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# An innovative new pouring design for steel castings

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**An innovative new pouring design for steel castings**

by

**Justin Daniel Walker**

A thesis submitted to the graduate faculty  
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Industrial Engineering

Program of Study Committee:  
Frank E. Peters, Major Professor  
Matt Frank  
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Iowa State University

Ames, Iowa

2008

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## Chapter 1 Introduction

In the steel casting industry, all castings are poured out of ladles. The two prominently used designs for pouring are the teapot ladle and bottom pour ladle. The teapot ladle is a cylindrical shaped ladle with a spout, out of which molten steel is poured. The bottom pour ladle is also a cylindrical shaped ladle, but pours from an opening in the bottom of the ladle that is controlled by a plug on the end of a stopper rod. Both of these techniques have considerable longevity in the industry but, also have aspects of the pouring process upon which improvements could be made. One of these aspects is the necessary pour height. For the purpose of this paper, pour height is defined as the vertical distance from the top of steel in the ladle, to the top of the pouring cup<sup>1</sup>.

Another aspect that both the teapot and bottom pour ladles could improve upon is controlling the pour; both of these ladle pours are currently preformed by an operator. Because of this, neither technique has adequate pour control to guarantee an optimal pour rate. Some operators have good pour control by eyeing their pours, but even the best operators will have variability in the process. Cause and effect of pouring height and control will be addressed in this paper.

### 1.1 Air Entrainment and Inclusions

Air entrainment is the capture of air into molten steel; entrained air almost instantaneously oxidizes with the steel to form inclusions. Inclusions can affect aesthetics, continuity, and even integrity of the casting and can result in otherwise unnecessary rework

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<sup>1</sup> The pouring cup is the cup in which molten steel is poured into the mold.

after the casting process. There are many portions of the steel casting process that can influence the amount of air entrainment in the final casting. Two of these factors that play a large role in steel castings are pouring velocity and lip shape.

The higher the pouring height of molten steel is, the higher the velocity of that steel when it hits the pour cup. A higher velocity pour has potential for a more violent and turbulent pour and the amount of air entrainment as it passes into the mold cavity also increases (Griffin 1995). Therefore pouring at the lowest possible height will have the lowest possible velocity and thus fewer inclusions and casting defects are likely.

The lip shape also plays a factor in the amount of air that the steel accumulates during pouring. Lip shape affects the shape of the stream and thus the surface area of the steel in that stream. Because having the steel be exposed to as little air as possible (i.e. having as little surface area as possible) is desirable, having a lip shape that reduces air exposure is desirable. It has been found that having a rounded lip cross section is the most beneficial to accomplish a lower surface area of the steel stream (Griffin 1995). Both of these aspects will be discussed further in the next chapter.

## **1.2 Pouring Consistency and Accuracy**

When metal is poured, it flows from the pour cup or sprue cup into the sprue. Then it flows through the gate and runner system and into the mold cavity. Having a consistent pour rate is important to this process. A steady pour avoids overflowing the pouring cup and ensures that the gate and runner system is completely full at all times during the pour. Keeping the gating and runner system full ensures an uninterrupted mold fill which could otherwise result in additional casting defects.

Pouring accuracy refers to keeping the aim of the stream of steel within the pour cup during the pour. In one instance during data collection, the primary author observed a set of pours at a casting facility in which the position of their teapot ladle was manually adjusted as the ladle was tilted during pouring in order to keep the stream centered appropriately. While this process was adequate, it required an additional operator to perform this secondary movement. This inefficiency can be easily eliminated with a new system design.

### **1.3 Other Ladle Designs and Pour Improvements**

Only a couple attempts to change the ladle shape have been made to improve the pouring process; one of these attempts was the quadrant pour ladle. The quadrant pour ladle is shaped like a wedge with a rounded back. It was designed to create a ladle that would pour at a constant pour rate. Another improvement that was more successful was the shroud. The shroud is a tube like attachment onto the nozzle of the bottom pour ladle that reduces the exposure of molten steel to air while pouring. These technologies and others will be discussed in the next chapter.

### **1.4 Proposed Solution**

The proposed solution to the problems of air entrainment and pour control involves creating a newly designed ladle and pour control system. This system utilizes a new ladle design and is proposed to be used in the 1,000 to 10,000 pound capacity range. The new ladle design will reduce the amount of air entrainment while pouring by reducing the pour height and including an ideal pouring lip. This design will be discussed in Chapter 4. The ladle will be carried via an apparatus that is designed to fit most, if not all, crane systems in

the steel casting industry. The apparatus will contain a system of motors and controls that will allow the ladle to pour at a prescribed pouring rate that will be input by the operator. It will also control the ladle's tilt during the pour to keep a low and centered pour over the top of the pouring cup.

## **1.5 Preview of the Contents**

Chapter 2 will review literature relevant to possible improvements with the current pour systems and attempts made in the industry to improve the pour system. Comments will be made on the benefits and drawbacks of each attempt in the steel pouring industry. Chapter 2 will also cover the research behind air entrainment in steel castings and its relation to pour height.

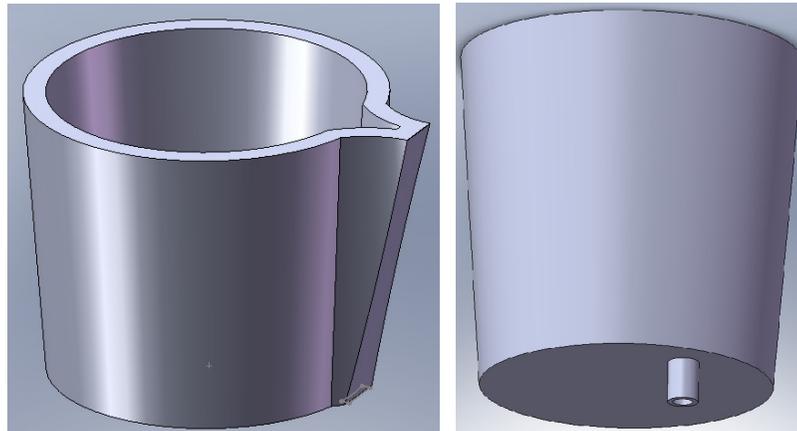
Chapter 3 will cover the design of the proposed pour system. Section 3.1 explores a new ladle design and compares the proposed ladle to the teapot and the bottom pour ladles. Section 3.2 discusses the design of a carrying apparatus for the ladle. It includes the components of the apparatus, how it will move, and its implementation. Section 3.3 will cover the control for the system. This system incorporates tool center point methodologies, weight based control, and PID controls for the system. These are all defined and discussed. Completing Chapter 3, Section 3.4 will address safety, limitations of the system, how the ladle will be filled and total costs of the system.

Lastly are Chapters 4 and 5. Chapter 4 will summarize all of the findings of the paper. It will cover the results of the paper, implications of the new design for the steel industry, and other innovations that could develop from this system. Chapter 5 will discuss the future work that could result from the discussion in this paper.

## Chapter 2 Literature Review

A search for literature regarding issues of steel pouring was conducted. This chapter will discuss literature regarding air entrainment in steel castings its causes and results. This chapter also contains general discussion of pour studies that were conducted regarding air entrainment their results. Lastly it discusses pouring improvements and technologies that have been attempted and their successes and shortfalls. Articles discussing attempts at improving these issues are also reviewed and discussed. Since there is not much published work on controlling pouring rate and location, additional background was attained from interviews of industrial personnel.

The two ladle design systems, shown in Figure 2.1, used in steel foundries are the teapot and bottom pour ladles, which are both problematic in the areas of pour control and pour height respectively.



**Figure 2.1** Sample Shape of Teapot Ladle and Bottom Pour Ladle

## 2.1 Causes of Air Entrainment

Air entrainment is the collection of air pockets into the steel pouring stream. The molten steel almost instantly oxidizes with the air pockets and causes inclusions in the steel casting. This section will focus on the effects of stream velocity and lip shape on air entrainment.

One of the sources of air entrainment in steel castings is caused by unnecessary velocity in the pour stream. As it pertains to this paper, the unnecessary velocity is caused by the additional pour height<sup>2</sup>, which is the vertical distance from the top of the molten metal in the ladle to the top of the pouring cup. The equation for the velocity of the liquid metal as it reaches the top of the sprue is  $V = \sqrt{2gh}$ , where  $V$  = velocity of the metal at the bottom of its travel,  $g$  is gravitational acceleration, and  $h$  is the vertical distance that the metal travels. In this case  $h$  is the distance from the top of the metal in the ladle to the top of the pouring cup or the pour height (Munson 1998). Based on this equation it can be stated that having a higher pour height will have a higher velocity.

As a stream of molten metal hits a solid surface or surface of liquid in the sprue, it will form vortices in which air entrainment occurs. Having a higher difference in the velocities of the metal hitting either of these surfaces can result in larger vortices and thus more entrained air. Having a higher velocity during the pour also increases stream surface roughness, which also increases the amount of air entrained during the pour (Griffin, 1995). The idea that a higher velocity pour will increase air entrainment and inclusions is an

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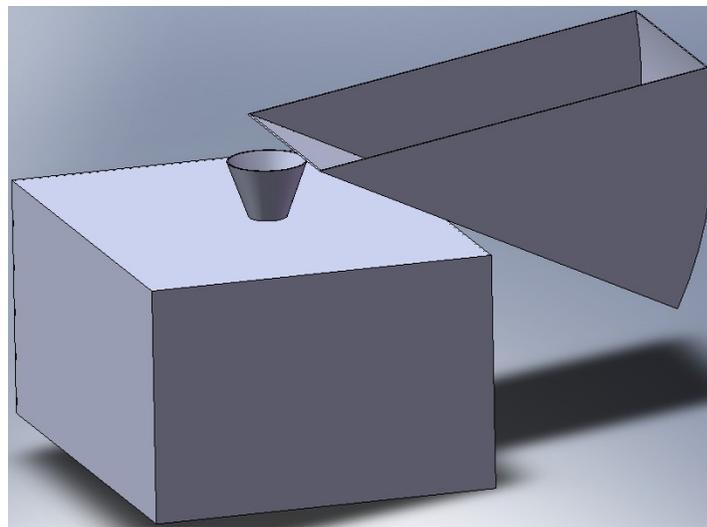
<sup>2</sup> Pour height is defined here as the distance from the top of the melt to the top of the sprue. The length of the sprue will also increase the height and therefore the velocity, but since this is not changed by the pouring systems considered here it is being ignored.

industry wide awareness and is supported in various other sources as well as Griffin.

Another cause of air entrainment is the spout and lip on the ladle (only applicable to the teapot ladle). In the teapot ladle, metal travels through the spout and exits without the use of a lip. It has been found that the shorter the spout and that having a semi-circular shaped lip will cause less air entrainment than lips with square and flat edges (Griffin 1995). This will be discussed further in the pour studies section.

## 2.2 Air Entrainment Pour Studies

Many studies have been performed on reducing the amount of air entrainment in steel castings. Studies included in this paper focused on papers that included comparisons of the quadrant ladle (shown in Figure 2.2) with the teapot and bottom pour ladle and also pour studies involving lip shape. The quadrant ladle was designed so that as it was tilted at a constant rate, it would have a consistent pour rate. The ladle's wedge shape also allowed it to have a lower pour height and better access the pour cup as is shown in Figure 2.2.



**Figure 2.2** An Illustration of the Quadrant Pour Ladle Accessing a Mold

Since it is a time and labor intensive process to pour steel for experimental reasons, researchers found that water modeling can be used to simulate the behavior of molten steel including the amount of air entrainment. One of these studies involved investigating the air entrainment during pouring of the teapot ladle, bottom pour, and quadrant pour ladles. It performed trials to determine the amount of air entrained while pouring from the teapot and quadrant pour ladle. It was found that pouring out of a quadrant ladle had 42% less air entrainment than a teapot ladle when using a 5.25 inch sprue and had 5% less air entrainment with a 10.25 inch sprue (Brown 1994). Further analysis from the authors of this paper in a later publication stated that this difference can be attributed to maintaining a low and constant height above the mold during pouring. Maintaining a pouring axis over the pour cup minimizes drop height of metal into the sprue (Griffin 1995).

Pour trials with the bottom-pour ladle were also conducted in this study. The study involved comparing differences in gating system and nozzle opening on the bottom pour ladle. When attempting to lower the pour rate by throttling the opening, there was 159% and 69% more entrainment respectively in each trial (Brown 1994). This concludes that any pour rate aside from fully open will have considerably more air entrainment.

Another study comparing the quadrant, bottom, and teapot ladle was performed in trials in 1995 at Keokuk Steel Castings. The experiment involved a simulated water pour, then measuring the amount of air entrainment. Air entrainment was measured in cubic feet of air per cubic foot of water poured. It resulted in air entrainment averages of 0.373 cubic feet of air for the bottom pour ladle (16 pour trials), 0.19 cubic feet for the teapot ladle (6 pour trials), and 0.17 cubic feet for the quadrant pour ladle (8 pour trials) (Kulkarni 1995). Although there was not a statistical analysis performed to support whether the difference

between all of the results is statistically reliable, it should be noted that the bottom pour ladle had considerably more air entrainment than the teapot and quadrant pour ladles (0.373 cubic feet versus 0.19 and 0.17 cubic feet respectively) and could be reasonably concluded that this is true.

Even though the quadrant pour appears to have had lower volumes of air entrainment than the bottom pour and teapot ladles, it had other problems that made it an undesirable replacement for either ladle. The pour stream trajectory of the quadrant ladle was inconsistent and difficult to pour. It needed to have adjustments during pouring to realign the stream with the pour cup due to its unpredictable trajectory. The quadrant pouring system had only crude positioning capabilities, which resulted in spills and difficulty with pouring (See 2006). To the best knowledge of the authors, there were no additional trials using the quadrant pouring system in foundries.

Another study analyzed many different aspects of pouring; applicable to this paper were the lip shape trials. Three different shapes of lips were compared to analyze which would result in a larger amount of air entrainment. A rounded lip, trapezoidal lip and square lip were compared. It was found that the larger the surface area of the pour lip, the more air entrainment that resulted. The round ladle lip had values of about 0.117 cubic feet of air per cubic foot of water poured, the trapezoidal and square had values of 0.150 and 0.160 respectively (Griffin 1995). The paper by Brown, 1994, had conclusions that were similar to this, stating that the rounded lip pours were best, but it was not the focus of the paper and thus more generally stated.

Another disadvantage of the bottom pour ladle, which is also a disadvantage with teapot ladle, is inadequate control of the pouring stream. As was observed in Facility 2, for

bottom pour ladles (Facility 1 and 2 were visited to observe and take data on the casting process for purpose of this paper), the operator regulates the flow via a stopper rod in the bottom of the ladle. As was observed in Facility 1, when pouring with a teapot ladle, the operator watches the sprue and turns a mechanical advantage wheel attached to the axis of the ladle to control the tilting of the ladle. For both of these processes, the goal is to fill the sprue as quickly as possible and then keep it full with a smooth flow of metal to minimize amount of molten steel exposed to the air. However, there is considerable variation in pouring skill and technique across operators, which can contribute to the formation of reoxidation inclusions.

Since the teapot ladle tilting is controlled by a manual pouring wheel, the size of the ladle is limited. The job still poses an ergonomic hazard, as the ladle is difficult to manipulate into place and tilt.

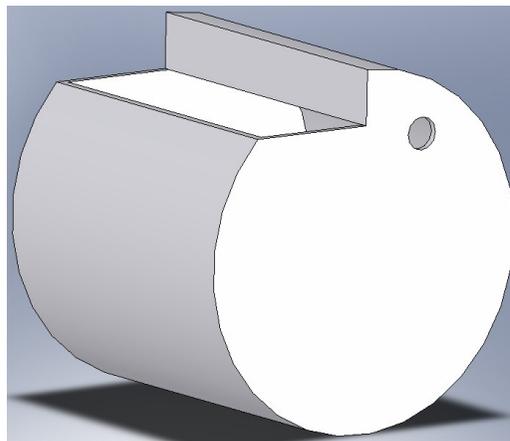
One of the recent advances with the bottom pour ladle that has been a success is the shroud pour. Shroud pouring is a recent advancement for bottom pour ladles to minimize the exposure of the metal to air. This system utilizes a pouring tube that is attached to the bottom of a bottom pour ladle and is inserted directly into the sprue. The metal exits the ladle through the tube and once the sprue is filled, the metal exposure to the air is significantly limited (Hartay 1998). This system can only be used with molds that are large enough and otherwise able to accept the shroud to be inserted into the sprue.

In one study, the number of defects on castings that were poured with and without a shroud was compared. It was found that there were defects on only two defects on one of 11 parts of the shroud poured castings while 33 of the other 35 castings poured without the shroud had more than five defects indicated (Hartay 1998). Although this study indicates a

statistical difference in the two, another studies by Bates, 1995 at the University of Alabama found the evidence to be inconclusive. According to Dr. Frank Peters, there are more studies that have been performed and proved this technology is successful, although their results have not been published. Based on this information, it can be concluded that although the technology does improve the bottom pour, there are still variable factors that can contribute to casting inclusions.

### 2.3 Other Pour Technologies

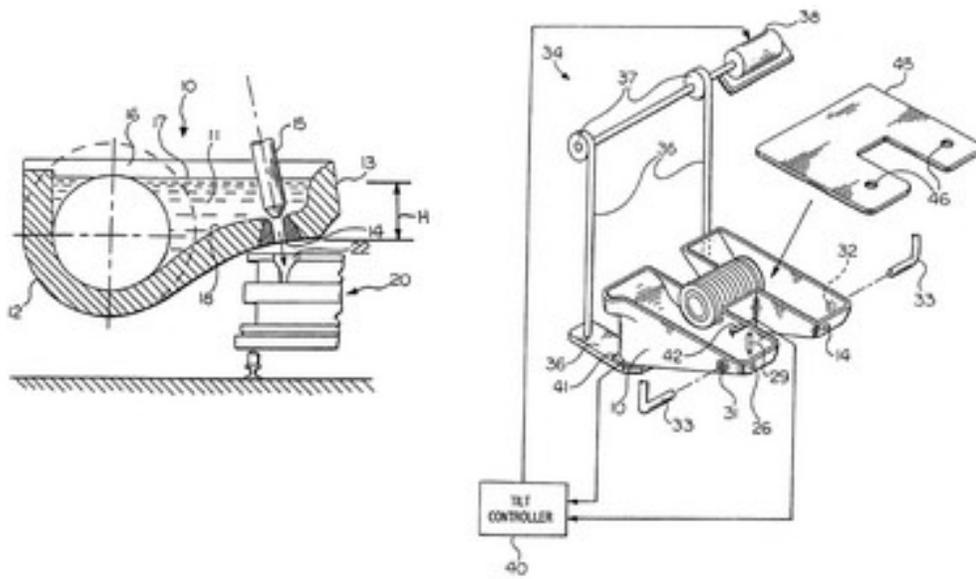
Aside from the quadrant ladles, there are a couple of other technologies that exist that involve a different shaped ladle. One of these is the rotary pour ladle. Although no documentation was found on the process, the primary author has learned about the process through industry experts and it will be explained and examined. The rotary pour method incorporates a cylinder shaped ladle, much like the teapot ladle, only the rotary pours flat ends are perpendicular with the ground. One of the flat ends contains a hole towards the out edge of the face. A sample concept is shown below:



**Figure 2.3** Concept Model of Rotary Pour

This ladle is designed to rotate about the pouring hole, thus allowing metal to pour through the hole. The rotary pour ladle is used as a stationary ladle and molds are brought to the ladle. According to Dr. Frank Peters this ladle is not conducive for transport; it is very bulky and heavy compared to the capacity of metal it can hold. It is also observed that for this to be a mobile ladle choice there needs to be a fairly large lip around the hole to be able to pour. The size and more importantly, the length of this lip would also be the furthest distance from which you could reach a pour cup. One last noticeable problem with this design is that it does not have a slag filtering system that would prevent oxides and other contaminants from getting into the mold while pouring. These are all reasons that this design was not considered for the application of this new system.

The design for another pouring technology is shown in Figure 2.4; from here on it will be referred to as System N. Much like the rotary pour there is no literature on the design, but it will be analyzed for feasibility and practicality. One of the differences with the design below and the ladle design proposed in this paper is how the metal leaves the ladle. System N uses a stopper rod like the bottom pour ladle. There are two ways that the proposed design is better than System N. One is that theoretically, the design proposed in this paper has H inches (the dimension “H” can be found in Figure 2.4) less pour height, than System N’s ladle. Another is that the ladle has a stopper which can increase the turbulence of a pour (Brown 1994). This design, like the system proposed in this paper, also has a scale integrated into it, however, the scale is not intended to control the pour rate of the system, but to give feedback for how much metal is in the ladle.



**Figure 2.4** Design of a Patented System for Steel Pouring (Minor 2005)

## **Chapter 3 New Pouring System**

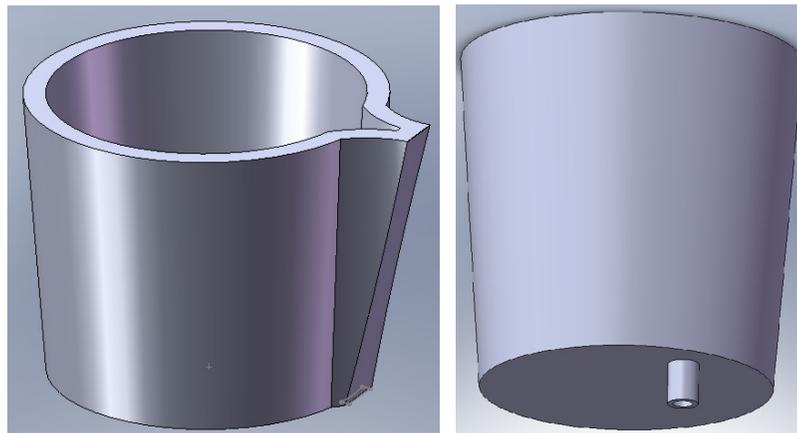
To overcome the problems with current pouring systems, a new system is proposed here. This system utilizes a new ladle design that is proposed to be used in the 1,000 to 10,000 pound pouring capacity range. As with the quadrant pour, the new ladle design will allow for the pouring lip to be placed directly at the sprue to reduce the pour height. In addition to the ladle, an apparatus is presented here that can control ladle location and pour rate. The entire apparatus and ladle will be carried via existing overhead cranes, but the fine movement of the ladle will be controlled via the apparatus. The user will be able to prescribe a pouring rate and volume for each casting design. Once the operator positions the ladle over the mold and locates the sprue, the system will automatically deliver the metal at the prescribed flow rate. A scale holding the ladle will provide the feedback to the controller to adjust the flow as needed.

### **3.1 Ladle Design**

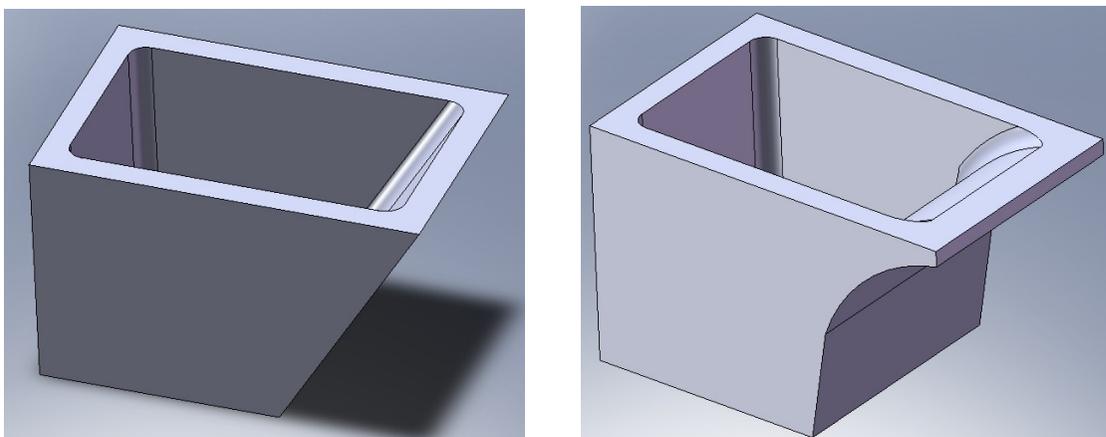
The new ladle design is intended to serve as a replacement for the teapot and bottom pour ladles in the 1,000 to 10,000 pound pour range. This design may be tested and found to be beneficial to larger and smaller ranges, but it is suspected that this is the ladle capacity range that will see the most benefit from a new system. Teapot ladles are used in weight capacities up to about 5,000 pounds and bottom pour ladle's capacity is from approximately 5,000 pounds and up. In this section, ladle shape, size, and features will be discussed. Comparisons to the teapot and the bottom pour ladle will also be conducted and explained.

### 3.1.1 Shape of the ladle

The first part of the new system is the ladle shape. The shapes currently used for the teapot ladle and bottom pour are shown in Figure 3.1. There are two proposed designs for the new system and they are shown in Figure 3.2. The ladle is designed to pour by tilting it, like the teapot ladle. There are two main differences between the ladle designs in Figures 3.1 and 3.2. The first difference is that the base shape of the new ladle is square. The second is that the front side of the ladle is cut back to create an overhanging side.



**Figure 3.1** Sample Shape of Teapot Ladle and Bottom Pour Ladle



**Figure 3.2** Base Shape for Ladle A and Ladle B

The reason the ladle is square shaped is that it is a simple and functional design. There are two sets of trunions<sup>3</sup> which are the contact points for suspending this ladle in the air, this is shown later in Figure 3.6. There will be more control when tilting the ladle with longer, flat distance between the trunions verses placing two sets of trunions on a shorter curved shape, which would be very hard to align. It also allows for a larger volume of metal in the ladle using the same width and height dimensions as a circular ladle. Although the ladle is designed as a square, this is not an ideal shape in which to hold the metal. It will contain generously rounded internal corners which will reduce surface area to volume ratio, and also improve refractory life. Surface area to volume ratio is important because a larger surface area allows for more heat to dissipate from the ladle, causing the steel to cool. If it cools too rapidly, it may produce undesirable properties in the casting or freeze in the ladle. Regarding the refractory life, corners create areas of high stress and high heat for refractory board, rounding the corners reduces this. If further analysis of the ladle finds that either the surface area to volume ratio or the refractory life is unacceptable, this shape can be modified in any way to improve these aspects without changing the principles and intentions of the new control system that will be introduced later.

The other difference in the designs is the cutback in the front of both designs; this was inspired by the quadrant ladle's shape. The quadrant ladle's shape, seen in Figure 2.2, was originally intended for a consistent pour rate, but having the pie shape of the quadrant ladle appeared to have the added benefit of being able to access more sprue placements on the mold without contacting the side of the mold. This cutback throat design was

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<sup>3</sup> Trunions are pegs on the side of the ladle. The bail will attach to the trunions.

implemented into the new ladle design because it will allow for pouring access to more areas of the mold. This will be discussed in more detail in Section 3.1.4.

### 3.1.2 Size of the Ladle

As stated earlier, the size of the new ladle is designed to have carrying weight so as to replace the teapot and bottom pour ladles in the 1,000 to 10,000 pound range. To accomplish this weight range, approximate dimensions are shown in Table 3.1 for four sizes. Each of the sizes in the table allows for three inches of refractory on each of the sides and fills the ladle until four inches below the rim.

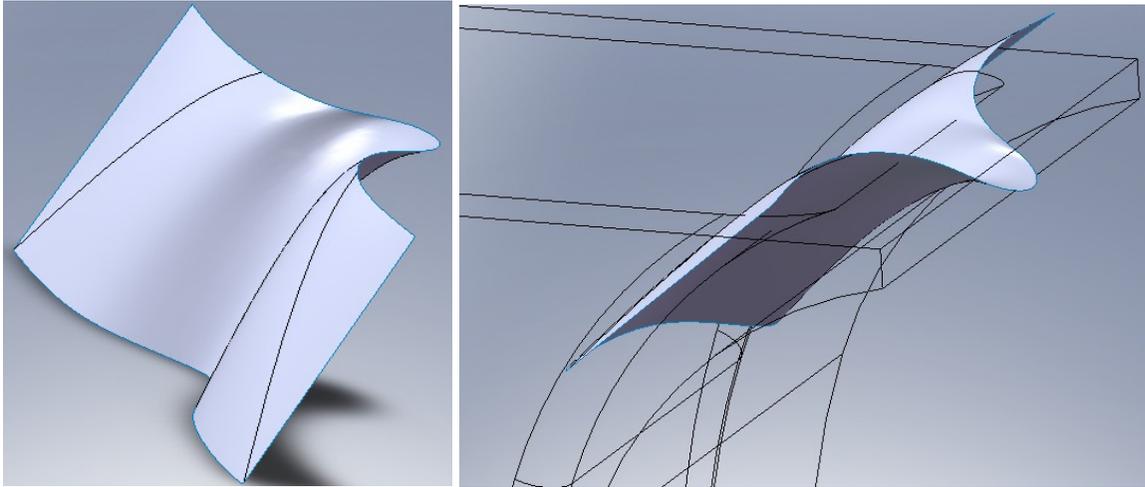
**Table 3.1** Dimensions for the New Ladle Design

New Ladle Actual Dimension				
	1,000 Pound Model	3,500 Pound Model	5,000 Pound Model	10,000 Pound Model
Height (in)	22.00	29.25	30.60	38.00
Width (in)	21.00	28.25	29.60	37.00
Short Length (in)	21.00	28.25	29.60	37.00
Long Length (in)	32.50	46.00	48.80	61.00
Volume Ladle A (cu-ft)	2.7	8.9	10.7	23.9
Volume Ladle B (cu-ft)	2.2	7.1	8.6	19.1
Pounds Steel in Ladle A	1,321	4,360	5,233	11,694
Pounds Steel in Ladle B	1,057	3,488	4,186	9,355

### 3.1.3 Lip and Throat Design, Slag Block, Bails, and Refractories

One of the issues discussed in the literature review was the lip design for the ladle. It was determined that a lip design with a rounded shape reduces the amount of air entrainment during pouring because it reduces the surface area of the pour channel and controls the shape and roughness of the pour stream during pouring; both of which affect

air entrainment in the final casting. This is the reason the lip is designed as shown in Figure 3.3. This lip is designed so that the metal is channeled to the lip and should have a half-circle profile where the metal exits the ladle. It should also have sides that will keep metal from flowing over the front edge of the ladle during the pour.



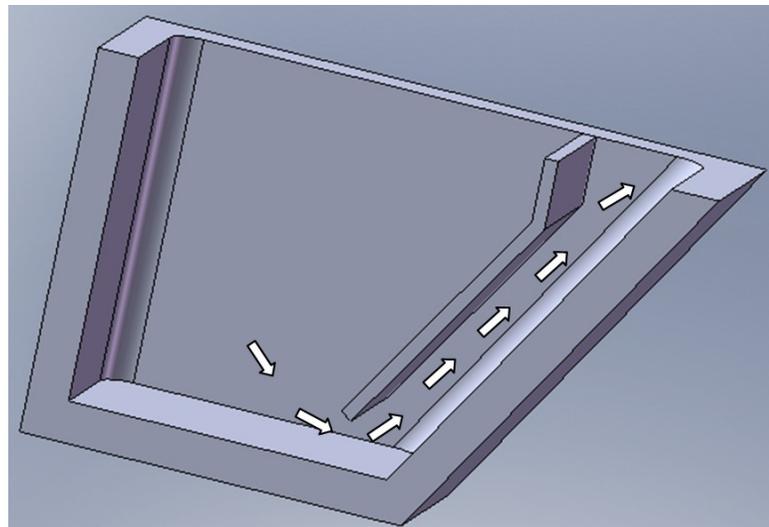
**Figure 3.3.** Example Extended Lip Design for the New Ladle

Another design component is the slag control for the ladle. Slag is a composition of oxides and impurities that float on top of the molten steel. If no preventative measures are taken, it will end up in the casting, forming defects. The slag control for the new ladle design is similar to the teapot ladle. A plate sits across the throat of the ladle and protrudes out of the molten metal. The plate forces the poured metal to come from under the surface, thus minimizing any slag or dross being poured into the casting. This action can be seen in Figure 3.4. Final placement for this piece will be determined by the size and shape of the throat.

The placement of the slag block will also determine how much total metal can be poured out of the ladle. The amount of metal left in the ladle is when the bottom of the slag block and the metal in the ladle are the same height. In the 3,500 pound model, if the bottom of the slag block is placed three inches from the bottom of the ladle, the volume of metal left will be about 434 pounds. Different slag heights for each size ladle and its respective weight left in the ladle is shown in Table 3.2. Note that this weight occurs when the ladle is tilted to approximately 40°.

**Table 3.2** Amount of Metal Left in the Ladle with Varying Slag Block Heights

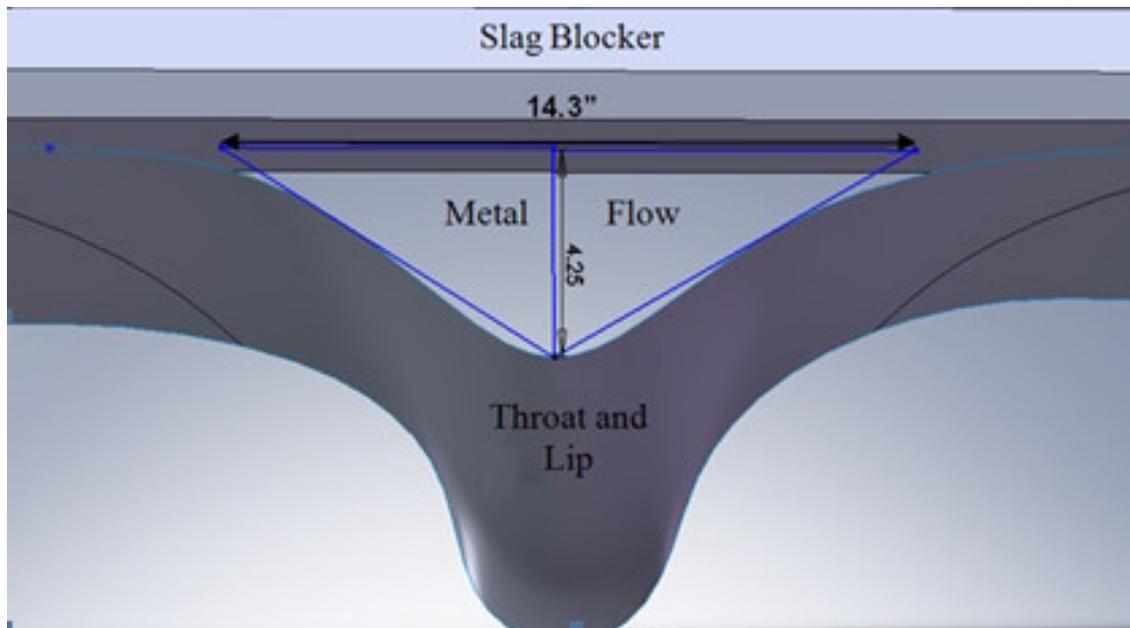
	1,000 Pound Model			3,500 Pound Model			5,000 Pound Model			10,000 Pound Model		
Slag Block Height	3.00	4.00	5.00	3.00	4.00	5.00	3.00	4.00	5.00	3.00	4.00	5.00
Width	15.00	15.00	15.00	22.25	22.25	22.25	24.80	24.80	24.80	31.00	31.00	31.00
Length	15.73	15.97	16.21	22.98	23.22	23.46	25.53	25.77	26.01	31.73	31.97	32.21
Volume Left in Ladle	0.4	0.6	0.7	0.9	1.2	1.5	1.1	1.5	1.9	1.7	2.3	2.9
Weight Left in Ladle	200	271	344	434	585	739	537	723	913	835	1,122	1,413



**Figure 3.4** Example of Metal Flow with Slag Block in Place

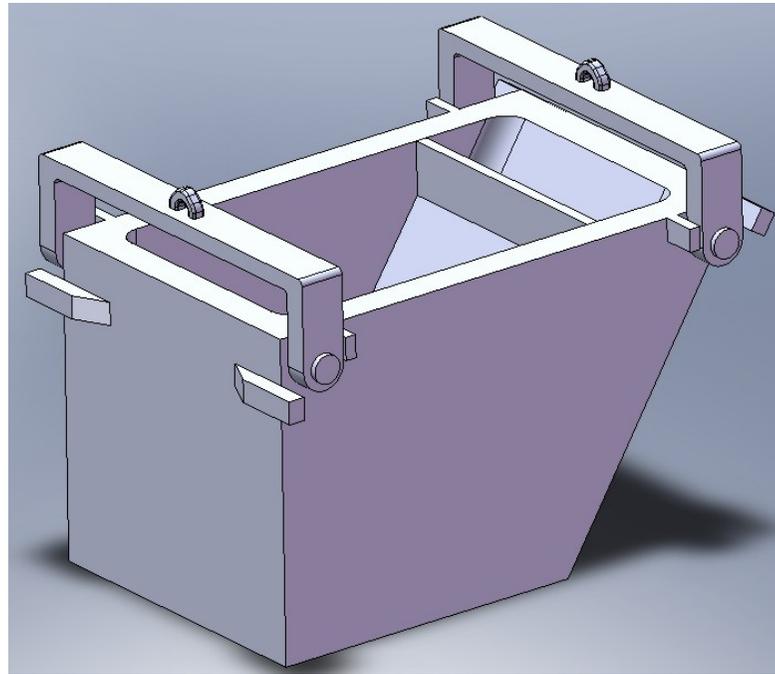
One of the industry problems with the teapot ladle is that the throat can freeze shut. If the area of the opening out of which the steel flows were bigger, this problem would be reduced or avoided altogether. The opening for the spout in the throat is usually no bigger than four inches in diameter in most teapot ladles; this is an area of 12.6 in<sup>2</sup>. This is an additional benefit of the throat and lip design shown in Figure 3.3. Having the rounded throat shape, as shown in Figure 3.5, allows additional channel area compared to the four inch circular opening in the teapot ladle. The throat shape then smoothly transitions into the curved lip, which provides the molten steel a pour path as the ladles is tilted for a smooth controlled pour.

The combination of the shape of the lip and the slag block will determine how large the area of the channel for steel flow will be. The slag blocker will be placed so it lies across the shape of the lip and will create an opening no smaller than 30.4 in<sup>2</sup> in the 3,500 pound model, an increase in area of almost 240% from a 4 inch diameter opening. This extra area will reduce the chance of the ladle freezing. This can be seen in the diagram in Figure 3.5.



**Figure 3.5** Pour Opening for Metal Flow

Since this ladle is being suspended via cables, a trunion and bail system was designed into the ladle. An example of the trunions and bails can be seen in Figure 3.6. The bails will have free motion of rotation, so safety stops were also designed into the ladle. The bail stops are designed so that the bails will never fall inward, over the ladle. An additional stop on the back of the ladle will not allow the bail to rest against the back side of the ladle, and another stop on the front will keep the operator from having to reach under the lip of the ladle to attach any cables. These stops are intended to increase the safety of the operator.



**Figure 3.6** Ladle Fitted with Trunions, Bails, and Bail Stops

Lastly are the refractories for insulating the ladle. It is proposed that the refractories used in the new ladle design be the same as the current refractories. New Ladle Design A and B are designed such that it can be lined with refractory board on both of the sides, the back and the bottom, like the current ladles are. A castable refractory will be required to create the lip for Ladles A and B.

### 3.1.4 Mold Access Comparison

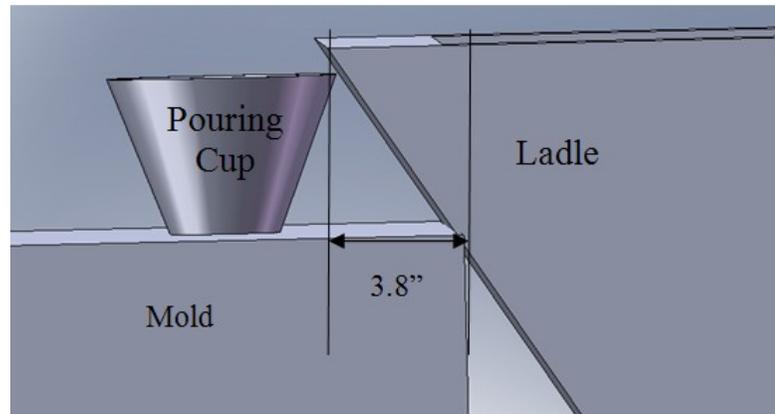
The main assets of the new ladle design are its ability to:

- 1) pour with a lower pour height than the bottom pour ladle,
- 2) pour at the same or lower pour height than the teapot ladle,
- 3) have better access to sprues than the teapot ladle.

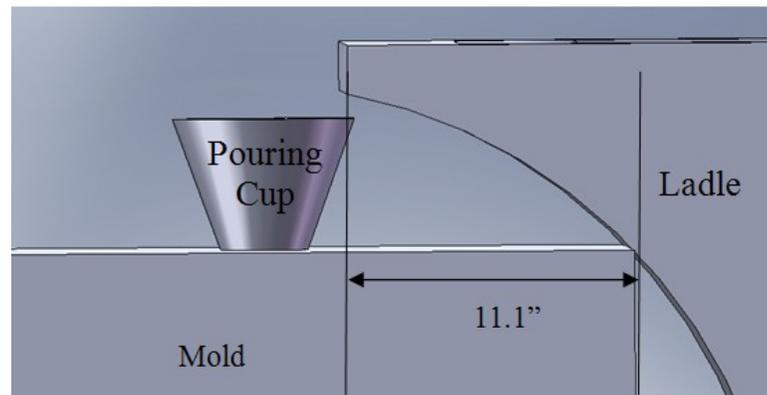
To be able to pour at a low pour height requires the ability to access more pouring cups directly with the ladle. The quadrant ladle allowed for a low pour height because the lip could directly access the cup without interfering with the mold. This concept was modified for the new ladle design; the throat has been cut back to allow for better access to the pouring cup.

The authors visited steel foundries to collect data on the practical constraints existing at the facilities. At Facility 1, where teapot ladles are exclusively used for pouring, special attention is given to sprue placement on the molds. All sprues are placed within seven inches of the edge of the mold to allow the teapot ladles easier access. The molds poured with an 800 and 3,500 pound ladle have pouring cups that are approximately five and three inches above the molds, respectively.

A comparison of sprue access for the two versions of the new ladle design is shown in the following section. Figures 3.7 and 3.8 show the difference in access of the ladle to the mold and pour cup (these figures contain the 3,500 pound model and a pour cup height of six inches). Shown in Table 3.3 are the pour cup access values for the new ladle design A and B for various values of height above the mold. As an example, Ladle A can access a six inch pouring cup approximately four inches from the mold edge without the extended lip shown in Figure 3.7 and 3.8. Ladle B can access the six inch pouring cup approximately eleven inches without an extended lip. This number was obtained using CAD models illustrated in Figures 4 and 5. The value obtained is based on the lateral distance from the tip of the ladle to the edge of the mold.



**Figure 3.7** Ladle A's Access to the Pouring Cup



**Figure 3.8** Ladle B's Access to the Pouring Cup

**Table 3.3** Access Dimensions for the New Ladle Design

	New Ladle A	New Ladle B
Pour Height (in)	Access (in)	Access (in)
1	0.6	3.8
2	1.3	5.9
3	1.9	7.6
4	2.5	8.9
5	3.1	10.1
6	3.8	11.1
7	4.4	12.1
8	5.0	12.8

### 3.1.5 Design Differences in Ladle A and B

The main reason for having two design suggestions for the new system is what was covered in the previous section, the difference in sprue and mold access. As is the case with Facility 1, many sprues are placed within a certain distance from the edge of the mold to accommodate the ladle's inability to reach areas closer to the center of the mold. The sprue is the opening to the runner system, which leads to the mold cavity, as the metal flows through the cavity, it can pick up air, sand, and debris. Not having to adjust the sprue and runner system to accommodate the ladle would help reduce optimize the runner system. Ladle B will allow foundries an additional 7 inches more freedom for sprue placement than Ladle A.

Even though Ladle B has better sprue access, there are two drawbacks for consideration. Ladle B will hold 20-25% less metal, and thus a larger ladle will be needed if the same capacity is desired. It also has a larger surface area to volume ratio which will decrease the amount of time the ladle can be inactive while it's pouring.

### 3.1.6 Pouring Height

Bottom pour ladles typically have capacities in excess of 5,000 pounds. Pour height for the bottom pour is determined by two factors 1) the height of the metal in the ladle 2) the distance from the bottom of the ladle to the top of the sprue. Data was taken by the primary author from the bottom pour ladles at Facility 2 to provide a comparison to the new design. The total height of one of their main ladles is 43 inches with an inner diameter of 32 inches and a capacity of about 8,000 pounds. There are two reasons for using an 8,000 pound ladle for this comparison as opposed to the 3,500 pound ladle used in the rest of this

paper. Firstly, the bottom pour ladles are not used in capacities as low as 3,500 pounds. Second and most importantly, the design of the new ladle could be compared at any size since it is design to have the same pour height for all capacities.

The last mold poured from a bottom pour inherently has the lowest pouring height. Most facilities will leave about 1,000 pounds in the bottom of the ladle so as to avoid pouring the slag that floats to the top into the casting. Leaving 1,000 pounds in a ladle with these dimensions results in a metal height of 4.4 inches. When added to the refractory thickness and spout length, this distance becomes approximately 11.4 inches of pour height. Table 3 provides the pouring height for an 8,000 pound bottom pour ladle at various amounts remaining in the ladle. Since the new ladle will have a pour height approaching zero, the bottom pour has, on average, approximately 24 inches more pour height.

**Table 3.4** Pour Heights for 8,000 Pound Ladle

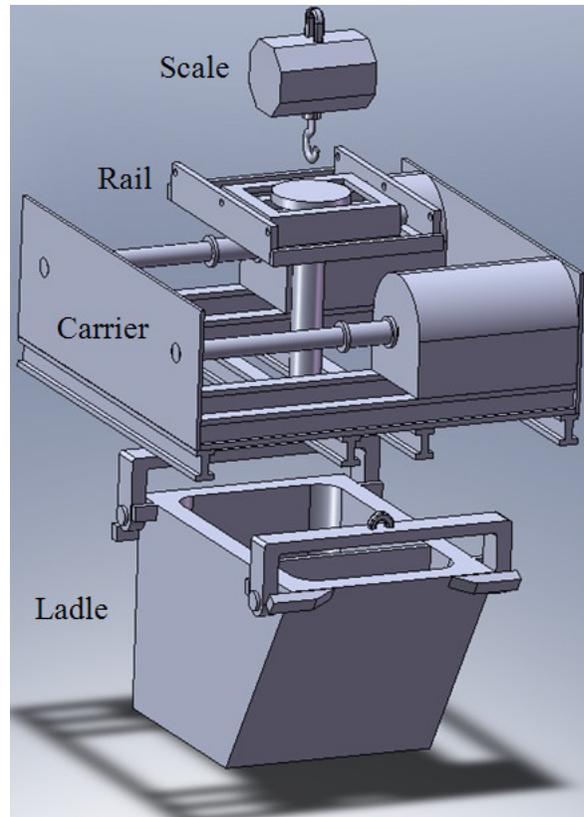
Pounds Remaining	Metal Height in Ladle (in)	Head Height with Refractory (in)	Head Height with Spout
500	2.2	5.2	9.2
1,000	4.4	7.4	11.4
2,000	8.8	11.8	15.8
3,000	13.2	16.2	20.2
4,000	17.6	20.6	24.6
5,000	22.0	25.0	29.0
6,000	26.4	29.4	33.4
7,000	30.8	33.8	37.8
7,500	33.0	36.0	40.0
Average	17.6	20.6	24.6

### 3.1.7 Space Constraints for Pouring

In many foundries the amount of available space on the pouring floor is limited. This creates a constraint on how long the new ladle design can be so that it will fit into the aisles and still be able to access the molds. At Facility 1, the average aisle width is 29 inches. Based on the measurements given in Table 3.1, the 1,000 pound ladle with a width of 21 inches would fit into this environment. In the case of larger sized ladles: at Facility 1 molds were moved to an open space for pour access, so there would be no required maximum length; at Facility 2, the given aisle space for an 8,000 pound ladle was 100 inches, within which the 10,000 pound ladle of the new design would fit. In both of these facilities, which are typical for the industry, the new ladle design would have little difficulty gaining access.

## 3.2 Apparatus

The major advantage of the system is that it can pour steel at a prescribed pouring rate. This feature will require a pouring apparatus which can control the positioning and rotation of the ladle. The prototype apparatus will consist of three parts: the scale, the rail, and the carrier (these three parts will be referred to as the apparatus), each of which have a function in controlling the pour process. Each of the pieces of the apparatus along with the ladle is shown in Figure 3.9. Note that connecting lines and cables are not shown in the diagram. The design of this apparatus is only intended to give perspective for the possible design. It is a design that will function as needed; other designs or considerations could be implemented. The following sections explain where the equipment will be, what it will do, the importance of height, and lastly, gross movement of the apparatus.



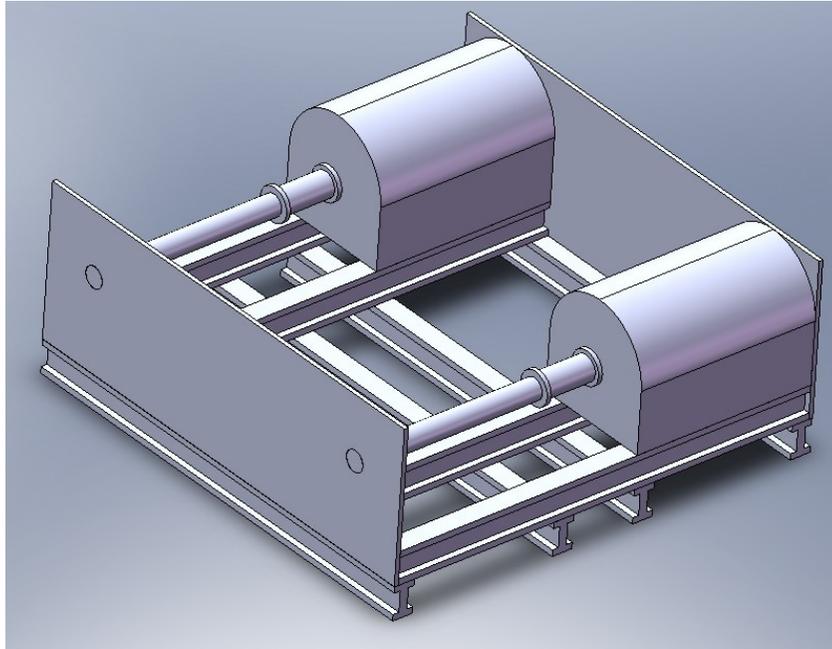
**Figure 3.9** Assembly Drawing of the Apparatus Components and Ladle. Cables are not shown in picture.

### 3.2.1 The Carrier

Shown in Figure 3.10 is a picture of the carrier by itself. The carrier's main function will be to house the two motors responsible for tilting the ladle. The motors will drive two axes; each axis will be connected to either the front or back of the ladle by cable. Based on the instructions from the controller, these motors will raise and lower the front and back of the ladle, controlling its tilt. The motors' size<sup>4</sup> and horsepower are determined based on the

<sup>4</sup> Motor size was determined based on the full load rating for each motor. The motor is the load rating with the lowest value above the necessary torque was used.

size of the ladle required and also the gear ratios of the gearboxes. A table showing results for different gear reducers is shown in Table 3.5.



**Figure 3.10** Carrier for New Ladle Design

**Table 3.5** Motor Sizes and Speed Calculated from Gear Ratios

3,500 Pound Ladle				
Gear Reducer (X:1)	50	100	250	500
Pulley Size (in)	4	4	4	4
Steel Weight	4,360	4,360	4,360	4,360
Ladle Weight	765	765	765	765
Total Weight with 100% Safety Factor	10,252	10,252	10,252	10,252
Gear Reducer Efficiency	0.80	0.80	0.80	0.80
Max Motor RPM	1,775	1,775	1,775	1,775
Max Actual RPM	35.50	17.75	7.10	3.55
Max Speed (in/sec)	7.44	3.72	1.49	0.74
Torque Needed (ft-lbs)	85.43	42.71	17.09	8.54

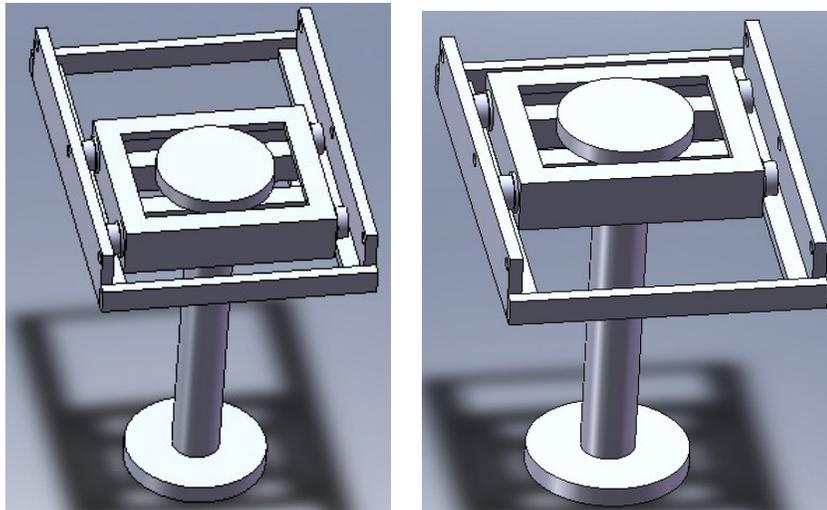
The size of the motors on the carrier drives the height of the carrier, so using a larger motor will result in less vertical space available for the ladle. The height dimension for the carrier for each sized ladle is shown in Table 3.6. The heights in Table 3.6 are based off of the motors using a gear reducer of 250:1, so for the 3,500 pound ladle, this is a 7.5 horsepower motor.

**Table 3.6** Height Dimension of Apparatus Components

(in)	1,000	3,500	5,000	10,000
Carrier	7.0	10.5	10.5	13.0
Rail	11.5	11.5	11.5	11.5
Scale	20.5	20.5	20.5	20.5
Suspension	8.0	8.0	8.0	8.0
Total	47.0	50.5	50.5	53.0

### 3.2.2 The Rail

The next piece of the apparatus is the rail shown in Figure 3.11. The frame of the carrier will be attached to the rail via a plate on the end of a rotating axis (this plate is visible at the bottom of Figure 3.11). The rotating axis will be driven by a motor on the rail. The rail will act as a station for both X-Y movement during the pour and for rotational movement for lining up the ladle with the mold before pouring. X-Y movement will be possible based on a cart within the rail that will “drive” forward and backward. An example of this motion is shown between the two images in Figure 3.11. The height that the rail adds to the total height of the apparatus is in Table 3.



**Figure 3.11** Rail Component of the Apparatus That Shows X-Y Movement

### 3.2.3 The Scale

Lastly is the scale from which the rail will hang. The scale will provide feedback to the controller, which will in turn send a signal to the motors so as to properly adjust the tilt of the ladle and thus the pouring rate. Approximate dimensions for its height are also shown in Table 3.6.

### 3.2.4 Addressing the Issue of Height in a Facility

One of the limitations of use of the system is the overall height, because of the limited crane rail clearance in many foundries. Height is the most important dimension of the apparatus. Some facilities have tight restrictions on vertical space due to crane rail height. At Facility 1, which had a relatively low crane height, they poured out of a 3,500 pound ladle and had a total of 127” of total pouring height with which to work.

There are three areas of this system that will determine total height required: the height of the apparatus, the amount of cable from which the ladle hangs, and the ladle height. Table 3.6 shows the apparatus' total height for each ladle size. This value is 50.5 inches for the 3,500 pound ladle. The length of cable that the ladle hangs from must be at least as much as required to lift the ladle to full tilt. Based on the value for the amount of steel left in the ladle (which was calculated in Section 4.1), the ladle will be considered empty when it is tilted to approximately  $40^\circ$ . Using simple trigonometry, there should be at least 26.5 inches of cable. Because the ladle should not be lifted until it contacts the bottom of the apparatus, 30 inches will be used to allow for 3.5" of safety height. This does not include the bail height, which is 4 inches. This height also needs to be added to this total, resulting in 34 inches of height. The height of the ladle is the distance from the bottom of ladle to the trunions to which the bails attach. This distance is 25 inches. The resulting total required height using a 3,500 pound ladle is 109.5 inches. This is a difference of 17.5 inches; the entire system will fit into this smaller ceiling height.

### 3.2.5 Gross Movement

Gross movement as it refers to this paper is defined as the method with which the ladle and apparatus will get the mold after being filled. The system's design is intended to fit the overhead crane system that most casting facilities have, thus not changing the gross movement system. Each apparatus will have a hook that will attach to the overhead crane via the scale.

### 3.3 Fine Control System

The fine control of the system consists of movement after the ladle has reached the mold via the crane system until the ladle needs to be moved to the next mold. The operator will have a hand held control center and be in charge of making any position adjustments to locate the ladle over the pour cup with: forward and backward motion based on the rail's movement, rotation of the ladle<sup>5</sup>, and up and down motion. Once the ladle is located over the pour cup the operator will specify the pour rate and amount and press "Go" on his controls. The system will then begin the pouring process based on a weight controlled feedback system. As the ladle tilts it will have three degrees of freedom, up and down, backward and forward, and tilting rotation. The ladle will follow a tool center point path to keep the pouring stream within the pour cup. This technique for controlling the pour will allow for the ladle shape to be changed without changing any major pieces of equipment as it is completely independent of the shape of the ladle.

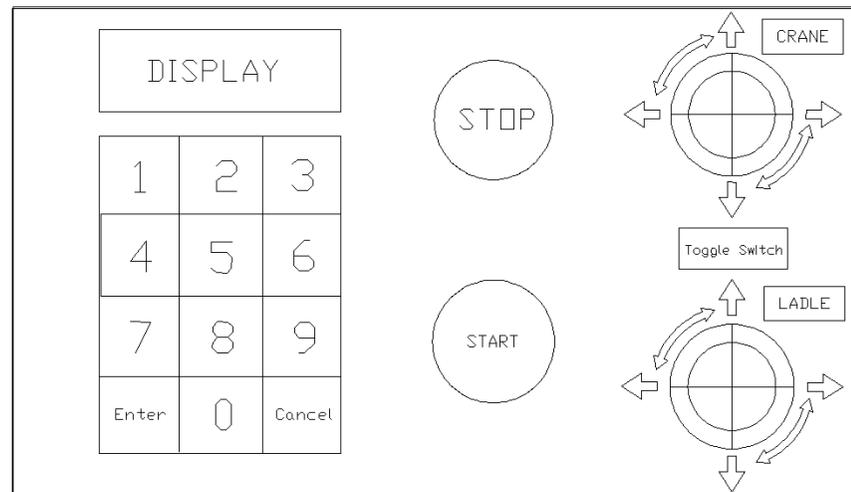
#### 3.3.1 Hand Held Operator Control

The operator will have a hand-held control system for performing fine movements. A sample of what this controller might look like is shown in Figure 3.12. The controls will include a joystick for the overhead crane (if necessary). One joystick will control three axes, up/down, back/forth, and left/right. The other joystick will control the ladle and also

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<sup>5</sup> This rotation is not tilting rotation, but is rotation from the axis on located on the rail or the apparatus.

control movement on three axes, up/down, back/forth, and ladle rotation<sup>6</sup>. The number pad will allow the operator to enter in the prescribed pour rate and pour weight. The start button will function to start the tilt of the ladle once the operator has entered the pour parameters. The stop button will function for emergency stops in the case of an error. If the operator has to stop the pour manually, the controls will allow him/her to finish the pour manually.



**Figure 3.12.** Example of Pour Controls for the Operator

### 3.3.2 Positioning the Ladle Before Pouring

As stated in the previous sections, once the ladle has been positioned via the crane, the operator will then need to position the ladle with respect to the pouring cup. The motor on the rail system will move the ladle forward and backward over the sprue cup. The rail allows for 15” of forward and backward motion, since the pour should not move more than 3.5 inches forward (half of the typical seven inch opening of the pouring cup), this will

<sup>6</sup> Ladle rotation here is intended to be spinning the ladle on the axis located on the rail for positioning, not tilting for pouring.

leave the operator almost one foot of back and forth movement to approach the mold for placement.

The other benefit of this system is its ability to rotate on an axis. In the case that there is an awkward pour cup or mold placement or if there is an obstacle, the system can rotate to accommodate this inconvenience. The rotation will be performed by a motor attached to a rotating axis on the rail.

### **3.3.3 Pour Control Based on Weight**

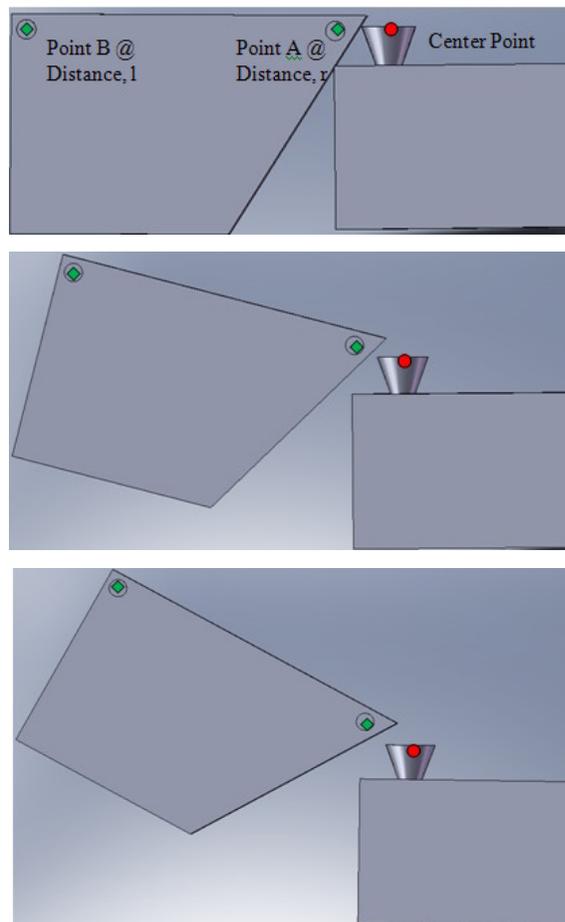
As stated earlier, the pour rate of the system will be controlled through the output of a scale that will hold up the entire system. The scale for this system has an output in the form of a current signal that will continuously be sent to the controller. The controller will interpret the readout signal and convert it to a weight reading. Based on the output, the controller will adjust the motors responsible for tilting the ladle. Essentially the system is finding the integral for weight lost from the ladle over time.

### **3.3.4 Tilting the Ladle**

Once the ladle is positioned over the pour cup, and the operator has entered in the pouring parameters for the control system, the ladle can now pour. Pouring in the new system will use tool center point mathematics to move the ladle and maintain a consistent stream location.

The tool center point concept is used for robotic applications and allows a program or operator to determine a point or line in space in which the robot should operate around or with respect to. This is the same idea that will be used in the proposed system. In this case,

the pour system has a specified imaginary axis that the new ladle design will rotate about while pouring; this axis will typically be located somewhere in the pour cup. An example showing the ladle rotating about the imaginary axis is shown in Figure 3.13 (the points chosen to rotate about the ladle are the diamonds on the trunions and the imaginary axis is represented by the circle on the pouring cup). Tilting it in this manner requires the ladle to be simultaneously moved both vertically and horizontally to achieve its desired rotation. The motors on the carrier will control up and down movement and the rail will control the horizontal movement during the pour. This will allow for a pour that will keep the pour stream low and centered over the pour cup at the specified rate.



**Figure 3.13** Tool Center Point Diagram

Most tool center point systems operate three dimensionally, however this system can be represented by a two dimensional model because it will only be moving in three axes. The ladle can be represented by choosing two points, just like what is shown in Figure 3.13. Note that the points that represent the ladle cannot be located on a single line that is parallel with the tilting axis because the ladle could then be rotated about the tilting axis without actually being tilted. These selected points will represent the ladle and be used to calculate its movement within the system.

When the operator presses the “Go” button, the system will detect that it is not pouring and thus determine that it needs a higher pour rate and the ladle will tilt  $\theta^\circ$ . As the motors for tilting both begin to lift, the motor responsible for moving forward and backward will also begin to move forward, all of these motions create the three axis motion that results in the rotation about the center point. Each rotation of  $\theta^\circ$ , will result in a new set of coordinates to move to for each of the selected points that represents the ladle. The mathematics behind this operation is discussed here.

First the center point of the system needs to be defined. For simplicity, the fixed center point will be the origin of the coordinate system, (0,0,0). Point A and Point B will be the two points that define the ladle. Point A is located  $r$  distance from the center point at angle  $\alpha$  and has coordinates  $(X_{1a}, Y_{1a}, Z_{1a})$ , and Point B is located  $l$  distance from the center point at angle  $\alpha$  and has coordinates  $(X_{1b}, Y_{1b}, Z_{1b})$  (Note that since this problem is two dimensional, all X-coordinate values will be equivalent). As the ladle rotates, Point  $A_1$  rotates about the origin to Point  $A_2 (X_{2a}, Y_{2a}, Z_{2a})$  and the same for Point B, this action is shown in Figure 14. The new coordinates for each point can be found using the following calculations:

$$X_2 = X_1$$

$$Y_2 = r \cos(\theta + \alpha)$$

$$= r(\cos\theta \cos\alpha - \sin\theta \sin\alpha)$$

$$= r \cos\theta \cos\alpha - r \sin\theta \sin\alpha$$

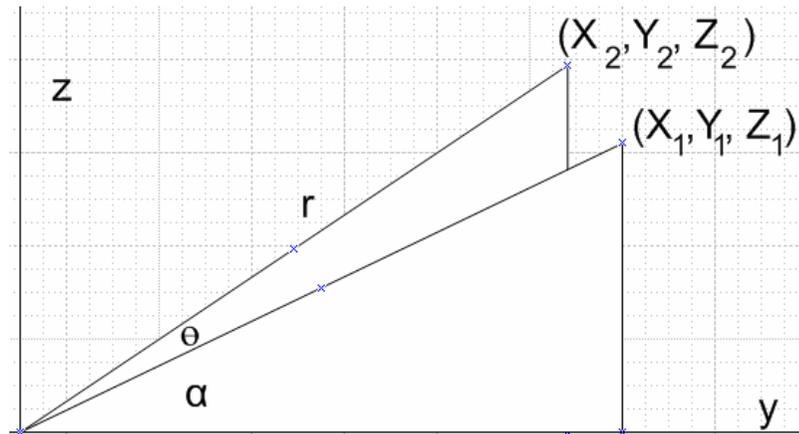
$$= Y_1 \cos\theta - Z_1 \sin\theta$$

$$Z_2 = r \sin(\theta + \alpha)$$

$$= r(\sin\theta \cos\alpha + \cos\theta \sin\alpha)$$

$$= r \sin\theta \cos\alpha + r \cos\theta \sin\alpha$$

$$= Y_1 \sin\theta + Z_1 \cos\theta \quad (\text{Lee 1999})$$



**Figure 3.14** Tool Center Point Graphic

As an example, if Point A were located a radius of 12 inches from the center point at an angle of  $15^\circ$  it would have coordinates (0, 11.59, 3.16). If the system told the ladle to rotate  $1^\circ$ , the resulting coordinate changes for Point A are (0, 11.53, 3.36). Once both initial and final coordinates for Point A are known, it can be determined that Point A will need to

go 0.06 inches forward and 0.20 inches up to achieve a tilt of  $1^\circ$ . The motor responsible for moving laterally will receive the value 0.06 and move accordingly, as will the motors responsible for lifting the ladle. The system will continue with these iterations until the pour is complete or it is manually stopped by the operator.

### 3.3.5 The Motor Controller

The motor controller will determine when and how the system will pour once the operator starts the pour. When the operator sets the prescribed pour rate before the pouring starts, he/she is determining the set-point for the controller. A PID (proportional-integral-derivative) controller will be used to keep the pour rate the prescribed pour rate.

A PID control is used to achieve a desired set-point, much like a house thermostat or cruise control on a car. It receives an output signal from a sensor, in the case of this pour system, the scale, and compares that input to the desired set-point. The difference between the two values is known as the control error (Visioli 2006). Based on this error, the controller then tells the motors how to move to increase or decrease the speed at which they are tilting the ladle. The tilting rate is determined by a combination of the proportional, the integral, and the derivative portions of the controller.

Proportional control action of the PID controller is based proportionally on the amount of control error; it interprets error in the present. The equation for the proportional action can be expressed as:

$$u(t) = K_p e(t) = K_p (r(t) - y(t)),$$

where  $u(t)$  is the output of the control action,  $K_p$  is the gain or amount of influence this portion of the equation has on the final controller output,  $r(t)$  is the current system value at

time  $t$ , and  $y(t)$  is the set-point value. A high gain setting for the derivative controller will result in a high response, but a high oscillatory function. The proportional controller is good at providing small changes for small amounts of error without excessive controlling efforts. However, it does produce a steady-state error. The next portion of the controller can account for this error (Visioli 2006).

The integral part of the PID controller is proportional to the integral of the control error. The integral action is the adjustment for actions that have occurred in the past. The equation for the integral action can be expressed as:

$$u(t) = K_i \int_0^t e(\tau) d\tau,$$

where  $K_i$  is the gain of the controller. A high gain setting for the integral controller will result in a slower but more stable system in terms of response. As stated above, one property of the integral action is that it automatically adjusts to correct the steady-state error of the proportional action. (Visioli 2006).

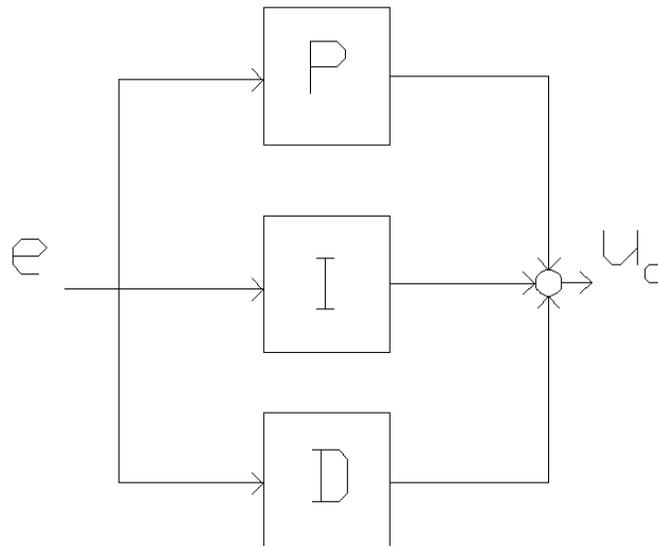
The last part of a PID controller is the derivative action. The derivative action is proportional to the derivative of the control error. The equation for derivative action can be expressed as:

$$u(t) = K_d \frac{de(t)}{dt},$$

where  $K_d$  is the gain of the derivative controller. The derivative action interprets the current change in the control error and predicts the future values for it. A high gain setting for the derivative controller will result in a damping effect on the movement (Visioli, 2006). One problem with the derivative controller is that it will amplify noise in the system. Because of this, it can cause unstable and undesirable effects if not properly tuned. According to Dr.

Greg Luecke, an application using weights of this magnitude should not need to have a derivative portion in the controller.

To overview, the scale will send values to the controller where it will determine the rate of change of metal in the ladle. Once it has this value, the PID controller will compute the control error based on the current pour rate and what the set-point rate is. The respective portions of the controller will then contribute to the output signal based on their gain values. This output signal from the controller will in turn tell the motors in the apparatus to rotate faster or slower to adjust for pour rate. A diagram of the PID function is shown in Figure 4.15.



**Figure 4.15** PID Portion of Control Loop (Johnson 2005)

Determining the gain for each portion of the controller can differ from system to system. Incorrect gain settings can cause overshoot, jerk, or an unstable system. Overshoot occurs when the system does not slow down fast enough to smoothly reach the set point (Visioli 2006) and would cause a pour rate that is too high and possibly spill metal during

the pour. Jerk is defined as the derivative of acceleration and could cause a sloshing effect in the ladle in which metal may be spill out of the ladle (Leucke, 2007). And an unstable system is a system that reaches a point where it will magnify the error and never reach the set point (Visioli 2006).

Because the loads for this application are so high, PID control is easier because there is less chance of overshoot and jerk. Because there is a smaller chance for overshoot, a high gain setting on the proportional controller with a low setting on the integral, and zero setting on the derivative would be best intuitive combination without further testing. This would actually be considered a PI controller and will encourage quicker responses from the system without the overshoot and jerk of some applications.

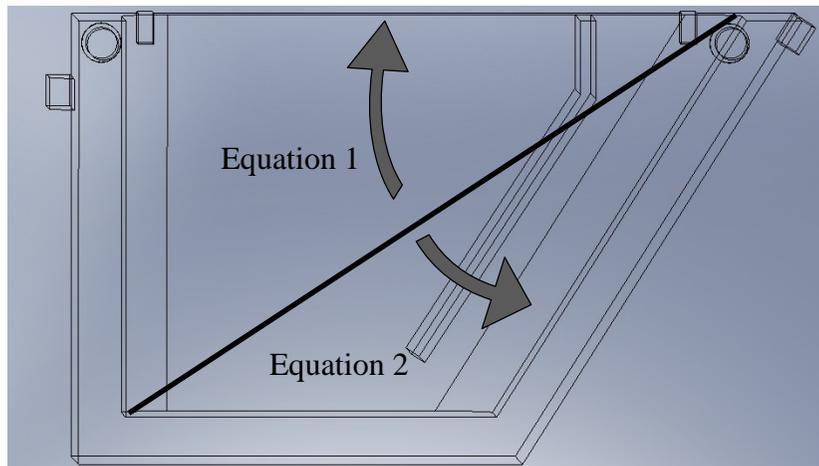
### 3.3.6 The Pour

The pour can be broken into two main parts, the pour weight and the pour rate. For the pour weight, the controller will take the starting pour weight and calculate the ending weight based on what the operator input. The pour rate will be dictated by the controller which, as was discussed in the previous section, will do this by controlling the speed and position of the motors.

There are two ways to determine the pour rate, one way is to take two readings from the scale and then determine the difference and divide by the time in between the two readings. This method would be accurate for determining pour rate with one minor problem; since the pour rate is based on an average it will not be the exact pour rate at time  $t$ . This may cause a small amount of error depending on how consistent the pour rate is over the sampled time, the larger the difference over the sample, the larger the error.

Another way to calculate the pour rate is to use the geometry of the ladle. This can be done by relating the weight in the ladle with respect to the tilt angle of the ladle. If the controller can relate the angle of the ladle to how much is in the ladle, it can then determine the pour rate based on the change in angular velocity. The equations and calculations for this method are shown below. This method does have problems as well. The calculations below are based on a theoretical geometric representation of the suggested ladle; it does not account for industry variability in shape and usage over time. However, it can be used as a guide for expected weights and rates in the ladle.

Based on the geometry of the 3,500 pound ladle, the equations for weight left in the ladle are shown below. There are two equations for the ladle because of the square shape. Figure 3.16 shows the line that determines where the equations change; the ladle will tilt  $33.27^\circ$  before the equations will switch.



**Figure 3.16** Divider to Determine Equations for Pour Weight

The equation for the first part of the pour is shown below.

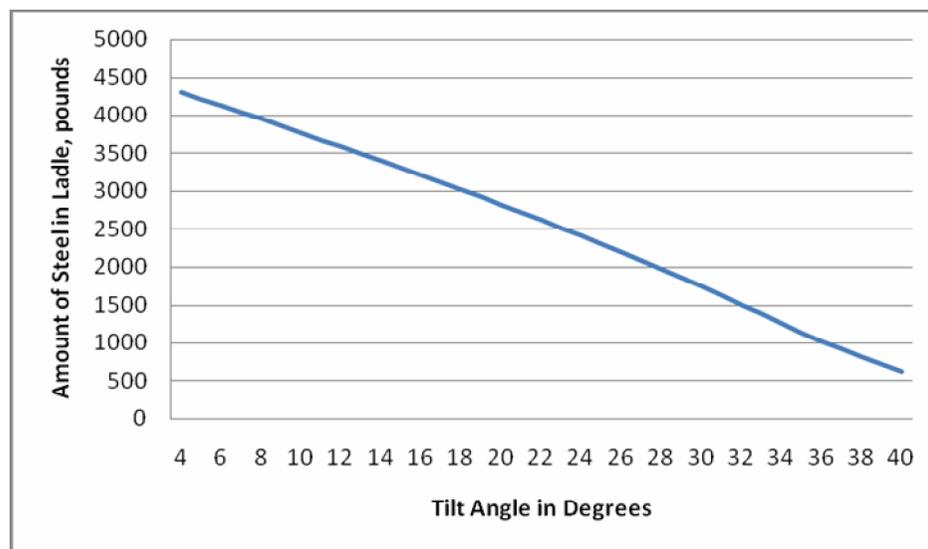
$$F(\theta) = \rho_{\text{steel}}(V_{\text{total}} - 0.5(L_{\text{ladle}} \times w_{\text{ladle}} \times L_{\text{ladle}} \tan(\theta)))$$

Where,  $\rho_{\text{steel}}$  is the density of steel,  $V_{\text{total}}$  is the total volume of the ladle,  $L_{\text{ladle}}$  and  $w_{\text{ladle}}$  are the long length and width of the ladle and  $\theta$  is the tilt of the ladle. The form for the second equation is:

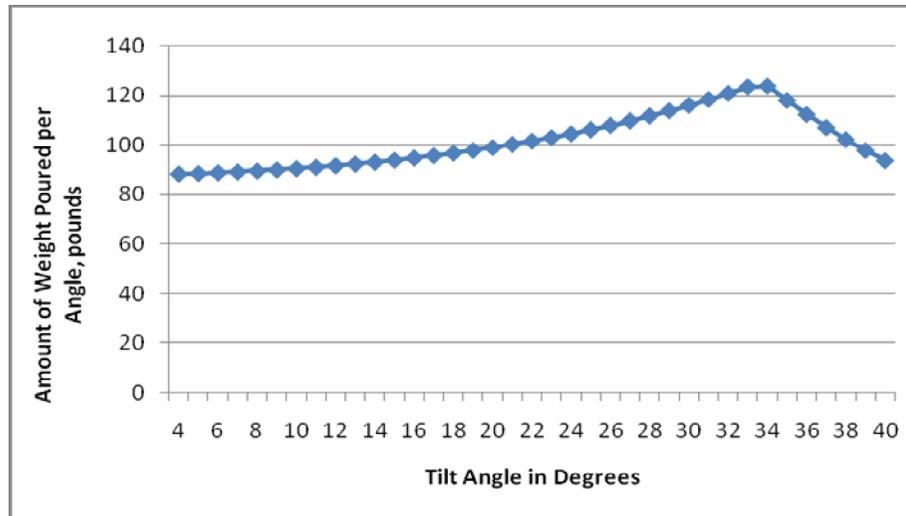
$$F(\theta) = \rho_{\text{steel}} \times 0.5[(L_{\text{ladle}} \times w_{\text{ladle}} \times h_{\text{ladle}}) - (h_{\text{ladle}} \times w_{\text{ladle}} \times h_{\text{ladle}} \tan(\theta)) - ((L_{\text{ladle}} - l_{\text{ladle}}) \times w_{\text{ladle}} \times h_{\text{ladle}})]$$

where,  $l_{\text{ladle}}$  is the short length of the ladle. A graph of both of these equations is shown in Figure 3.17. The scale for this graph does not show well the differences in slope change.

Figure 3.18 shows the graph for the amount of weight poured out of the ladle per one degree of rotation at the given ladle tilt to better depict the change. For example, when there is  $6^\circ$  of tilt in the ladle and it rotates one degree to  $7^\circ$ , it will pour approximately 89 pounds of metal.



**Figure 3.17** Amount of Weight at Given Tilt Angle



**Figure 3.18** Amount of Weight Lost per Degree of Tilt When Ladle is at the Tilt Angle

### 3.4 Additional System Considerations

The following sections cover additional ideas that should be addressed with this system. These include safety considerations, supplying power to the system, filling the ladle, and cost of the system.

#### 3.4.1 Safety

Safety of the new system is of paramount importance. The new system will eliminate the ergonomic hazard associated with moving and controlling a teapot ladle. For both teapot and bottom pour ladles, the operators are currently required to be immediately adjacent to the ladle during pouring. This system will allow the operator to move away from the mold once the ladle is lined up to the sprue and the system is controlling the pouring.

The pouring apparatus and supports need to be fully evaluated to ensure that they will be reliable and if necessary, redundant.

### **3.4.2 Supplying Power to the System**

A challenge for this system is supplying power to the control system, both in how the power gets there and how it's protected in the adverse environment. All power supplies will need to have protective shielding and appropriate safety mechanisms to reduce exposure. The closest power source to the system will be the crane. The power will need a path that would be free of crushing and pinching potential from the crane. Having retractable cord devices to keep slack from being caught and/or tangled may be necessary.

### **3.4.3 Filling the Ladle**

Facilities have different techniques for filling their ladles from the furnace. The method used by Facility 1 is that they fill a larger ladle, transport this ladle to a hydraulic platform and then fill smaller ladles by tilting the platform. In this case, the new ladle design, which is intended to be filled from either of the sides, would not have any issues with filling. In Facility 2 where there are larger ladle capacities, the ladles are lowered into a pit in front of the furnace and filled while they are held by the crane. In this system, the new design may have a problem with the apparatus interfering with the furnace. A simple solution would be to put excess cable length into capacity of the apparatus and lower the ladle as much as possible to create the necessary room for the furnace to pour into the ladle. If this did not allow for enough space, an extended shoot could be placed onto either the side of the ladle or onto the spout of the furnace while filling the ladle.

### 3.4.4 Equipment Considerations

As with other equipment in the casting industry, this system will also have to be designed with robust components. Since the controls for this system are based on a motor controller and an accurate scale measurement, it is necessary to have equipment that is both reliable and durable to endure the adverse environment.

### 3.4.5 Cost of the System

Table 6 is an estimate of the cost of the new pour system. The cost of the new ladle is for materials and fabrication. The carrier cost includes costs of materials, motors, controller, gear boxes, encoders and fabrication. The rail cost includes costs of materials, motors, gear boxes, and fabrication. The scale cost only includes the cost of the scale, there are no other requirements. Refractory costs are not included since they will be similar to current costs for ladle refractories.

**Table 3.7** Component Cost for New System Design

System Cost	1,000 lb Ladle	3,500 lb Ladle	5,000 lb Ladle	10,000 lb Ladle
Vessel	\$ 3,436	\$ 3,983	\$ 4,269	\$ 4,951
Carrier	\$ 10,250	\$ 11,450	\$ 11,550	\$ 13,630
Rail	\$ 3,500	\$ 3,500	\$ 3,500	\$ 3,500
Scale	\$ 6,100	\$ 6,500	\$ 6,500	\$ 7,100
System Set-up	\$ 8,000	\$ 8,000	\$ 8,000	\$ 8,000
Total	\$ 31,286	\$ 33,433	\$ 33,819	\$ 37,181

## Chapter 4 Conclusions

This paper shows that a new pour system with a new ladle design could prove beneficial to the steel pouring industry. Two ladle designs were proposed to give an additional option if more access to the sprue and pouring cup is desirable. A summary of the results show the following conclusions:

- There are areas for improvement regarding air entrainment and in pouring control in the current steel pouring practices using a teapot and bottom pour ladle.
- A new ladle design could decrease air entrainment by reducing the pouring height and incorporating a lip into the design. The pour height was shown to be improved by an average of 24 inches in the 8,000 pound capacity bottom pour ladle. Even though it was not quantified, studies evaluated in the literature review showed that a rounded, more semicircular lip shape was beneficial to reducing the amount of air entrainment while pouring.
- This design would maintain at least the same amount of access to the sprues for pouring when compared to the teapot ladle and in many instances, would improve it if the sprue and pour cup were not located on the edge of the mold.
- The introduction of an apparatus to control the pouring mechanics is necessary and in the cases of Facilities 1 and 2 would be implementable even with the needed increase in vertical space required for the system.
- Both teapot and bottom pour ladles require an operator to control pouring rate. This operator reliance is eliminated with this new design. The operator will be able to

line up the mold, push a button, and the pour will be completed as programmed per weight and pour rate. This will increase the ergonomic situation for the error and also reduce any casting defects caused by operator error in pour rate for both ladle types.

- Having the ladle follow a tool center point pour will provide for a controlled pour that maintains a pouring axis within the pouring cup. It will also eliminate the need for unnecessary manual ladle position adjustments during pouring for the teapot ladle.

Overall the new pouring system would be beneficial to the steel casting industry. It will decrease air entrainment and inclusions and create a smooth, controlled pour both in motion and in rate.

## Chapter 5 Future Work

The next step for this idea is to create a prototype model to test the theories of the system. All of the calculations and procedures in this paper work on the idea that everything works in reality as it works in theory; as the time has shown, these can be far from similar at times. Therefore, the following steps should be taken to advance this idea to the next level:

- Creating the new ladle, designed behind the theories outlined in this paper. This ladle should incorporate the lip and slag block design included and the shape should be tested for industry feasibility, although no major changes are foreseen.
- Creating an apparatus that works on the principles outlined in this paper will also be required. This includes the ability to suspend, tilt, and rotate the ladle and also to move it forward and backward for positioning reasons.
- The control system will also need to be developed. The PID portion of this paper was only intended to demonstrate capabilities; actual values for gain were not calculated and developed to determine the optimal pour. PID controllers often need to be tuned depending on the system.

When these main parts of the system have been developed further, this system can be tested and evaluated on performance and will benefit pouring technology for the steel casting industry.

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