental castings are produced the exact results of using this type of gating system will remain unknown.

Future Work

Further analysis could investigate the possibility of switching the casting material from iron to steel. This would increase the pouring temperature which in turn, should increase the maximum temperature the gating system reaches. Other material combinations could be further investigated, possibly including combinations where the gating system has a lower melting point than the metal of the casting.

Another area that could be further investigated is decreasing the wall thickness of the pipes used to manufacture the gating system. The difficulty of making this change lies in creating a mesh for the simulation. As the thickness of the gating system is decreased, creating an acceptable mesh becomes increasingly more difficult due to the thin wall section of the gating system.

The most important future work that could be completed would be to create and test an experimental casting. The calculations from this thesis could be modified to analyze any internal gating system exposed to the same processes as the one in this thesis. If the material and geometric inputs were updated, the formulas found in the appendixes should provide a fairly accurate prediction as to whether the gating system will successfully produce a casting. Despite the calculations, there are still many unknowns when using an internal gating system. The only way to truly know the outcome of using an internal gating system is to create an experimental casting.

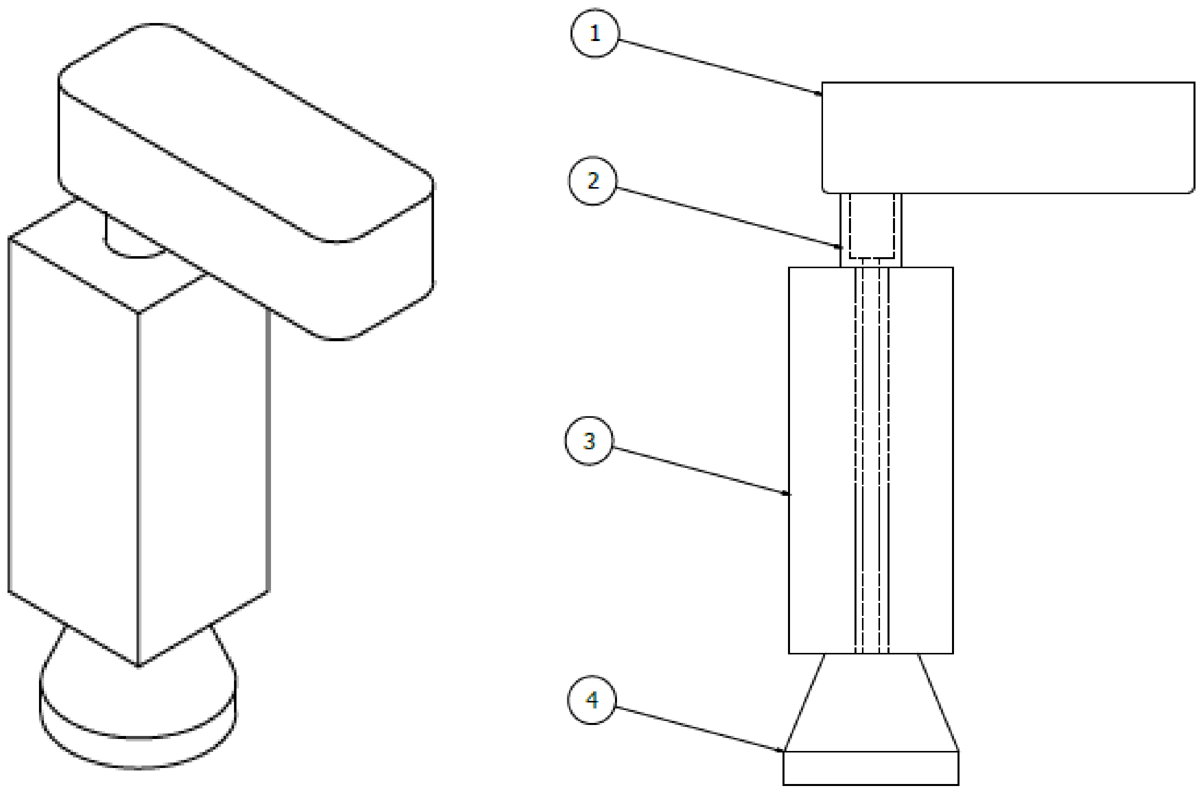
Appendix A

Material Data

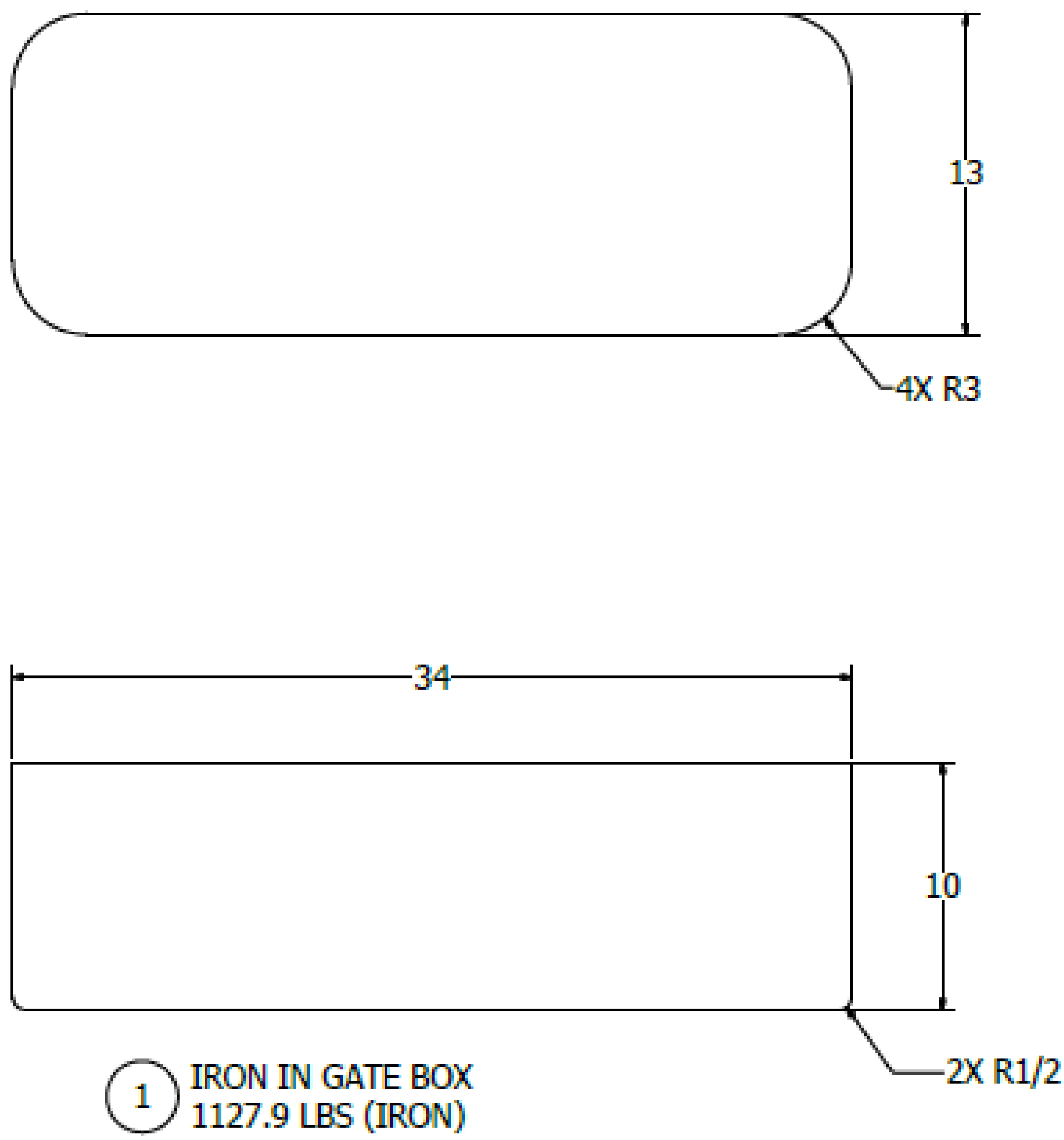
	Cast Iron	Steel
Composition (6)		
Iron	93.4% - 93.5%	98% - 98.5%
Carbon	3.2%	0.14% - 0.2%
Manganese	0.6%	1.3% - 1.6%
Phosphorus	0.1%	0.0% - 0.04%
Sulfur	0.0% - 0.15%	0.08% - 0.13%
Silicon	2.6%	---
Material Properties		
Density (6)	0.26 lb/in^3	0.28 lb/in^3
Kinematic Viscosity at 2460 °F	--- in^2/sec	N/A
Dynamic Viscosity at 2460 °F	--- lbm/in-sec	N/A
Thermal Properties		
C_p at 68°F	--- Btu/lbm-R	--- Btu/lbm-R
C_p at 2288°F	--- Btu/lbm-R	--- Btu/lbm-R
C_p at 2450°F	--- Btu/lbm-R	--- Btu/lbm-R
C_p at 2460°F	--- Btu/lbm-R	--- Btu/lbm-R
k at 68°F (7)	3.9 Btu/h-in-R	3.1 Btu/h-in-R
k at 2460°F (7)	1.55 Btu/h-in-R	N/A
Latent Heat	--- Btu/lbm	112 Btu/lbm (6)

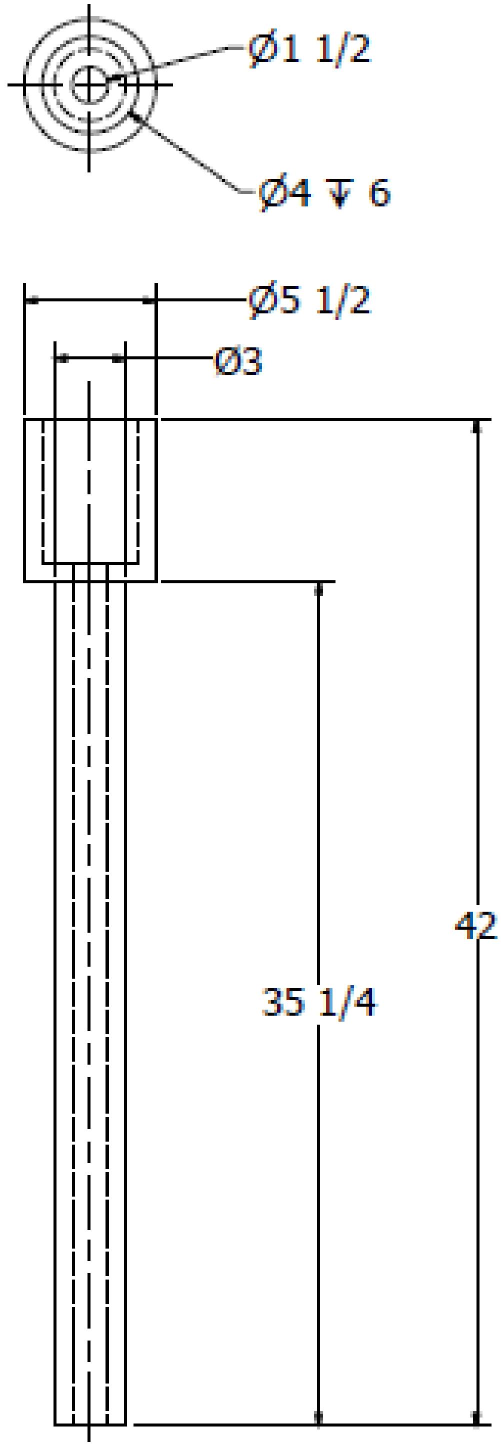
Appendix B

Drawings of Model Used for Hand Calculations

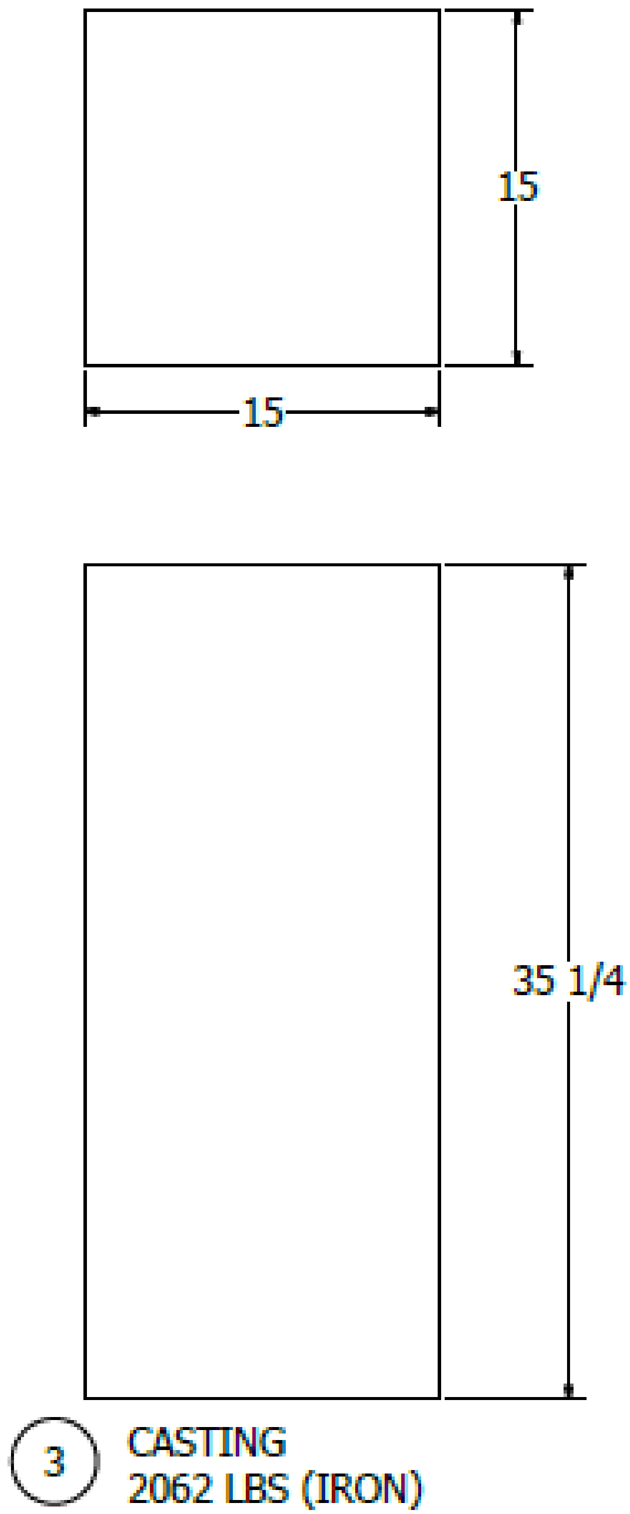


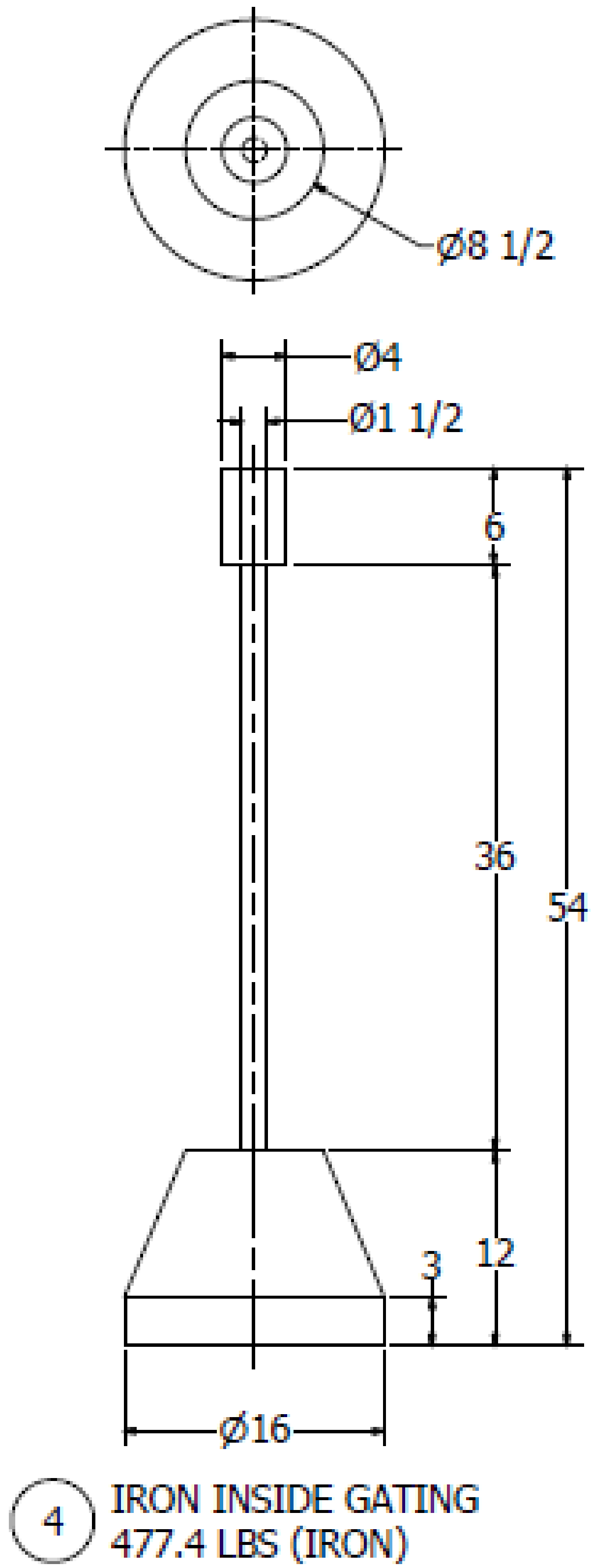
Left: Isometric view of gate box, internal gating system, and casting. Right: Orthographic view with hidden lines labeling the parts of the model. 1: Iron that fills the gate box; 2: The internal gating system; 3: The casting; 4: The iron that will flow through the gating system. In earlier concepts an area was placed below the casting to break the energy of the falling metal, this was replaced with a cap in later concepts. All drawing dimensions are inches.

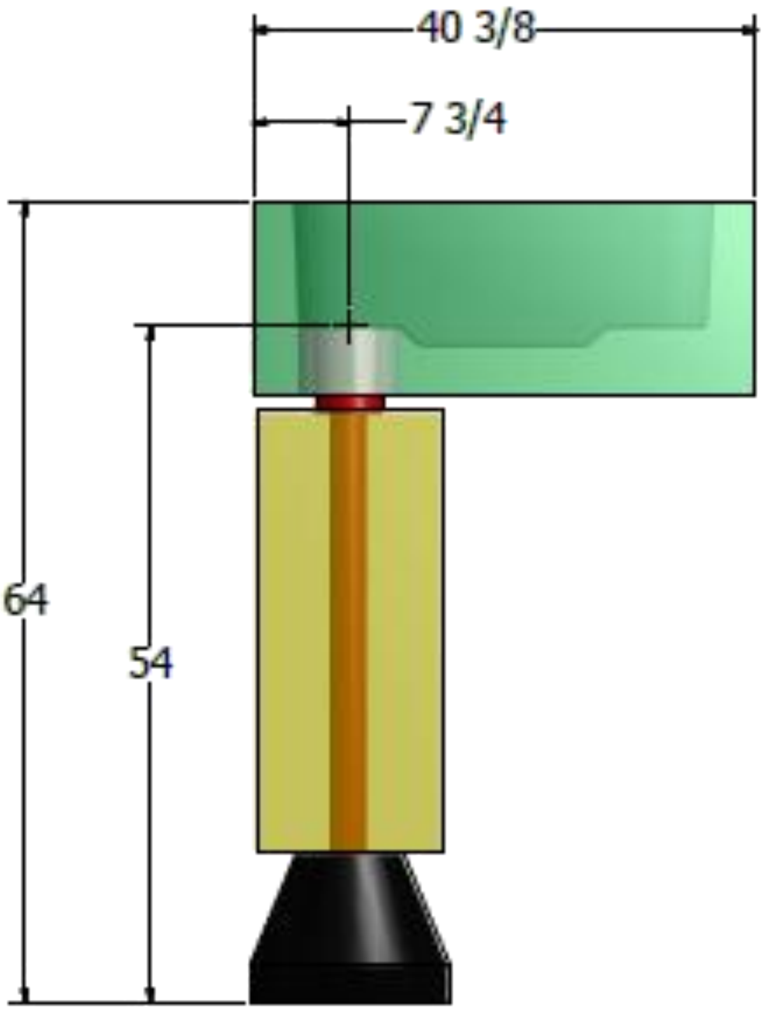

13
4X R3
34
10
2X R1/2
1
IRON IN GATE BOX
1127.9 LBS (IRON)



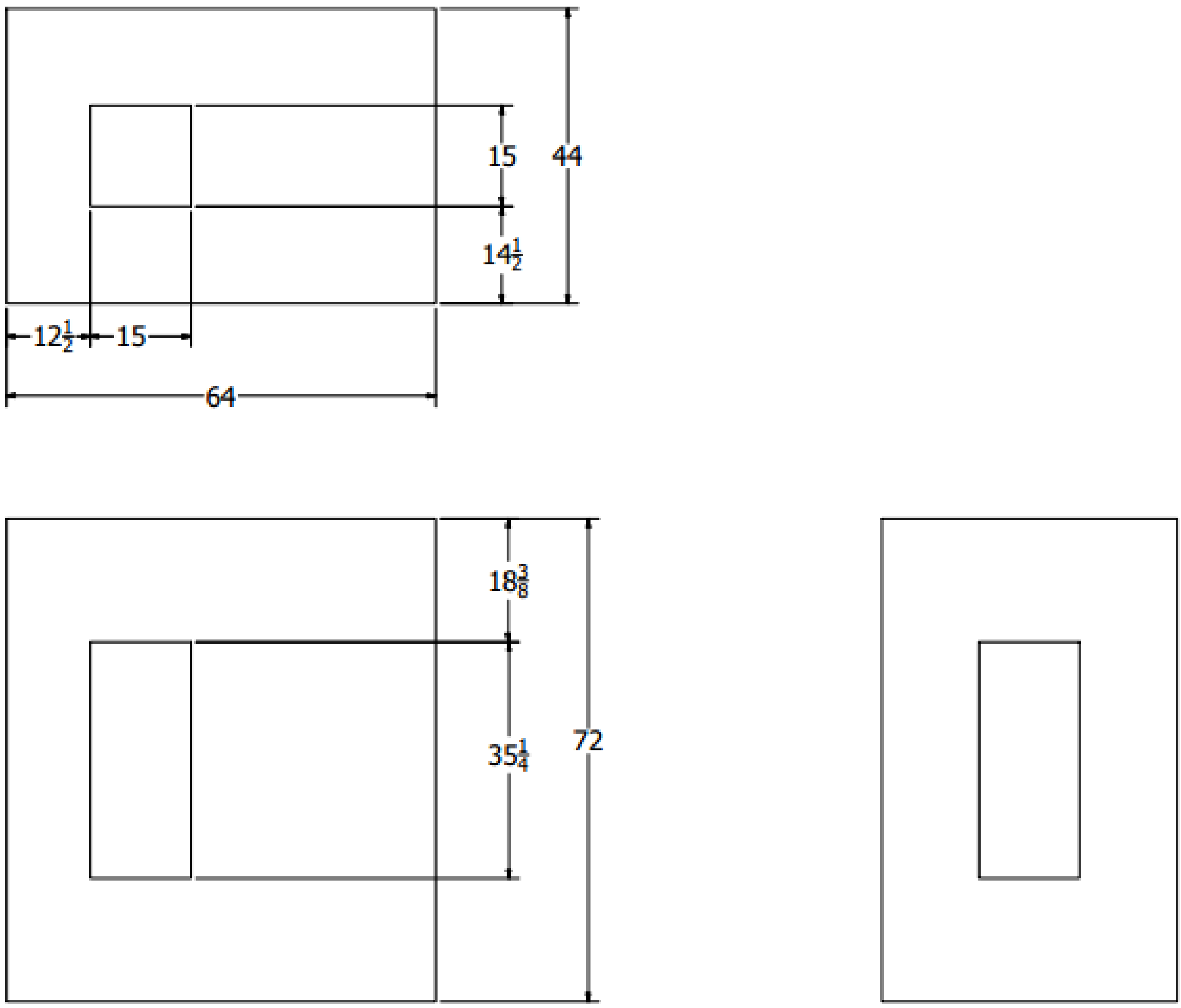
2 GATING
70.3 LBS (IRON)


15
15
35 1/4
3
CASTING
2062 LBS (IRON)


Ø8 1/2
Ø4
Ø1 1/2
6
36
54
12
3
Ø16
4
IRON INSIDE GATING
477.4 LBS (IRON)



Drawing shows the location of the origin. The origin is shown as a point and is centered at the top of the internal gating system.



Drawing shows the location of the casting within the mold sand.

Appendix C

Force on the Mold Sand from the Iron Entering the Mold

The stress on the mold was determined by calculating the velocity of the iron hitting the mold, the velocity was then used to find the force on the mold and the force was used to calculate the stress.

Velocity Calculation:

$$(V_1)^2 = (V_0)^2 + 2g(\Delta height)$$

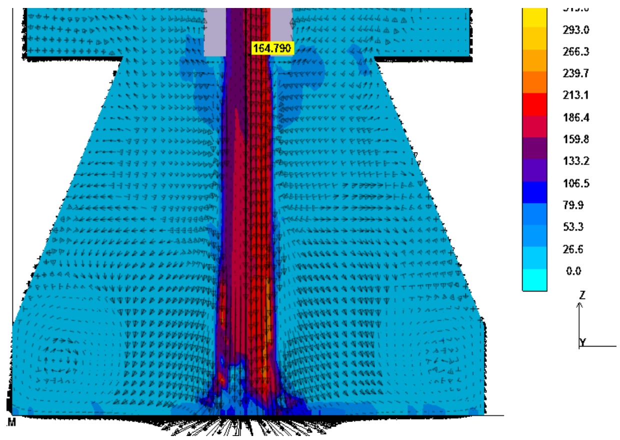
V_1 : Final Velocity
V_0 : Initial Velocity
g : Gravity
$\Delta height$: Change in height

$$\Delta height = -1065.41mm = -41.9in$$

$$(V_1)^2 = \left(0\frac{in}{\sec}\right)^2 + (2)\left(-386.4\frac{in}{\sec^2}\right)(-41.9in)$$

$$V_1 = 179.9\frac{in}{\sec}$$

$$\%Difference = \left|\frac{Difference}{Average}\right| * 100\%$$



Results of the MagmaSoft® simulation for velocity in the z-direction used to verify hand calculations. The probe is located at (1.14, -0.01, -1065.41) mm relative to the origin (shown in Appendix B), the value of the probe is 164.790 in/sec.

$$\%Difference = \left|\frac{\left(179.9\frac{in}{\sec} - 164.79\frac{in}{\sec}\right)}{\left(\frac{179.9\frac{in}{\sec} + 164.79\frac{in}{\sec}}{2}\right)}\right| * 100\%$$

$$\%Difference = 8.8\%$$

The bottom of the mold is located 12 inches below the probe. The probe was not placed at the bottom of the mold because the effects of the currents would not allow for an accurate value when the metal first made contact with the bottom of the mold. The velocity calculation above was calculated using $\Delta height$ = -54 inches to find a velocity of the metal at the bottom of the mold; the velocity is 204.3 in/sec. This calculation assumed no losses as the metal flows through the gating system.

Force Calculation (8):

$$F = (\rho)(g_c)(Q)(\Delta V)$$

F : Force
ρ : Density
g_c : Gravitational Constant
Q : Volumetric Flow Rate
ΔV : Change in Velocity

$$V_{\max} = 204.3\frac{in}{\sec}$$

$$Q = (V)(A)$$

Q : Volumetric Flow Rate
V : Maximum Velocity
A : Cross-sectional Area

$$Q = \left(204.3\frac{in}{\sec}\right)\left[\left(\frac{\pi}{4}\right)(1.5in^2)\right]$$

$$Q = 361.0\frac{in^3}{\sec}$$

$$F = \left(.26\frac{lbm}{in^3}\right)\left(\frac{lbf - s^2}{386.4lbm - in}\right)\left(361.0\frac{in^3}{\sec}\right)\left(204.3\frac{in}{\sec} - 0\frac{in}{\sec}\right)$$

$$F = 49.6lbf$$

Stress Calculation:

$$\sigma = \frac{F}{A}$$

σ : Stress
F : Force
A : Cross-sectional Area

$$\sigma = \frac{49.6lbf}{\left(\left(\frac{\pi}{4}\right)(1.5in)^2\right)} = 28.1psi$$

Factor of Safety Calculation:

Binder	CHEM-REZ 284 @ 1.2% weight of sand
Catalyst	Catalyst 2009 @ 35% weight of binder
Working Time in Minutes	4.5
Strip Time (from mold) in Minutes	8.3
Tensile Strength in psi at 1 hour	141
Tensile Strength in psi at 3 hours	279

*The sand is machine mixed at 72°F

Strength of furan sand (9)

$$FOS = \frac{\sigma_{allow}}{\sigma_{design}}$$

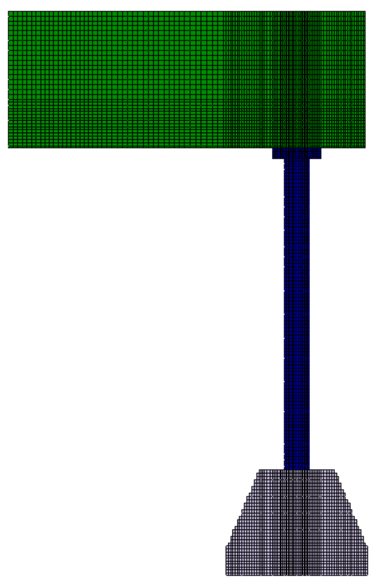
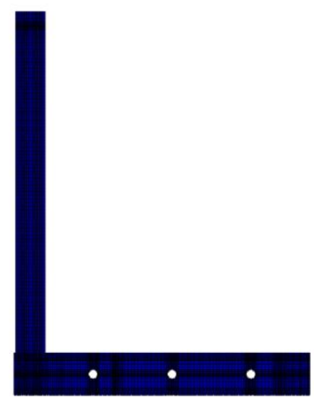
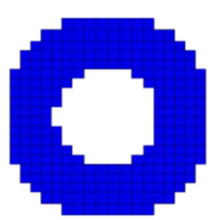
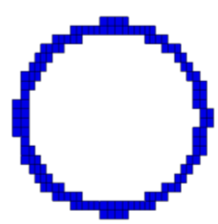
FOS : Factor of Safety
σ_{allow} : Allowable Stress
σ_{design} : Design Stress

$$FOS = \frac{279psi}{28.1psi} = 9.9$$

Although this factor of safety seems high there are many factors which could cause the value to decrease. The mold sand could be have a lower strength than anticipated due to external factors such as variations in the amount of catalyst and binder used or sand temperature. The height of the gating system could also be greater than that of the model used for the calculation. Due to unknown variations in the system, preventative measures were incorporated to avoid mold erosion.

Appendix D

MagmaSoft® Inputs for Simulations

	Model #1- Hand Calculation Model	Model #2 – Steel Gating System
Inlet for metal to enter system:	Ø6”	Ø6”
Materials:		
Casting:	Class 40 Grey Iron	Class 40 Grey Iron
Gating System:	Class 40 Grey Iron	Steel
Mold Sand:	Furan	Furan
Pour Time:	25 sec	40 sec
Pouring Temperature:	2460°F	2460°F
Room Temperature:	68°F	68°F
Mesh:	3,879,600 Elements 	17,960,976 Elements 
Mesh showing Cross-section of Gating System:		

Appendix E

Temperature of Gating System at the End of the Pour

The pour takes 25 seconds to fill the mold, this is an input entered into MagmaSoft®.

Energy Released by Liquid Metal Flowing Through the Gating System Calculation (10):

$$\dot{Q} = \dot{m} C_p (T_e - T_i)$$

Q_{dot} : Heat Transfer Rate
m_{dot} : Mass Flow Rate
C_p : Specific Heat
T_e : Average Temperature at Exit
T_i : Average Temperature at Entrance

Mass Flow Rate Calculation:

$$\dot{m} = \frac{m}{t}$$

m : Mass – From Model
t : Time – MagmaSoft® Input

$$\dot{m} = \frac{1127.9 lbm + 2062 lbm + 477.4 lbm}{25 \sec}$$

$$\dot{m} = 146.7 \frac{lbm}{\sec}$$

Average Temperature Calculation:

It takes six seconds for the gating system to be filled with liquid iron; data was taken from six seconds unto the end of the pour at twenty five seconds.

Time (sec)	Temperature at Entrance from MagmaSoft® (°F)	Temperature at Exit from MagmaSoft® (°F)
6	2451.7	2443.6
6.5	2451.2	2446.0
7	2452.2	2444.6
7.5	2453.5	2445.5
8	2452.1	2445.4
8.5	2453.1	2446.1
9	2454.1	2446.7
9.5	2453.0	2446.4
10	2451.3	2445.2

10.5	2450.6	2445.5
11	2449.4	2443.8
11.5	2453.4	2449.5
12	2452.7	2449.6
12.5	2452.1	2448.3
13	2451.5	2449.4
13.5	2451.3	2449.3
14	2450.6	2449.7
14.5	2450.5	2448.8
15	2448.8	2447.7
15.5	2448.9	2447.6
16	2450.0	2447.0
16.5	2451.6	2447.7
17	2451.2	2449.1
17.5	2451.0	2449.4
18	2453.1	2449.9
18.5	2453.6	2449.2
19	2452.3	2447.3
19.5	2451.8	2449.9
20	2452.3	2449.9
20.5	2451.7	2450.6
21	2450.5	2449.4
21.5	2450.4	2449.0
22	2451.0	2449.8
22.5	2452.9	2451.3
23	2452.5	2448.8
23.5	2452.3	2448.8
24	2452.8	2449.6
25	2452.3	2449.2
Average	2452	2448

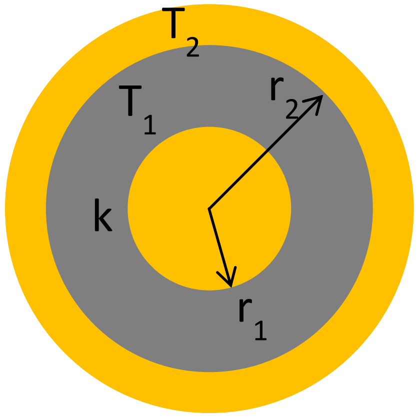
$$\dot{Q} = \dot{m} C_p (T_e - T_i)$$

$$Q = -2773 Btu$$

Energy Absorbed by Gating System by Conduction Calculation (10):

Conductivity was calculated each time the depth of the iron in the casting increased six inches. The metal reaches the bottom of the casting at 10.9 seconds into the pour.

$$\dot{Q} = \frac{(T_2 - T_1)(2\pi L)(k)}{\ln\left(\frac{r_2}{r_1}\right)}$$



Grey: Gating System
Yellow: Liquid Iron

T_2 : Temperature of Liquid Iron
T_1 : Temperature of Gating System
L : Length of Gating System exposed to Liquid Metal
k : Thermal Conductivity of Gating System at 68°F
r_2 : Outside Radius of Gating System
r_1 : Inside Radius of Gating System

Time for Liquid Metal to Reach Gating System Calculation:

$$T = \frac{V}{Q}$$

T : Time
V : Volume – From Model
Q : Volumetric Flow Rate

Volumetric Flow Rate Calculation:

$$Q = \frac{\dot{m}}{\rho}$$

Q : Volumetric Flow Rate
m_{dot} : Mass Flow Rate
ρ : Density

$$Q = \frac{146.7\,\frac{lbm}{\sec}}{0.26\,\frac{lbm}{in^3}}$$

$$Q = 564.2\,\frac{in^3}{\sec}$$

$$T = \frac{6174.2\,in^3}{564.2\,\frac{in^3}{\sec}}$$

$$T = 10.9\sec$$

Time for Metal to Rise 6" In Casting Calculation:

$$T = \frac{V}{Q}$$

$$T = \frac{1350 in^3}{564.2 \frac{in^3}{\sec}}$$

$$T = 2.39 \sec$$

$$\dot{Q} = \frac{(T_2 - T_1)(2\pi L)(k)}{\ln\left(\frac{r_2}{r_1}\right)}$$

$$\dot{Q} = \frac{(2460°F - 68°F)(2\pi * 6in)\left(3.9\frac{Btu}{h - in - R}\right)}{\ln\left(\frac{1.50in}{0.75in}\right)}$$

$$\dot{Q} = 507{,}378\frac{Btu}{hr}$$

$$Q = (\dot{Q}_1)(t_2 - t_1)$$

Q : Heat Transferred
Q_{dot1} : Heat Transfer Rate for Time Interval 1
t_1 : Time Metal Reaches Bottom of 6" Interval
t_2 : Time Metal Reaches Top of 6" Interval

$$Q = \left(507{,}378\frac{Btu}{hr}\right)\left(\frac{1hr}{3600\sec}\right)(13.3\sec - 10.9\sec)$$

$$Q = 338 Btu$$

Time (seconds)	Q_{dot} (Btu/hr)	Q (Btu)
13.3 – 15.7	1,014,756	677
15.7 – 18.1	1,522,133	1015
18.1 – 20.5	2,029,511	1353
20.5 – 22.9	2,536,889	1691
22.9 – 25.3	2,980,844	1987
Total	10,084,133	7061

The total energy absorbed by the gating system during the pour is the total amount of energy the liquid metal releases while flowing through the gating system, and the energy absorbed from conduction. The conduction calculation would be more accurate if calculated as convection but some variables for the convection calculation could not be solved for. The error from using conduction compared to convection is assumed to be negligible because of the short amount of time that it takes to fill the mold compared to the total amount of time the gating system is exposed to the liquid metal.

Total Energy Absorbed by the Gating System Calculation:

$$Q = 2773Btu + 7061Btu$$
$$Q = 9834Btu$$

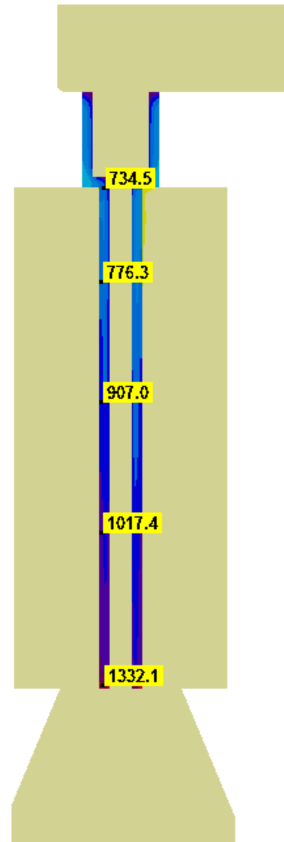
Temperature of Gating System at End of Pour Calculation (10):

$$Q = (m)(C_p)(T_2 - T_1)$$

Q : Total Energy
m : Mass of Gating System – From Model
C_p : Specific Heat
T_2 : Final Temperature
T_1 : Initial Temperature

$$T_2 = 1344.3°F$$

The picture on the right shows the MagmaSoft® temperature result of the gating system at the end of the pour. The temperature calculated is comparable to the temperature probe at the bottom of the gating system with a value of 1332.1°F. The bottom of the gating system is used to compare to the hand calculation because this is the location that is exposed to both the flow of the liquid metal and conduction for the times used in the hand calculations.



$$\%Difference = \left|\frac{Difference}{Average}\right| * 100\%$$

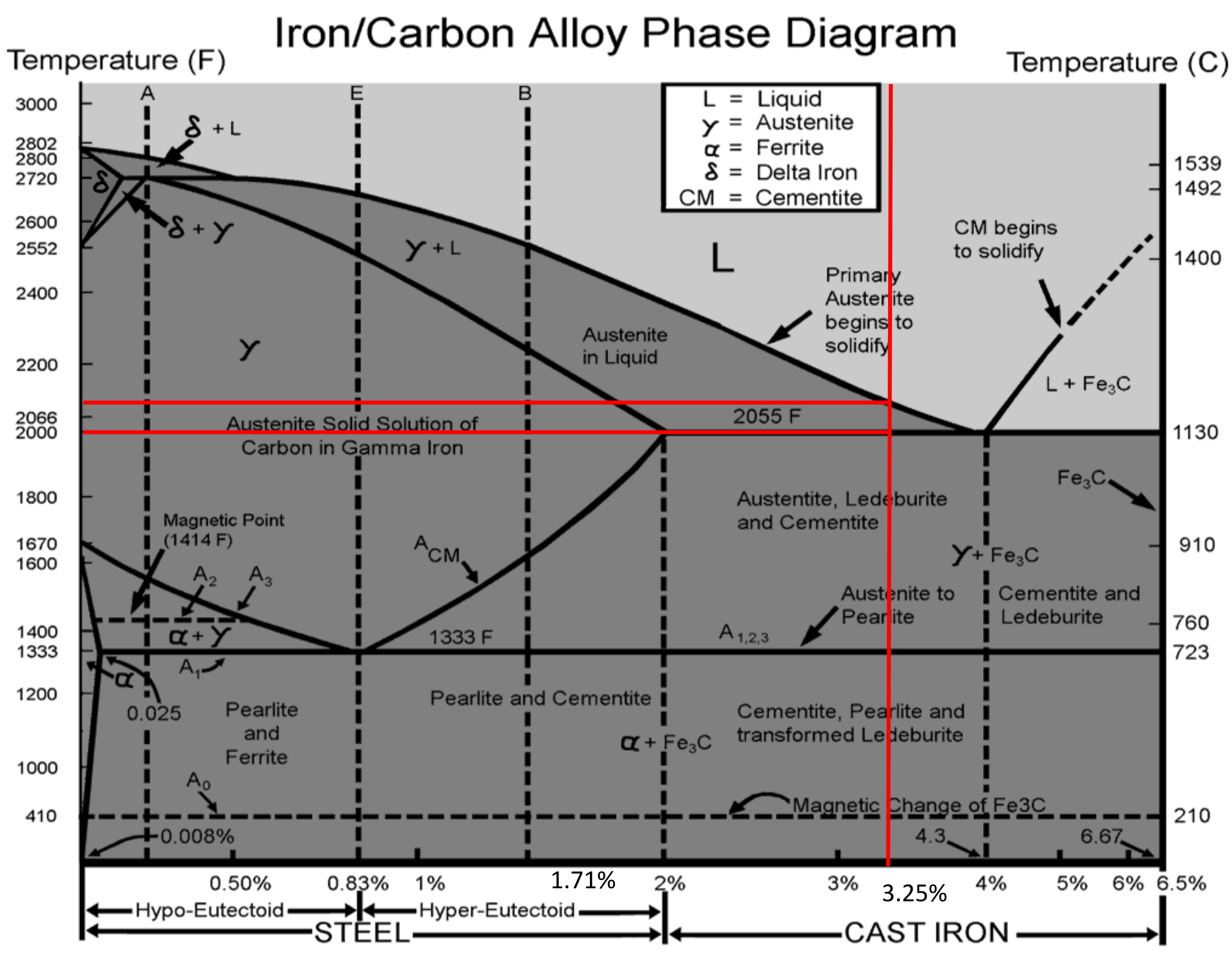
$$\%Difference = \left|\frac{1344.3°F - 1332.1°F}{\left(\frac{1344.3°F + 1332.1°F}{2}\right)}\right| * 100\%$$

$$\%Difference = 0.91\%$$

Appendix F

Iron/Carbon Phase Diagram

The solidus temperature of iron with 3.25% carbon by weight is about 2055°F; the liquidus temperature is about 2100°F. The solidus and liquidus temperature for the gating system can be estimated using this method assuming an estimation can be made for the carbon content of the material.



Carbon Content Percent (by weight)

Appendix G

Equilibrium Temperature and Time Calculations

Equilibrium Temperature Calculation (10):

$$Q = mC_p\left(T_2 - T_1\right)$$

Q : Heat Transfered
m : Mass
C_p : Specific Heat
T_2 :Final Temperature
T_1 : Initial Temperature

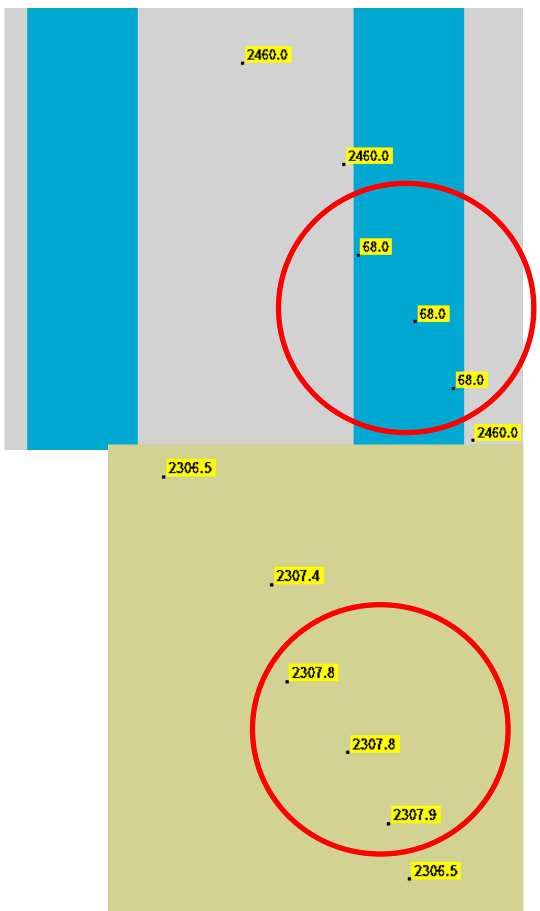
$$Q_{solid} = Q_{liquid}$$
$$T = 2414°F$$

The picture to the right shows the MagmaSoft® result in which equilibrium is reached. Equilibrium is reached 940 seconds after the pour starts, this is 15.25 minutes into the solidification of the casting.

$$\%Difference = \left|\frac{Difference}{Average}\right| * 100\%$$

$$\%Difference = \left|\frac{2414°F - 2307°F}{\left(\frac{2414°F + 2307°F}{2}\right)}\right| * 100\%$$

$$\%Difference = 4.5\%$$



Top: Shows temperature (˚F) as the metal initially enters the mold, grey shows the liquid metal, blue shows the gating system. Bottom: Shows the temperature for the same locations when equilibrium is reached.

Equilibrium Time Calculation (10):

Lumped system analysis was used to calculate the equilibrium time of the liquid metal and the gating system.

$$Bi = \frac{hL_c}{k}$$

Bi : Biot Number
h : Convection Heat Transfer Coefficient
L_c : Characteristic Length
k : Thermal Conductivity at 68 °F

Convection Heat Transfer Coefficient Calculation (10):

$$h = \frac{(Nu)(k_{2460°F})}{x}$$

Nu : Nusselt Number
x : Length

Nusselt Number Calculation (10):

$$Nu = 6.3 + 0.0167(\mathrm{Re})^{0.85}(\mathrm{Pr})^{0.93}$$

Re : Reynolds Number
Pr : Prandtl Number

Reynolds Number Calculation (10):

$$\mathrm{Re} = \frac{(V_{avg})(D)}{\nu}$$

V_{avg} : Average Velocity of Liquid Iron
D : Inside Diameter of Ingate
υ : Kinematic viscosity at 2460°F

Average Velocity Calculation:

Time starts when the gating system is filled with metal and ends when the pour is complete.

Time (seconds)	Velocity at Entrance of Gating System (in/sec)	Velocity at Exit of Gating System (in/sec)
6.5	144.282	173.078
7	128.083	181.139
7.5	130.128	181.734
8	144.847	182.646
8.5	147.573	182.334

9	142.637	181.785
9.5	157.335	183.210
10	154.909	184.064
10.5	136.633	182.777
11	147.737	181.756
11.5	324.960	378.412
12	294.843	393.776
12.5	322.658	372.652
13	339.534	382.726
13.5	275.129	401.402
14	307.827	417.635
14.5	330.092	404.335
15	300.918	393.103
15.5	314.979	400.231
16	305.866	381.547
16.5	332.286	391.434
17	341.196	421.181
17.5	332.852	414.306
18	324.062	429.082
18.5	301.569	386.436
19	319.342	376.872
19.5	308.864	415.319
20	337.171	395.452
20.5	334.101	394.040
21	338.587	416.100
21.5	341.122	425.601
22	325.436	423.513
22.5	332.537	414.838
23	337.032	390.730
23.5	322.415	377.296
24	341.467	383.076
25	332.448	392.316
Average	274.400	340.200

Reynolds Number Calculation:

$$\mathrm{Re} = \frac{(V_{avg})(D)}{\nu}$$

Re = 282,791

Prandtl Number Calculation:

$$\Pr = \frac{(\mu)(C_p)}{k}$$

μ : Dynamic Viscosity at 2460 °F
C_p : Specific Heat at 2460 °F
k : Thermal Conductivity at 2460°F

$$\Pr = 0.186$$

$$Nu = 6.3 + 0.0167(\text{Re})^{0.85}(\Pr)^{0.93}$$
$$Nu = 6.3 + 0.0167(282{,}791^{0.85})(0.186^{0.93})$$
$$Nu = 156.68$$

$$h = \frac{(Nu)(k_{2460°F})}{x}$$
$$h = \frac{(156.68)(1.55\frac{Btu}{h - in - R})}{35.25in}$$
$$h = 6.89\frac{Btu}{hr - in^2 - R}$$

$$Bi = \frac{hL_c}{k}$$
$$Bi = \frac{(6.89\frac{Btu}{hr - in^2 - R})(35.25in)}{3.9\frac{Btu}{h - in - R}}$$
$$Bi = 62$$

Lumped system analysis is typically only used when the biot number is less than or equal to 0.1, the biot number corresponds to the expected error in the calculations. Solving for the biot number shows that a high percent difference is expected when using lumped system analysis. This analysis was used to simplify the problem; other methods would involve temperature gradients.

Lumped System Analysis - Equilibrium Time Calculation (10):

$$b = \frac{h}{\rho(C_p)L_c}$$

b : Exponent
h : Convection Heat Transfer Coefficient
ρ : Density
C_p : Specific Heat at 68°F
L_c : Characteristic Length

$$b = 6.9\frac{1}{hr}$$

$$\frac{T(t) - T_\infty}{T_i - T_\infty} = e^{-bt}$$

$T(t)$: Temperature at Time of Interest
T_∞ : Ambient Temperature
T_i : Initial Temperature
b : Exponent
t : Time

$$\frac{(2414°F - 2460°F)}{(1344°F - 2460°F)} = e^{-(\frac{6.9}{hr})t}$$

$$t = .46hr$$

Total Time to Reach Equilibrium Temperature Calculation:

$$T = P + E$$

T : Total Time
P : Length of Pour
E : Time to Reach Equilibrium Temperature

$$T = 25\sec + (.46hr)\left(\frac{3600\sec}{1hr}\right)$$

$$T = 1681\sec$$

$$\%Difference = \left|\frac{Difference}{Average}\right| * 100\%$$

$$\%Difference = \left|\frac{1681\sec - 940\sec}{\left(\frac{1681\sec + 940\sec}{2}\right)}\right| * 100\%$$

$$\%Difference = 57\%$$

Appendix H

Energy Released by the Liquid Metal

Energy Consumed by the Gating System Calculation:

Energy Absorbed from Metal Flowing Through Gating System: 2773 Btu

Energy Absorbed from Metal Surrounding Gating System during Pour: 7061 Btu

Energy Absorbed to Reach Equilibrium Temperature Calculation (10) :

$$Q = \dot{m}C_p(T_1 - T_2)$$

Q : Heat Transferred
m : Mass of Gating System
C_p : Specific Heat of Iron at 68°F
T_1 : Equilibrium Temperature
T_2 : Average Temperature of Gating System at the End of the Pour – From Magma

$$Q = 11{,}253 Btu$$

Energy Needed to Change Phase Calculation:

$$Q = (LatentHeat)(Mass)$$

$$Q = 6496 Btu$$

Total Energy Consumed By Gating System Calculation:

$$Q = 2773 Btu + 7061 Btu + 11{,}253 Btu + 6496 Btu$$

$$Q = 27{,}583 Btu$$

Energy Transferred into the Mold Sand from the Liquid Metal Calculation (10):

$$\dot{Q} = \frac{(k)(A)(T_1 - T_2)}{L}$$

k : Thermal Conductivity of Mold Sand at 68 °F (4)
A: Cross-Sectional Area of Sand
T_1: Temperature of Liquid Metal
T_2 : Temperature of Sand
L : Depth of Cross-Sectional Area

$$\dot{Q}_1 = \frac{\left(0.0028 \frac{Btu}{h - in - R}\right)(72in * 64in)(2460°F - 68°F)}{74.5in}$$

$$\dot{Q}_1 = 2128 \frac{Btu}{hr}$$

	Q_2	Q_3	Q_4	Q_5	Q_6
Area (in^2)	4608	2816	2816	3168	3168
Length (in)	14.5	18.375	18.375	36.5	12.5
Q_{dot} (Btu/hr)	2128	1026	1026	581	1679

Total Heat Transfer Rate: 8568 Btu/hr

Energy Released By Liquid Metal before Solidifying Calculation (10):

$$Q = \dot{m}C_p(T_1 - T_2)$$

Q : Heat Transferred
m : Mass of Liquid Iron
C_p : Specific Heat of Iron at 2288°F
T_1 : Initial Temperature of Liquid Iron
T_2 : Solidus Temperature

$$Q = 131{,}573 Btu$$

Time for Casting to Solidify Calculation:

Energy Released by Liquid Metal – Energy Absorbed by Gating System during Pour
131,573 Btu – 27,583 Btu = 103,990 Btu

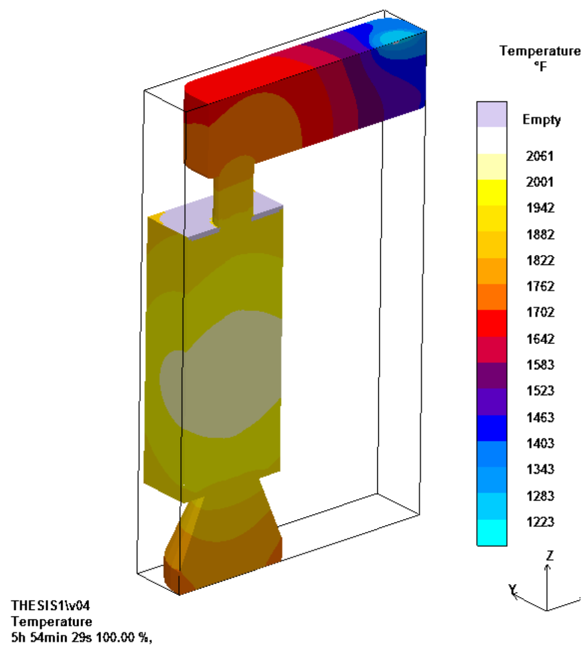
Energy Remaining until Casting Solidifies ÷ Energy Transferred Into Mold Sand

$$\frac{103{,}990\,Btu}{8568\,\frac{Btu}{hr}} = 12.1\,hr$$

$$\%Difference = \left|\frac{Difference}{Average}\right| * 100\%$$

$$\%Difference = \left|\frac{726\min - 354\min}{\left(\frac{726\min + 354\min}{2}\right)}\right| * 100\%$$

$$\%Difference = 69\%$$



MagmaSoft® result showing the system when the casting solidifies. Time: 5 hr 54 min

Appendix J

Spreadsheet

Inputs

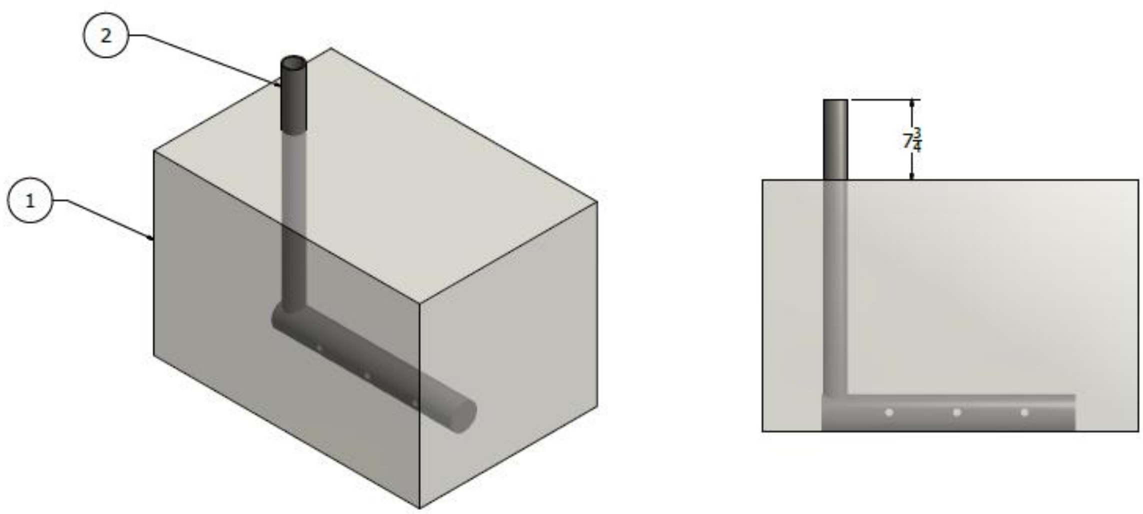
Gating (Iron)			
	Initial Temperature	68	°F
	Mass	70.3	lbm
	$Cp_{Room\ Temp}$		
	Ingate ID	1.5	in
	Ingate OD	3.00	in
	Ingate Length	35.25	in
	$k_{Room\ Temp}$	3.9	Btu/h-in-R
	Latent Heat		
Liquid Iron			
	Casting Mass	2062	lbm
	Total Pour Mass	3667	lbm
	Pour Temperature	2460	°F
	Average Velocity	307.3	in/sec
	Pour Length	25	sec
	$\upsilon_{Pour\ Temp}$		
	$Cp_{Pour\ Temp}$		
	$k_{Pour\ Temp}$	0.000431	Btu/s-in-R
	Ingate Entrance Temp	2452	°F
	Ingate Exit Temp	2448	°F

Outputs

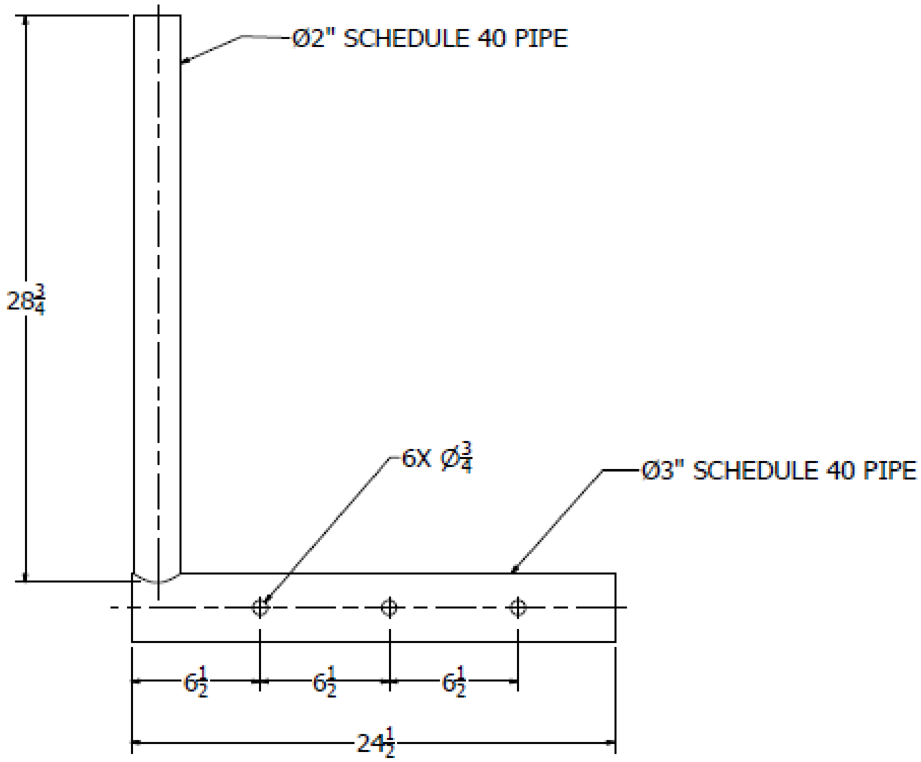
Re		282,791	
Pr		0.185	
Nu		156	
h		6.86	Btu/h-in^2-R
$Q_{metal\ flowing\ through\ gating}$		2758	Btu
$Q_{conduction}$		6955	Btu
Total Energy Absorbed During Pour		9713	Btu
Equilibrium Temp		2413	°F
Temp at Top of Gating at End of Pour		426	°F
Temp at Bottom of Gating at End of Pour		1329	°F
Energy Needed to Reach Equilirbrium		11,836	Btu
Energy to Change Phase		6496	Btu
Energy Needed to Melt		28,044	Btu
Energy Available		133354	Btu
Is the Equilibium Temp Above the Liquidus Temp?	Yes		
Does the Liquid Metal Release More Energy Than the Gating System Requires to Melt?	Yes		

Appendix K

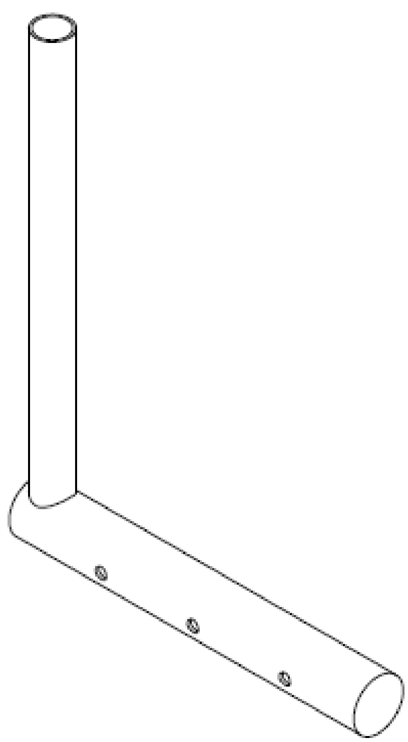
Drawings for Second Model



Left: Isometric view of steel internal gating system within a rectangular casting. Right: Orthographic view dimensioning the portion of the gating system from the top of the casting to the top of the mold (mold not shown).



(2) GATING SYSTEM - STEEL
24.4 LBS

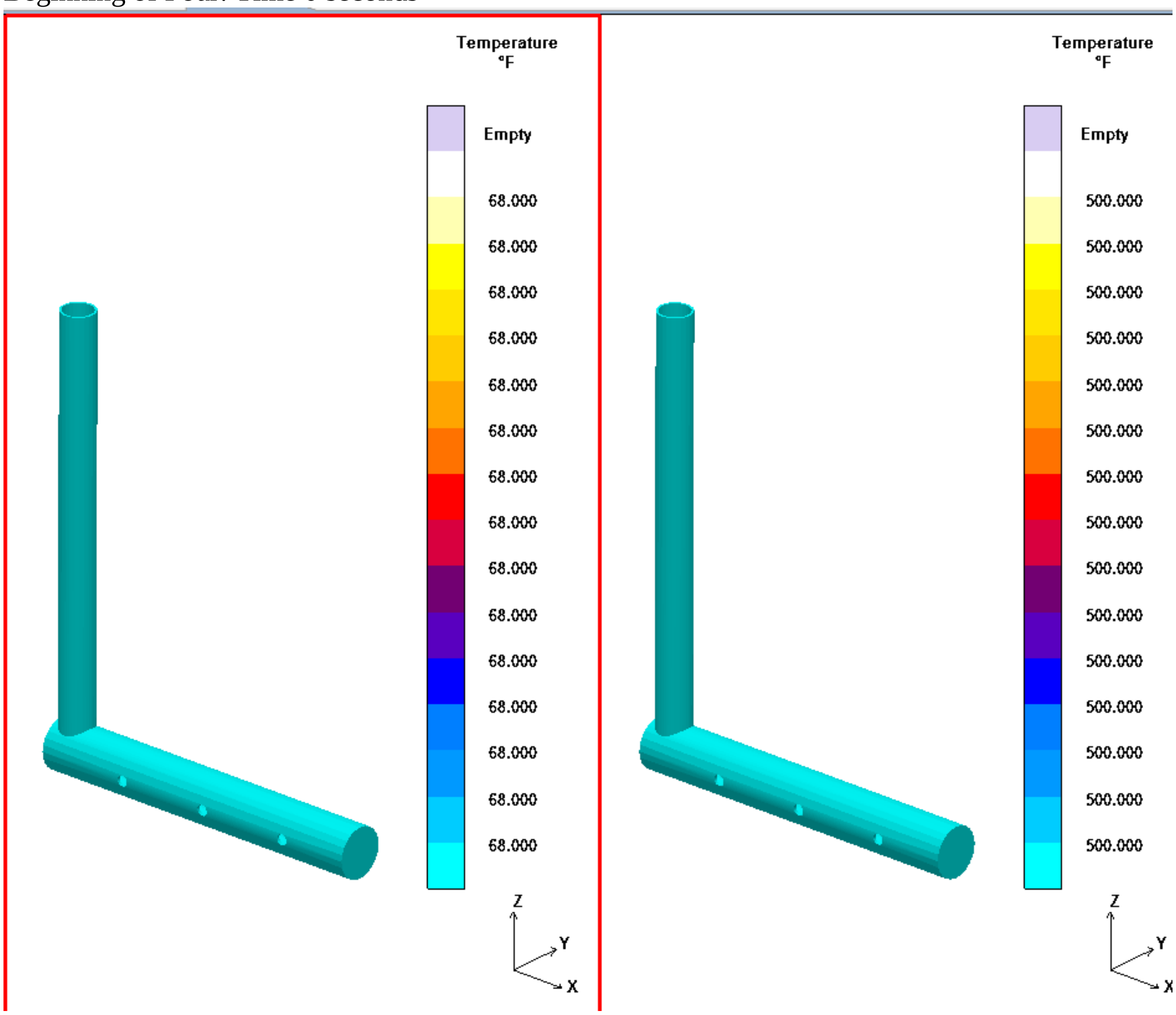


Appendix L

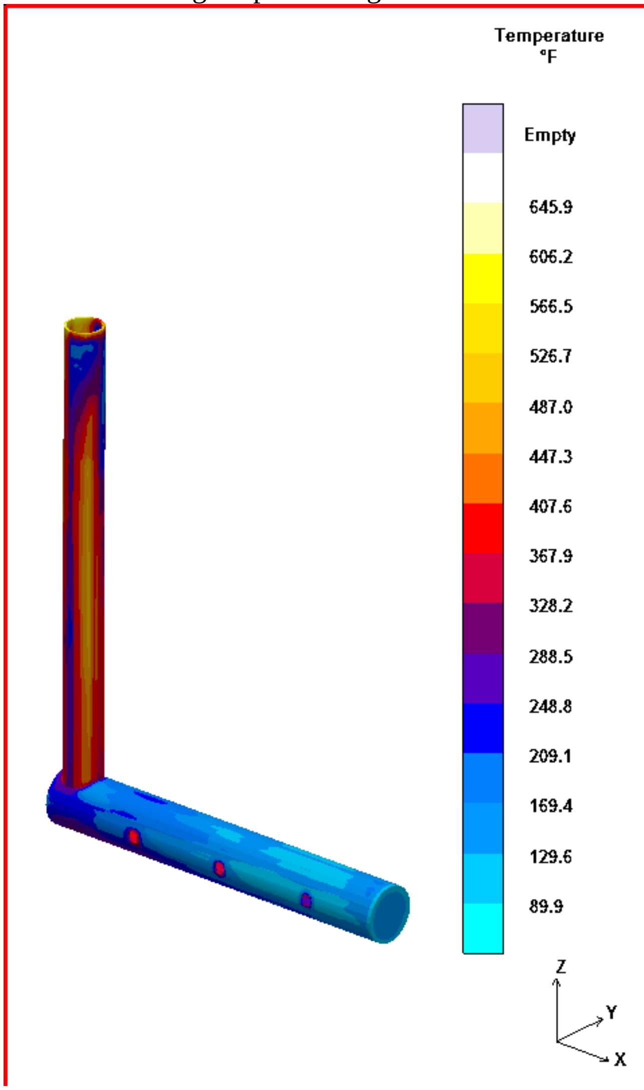
Summary of MagmaSoft® Results for the Second Model

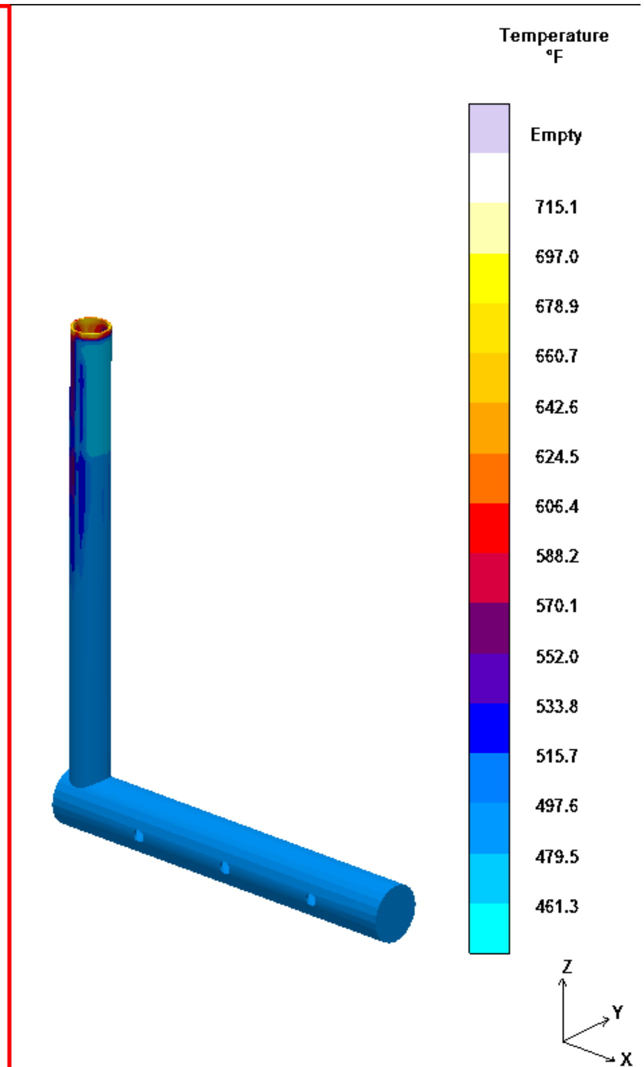
Results shown on the left, surrounded by red, used an initial temperature for the gating system of 68°F. Results on the right show the results of the simulation that used an initial temperature of 500°F for the gating system. All inputs, other than the initial temperature of the gating system, remained the same. As the results progress a cold band can be seen on the top of the sprue, this is the part of the gating system between the pouring basin and the top of the casting cavity sand, shown in the drawings in Appendix K.

Beginning of Pour: Time 0 seconds

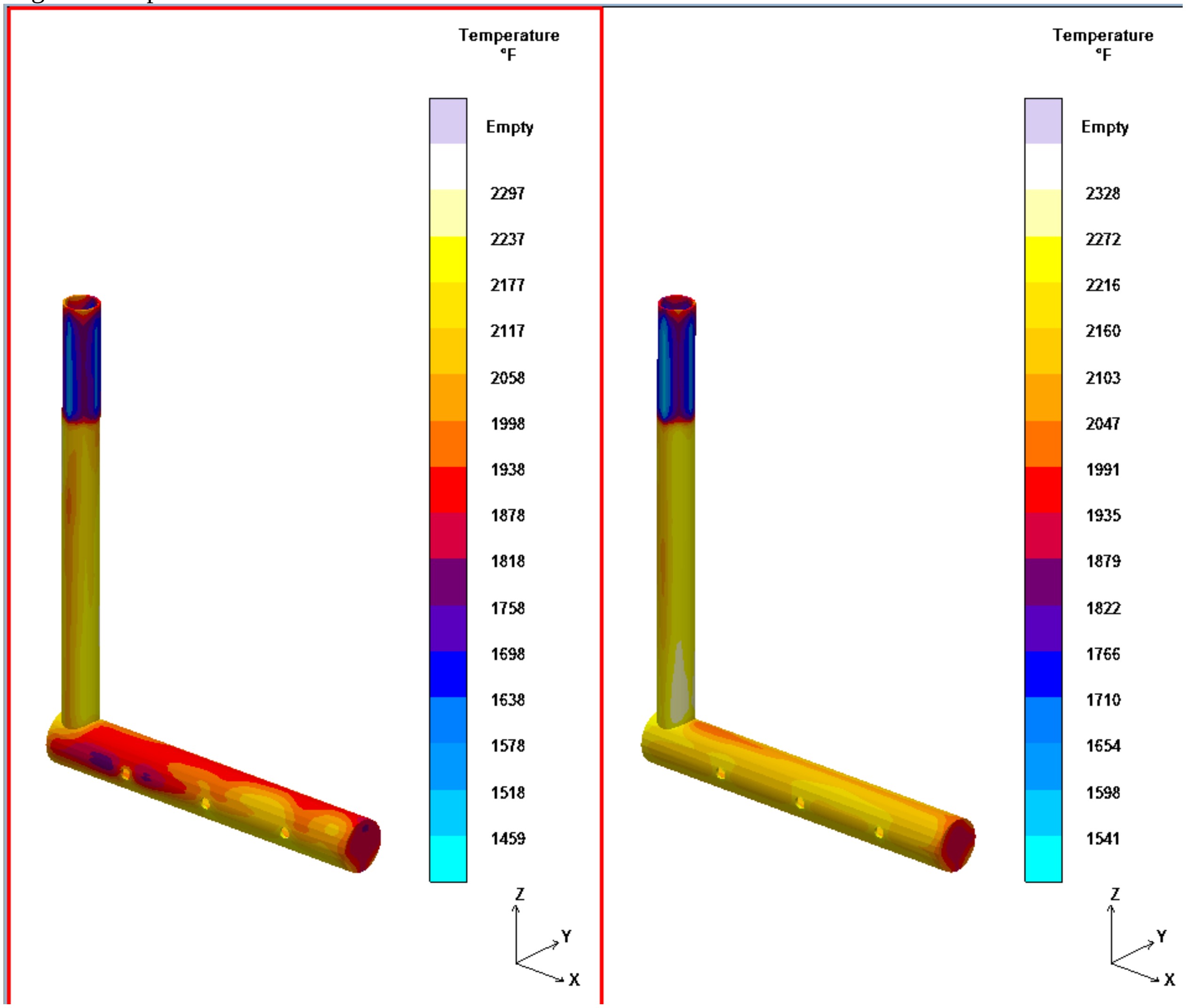


Preheated Gating Stops Cooling Down: Time 4 seconds

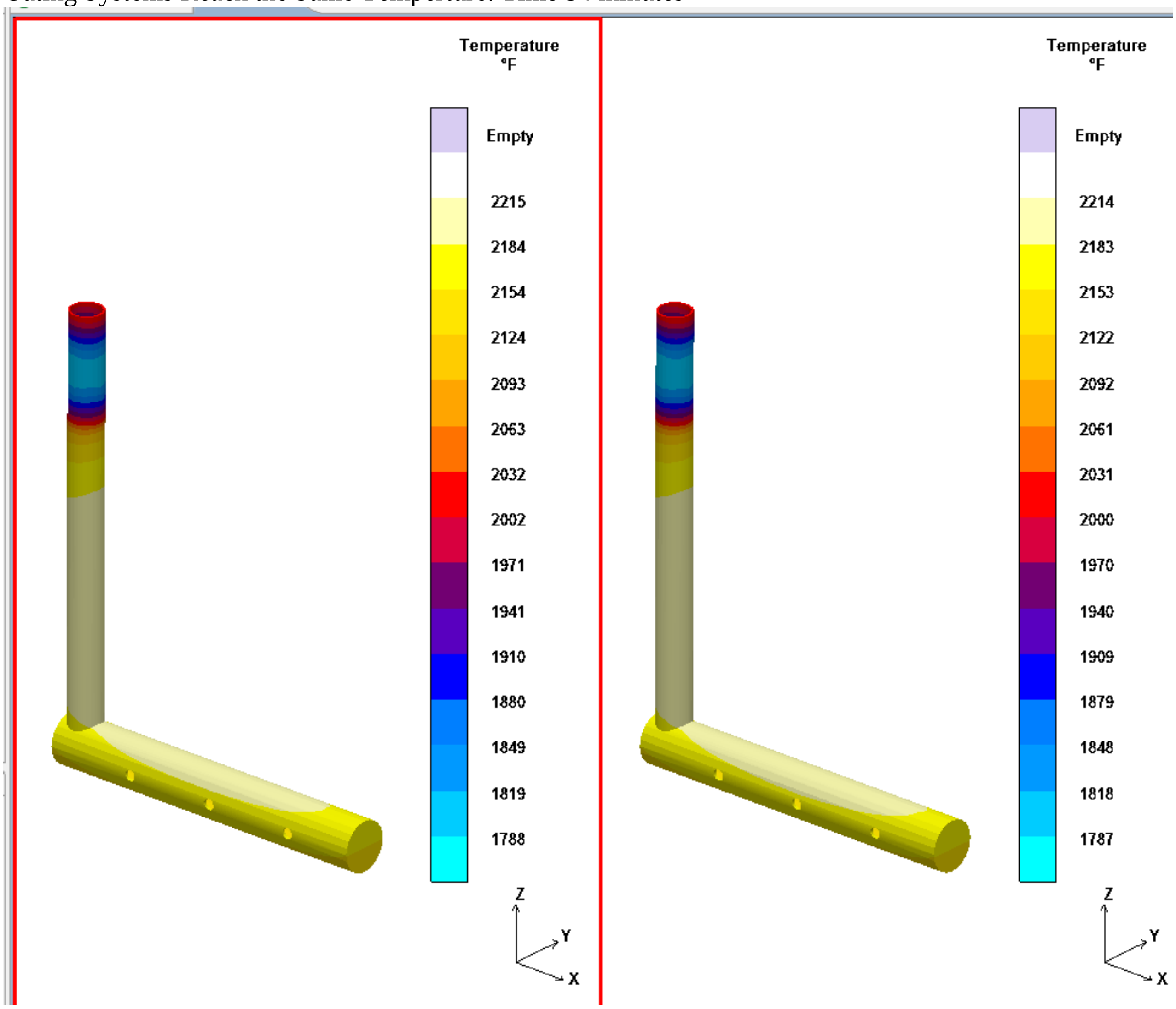




Highest Tempurature Reached: Time 40 seconds – End of Pour



Gating Systems Reach the Same Temperture: Time 54 minutes



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ACADEMIC VITA

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Education:

Bachelor of Science Degree in Mechanical Engineering Technology, Penn State Erie, Spring 2014
Minor in Operations and Supply Chain Management
Certificate in Enterprise Resource Planning (ERP) with SAP
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Thesis Title: Development and Analysis of an Internal Gating System for Metal Castings
Thesis Supervisor: Richard Englund

Related Experience:

Mechanical Engineering Intern; 2012-Present
Hodge Foundry, Greenville, PA
-Model castings from customer drawings in Autodesk Inventor
-Run MagmaSoft® and analyze the results to determine casting set-up and mold design
-Design, present, and document projects to increase efficiency in the casting making process

Industrial Engineering Assistant; 2010-2012
Advanced Cast Products Inc., Meadville, PA
-Collaborated with shop foremen to validate, organize, and update process sheets
-Programmed a new attendance system in Microsoft Access
-Constructed core assemblies and wrote a detailed report explaining the process

Association Memberships/Activities:

American Foundry Society (AFS) – Northwestern Pennsylvania Chapter