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A Computational Study of Feeding Rules and Yield Improvement Techniques

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Abstract

The results of a computational study of feeding and the promotion of feeding by yield improvement techniques is presented. The computer simulations were performed using a commercial solidification software package examining the simple plate-like geometries addressed in the SFSA feeding rules. Solidification criteria from the computer model were used to develop simulation determined feeding distances which are then compared with feeding distances determined by the SFSA guidelines. In many cases these comparisons indicate that the present feeding guidelines are overly conservative. The advantages of increasing casting yield through increased feeding distance by using yield improvement methods is also investigated. Improved feeding distances and casting yields resulting from using insulating riser sleeves and block chills (termed passive methods), and active heating and cooling are presented and compared. The benefits of increasing the casting yield through the vertical stacking of castings, and the semi-continuous casting of vertically coupled and stacked castings is also presented.

1. Introduction

The present study was undertaken to determine feeding distances and examine yield improvement techniques using a modern casting simulation code (MAGMAsoft). The risering guidelines presently accepted and published by the Steel Founders' Society of America (SFSA) [1] provide a set of graphs and nornographs for the feeding distances in plates ($W \geq 2T$), semi-plates ($T<W<2T$), and bars ($W=T$). These basic shapes can be used and combined to determine feeding distances for more complicated casting geometries. Various riser configurations, chills, taper, and molding materials are considered in the guidelines for both carbon and high alloy steels. The SFSA feeding guidelines are based primarily on computer simulations conducted by Wallace and coworkers in the late 1960s, but were also supported by limited experimental work. A casting yield survey [2] among steel foundries in North America was recently undertaken by the present investigators which revealed that at least 40% (by weight) of all castings are risered using the SFSA published guidelines or rule-based software developed from those guidelines. Re-examination of the SFSA guidelines would produce improved rules for those already using the guidelines, and promote use of the rules among those foundries which currently do not use the SFSA rules.

The present computational study was undertaken as part of a larger research project on yield improvement. The goal of this study is not only to examine feeding rules, but also to investigate conventional and new yield improvement techniques. The objectives of the study can be summarized as follows:

(1) Examine how, and how accurately, a modern casting simulation code can reproduce the feeding rules in the SFSA guidelines.

(2) Develop, if possible, more accurate feeding rules for the basic casting shapes in the SFSA guidelines.

(3) Extend the current rules to cover thinner and thicker sections, additional basic shapes, and other steel grades, as they may be commonly encountered in modem practice.

(4) Examine if and how feeding rules can be tailored to the class of soundness required in some or all parts of a casting.

(5) Use simulation to examine and improve the conventional techniques for the purpose of yield improvement.

(6) Use simulation to examine the effectiveness of new and unconventional directional solidification techniques for the purpose of substantial yield improvement.

This paper summarizes results that were obtained during the first year of the project. They satisfy most of objective (1), some of objective (2), a limited portion of objective (3), none of objective (4), and some of objectives (5) and (6). Once complete, all results will be published in a SFSA Technical Report.

In the near future, casting trials will be performed using 3 inch thick plates, which was found to be the average casting section thickness reported in the casting yield survey [2]. It is expected that the plant trials will verify the predictions from the simulations.

Finally, it is not expected that the new feeding rules established here will diminish the need for complete casting simulations in steel foundries. Given the great variety of complex shapes encountered in practice, simple rules will either not be applicable, or application of the rules in combination will not result in optimal risering. Instead, the fundamental work performed here will determine how conservative the existing rules are, and establish trends and estimates for improved rules. This insight will guide initial rigging layout. It will also result in additional confidence in simulation, guidance in using simulation effectively, and support the establishment of improved directional solidification techniques for yield improvement.

2. Methodology for Determining Feeding Distances through Simulation

The feeding distance is measured from the riser edge and designates the maximum distance over which a riser can supply liquid feed metal. In the event that risers are unable to provide the required feed metal, local porosity will form in the casting in the last region to solidify. For example, in the case of bars or plates longer than the required feeding distance, sound zones are observed adjacent to the riser and to the end opposite to the riser, but there will be an unsound section located between these zones.

Quantitative models and correlations relating solidification parameters to porosity formation of castings have been sought for a long time. Niyama et al. [3] developed a general, and often used, criterion to predict shrinkage defects. They found that a plot of the parameter $G/\sqrt{R}$ (the temperature gradient divided by the square root of the cooling rate at the end of solidification at each point within a casting) corresponded well to the distribution of shrinkage porosity, either the gross type or centerline type. Also, they found that the critical value of the parameter for shrinkage formation was independent of the alloy cast, and the size and shape of the casting in the range studied. The critical value for steel was about 1.0 $deg^{1/2}$ $min^{1/2}$ cm^{-1}. Currently the Niyama criterion is used in a number of commercial casting simulation software packages, and is generally believed to work well for short freezing range alloys such as steel.

In the present study, the postprocessor of the commercial casting simulation software used to calculate the heat transfer during solidification provides the Niyama value distribution in the casting. The Niyama values are then used to determine the required feeding distance, as will be described below. Additionally, the software provides predictions of the feeding percentage at any particular location in the casting. Feeding percentage is considered to be an indication of larger shrinkage holes or macroporosity. The question of which parameter is the best indicator of porosity and shrinkage is still open for debate, and more experiments coupled with simulations are needed to clarify this issue. Nonetheless, for the lack of a more reliable method, the Niyama values are used in the present study to calculate feeding distances as of the present time.

Attempts were made to correlate the Niyama value with the shrinkage classes used in foundry practice. According to practitioners of casting simulation, when the minimum Niyama value is in the range of 0.7 to 1.4 $deg^{1/2}$ $min^{1/2}$ cm^{-1} the casting is generally considered to be sound. Although, some segregation may be present. When the minimum value is less than 0.7, it generally indicates Class IIshrinkage porosity or worse. A critical value of 0.7 is adopted in this study. Class II is also the shrinkage category on which the present SFSA guidelines [1] are based.

The following procedure was used to determine the feeding distance by computer simulation.

(1) A casting is selected from the basic shapes, i.e., bars, semi-plates or plates. The thickness, T, and width, W, of the casting are fixed.

(2) The rule feeding distance is found for the given geometry by reading the corresponding nomographs in the SFSA guidelines [1]. The rule feeding distance is denoted by FD_R.

(3) The riser diameter and the casting length are calculated based on T, W, and FD_R according to the SFSA guidelines [1]. The riser height is set to be the same as the riser diameter to maintain a minimum sufficient riser size.

(4) The solidification process is simulated with consideration of mass energy transport through the riser neck. The Niyama values are then visualized using the software postprocessor without interpolation after simulation.

(5) If the minimum observed Niyama value is everywhere (except the riser) greater than the minimum threshold value (0.7) the casting length is increased. If the minimum Niyama value at any point (except the riser) is less than 0.7 the length is decreased. In addition, if the minimum Niyama value is equal to 0.7, but the area with this value is large, the length is decreased too. In order to establish narrow bounds on the feeding distance, the casting lengths are varied in small increments in all simulations in this report (usually, the increments of feeding length are only 0.25”).

(6) A sufficient number of simulations are performed (usually no more than five) with different lengths, until the casting length is found where the minimum Niyama value of 0.7 first appears in a given computational cell.

(7) For this casting length, the distance from the edge of the riser to the end farthest away from the riser is the feeding distance from the simulations, and is denoted by FD_S.

With the feeding distance determined, the yield of the casting corresponding to that feeding distance is calculated here by dividing the weight of the casting by the sum of the weights of the casting and the riser (the gating system is not included).

The simulations within the software require conditions and parameters to be set. Unless otherwise noted, all simulation cases are based on the assumptions of sufficient riser size, initial steel temperature of 1620°C, perfect plate geometry (no swell), no filling and no convective flow. All other conditions were chosen so as to duplicate the conditions on which the SFSA guidelines [1] are based. Unless otherwise noted, the simulation parameters are:

Cast material - steel (carbon or low alloy)
Mold material - silica
Core material - dry silica
Chill material - steel
Initial steel temperature - 1620°C
Initial temperature of mold, core and chill - 20°C
Interfacial heat transfer coefficient between cast and mold materials - 1,000 W/m^2K
Interfacial heat transfer coefficient between chill and cast materials - 1,500 W/m^2K
Interfacial heat transfer coefficient between chill and mold materials - 1,000 W/m^2K
Mold material thickness - ≥2”
Feeding effectivity - 35%

All thermophysical properties were taken from the software database.

A base case was chosen, consisting of a horizontal plate with a thickness of 4”, width of 8’’ and variable length. Simulations performed on the base case according to the present procedures resulted in the Niyama and feeding percentage distribution plots shown in Figures 1 and 2. The minimum observed Niyama in the base case plate as shown in Figure 1 is 0.7, which corresponds to the threshold value established for Class II shrinkage porosity. A V-shaped shrinkage pipe, resulting from contraction , is visualized as expected in Figure 2. The riser size is deemed sufficient. The resulting simulation feeding distance (FD_S=17.75”) is very close to the feeding distance from the SFSA guidelines (FD_R=18”). The agreement is purely coincidental, since it will be shown that the differences between FD_S and FD_R can be substantial in many cases. Nonetheless, the base case results establish confidence in the present methodology.

3. Results and Discussion

3.1 Overview of Simulation Cases Reported Here

Numerous simulations were performed to investigate feeding distances and various yield improvement techniques. In this paper, we present only a limited set of simulations, selected to illustrate the most interesting results that have been obtained so far. An overview of the cases discussed in the following is provided in the table below.

SFSA Rule Cases	Other Configurations	Passive Yield Improvement Techniques	Unconventional Directional Solidification Techniques
End effect End chill Side riser	Thick sections Thin sections	Elliptical riser cross section Insulating riser sleeves	Water-cooled copper chill Direct water chilling Arc heating Stacking of castings

3.2 Examination of Basic Shapes and Configurations

3.2.1 End effect

The geometry for investigation of the end effect is illustrated in Figure 3. Each basic shape (bar, semi-plate, and plate) was simulated. The resulting feeding distances from the simulations (FD_S) and their comparison with rule feeding distances (FD_R) are summarized in Figures 4 and 5. It can be seen that for bars and plates, the feeding distance generally increases with thickness. The agreement between FD_S and FD_R can be considered good for small thicknesses, but deteriorates with increasing thickness and increasing width. The largest difference can be observed for the largest thickness and width plate simulated (FD_S is about 70% greater than FD_R for a T=6” and W=36” plate). According to the SFSA guidelines, the feeding distance does not increase significantly beyond a width to thickness ratio of 2. However, as shown in Figure 5, the simulated results show that this does not hold for plates with a thickness greater than about 4”.

The yield for the plates with simulation feeding distances was also calculated, where the riser size is determined according to SFSA rules. The results and their comparison with the yield calculated according to rule feeding distances are summarized in Figure 6. It can be seen that for plates with the same width to thickness ratio, the yield decreases with an increase in plate thickness according to the rules, while the yield is approximately a constant value according to the simulations. When the plate thickness is greater than 4” or width to thickness ratio is greater than 2, yield improvement is observed.

3.2.2 End chill

The configuration for the investigation of the effect of an end chill is shown in Figure 7. The simulation feeding distances for plates with a thickness of 4” are summarized in Figure 8 and compared with the rule feeding distances. The interfacial heat transfer coefficients between the chill and the casting and between the chill and the sand were set to 1500 $W/m^2/K$ and 1000 $W/m^2/K$, respectively. Also, the chill geometry was fixed with the chill thickness, CT, set to 2/3T, and the chill width, CW, set to T, where T is the plate thickness. The chill material was steel.

It can be seen from Figure 8 that for the base case of a 4”x8” plate (W/T=2), there is almost perfect agreement between FD_S and FD_R, as was already observed for the case without a chill. Note that the chill increases the feeding distance in this case from 17.75'' to 22.8". For other widths, Figure 8 show that the agreement between FD_S and FD_R follows the same trends as in the cases without a chill, i.e., the agreement deteriorates with increasing width to thickness ratio. In other words, the large disagreements for the W/T=6 cases, for example, observed in Figures 4 and 5, will also be present with a chill. More simulations would need to be performed to verify this and establish new rules for the end chill cases.

3.2.3 Side riser

The configuration for the simulation of the side risering is shown in Figure 9. The feeding distance of a side riser in the forward direction is considered equivalent to that of a top riser for the plate with end effect. If the width of the plate is larger than the forward feeding distance, the feeding distance in the lateral direction (denoted as FD) will be zero. In this case, a defect always appears in the plate no matter how small the length is. It should be noted that for the plate with end effect, the simulation feeding distances (FD_S) increase with the width to thickness ratio, as shown in Figure 5. Therefore, the forward feeding distances will increase with the plate length for the side riser cases.

Simulations were first performed for 4" thick plates with different widths. In Figure 10 the simulation feeding distance as a function of the width to thickness ratio and a comparison to the rule values from the SFSA guidelines are plotted. It illustrates that the simulation feeding distance is larger than the rule feeding distance, and larger width to thickness ratios lead to larger differences. According to the rules, the feeding distance in the lateral direction for a 16" plate is zero, while the present simulations predict a feeding distance of about 20". However, simulation feeding distance is indicated to be zero when the width increases to 24" (W/T=6). It should be noted that for the 20" wide plate (W/T=5) the feeding length should be more than 16" to avoid the defects caused by the large width.

The yield for plates with side riser was also calculated. With the riser sizes determined according to the SFSA rules, the results for the yield from the simulation feeding distances and the results from the rule feeding distances are summarized in Figure 11. It is obvious that the yield improvement increases with an increase in width to thickness ratio. When the ratio is equal to 3.5, the yield improvement is about 16%.

Simulations with different plate thicknesses were also performed. All the simulation results as a function of plate thickness and the rule feeding distances are compared in Figure 12. Contrary to the rules, the simulation feeding distance increases with the width to thickness ratio. However, both simulation and rule results are in agreement that when the width of the plate is large enough, the feeding distance are indicated to be zero. It is interesting to note that, according to the SFSA guidelines, the feeding behavior of bars and semi-plates with side risers is much different from that for plates with W>2T, which is is not indicated by the simulation result in the present study. Certainly more study, and possibly even some trial castings will be needed to explain the inconsistencies between the current rules and the simulations.

3.2.4 Thick sections

For the end effect cases, the plate thicknesses presented by the feeding distance nomogragh in the SFSA guidelines are from 1.5" to 6". In order to determine feeding distances and further establish rules for thicker sections, simulations were performed for plates with a thickness of 12", which is the average maximum casting thickness according to the survey [2]. The results are plotted as a function of the width to thickness ratio (W/T) in Figure 13. A comparison with the feeding distances according to McNaughton [4] and those extrapolated from the rules is also shown in Figure 13. The rule extrapolated results are in fairly good agreement with those given by McNaughton [4], but both results are much lower than the present simulation results, especially for plates of a width to thickness ratio over 2. For the 72" wide plate, the rule extrapolated result is 35.8" and the simulation result is 80.5". This remarkable difference is in good agreement with the results obtained for the 2" to 6" thick sections: the larger the thickness, and width to thickness ratio, the larger the difference between FD_S and FD_R.

The yields corresponding to the simulation feeding distance cases were calculated for the thick-section plates. These results, and the corresponding results of McNaughton [4] (for feeding distance and rule extrapolated feeding distance) are compared in Figure 14. It can be seen that the maximum yield is improved by up to 7% when the simulation feeding distance is used. Also, it should be noted that the number of risers can be reduced with larger feeding distances, which will further increase the yield.

3.2.5 Thin Sections

Explicit rules for thin sections (T<2") are not provided in the SFSA guidelines [1]. However, thin section guidelines are presented in SFSA Techntcal report No. 30 [5] as: FD=12T (class II shrinkage level) and FD=8T (perfect casting) for plates with thicknesses less than 0.5". It is interesting to note that extrapolating the SFSA rules [1] to thinner sections would result in a negative feeding distance. This is an illustration that rules specifically developed for thin sections are necessary to improve the casting yield and reduce scrap in castings with thin sections.

The effect of filling (and its proper consideration in simulation) is believed to be important for thin sections. Simulations with and without filling were performed on a plate with a thickness of 0.25" (chosen since the average minimum thickness from the survey [3] was found to be 0.3"). In addition, simulations were performed on a 0.25"x1" plate to investigate the effect of varying the filling conditions. The feeding distances with different pouring temperatures (Ti), filling times (FT) and ingate sizes were determined from simulations. In addition, the feeding distance with consideration of thermal and solutal convection during solidification was also determined. The gating system for the filling simulations was designed according to AFS tutorial materials [6].

All results and their comparison with the feeding distance calculated according to the SFSA technical report [5] are summarized in Figure 15. It can be seen that the average simulation feeding distance for the 0.25 " plate is about the same as the result from the SFSA Technical report [5] for the perfect castings. Comparing all results in Figure 15, it can be seen that:

(1) With the same initial temperature, FD_S with filling is larger than cases without filling. A longer filling time also leads to an increase in the FD_S. With a filling time of 5s, the simulation feeding distance is about 33% longer than that with a filling time of 2s.
(2) Lower pouring temperature will decrease the simulation feeding distance.
(3) Too large or too small ingate size will decrease the simulation feeding distance. In this case, the proper ingate is 0.11 " deep and 0.22” wide. Using the same depth, the wider ingate is set to 0.5” wide and the narrower ingate is made 0.1” wide. The resulting simulation feeding distance decreases 24% for the wider ingate, and 33% for the narrower ingate.
(4) FD_S with consideration of convective flow in the liquid metal is lower than that without flow modeling. This could be explained by the fluid flow causing a more uniform temperature gradient which in turn leads to a lower Niyama value.

For all these results, the lesson learned is that longer filling time, higher pouring temperature and proper designed gating system will increase the feeding distance for the 0.25" thick plate. However, this conclusion should be viewed as a preliminary finding since it is drawn from limited simulation cases. In fact, it is not clear at the present time whether rules for thin sections can be developed at all.

3.3 Examination of Passive Yield Improvement Techniques

3.3.1 Elliptical riser cross section

The configuration for the simulation of elliptical riser cross sections is schematically shown in Figure 16. Simulations were performed for the base case, the 4"x8” plate, with elliptical cross section risers of axis ratios (b/a) of 3 and 5. For these cases the feeding distance is given by the shortest distance from the edge of the ellipse to the corner of the plate, as shown in Figure 16. The resulting feeding distances and their corresponding plate lengths are summarized in Figure 17. It can be seen that feeding distance decreases with ellipse axis ratio, while the corresponding plate length, on the other hand, increases with the ratio. Elliptical risers with axis ratio of 3 and 5 can feed plates with lengths of 49.5” and 56.5”, respectively. According to the rules [1], multiple risers should be applied when the plate feeding length is longer than the feeding distance. For these two cases, two risers should be applied according to the rules [1]. The yield for plates with elliptical risers and multiple cylindrical risers can be calculated, and the results are functions of plate length as given in Figure 18. It can be seen that the yield for plates with elliptical cross section risers increases 4.8% for the L=49.5” plate, and decreases 3.7% for the L=56.5” plate, relative to the plate with two circular risers. Therefore, if the plate length is within several inches longer than the length one circular riser can feed an elliptical cross section riser is recommended, which can improve the yield by up to 8.7% (when L=43.55”) for the 4”x8” plate.

3.3.2 Insulating riser sleeves

Simulations were performed to examine the effect of varying the thickness of insulating riser sleeves. The configuration is shown in Figure 19 . The simulations were conducted on the base case, a 4”x8” plate. The sleeve thicknesses simulated were 0.25”, 0.5”, 1”, 1.5”, 2”, 3”, and 4”. The sleeve material is offset with a gap from the riser casting junction by 10% of riser diameter, as shown in Figure 19. In an effort to compare the yield of castings with different sleeve thicknesses, risers of a just sufficient size are utilized in the simulations. The feeding distance and yield results of the simulations are shown in Figure 20, where the yield is calculated for plates of length equal to the simulation feeding distance. It can be seen that the simulation feeding distance increases with an increase in the sleeve thickness. This is to be expected when the mass energy transport is modeled since hotter liquid from the insulated riser promotes feeding. The yield, however, after initially increasing rapidly with an increase in sleeve thickness, levels off to a constant value of 91.5% when the sleeve thickness is greater than 1 .5”. These results imply that the casting yield cannot be improved by using an insulating sleeve thickness beyond a certain value. From these results the recommended sleeve thickness is between 0.5” to 1.5”, which results in casting yield increases between 16.2% and 19%.

3.4 Examination of Directional Solidification Technique

3.4.1. Water-cooled copper chill and direct water chilling

The effect of a water-cooled copper chill and direct water chilling were examined for the base case, the 4"x8" plate. The water-cooled copper chill is simulated by inserting a cooling pipe into a conventional end chill as shown in Figure 21. The water cooling serves to maintain the chill temperature at a low value during solidification, resulting in much higher heat fluxes at the plate end.

Direct water chilling was simulated by first placing a large cooling medium, a reservoir kept at a constant low temperature, next to the casting and then setting the heat transfer coefficient between the casting and the cooling medium to a suitably large value. This configuration is shown in Figure 22 . Direct water chilling will result in a large heat transfer coefficient (HTC) between the water and the casting (typically 2,000-3,000 $W/m^2/K$). Since a large temperature difference between the casting and the water also exists, a very high cooling flux results.

Simulation results are only slightly affected by the HTCs between the chill and cooling water, and the casting and direct chilling medium. The simulation feeding distances for the base case with four different end conditions are shown in Figure 23. Note that a water-cooled copper chill is only slightly more effective than a conventional chill in improving the feeding distance. Most of the chilling effect appears to be confined to the end of the plate even though the water-cooled copper chill is much colder than the steel. Compared to the water-cooled copper chill, direct water chilling increases the feeding distance by about another 1.5 inch. This very modest increase indicates, again, that the feeding length is no longer limited by the cooling heat flux at the plate end, but by lateral heat losses. A representative plot of temperatures during solidification with direct water chilling is shown in Figure 24.

The corresponding maximum yields (yield for plates of length equal to the simulation feeding distance) are summarized in Figure 25. It can be seen that when using a water cooled copper chill, the yield is only 0.5% more than for a conventional chill, and direct water chilling increases the yield by another 0.8%. These slight increases in yields are the results of the marginally increased feeding distances. Therefore, the potential for increased casting yields through water-cooled copper chills or direct water chilling seems limited.

3.4.2 Arc heating

Arc heating of a riser was simulated by placing a volume of heating medium inside the riser, as shown in Figure 25. Once again, the simulations were performed on the base case, a 4"x8" plate. The heating medium is held at a constant high temperature during the solidification. The heat flux is controlled by setting the HTC between the heating material and the riser; an extremely high HTC when the arc heating is on, and an extremely low HTC when the arc heating is turned off. The simulation feeding distance and corresponding yield with arc heating are compared in Figures 27 and 28 with the results of the base case without arc heating. It is seen that the feeding distance increases by only 0.5 inch. The yield improvement, however, is above 20%. This is, of course, a direct consequence of the low and flat metal level in the riser at the end of solidification with arc heating, as illustrated in the feeding percentage plot of Figure 29. Arc heating can therefore be considered to be a promising technique for improving casting yield.

3.4.3 Stacking of castings

Two kinds of vertical stacking configurations were simulated to investigate the potential benefit of stacking. The first case is performed for vertical stacking of horizontal plates fed by one side riser, as shown in Figure 30. The plate selected is the base case (4”x8") plate with a length of 25.5”, where the feeding length is the same as the simulation feeding distance for one plate with side riser. The riser diameter is calculated according the rules for one plate with side riser. Simulations were performed by varying the casting distance (noted as CD) until the smallest riser height is found. The feeding percentage plot for the two stacked plates case with optimum riser height is shown in Figure 31, illustrating the distribution of shrinkage in the riser. Casting yields for one, two, and three stacked plates were calculated. The results are shown in Figure 32. It can be seen that the yield is about 13% more for two stacked plates than for one plate; however, the yield is about the same for the three and the two stacked plates cases. One explanation for this is that increases in the riser modulus are limited for constant diameter risers since only the height can be increased; this limits the number of plates the riser can feed for a small casting distance.

The second stacking case is performed for vertical stacking of vertical plates, as shown in Figure 33. The plates are 2” thick, 4” wide and 8” long. The lengths are slightly shorter than the feeding distance from McNaughton [4], which is 8.63” for 2” thick vertical plates. The castings are solidified one at a time, in a semi-continuous process. In this process, the bottom casting is filled and is solidified first, using the slowly poured (intermittently filled) liquid metal in the casting above it as a feeder. Once the first casting is solidified, it is chilled as the second casting (above the first) is completely poured and begins to solidfy. In this way, for the second casting, the lower most casting is serving as our active chill, and the upper most casting (third casting) is serving as its feeder as it is filled. It is envisioned that the casting which is serving as a feeder would be kept liquid through active heating. In addition, the solidified casting currently serving as the chill would be actively cooled.

On the computer, the process is simulated by varying the HTCs for castings at different times. The simulation is stopped at 1800s when the middle casting is fully solidified. The Niyama or feeding shrinkage plots (not shown) indicate that the castings are sound. The temperature distributions are shown in Figures 34 through 36 for three different times during the simulation. For the middle casting, the bottom part solidifies first, whereas the top part remains superheated much longer. The entire solidification path, as a distribution of local solidification times, is given in Figure 37. The presence of directional solidification is clearly seen. In this kind of vertical stacking, almost no riser is needed, and only the small connection between the castings would be scrapped. These hypothetical simulations demonstrate that sound castings can be produced using this technique, and they would be produced with the added integrity and strength associated with castings produced by directional solidification. If it can be applied successfully in a foundry, both the yield and the quality would be dramatically improved .

VI. Conclusions and Future Work

A computational study has been performed to investigate feeding rules and a variety of directional solidification techniques in steel castings. A methodology has been established to determine feeding distances using a commercial casting simulation code by relating the predicted Niyama values to porosity and the desired soundness level.

In the first part of the study, comparisons are made with the feeding rules published in the SFSA guidelines [1]. The agreement between the present simulations and the rules is good in some cases, but often there exist considerable differences showing that the present rules are overly conservative. This points out the need for additional research, and it is anticipated that such research will be conducted in the near future as part of the ongoing research project for which the present work was conducted. While the present work does not yet establish new guidelines, it has laid the ground work for such development.

In the second part of the study, thicker sections (T=12") and thinner sections (T=0.25") were examined. However, this work is not yet completed and will be continuing . In addition, an investigation of passive and active yield improvement techniques was performed using simulations. Some interesting results have been obtained which point out the limitations of chills and riser insulating materials.

In the final part of this paper simulations were presented examining directional solidification techniques for improving yield. By stacking castings and employing a hypothetical semi-continuous process, the possibility of more remarkable yield improvement has been demonstrated. These results are certainly preliminary, but they demonstrate that entirely new concepts in casting practice are possible, and this research will be continued.

Experiments for plate shaped castings are currently being performed in several foundries for comparison with the simulations presented here. With the experimental results in hand, the simulated Niyama and/or feeding percentage values can be better correlated to the observed shrinkage and microporosity level according to the soundness level required.

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REFERENCES

[1] S. F. S. A.: Risering Steel Casting, Steel Founders' Society of America, 1973.

[2] Hardin, R.A., and Beckermann, C., "The Current State of Casting Yield: Results from the 1997 Steel Founders' Society of America Casting Yield Survey," 1997 SFSA Technical and Operating Conference, 1997.

[3] E. Niyama, T. Uchida, M. Morikawa, S. Saito: A Method of Shrinkage prediction and Its Application to Steel Casting Practice, AFS International Cast Metals Journal, Vol. 7, 1982, pp. 52-63.

[4] J. McNaughton: Feeding Ranges of Risers for Uniform Sections, Steel Foundry Facts, April 1966, pp. 15-24.

[5] S. F. S. A.: Determination of the Factors Influencing Riser Efficiency; The Distance Risers will Feed Uniformly Thick Sections, Steel Founders Society Research Report No. 30, September, 1953

[6] A.F.S.: Basic Principle of Gating and Risering, AFS tutorial materials.

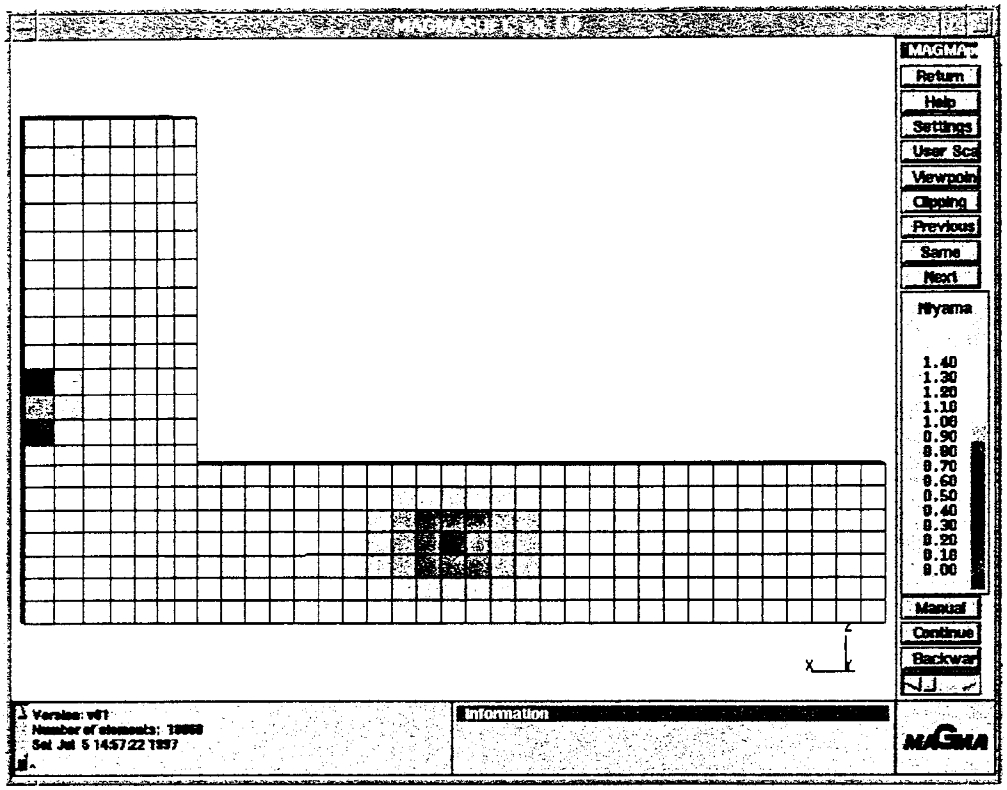


Figure 1 Niyama plot for base case, 4″×8″ plate with simulation feeding distance, FD_S=17.75″

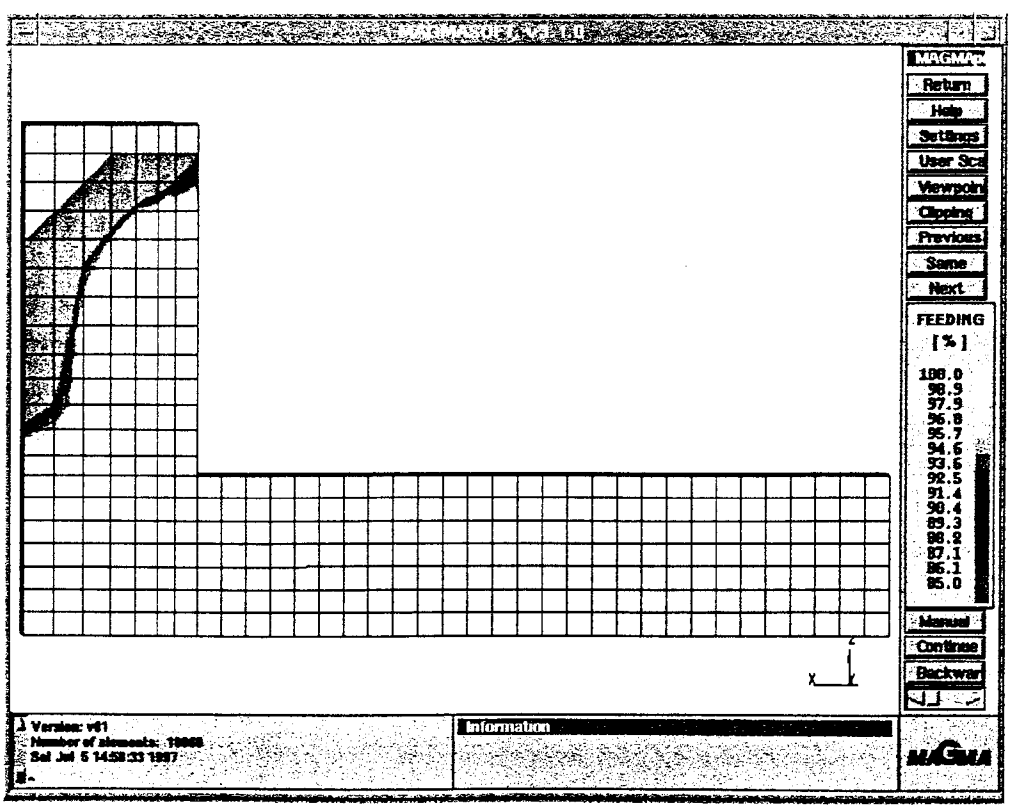


Figure 2 Feeding percentage plot for base case, 4″×8″ plate with simulation feeding distance, FD_S=17.75″

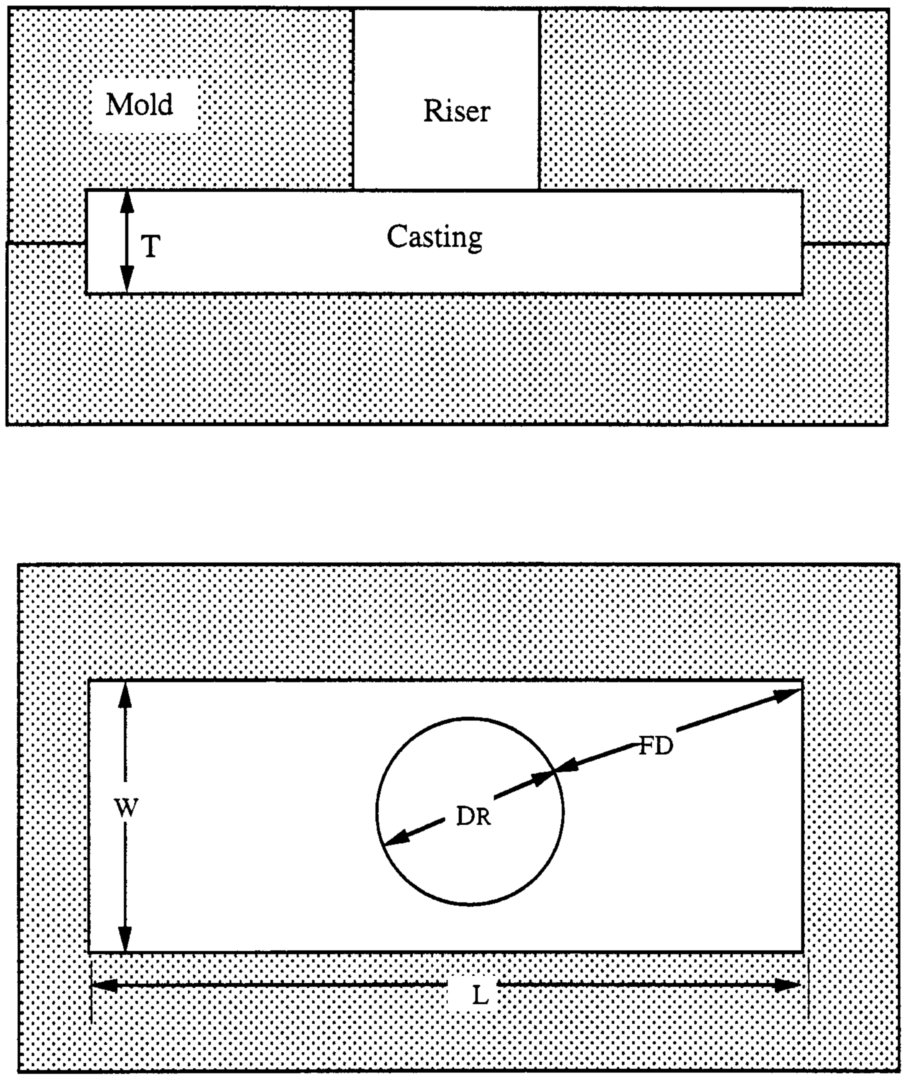


Figure 3 Simulation model for plate with end effect

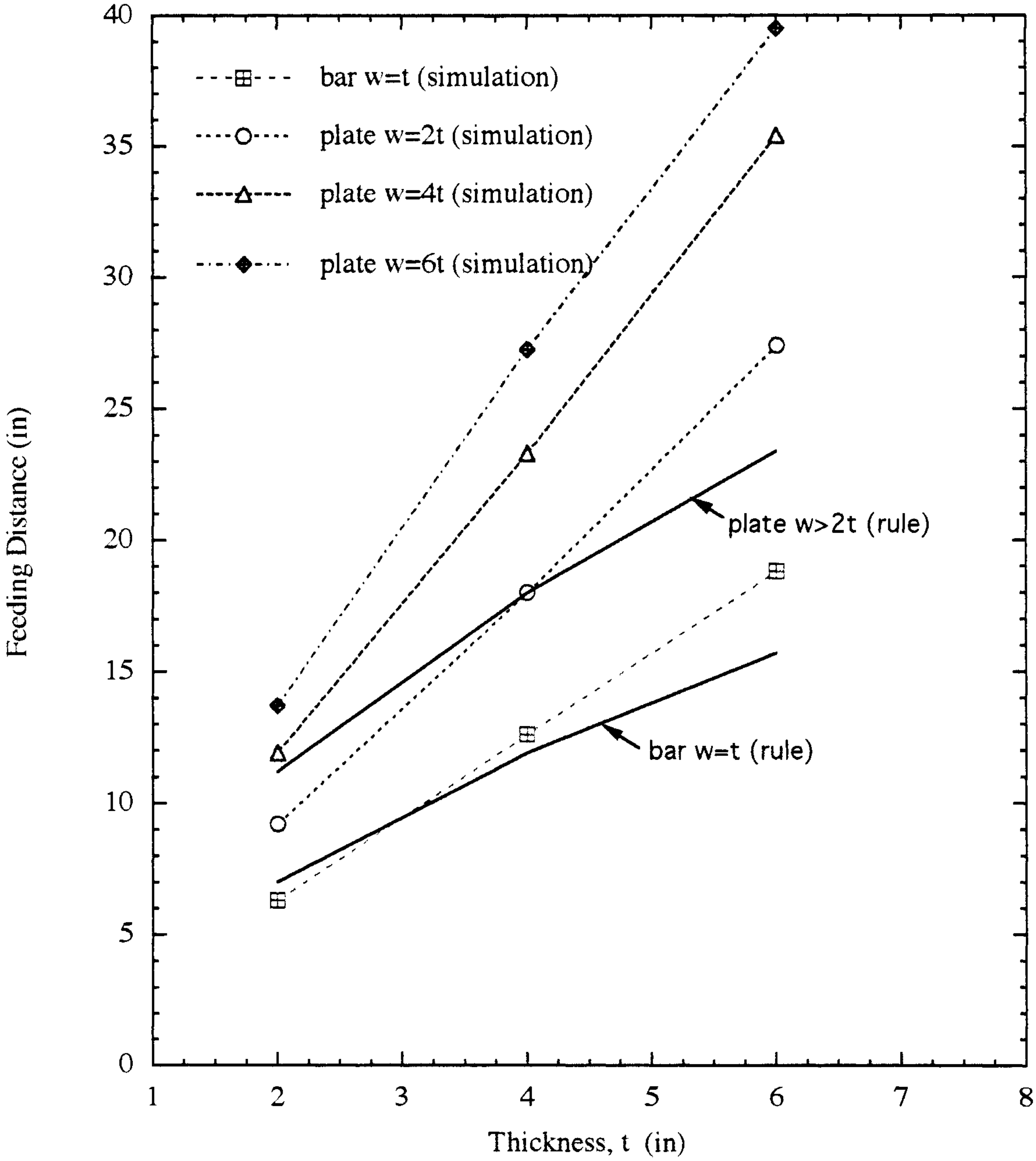


Figure 4 Simulation feeding distance vs. thickness for end effect cases and its comparison with rule feeding distance

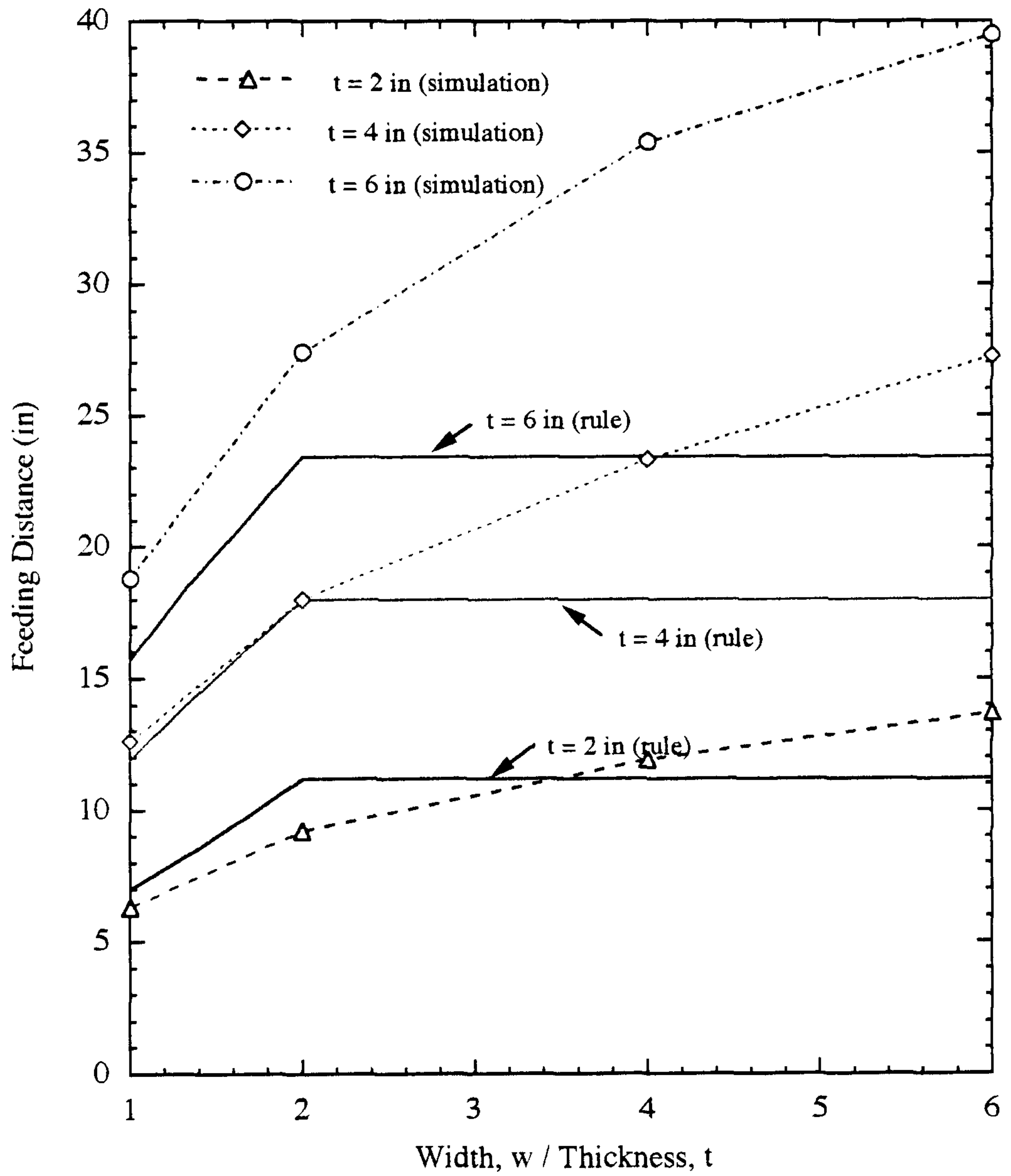


Figure 5 Simulation feeding distance vs. width to thickness ratio for end effect cases and its comparison with rule feeding distance

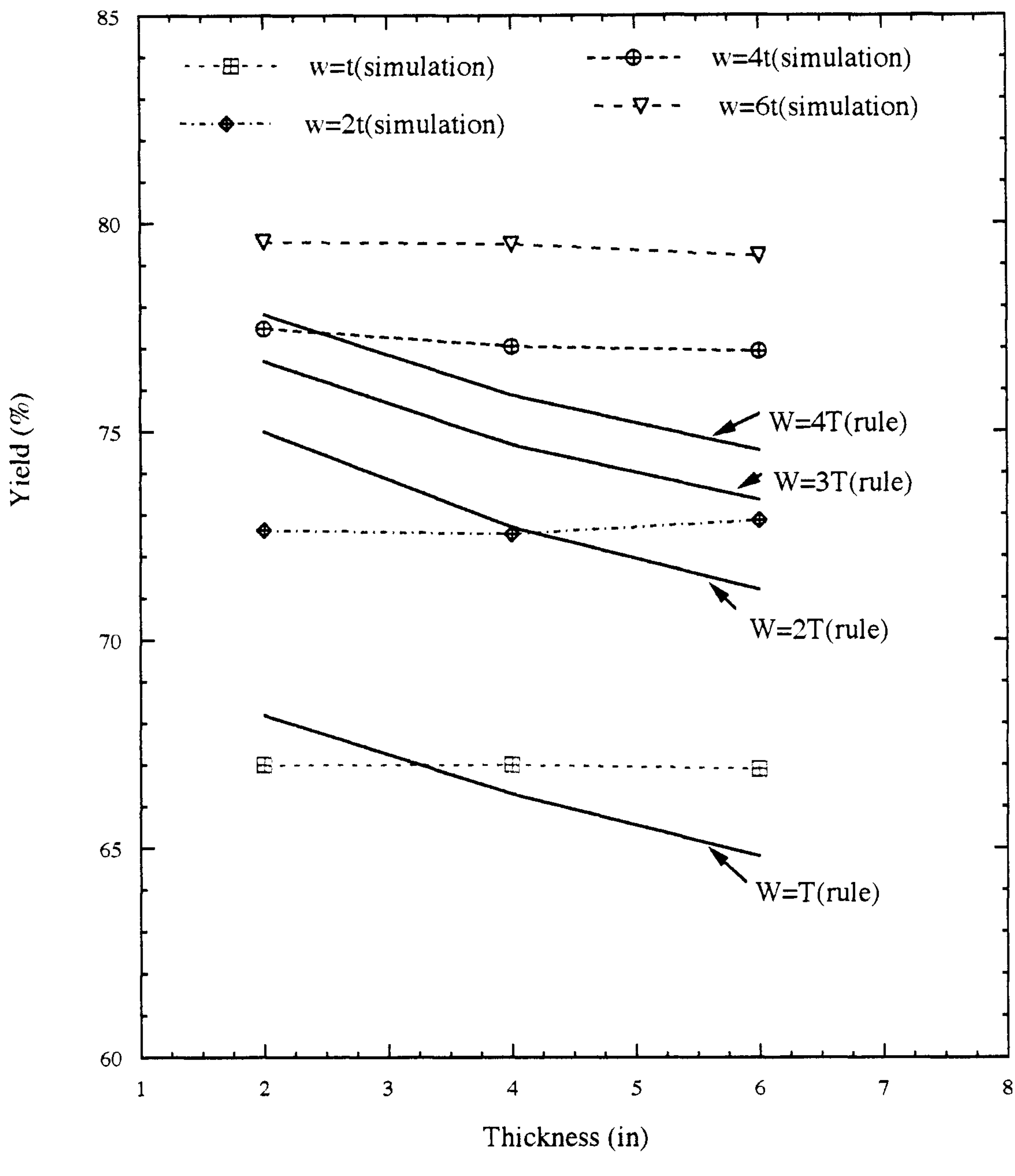


Figure 6 Yield versus thickness for plate lengths determined by the rule and simulation feeding distances (plates with center top riser, riser size is calculated according to SFSA rules)

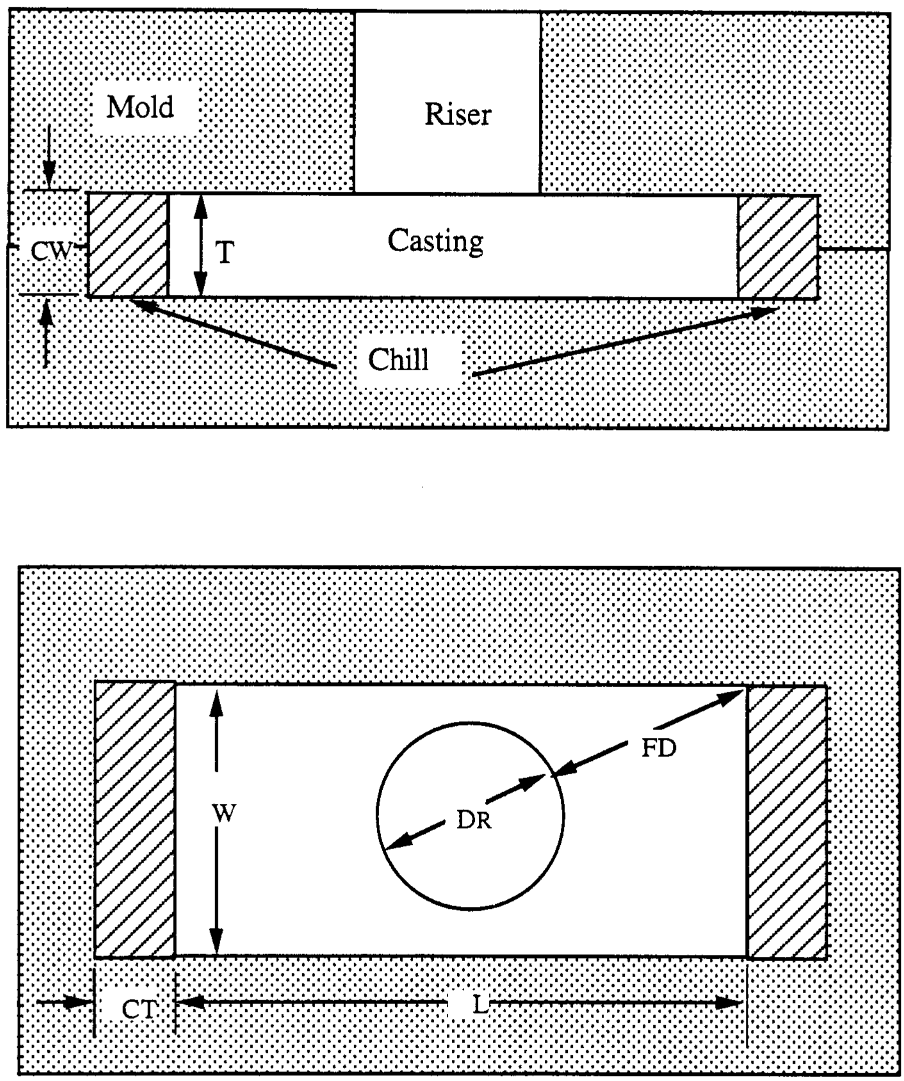


Figure 7 Simulation model for plate with end chill

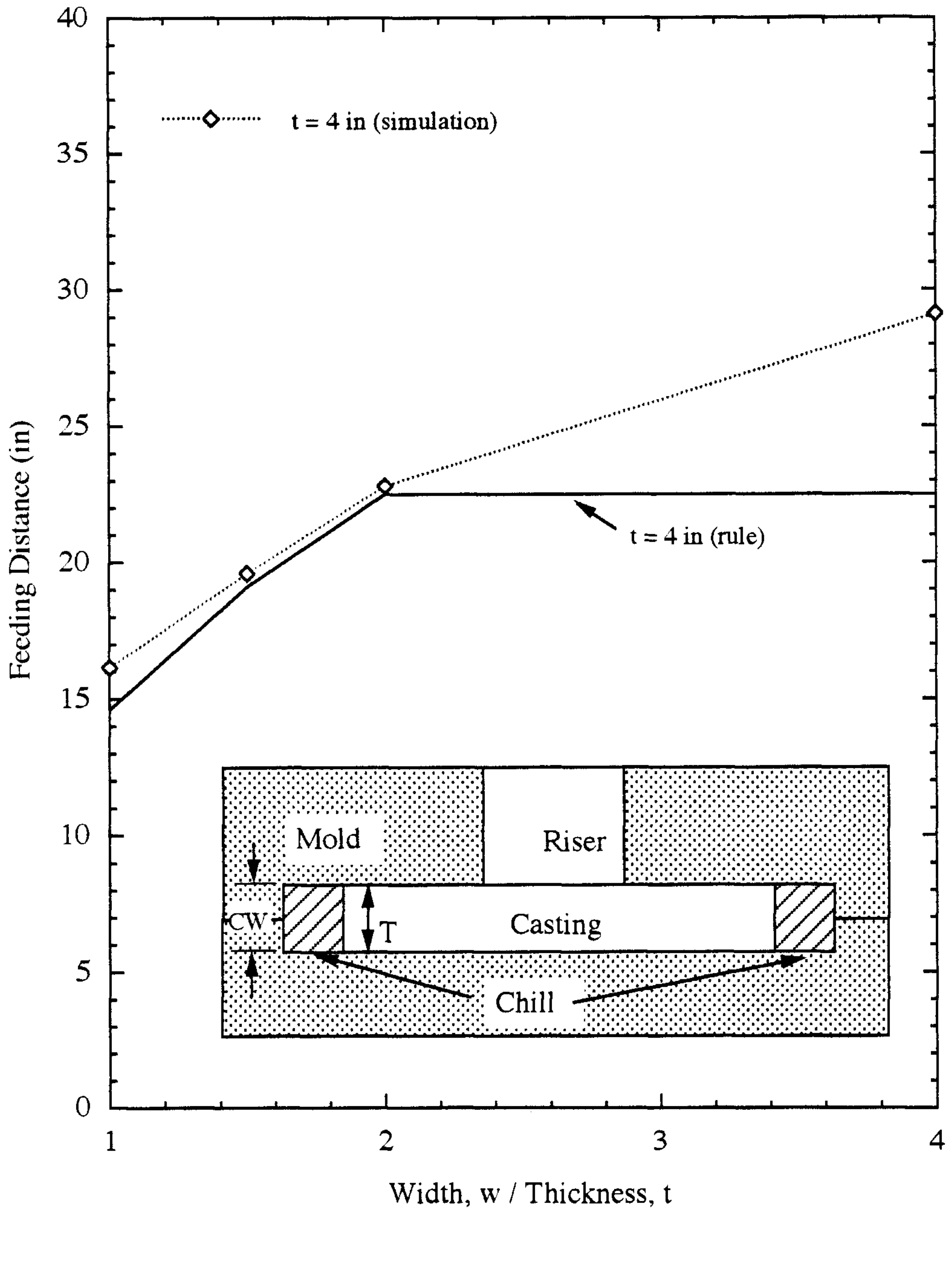


Figure 8 Simulation feeding distance vs. width to thickness ratio for end chill cases and its comparison with rule feeding distance

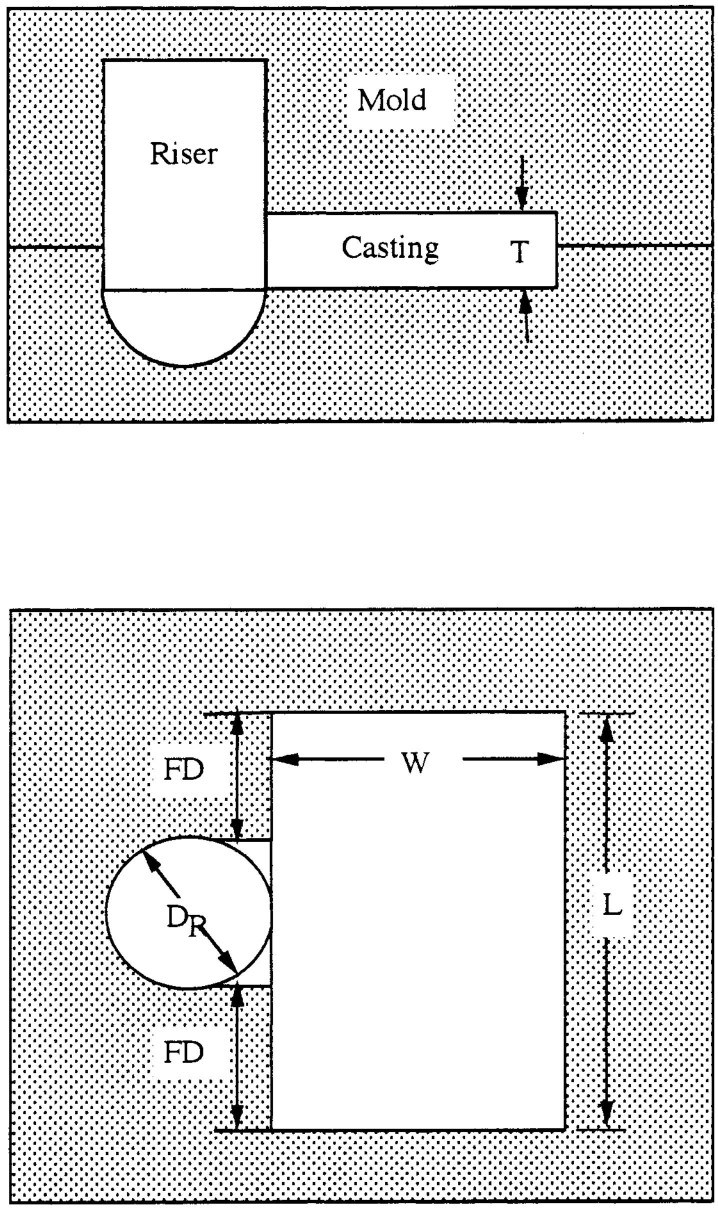


Figure 9 Simulation model for plate with hemispherical bottom side riser

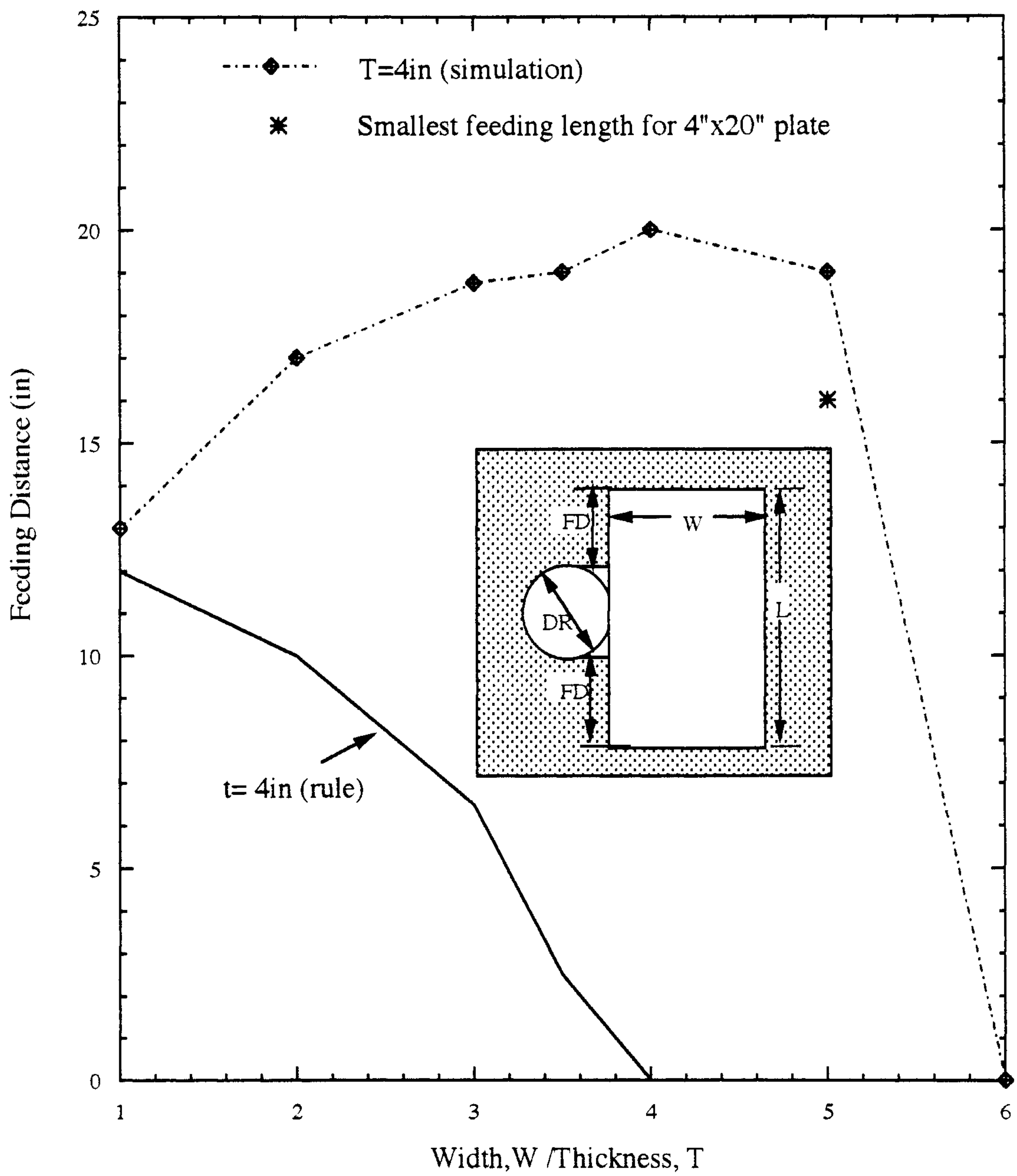


Figure 10 Feeding distances for side risered sections of various widths

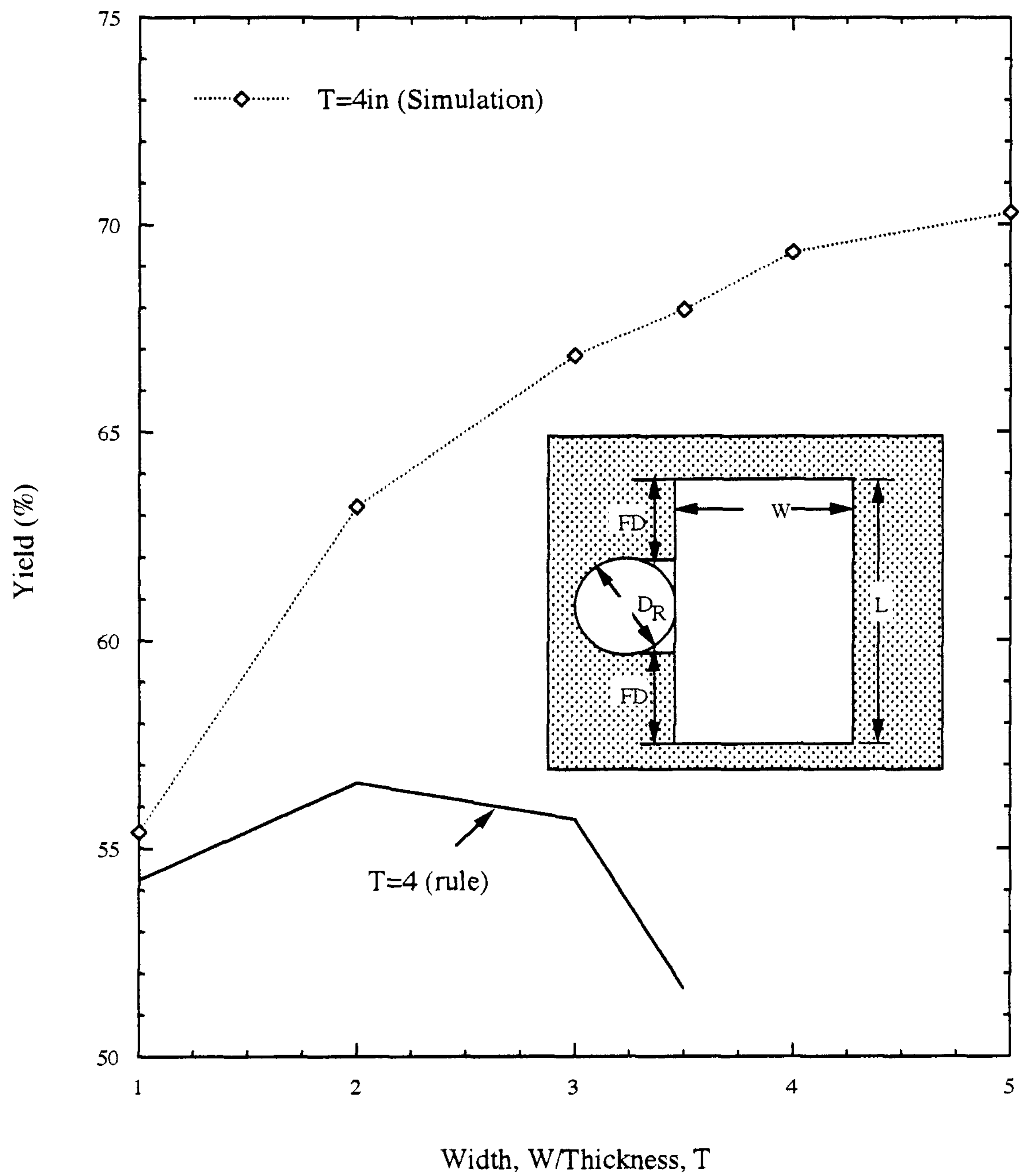


Figure 11 Yield versus thickness for plate lengths determined by the rule and simulation feeding distances (riser size is calculated according to SFSA rules)

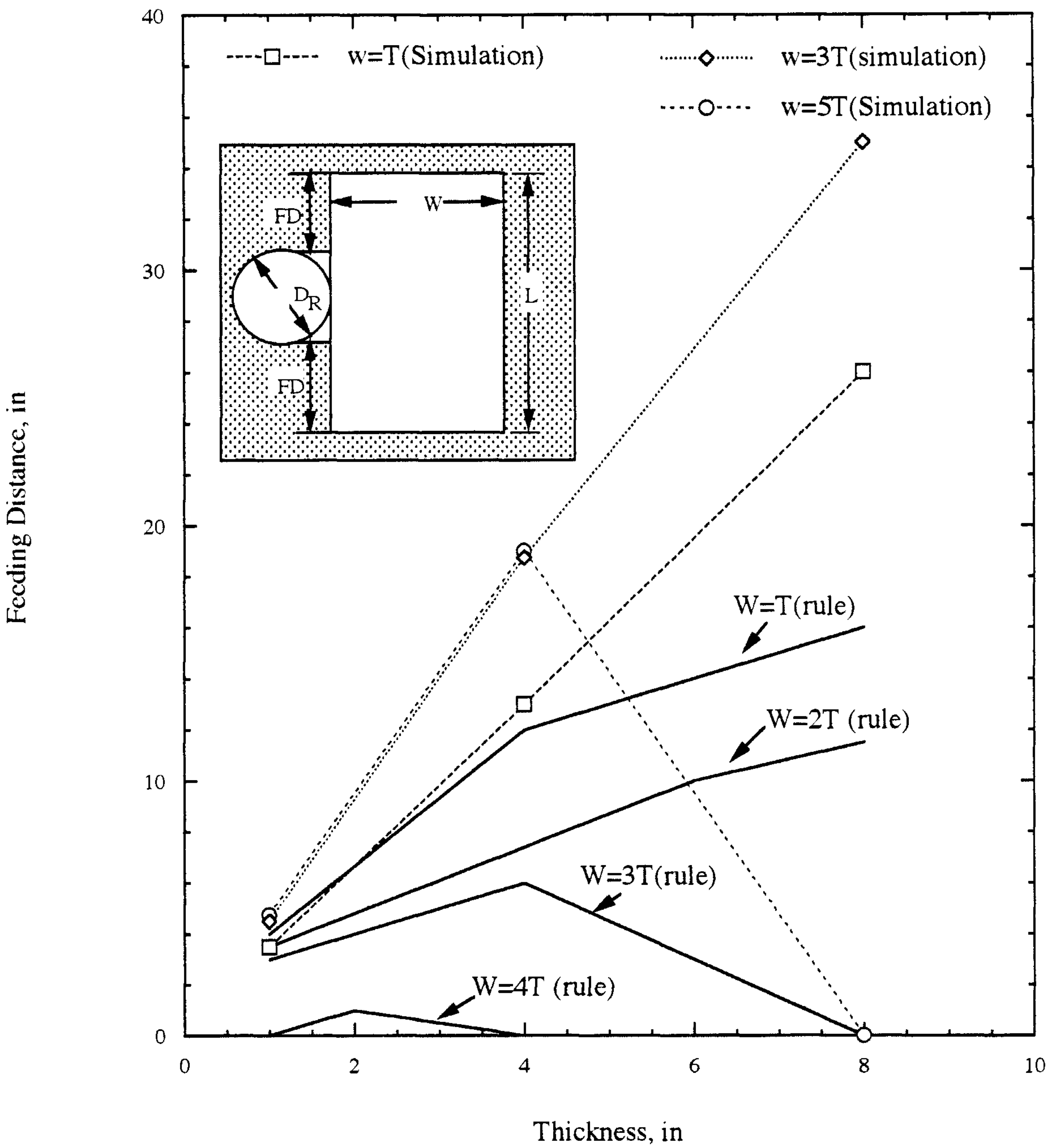


Figure 12 Feeding distance (FD) for side risered sections of various thicknesses and widths

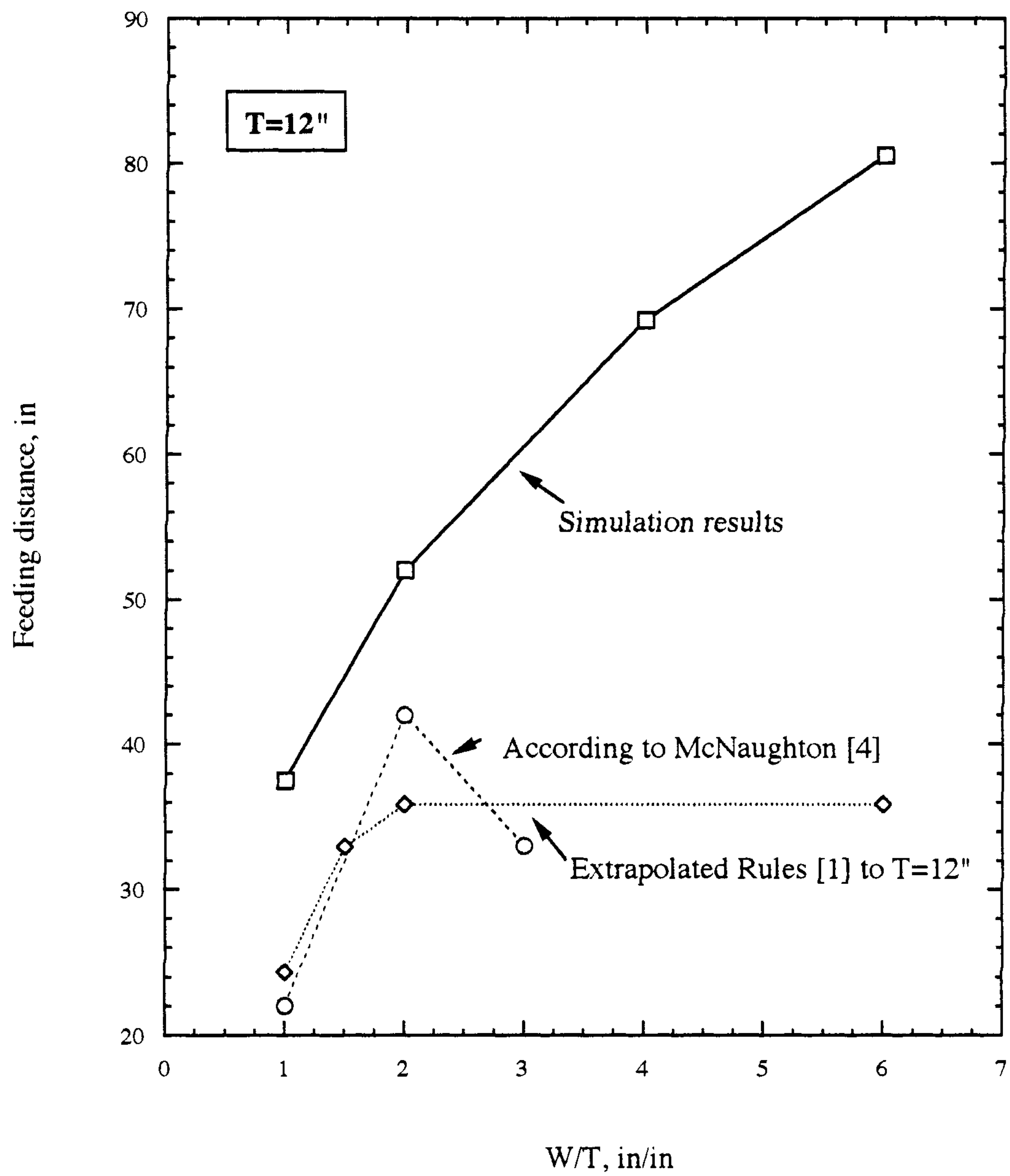


Figure 13 Simulation feeding distances versus the width to thickness ratio for T=12" plates with end effect and comparison with feeding distances from reference [4] and extrapolated from guidelines [1].

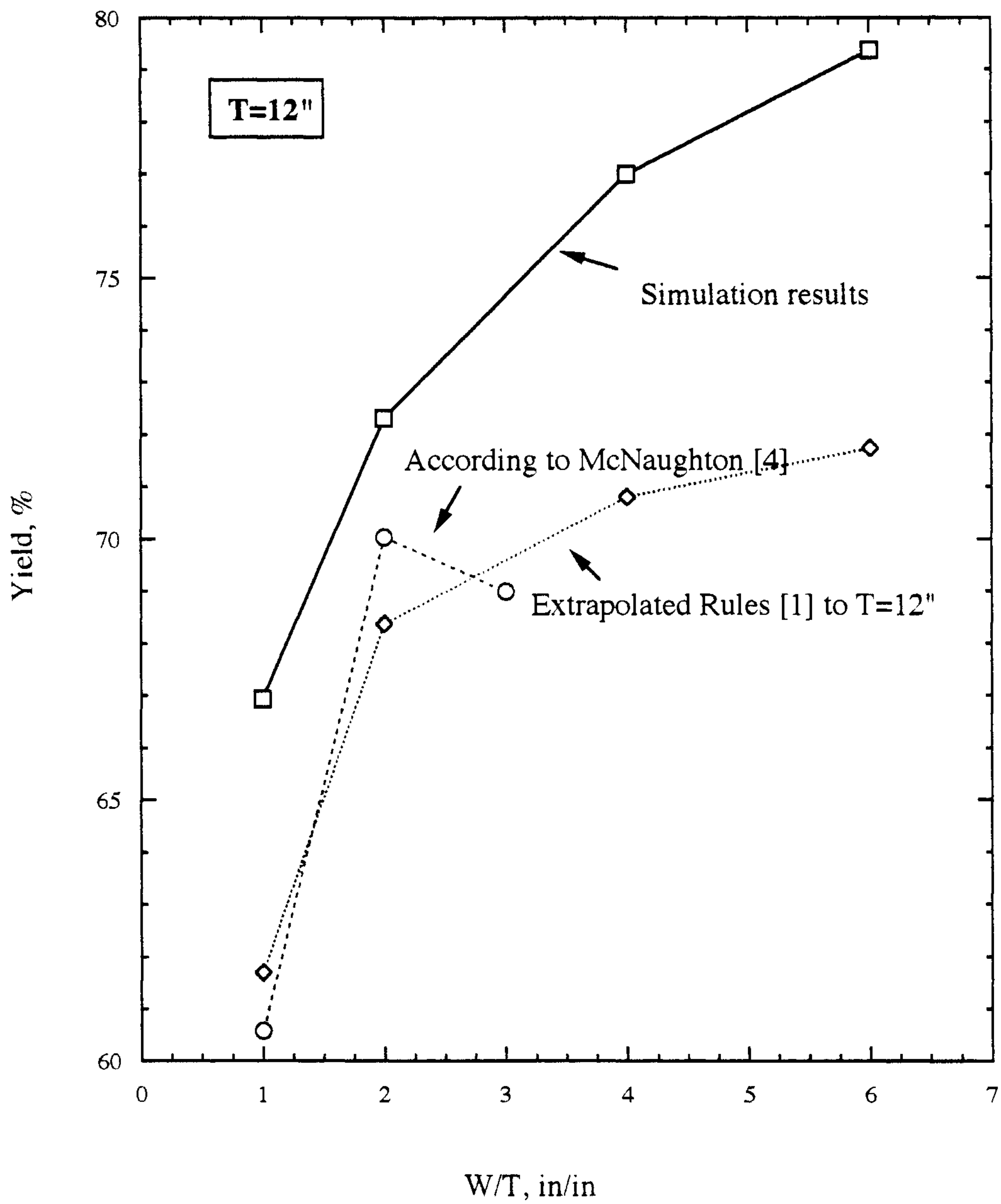


Figure 14 Yield for t=12" plate of simulation feeding distance versus the width to thickness ratio and comparison with yield for plate of feeding distances from reference [4] and extrapolated from guidelines [1].

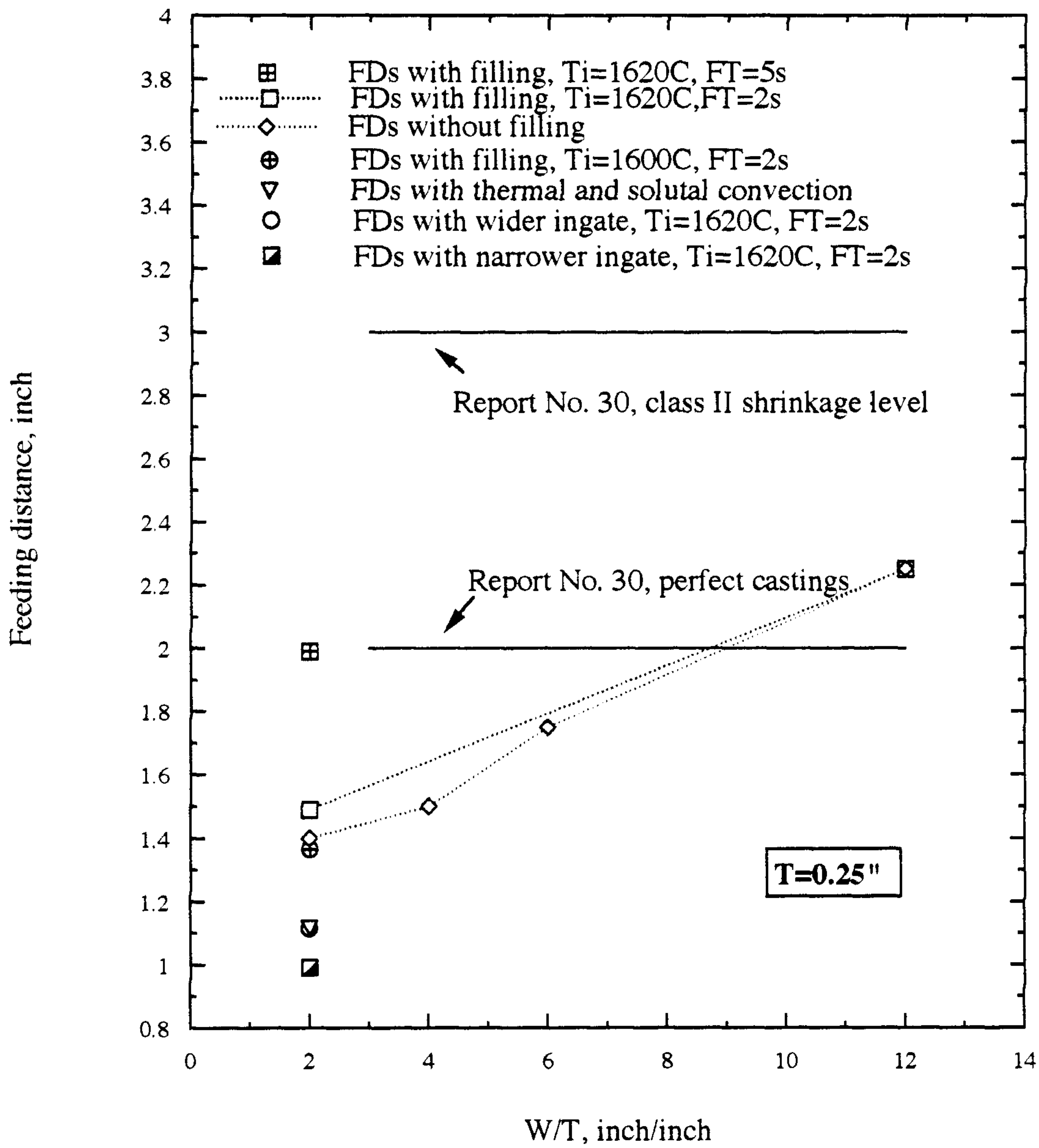


Figure 15 Simulation feeding distances versus the width to thickness ratio for T=0.25" plates with different simulation conditions and their comparison with feeding distances from SFSA Research Report 30. (Extrapolating rules for thicker sections (T=2" to 6") would result in a negative feeding distance)

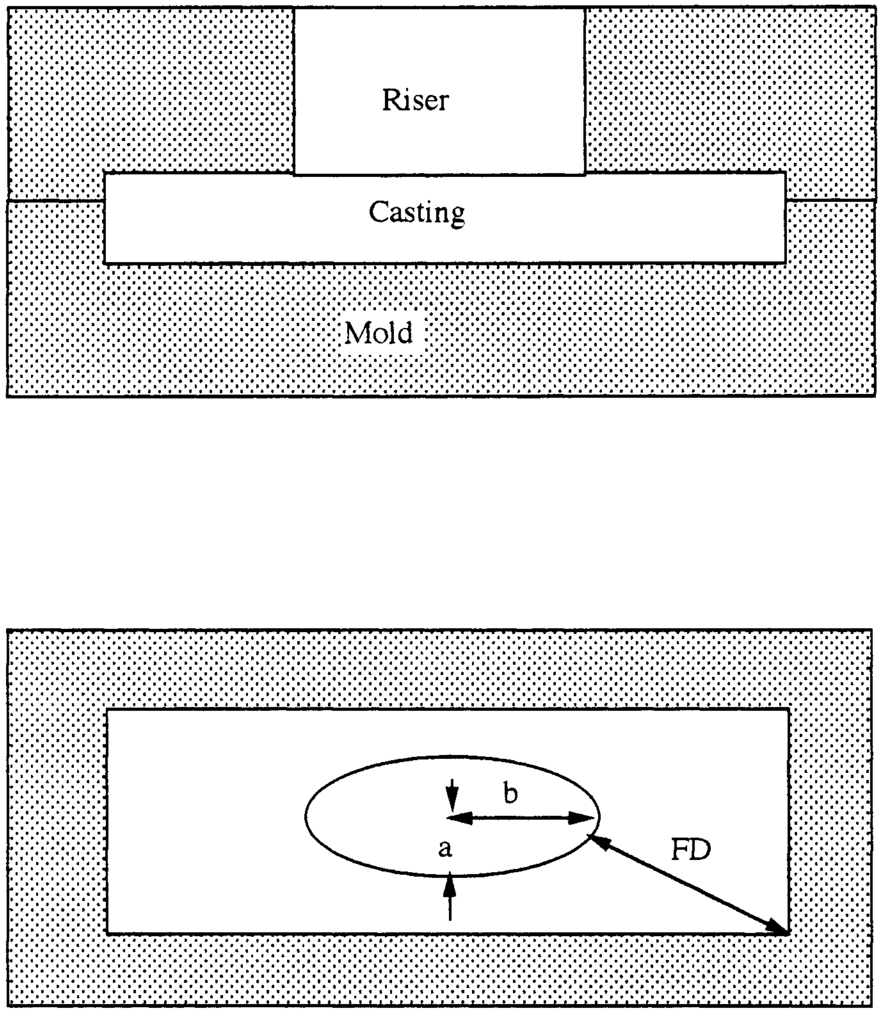


Figure 16 Simulation model for elliptical cross section riser

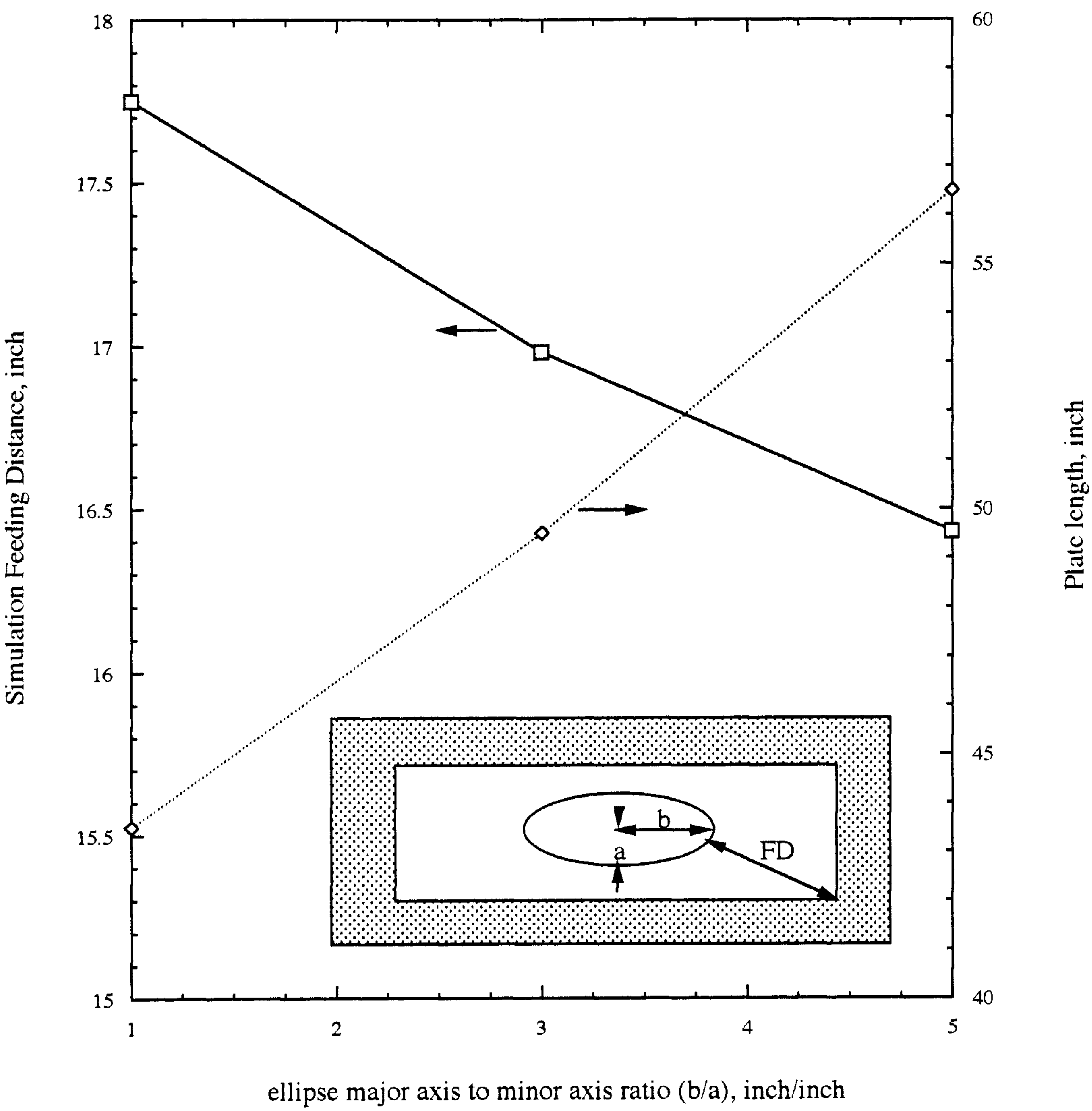


Figure 17 Simulation feeding distances and corresponding lengths for 4"x8" plate with elliptical risers

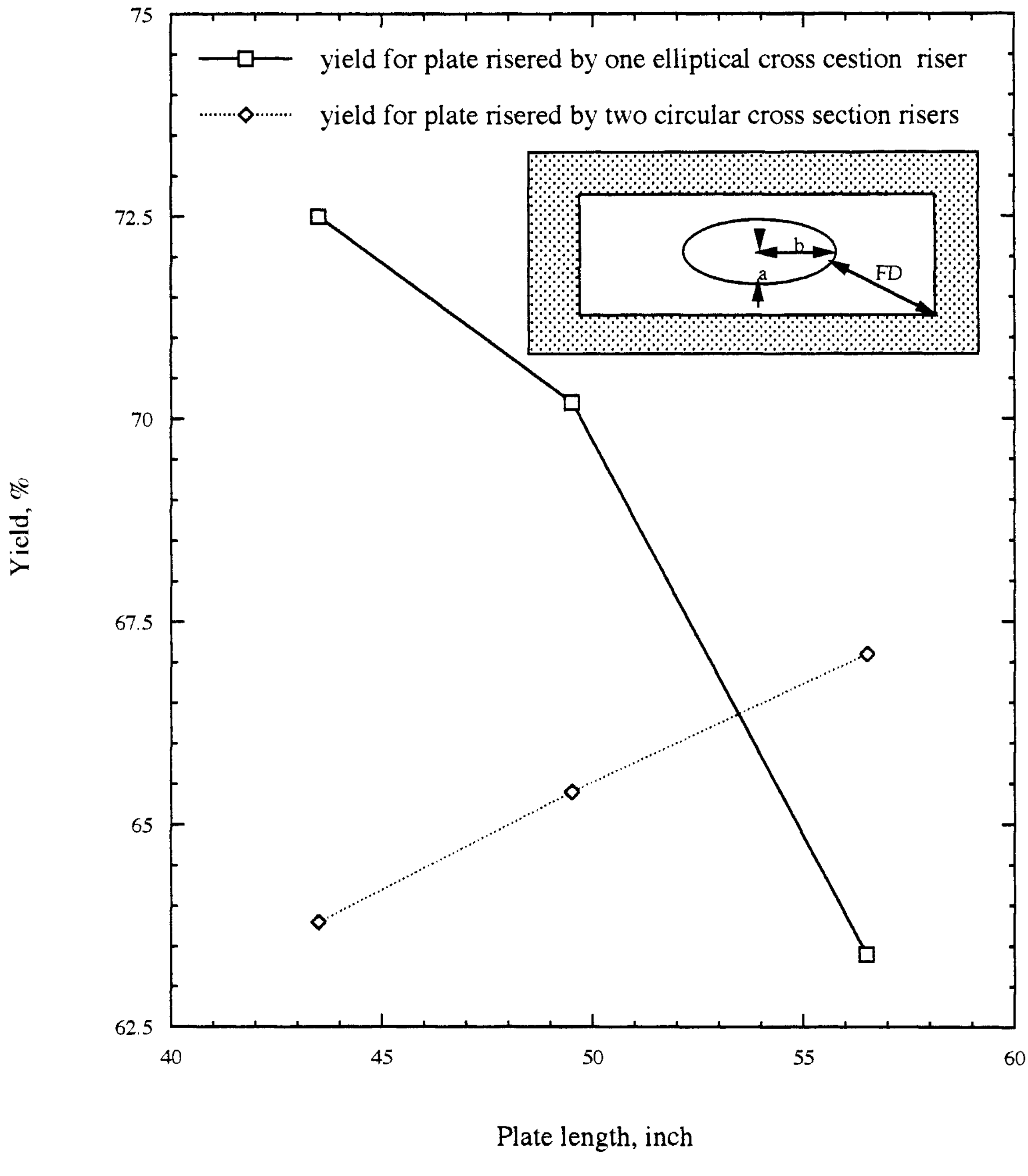
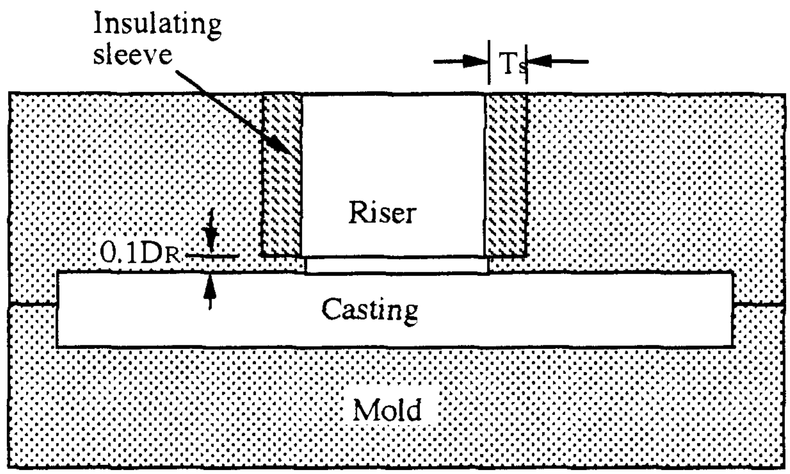


Figure 18 Yield for 4"x8" plates with elliptical cross section risers and the comparison with the yield for plates with multiple circular cross section risers



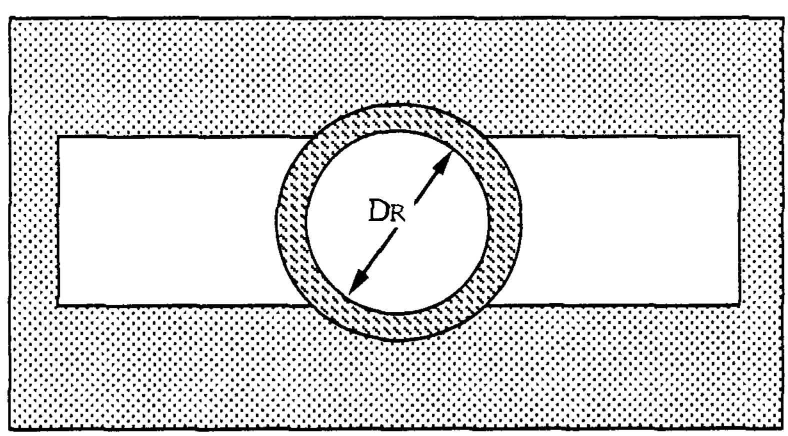


Figure 19 Simulation model for insulating sleeves of varying thickness

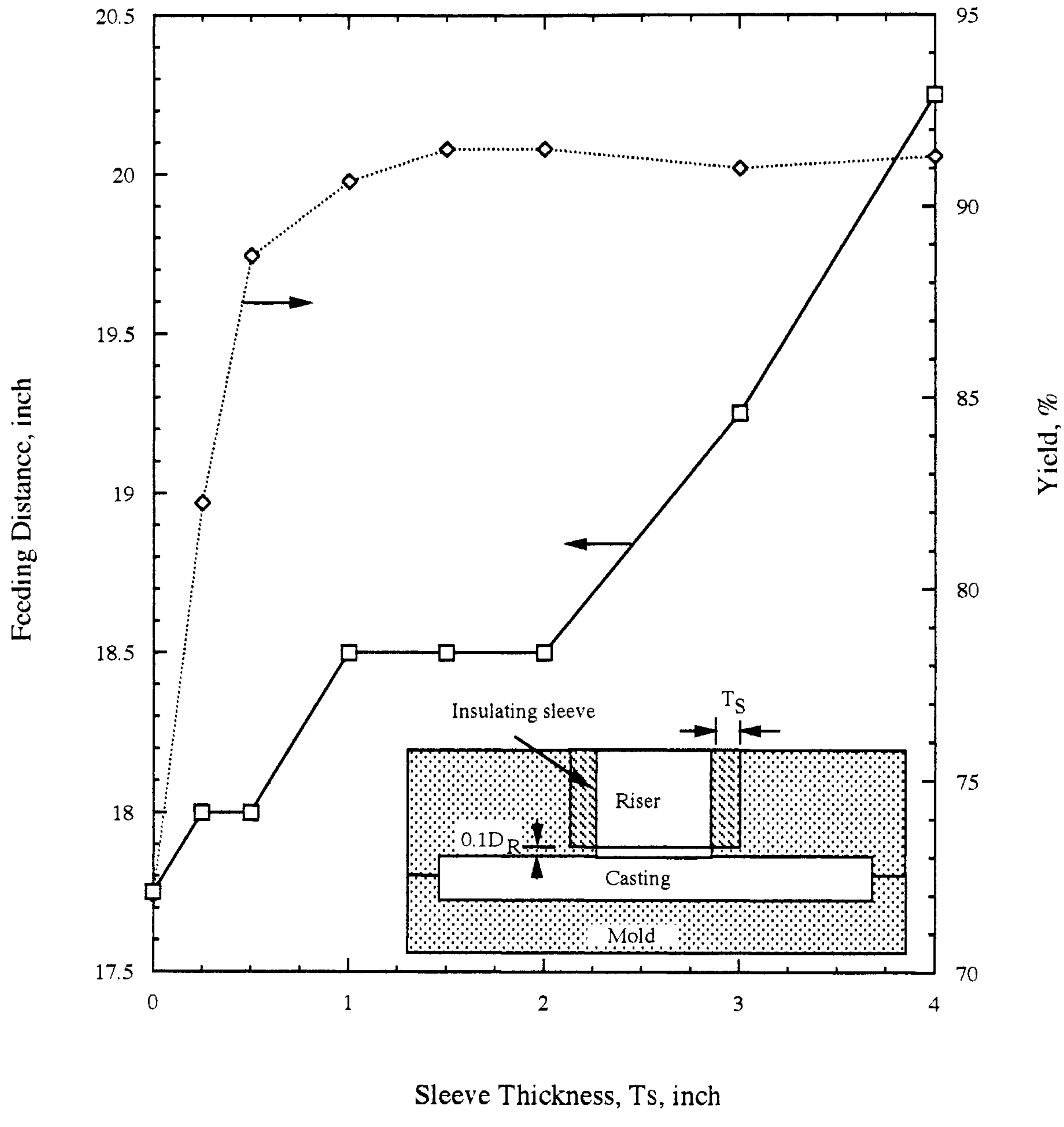


Figure 20 Simulation feeding distances and casting yield for 4"x8" plate with sleeve insulated riser versus different sleeve thickness

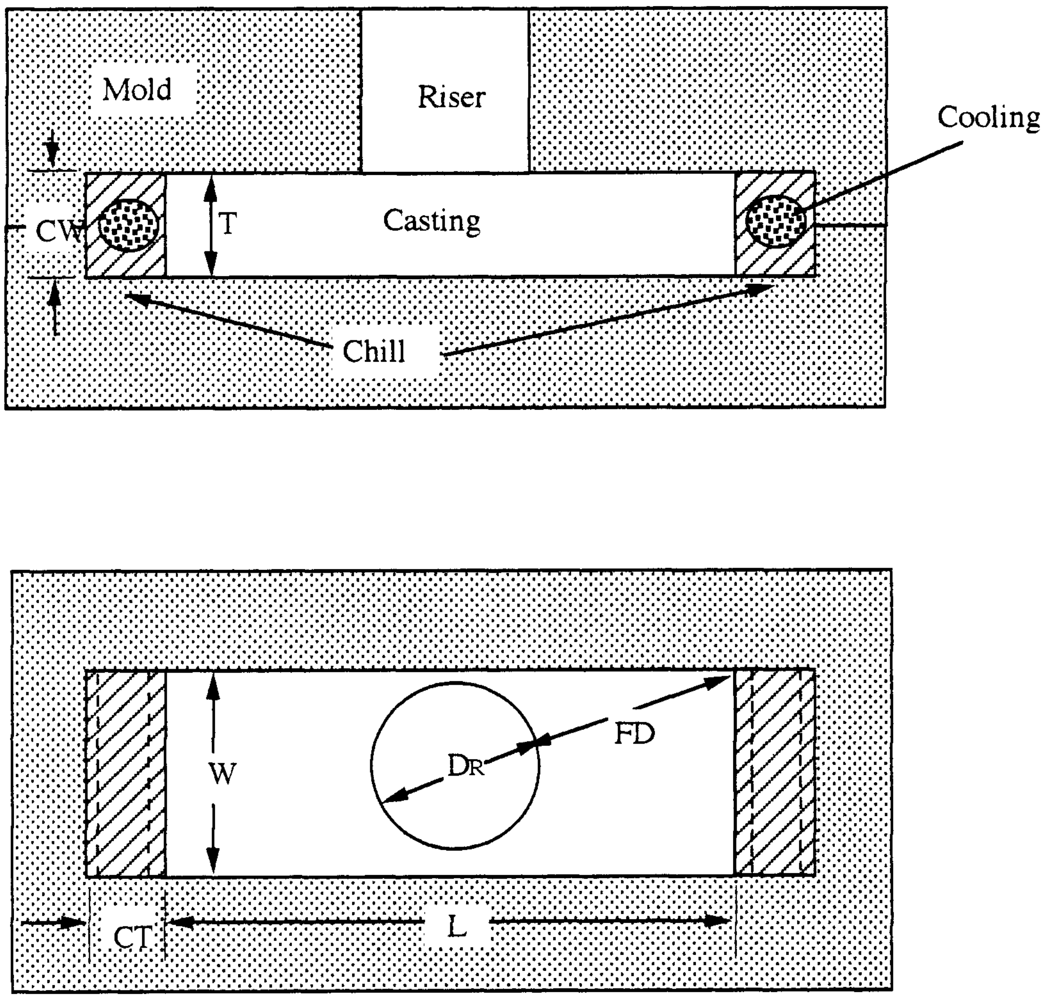


Figure 21 Simulation model for plate with water-cooled copper chill

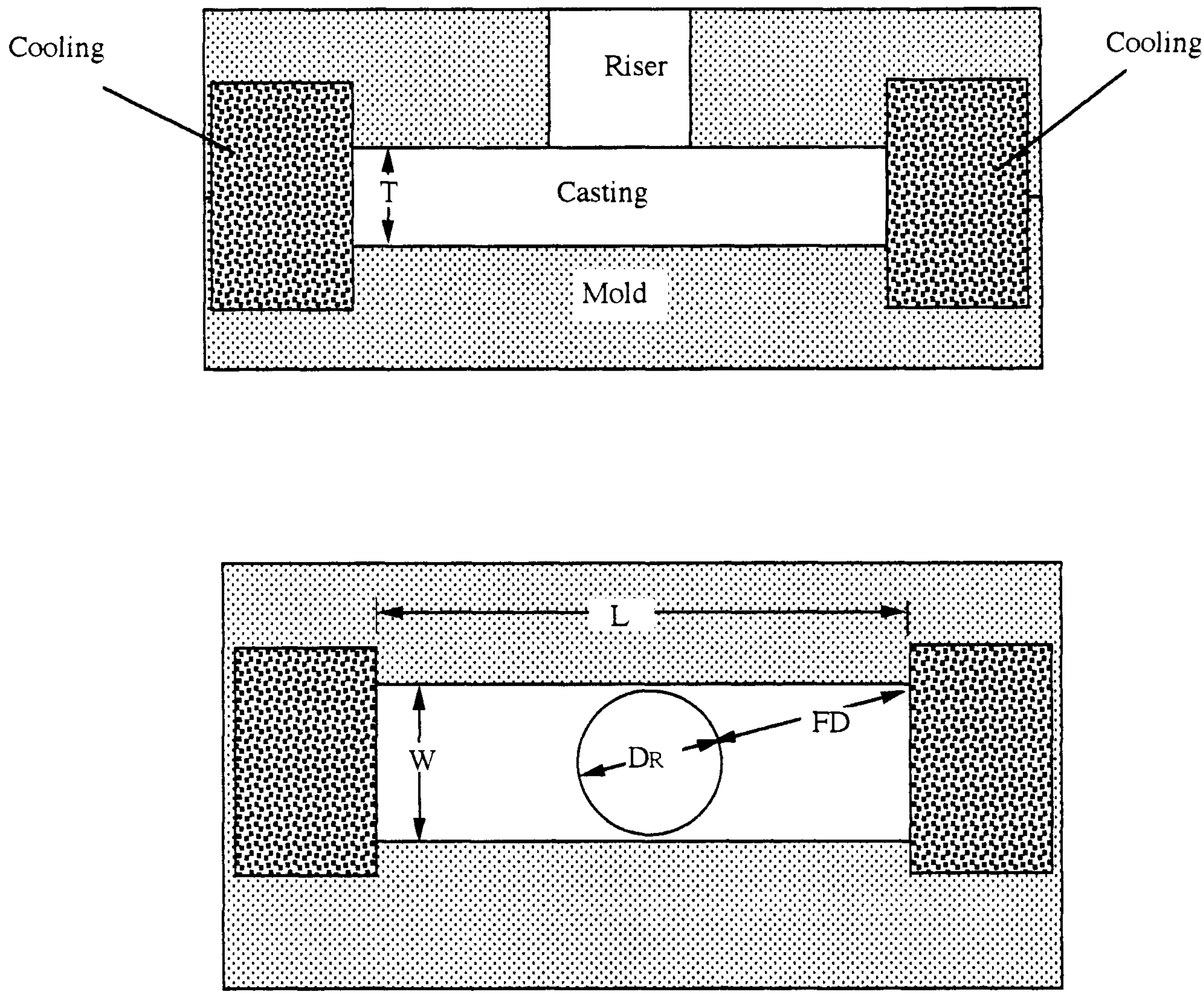


Figure 22 Simulation model for plate with direct water chilling

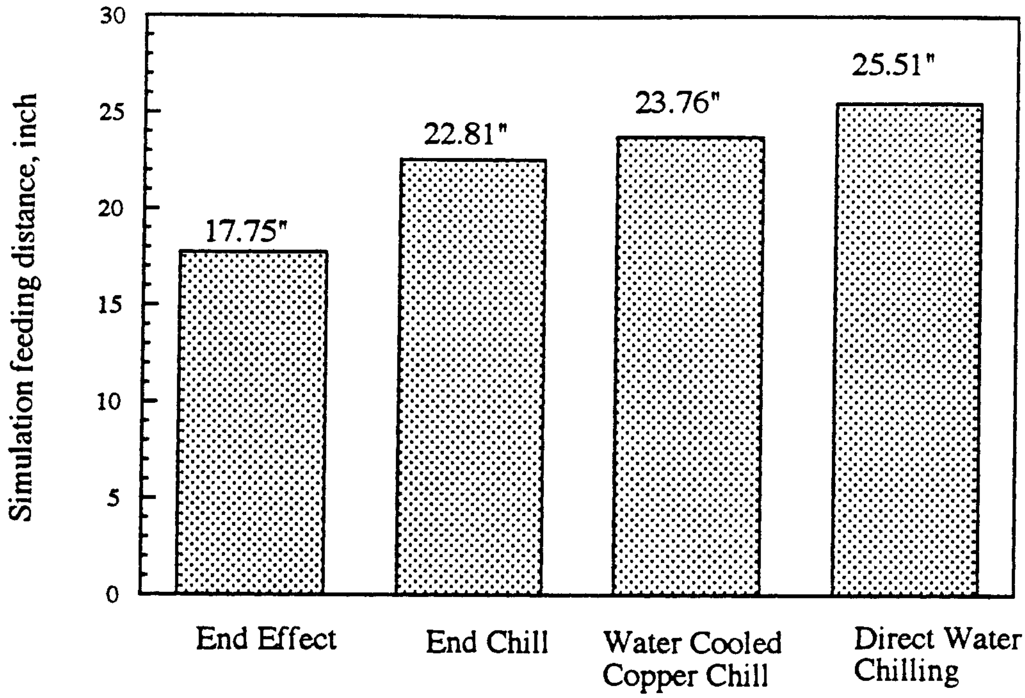


Figure 23 Simulation feeding distances for the base case (4"x8" plate) with different end conditions

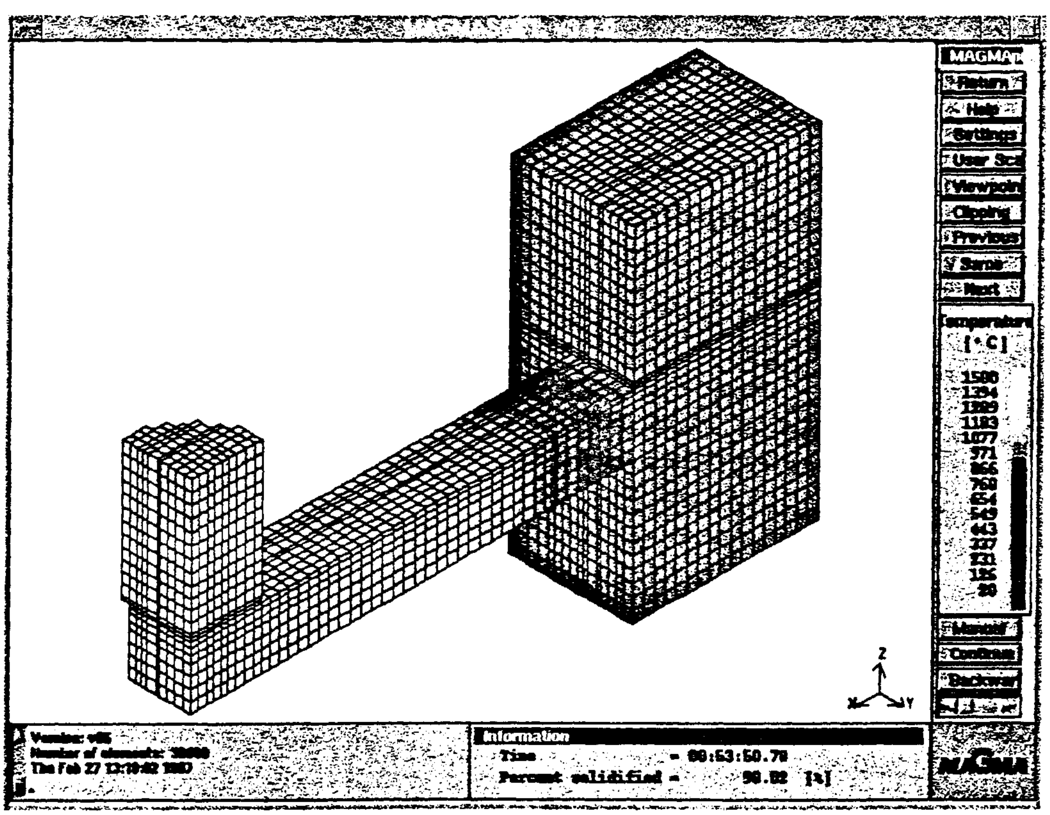


Figure 24 Temperature distribution plot for 4″×8″×59.5″ plate with direct water chilling (FL=FD_S=25.5″)

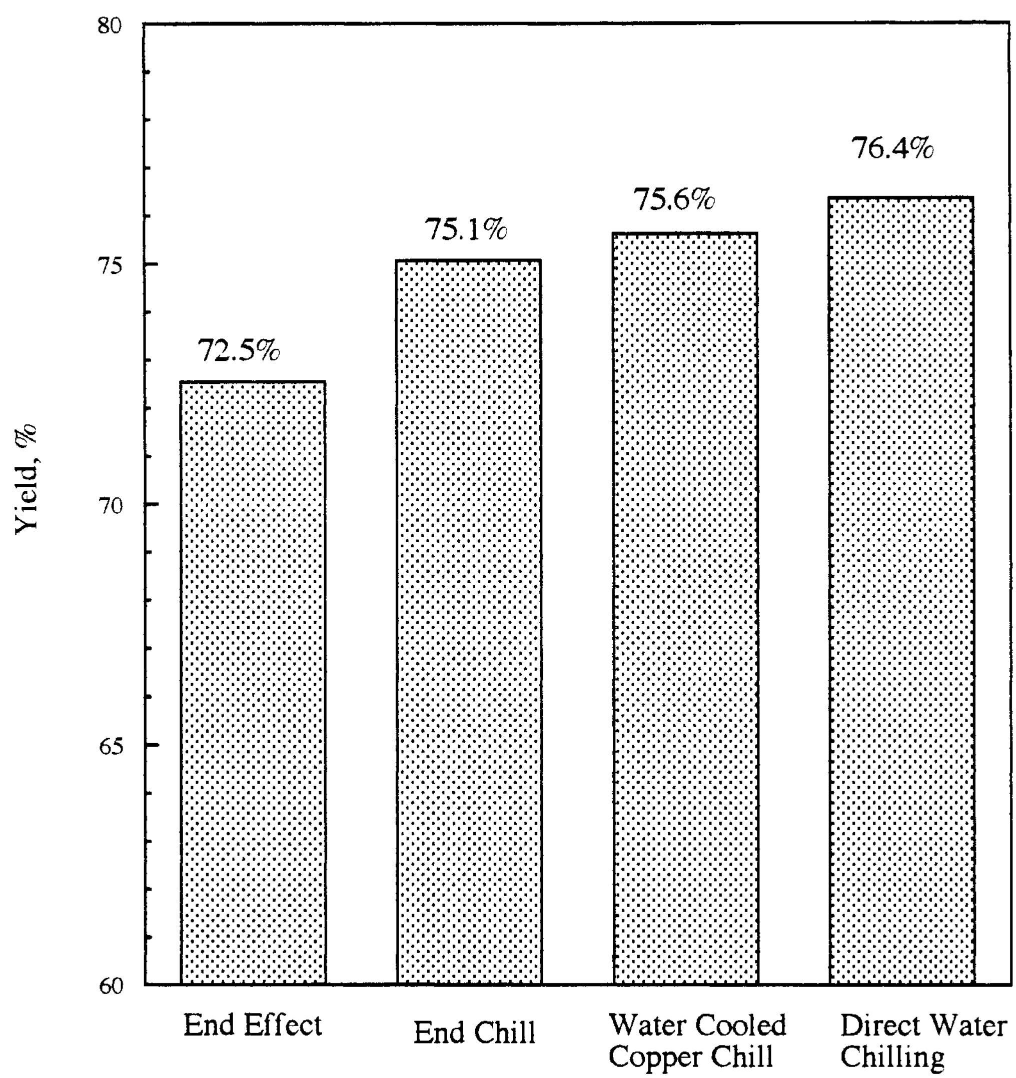


Figure 25 Maximum yield for the base case (4"x8" plate) with different end conditions

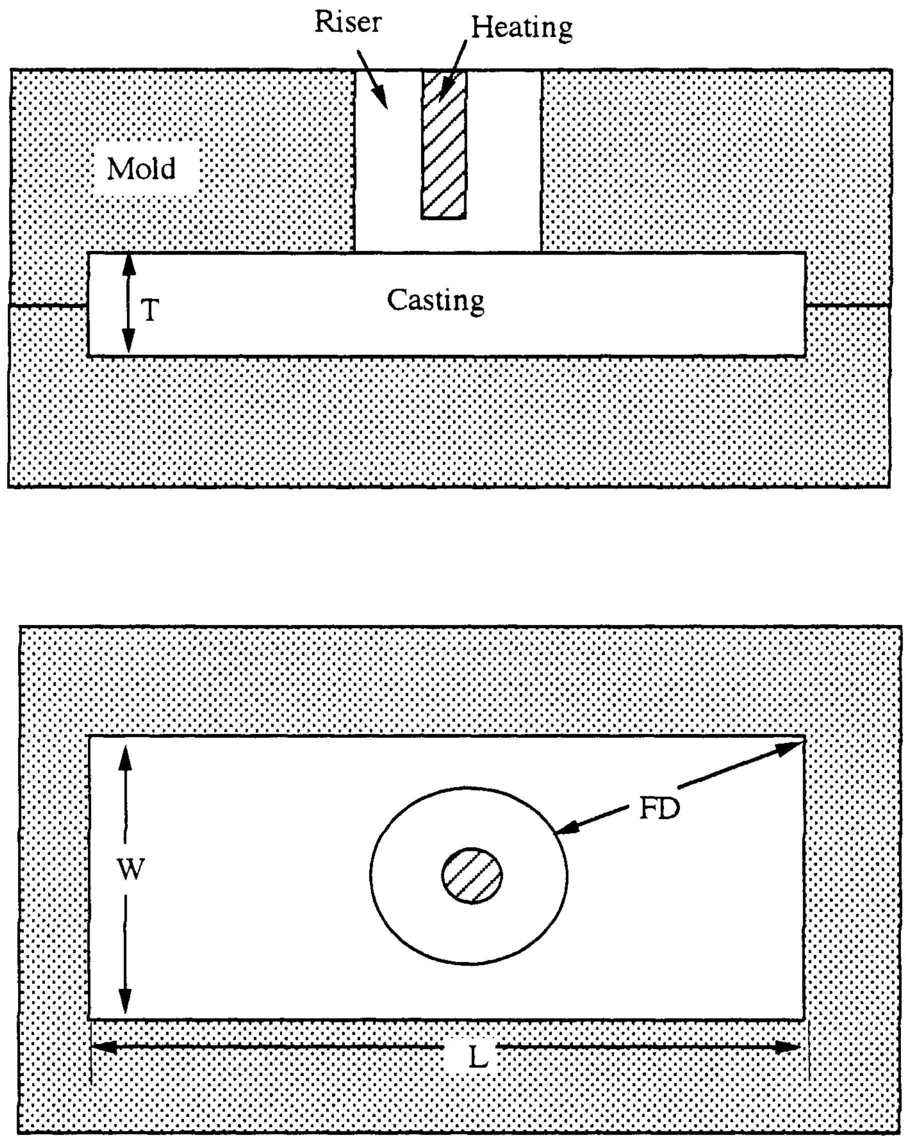


Figure 26 Simulation model for arc heating

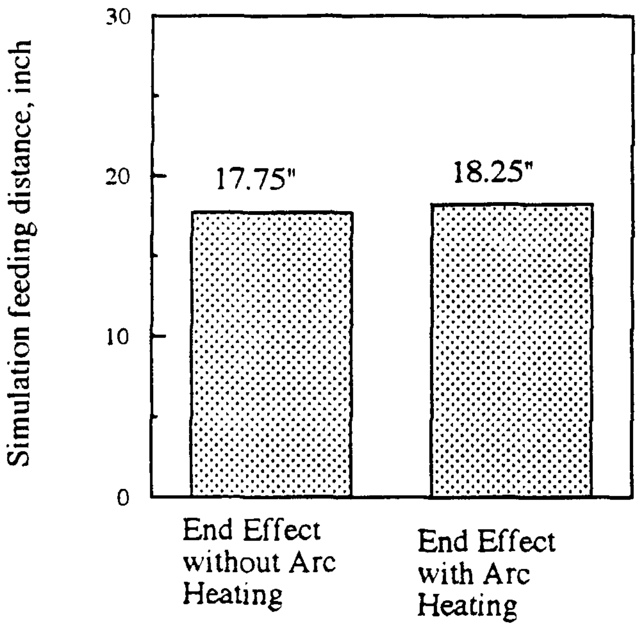


Figure 27 Simulation feeding distances for base case (4"x8" plate) with arc heating and withour arc heating

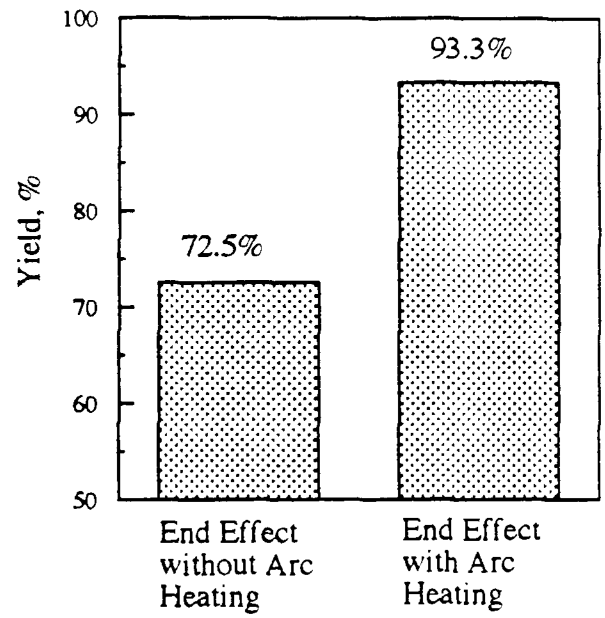


Figure 28 Maximum yield for base case (4"x8" plate) with arc heating andwithour arc heating

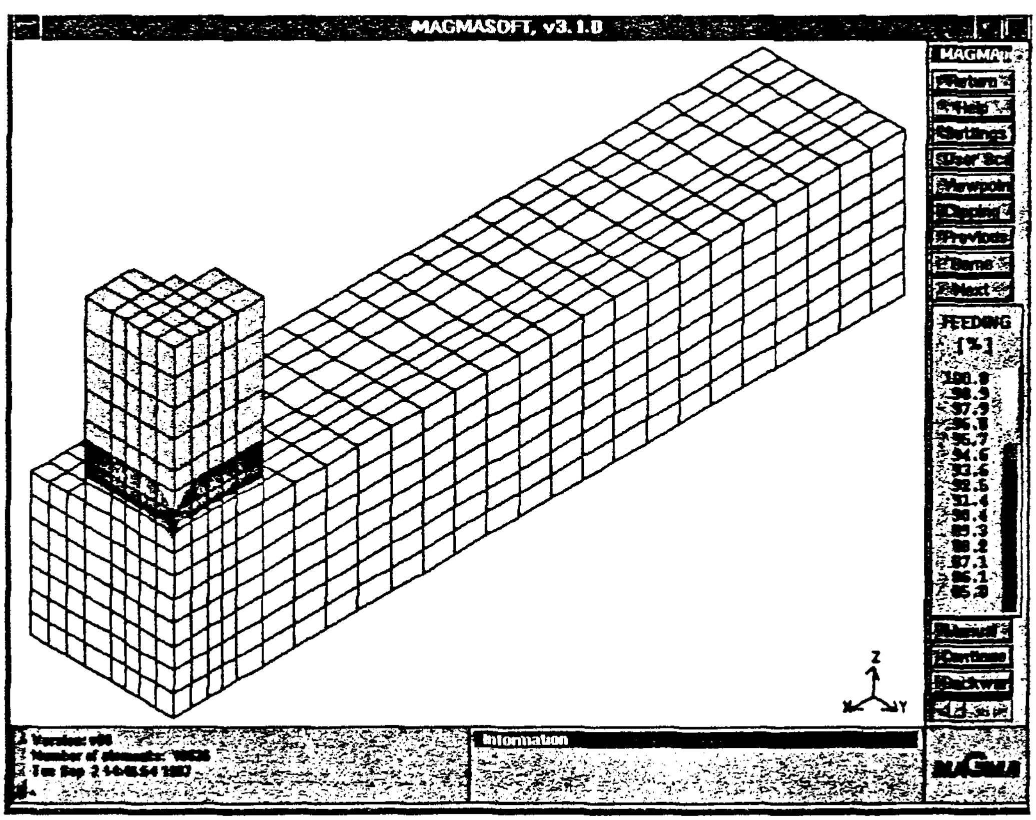


Figure 29 Feeding percentage plot for 4″×8″×41.2″ plate with arc heating ($FL=FD_s=18.25''$)

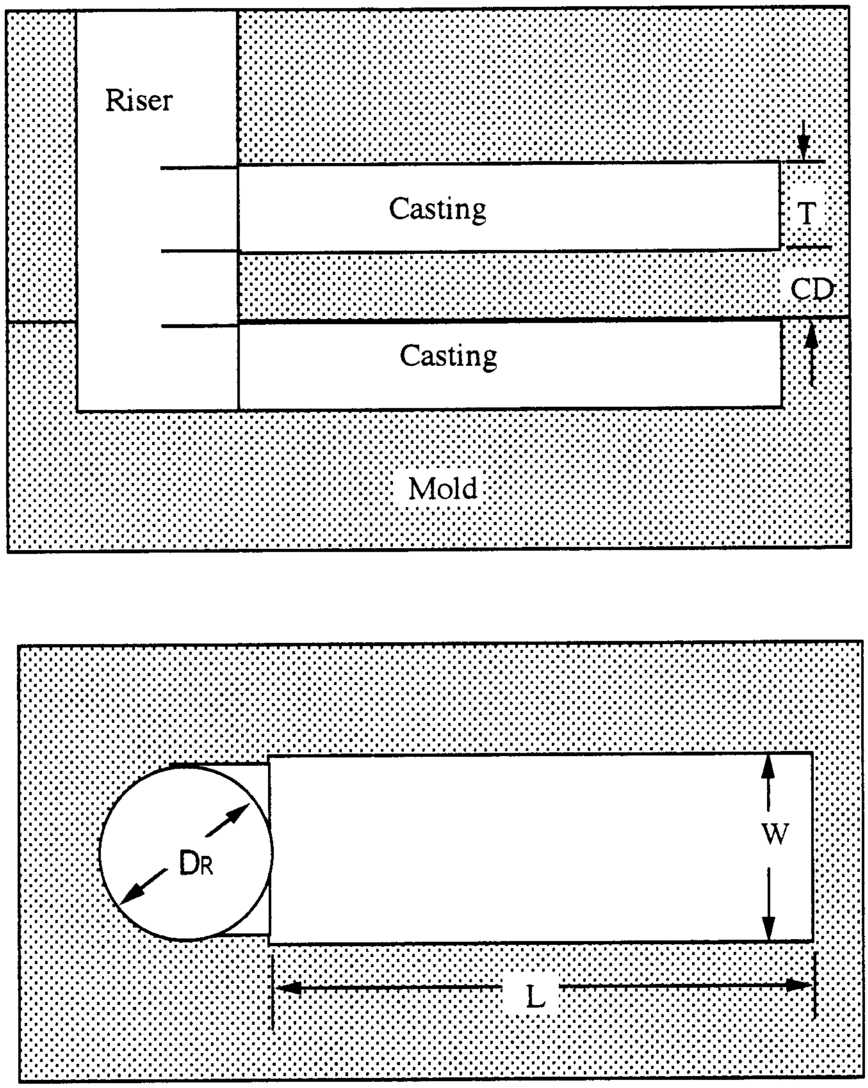


Figure 30 Simulation model for vertical stacking of horizontal plates with side riser

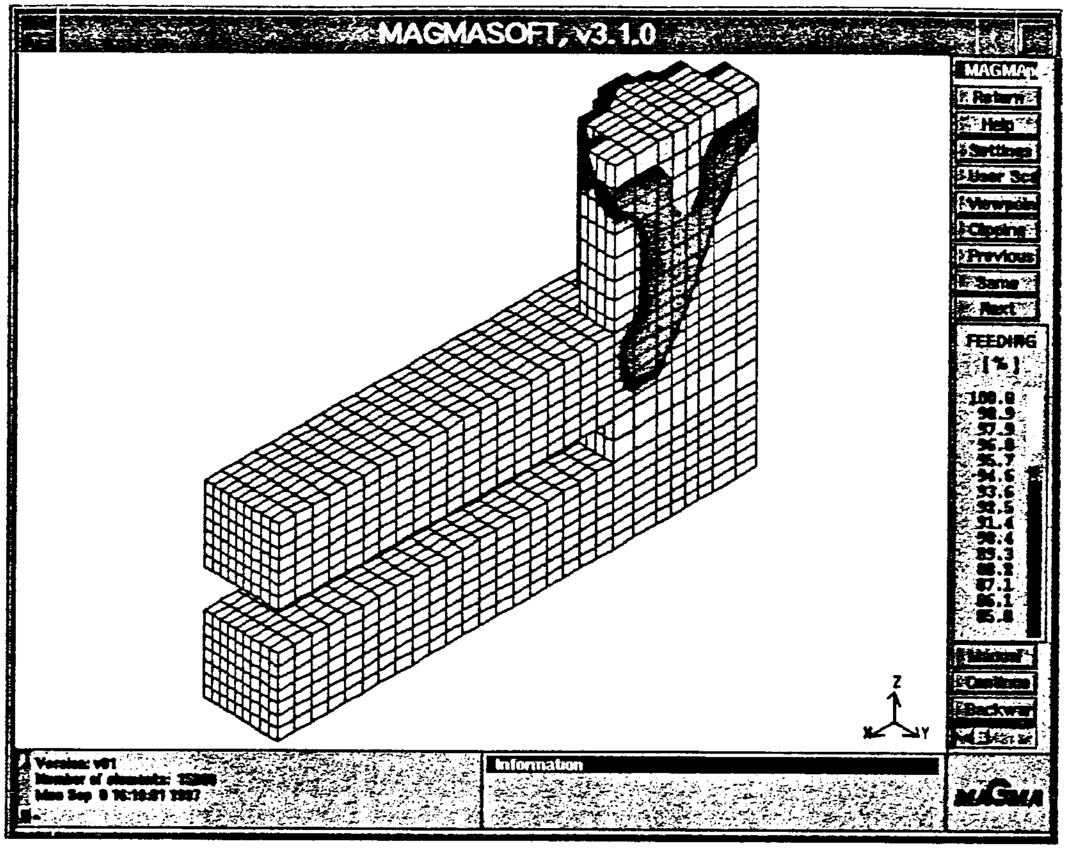


Figure 31 Feeding percentage plot for two stacked plates with optimum riser height (CD=2″)

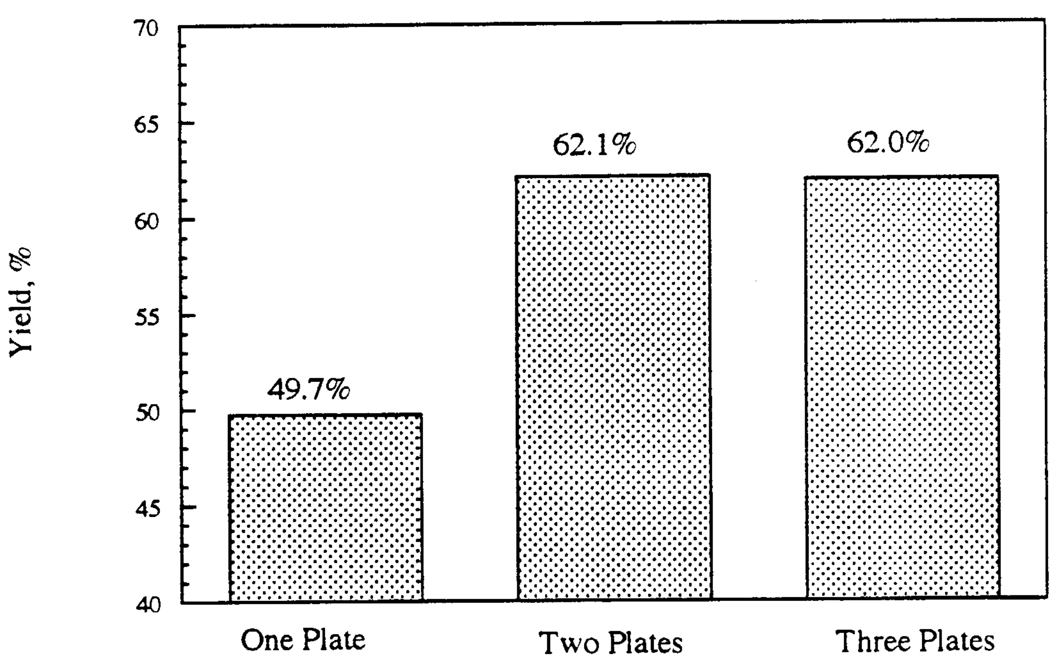
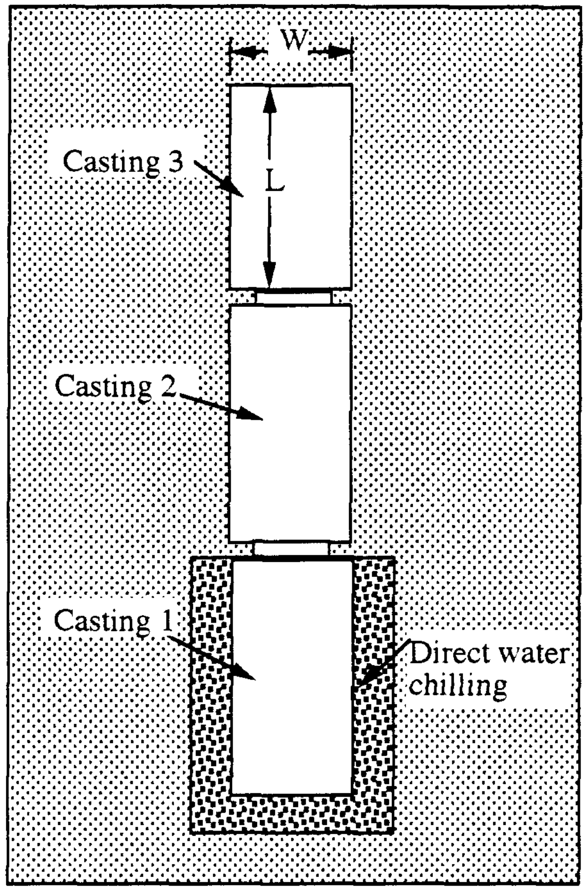


Figure 32 Yield for vertical stacking of horizontal plates



— Casting geometry demensions (TxWxL): 2"x4"x8"

— Solidification and filling proceeds from bottom (Casting 1) to the top (Casting 3).

— Once Casting 1 is solidified, it is chilled while Casting 2 begins to solidify. Meanwhile Casting 3 slowly poured and heated to serve as feeder for Casting 2.

— The simulation is stopped when Casting 2 is fully solidified.

Figure 33 Schematic diagram of simulation model for vertical stacking of castings of vertical plates

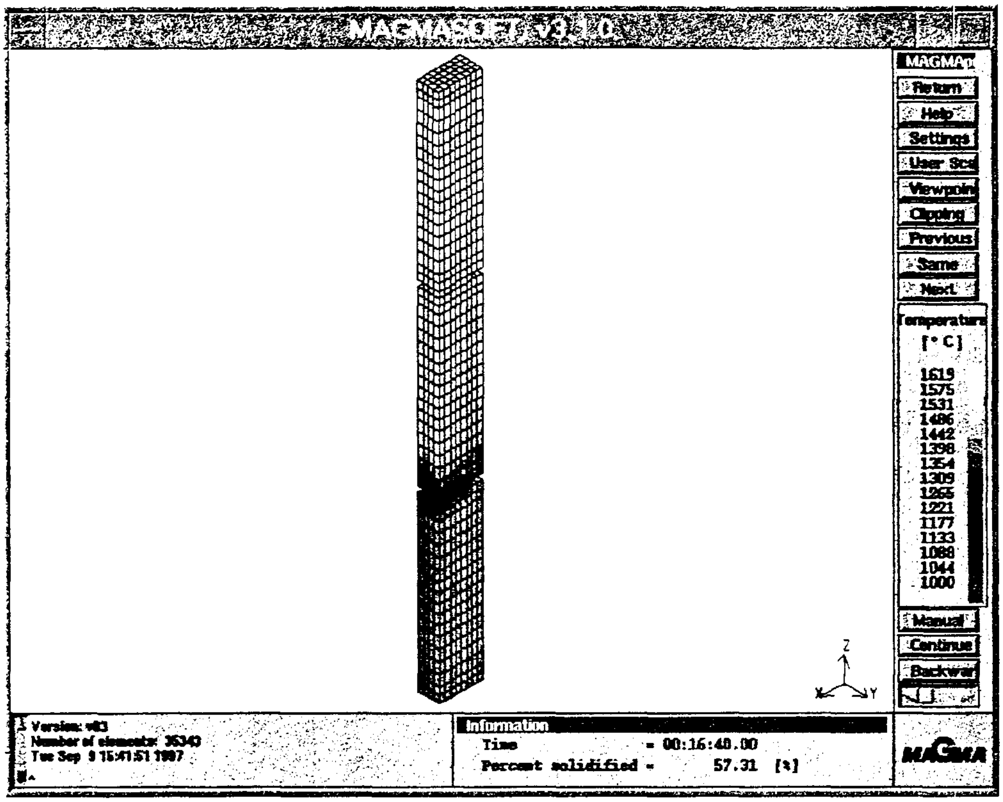


Figure 34 Temperature distribution at 1000s

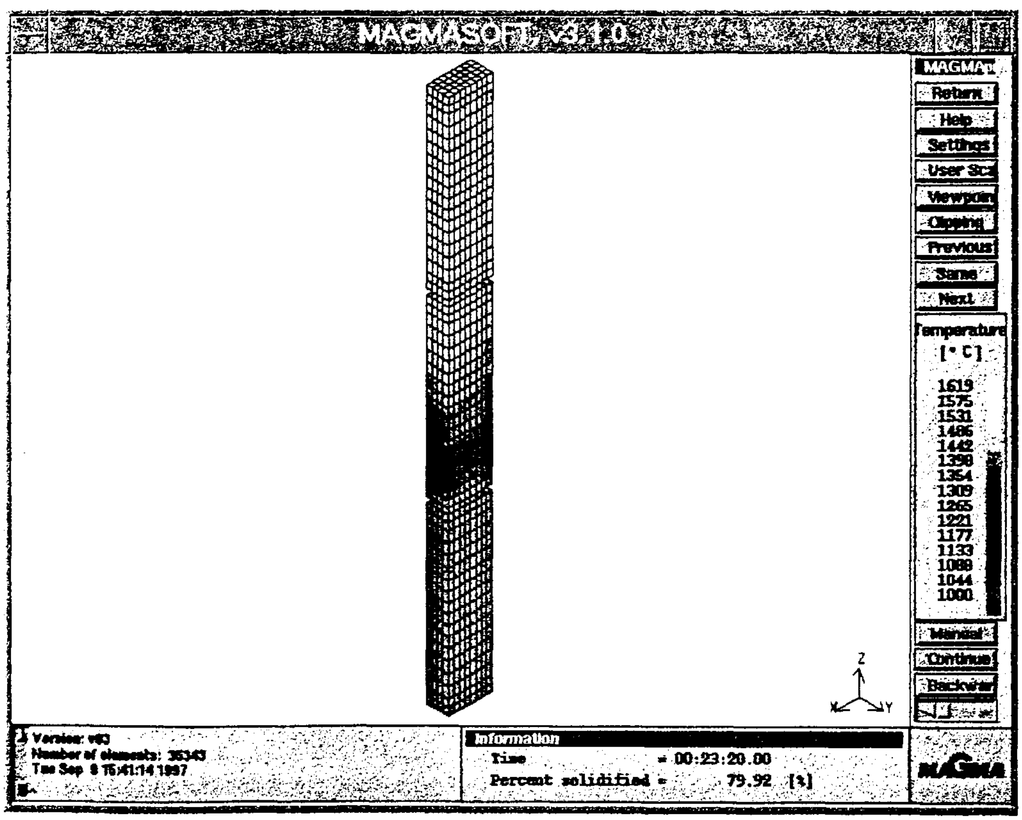


Figure 35 Temperature distribution at 1400s

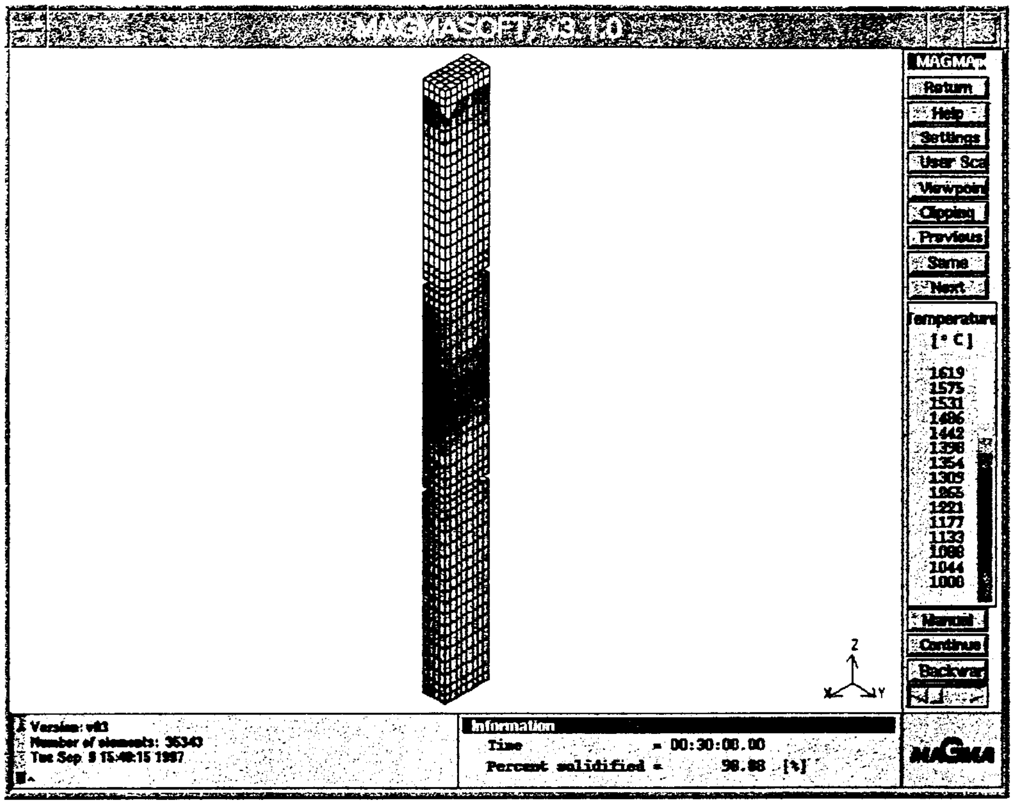


Figure 36 Temperature distribution at 1800s

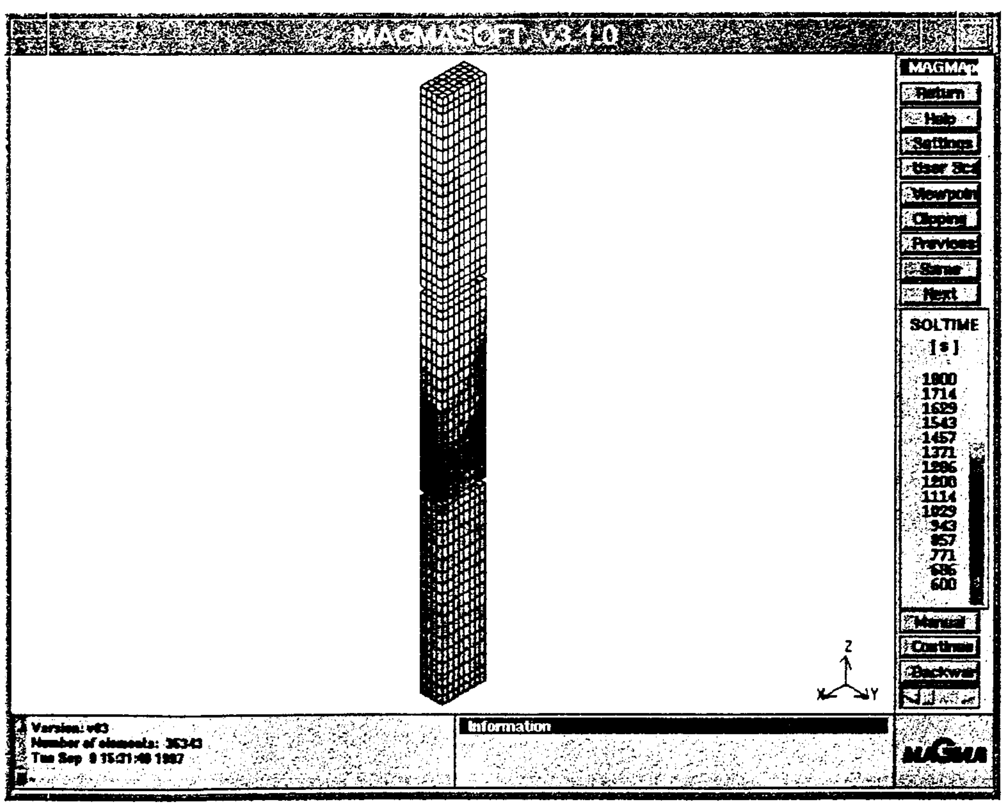


Figure 37 Solidification time plot for the vertical stacking of vertical plates