# Thin Slab Continuous Casting Mould Taper Design

## **Prepared for:**

Nucor Steel RR #2, Box 311 County Road 400 East Crawfordsville, Indiana 47933-9450

> Steve Wigman Meltshop Metallurgist

## **Prepared by:**

UNDERGRAD Consulting 2009 Mechanical Engineering Lab 105 S. Mathews Urbana, IL 61801

> Consulting Team Jay Paidipati Brad Sharos Christina Slayton Jennifer Wood

Advisor Professor Brian Thomas

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## ABSTRACT

This study was a professor sponsored project conducted in conjunction with Nucor Steel in Crawfordsville, Indiana. Nucor Steel produces steel sheet by a process known as thin slab continuous casting. Nucor is experiencing defects in their final product which they attribute to excessive taper in the narrow face of their funnel mould. The narrow face of the mould is tapered to take into account the shrinkage of the steel as it solidifies. Taper measurement data from casting runs support the idea that there is excessive taper. The main goals of this project were to model the process numerically to obtain a method to calculate ideal narrow face tapers and investigate Nucor's taper control and measurement method.

A numerical model, CON1D, was successfully calibrated and used to analyze Nucor's process and derive an ideal narrow face taper prediction equation. A finite-element analysis conducted by a graduate student in the Continuous Casting Consortium concluded that plastic strain has an effect during the casting of low carbon steels. The ideal taper predictions show that Nucor is indeed implementing a taper greater than the ideal taper for both high and low carbon steels, thus validating their hypothesis of excessive taper.

The investigations of Nucor's taper control and measurement systems identified a probable source of error. Nucor is currently using their control system as a means to measure the taper implemented during casting. There is a certain amount of "slop" present in the gear boxes of the transmission system that controls the narrow face taper. Currently, the acceptable level of "slop" is 0.6 mm and is significant when compared to an average taper of 1 to 3 mm. The gearboxes are sent out to be calibrated to remove the "slop", but only 4 to 5 gearboxes are recalibrated a year. It is recommended that the acceptable level of "slop" be decreased and that the gear boxes be sent out more frequently for calibration.

In the past Nucor has tried to measure the taper using inclinometers made by Jewell Instruments specifically for continuous casting. The inclinometers were made to handle mould oscillations of 1 Hz not 4-6 Hz, which is the frequency that Nucor's mould oscillates. Other possible inclinometers were researched, but none possessed adequate resolution. It is recommended that Nucor collaborate with inclinometer companies to design an inclinometer that can handle the oscillations while having adequate resolution.

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## **INTRODUCTION**

#### BACKGROUND

Continuous Casting is the process whereby molten steel is solidified into a billet, bloom, or slab for subsequent rolling in the finishing mills. The process begins when liquid steel is fed into a mould where the steel partially solidifies, producing a steel strand with a solid outer shell and a liquid core. Liquid steel continues to pour into the mould to replenish the withdrawn steel at an equal rate. This rate depends on the cross-section, grade and quality of steel being produced, and may vary between 12 and 300 inches per minute. When the strand exits the mould, it enters a roller section and cooling chamber in which the steel is sprayed with water to promote solidification. Once the steel is fully solidified, the strand is cut into individual pieces of as-cast product. The slabs, which are then coiled into rolls of steel, are of rectangular cross section and must be at least twice as wide as thick. Before the above process was introduced in the 1950's, steel was poured into stationary moulds to form cast metal. The cast metal then had to be reheated and rolled into the desired shape. The aim of continuous casting is to cast the liquid steel into a shape that closely resembles the finished product, minimizing the amount of rolling that must be done before the steel is sold. Continuous casting has since evolved to achieve improved yield, quality, productivity and cost efficiency.

Nucor currently uses the most advanced casters in commercial service known as thin slab casters to produce slabs less than 2 inches thick, see Appendix A-1 for a picture of Nucor's funnel mould. The crux of the thin slab casters is the funnel formed in the wide faces of the mould to allow the submerged entry nozzle to pour molten steel into the mould, see Appendix A-2 for a picture of the funnel. The submerged entry nozzle was designed for traditional continuous casting process and is thicker than 2 inches. Thus, the funnel was built into the wide faces of the mould so that in order to cast thin slabs of steel, the only part of the process that would have to be changed would be the mould itself; everything above and below the mould could remain the same. This allows traditional continuous casting plants to convert to thin slab casting without changing their entire process. However, the funnel must be shaped such that the steel's transition from bent to straight is gradual and produces the minimal amount of extra strain on the steel, see Figures 1 and 2.



Figure1: Top View of Solidifying Steel Shell near Meniscus

Figure 2: Top View of Solidifying Steel Shell near Bottom of Mould

The wide faces of the mould are most responsible for liberating the heat from the steel, thus the narrow faces must be tapered to account for the steel shrinkage along the wide face. Narrow face taper is defined as the change in position of the narrow face from the top to the bottom of the mould as seen below in Figure 3.





Figure 3: Side view schematic of mould to show the narrow face taper (left) and a top view of the funnel mould (right)

Nucor's funnel moulds have been designed to allow for thermal expansion. This minimizes the problem of cracks in the mould due to the cyclic thermal loading. In Nucor's funnel moulds, the west narrow face is connected to the bottom of the mould with a slotted pin. The slotted pin connection allows the west narrow face to move outwards to relieve thermal strain in the mould and extend the life of the mould.

During the continuous casting process, mould flux is used as a lubricant along the interface between the solidifying steel shell and the walls of the mould to prevent the steel shell from sticking to the mould. The mould flux also aids in heat removal due to its high thermal conductivity relative to air. At Nucor, the mould flux consumption rate is 0.95 lbs. of mould flux per ton of steel produced.

Nucor currently produces slabs less than 2 inches thick. The aim of thin slab continuous casting is to have the steel exit the mould as close to the final thickness as possible, which allows the continuous casting plant to save money and energy. In the late 1970's, the Department of Energy started an initiative to make thin slab continuous casting a viable technology and Nucor Steel was the first company to implement the technology. A significant amount of energy goes into the processing of steel, both in the casting phase and the rolling phase. Thin slab continuous cast steel requires less rolling, thus saving energy. This benefits society as a whole because more energy is available for other uses. Thus, this project has a positive societal effect.

Less energy usage also has a positive environmental impact. A vast majority of the energy produced in the United States still comes from fossil fuel based sources. If significantly less energy is used for the casting of steel, this will result in less fossil fuels being burned. Therefore, less pollutants will be released, causing less damage to the environment.

Thin slab continuous casting is also economically desirable, for both the producer and the customer. The majority of the money spent in constructing a continuous casting plant is in the hot mill where the steel slabs are rolled to the desired thickness. At Nucor, their single hot mill cost \$25 million dollars. In a traditional continuous casting plant there could be three or four hot mills. Thus, a thin slab continuous casting plant can produce thin steel sheet at a cheaper cost than a traditional continuous casting plant. This cost savings is then passed on to the customer.

#### **PROBLEM STATEMENT**

A problem arises with thin slab continuous casting because of the demands for higher quality slabs, free from surface and internal defects. Some of the quality problems that plague this method can be traced to the mould and the taper of the narrow face. Currently Nucor is using an approximate1% linear taper, which changes slightly with different steel grade and desired final product width. It appears that currently there is excessive taper in the narrow face,

which causes too much contact between the narrow face of the mould and the solidifying steel slab. The narrow face taper is used to compensate for the wide face shrinkage of the shell, which is dominated by thermal strain controlled by mould heat transfer. The heat transfer includes the transfer through the solidifying shell, from the shell surface to the copper mould outer surface, through the copper mould, and from the copper mould inner surface to the mould cooling water. The optimal narrow face taper allows proper solidification of the steel strand by staying in contact with the steel strand while it shrinks to continue the solidification process, but not imposing any force on the steel shell.

Excessive taper causes numerous imperfections in the slabs of steel produced. One such problem is the narrow face of the mould wears away. If this occurs, the narrow face squeezes the steel shell, the friction between the steel shell and the narrow face wears away copper from the narrow face and subsequently the narrow face is worn down. The copper gets into the steel and changes its composition and the resulting product is not what was specified by the customer. Excessive taper also creates an extra tensile stress which results in transverse cracking that ranges from rough edges on the final coil of steel to shallow transverse cracks that penetrate from 2 to 4 inches into the coil. Another problem is that the wide face of the steel shell buckles due to too much contact between the steel shell and the narrow face of the mould. This causes longitudinal cracks in the steel slab because the heat transfer by conduction is hindered. See Appendix A-3 for pictures of these defects.

However, insufficient taper can also cause numerous problems. The worst are breakouts in the steel shell, which result in molten steel pouring over the casting equipment. This is extremely undesirable because it results in production loss and damage to the equipment.

The major concern with defects in the steel slab is the loss of revenue. Nucor loses \$90-100 a ton if they have to sell the slabs  $2^{nd}$  grade due to defects. Approximately three percent of Nucor's steel is sold  $2^{nd}$  grade. Nucor produces approximately 5500 tons per day. This works out to a cost penalty of \$4.3 million dollars per year. Furthermore, if the steel is defective, then the company must stay out of certain markets. For example, peritectic steels are not cast.

Nucor also experiences problems in controlling the narrow face taper. Currently the linear screw system used to adjust the position of the narrow faces is also the measurement device for narrow face taper. See Appendix A-4 for a picture of Nucor's linear screw system. A geometric relationship between the position of the top and bottom of the narrow face defines the

taper of the narrow face. Preliminary evidence, to be presented later in the Data Collection section of this paper, shows evidence of this problem. Optimal narrow face taper is only half the solution; in order to effectively use the desired taper, the narrow face control system has to be accurate enough to implement it.

#### **PROJECT GOALS AND OBJECTIVES**

The major goal of this project is to recommend the proper taper designs to eliminate the problems in thin slab continuous casting. In order to accomplish this, a finite-difference code written to analyze traditional continuous casting, CON1D, must be calibrated and altered to account for thin slab conditions including the funnel present in the mould. In the process of doing so, the user-friendliness of the program will be evaluated and appropriate changes will be made. CON1D was originally written for traditional continuous casting, moulds that had flat, parallel wide faces. Thus, a procedure must be defined to use the outputs from CON1D and the relationship between the shape of the funnel and the extra perimeter in the wide face in order to make an educated prediction of the optimal narrow face taper. In addition to altering CON1D, it must be calibrated to simulate the casting conditions at Nucor's facility. Thus, data will be collected from plant measurements including heat flux data, temperature gradients, dimensions of the mould, specifications of the cooling water, etc. to be used as inputs for CON1D. To validate CON1D results, a different taper prediction model created by Rob Nunnington, a steel industry consultant, will be studied and used. Along with the numerical analysis, the effect of plastic strain on the taper will be investigated. The plastic strain imparted by the shape change of going from a funnel to a flat wall, see Figures 1 and 2 above, will also be considered in our analysis.

The second goal is to help improve the method in which the narrow face taper is controlled and measured. After the proper taper has been found, it must be implemented accurately to find whether or not the predictions are correct. The taper is currently controlled with a linear screw configuration for which the linear distance of travel per rotation has been calculated. This system, however, is believed to be inaccurate and Nucor is unsure if they are actually implementing the target taper. Nucor has tried to measure the taper with inclinometers, see Appendix A-5 for a picture of the Jewell Inclinometer previously used by Nucor, but their

efforts have proved unsuccessful. Thus, the goal is to gain an understanding of Nucor's procedures for setup and operation, and to find areas of improvement. If a new system could be devised to control and measure the taper, it could improve the quality of the final product.

In achieving these goals, two positive effects will result for Nucor. The first is that they will have an increased profit because they will be able to sell less of their steel at 2<sup>nd</sup> grade. The second effect is that it will enhance their manufacturing capabilities. As previously mentioned, Nucor only casts high and low carbon steels. They currently do not cast peritectic or stainless steels. If meeting these goals can improve their casting process, Nucor could move into those markets and grow as a company.

## DISCUSSION

### LITERATURE REVIEW

In order to understand the phenomena and current state of continuous casting, it was necessary to conduct a thorough literature search.

Thomas, Ho, and Li [1] discuss the theory and formulation of the CON1D program used in this analysis. They present the phenomena occurring in continuous casting and the equations and assumptions used in CON1D to analyze traditional continuous casting. Most importantly, the paper discusses how comparing outputs and computations with actual plant data validated the code. It provides proof that the CON1D program is an adequate tool for analyzing continuous casting.

Lait, Brimacombe, and Weinberg's [2] paper, which discusses the use of a onedimensional finite-difference model to analyze continuous casting, again demonstrates the usefulness and effectiveness of creating a numerical model to better understand a complex process. They examine in-depth the temperature profiles and pool profiles that develop in continuous casting.

In a paper by Won and Thomas [3], the method by which the program CON1D calculates steel properties as a function of composition is presented. Several equations and tables are included to explain the theory behind the model. Thus, in CON1D, the user inputs the chemical composition of the steel and CON1D calculates such quantities as the steel liquidus temperature and the steel density.

Park, Thomas, and Samarasekara [4] present a rigorous analysis of thin slab casting, for both parallel and funnel moulds, and present a thermal-elastic-plastic-creep finite-element model that is validated. They provide an analysis of funnel geometry that is rederived in the Theoretical Background section of this paper and utilized in this project. This funnel analysis was used to examine the effect of the funnel shape on several parameters in the mould. The paper also included several plots of variables such as thermal expansion and mould flux thickness that were used to check the numerical model, CON1D, used in this project. In addition, this paper offered a comprehensive literature review of work done to model traditional and thin slab continuous casting.

Park, Thomas, Samarasekera, and Yoon [5] and [6] wrote a two part paper on the thermal and mechanical behavior of copper moulds during thin slab casting. The first part discusses a three-dimensional finite-element thermal-stress model developed to predict the phenomena occurring in funnel and parallel moulds during casting. The second part discusses crack formation in the moulds. Several important ideas and concepts about thin slab continuous casting were gained from these papers.

The copper mould is also the subject of a paper by Thomas, Moitra, and Habing[7]. A three-dimensional finite-element thermal-stress model is presented to examine what factors effect the distortion of the mould. Another significant finding from the paper is what factors do not effect mould distortion. These are mould clamping forces, bolt pre-stress, friction, and ferrostatic pressure.

Several studies have suggested that non-linear taper would improve the overall heat transfer and solve some of the problems associated with taper. A report from the billet casting industry [8] says a parabolic taper can improve product quality by decreasing defects and increasing casting speed. Cristallini, et al [9] also presented the benefits of implementing non-linearity in mold design.

Stone and Thomas [10] conducted an investigation into measuring and modeling heat transfer across the mould flux layer. This paper discusses the previous work in this area and the uncertainty surrounding the value of the thermal conductivity of the flux layer. The study provides a justification for the alteration of this value for calibration purposes in CON1D.

## THEORETICAL BACKGROUND

## CON1D

A complex mix of heat transfer, mass transfer, and fluid mechanics are present in continuous casting and dictate how the steel solidifies. Figure 4, from reference 1, is a close up view of what is occurring at the steel-mould interface.



Figure 4: Schematic of interface between solidifying steel and mould.

In order to do a complete analysis of Nucor's casting process, the mechanics of how the steel is forming must be understood and be able to be modeled. Several pertinent equations must be solved for this analysis. The first is the transient heat conduction equation that governs the temperature in the thin solidifying shell. The equation is

$$\rho C_{p} \frac{\partial T}{\partial x} = k \frac{\partial^{2} T}{\partial x^{2}} + \frac{\partial k}{\partial T} \left( \frac{\partial T}{\partial x} \right)^{2}$$
(1)

$$\label{eq:rho} \begin{split} \rho &= Density\\ C_p &= Specific heat\\ k &= Thermal conductivity\\ t &= Time\\ T &= Temperature \end{split}$$

The two dimensional, steady state temperature within a rectangular vertical section of the mould is governed by the equation,

$$k_m \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) = 0 \tag{2}$$

 $k_m =$  Mould thermal conductivity

Also, mass and momentum balances must be performed on the material moving through the funnel.

During the casting process, Nucor measures the heat removal from each face independently by monitoring the change in temperature of the mould cooling water and using the equation,

$$\dot{q} = Q\rho C_{p} \Delta T \tag{3}$$

q = Heat removal in units of energy per timeQ = Cooling water flow rate $\rho = Density of water$ C<sub>p</sub> = Specific heat of water

This heat removal needs to be converted to a heat flux. The equation used is

$$q'' = \frac{q}{((Mould \_Length - Meniscus \_Depth)/1000) * (Mould \_Width/1000))}$$
(4)

q(dot)" = Heat flux q(dot) = Heat removal from Equation 3 Mould\_Length = Entire mould length, 1100 mm in mould analyzed in this study Meniscus\_Depth = Instantaneous meniscus depth as recorded by Nucor (mm) Mould\_Width = Instantaneous mould width as recorded by Nucor (mm)

#### Narrow Face Taper

As previously stated in the Background section of this paper, taper in Nucor's funnel mould is defined as the change in position of the narrow face from the top to the bottom of the mould. Narrow face taper can be represented in three ways. The first is by percent taper per meter (%taper/m), the second is by percent taper per mould (%taper/mould), and the third is by a distance value in millimeters. The first two representations of taper can be used to acquire the third, which is the most useful during the casting operation. There is a difference however between %taper/m and %taper/mould in terms of calculating taper in millimeters. The %taper/m can be used to find the change in narrow face position anywhere along the narrow face. Whereas the %taper/mould only gives the absolute change in narrow face position between the top and the bottom of the mould. At Nucor, %taper/mould is the common value used to calculate taper.

$$NFT(mm) = (\% taper / m) * (Position \_Below \_Meniscus) * (Bottom \_Width)$$
(5)  
$$NFT(mm) = (\% taper / mould) * (Bottom \_Width)$$
(6)

NFT = narrow face taper

%taper/m = the percent taper per meter based on the grade of steel that is cast Position\_Below\_Menisucs = vertical distance from the meniscus (mm) Bottom\_Width = Exit mould width (in meters for Equation 5 and millimeters in Equation 6)

The numerical model, CON1D which is used in this study, calculates a suggested linear narrow face taper with the following equation,

$$TP(\%/m) = \frac{TLE(T_{sol}) - TLE(T_{s,(mould\_exit)})}{Z_m}$$
(7)

 $T_{sol}$  = Solidus temperature of the steel,

 $Z_m = Mould length$ 

TLE = Thermal linear function of the steel grade that is calculated from weighted averages of the phases present

 $T_{s,(mould\_exit)}$  = Surface temperature of the steel at mould exit

For this study, it was important to understand how Nucor is currently calculating taper. The target narrow face taper is currently determined at Nucor by the chart seen in Appendix A-6. This chart was constructed by the following equation for a given %taper/mould based on the grade of steel and the desired bottom width of the mould.

$$TNFT = \left[ (Bottom_Width * \% Taper / mould) - Funnel_Taper \right] / 2$$
(8)

TNFT = Target Narrow Face Taper on one narrow face (mm)
Bottom Width = Desired width of slab exiting the mould
% Taper/mould = Values depends on Nucor's grade of steel cast
Funnel Taper = The extra length at the meniscus level in the mould
= Taper induced in funnel mould, due to the change in perimeter of the wide face, because of the funnel shape

The narrow face taper can also be determined for a desired top width of the mould.

$$TNFT = \left\{ \left[ \frac{(Top\_Width + Funnel\_Taper) * \% Taper / mould}{1 + \% Taper / mould} \right] - Funnel\_Taper \right\} / 2 \quad (9)$$

Top\_Width = Desired top width of mould

A chart that shows how the narrow face taper varies as a function of top width and %taper/mould is shown in Appendix A-7.

The extra length at the meniscus level in the mould, which is described as the funnel taper in Equations 8 and 9 above, is determined by the following equation derived in Reference 4 by Joong Kil Park. See Appendix A-8 for the rederivation.

$$EL = 2*\left\{ \left[ \frac{a^2 + b^2}{2b} \sin^{-1} \left( \frac{2ab}{a^2 + b^2} \right) \right] - a \right\}$$
(10)

EL = Extra length (mm)

a = Half width of funnel

b = Funnel depth at a given distance from the top of the mould

The extra length calculation provides the additional perimeter length for one wide face relative to the mould bottom, due to the shape of the funnel, at a given distance from the top of the mould, see Figure 5 below. The funnel depth, b, is computed with the following equation.

$$b = (D - Y) * \tan \theta \tag{11}$$

$$\tan\theta = b_o / D \tag{12}$$

b = Funnel depth at a given distance from the top of the mould

D = Total height of funnel

Y = Distance from the top of the mould

 $\theta$  = Angle between the center of the funnel on the wide face and the vertical centerline of the mould

 $b_o =$  Funnel depth at the top of the mould



Figure 5: Diagrams related to equations for extra length and funnel depth. The left picture is a top view of one wide face in the mould. The right picture is a cut section through the center of the wide face.

## **DATA COLLECTION**

The following section is a detailed discussion of what data was collected from Nucor and what significance it has.

Nucor uses two sizes of thin slab moulds. The first has a funnel width of 1020 mm and the second has a funnel width of 880 mm. The 1020 mm funnel mould is the most commonly used mould at the plant. This mould can cast steel slabs with a width as small as 980 mm. If the

customer wants a smaller width, the 880 mm funnel mould is used. The funnel is necessary to allow the submerged entry nozzle (SEN) to enter the mould. The SEN is responsible for pouring the molten steel into the mould, which extends down 175 mm from the top of the mould.

Uniform heat removal is an important aspect of the continuous casting mould. In Nucor's funnel moulds, the inlet cooling water temperature is kept at a constant 100 °F. The 1020 mm funnel mould has water channels running the length of the wide and narrow faces in which the cooling water flows through to remove heat from the steel. The 880 mm funnel mould has rifle drilled holes through the length of the wide and narrow faces for the cooling water to flow through. The cooling water flow rate on the wide face is 1200 gal/min while on the narrow face it is 30 gal/min.

The sequence data from several casting runs was obtained from Nucor. The spreadsheets obtained are attached electronically to this report, but a sample of the sequence data in graphically from can be found in Appendix A-9. The sequence data contains all the parameters that Nucor measures and records during casting. Also included in the sequence data are several calculations Nucor performs for monitoring purposes. One such calculation is finding the heat removal by Equation 3.

Currently, Nucor is implementing a linear screw system, see Appendix A-4 for a photograph, to control the position of the narrow faces and the amount of taper. In the past, Nucor has attempted to use inclinometers attached to the narrow faces to measure and control the taper, but the inclinometers failed to produce accurate and consistent measurements. Nucor's mould oscillates at a frequency between 4 to 6 Hz during the casting operation. The oscillations were detrimental to the inclinometer readings and thus it was never clear exactly at what value the narrow face taper had been set.

The narrow face positions as well as the narrow face taper are continuously recorded by computer during the continuous casting operation. At the end of a casting run the casting operators measure the narrow face taper using a hand inclinometer, see Appendix A-10 for a picture of the hand inclinometer, and this measurement is compared to the final narrow face taper displayed on the computer screen. These two final narrow face taper values are then compared to the target taper initially set. Approximately fifty samples of this data were collected from Nucor and one sample, as an example, is displayed below in Table 1.

DATE OF CASTING OPERATION	GRADE OF STEEL CAST	FINAL DISPLA THE COI PUL (m	TAPER VED IN MPUTER -PIT m)	TAPER MEASUREMENT AT THE END OF THE RUN (mm)		NUC TARGEI FROM C TAI EQUA	OR'S D TAPER URRENT PER ATION m)
2/21/2002	1026M2	E	W	E	W	E	W
3/21/2002	10261012	0.78	0.78	0.50	0.20	1.92	1.92

Table 1: A comparison of two narrow face taper measurements to the initially set target taper

A statistical analysis was preformed on the narrow face taper collected to determine a relationship between the taper displayed on the computer, the taper measured by hand, and the target taper. An excerpt from the statistical analysis can be seen below in Table 2. See Appendix A-11 for the complete record of all fifty samples. This data provides preliminary evidence to support Nucor's hypothesis that the defects in their final product are attributed to excessive taper in the narrow face because the majority of the time the final displayed taper and final measured taper are less than the target taper.

	DIFFEF BETWEE TAPER DI ON COM AND NU TARGET (m E	RENCE EN FINAL SPLAYED MPUTER JCOR'S TAPER m) W	DIFFEI BETWEE MEASURE END OF AND NI TARGET (m E	RENCE N TAPER ED AT THE THE RUN JCOR'S TAPER m) W
Number of times difference > 0	6	9	17	8
Number of times difference < 0	35	39	33	42

Table 2: This table accounts for all high and low carbon data collected. When the difference is >0 this shows that the final taper displayed or measured was greater than the target taper. When the difference is <0 this shows that the final displayed or measured was less than the target taper.

Narrow face wear data also collected at Nucor is shown in Tables 3 and 4 below. This data shows that during the casting operation the copper in the narrow faces is indeed being worn away.

		Worn Nar	row Faces		
	Unworn	Worn #1	Worn #2	Worn #3	Worn #4
Distance					
From Top			Width (in)		
(in)					
0	2.375	2.260	2.260	2.199	2.279
5	2.359	2.267	2.257	2.196	2.283
10	2.358	2.260	2.259	2.196	2.282
15	2.357	2.255	2.255	2.192	2.277
20	2.357	2.257	2.253	2.190	2.278
25	2.357	2.252	2.247	2.189	2.276
30	2.357	2.248	2.241	2.190	2.269
35	2.359	2.246	2.235	2.187	2.265
40	2.359	2.236	2.221	2.185	2.252

Cu Side of Narrow Face



Width

Distance From Top of Narrow Face



Distance from Side (in)	0	0.06	0.13	0.25	0.5	0.75	1	1.25	1.5	1.75	1.88	1.94
Width of Narrow Face (in)	2.15	2.15	2.17	2.18	2.18	2.18	2.18	2.18	2.18	2.17	2.15	2.14
			Width									
Distance From Side												



### CON1D

A previously created Fortran program called CON1D solves Equations 1, 2, and many others related to continuous casting. CON1D utilizes a 1-D transient finite-difference calculation of heat conduction within the solidifying steel shell coupled with 2-D steady-state heat conduction within the mold wall. CON1D also handles heat transfer across the interfaces of the copper, mould flux and solidifying steel, while simultaneously performing mass and momentum balances on the flux layers. It also takes into account radiation phenomena. For more information regarding the formulation and theory employed in CON1D, refer to the user manual for CON1D or to Reference 1. This code has been employed in the Continuous Casting Consortium for the past several years, and has been proved an accurate tool for analyzing continuous casting.

CON1D outputs various types of information that are critical for a continuous casting analysis. An analysis can be performed on the wide face or narrow face of the mould. All input and output data pertain to the domain of that face. The program computes several quantities related to this project, such as the variation of heat flux, shell surface temperature, shell thickness, and shell shrinkage as a function of distance below the meniscus. These plots are illustrated in Figures 6, 7, 8, and 9 respectively.



Figure 6: Computed heat flux as a function of distance below meniscus for a high carbon (0.83% C) steel.



Figure 7: Shell surface temperature as a function of distance below meniscus for a high carbon (0.83% C) steel.



Figure 8: Shell thickness as a function of distance below meniscus for a high carbon (0.83% C) steel.



Figure 9: Steel shell shrinkage as a function of distance below meniscus for a high carbon (0.83% C) steel.

The focus of this project is narrow face taper and CON1D calculates an ideal mould taper, on a percent per meter basis, based on Equation 7. Plots of the instantaneous and cumulative tapers are plotted in Figures 10 and 11.



Figure 10: Instantaneous taper as a function of distance below the meniscus for a low carbon (0.04% C) steel.



Figure 11: Cumulative taper as a function of distance below the meniscus for a low carbon (0.04% C) steel.

In order to properly utilize CON1D to examine Nucor's process and taper calculations, the program must be calibrated to the process being examined. This was done by inputting certain process parameters, running the program, and comparing certain outputs to known, recorded quantities from the actual process. The input parameters were put into an input file, which is shown in Appendix A-12. After the program ran, the compared quantities were the temperature change of the water in the cooling channels and the mean heat flux in the mould for the face modeled. These values are output in an exit file, as shown in Appendix A-13. The computed values must match the recorded values within three percent for an accurate calibration. If after the first run, the values do not match, specific parameters can be changed. These include the mould flux conductivity, the air gap present along the copper-flux interface, and the velocity ratio of the flux powder to the steel strand. After the computed and recorded values match, the output files can be used for further analysis and parametric studies. Table 5 below provides a listing of all the simulations and highlights the comparison made between the heat flux and temperature change outputs from CON1D to the actual data retrieved from Nucor.

FILE NAME	RECORDED ∆T (°C)	RECORDED HEAT FLUX (W/m <sup>2</sup> )	COMPUTED ∆T (°C)	COMPUTED HEAT FLUX (W/m <sup>2</sup> )
hic 1	7.83	2310	7.83	2193.3
hic 4	7.88	2237	7.85	2185
hic 5	7.88	2242	7.88	2197
loc 1	11.66	2732.48	11.64	2780
loc 3	8.33	2310	7.93	2170
loc 4	6.67	2059.7	6.6	2017
peri	7.22	2177	7.24	2142

Table 5: Listing of recorded parameters and computed parameters for calibration purposes

Attached in Appendix A-14 is a listing of every input parameter with an explanation on where it came from or a justification for the value input and other relevant information. Also included in this appendix are any steps taken to account for the fact that Nucor is running a thin slab caster with a funnel mould. A large amount of the Nucor specific parameters came from sequence data provided by Nucor Steel. Data from a high carbon steel run, two different low carbon steel runs, and a run of a steel that was almost peritectic were provided. Simulations were performed on all four grades at different mould widths and casting speeds. Table 6 is a listing of the file names and pertinent source data details.

FILE NAME	DESCRIPTION	%С	SEQUENCE DATA FILE NAME	TIME OF DATA POINT
hic1	High carbon steel	0.83	Sequence of 1085S1, 1-17-02, C2	12:43
hic2	Used for speed study	0.83	Sequence of 1085S1, 1-17-02, C2	12:43
hic3	Used for mold thickness test	0.83	Sequence of 1085S1, 1-17-02, C2	12:43
hic4	High carbon at mould width of 1025	0.83	Sequence of 1085S1, 1-17-02, C2	11:38
hic5	High carbon at mould width of 1033	0.83	Sequence of 1085S1, 1-17-02, C2	11:11
hicn	Narrow face simulation of high carbon	0.83	Sequence of 1085S1, 1-17-02, C2	12:43
loc1	Low carbon steel	0.04	Sequence of 1005P1, 1-17-02 and 1008A2, 1-30-02, C2	1:36
loc3	Low carbon steel at mould width of 1103.9 mm	0.055	Sequence of 1005P1, 1-17-02 and 1008A2, 1-30-02, C2	7:37
loc4	Low carbon steel at mould width of 1020.2 mm	0.055	Sequence of 1005P1, 1-17-02 and 1008A2, 1-30-02, C2	11:03
peri	Approximately peritectic steel	0.074	Casting data on 220126 on 4-22-02, C1	5:45

Table 6: Listing of simulation file names with explanation of source of data

After the calibration was complete, it was necessary to validate that the simulation was adequately modeling in the plant. Thus, simulations were performed keeping the calibrated

variables constant, but looking at different data points where the width and casting speed were different. Again, the computed values matched the recorded values. This gave merit to the outputs calculated by CON1D.

Previously made calculations for wide face thermal expansion and flux layer thickness found in Park, Thomas, and Samarasekara's paper [4] were matched to further validate the analysis performed in CON1D. Also, the negative strip time seen on the exit output files correlates to the maximum oscillation mark depth shown in Appendix A-15.

Another tool used in the numerical analysis was an analytical model developed by a steel industry consultant, Rob Nunnington. Mr. Nunnington's model is a Microsoft Excel spreadsheet based formulation based upon analytical equations to predict a suggested linear taper. The equations are too extensive to be included, but the model is included in the electronic attachment to this report. After a thorough understanding of the model was established, the required inputs were entered for the steels simulated with CON1D. The necessary inputs were; steel temperature at mould exit, steel composition, casting speed, and mould length and width. The phase diagram for each steel was also required, but not available. Phase diagrams provided with the model for steels with similar compositions were used.

The comparison's of suggested linear tapers appears in Table 7. The effect of casting speed on the exit temperature and resulting taper calculations was examined for the 0.083% steel and the results are also shown in Table 7.

			Suggested Ta		
CARBON CONTENT (%C)	MOULD WIDTH (mm)	CASTING SPEED (m/min)	TAPER (%/mould) DIPPENAR	TAPER (%/mould) OLD METHOD	SUGGESTED TAPER FROM NUNNINGTON MODEL (%/mould)
0.83	1021.3	3.2	0.87	0.75	0.95
0.83	1021.3	3.73	0.83	0.71	0.88
0.83	1021.3	4	0.8	0.69	0.84
0.83	1021.3	4.5	0.74	0.63	0.79
0.83	1021.3	5	0.69	0.59	0.74
0.83	1021.3	5.5	0.66	0.55	0.7
0.83	1021.3	6	0.61	0.52	0.67
0.04	1555.2	4.5	1.83	1.5	1.47
0.055	1103.9	4.7	1.42	1.03	1.06
0.055	1020.2	4.5	1.35	1	1.03

Table 7: Comparison of CON1D taper outputs to taper outputs from Rob Nunnington's model

From Table 7, it can be seen that the predictions from the Nunnington model roughly match the CON1D predictions. This adds weight to the validation of the CON1D calibration.

Currently CON1D does not take into account the extra length imparted to the perimeter by the funnel into its taper calculation. The extra length can be accounted for in heat transfer by adding the extra length to the mould width value inputted. An ideal taper calculation equation, the details of which will be explained later, was implemented into CON1D. The first attempt failed because the outputs did not differ from the outputs without funnel taper considered. The code was rewritten and is included in Appendix A-16.

#### NARROW FACE TAPER CONTROL AND MEASUREMENT

Currently, the narrow face taper of Nucor's funnel moulds are controlled by a linear screw system, or ram drive system. A simple schematic of this narrow face taper control system is shown below Figure 12 and a picture taken at Nucor of the linear screw system is in Appendix A-4. The linear screw system controls and measures taper by keeping track of the position of the top and bottom of the narrow face. The linear screws are driven by independent electric motors, which are controlled by the operator in the computer pulpit. The linear position of the top and bottom of each narrow face can be adjusted at 48.26 mm/min (1.9 in/min) during set-up and at 12.7 mm/min (0.5 in/min) during the casting run. When the desired position of the narrow face is achieved, a clamping mechanism holds each ram drive firmly such that the gears are unable to rotate. If a bottom width change or narrow face taper change is made during the casting operation, the ram drives are unclamped, the position of the narrow faces are adjusted, and then the ram drives are reclamped to hold the position change.



Figure 12: Simple schematic of the linear screw system

After interviewing several of the operators at Nucor a generic set-up and operational procedure was found with regard to how they use the linear screw system to measure and control the narrow face taper. The details of this procedure are described in Appendix A-17. There are actually four different crews that work on the continuous casters in shifts during the day and night. Each of the crews follow the same general set-up and operational procedure described in Appendix A-17 with small differences in terms of the initial narrow face taper set-up and the changes made in narrow face taper during the casting operation. The important point to note about their procedure is that they are aware that "slop" exists in the gearboxes and the operators try to take out as much of the "slop" as possible, if not all of it. The set-up and operational procedure is sound, especially if the operators make sure that the last narrow face movement during the set-up is inward, toward the center of the mould, and that the initial top width and narrow face taper on each side is carefully measured to accurately calibrate the computer. If the mould is correctly set-up and during the casting operation the narrow faces are always moved inward, then the "slop" in the screw system will not be an issue in terms of accurately controlling the narrow face taper.

However, the wide face thermal expansion is a probable source of error in the narrow face taper accuracy. During the casting operation, the wide faces exert a pressure of 800 psi on the narrow faces. Nucor has found that this pressure adequately holds the mould faces together and allows the narrow face position to be changed without scraping off copper from the wide

face of the mould. This pressure converts to a force of  $\sim$ 340 kN along the length of the narrow face. The wide face expands the most just below the meniscus where the copper reaches the highest temperature  $\sim$ 400-500 °C. With a linear thermal expansion coefficient of 16\*10^-5 °C<sup>-1</sup>, Appendix A-18 shows the source of this coefficient, the linear thermal expansion of the wide face is  $\sim$ 3-4mm overall. Assuming a coefficient of friction of 0.3, the friction force between the wide and narrow face is  $\sim$ 100kN. Thus it is possible that the top of the narrow face is shifted when the top of the wide face thermally expands, but the major concern is that the computer which controls the position and taper of the narrow face is not aware of this movement. The computer is unaware of the change in the narrow face position because the computer only uses the number of screw rotations to determine the position of the narrow face, not the global position of the narrow face based on a grounded reference point. So, the actual narrow face taper is greater than the taper initially set and displayed on the computer screen.

Another possibility is that the wide face is able to slide pass the narrow face when it expands. So, at the end of the casting run when the wide face cools it "grabs" the narrow face, and if there is any "slop" in the screw system, pulls the top of the narrow face inward. Thus, the narrow face taper measured at the end of the casting run using the hand inclinometer will not be an accurate account of the final taper, and a comparison between the final taper displayed on the screen and the final taper measured would show the final taper displayed to be higher than the final taper measured. However, from the statistical analysis on the narrow face taper data collected to determine a relationship between the taper displayed on the computer, the taper measured by hand, and the target taper seen in Appendix A-11, the final taper displayed on the computer screen was overall lower than the taper measured as shown below in Table 8.

	Difference Between Final Taper Displayed on Computer Screen and Taper Measured at the end of the run (mm) E W			
Number of times Final Taper Displayed > Taper Measured	22	18		
Number of times Final Taper Displayed < Taper Measured	33	37		

 Table 8: Comparison of Final Taper Displayed on Computer Screen and Taper Measured

 at the end of the run for all high and low carbon data samples collected

Five years ago, Nucor started to use the linear screw system already in place to control the position of their narrow face taper to measure the taper of the narrow face as well. Nucor had attempted to use inclinometers to measure the narrow face taper, however the inclinometers proved to be inaccurate. The inclinometer that Nucor chose to implement was from Jewell Instruments. This particular inclinometer has a very good resolution of 0.0011mm. However, during the casting operation the entire mould is oscillating between 4 to 6 Hz. These oscillations caused fluctuations in the readings from the inclinometer which was originally designed for traditional continuous casting process where the frequency is generally 1 Hz, see Appendix A-19 for a schematic of the Jewell inclinometer and specifications.

The Jewell inclinometer measures taper based on the position of a floating buoy, connected to a potentiometer, which sits on top of a pool of oil. A change in the orientation of the inclinometer is determined by the resistance of the potentiometer based on the position of the buoy due to the movement of the oil. Thus, the output voltage signal from the inclinometer determines the taper of the narrow face, see Figure 13. However, due to the oscillations of the mould, the output voltage varies and thus it is uncertain what the exact narrow face taper is, see Figure 14.



Figure 13: A change in orientation of the Jewell Instruments Inclinometer affects the output voltage and determines the taper of the narrow face.



Figure 14: Oscillations cause a continuously varying output voltage, thus making the actual taper difficult to determine.

Other inclinometers from U.S. Digital, MicroStrain and Sidersistem, (see Appendix A-20 for the schematics and specifications of these inclinometers), have been researched in an attempt to find a device that can accurately measure taper. U.S.Digital and Microstrain make general purpose digital inclinometers that are used for: vehicles, platforms, heavy equipment, manufacturing, etc. Sidersistem makes electronic inclinometers specifically for continuous casting. Although these may or may not be able to withstand the oscillations, they do not possess the desired resolution necessary to determine taper. The best, Sidersistem, had a resolution of 0.1 mm. The smallest taper change made during operation, and thus the desired resolution, is 0.05mm. Therefore, the current technology is not adequate to measure the narrow face taper.

### **IDEAL NARROW FACE TAPER**

In order to alter CON1D to predict the ideal taper for a given grade of steel and a given exit slab width, a procedure for determining the ideal taper based on outputs from CON1D had to be formed. The main contributions to the ideal narrow face taper come from the shell shrinkage, the thermal expansion of the wide face, the flux layer thickness, and the extra length in the funnel. The first three are calculated by CON1D while the extra length is calculated by Equation 10. It was found the ideal narrow face taper is calculated by subtracting from the shell shrinkage, the change in extra length, the change in wide face thermal expansion, and the change in total flux layer thickness.

$$Ideal\_Taper(mm) = SS - (EL_0 - EL) - (TE_0 - TE) - (TFL - TFL_0)$$
(13)

SS = Steel Shell Shrinkage

EL = Extra Length at a given distance from the top of the mould

 $EL_0$  = The extra length at the distance from the top of the mould where the shell shrinkage begins

TE = Thermal Expansion of the wide face of the mould

 $TE_0$  = The thermal expansion of the wide face of the mould where the shell shrinkage begins

TFL = Total Flux Layer thickness

 $TFL_0$  = The total flux layer thickness where the shell shrinkage begins

The code for this procedure to be implemented into CON1D can be found in Appendix A-16.

Four steels were analyzed in order to determine the ideal narrow face taper: a common high carbon, a common low carbon, a difficult low carbon to cast, and an approximately peritectic steel. Appendix A-21 contains a sample of the spread sheets that show the analysis for each of these steels. Each graph has a plot of the shell shrinkage, extra length from the funnel, wide face linear thermal expansion, and the total flux layer thickness for a given distance below the meniscus. Also shown on each graph are the narrow face target narrow face taper used by Nucor and calculated by Equation 8, and the ideal narrow face taper as predicted by Equation 13.

CON1D does not take into account the effects of plasticity. One of the project goals was to determine whether plastic strain in the form of creep plays a role during the solidification process. In order to determine the importance of plasticity in high and low carbon steels, CON2D, another FORTRAN program developed at the University of Illinois by Professor Brian Thomas, was implemented. Claudio Ojeda, a graduate student of Professor Thomas, ran the CON2D program for all four of the steels analyzed. CON2D utilizes some of the same input parameters from CON1D including the casting speed, pour temperature, and the working mould length, and it also utilizes the resulting wide face heat flux profile from each CON1D analysis. See Appendix A-22 for a sample of the input files used in CON2D in order to run each analysis. The resulting shell shrinkage calculation from CON2D for the common high carbon, the common low carbon, the difficult to cast low carbon, and the approximate peritectic steel provided the necessary insight to determine that plastic strain is a significant effect for low carbon steels and a negligible effect for high carbon steels.

It was necessary to validate what CON2D had calculated. This was done by comparing certain strains calculated by CON2D to the total strain calculated by CON1D. The flow strain and thermal strain added together should equal the strain calculated by CON1D with Equation 7. If they match, this adds validation to the CON2D simulation. A sample of the CON2D outputs can be seen in Appendix A-23. This was done and for the low carbon steel, the final strain from CON2D was -0.006 and CON1D calculated a value of -0.0068. For the high carbon steel, CON2D gave a value of -0.013 and CON1D computed a value of -0.0132. These both helped to validate the CON2D simulation.

The first type of steel analyzed was Nucor's 1085S1, a common high carbon steel cast by Nucor, see Figure 15 below. As shown in this graph the ideal narrow face taper is significantly less than the taper presently used by Nucor. This result correlates with the preliminary evidence found in Table 2, which shows that during the casting operation the narrow face taper has to be reduced in order to produce steel slabs with little or no defects. However, the graph shows that the ideal narrow face taper is negative. This is not an uncommon phenomenon, but rare for high carbon steels with a final product width of 1020mm according to Nucor's experience. The problem lies in the shell shrinkage. For this case, the extra length in the funnel greatly affects the narrow face taper. Thus, the narrow face taper actually has to be negative because the extra length in the funnel is too high compared to the shell shrinkage. In other words, the funnel is accounting for more shrinkage in the steel then is necessary. Thus, to make up for the difference in shrinkage, the analysis shows that the narrow face should have a negative taper.



Figure 15: Ideal Narrow Face Taper Prediction for a common high carbon steel cast by Nucor with CON1D calculated shell shrinkage

The second type of steel analyzed was Nucor's 1008A2, a common low carbon steel cast by Nucor, see Figure 16 below. In Figure 16, the shell shrinkage is calculated from the CON1D analysis and the ideal narrow face taper predicted for this steel is almost exactly what is currently used by Nucor. The low carbon steels tend to have higher amounts of shell shrinkage. As compared to the high carbon steel, the difference between the shell shrinkage and the extra length in the funnel allows the ideal narrow face taper to have a positive value. However, this analysis contradicts the preliminary evidence. For high and low carbon steels, according to the data in Table 2, Nucor is consistently using excessive narrow face taper. However, the results for this 1008A2 steel show that the narrow face taper used by Nucor is correct.



**Position Below Meniscus (mm)** 

Figure 16: Ideal Narrow Face Taper Prediction for a common low carbon steel cast by Nucor with CON1D calculated shell shrinkage

The reason for this discrepancy is the fact that plasticity is not taken into account in this common low carbon steel analysis. In Figure 17, the shell shrinkage for this steel was calculated using CON2D. The thermal expansion and flux layer thickness data from the CON1D analysis were kept the same. In comparing the Figures 16 and 17, there is a noticeable change in the shell shrinkage which correlates to the ensuing change in the ideal narrow face taper prediction in Figure 17. This ideal narrow face taper prediction does agree with the trend present in Table 2 and is further evidence that Nucor is implementing excessive taper in both high and low carbon steels.



**Position Below Meniscus (mm)** 

Figure 17: Ideal Narrow Face Taper Prediction for a common low carbon steel cast by Nucor with CON2D calculated shell shrinkage

The third type of steel analyzed was Nucor's 1005P1. This is one of the more difficult steels to cast based on its chemical makeup and phase diagram, see Appendix A-24 for the chemical makeup and phase diagram for this particular steel. The graph of the analysis according to CON1D for this steel is shown in Figure 18. Nucor has gone through thousands of tons of steel to find a narrow face taper (0.85%taper/mould) for this type of steel that allows them to cast 1005P1 with a small amount of defects. The analysis shows that Nucor's taper for 1005P1 is too low and that it should be increased based on the amount of steel shrinkage calculated by CON1D. Similar to the CON1D analysis of the common low carbon steel, this contradicts the data found in Table 2. Nucor feels that this analysis does not accurately predict the correct steel shrinkage profile based on their results from trial and error experiments.



Figure 18: Ideal Narrow Face Taper Prediction for a difficult to cast low carbon steel with CON1D calculated shell shrinkage

Figure 19 presents the ideal narrow face prediction for this difficult to cast low carbon steel based on the shell shrinkage calculation from CON2D. Again, as shown previously for the case of the common low carbon steel, the effects of plasticity make an important contribution to the prediction of the ideal narrow face taper based on the difference in shell shrinkage between Figures 18 and 19. Thus, the results from this analysis provide further evidence that Nucor's current taper implementations are excessive.



Position Below the Meniscus (mm)



The fourth type of steel analyzed was an almost peritectic steel with a carbon content of 0.07%. As in the previous case with Nucor's 1005P1, peritectic steels are difficult to cast and Nucor has had trouble perfecting the narrow face taper so that peritectic steel slabs are produced without defects. The ideal narrow face taper analysis in Figure 20, pertaining to the shell shrinkage calculated by CON1D, shows that the ideal narrow face taper should be increased to match the desired shell shrinkage. However, this also conflicts with the data in Table 2 and thus again this insinuates doubt in the accuracy of the shell shrinkage calculated by CON1D.



**Position Below Meniscus (mm)** 

Figure 20: Ideal Narrow Face Taper Prediction for an almost peritectic steel cast by Nucor with CON1D calculated shell shrinkage

Figure 21 shows the ideal narrow face taper prediction for this almost peritectic steel based on the shell shrinkage calculated from CON2D and the thermal expansion and flux layer thickness calculated from CON1D. As seen before in the previous low carbon analysis, the shell shrinkage decreases in Figure 21 as compared to Figure 20 and thus the ideal narrow face taper prediction is less than the current narrow face taper implemented by Nucor. This final analysis further strengthens the argument that Nucor's current narrow face taper is excessive for both high and low carbon steels.



Figure 21: Ideal Narrow Face Taper Prediction for an almost peritectic steel cast by Nucor with CON2D calculated shell shrinkage

## CONCLUSION

#### ALTERNATIVE DESIGNS NOT PURSUED

During the course of the project several possible courses of action presented themselves, but were not pursued. An original goal of the project was to possibly redesign the taper control system. There was a problem with the control system, the "slop" present, but adequate procedures existed to deal with it. The problem was that the procedures were not implemented consistently. Since the current system is capable of being adequate, a redesign was not pursued.

When the problem with inclinometer technology was identified, the idea of redesigning the technology came up. It quickly became apparent that a redesign would be a complete project in of itself and it was not pursued.

At the outset of the project, it was thought that simply running CON1D and using the suggested linear taper a solution would be enough. Yet, after effects such as wide face thermal linear expansion and plastic strain were considered, it was deemed that the CON1D prediction alone would not be enough because the CON1D software did not take these effects into consideration in its taper calculation.

Another possible solution at the outset was to use the non-linear steel shell shrinkage profile as a recommended taper. As indicated in references 8 and 9, implementation of nonlinear tapers had resulted in improved steel quality and the ability to cast at higher speeds. The steel shell shrinkage profiles were not used because they did not take into account all the factors included in the derived ideal taper equation; namely the extra length imparted by the funnel, the thickness of the mould flux layer, and the thermal linear expansion of the wide face.

#### ACCOMPLISHMENTS AND CONCLUSIONS

Several of the goals of this project were not related to improving taper directly, rather they were a series of tasks to accomplish. The first was to calibrate CON1D to Nucor's casting process. The second was to alter CON1D to account for the funnel mould and predict ideal taper based upon current CON1D outputs for thin slab casting. The third was to calibrate and gain an understanding of Rob Nunnington's taper prediction model. In the process of completing these tasks, the user-friendliness of the CON1D was evaluated and small improvements were made. In order to calibrate CON1D, the necessary data was obtained from Nucor; this included recorded sequence data, mould geometry, and other casting conditions. CON1D was successfully calibrated and validated by several methods previously discussed, thus concluding the first step in ideal taper prediction. The next step was to alter the CON1D code to account for the funnel geometry and other effects for predicting taper from computed CON1D outputs such as flux layer thickness and steel shell shrinkage. The funnel geometry was derived, as seen in Equations 10, 11, and 12, along with a new equation to calculate taper, Equation 13. This code has been written, as seen in Appendix A-16, but not yet implemented into the program.

An analytical taper prediction model was obtained from a steel industry consultant, Rob Nunnington. The purpose of using this model was to validate and compare the current taper prediction of CON1D. A thorough study was conducted of the model and an understanding was gained of how it worked. The tapers suggested by the analytical model matched those output by CON1D.

While working with CON1D, it was desired that the user-friendliness of the program be evaluated. Several minor problems were found and corrected. The current method for calculating the necessary time step was unclear in regards to the necessary hand calculations and the fact that hand calculations had to be done. The code was changed to automatically calculate the time step. In the input file template, explanations of individual input were missing and default labels were inconsistent. These problems were identified and corrected during the course of the project.

The main goal of this project was to formulate a method in which ideal narrow face taper can be computed for a given steel composition and desired product width. By deriving an equation based upon computed quantities from the CON1D program and the rederived funnel geometry equation, this goal was accomplished and resulted in producing Figures 15 - 21.

In the course of accomplishing these tasks, several important conclusions were reached relating to the goals of this project. From the analysis of the high carbon steel using CON1D and the formulated ideal taper equation, Nucor's original hypothesis of excessive taper has been strengthened because the computed ideal taper is less than what Nucor currently uses. From the analysis of the three different low carbon steels the same result was obtained. Nucor is also implementing excessive taper in casting low carbon steels. However the analysis of the low carbon steels required the additional effects of plastic strain in the ideal taper equation. The

motivation for this project goal came from the heat caster data which presented evidence that excessive taper existed for high and low carbon steel because approximately 80% of the time, the final taper measured at the end of the casting operation was less then Nucor's target taper for the final steel slab produced in that casting sequence as seen Appendix A-11.

A problem of "slop" was identified as a possible problem in the linear screws of the transmission system that controls the position of the narrow faces in the mould. The current acceptable value for the "slop" is 0.6mm, which is significant considering that the range of implemented tapers is typically between 1 to 3 mm. Nucor also uses this system for taper measurement and evidence collected suggests that the "slop" is also the reason for taper measurement disparities. In the past, Nucor had tried to employ inclinometer technology for taper measurement, but the inclinometers took inaccurate and inconsistent measurements. Research into the inclinometer system suggests that the inclinometer was not designed to handle the mould oscillations present in Nucor's process. Other inclinometers from different companies were researched, but they did not have adequate resolution to detect Nucor's small taper changes.

#### RECOMMENDATIONS

The analysis performed gives Nucor confidence to decrease their narrow face taper. The procedure used in this study can provide recommended values for what the taper should be decreased to. The following step by step procedure to obtain an ideal narrow face taper was constructed during this project.

- 1. Obtain necessary sequence data.
- 2. Input data into CON1D and calibrate.
- 3. Use inputs and CON1D outputs to run CON2D. Determine if plasticity is significant.
- 4. If plasticity is not significant, input the steel shell shrinkage from CON1D into the electronically attached Microsoft Excel ideal narrow face taper spreadsheet used to solve Equation 13. If plasticity is significant, use the steel shell shrinkage from CON2D.
- 5. Enter the necessary funnel mould geometry and meniscus height into the ideal taper spreadsheet to calculate the extra length.
- Input the mould hot face temperature distribution and mould flux layer thickness from CON1D into the ideal taper spreadsheet.

- 7. Obtain the ideal narrow face taper from Equation 13.
- 8. To convert the ideal taper value from mm to %taper/mould, plug in the value obtained from Equation 13 for the TNFT value and the initial extra length value (the extra length at the meniscus) found from step 6 into Equation 8.

In regards to the numerical simulations, the fact that plasticity is present means analysis with CON1D is not enough. Steps must be taken to develop a numerical model that takes into account all of the strains present during casting. A suggestion is a full three-dimensional finite element analysis in order to construct a complete model of the funnel mould.

Another problem contributing to the disparity between the ideal taper and current target taper could be inadequate mould flux distribution. If the mould flux is not distributed properly, heat transfer from the steel is hindered. Decreased heat transfer from the steel results in less shrinkage. If the steel does not shrink as much as expected, the steel will scrape against the narrow faces, and the taper will be excessive. It is recommended that if the above ideal narrow face taper procedure does not yield fewer defects, then a study should be conducted to examine if the mould flux is being distributed properly along the faces of the mould.

With regards to the "slop" present in the linear screw system; there are steps taken to remove the "slop" before casting. The problem lies in the fact that there are four different work crews that prepare moulds for casting. All four crews handle the problem differently. It is recommended that the four work crews collaborate to create a formal procedure to remove "slop" that will be followed each time. This will result in a more consistent process upon which the effectiveness can be measured.

However, even if the formalized "slop" removing procedure is implemented, the "slop" will still develop over time. Currently the acceptable value is 0.6 mm. This is unacceptable considering the implemented tapers range from 1 to 3 mm. This threshold value needs to be lowered, and a suggested value is 0.3 mm. The consequence though in increasing the frequency of calibration is increased cost. It costs \$1,000 to have a gear box calibrated. Yet, the cost benefit of lowering the acceptable "slop" value is potentially large. Reducing the defects by as little as one percent results in a cost savings of \$43, 000.

It was concluded that inclinometer technology as it stands is inadequate. The inclinometers that could supposedly handle the oscillations do not have enough resolution to

detect the smallest narrow face taper change made by Nucor. The inclinometer that did have enough resolution could not handle the oscillations. In spite of the current problems with the technology, it is recommended that inclinometer technology be pursued as a method of measuring taper. Inclinometers provide a taper measurement independent of any effects due to wide face thermal linear expansion, sticking of the narrow face, or inaccurate control of the narrow face due to "slop". Inclinometers will give a global reading of the taper, not a relative reading based upon the linear screw system. Thus, it is recommended that Nucor collaborate with the companies that make inclinometers to develop an inclinometer is capable of both handling the oscillations present in Nucor's casting process and detecting smallest change made to the narrow face taper. This could be a feasible future MIE 280 design project.

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## **APPENDICES**

- A-1: Photograph of Nucor's thin slab continuous casting funnel mould
- A-2: Photograph of funnel on thin slab continuous casting mould
- A-3: Pictures of defects
  - a: Transverse cracking and rough edges
  - b: Longitudinal cracking
  - c: Copper Pickup

A-4: Photograph of linear screw system that controls narrow face position

- A-5: Picture of Jewell Inclinometer attached to narrow face of mould
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- A-14: Listing of every input parameter with explanation or validation
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A-21: Sample of spread sheet that shows values for the high carbon ideal taper graph

- A-22: Sample input file from CON2D
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- A-24: Chemical make-up and phase diagram for the difficult to cast low carbon steel
- A-25: Extra length and funnel radius calculation for current 1020mm funnel mould and old 880mm funnel mould

All photographs courtesy of Nucor Steel