

## **Characterization of the Thermophysical Properties of Riser Sleeve Materials and Analysis of Riser Sleeve Performance**

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### **Abstract**

Riser sleeves are an effective tool in the steel foundry industry for minimizing riser size and increasing casting yield. Reliable simulation of the performance of riser sleeves requires accurate temperature dependent thermophysical properties. Unfortunately there is little or no such property data available in the open literature. A limited number of sleeve manufacturers provide advice and properties as "black box" databases. The "black box" temperature dependent property data and boundary conditions are proprietary, hidden from the simulation software user. Validated sleeve properties that are openly available to modelers are as necessary as the "open" mold and metal properties they routinely use in designing casting processes. Here a procedure for determining sleeve thermophysical properties and its results are presented. In the procedure, temperature dependent properties of several commonly used sleeve materials are determined through achieving agreement between measured and predicted temperatures throughout the casting process. In order to address the lack of information regarding optimal use of riser sleeves, the performance of different sleeve materials is analyzed using the properties in casting simulations. The modulus extension factor, a quantity which describes sleeve performance, is calculated for several sleeve materials. Analyzing the effect of sleeve performance characteristics on casting yield, it is found that the exothermic reaction provides no discernable advantage to casting yield improvement unless it also increases the modulus extension factor, regardless of casting size for the sleeves tested in this study. From the analysis of the effect of sleeve thickness on casting yield, it is found that most commercially available riser sleeves have thicknesses which are too small to maximize the casting yield, particularly for risers of 8" diameter and larger.

### **Introduction**

The riser sleeve is a reliable tool for increasing casting yield and its use is ubiquitous throughout the metal sand casting industry. It is estimated that about 80% of all steel castings are produced using riser sleeves, and the U.S. steel foundry industry alone spends about \$38 million per year on riser sleeves. Riser sleeves used in steel casting are generally formulated as purely insulating or exothermically insulating, where a thermite reaction is typically used for heat generation. In short, they are referred to as *insulating* or *exothermic* sleeves. Despite the extent of sleeve use, a survey of foundries found that there is a lack of consensus on how to properly use riser sleeves.<sup>1</sup>

Sleeve suppliers use different raw materials of unknown and proprietary compositions and properties in their manufacturing processes. They provide advice and guidance on sleeve use. As a result, application of riser sleeves in foundries is largely based on trusting the supplier, guesswork, and trial-and-error testing by foundries. There is little quantitative data provided to foundries for deciding which sleeve, from which supplier, is most effective for a given casting

application. Most foundries use computer casting simulation to determine riser sizes. However, the sleeve material thermophysical properties required as input data for simulations either are either not available, or are provided by a limited number of suppliers for their products as “black box” databases. These “black box” property databases also include supplier recommended temperature dependent heat transfer coefficients between various casting system materials (i.e. the casting-sleeve and sleeve-mold interfaces); these are also hidden from the user. The accuracy of these properties and coefficients is unknown. The foundry trusts that the suppliers’ databases are accurate. Since the “black box” property data is hidden from the software user, thorough calibration using measured temperatures to validate the data for a given foundry’s casting practice is not possible. Finally, since the details of the thermophysical properties are unknown, it is difficult to say what causes one sleeve to appear superior to another for a given application.

It is estimated by the Steel Founders’ Society of America (SFSA) that if the thermophysical properties of riser sleeve materials were known accurately, selection of riser sizes could be optimized such that the industry’s casting yield could be increased by at least 10% (from approximately 50% currently to 55%). The resulting energy savings would be about 1.5 trillion BTU per year for the U.S. steel foundry industry. Significant additional benefits would arise from improved quality, reduced costs, and increased production capacity.

Literature on riser sleeve material properties and their measurements is scarce or incomplete if available. Older literature presents some data on the sleeve performance and their effects on cooling history and solidification time, effective increase in riser modulus, and their effect on riser piping and resulting riser volume reduction<sup>2-5</sup>. Foseco has provided guidance over the years for many of their sleeve products in their *Foundryman’s Handbook*<sup>5</sup>, and nomographs and *FeederCalc* software<sup>5</sup>. More recently general temperature dependent curves for density, specific heat and thermal conductivity have been published<sup>6</sup> but these curves are incomplete. The plots of data in this work give no numerical values and only provide the reader trends of the properties’ dependency on temperature. Because of the lack of property data for accurate simulation, SFSA members have developed their own practices for using riser sleeve products, such as deciding when to use an insulating or exothermic sleeve<sup>1</sup>. Sleeve manufacturers ASK Chemicals and Foseco have provided sleeve material properties to users of the casting simulation software *MAGMAsoft*<sup>7</sup> through its property database. However, these are proprietary data and hidden from the user.

In the work described here, temperature dependent sleeve material property data are developed by matching experimental temperature data recorded during casting trials to simulation temperature results through iteratively modifying the sleeve material properties used in the simulations to achieve agreement. Such a property estimation technique is generally referred to as *inverse analysis*. A similar inverse approach to sleeve and sand mold material property estimation was taken by Ignaszak *et al.*<sup>8,9</sup>. Rather than develop temperature dependent data, they determined average exothermic sleeve material property data (single values) for use in simulation. Their experiments were similar to the current work, where cylindrical castings were poured. They placed two temperature sensors in the metal of each cylinder, one at the centerline and one 30 mm from the outer diameter. In the experiments one cylinder was cast without a

sleeve, from which properties of the mold and metal were estimated. Here the experimental casting without sleeve is referred to as a *control* casting. The property data determined by Ignaszak et al. are for sleeve materials they describe as “insulating-exothermic” and are labeled in their work as “L2” and “L5”. The relevant property data they determined for the sleeve materials are: heat capacity,  $\rho c_p = 560$  and  $500 \times 10^3$  (kJ/m<sup>3</sup>-K), conductivity,  $k = 1.09$  and  $0.98$  (W/m-K), exothermic heat generation =  $2,257$  and  $1,857$  (kJ/kg), and exothermic ignition temperature  $150$  (°C), respectively for the “L2” and “L5” sleeves. Ignaszak et al. acknowledge this ignition temperature is “relatively low” and mention that is produced the lowest error when compared with measurements in the inverse modeling.

In the current work, experiments are performed to measure temperatures for cylinder-shaped steel castings for use in property estimation via inverse modeling. In these casting experiments, thermocouples are used to record temperature data in the steel, riser sleeve, and sand mold as the casting cools. The experiments were performed in heats of approximately 300 pounds per pour. For each experimental heat, a control casting was poured having no sleeve. From the control casting experiment the temperature dependent properties and solidification parameters for the mold and metal were determined, such that the error between the measured temperatures and the simulation temperatures was minimized for each heat of steel. In addition to the control casting poured in each experimental heat, between two and five cylindrical castings with sleeves were poured depending on the sizes of the sleeves used. Using the properties determined for the steel and mold from the control experiment, iterative simulations were run for the sleeved cylinders where the thermophysical properties of riser sleeve materials were estimated by adjusting the sleeve properties. Final sleeve material properties are determined such that the error between the experimental temperature data for the castings with sleeves and their simulated temperature data is reduced to the smallest error obtainable over approximately 100 iterative simulations performed per sleeve. The casting software *MAGMASoft* is used for the simulations performed in this study. After the sleeve material properties were determined, parametric studies were carried out to understand how sleeve properties affect sleeve performance. Using the riser sleeve properties estimated, a method of quantifying sleeve performance is proposed and detailed in the current work using the modulus extension factor. A study of sleeve performance characteristics on casting yield is presented. This study investigates how exothermic and insulating sleeve characteristics influence riser size and casting yield. Finally, the effect of sleeve thickness on sleeve performance through increasing casting yield is evaluated, and observations are made on commercially available sleeve sizes and optimal sleeve thickness for maximizing casting yield.

## **Casting Experiments**

Rather than perform bench top sleeve material property measurements outside of the casting process, it was decided that the inverse modeling approach would be used to determine the best effective sleeve material properties and boundary conditions for modeling sleeves in an actual casting situation. In a real casting application, there are physical phenomena such as the gases evolved by the sleeve exothermic reaction or the burning off of the sand mold binder which affect heat transfer at the sleeve-metal and mold interfaces and cannot be ignored. Also, sleeve properties before and after the exothermic reaction are expected to be different, introducing a

hysteresis effect as the casting cools. By using an actual casting process for estimating the properties, issues like this can be taken into account in the property determination. In addition, the accuracy of the properties developed can be readily evaluated by comparing measured and predicted temperatures.

The casting experiments presented in this paper were conducted at the University of Northern Iowa (UNI) Metal Casting Center. As described above, the casting experiments were performed over multiple steel heats. Using a control casting in each heat ensures that accurate steel and sand properties specific to each heat are used. Silica sand molds were used in all experiments with a 1.25% Pepset polyurethane no bake binder based on total sand weight. All castings were poured using a low-alloy steel, ASTM A216 Grade WCB steel. The range of liquidus and solidus temperatures in the experiments found from the steel temperature measurements were 1470 to 1505 °C (2678 to 2741°F) and 1340 to 1410°C (2444 to 2570°F), respectively. A formal survey of riser sleeve use by SFSA member foundries was conducted<sup>10</sup>. The most commonly used riser sleeve products identified by the survey were investigated in this study as listed in Table I. The sizes of sleeves and castings used in the experiments are given in Table I as well and were chosen by SFSA member foundries that provided sleeves for study.

Table I. Riser sleeve and experimental casting dimensions.

Manufacturer	Sleeve	Insulating/ Exothermic	Sleeve Inner Diameter	Casting Height	Sleeve Thickness	Control Casting Diameter	Control Casting Height
FOSECO	Kalminex 2000	Exothermic	3.5"	6"	0.5"	4.5"	6"
	Kalminex 21	Exothermic	8"	8"	1"	6"	6"
	Kalfax 100	Exothermic	3"	6"	0.625"	3"	5"
	Kalmin 70	Insulating	2.5"	6"	0.375"	6"	8"
Joymark	CFX 700	Exothermic	5"	5"	0.5"	5"	8"
	CFX 760	Exothermic	4.5"	6"	0.75"	4.5"	6"
	CFX 800	Exothermic	6"	6"	1"	4.5"	6"
Exochem	ES	Exothermic	3"	6"	1.25"	3"	5"
	ESPX	Exothermic	3"	5"	0.5"	3"	5"
	SNA	Insulating	6"	6"	0.5"	6"	6"
ASK	ExactcastEX	Exothermic	4.5"	6"	0.5"	4.5"	6"
	Exactcast IN	Insulating	4.25"	6"	0.375"	4.5"	6"
AMCOR	Rosstherm K	Insulating	4"	4"	0.5"	3"	5"

An experimental setup was devised to measure the effect of the sleeve on the casting solidification process without interference from other casting process variables. For example no hot topping was used and a mold top of 2" thick was also used for a consistent heat loss through the top surface of the castings. A sand mold pouring cup was placed on top of the mold through which the castings were filled. A schematic diagram of the experimental setup is shown in Figure 1(a) for a casting with a sleeve and Figure 1(b) for a control casting. As described above, when simulating castings with sleeve, only the sleeve properties were modified to achieve agreement between simulation and experimental temperature data. Thermocouples (TCs) are placed in the steel, sleeve, and sand mold in order to thoroughly capture the sleeve's effect on the solidification process. The thermocouple placed in the sleeve also allows for the detection and measurement of exothermic properties of sleeves. As diagramed in Figure 1, two type-K thermocouples were used in the sand mold and type-B Platinum Rhodium thermocouples were used to measure temperatures in the steel and sleeve. All

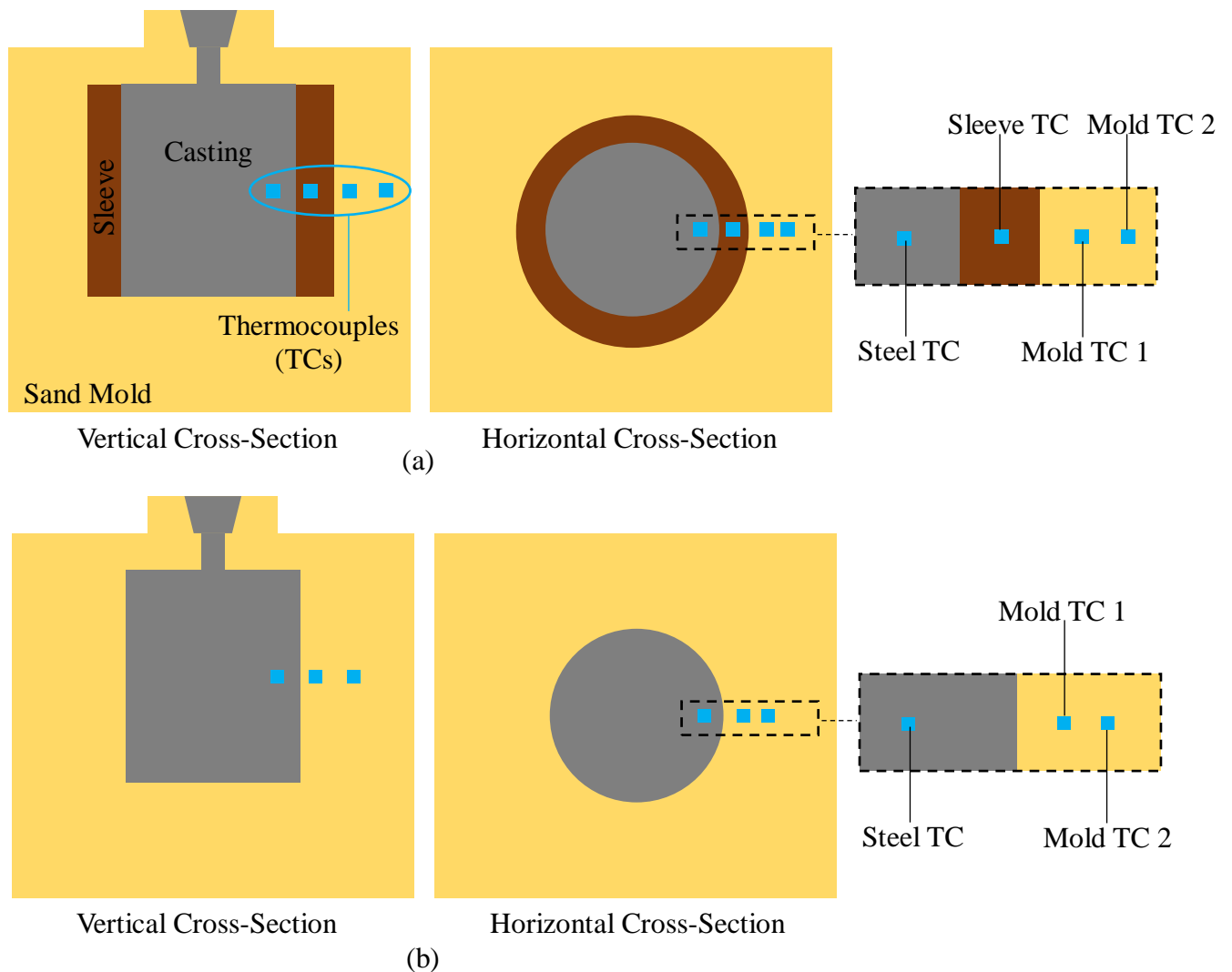


Figure 1. Schematic diagrams of experimental casting setups for (a) castings with sleeves and (b) castings without sleeve.

thermocouples were positioned at approximately the riser mid-height. The sand mold thermocouples were positioned approximately 10 and 20 mm from the mold-steel or mold-sand interfaces. The thermocouple in the metal was positioned approximately 50 mm from the metal-mold or metal-sleeves interfaces, such that the initial cool down from pouring to liquidus temperature, and the liquidus temperature and start of solidification could be sensed. The thermocouple positions varied slightly experiment-by-experiment due to the limitations of instrumenting the molds in a foundry setting; the average position variation was 2 mm and the maximum was 5 mm. However, the final TC positions were carefully measured experiment-by-experiment before pouring and were recorded for each experiment so the TC locations in the simulations could match the experiments as closely as possible. Whenever and wherever possible, TC positions were confirmed after the casting cooled to room temperature. It was found that having accurate knowledge of the TC positions greatly reduces the inverse modeling simulation iterations required to achieve decent agreement between all measured and simulated TCs. This knowledge also reduces uncertainty in the final data judged by the error between the final measured and predicted temperatures.

An example of agreement between measured (red curves) and simulated (black curves) temperatures for a control casting with no sleeve is shown in Figure 2(a) for the steel TC and in Figure 2(b) for the sand mold TCs. In Figure 2(b) there are thermocouples at 10 mm (dashed curves) and at 20 mm (solid curves) from the mold-metal interface. This agreement between measured and predicted temperatures is similar to that found in all control cases once the final metal and mold properties were determined. After this these properties are fixed for the experimental heat and the sleeve properties are determined.

### Developing Riser Sleeve Thermophysical Properties

In Figure 2 there is good agreement between measured and simulated temperatures for the control case shown once the properties for the steel and mold have been determined. Using these

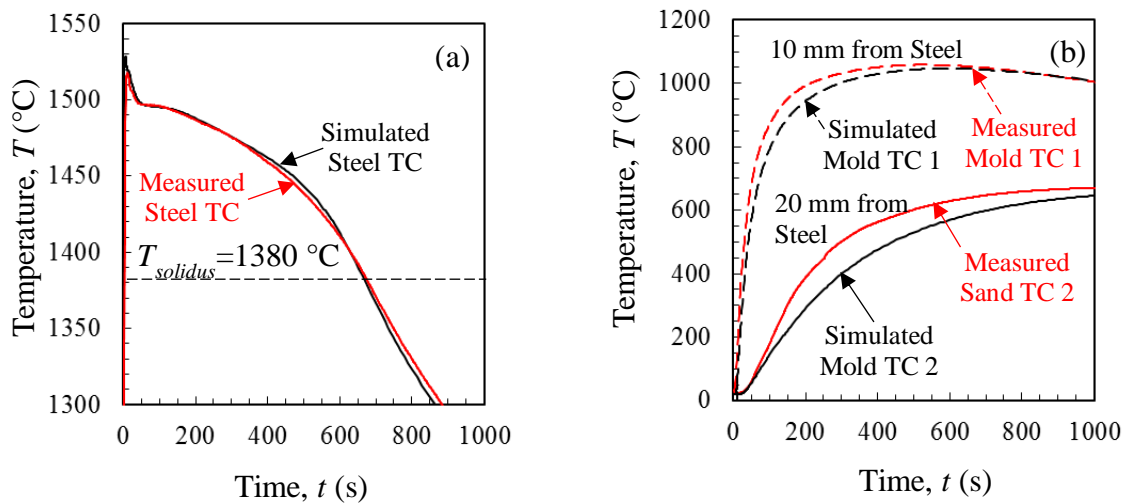


Figure 2. An example of agreement between measured (red curves) and simulated (black curves) temperatures for a casting without sleeve in the (a) steel and (b) sand mold. Line type denotes position at 10 mm (dashed line) and 20 mm (solid line) from steel-mold interface.

mold and steel properties for a given heat poured, the properties are determined for the sleeved risers poured in that heat. It was found that only small changes needed to be made to the mold properties from one experimental control case dataset to the next to achieve agreement between measured and predicted temperatures. For the steel, the solidification temperatures and solid fraction curves required heat-to-heat modification, which also did not vary to a great degree due to the similar steel compositions used throughout the study. The temperature dependent interfacial heat transfer coefficient (HTC) applied at the steel-sand and steel-sleeve interfaces in the simulations performed in this study is shown in Figure 3. The steep drop in HTC results from the gap formation between the steel and mold due to metal contraction, which reduces the heat flow.

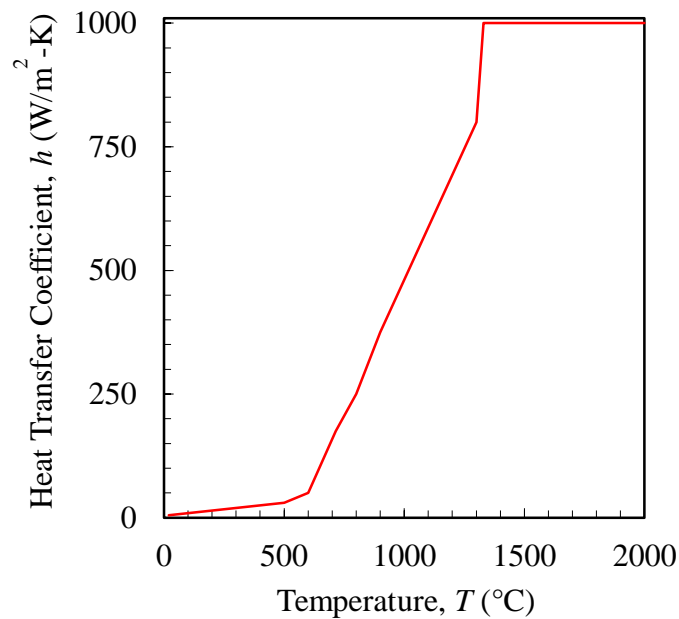


Figure 3. Temperature dependent interfacial heat transfer coefficient applied at the steel-sand and steel-sleeve interfaces in simulations performed in this study.

The fundamental sleeve thermophysical properties for casting simulation are: density  $\rho$ , specific heat  $c_p$ , and thermal conductivity  $k$ . In modeling heat transfer using the conservation of energy equation, the thermal conductivity appears in the equation independently. Whereas density and specific heat always appear as the product  $\rho c_p$ , the heat capacity. In addition to the three fundamental properties appearing in the energy equation, for exothermic sleeves the casting simulation software *MAGMASoft* uses additional parameters to describe the exothermic heat release: the ignition temperature, the burn time, and the heat generation per unit mass.

Determining temperature dependent thermophysical properties  $\rho$ ,  $c_p$  and  $k$  for all sleeves can be simplified by using the heat capacity and  $k$ . Creating unique property versus temperature data for  $\rho$ ,  $c_p$  and  $k$  for each sleeve would be unnecessarily time consuming. Extending this idea, it would be still more preferable to predetermine all properties except for one, and then focus on developing a temperature dependent curve for just one property. In this case, temperature dependent data for whichever property is most influential on simulation results will be

developed, while all other properties are predetermined. The predetermined properties can be considered to be representative of the effective average property values.

In order to determine which thermophysical property is the most influential on sleeve performance and simulation results, a simple cylinder casting was simulated. The cylinder is surrounded by a riser sleeve with base thermophysical properties  $k$ ,  $\rho$ , and  $c_p$ . The most influential of the properties can be discerned by modifying the thermal conductivity,  $k$ , and heat capacity,  $\rho c_p$  and determining the sensitivity of a measure of sleeve performance to the property changes. The casting solidification time is taken as the measure of performance.

The results of this investigation are shown in Figure 4. Here the percentage difference in solidification time for a cylinder casting as predicted by *MAGMASoft* is plotted in a bar chart for all permutations of cases where the sleeve material thermophysical properties  $k$  and product  $\rho c_p$  are multiplied by factors of 0.5 and 2. The difference percentages are calculated relative to the unmodified case using  $k$  and  $\rho c_p$ . Cases are grouped according to thermal conductivity used (i.e. multiplier of  $k$ ) and the individual bars correspond to cases of  $\rho c_p$  as labeled on the abscissa axis. The first two bars on the left side of the plot show that for the baseline values of  $k$  the solidification time only changes by +3% to -5% when the heat capacity is changed by factors of 0.5 and 2, respectively. Considering next the middle three bars labeled “0.5k”, the leftmost bar is for the baseline value of  $\rho c_p$  and the solidification time changes by about +45% when  $k$  is halved. Considering the three rightmost bars on the plot labeled “2k”, the leftmost of these is for the baseline value of  $\rho c_p$  and the solidification time changes by about -30%. The remaining bars of data show that regardless whether one halves or doubles the thermal conductivity, the effect of also halving and doubling  $\rho c_p$  for each case is only about a 10% to 15% absolute change in

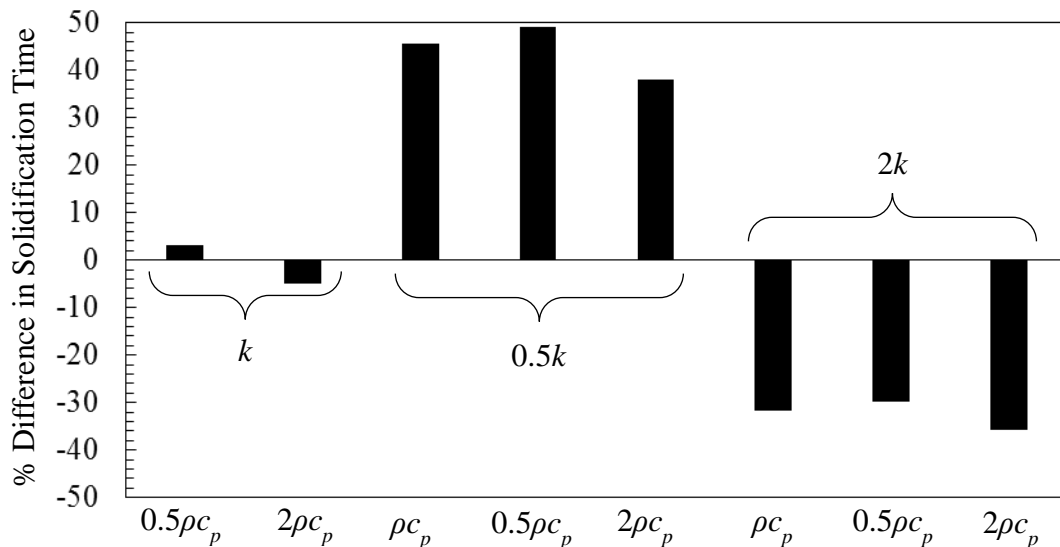


Figure 4. The difference in solidification time percentage for a cylinder casting predicted by *MAGMASoft* for all permutations of cases where the sleeve material thermophysical properties  $k$  and product  $\rho c_p$  are multiplied by factors of 0.5 and 2. Differences are relative to the unmodified case. Cases are grouped according to multiplier of  $k$ , and individual bars correspond to cases of  $\rho c_p$ .



solidification time. The changes in solidification time are about 2 to 3 times more sensitive to changes in  $k$  than they are to changes in  $\rho c_p$ . It is clear from this brief study that the thermal conductivity is the most influential property. These findings are also supported by those of Midea *et al.*<sup>6</sup> who studied sensitivities of solidification times at the riser neck and near the casting-riser interface to changes in  $k$  and  $\rho$  or  $c_p$ . As a result, in this study the density and specific heat were set to pre-determined or average values and the temperature dependent property development is focused on determining appropriate thermal conductivity data.

Midea *et al.*<sup>6</sup> provide a density versus temperature curve with no numbers, but density is shown to decrease with increasing temperature. The curve levels to a constant value at high temperatures. The sleeve densities in this work are set as constant and are equal to the measured room temperature density of the sleeve. These densities are listed in Table II.

Table II. Riser sleeve densities used for simulation

Manufacturer	Sleeve	Density (kg/m <sup>3</sup> )
FOSECO	Kalminex 2000	422.00
	Kalminex 21	620.53
	Kalfax 100	533.51
	Kalmin 70	422.00
Joymark	CFX 700	451.07
	CFX 760	451.07
	CFX 800	451.07
Exochem	ES	676.07
	ESPX	530.90
	SNA	478.88
ASK	Exactcast EX	529.25
	Exactcast IN	394.50
AMCOR	Rosstherm K	255.98

Midea *et al.*<sup>6</sup> provide a specific heat versus temperature curve with no numbers but the curve shows that specific heat increases with increasing temperature. In this work the temperature dependent specific heat is modeled by a common curve for all sleeves having a value of 400 J/kg-K at 0°C (32°F) that increases to and ranges from 600 to 700 J/kg-K between temperatures of 380 of 2000°C (716-3632°F). The shape of the curve used in the current work is similar to the

plot given by Midea *et al.*<sup>6</sup> Setting  $\rho$  and  $c_p$  leaves thermal conductivity data to be developed using the inverse modeling method.

Development of the thermal conductivity data is accomplished by iteratively adjusting the temperature dependency curve for  $k$  used in simulations. Depending on how a modification during an iterative simulation run affects the agreement between simulated and measured temperatures, further modifications are made to progressively improve the agreement. In Figure 5(a) an example of a final temperature dependent thermal conductivity curve for an insulating sleeve is shown in black, labeled “ $k$ ”. Also shown in Figure 5(a) are curves resulting from

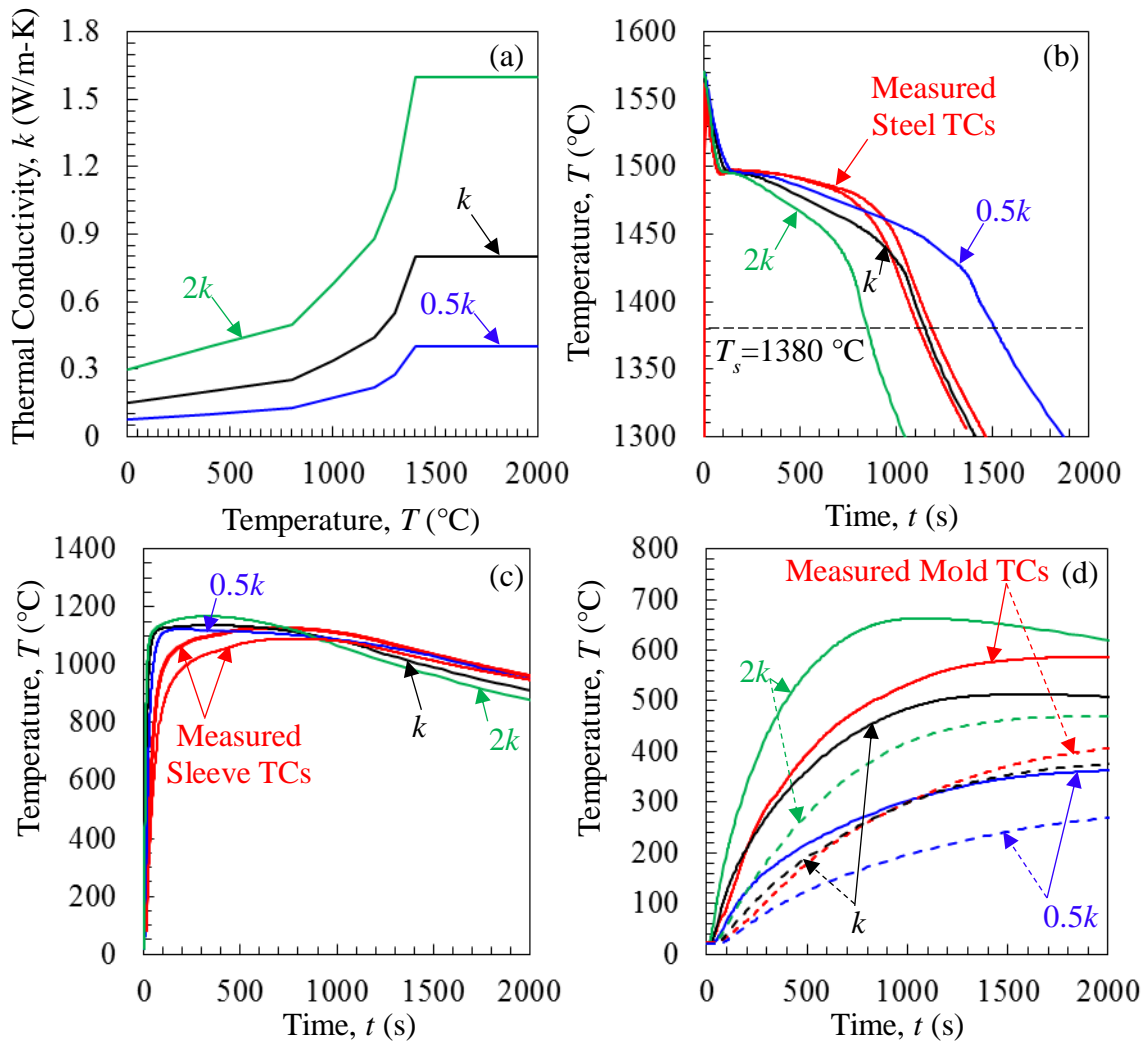


Figure 5. (a) Temperature dependent riser sleeve thermal conductivity curve determined for the ASK Exactcast IN insulating sleeve material properties, as well as curves multiplied by factors of 0.5 and 2. Measurements cooling curves (red curves) are compared to predicted curves in the (b) steel, (c) sleeve, and (d) sand mold showing the effects of multiplying the sleeve thermal conductivity by the corresponding factors of 0.5 and 2 in the blue and green curves, respectively. In (d) there are two measured mold TC in the plot at 10 mm and 20 mm from the sleeve-metal interface corresponding to the solid and dashed curves, respectively.

multiplying the final thermal conductivities in the curve by factors of 0.5 and 2 corresponding to the blue and green curves, respectively. Note that in the inverse modeling procedure, changes to the curve were made that were much smaller than the factors of 0.5 and 2. Curves for these relatively large factors are shown here to illustrate how changes to the thermal conductivity curve affect the simulated temperatures in the steel, sleeve, and sand. Predicted temperature versus time data at the thermocouple measurement locations are compared to the measurements (red curves) in the steel, sleeve and sand mold in Figures 5(b), (c) and (d), respectively. In Figure 5(d) two TCs curves are plotted at approximately 10 mm and 20 mm from the sleeve-metal interface corresponding to the solid and dashed curves, respectively. These cooling curves show the effect of modifying the sleeve thermal conductivity by factors of 0.5 and 2 on the predicted temperature curves. These figures demonstrate the tradeoffs that are made in determining the final sleeve thermal conductivity curve that gives reasonable agreement at all thermocouple locations in the steel, sleeve and sand mold. Generally speaking though, achieving agreement between measured and predicted temperatures in the steel is most important since solidification time for the steel is a very important sleeve performance measure. The final thermal conductivity curves for all sleeves were determined such that similar agreement between measured and predicted cooling curves was obtained in the steel, sleeve and mold as that shown in Figures 5(b), (c) and (d).

For exothermic sleeves the three exothermic properties are also determined by inverse modeling. While there are three exothermic properties which must be determined, simulation studies with them indicated they affect sleeve performance independently of each other. Exothermic sleeves produce a noticeable heating spike in the sleeve temperature-time curve. Ignition temperature was found to have an insignificant effect on the simulated temperature results in the range from 400°C to 800°C (752°F to 1472°F). It was found that setting it to 600°C (1112°F) produced reasonable agreement with the heating temperature spike for the exothermic reaction in all exothermic sleeves. The exothermic heat generation was found to influence the height of the spike of the temperature-time curve, while the burn time influenced the width (time span) of the exothermic heating spike. Measured (red curves) and predicted (black curves) temperature versus time curves in the steel and sleeve are shown in Figure 6 for two exothermic sleeves. In Figures 6(a) for the steel TC and Figure 6(b) for the sleeve TC, the predictions use properties determined in this study for the Kalminex 21 sleeve material. In Figures 6(c) for the steel TC and Figure 6(d) for two sleeve TCs, the predictions use properties determined in this study for the Joymark CFX 760 sleeve material. The two measured sleeve TCs, red curves, shown in Figure 6(d) give a sense of experimental reproducibility for the sleeve TC measurements, since every effort was made to position them at the same thickness position. The exothermic sleeve TC measurements can be very sensitive to position. However, the difference in the two repeated experimental measurements might indicate sleeve-to-sleeve performance variability as well; this is an interesting issue but outside the scope of the current work. Note that the sleeves in Figure 6 are different sizes and geometries (Kalminex 21 is 8" diameter and the Joymark CFX 760 is 4.5" diameter) and no comparisons about the performance of the sleeve products relative to each other can be made or inferred from these plots.

Next the effects of modifying the exothermic parameters (the heat generation and burn time) on the agreement between measured and simulated temperatures are shown in Figures 7 and 8 for the Kalminex 21 sleeve in the steel and sleeve, respectively. Similarly, effects of modifying the

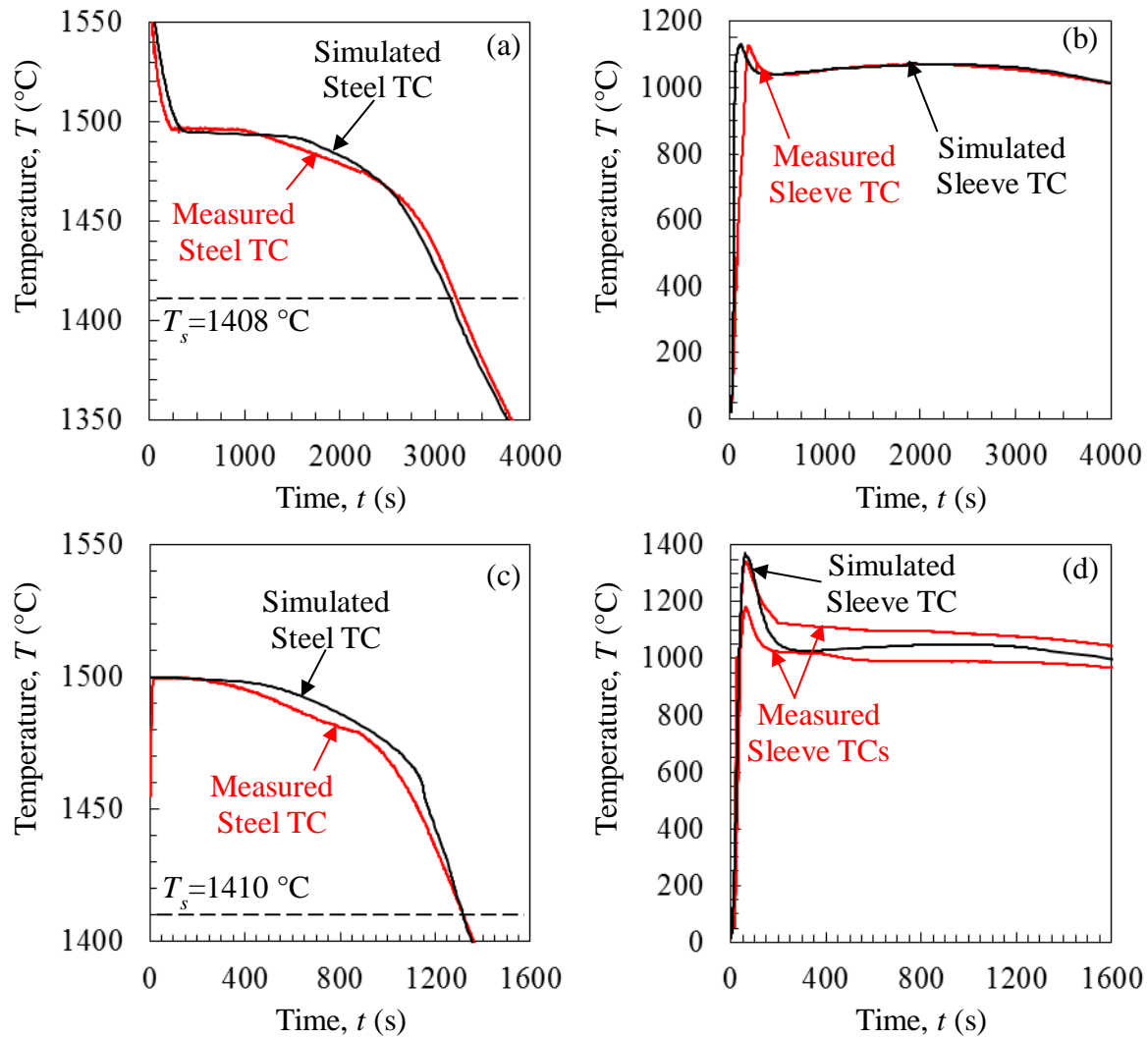


Figure 6. Measured (red curves) and predicted (black curves) temperature versus time curves in the steel and sleeve for two exothermic sleeves. Predictions use properties determined in this study for the Kalminex 21 sleeve material in the (a) steel and (b) sleeve, and for the Joymark CFX 760 sleeve material in the (c) steel and (d) sleeve. Note that the sleeves in this figure are different sizes and geometries and no comparisons about the performance of the sleeves relative to each other can be made or inferred from these plots.

exothermic parameters on the agreement of the predicted and measured temperatures in the steel and sleeve are shown in Figure 9 for the Joymark CFX 760 sleeve. The modifications made to the exothermic properties in Figures 7, 8 and 9 are to multiply the value determined in the study (corresponding to the black curves) by factors of 0.5 (the blue curves) and 2 (the green curves). The effect of changing heat generation on the temperature in the steel for the Kalminex 21 is more noticeable when it is doubled, especially as shown in Figure 7(b) in the initial cooling down to liquidus. Changes in the burn time have no effect on the temperature predictions in the steel for the Kalminex 21 sleeve as shown in Figures 7(c) and (d). Looking at the sleeve

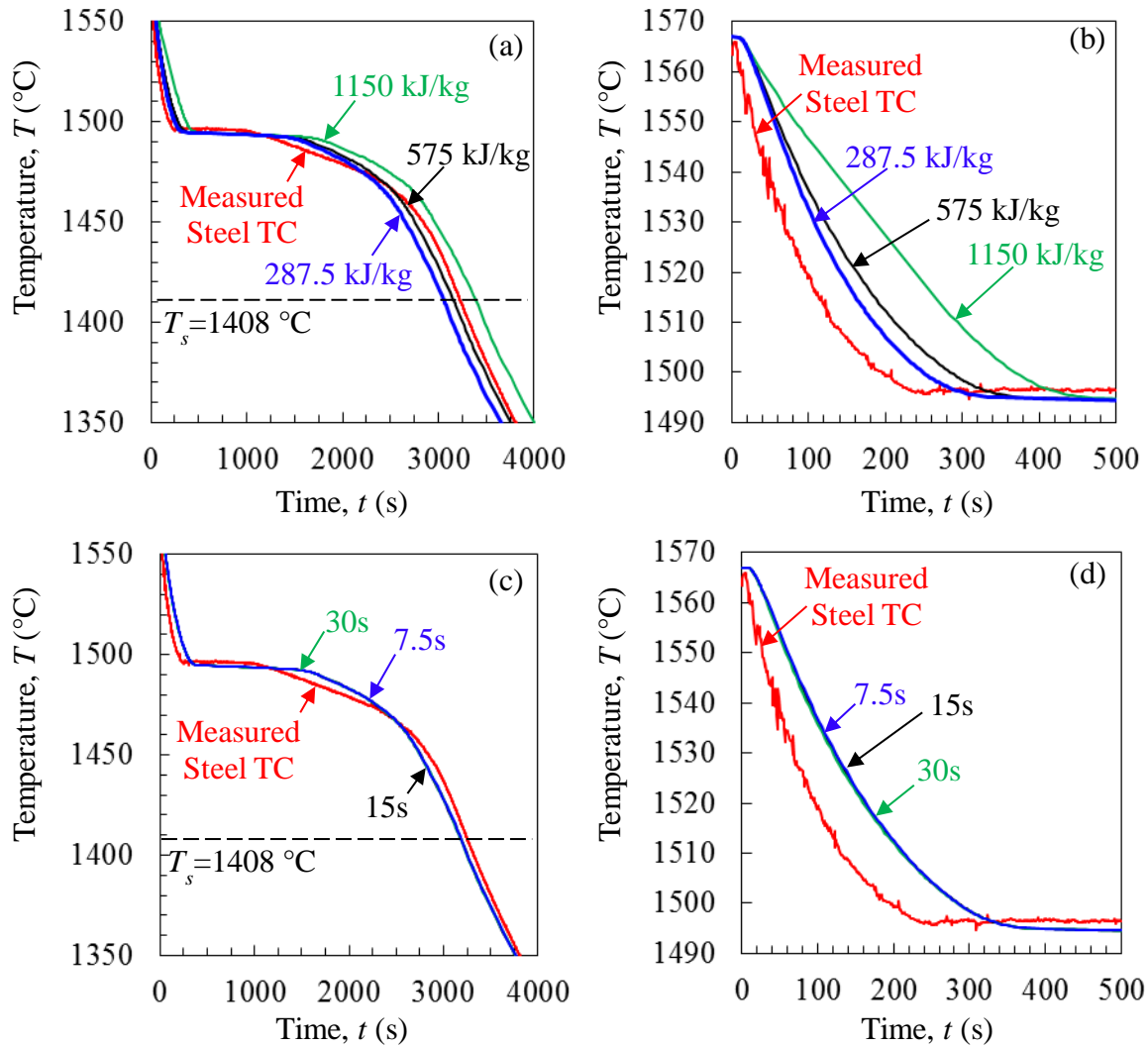


Figure 7. Temperature curves in the steel for the Kalminex 21 sleeve showing in (a) and (b) the effect of modifying the heat generation material property on agreement between measured and predicted temperatures on long and short time scales, respectively. Figures (c) and (d) show the effect of modifying the burn time material property on agreement between measured and predicted temperatures.

temperature predictions in Figure 8, changes in both heat generation and burn time have no effect on the temperature predictions over the long time scales as shown in Figures 8(a) and (c). Note for Figures 8(a) and (c) that the temperature scales are different and that doubling the heat generation increases the maximum temperature in the sleeve to about 1700°C in Figures 8(a) and (b). From Figures 8(b) and (d) it is clear that the predictions lead the measurement, additional inverse modeling iterations or changing other properties that were fixed (like ignition temperature, specific heat and density) could eliminate this discrepancy. Still, on the casting solidification time scale, and in the steel, the predictions and measurement agree quite well. For the Joymark sleeve shown in Figure 9, the conclusions of the exothermic property modification study are similar. Modifying the heat generation in Figures 9(a), (b) and (c) show the most noticeable effect in the metal is when it is doubled, and doubling it produces a very high

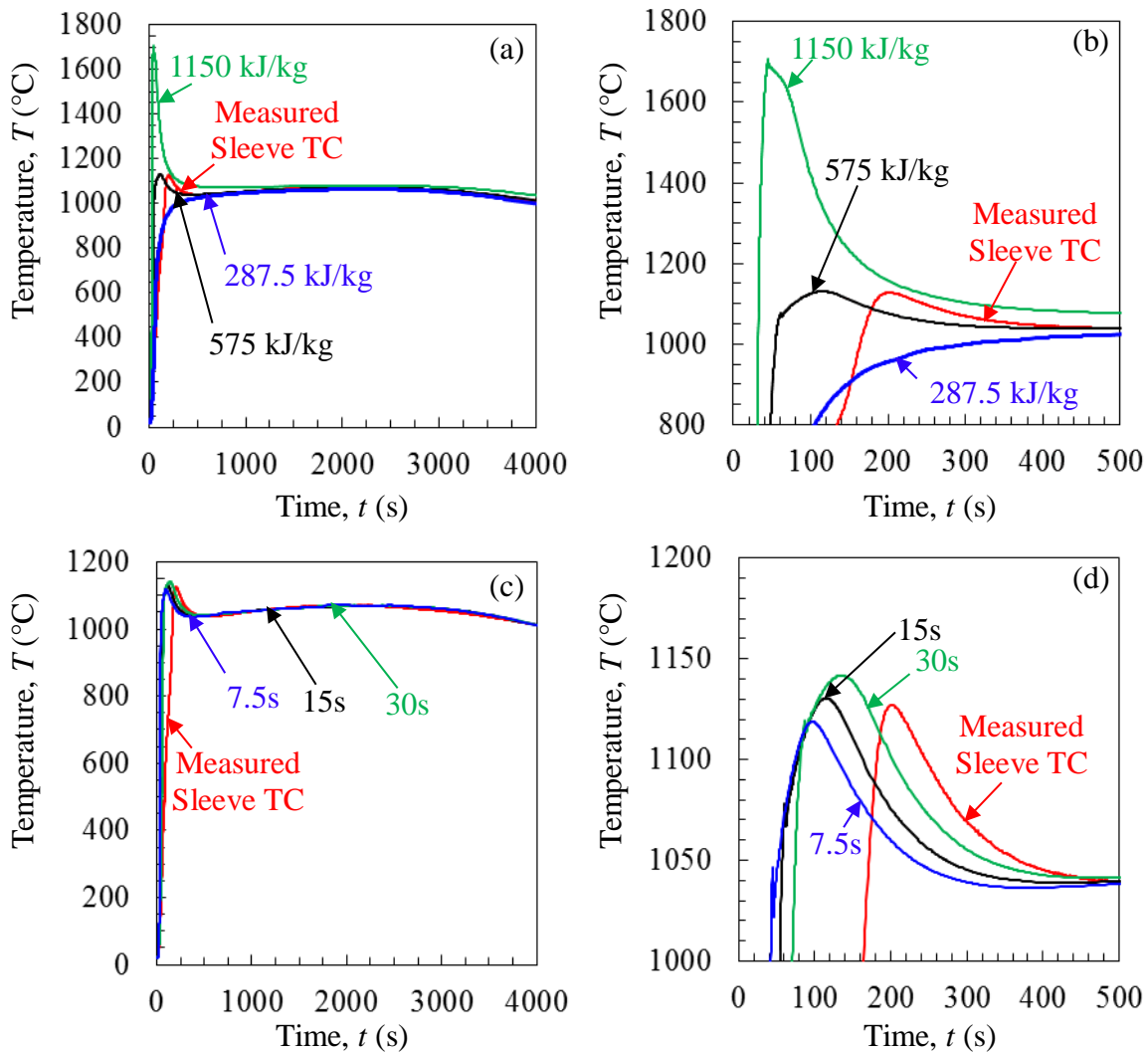


Figure 8. Temperature curves in the sleeve for the Kalminex 21 sleeve showing in (a) and (b) the effect of modifying the heat generation on agreement between measured and predicted temperatures on long and short time scales, respectively. Figures (c) and (d) show the effect of modifying the burn time on agreement between measured and predicted temperatures.

temperature, which was not measured. If the temperature were very high, as high as 2000°C the type B thermocouple sensor would probably have failed. Modifying the burn time shown in Figures 9(d), (e) and (f), no effect on prediction is seen in the steel, and in the sleeve the prediction are only different in the first 400 seconds.

The exothermic properties determined for all sleeve materials are listed in Table III. In the inverse modeling of a few sleeves, the thermal conductivity was slightly modified after the exothermic properties were determined. The temperature dependent thermal conductivity curves determined for all sleeve materials in this study are shown in Figure 10.

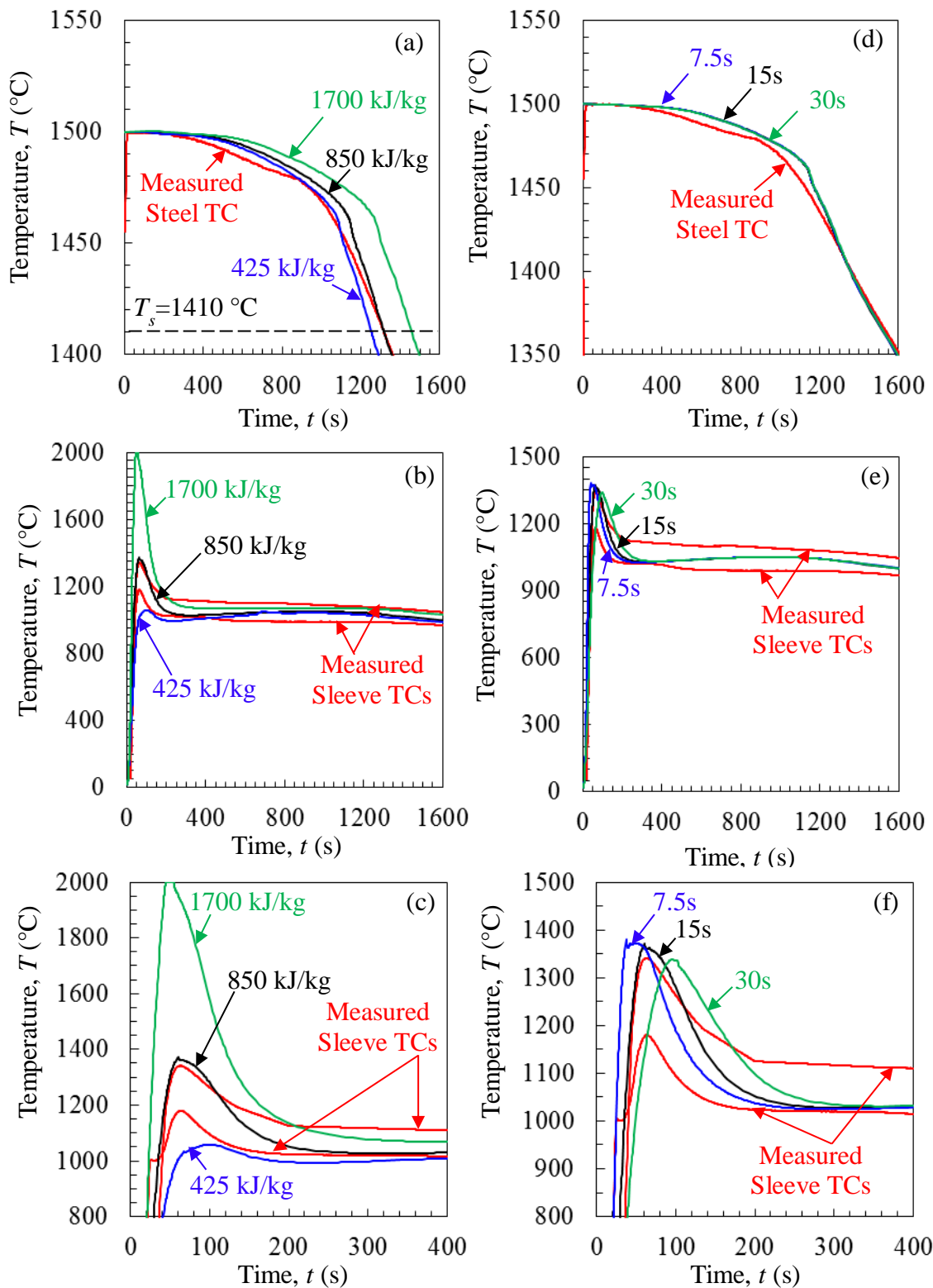


Figure 9. Temperature curves in the steel and sleeve for the Joymark CFX 760 sleeve showing in (a), (b) and (c) the effect of modifying the heat generation on agreement between measured and predicted temperatures on long times scales in (a) and (b) and a short time scale for the sleeve in (c). Analogous temperature curves showing effect of modifying the burn time on agreement between measured and predicted temperatures are shown in (d) for the steel and (e) and (f) for the sleeve.

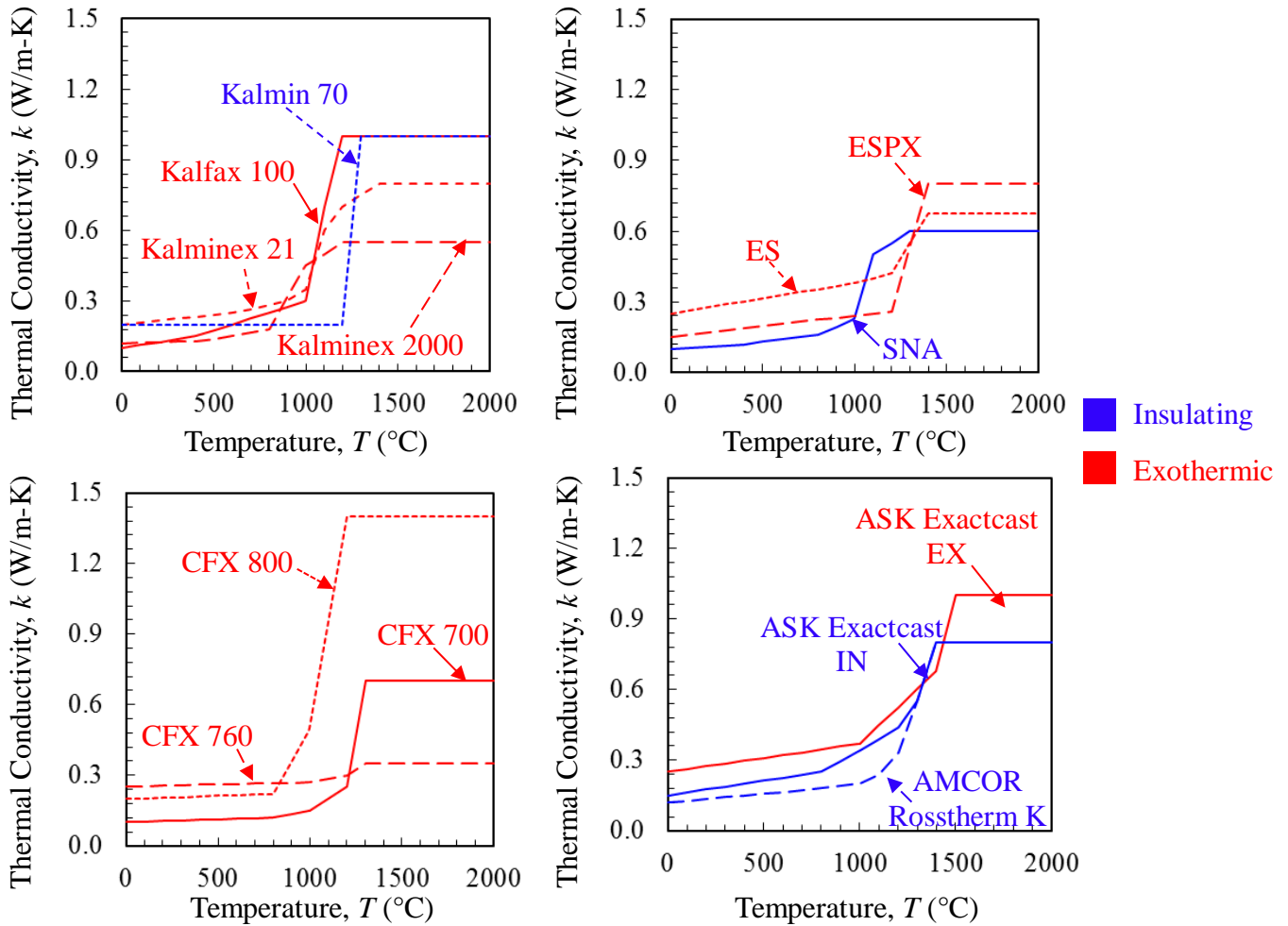


Figure 10. Riser sleeve temperature dependent thermal conductivity curves for sleeve materials sorted by sleeve manufacturer. (a) FOSECO (b) Exochem (c) Joymark (d) AMCOR and ASK Chemical.

### Modulus Extension Factor and Its Determination

Thermophysical properties have been developed for several commonly used riser sleeve materials. The relative performance of these riser sleeve materials can be determined by applying these sleeve properties to casting simulations. Most previous studies investigating riser sleeve performance have looked at solidification time of a riser above a casting or the riser piping depth and safety margin. While such studies may be useful for a particular sleeve or casting, the results cannot be generalized as a standard measure of performance. Ideally, a sleeve's performance should be characterized by a unique measure of performance that is entirely general. Traditionally, rising of castings was accomplished by analyzing the casting modulus as defined in Chvorinov's rule:

$$t_s = K \left( \frac{V}{A} \right)^2 \quad (1)$$



Table III. Riser sleeve exothermic properties used for simulation

Sleeve	Heat Generation (kJ/kg)	Burn Time (s)	Ignition Temperature (°C)
Joymark CFX 760	850	15	600
Joymark CFX 700	750	15	
FOSECO Kalminex 21	575	15	
Exochem ESPX	520	60	
Exochem ES	500	45	
ASK Exactcast EX	425	30	
Joymark CFX 800	425	18	
FOSECO Kalminex 2000	250	40	
FOSECO Kalfax 100	250	20	

where  $t_s$  is the time to solidification of a casting section,  $K$  is a grouping of sand mold and steel properties,  $V$  is the volume of the casting section, and  $A$  is the heat loss surface area of the casting section. The geometric casting modulus is defined as the quotient  $V/A$ . Equation 1 states that the time to solidification of a casting section is proportional to the square of the modulus of the casting section. This equation can be directly applied to risers without sleeves. When a riser sleeve is used however, the solidification time increases despite the geometric modulus remaining constant. To explain the increased solidification time, the riser is said to have an *apparent* modulus which is larger than its geometric modulus. The two moduli are related by the equation:

$$M_A = f M_G \quad (2)$$

where  $M_A$  is the apparent modulus of a sleeved riser,  $M_G$  is the geometric modulus of a sleeved riser, and  $f$  is the modulus extension factor. While the apparent modulus will change based on the geometry of the riser, the modulus extension factor should be independent of the riser geometry and be generally representative of a sleeve's performance. The modulus extension factor can be calculated for a given sleeve as the ratio of the apparent modulus to the geometric modulus of the riser encompassed by the sleeve. However the apparent modulus is not a readily available quantity and must be determined experimentally.

A method of determining the apparent modulus was published by Foseco<sup>4</sup>. In order to determine the apparent modulus the solidification time of a sleeved riser is measured. Since it is hard to pinpoint the exact location of final solidification, a thermocouple is instead placed at the center of the junction between a sleeved riser and a casting underneath it. The thermocouple is then used to measure the time to solidus temperature at that location. The same is done for a larger sand riser without a sleeve and feeding an identical casting below it. The time to solidus is

measured for increasingly larger sand risers until one is found to match the time to solidus in the smaller riser with sleeve. The geometric modulus of this larger sand riser is then adopted as the apparent modulus of the smaller sleeved riser. With the apparent modulus determined, the modulus extension factor can then be easily calculated.

In order to compare sleeve performance, a standard method of determining modulus extension factor is proposed using an 8" cube casting. The casting is fed by a 6" high cylindrical top riser with 6" diameter and a 0.5" thick riser sleeve as shown in Figure 11. A 4" thick layer of silica sand is set around the casting, and the top of riser is open to the atmosphere. No hot topping is used. Simulations were performed to test this proposed procedure. In these *MAGMASoft* simulations, an open riser (feeder) was used in conjunction with the default *MAGMASoft* boundary condition for external heat loss. WCB steel properties were used with a superheat of 30°C (54°F). A virtual thermocouple is placed at the junction between the riser and casting, where the solidification time for the riser is determined. A schematic for this configuration is shown in Figure 11. The configuration for the casting without sleeve is the same as that with the sleeve, except for the exclusion of the sleeve and a larger riser size. It is important to keep the aspect ratio (diameter/height ratio) of the riser constant and equal to 1, when increasing the size of the riser. The sand riser size is increased in 0.25" diameter increments until consecutive increments have a smaller and larger time to reach solidus temperature than the sleeved riser. For example, an 8.25" diameter sand riser with a smaller time to solidus than the sleeved riser, and an 8.5" riser with a larger time to solidus, would be the sand riser sizes used to determine the apparent modulus. Using these sizes and their solidification times, the riser diameter used in calculating the apparent modulus is interpolated at the sleeved riser solidification time. This diameter is then used to calculate the apparent modulus and then the modulus extension factor.

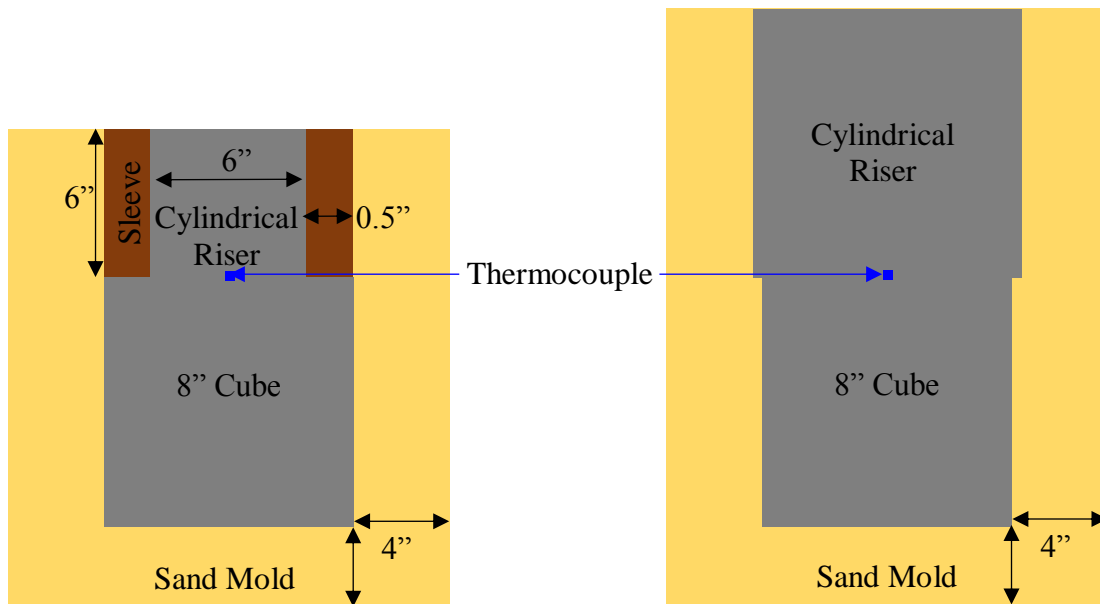


Figure 11. Simulation geometry used to determine the apparent modulus and modulus extension factor for a given riser sleeve. The riser without sleeve has a variable diameter. Riser aspect ratio is always 1.

The method outlined above is a reliable way to determine a modulus extension factor. However, be aware that there are several casting parameters that affect the value of  $f$  and that these should be controlled for consistent results. Figure 12 shows the calculated value of  $f$  for one insulating sleeve from this study depending on the modification of several parameters. Shown in Figure 12, parameters such as casting size and steel alloy have relatively small effect on  $f$ , while superheat has a large effect. Despite the variability due to superheat, the modulus extension

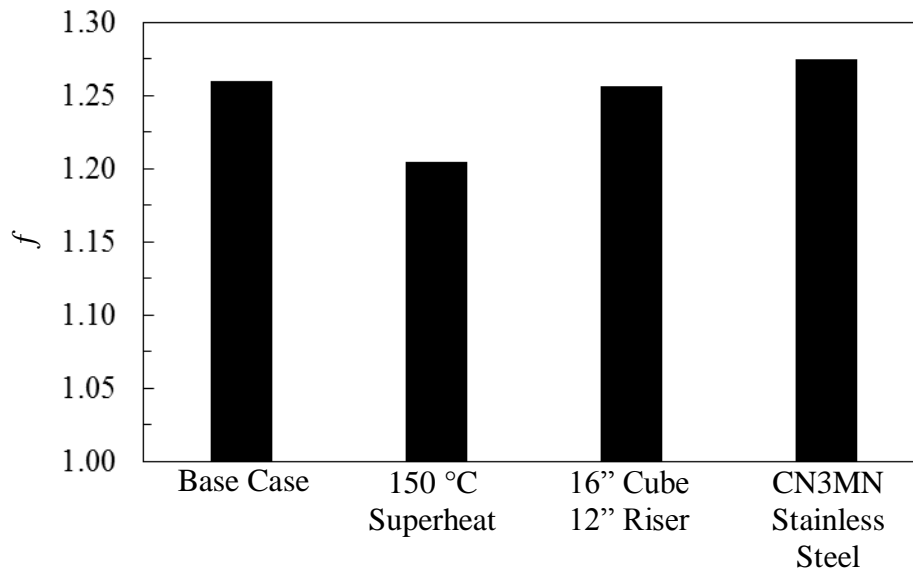


Figure 12. Sensitivity of the modulus extension factor  $f$  to three casting parameters; superheat, casting size and alloy. Base case is an 8'' cube casting with 6'' riser, 0.5'' sleeve, and WCB alloy steel with 30 °C superheat.

factor still provides a clear performance measure of a given sleeve material. Modulus extension factors, calculated via the method in the preceding paragraph, are shown in Figure 13 for the sleeve materials investigated in this study. The  $f$  values calculated in Figure 13 correspond to a constant sleeve thickness 0.5'' so their material performance can be compared. **It is very important to understand that Figure 13 does not provide data on how a sleeve product performs.** The performance of actual products will be different, based for example on a product's actual thickness and geometry. The  $f$  factors in Figure 13 can be applied in modulus calculations to estimate whether a riser with a given sleeve will be able to feed a casting section. Multiplying the geometric modulus of a riser by the modulus extension factor will yield the apparent modulus of the sleeved riser. This apparent modulus can be used as the modulus of the riser in traditional modulus calculations. These results would be preliminary and should be checked via simulation using the developed riser sleeve properties. The modulus extension factors, shown in Figure 13, provide a level comparison of sleeve materials and an estimate of sleeve material performance. How these factors translate into casting yield, and whether the exothermic effect may provide more benefit in smaller or larger castings, is discussed below. The sleeve material  $f$  values calculated above are for 0.5'' thick sleeve, and sleeve thickness affects sleeve performance. A study of optimum sleeve thickness for the purpose of increasing casting yield is presented next.

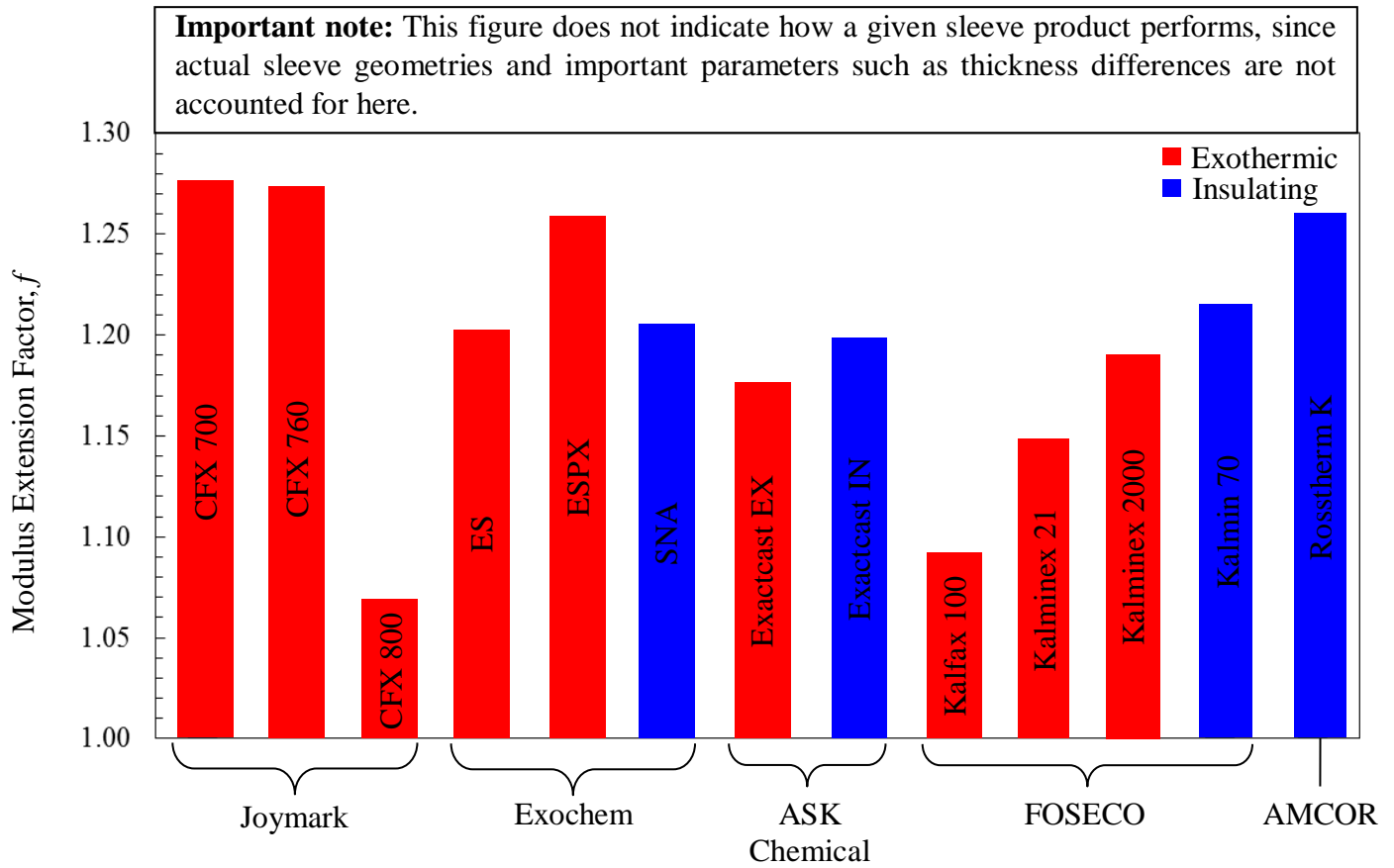
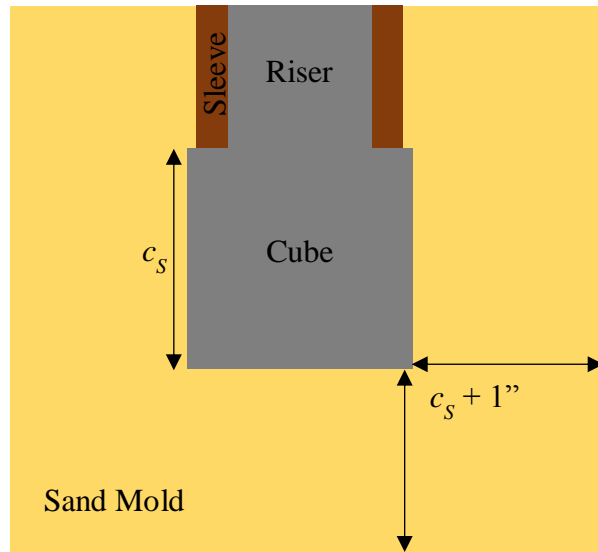


Figure 13. Modulus extension factors for the 13 sleeve materials investigated. Factors were determined via simulation for identical 0.5” thick sleeves insulating a 6” diameter x 6” tall cylindrical top riser on an 8” cube casting.

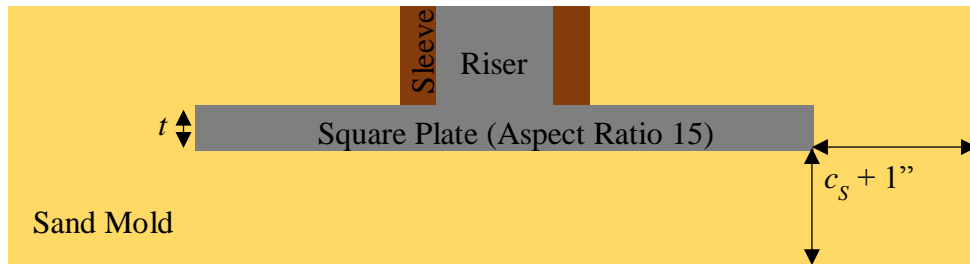
### Riser Sleeve Effects on Casting Yield

Increased casting yield is among the most prominent reasons for using a riser sleeve. If a given riser sleeve does not result in the use of a smaller riser, using that specific sleeve is unnecessary and a waste of resources. It is therefore important to clarify what improvements in casting yield are achievable by using riser sleeves. By analyzing the effect of sleeves on improving casting yield across a range of casting sizes and shapes, it is possible to answer longstanding questions, such as whether exothermic sleeves are more beneficial for smaller or larger riser diameters.

In order to investigate the effect of sleeves on casting yield, two types of casting geometries were designed for study via simulation. These geometries are shown in Figure 14. The first geometry is a cube which is a simple approximation of a *chunky* casting. This casting has a high feeding demand on the riser. Cubes of side lengths ( $c_s$ ) 3, 6, 9, 12, 18, and 24 inches were simulated in this study. The second geometry is a square plate with thickness  $t$  and aspect ratio 15. This casting geometry is *rangy* and is a casting with a low feeding demand. Plate volumes used in this study are equivalent to the volumes of the six simulated cube sizes. The goal of this casting study was to determine the smallest size of top riser required to feed the casting’s solidification shrinkage. This means that the riser size is highly variable. The riser diameter variability introduces the need for a consistent approach for determining the sleeve thickness used for a



(a)



(b)

Figure 14. General schematics of the simulation geometries used to study achievable casting yield. (a) Schematic geometry for a cube of side length  $c_s$ . Side lengths of 3, 6, 9, 12, 18, and 24 inches were used. (b) Schematic geometry for a square plate of thickness  $t$  and aspect ratio 15. The six plate castings studied have volumes equivalent to the six cube volumes.

given riser size. To address this need, a linear approximation of commercially available sleeve thickness based on riser diameter was created. The approximation can be seen in Figure 15 where sleeve thickness  $t$  versus riser diameter  $D$  values from manufacturer's product data is plotted. The linear fit,  $t = 0.08D + 0.126$ , indicates that the riser sleeve thickness increases with the riser sleeve inner diameter with slope indicating the sleeve thickness is about 8% of the riser diameter. With the sleeve thickness now determinable for any riser size, the size of the risers for these chunky and rangy castings can be minimized.

The minimum riser size will be determined based on a 10% minimum margin of safety (based on the riser height) between the casting surface and the closest region of porosity predicted in the riser's shrinkage pipe. Because the investigation will be performed using simulation software, it is needed to define the edge of the riser's shrinkage porosity region, and here it is defined at the

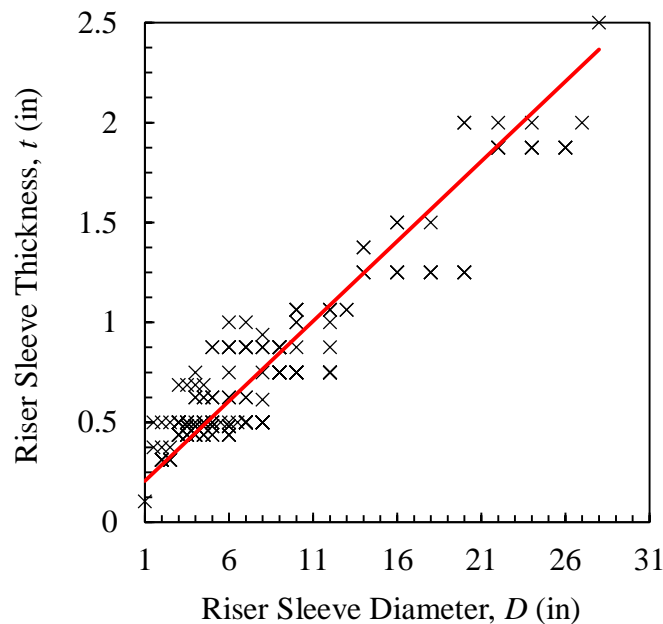


Figure 15. Plot of riser sleeve dimensions as listed in manufacturer’s product data. The red line is a linear approximation of the data. The fit indicates that the riser sleeve thickness in inches,  $t$ , increases with the riser sleeve inner diameter in inches,  $D$ , according to the equation  $t = 0.08D + 0.126$ .

0.7% porosity level. For simplicity, the risers will have an aspect ratio of 1. For consistency, simulation properties for the WCB alloy will be used with a superheat of 30°C (54°F) and a feeding effectivity of 70%. Feeding effectivity is the main simulation parameter used in *MAGMASoft’s* algorithm for riser shrinkage pipe prediction. Minimization of the riser size is illustrated in Figure 16 for cases with a riser pipe safety margin that is 7% (left side image) and 12% (right side image), where the smallest allowable riser size increment is 0.1”. The 12% safety margin case is taken as the minimum riser size, or it is the case having the maximum achievable casting yield. Riser sleeve material properties for the Joymark CFX 760, Kalminex 2000 and Kalmin 70 were used in the casting yield study. The Kalminex 2000 and Kalmin 70 material data was used since they correspond to the value of  $f \approx 1.2$ , and are representative of both insulating and exothermic sleeve materials studied referring to Figure 13. The Joymark CFX 760 was chosen since it has one of the largest values of  $f = 1.27$ .

The results of this casting yield investigation are shown for the chunky and rangy castings in Figure 17(a) and (b), respectively. Immediately noticeable is that the rangy plate castings on the right side plot have much higher casting yields than cube castings of the same volume. Also noticeable is that the maximum achievable casting yields for the insulating (Kalmin 70) and exothermic (Kalminex 2000) sleeve materials with  $f = 1.2$  overlap each other entirely. One would expect a difference in casting yield between these insulating and exothermic sleeve materials if the exothermic effect made a difference at a given casting size, because these sleeves have a similar  $f$  value. On the other hand, for the chunky castings and the Joymark CFX 760 sleeve material with  $f = 1.27$ , there is a noticeable increase in casting yield for all casting

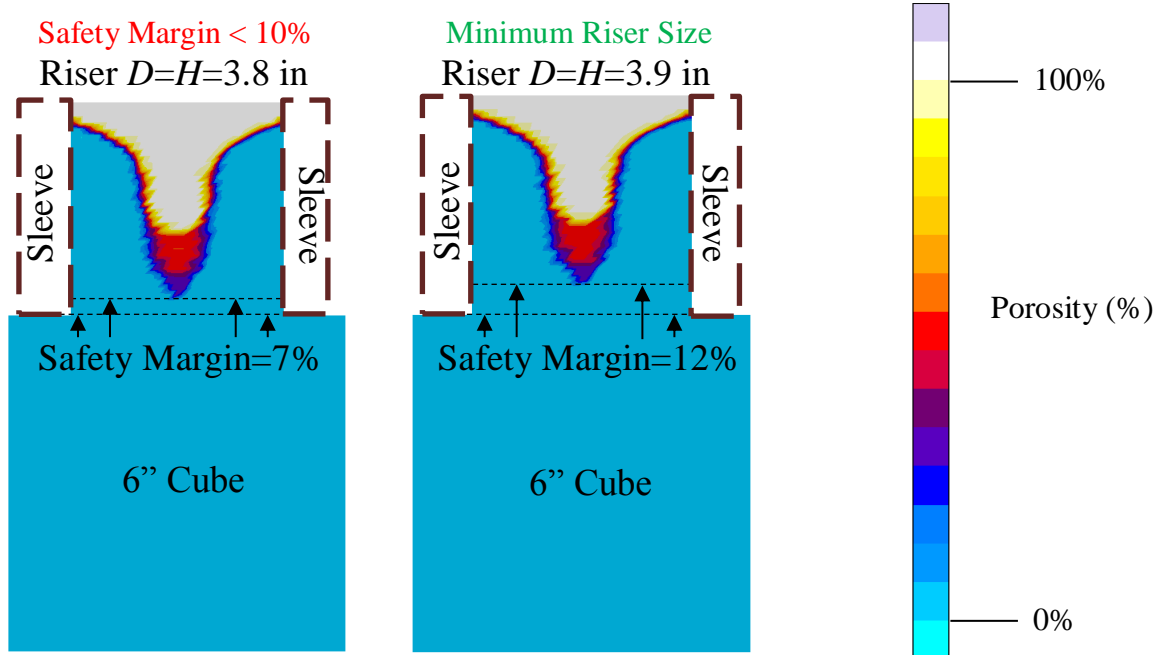


Figure 16. Examples of *MAGMASoft* shrinkage porosity used to determine maximum achievable casting yield. A 0.7% porosity threshold was used to determine the extent of the riser pipe. The minimum margin of safety goal was 10% of the riser height.

volumes over the  $f = 1.2$  sleeve materials. For this sleeve material applied to rangy castings (though not plotted in Figure 17(b)), there is only a 0.5% increase in the casting yield over the  $f = 1.2$  sleeve materials at the largest casting volume. In other words, a conclusion from this part of casting yield study is that what matters for a sleeve is its  $f$  value. If the exothermic effect increases the  $f$  value, then it is beneficial. It is fair to conclude that whether a sleeve is exothermic or insulating is not alone relevant to performance. Rather the overall quality of the sleeve will determine its performance. Additionally, the thickness of a sleeve plays an important role in the performance of the end product.

In order to determine the effect of sleeve thickness on casting yield, the same procedure is employed using the cube and square plates of varying sizes as in the yield study. Only now, rather than using a continuously varying sleeve thickness with riser size, the riser size will be minimized for a set sleeve thickness. Simulations were performed for cube castings of side length 3, 6, 12, and 24 inches and square plate castings of equivalent volumes. Riser sleeve properties for the typical exothermic riser sleeve material (value of  $f \sim 1.20$ ) used in the yield study will be applied to these simulations.

The results of the simulations studying the effect of sleeve thickness on casting yield are shown in Figure 18. The results are presented as the absolute increase in yield for the exothermic sleeve riser casting over the same casting with no sleeve for variable sleeve thickness. In the plot, the sleeve thickness is presented as scaled with the riser diameter ( $t/D$ ). This manner of presentation is used since logic dictates that a riser with twice the diameter should have a sleeve twice as thick. This logic is proved true given that the results in Figure 18 collapse to well-defined curves

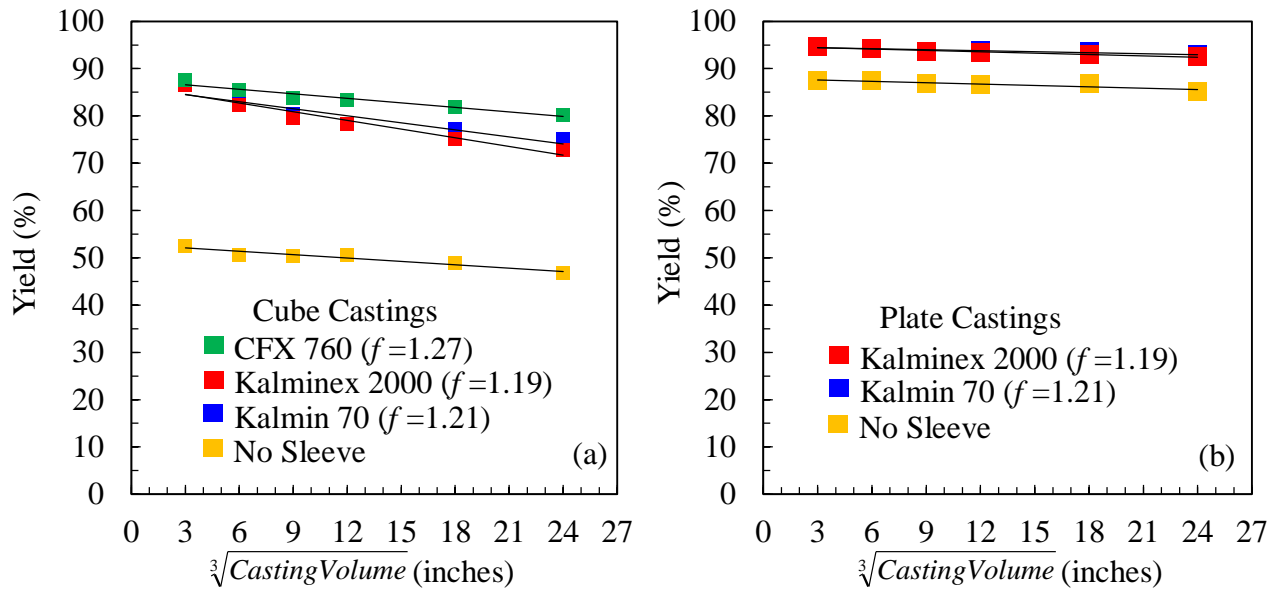


Figure 17. Maximum achievable casting yield for (a) cube castings and (b) square plate castings without sleeve, castings with insulating riser sleeves, and castings with exothermic sleeves. Insulating and exothermic sleeves behave similarly at all sizes.  $f$  values are those from Figure 12.

for cube and plate castings when the thickness is scaled. Note that Figure 18 shows that increase in casting yield for rangy plates (triangle symbols) arising from using the sleeve are about 5 times less than for the cube castings. These results indicate that sleeves might not be as useful for rangy castings, if yield increase is the goal. There are other reasons than casting yield why sleeves might be needed in rangy castings such as product quality improvement. Note too that if a riser sleeve is used for a rangy plate, the scaled sleeve thickness does not need to be more than 0.1 for a typical sleeve; beyond that there is little benefit. For chunky castings such as cubes however, the results show that riser sleeves generate large increases in yield, up to 40% in an absolute sense. This trend was apparent in Figure 17 with casting yield increasing from about 50% to over 80% for the sleeve cube casting. Figure 18 also suggests that an optimal sleeve thickness for chunky castings is *at least* 0.2 times the riser diameter.

Note that the data in Figure 18 and the optimum sleeve thickness will be different for a different sleeve material  $f$  value. It is logical that for higher sleeve material  $f$  values, the maximum possible casting yields in Figure 18 will be larger, and that the increasing yield with increasing thickness curves will be steeper.

Using the information in Figure 18 for chunky castings with higher geometric moduli, the plot in Figure 15, showing the commercially available sleeve thicknesses ( $t$  vs.  $D$ ), can be transformed into  $t/D$  vs.  $D$ . Then adding into this data the absolute yield increases corresponding to chunky castings for the scaled sleeve thickness  $t/D$  from Figure 18, a plot of commercially available sleeves and their impact on yield improvement for chunky castings for riser diameters from 1" to about 30" results as, seen in Figure 19. The data plotted in Figure 19 give foundries insight into



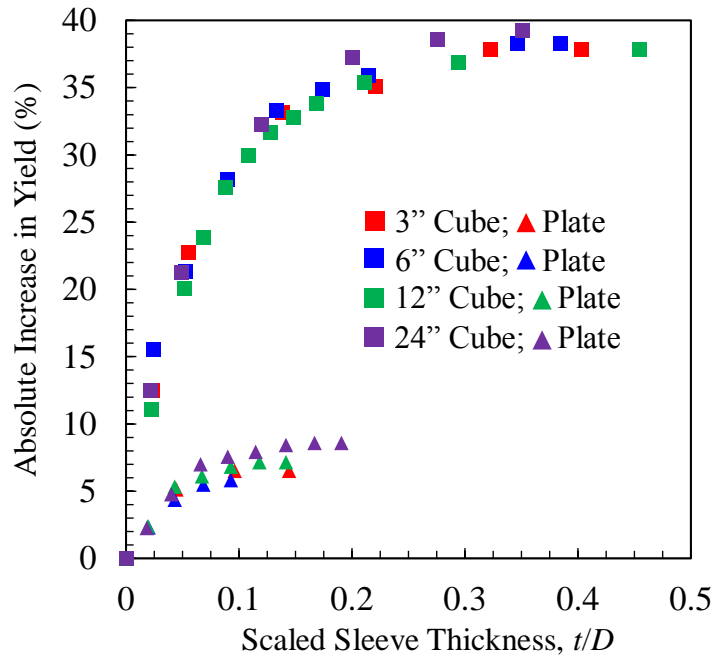


Figure 18. Absolute increase in maximum achievable casting yield for the exothermic rise casting over the casting with no sleeve case versus the scaled sleeve thickness ( $t/D$ ) used. Results are shown for cube castings (squares) and square plate castings (triangles) with an aspect ratio 15 having volumes equal to those of the cube castings.

the feeding aids available to them for a range of riser diameters and their performance from a casting yield perspective. The figure demonstrates that opportunities exist for substantial yield increases in larger castings sections with higher geometric moduli.

The transformed plot in Figure 19 shows that most commercially available riser sleeves should give at least a 25% increase in casting yield. This study shows that doubling the riser sleeve thickness at larger diameters could result in an absolute increase in casting yield by 10%. This is a result that should be of great interest to the steel foundry industry. It remains to be seen whether this deficiency in sleeve products currently available to the industry is an issue any sleeve producers might address. There is also the question of whether the additional *assumed* cost for improved/thicker sleeves would be a cost that foundries are willing to bear.

For the chunkier castings, results from the casting yield and sleeve thickness study shown in Figure 18 indicate that if the scaled sleeve thickness is less than about 0.1 there will be a dramatic drop off in the maximum possible casting yield. It is apparent from Figure 19 that there are a considerable number of sleeve products supplied at or below this scaled sleeve thickness, and many of those are for larger riser diameters, which presumably will be used on larger chunkier castings.

## Conclusions

Riser sleeves have been used in the metal casting industry for decades. Despite the longevity and ubiquity of their use, there are many uncertainties and gaps in our knowledge of their thermophysical properties and their optimal use. In this study, thermophysical properties for

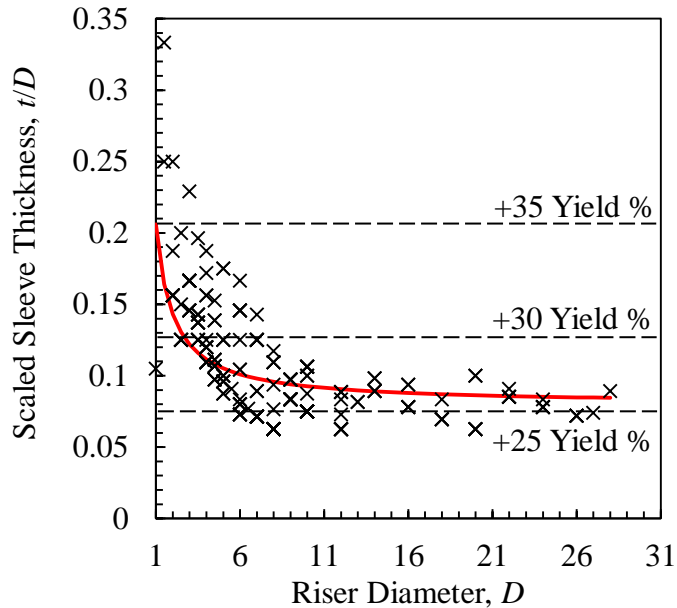


Figure 19. Scaled sleeve thickness of commercially available riser sleeves as determined from manufacturer product information and approximate predicted increases in casting yield for high moduli castings. Predicted increases in yield correspond to the absolute increase in yield over chunky castings with no sleeve. The red curve is the approximation of commercially available sleeve thicknesses derived from Figure 14.

thirteen commonly used riser sleeve materials have been developed. Using these properties, simulations have been performed in order to analyze sleeve performance and investigate important sleeve parameters and their effects on casting yield.

The modulus extension factor, a concise measure of a riser sleeve's performance has been calculated for several sleeve materials based on a common/uniform sleeve geometry (0.5" thick, 6" diameter and 6" high). While this result does not indicate the performance of a given sleeve product (since product geometry is not considered), this quantity can be used in traditional modulus calculations to estimate a sleeve material's performance. An investigation of casting yield improvement was performed using exothermic and insulating sleeves of identical thickness and geometry. This study showed that for insulating and exothermic sleeve materials having properties that result in the same modulus extension factor ( $f \approx 1.2$ ), the exothermic effect makes little difference in sleeve performance at small or large riser sizes. For the range of casting volumes studied (from 3 to 24 in<sup>3</sup>), it was found that the mechanism of achieving a high modulus extension factor for a sleeve (i.e. insulating or exothermic material) is not what is important, a given sleeve product's overall quality is determined by its material and its geometry. It was found that up to a 40% absolute increase in casting yield was possible when using top riser sleeves on chunky cube-shaped castings for both insulating and exothermic sleeves having  $f \approx 1.2$ . For rangy castings, having a square plate-shaped geometry with aspect ratio of 15, it was found that only a maximum absolute increase in casting yield of 8% is possible. In general, sleeves were found to provide a relatively small payback in casting yield improvement for rangy castings when compared to the chunky castings. An important conclusion here is that using

sleeves in rangy casting applications to increase casting yield might be unnecessary. It is acknowledged though that there are reasons other than yield for using sleeves, such as increasing casting soundness, quality improvement and addressing difficulties in feeding a particular casting.

In another part of the casting yield and sleeve use investigation, the maximum achievable casting yield was found to be highly dependent on sleeve thickness. Data on commercially available riser sleeve product geometry was collected and presented as a plot of sleeve thickness  $t$  versus diameter  $D$ . It was found that the best-fit curve  $t = 0.08D + 0.126$  describes the overall relationship between thickness and diameter. When the scaled thickness  $t/D$  for this data is compared to the results of the casting yield study, it was found that many riser sleeve products have below the optimum thickness for maximizing casting yield, particularly for larger risers in the range of 10" to 30" diameter. The optimum scaled thicknesses for maximizing the casting yield of rangy and chunky castings was found to be approximately 0.1 and 0.22, respectively. These optimum sleeve thicknesses correspond to a sleeve material  $f \approx 1.2$ . For higher sleeve material  $f$  values, the maximum possible casting yields will be larger the 40% and 8% values found for  $f \approx 1.2$  sleeve material applied to chunky and rangy castings, respectively. Also, with larger values of  $f$ , it is a logical conclusion that the optimum thickness will be less than the scaled thickness values of 0.1 for rangy castings, and 0.22 for chunky castings.

### **Acknowledgements**

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