Development of New Feeding-Distance Rules Using Casting Simulation: Part II. The New Rules

SHOUZHU OU, KENT D. CARLSON, RICHARD A. HARDIN, and CHRISTOPH BECKERMANN

Based on a correlation between the Niyama criterion and radiographic casting soundness developed in Part I of this work, a new set of riser feeding-distance rules is developed for low-alloy steel castings. These rules are designed to produce radiographically sound castings at 2 pct sensitivity. Rules are provided for the riser-zone length, end-zone length, end-effect feeding distance and lateral feeding distance for top risers, and feeding distance for side risers. In addition, the relationships between the end-zone length, riser-zone length, and the various feeding distances are discussed. Multipliers are given to apply these rules with end chills and drag chills, and multipliers are also provided to tailor these rules to different steel alloy compositions, sand mold materials, and pouring superheats. In comparison with previously published rules, the present rules are shown to provide longer feeding distances in most casting situations.

I. INTRODUCTION

AS computer technology continues to advance, computer simulation of the metal casting process is becoming an increasingly popular tool. Through the use of simulation, foundries are able to evaluate modifications to casting designs without having to actually produce the casting, thus saving time, material resources, and manpower. However, computer simulation must be applied on a case-by-case basis, and its effective use requires expertise as well as accurate data for many process variables. Furthermore, casting simulation does not provide the initial riser design for a casting, nor does it automatically optimize the risering. Due to these limitations, feeding rules are still widely used in the steel casting industry to determine the size and placement of risers.

The development of feeding-distance rules for steel castings began in the early 1950s. One of the two major efforts involved in this early work was carried out at the Naval Research Laboratory (NRL) by Pellini and co-workers.[1–4] They developed feeding-distance rules by analyzing the radiographic testing results of extensive plain-carbon steel casting trials. Pellini *et al.* define the feeding distance as the longest distance from the edge of the riser to the edge of the casting that will result in a sound casting, where "sound" is defined as no visible shrinkage on radiographs filmed at 1.5 pct sensitivity. The first published study from this work[1] involves several different top-risered casting shapes: semicircular plate castings of a thickness of $T = 1.27$, 2.54, 3.81, and 5.08 cm (0.5, 1, 1.5, and 2 in.); circular plate castings of a thickness of $T = 2.54$ and 5.08 cm (1 and 2 in.); and rectangular plate castings of a thickness of $T = 5.08$ cm (2 in.), with widths (W) ranging from 2 to 5 T. The primary result of this study is that the feeding distance for plates is equal to 4.5 T, where "plate" is defined as $W/T \geq 3$.[1] This feeding distance of 4.5 T is composed of two regions: 2.5 T is made sound by the chilling effects of the edges of the plate, where the casting meets the mold, and the remaining 2 T (adjacent to the riser) is made sound by the temperature gradient created by the riser itself. These two regions will be discussed frequently in this article, and are, hereafter, referred to as the end zone and riser zone, respectively. Bishop and Pellini[1] note that, when the feeding distance is exceeded and shrinkage forms, it occurs in the intermediate zone that develops between the riser and end zones, which remain sound.

Next, Bishop *et al.*[2] reported a feeding-distance rule for top-risered bars, where the "bar" is defined as $W/T = 1$ (*i.e.*, $W = T$). This rule is based on 5.08, 10.2, 15.2, and 20.3 cm (2, 4, 6, and 8 in.) bars, cast both horizontally and vertically. The feeding distance for the 5.08 to 15.2 cm (2 to 6 in.) bars, both horizontal and vertical, is given as $9.56\sqrt{\mathrm{T}}$ cm, where T is in cm (or $6\sqrt{\mathrm{T}}$ in., if T is in inches). The feeding distance of the horizontal 20.3 cm (8 in.) bars is a little smaller than the value given by this rule, while the feeding distance of the vertical 20.3 cm (8 in.) bars is somewhat longer, due to convection current effects.[2]

The following year, Myskowski *et al.*[3] provided feeding-distance rules for plates and bars with end chills or drag chills. The end-chill rules were based on 5.08, 7.62, 10.2, 15.2, and 20.3 cm (2, 3, 4, 6, and 8 in.) bars, and $W/T = 5$ plates with a thickness of $T = 2.54$, 5.08, 7.62, and 10.2 cm (1, 2, 3, and 4 in.). The feeding distance for bars is given as $6\sqrt{T} + T$ in., where T is in inches (equal to $9.56\sqrt{T} + T$ cm, with T in centimeters). The feeding distance for plates with an end chill is $4.5\,T + 2$ in. (equal to $4.5\,T + 5.08$ cm, with T in centimeters). These values were obtained using end chills with a chill thickness (dimension normal to the chill surface) of $CT = 0.5\,T$ for bars and $CT = T$ for plates. These values of chill thickness were chosen based on experiments that indicated that larger values than these did not significantly increase the feeding distance.[3] An important point is brought out in this study regarding how end chills work: end chills increase the feeding distance by increasing the length of the end zone; they have no effect on the riser zone. In addition to the end-chill experiments, drag chills were also evaluated for 5.08 and 7.62 cm (2 and 3 in.) bars and plates (again, with $W/T = 5$). The value of $CT = T$ was used for the bars, and $CT = 2\,T$ was used for

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the plates. Based on the experimental results, Myskowski *et al.* conclude that adding a drag chill essentially develops an artificial casting-edge condition between the risers. In effect, this divides the casting section at the midline between the risers into two sections, each being sound over a distance from the midline essentially equivalent to that produced by an end chill at the end of a casting with that cross section.[3]

Finally, all of the feeding-distance rules discussed previously were summarized very concisely by Pellini.[4] This work includes a summary of feeding-distance experiments performed for joined sections, which are sections of different thickness that are joined together.[5] The main conclusion from that study is that joined sections tend to increase the feeding distance in the thinner section and decrease the feeding distance in the thicker section. However, these effects can be reversed if the difference in thickness is very large or very small.[5]

At about the same time the NRL casting trials were being performed for the work discussed previously, the Steel Founders' Society of America (SFSA) conducted a separate set of plain-carbon steel casting trials to supplement the information produced by the NRL. For the SFSA trials, the feeding distance was, again, defined as the longest distance from the edge of the riser to the edge of the casting that will result in a sound casting. However, the definition of sound used for these trials was "commercially sound;" *i.e.*, the radiographs of the castings (filmed at 2 pct sensitivity) had to pass ASTM class 2 radiographic standards, which allow a small amount of shrinkage to be present.[6] For these trials, plates were cast with a thickness of $T = 1.27$, 2.54, 5.08, and 10.2 cm (0.5, 1, 2, and 4 in.), with W/T values ranging from 14 to 48 for the 1.27 cm (0.5 in.) plates, from 2 to 24 for the 2.54 cm (1 in.) plates, from 2 to 13 for the 5.08 cm (2 in.) plates, and with $W/T = 2$ for the 10.2 cm (4 in.) plates. In addition, 2.54, 5.08, and 10.2 cm (1, 2, and 4 in.) bars ($W/T = 1$) were cast as well. In addition to the SFSA casting trials, this report also includes a description of the NRL trials discussed previously,[1,2] and the results of both sets of trials are summarized together.[6] The feeding distances for commercial soundness found in the SFSA trials are given as follows. For $W/T \geq 3$ (plates), the feeding distance is 12 T for $T \leq 1.27$ cm (0.5 in.) and 6 T for $T =$ 2.54 and 5.08 cm (1 and 2 in.). For $1 < W/T < 3$, the feeding distance is 7 T for $T = 2.54$ cm (1 in.), 6 T for $T = 5.08$ cm (2 in.), and 5 T for $T = 10.2$ cm (4 in.). For $W/T = 1$ (bars), the feeding distance is 4.5 T for $T = 2.54$ to 10.2 cm (1 to 4 in.). In summarizing the NRL results, the standard feeding distance of 4.5 T is listed for the $T =$ 2.54 and 5.08 cm (1 and 2 in.) plates, and 8 T is listed for the $T = 1.27$ cm (0.5 in.) plates. Finally, the summary lists the NRL feeding distance for bars, 6 $\sqrt{T}$ in. (9.56 $\sqrt{T}$ cm), for 2.54 to 20.3 cm (1 to 8 in.) bars. This is not entirely correct, however, as Bishop and Pellini[1] did not provide results for 2.54 cm (1 in.) bars (the smallest bars were 5.08 cm (2 in.)).

The remainder of the feeding-distance literature is based primarily on the work of Pellini and co-workers.[1–4] Cech[7] summarizes the risering procedure for steel castings and gives plots of end-zone and riser-zone lengths as a function of casting thickness. He uses the values given by Bishop and Pellini[1] for plates, but he defines a plate as having $W/T \geq 5$, rather than $W/T \geq 3$. He uses slightly more conservative values than Pellini *et al.*[2] for bars. Then, he fills in the gaps between the bar ($W/T = 1$) and plate ($W/T = 5$) curves in these figures with curves representing W/T values of 1.5, 2, 3, and 4. Wlodawer[8] repeats the riser-zone and end-zone length plots of Cech[7] and adds a plot showing the sum of the riser- and end-zone lengths, which is simply the feeding distance. Wlodawer also includes a figure summarizing the riser-zone lengths, end-zone lengths, and feeding distances for bars and plates, with and without chills, very similar to Figures 15, 16, and 24 in the article by Pellini.[4]

In the 1960s, the concept of determining feeding distances numerically was investigated at Case Western Reserve University (Cleveland, OH) by Spiegelberg,[9,10] Maier,[11] and Ghun,[12] under the direction of Professor J.F. Wallace. The idea of this work was that the solidification gradient could be used to determine whether shrinkage porosity would form in a casting. Spiegelberg theorized that if the solidification gradient near the end of solidification dropped below some minimum value, shrinkage porosity would form. They determined the minimum value by comparing their numerical results to the NRL casting-trial results of Pellini and co-workers.[1–4]

In 1973, the SFSA compiled the results of the NRL casting trials,[1–5] together with the numerical simulations performed at Case Western Reserve University,[9–12] into the handbook *Risering Steel Castings*.[13] This handbook contains charts, nomographs, equations, and procedures useful for risering both low- and high-alloy steel castings; it is intended to assist foundry engineers in the placement and sizing of risers on steel castings. There are a few differences between the definitions given in *Risering Steel Castings* and the definitions used in the work on which this handbook was based. First, the handbook defines a "plate" as $W/T \geq 2$, rather than $W/T \geq 3$, as in References 1 through 6. Second, the feeding-distance rules in this handbook were developed to produce castings with ASTM class 1 or better soundness at 2 pct radiographic sensitivity, rather than radiographically sound castings at 1.5 pct sensitivity, as in References 1 through 5. Third, the handbook indicates that for top-risered plates, the feeding distance is defined as the distance from the riser to the comer of the casting, rather than the casting edge, as in the NRL and SFSA casting trials[1–6] (it is still defined as in References 1 through 6 for $W/T < 2$, however). The handbook definition of feeding distance and the definition used in the NRL and SFSA casting trials[1–6] are shown in Figure 1 as *FD* and *FD**, respectively. However, when the handbook repeats the results of the casting trials for 1.27 and 2.54 cm (0.5 and 1 in.) plates, it gives the same values stated in References 1 through 6, indicating that the same definition of feeding distance (*FD**) was used. Also, when the handbook gives feeding-distance rules for plates, the values remain the same for all $W/T \geq 2$ plates. Considering Figure 1, this means that for a given T value, *FD* would remain constant as W increases.

Ruddle[14] published another risering handbook in 1979, which includes some of the feeding-distance information contained in *Risering Steel Castings*.[13] However, he reverts to the definition of feeding distance as the distance from the riser edge to the edge of the casting (*FD** in Figure 1). Ruddle lists feeding distances for casting sections with end

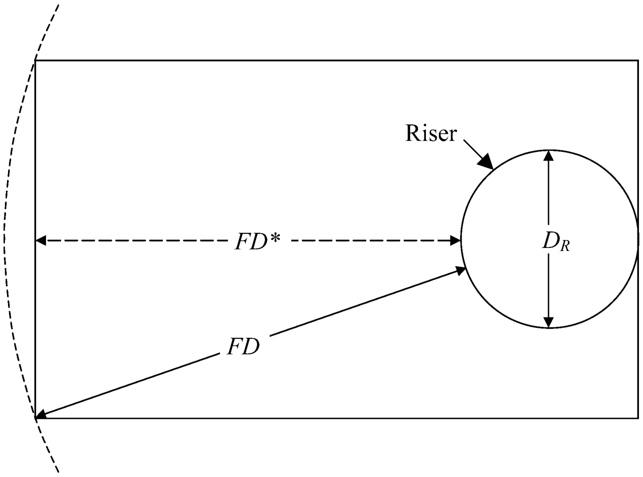


Fig. 1—Alternate definitions of feeding distance: both begin at the edge of the riser, but *FD** extends to the edge of the casting, while *FD* extends to the furthest point in the casting section.

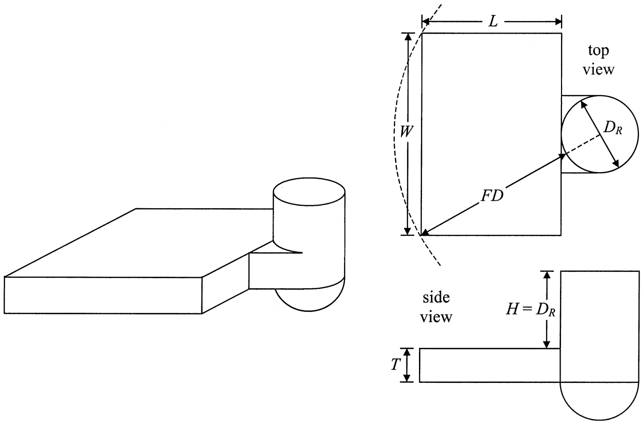


Fig. 2—Definition of plate dimensions for a side-risered section with end effect.

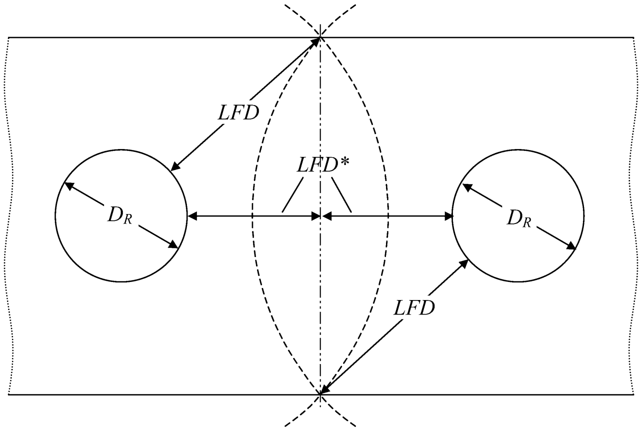


Fig. 3—Illustration of lateral feeding between two risers; the lateral feeding distance *LFD* is measured from the edge of the riser to the furthest point in the casting section to be fed by that riser.

effect, lateral feeding, end chills, and drag chills, for thicknesses ranging from 5.08 to 50.1 cm (2 to 20 in.), along with equations for bars, plates ($W/T = 2$), and rectangular sections with $W/T = 1.33$ and 1.67. Some of the equations he lists are identical to those in Reference 13, and some result in feeding distances that are very similar to the values given in Reference 13. However, there are a few differences: for $T \geq 38.1$ cm (15 in.), Ruddle's values for drag-chill feeding distances in plates are 5 to 8 pct longer than those in Reference 13, and his values for end-chill feeding distances in bars are 4 to 7 pct shorter than those in Reference 13; most notably, though, Ruddle's value for the end-chill feeding distance in plates is 8 pct lower for $T = 25.4$ cm (10 in.) than the value in Reference 13 and decreases as T increases, until it is 26 pct lower for $T = 50.8$ cm (20 in.). Finally, the feeding-distance information in Ruddle's handbook was repeated by Wukovich,[15] in an article that re-examines feeding distances in steel.

Feedback from the steel casting industry indicates that the feeding-distance rules discussed thus far, while adequate, are often too conservative. The objective of the present study is to develop a new set of feeding-distance rules that more accurately predict the feeding distance, thus removing these excessively conservative predictions, which, in turn, will increase casting yield. In Part I of this article, a methodology was established to numerically determine feeding distances in steel castings through the use of the Niyama criterion, which is a local thermal parameter defined as $G/\sqrt{\dot{T}}$, where G is the temperature gradient and $\dot{T}$ is the cooling rate. The Niyama criterion, originally proposed by Niyama *et al.*,[16] is discussed in detail in Part I of this article. By comparing radiographic testing casting-soundness results from an extensive set of plate casting trials with Niyama-criterion values computed from simulations corresponding to each casting trial, a correlation was found between casting soundness and the minimum Niyama-criterion value. It was determined that, if the minimum Niyama value of a casting section is greater than 0.1 $\text{K}^{1/2}\ \text{s}^{1/2}\ \text{mm}^{-1}$, the section will be radiographically sound (*i.e.*, no shrinkage is visible on the X-ray). Further, if a section is unsound, shrinkage is likely to occur in regions where the Niyama criterion for that casting section is below the threshold value. Once this correlation was established, a large number of simulations were performed in order to determine feeding distances for a wide variety of casting conditions. The feeding-distance rules resulting from this work are presented in this article.

II. FEEDING-DISTANCE TERMINOLOGY

For the present study, the feeding distance is defined as the maximum distance a riser can feed a casting section such that the section remains free of visible shrinkage porosity (*i.e.*, resulting in a radiographically sound casting section). The distance is measured from the edge of the riser to the furthest point in the casting section fed by that riser. This is illustrated for a plate with a top riser in Figure 1 (*FD*, rather than *FD**), and for a plate with a side riser in Figure 2. When multiple risers are present, the feeding that occurs between the risers is called lateral feeding. The lateral feeding distance (*LFD*) is, again, the maximum distance over which a single riser can supply feed metal. If one would draw a line separating the casting section to be fed by a riser and the section to be fed by an adjacent riser, *LFD* is then the distance from the edge of the riser to the furthest point in the casting along this line. This is illustrated in Figure 3, along with an alternate definition, *LFD**, that is consistent with *FD**, shown in Figure 1.

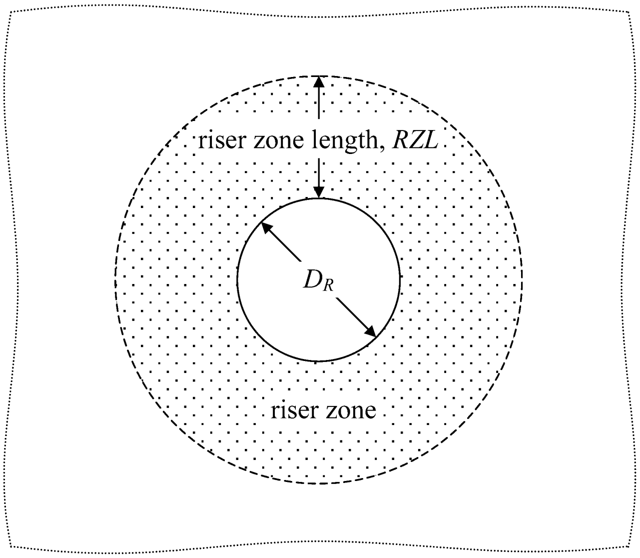


Fig. 4—Illustration of the riser-zone length *RZL* of a casting section without end effects; note that *RZL* is independent of the riser diameter D_R.

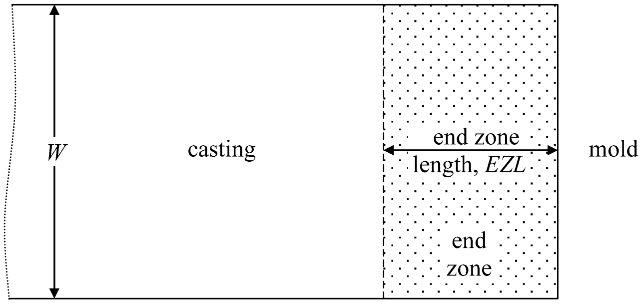


Fig. 5—Illustration of the end-zone length *EZL* of a casting section; note that *EZL* is a function of *W* for $W/T < 7$.

Another way to explain how feeding distances are measured is to draw a circle centered about the riser with a radius equal to the feeding distance plus the riser radius (Figures 1 through 3). Then, the casting section inside the circle is fed by that riser. For multirisered castings (such as in lateral feeding), the circles must overlap such that all sections of a casting are inside these circles.

There are two terms that are important to understand when considering feeding distances: the riser zone and end zone. Since the riser remains hotter than the casting section to be fed, it provides a temperature gradient that facilitates feeding. The length over which this riser effect acts to prevent shrinkage porosity is called the riser-zone length (*RZL*), which is measured radially outward from a riser. This is illustrated for a top riser in Figure 4. The cooling effect of the mold at the end of a casting section also provides a temperature gradient along the length of the casting section to be fed. This is called the end effect, and it produces a sound casting over the so-called end-zone length (*EZL*), which is measured normal to the end of a casting section. This is depicted in Figure 5. The feeding distances, *FD* and *LFD*, are functions of *RZL* and *EZL*; the riser-zone and end-zone lengths are discussed in the next section, and feeding distances are discussed in Section IV.

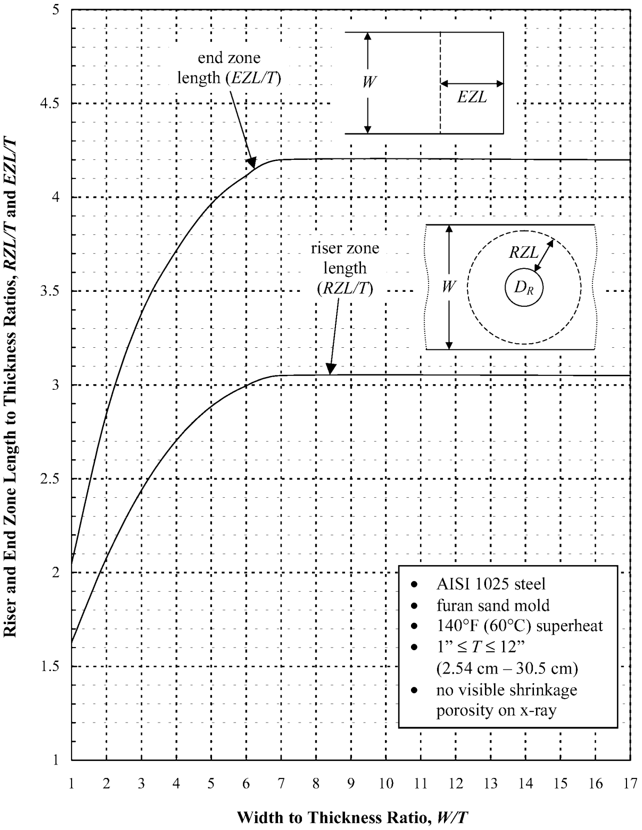


Fig. 6—Riser-zone length and end-zone length as a function of width and thickness.

III. CASTING SOUNDNESS IN TERMS OF RISER AND END ZONES

Riser zones and end zones are regions that are free of shrinkage porosity, because a thermal gradient exists in these regions that promotes directional solidification and facilitates feeding flow. By comparing the Niyama-criterion values from simulation to the threshold value for radiographic soundness discussed earlier, it was possible to determine the size of riser zones and end zones for a wide range of width-to-thickness ratios. The results are given in Figure 6, which shows the normalized riser-zone length (RZL/T) and end-zone length (EZL/T) as functions of the normalized section width *W/T.* The curves in Figure 6 are valid for the casting conditions listed in the inset (note also Section IV). Notice that, as *W/T* increases from 1, both of these curves initially increase and then plateau at their respective maximum values at around $W/T = 7$. Fourth-order polynomial curve fits of *RZL/T* and *EZL/T* for $W/T < 7$ are given in the Appendix.

Considering first the *EZL/T* curve, the thermal gradient created by the mold for large *W/T* values (*i.e.*, $W/T > 7$) extends a distance of $EZL/T = 4.2$ into the casting. As *W/T* decreases below 7, however, *EZL/T* begins to decrease. This can be explained by considering that there are actually three end zones acting on the casting section, shown schematically above the *EZL/T* curve in Figure 6. The end zone labeled in this figure extends from the right edge of the casting, but there are also end zones extending from both sides (*i.e.*, the top and bottom edges in this figure) in the width direction. The directional solidification created by these side end zones causes solidification fronts to move

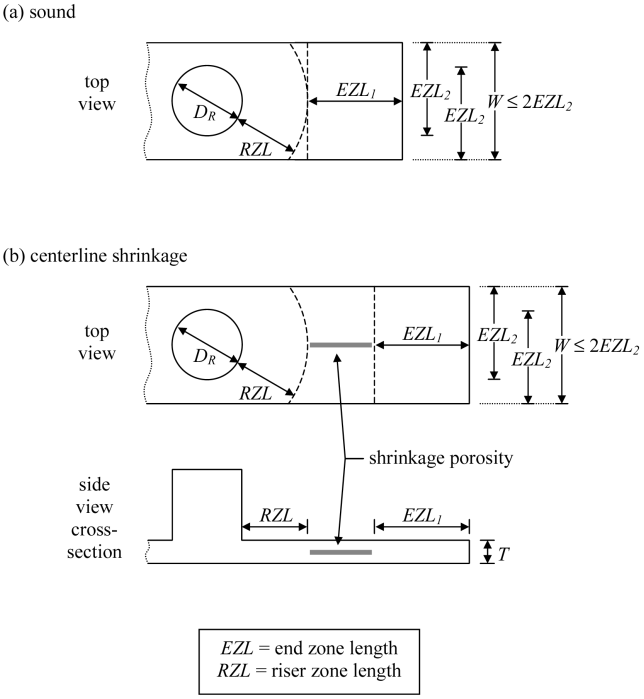


Fig. 7—Top-risered plate with end effect for plates with width $W \leq 2EZL_2$. (*a*) The plate is sound if the riser zone and the end zone extending from the right edge of the casting section are tangent (as shown) or overlap. (*b*) The plate has centerline shrinkage between these zones if they do not meet.

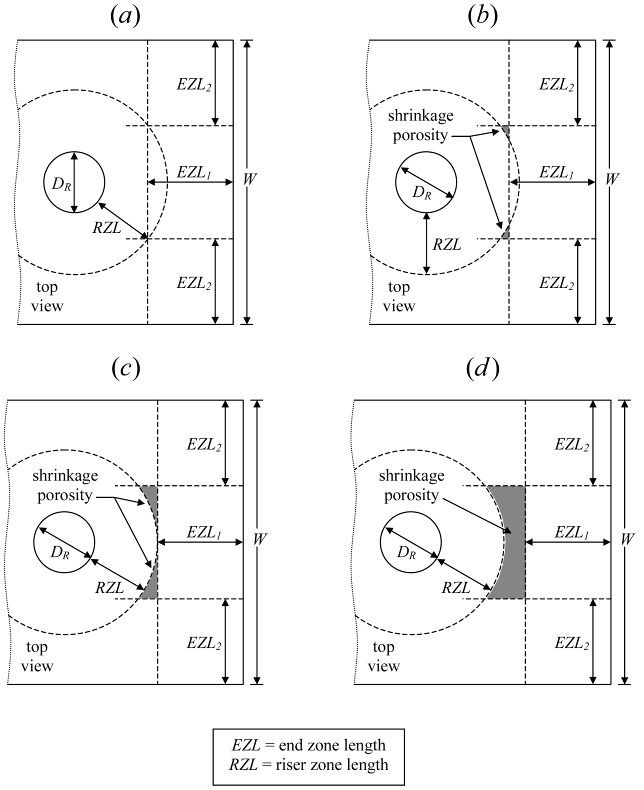


Fig. 8—Top-risered plate with end effect for plates with width $W > 2EZL_2$. (*a*) The plate is sound if the intersections of the end zones lie within or intersect the riser zone. (*b*) through (*d*) Places where porosity forms as the plate length increases.

from the sides into the casting, just as the right end zone causes a solidification front to move from the right edge into the casting. As W/T decreases below 7, the solidification fronts extending from the sides begin to meet at the centerline before the solidification front extending from the right edge can travel the entire end-zone length. When the solidification fronts extending from the sides meet, they cut off feeding flow to the right end zone and effectively reduce the size of that end zone. This causes the decrease seen in EZL/T as W/T approaches 1. The decrease in RZL/T can be similarly explained: for small W/T values, the end zones extending from the sides in the width direction of the casting section meet at the centerline and effectively reduce the size of the riser zone. For $W/T > 7$, the riser-zone length is simply given by $RZL/T = 3.05$, which is independent of the riser diameter.

By utilizing the riser-zone and end-zone concepts, it is possible to determine whether or not a casting section fed by a riser will be sound, as well as where porosity will form if the casting section is not sound. This is shown in the following subsections for (1) a top riser feeding a casting section that ends in the mold, (2) lateral feeding between top risers, and (3) a casting section fed by a side riser.

A. *Top-Risered Casting Section Ending in the Mold*

Figures 7 and 8 illustrate two different situations involving a top riser feeding a casting section that ends in the mold. Figure 7 depicts the case when the casting-section width is less than or equal to twice the size of the end zones extending from the sides in the width direction of the casting section (*i.e.*, $W \leq 2\ EZL_2$). It should be noted that the end-zone lengths EZL_1 and EZL_2 can be different, because they are functions of the length of the casting-mold interface from which they originate. Thus, EZL_1 is a function of W, and EZL_2 is a function of the length of the side edges of the section shown (not labeled). Figure 7(a) shows a sound casting section. The only regions of this casting section that do not lie within either the riser zone or the end zone extending from the right edge of this casting section (*i.e.*, EZL_1) are the regions between the dashed lines (one above the centerline and one below). But, these regions lie within the end zones extending from the side edges in the width direction of the casting section. Hence, the entire casting section not beneath the riser is covered by a riser zone or an end zone, and the casting section is sound. Figure 7(b) shows that, if the distance between the riser and the right edge of the casting section is increased, shrinkage porosity will result along the centerline between the riser zone and the end zone extending from the right edge of the casting. It may seem that this casting section should be sound, because the entire section lies within either the riser zone, the end zone extending from the right edge, or the end zones extending from the side edges. However, due to the directional solidification caused by the end zones extending from the side edges of the casting section, solidification fronts will advance from the side edges toward the centerline. These fronts will meet at the centerline, and feed metal from the riser zone to the end zone extending from the right edge of the casting section will be cut off. This will result in the centerline shrinkage porosity shown in Figure 7(b).

Figure 8 illustrates the case when the width of a casting section is greater than twice the size of the end zones extending from the side edges of the casting section shown

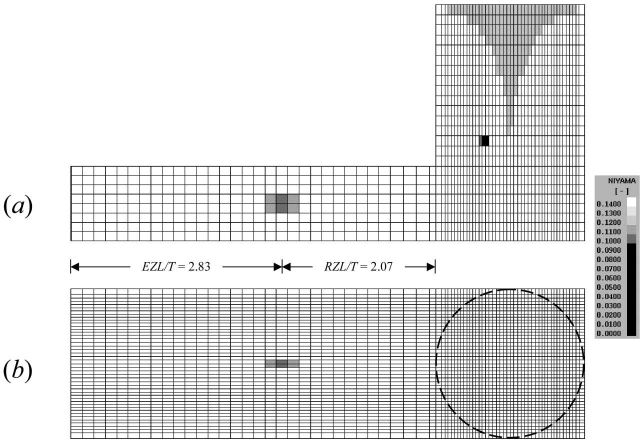


Fig. 9—Cross-section (*a*) side view and (*b*) top view of Niyama plots from a simulation of a 7.62 by 15.2 by 52.6 cm (3-in. *T* by 6-in. *W* by 20.7-in. *L*) top-risered plate.

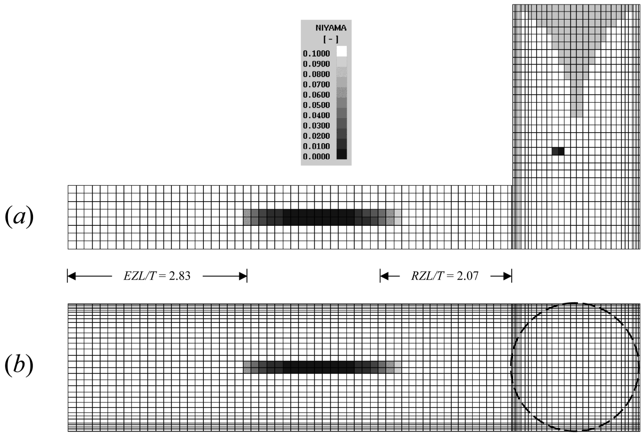


Fig. 10—Cross-section (*a*) side view and (*b*) top view of Niyama plots from a simulation of a 7.62 by 15.2 by 68.6 cm (3-in. *T* by 6-in. *W* by 27-in. *L*) top-risered plate.

(*i.e.*, $W > 2\ EZL_2$). Figure 8(a) depicts a sound casting. Again, the entire casting section not directly beneath the riser lies within a riser zone or an end zone. Figure 8(b) shows the onset of shrinkage porosity as the distance from the riser to the right edge of the casting section increases beyond the maximum distance for a sound casting, shown in Figure 8(a). Note that, when $W > 2\ EZL_2$, the shrinkage porosity begins to form in the two small regions not covered by an end zone or riser zone, rather than along the centerline, as in the case depicted in Figure 7 when $W \leq 2\ EZL_2$. Figures 8(c) and (d) show how the shrinkage-porosity regions grow and eventually merge into one region as the distance between the riser and the right edge of the casting section continues to increase. An important difference between the cases depicted in Figures 7 and 8 can be seen by comparing Figures 7(a) and 8(c). Note that these two figures are similar, since the end zone extending from the right edge of the casting is tangent to the riser zone in both figures. However, due to the difference in casting-section widths in these two figures, Figure 7(a) results in a sound casting, while Figure 8(c) results in shrinkage porosity.

Two numerical examples that illustrate some of the phenomena just described for casting sections that end in the mold are provided in Figures 9 and 10. These figures contain midplane cross-sectional Niyama plots from simulations of two top-risered plates with the same width and thickness, but two different lengths. Figure 9 shows Niyama values for a 7.62 by 15.2 by 52.6 cm (3 by 6 by 20.7 in.) plate (thickness by width by length, respectively). Notice that there are no Niyama values in the plate with a value below 0.1 (the darkest cells in the middle of the plate have values of Ny = 0.104). By the criterion developed in Part I of this article, this plate is radiographically sound, since $\mathrm{Ny}_{\min} > 0.1$. However, if the plate is made any longer, this minimum Niyama value will decrease and will drop below 0.1. Thus, the plate shown in Figure 9 corresponds to the longest sound plate that can be cast with the casting conditions used. The end-zone and riser-zone lengths for this plate can be determined from Figure 6, using the values for $W/T = 2$. This results in $RZL/T = 2.07$ and $EZL/T = 2.83$; these lengths are shown in Figure 9. Excluding the portion that is directly under the riser, the plate has a length of 4.9 *T*, which is exactly the sum of *EZL* and *RZL*. In other words, the situation shown in Figure 9 corresponds to Figure 7(a), where the riser zone and the end zone meet at a point of tangency. If the plate is made longer, the point where Ny would first drop below 0.1 (and, hence, where one would expect shrinkage to begin to develop) is where $\mathrm{Ny}_{\min}$ (equal to 0.104) occurs in Figure 9; *i.e.*, when the plate length exceeds the sum of the riser-zone and end-zone lengths, shrinkage will occur in the region between these zones. This is clearly seen in Figure 10, which contains Niyama plots for a 7.62 by 15.2 by 68.6 cm (3 by 6 by 27 in.) plate (thickness by width by length, respectively). Note that the scale for the Niyama criterion is different than in the preceding figure. In Figure 10, only cells with a Niyama value below the 0.1 threshold are shaded. Therefore, the shaded cells represent the region in the plate where shrinkage is expected to occur. This figure corresponds very well to Figure 7(b), with the shrinkage region confined to the centerline of the plate, between the riser zone and end zone. Notice that there is a little overlap between the shrinkage region in Figure 10 and the riser zone. This was also noted by Pellini *et al.*, who state that the riser-zone length is only equal to the rule value (2 *T*, in their work) for sound plates; if shrinkage occurs, the shrinkage region will extend closer to the riser, and the riser-zone length will be reduced.[1,4]

B. *Lateral Feeding in a Top-Risered Casting Section*

Different examples of top-risered lateral feeding are presented in Figures 11 through 13. Figure 11 illustrates the case when the casting-section width is less than or equal to twice the size of the end zones extending from the side edges in the width direction of the casting section (*i.e.*, $W \leq 2\ EZL$). Figure 11(a) shows a sound casting. The riser zones are tangent to each other, encompassing all of the casting section except for the areas between the dashed lines. These areas fall within the end zones that extend from the side edges of the casting section, shown in Figure 11(a). When the distance between risers increases, as in Figure 11(b), the riser zones do not intersect. Similar to the situation shown in Figure 7(b), the solidification fronts advancing from the side edges of the casting section in Figure 11(b) meet at the centerline and cut off feeding from the riser zones. This results in the centerline shrinkage shown in

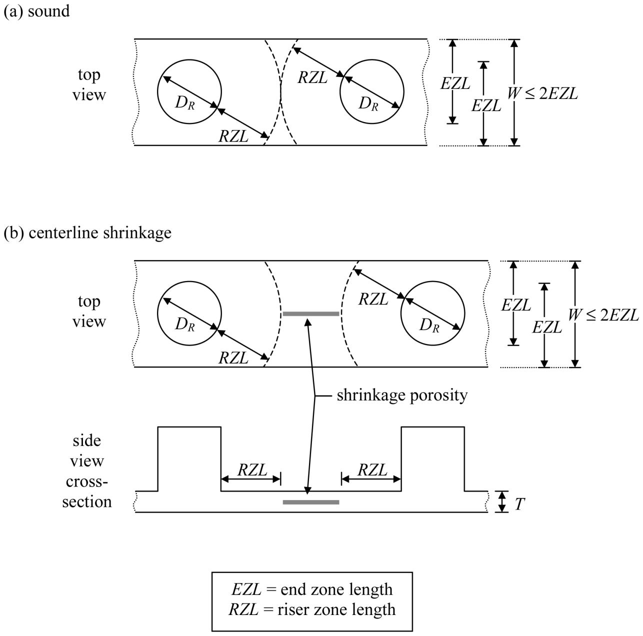


Fig. 11—Top-risered plate with lateral feeding for plates with width $W \le 2EZL$. (*a*) The plate is sound if the riser zones are tangent (as shown) or overlap. (*b*) The plate has centerline shrinkage between the riser zones if they do not meet.

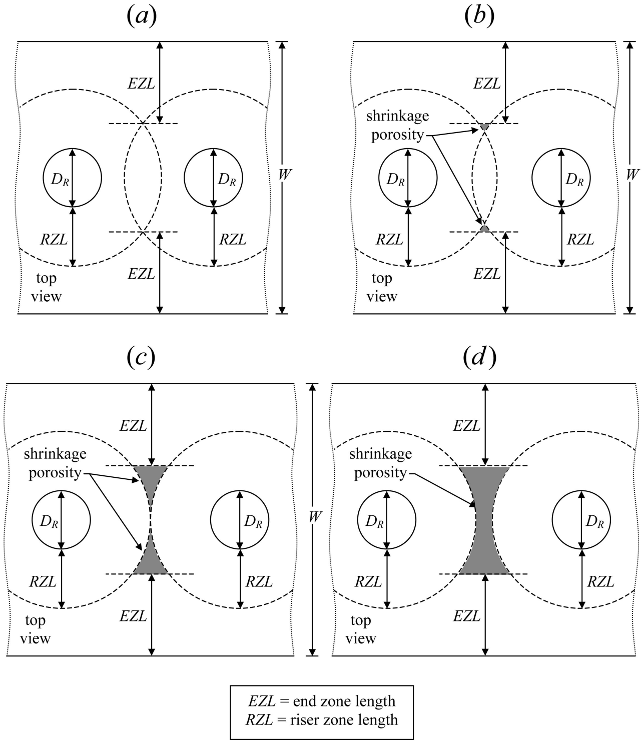


Fig. 12—Top-risered plate with lateral feeding for plates with width $W > 2EZL$. (*a*) The plate is sound if the end-zone lines lie within or intersect the riser zones. (*b*) through (*d*) Places where porosity forms as the distance between risers increases.

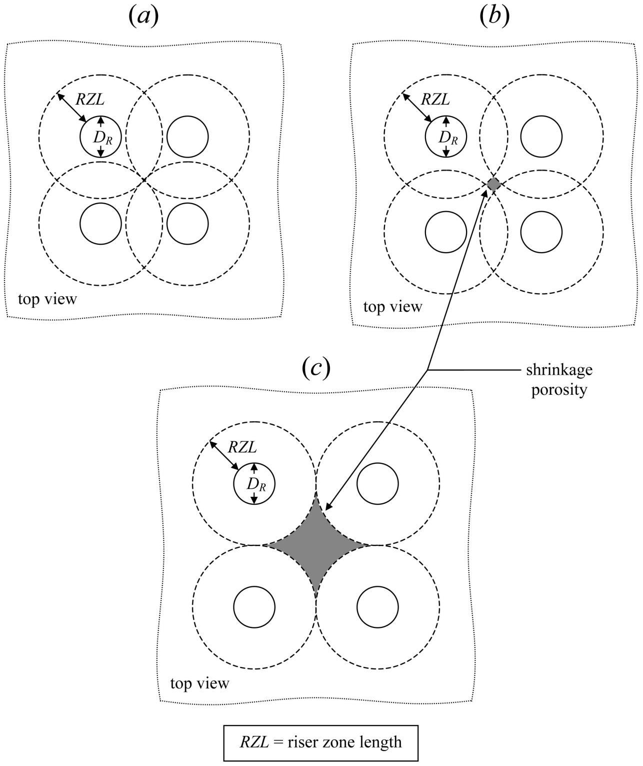


Fig. 13—Top-risered plate with lateral feeding for a plate section without end effects. (*a*) The region of the plate between the risers is sound if it is completely contained within one or more riser zones. (*b*) and (*c*) Places where porosity forms as the distance between risers increases.

Figure 11(b). Figure 12 depicts the case when the width of a casting section is greater than twice the size of the end zones extending from the side edges of the casting section shown (*i.e.*, $W > 2\,EZL$). Figure 12(a) shows a sound casting. Again, the entire section lies beneath a riser, or in a riser zone or an end zone. When the distance between the risers is increased, shrinkage porosity begins to form in the casting in the regions not covered by riser zones or end zones. This is illustrated in Figure 12(b). Analogous to Figure 8, the regions of shrinkage porosity grow and merge as the distance between risers continues to increase, as seen in Figures 12(b) through (d). Note that Figures 11(a) and 12(c) are similar, since in both figures the riser zones are tangent to each other. However, due to the difference in widths, the casting in Figure 11(a) is sound, while the casting in Figure 12(c) has shrinkage porosity. Figure 13 shows the case when there are no end effects in the region of interest. In order for the casting to be sound, the casting section between all of the risers must lie within one or more riser zones. This is shown in Figure 13(a). Figures 13(b) and (c) show where shrinkage porosity first occurs and how this region grows as the risers are placed further apart.

A numerical example of the riser-zone and end-zone concepts, as they apply to lateral feeding, is given in Figure 14. This figure contains midplane cross-sectional Niyama plots for a 7.62 by 99.1 by 183 cm (3 by 39 by 72 in.) plate (thickness by width by length, respectively) with lateral feeding between two top risers. As in Figure 10, only cells with Niyama values below the 0.1 threshold are shaded, so the shaded region corresponds to where shrinkage is expected. Figure 14(a) shows that the shrinkage region is still confined to the midthickness plane of the plate. However, Figure 14(b) shows that, because $W > 2\,EZL$, the shrinkage is not centerline shrinkage, such as in Figure 10. Rather, this shrinkage region looks quite similar to the one shown

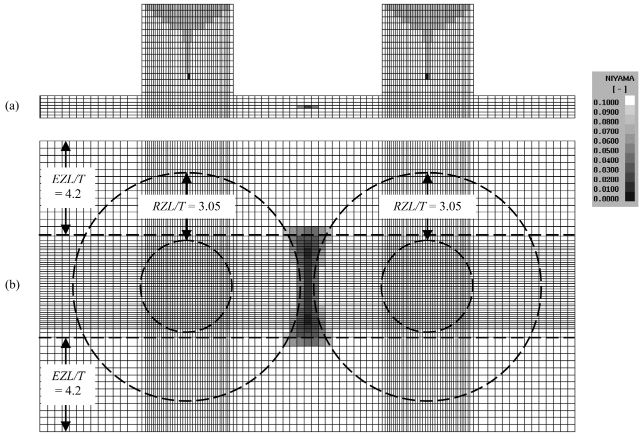


Fig. 14—Cross-section (*a*) side view and (*b*) top view of Niyama plots from a simulation of a 7.62 by 99.1 by 183 cm (3-in. *T* by 39-in. *W* by 72-in. *L*) plate with lateral feeding between two top risers.

in Figure 12(d). Because of the thermal symmetry that occurs at the midpoint between risers, simulations will always result in a Niyama value of about zero between two risers in lateral feeding, regardless of how close the risers are to each other (recall that the numerator of the Niyama criterion is the temperature gradient, which has a value of zero in areas of thermal symmetry). However, this only affects the middle column of cells between the risers.

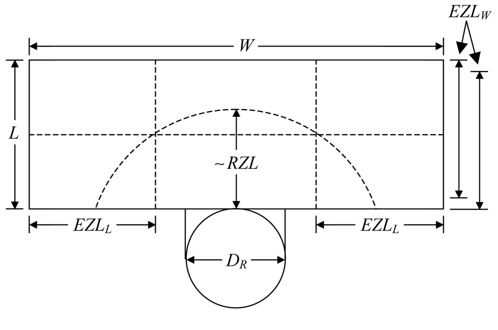
It is worth noting that, due to this limitation in the use of the Niyama criterion to determine the soundness between two risers, the lateral feeding-distance rules presented in the next section were not simply determined by simulating plates with two top risers, as in Figure 14. Instead, lateral feeding distances were determined by simulating single top-risered plates. To understand the methodology used, consider Figures 9 and 11(a). In Figure 11(a), note that for given *W* and riser-diameter (D_R) values, if $W \leq 2\ EZL$, then *RZL* is the only other length necessary to determine the lateral feeding distance, LFD (defined in Figure 3). Thus, when the maximum plate length that yields a sound plate is determined (as in Figure 9), *RZL* for this situation is known, and *LFD* can be computed. In other words, if one were to "cut off" the end zone in Figure 9 and mirror the remaining casting about the cutting plane, the result would be the situation shown in Figure 11(a). This procedure also works if $W > 2\ EZL$.

Based on the cases presented in Figures 7, 8, and 11 through 13, it can be stated that a casting section will be sound provided that ALL THREE of the following conditions are met.

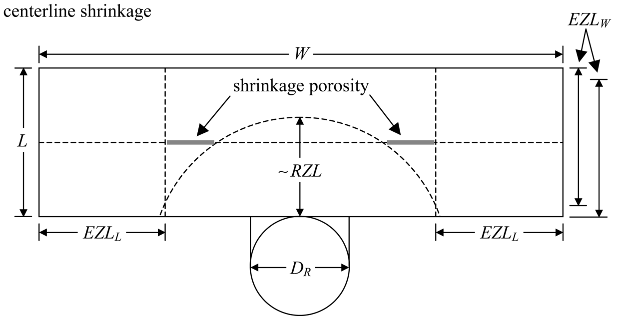
(1) The entire casting section not directly beneath a riser must lie within either a riser zone or an end zone.
(2) If two or more end zones intersect, their point(s) of intersection must lie on or within the boundary of a riser zone.
(3) If two or more riser zones intersect and end effects are present in the region, the point(s) of intersection of the riser zones must lie on or within the boundary of an end zone.

For example, consider Figure 7. The end zones extending from the side edges of this casting section meet at the centerline (not shown). Hence, these end zones share a common boundary, which is the centerline of the casting section. The intersection between this boundary and the boundary of the end zone extending from the right edge of the casting section is the midpoint of the vertical dashed end-zone boundary line, shown in Figure 7. In Figure 7(a), this intersection is the point where the riser zone and the end zone extending from the right edge meet. Hence, the aforementioned conditions 1 through 3 are satisfied, and the casting section is sound. In Figure 7(b), the intersection of the end zones is outside the riser zone. Condition 2 is violated, and shrinkage porosity develops.

(a) sound



(b) centerline shrinkage



RZL = riser zone length (approximate)
EZL_L = end zone length based on *L*
EZL_W = end zone length based on *W*

Fig. 15—An example of the application of riser-zone and end-zone concepts to a side-risered plate. (*a*) The plate is sound if the intersections of the end zones fall in or on the boundary of the riser zone. (*b*) Shrinkage porosity develops between these intersections and the riser zone if they do not meet.

C. *Side-Risered Casting Sections*

Although the discussion of riser zones and end zones to this point has been limited to top-risered sections, these concepts can also be considered in terms of side risers. The concept of end zones is the same as for top risers, because end zones are only a function of the casting/mold interface and not of risers. However, the concept of a riser zone is slightly different, because side risers do not feed radially in all directions like top risers, and there are competing effects between the riser zone and the end zones adjacent to the riser. Figure 15 shows an example of a casting that is fed with a side riser. This casting has at least part of all four of its sides in contact with the mold, so there are four end zones present. The end zones extending from the right- and left-hand sides in Figures 15(a) and (b) are functions of the length (*L*), and the end zones extending from the upper and lower sides are functions of the width. The riser zone drawn in Figures 15(a) and (b) is approximate. As mentioned previously, side risers do not feed the casting in the same manner as top risers. With side risers, some of the feed metal entering the casting moves radially (as with top risers). However, feed metal also has to turn corners to feed the casting on the right- and left-hand sides of the riser contact. In addition, the thermal gradient created by the hotter metal in the riser is competing with the cooling effects of the mold on the edges of the casting near the riser contact. Due to these differences between side-riser feeding and top-riser feeding, the riser zone can only be approximated as a circular arc, as depicted in Figure 15. However, the basic concepts are still useful and valid.

The casting section shown in Figure 15(a) is sound. The intersections of the end zones fall on the riser zone, and the entire casting is covered by a riser zone or an end zone. Thus, the three conditions listed in Section III–B are satisfied. Figure 15(b) shows that as the width is increased, the intersections of the end zones move outside of the riser zone. As in Figures 7 and 11, shrinkage porosity forms along the horizontal centerline between the riser zone and the intersections of the end zones.

Analogous to Sections III–A and III–B, a wide range of geometries can also be considered for side risers, using the same procedures demonstrated thus far in this section. When considering the soundness of side-risered casting sections in terms of *RZL* and *EZL*, the curves given in Figure 6 can be utilized, but the values of *RZL* should be considered approximate.

IV. CALCULATION OF FEEDING DISTANCE

The feeding distance, measured from the edge of a riser to the furthest point in the casting section, indicates the length of a casting section that can be fed by that riser *without developing visible shrinkage defects in radiographic testing* (*i.e.*, *better* than ASTM shrinkage X-ray level 1). As shown in Figures 1 through 3, the concept of a feeding distance is most easily applied by drawing a circle centered about a riser, with a radius equal to the feeding distance plus the riser radius. Then, the casting section inside this circle is fed by that riser.

The feeding-distance rules presented in this section were developed for casting sections with a thickness ranging from 2.54 to 30.5 cm (1 to 12 in.). For thin casting sections (*i.e.*, less than 2.54-cm (1-in.) thick), the feeding distance becomes highly dependent on the filling process.[13] If a thin section is gated through the riser, feeding distances nearly twice as long as those predicted with rules for thicker sections have been reported.[1] Bearing the effects of filling in mind, the feeding rules provided here can be used for thin sections, but they will give an overly conservative estimate of the feeding distance in many instances.

Sections IV–A through E provide equations and charts that can be used to calculate the feeding distance for a casting section with given dimensions. Top risers, side risers, and different end cooling conditions (regular end effect, lateral feeding, and chills) are considered. The feeding distances discussed here are valid for the following base casting conditions:

(1) AISI 1025 steel,
(2) furan (chemically bonded no-bake) sand mold, and
(3) 140 °F (60 °C) pouring superheat.

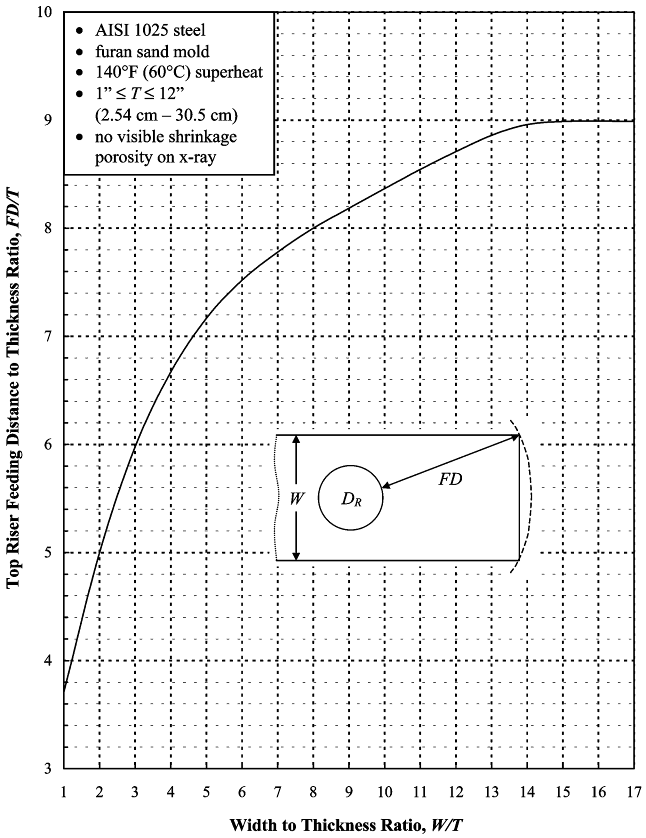


Fig. 16—Feeding distance (*FD*) as a function of width and thickness for top-risered sections.

Application of these feeding distances to sections cast with different alloy compositions, molding materials, and pouring superheats is explained in Section IV–E. As with the *RZL*/*T* and *EZL*/*T* curves in the previous section, fourth-order polynomial curve fits are provided in the Appendix for the curves given in this section.

A. *Top Riser With End Effect*

Feeding distances for top-risered sections with an end effect are given graphically by the curve in Figure 16, where *FD*/*T* is plotted against *W*/*T*. By dividing *FD* and *W* by the thickness *T* (the dimension into the page for the casting sketch shown in Figure 16), a single curve can be used to represent the feeding distances for all section thicknesses in the range being considered. This is more clearly seen in Figure 17, which shows the simulation results on which the curves in Figures 6 and 16 are based. The curves given in Figures 6 and 16 were generated using the average values at each *W*/*T* ratio for casting sections with thicknesses ranging from 2.54 to 30.5 cm (1 to 12 in.). The feeding-distance curve for the end effect given in Figures 16 and 17 terminates at a *W*/*T* value of about 15. For larger *W*/*T* values, the width of the section becomes larger than its length (for a standard riser diameter), and the two can be switched around.

The general relationship between the riser-zone and end-zone lengths and the feeding distance can be seen by comparing Figures 6 and 16. Consider, for example, $W/T = 1$. For

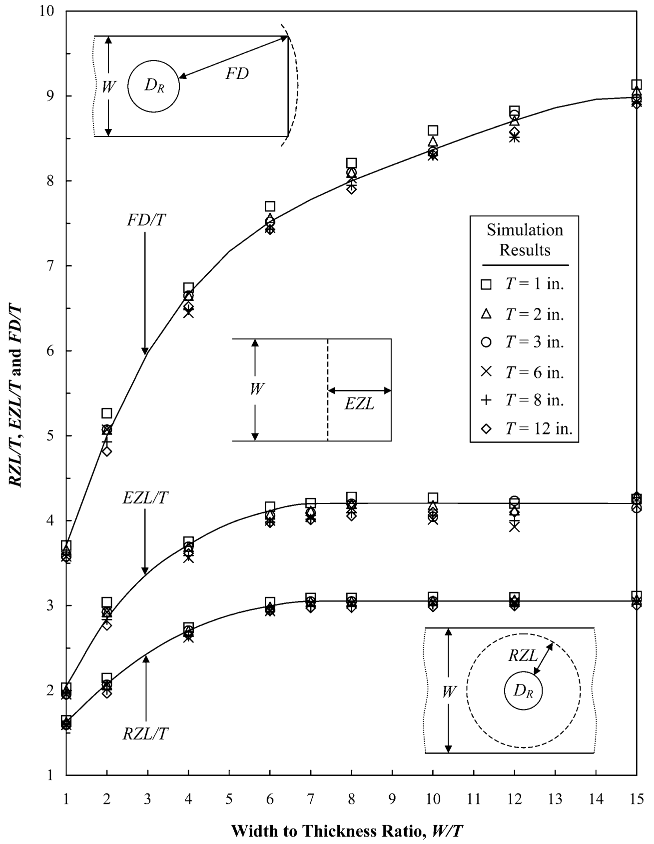


Fig. 17—Riser-zone length, end-zone length, and feeding-distance curves, all normalized by the thickness T, shown with simulation results for various thicknesses.

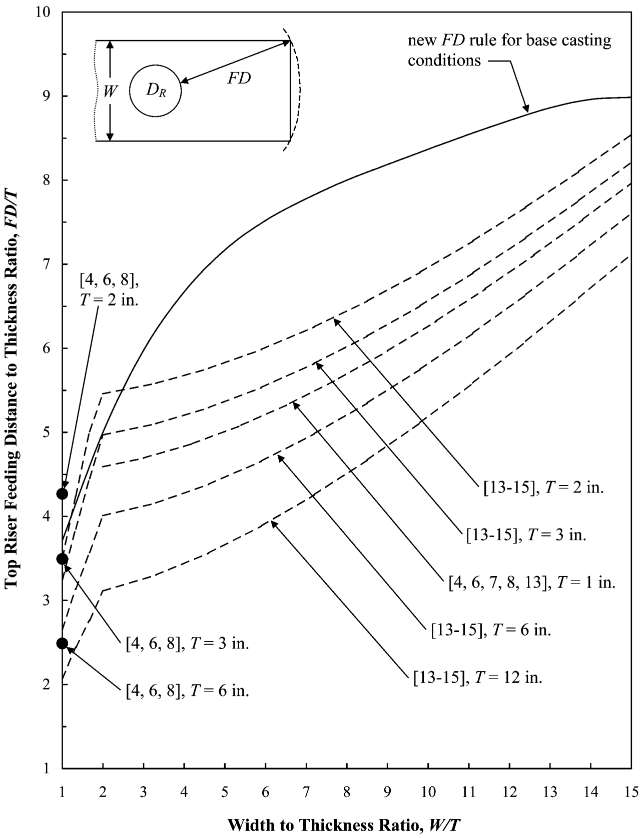


Fig. 18—Comparison between present feeding-distance rule and previously published rules.

small W/T values, the largest sound casting section corresponds to Figure 7(a), where the riser zone is tangent to the end zone. Because W is small, FD is approximately equal to the distance along the centerline from the riser edge to the right edge of this casting, which is simply $RZL + EZL$. From Figure 6, the values of RZL/T and EZL/T for $W/T =$ 1 are 1.65 and 2.05, respectively. Their sum is 3.7, which is about the value of FD/T for $W/T = 1$ in Figure 16. As W/T increases, RZL/T and EZL/T increase until about $W/T = 7$, where they reach their maximum values and then remain constant. The value of FD/T increases slightly faster than the sum of RZL/T and EZL/T from $W/T = 1$ to 7. Beyond $W/T = 7$, FD/T continues to increase with W/T, even though RZL/T and EZL/T remain constant. This is because FD/T is the diagonal distance from the riser to the furthest corner of the casting section, and since W/T continues to increase, so does FD/T. Once W/T is larger than 2 $(EZL_{\max}/T) = 8.4$, the largest sound casting section corresponds to Figure 8(a). Again, as W/T continues to increase, so does FD/T. This occurs until about $W/T = 15$, where FD/T reaches its maximum value of about 9.0.

A comparison between the present rule for feeding distance and previously published feeding-distance rules is provided in Figure 18. Note that all of the previously published feeding-distance rules shown in Figure 18 used FD^* (Figure 1) as the feeding distance, rather than FD, as in the current work. To compare these values, the feeding distances were converted from FD^* to FD, which requires knowledge of the riser diameter. Since the riser dimensioning guidelines provided by the SFSA[13] were used to size the risers for the casting trials and the simulations used to develop the current rules, these guidelines were also used to convert the feeding distances for these comparisons. The filled circles shown for $W/T = 1$ are simply values determined from Pellini's feeding-distance rule for bars,[4] $FD^* = 9.56\sqrt{T}$ cm ($6\sqrt{T}$ in.). Pellini's rule for bars was also given in References 6 and 8. The new rule (solid curve) has a value at $W/T = 1$, close to Pellini's value for $T = 7.62$ cm (3 in.). The dashed curve labeled "$T = 1$ in." is Pellini's feeding-distance rule for plates,[4] $FD^* = 4.5\ T$, also frequently repeated by other researchers. According to *Risering Steel Castings*,[13] this curve is valid for $T = 2.54$ cm (1 in.) plates ($W/T \geq 2$); it is valid for plates ($W/T \geq 3$) of any thickness, according to Pellini[4] and Briggs,[6] and for plates ($W/T \geq 5$) of any thickness, according to Cech[7] and Wladower[8] (below $W/T = 5$, this curve branches into different curves for different thicknesses,[7,8] connecting to $W/T = 1$ values that are a bit more conservative than those shown in this figure). The dashed curves for $T = 5.08$, 7.62, 15.2, and 30.5 cm (2, 3, 6, and 12 in.) are originally from *Risering Steel Castings*, later reproduced by Ruddle[14] and Wukovich.[15] The reason the curve labeled $T = 1$ in. lies between the curves $T = 3$ in. and $T = 6$ in., rather than above the curve labeled $T = 2$ in., is that the $T = 1$ in. curve was developed to produce radiographically sound castings, while the other dashed curves were developed to produce ASTM class 1 or better castings. Notice that, under almost all conditions, the new rule (which was developed to produce

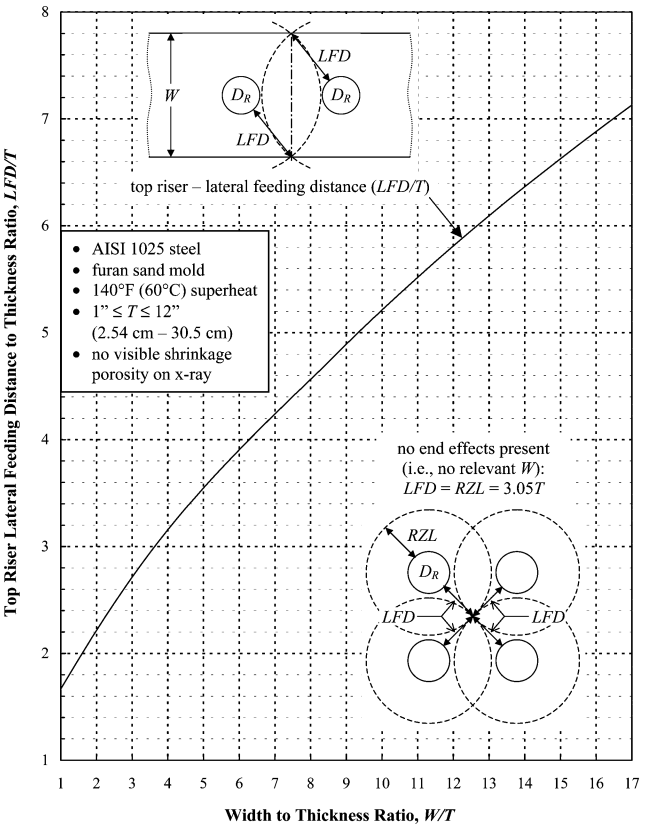


Fig. 19—Lateral feeding distance (*LFD*) as a function of width and thickness for top-risered sections.

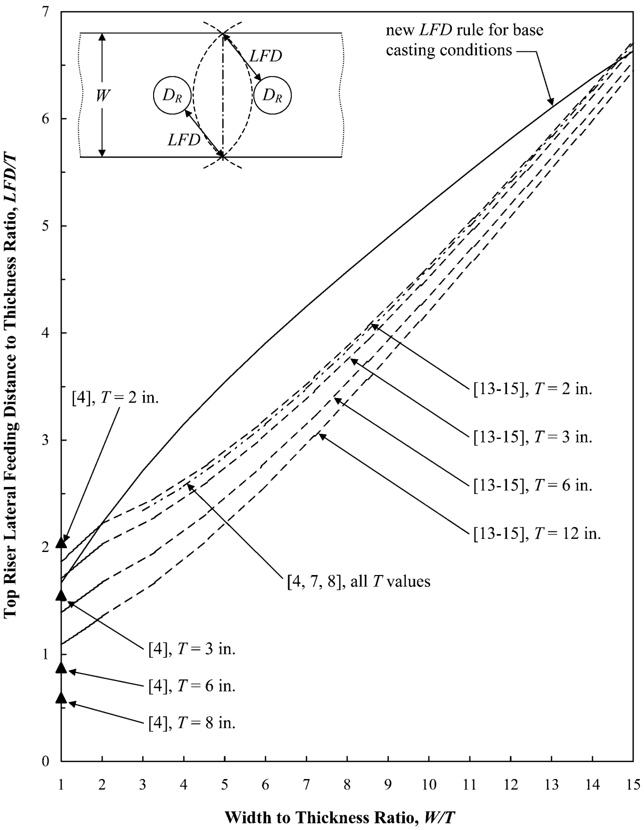


Fig. 20—Comparison between present lateral feeding distance rule and previously published rules.

radiographically sound castings) gives longer feeding distances than previously published rules, including the SFSA rules that were developed for ASTM class 1 castings. The new-rule feeding distances for plates are on the order of 1 to 2 *T* longer than those of Pellini.[4] The new rule produces nearly the same value as the SFSA curve[13] for $T = 7.62$ cm (3 in.) at $W/T = 2$ and a similar value to the SFSA curve for $T = 5.08$ cm (2 in.) at $W/T = 1$. For $W/T \geq 3$, the new rule produces longer values than all the SFSA rules shown. Because of the thickness dependence of the SFSA rules, the improvement in feeding distance with the new rule becomes more pronounced as the thickness increases.

B. *Lateral Feeding (Feeding Between Top Risers)*

The normalized lateral feeding distance for top risers, *LFD*/*T*, is plotted as a function of the width-to-thickness ratio in Figure 19. For relatively small values of *W*/*T*, the lateral feeding distance is equal to about 48 pct of the end-effect feeding distance, *i.e.*,

$$\frac{LFD}{T} = \left(\frac{FD}{T}\right)_{\text{lateral}} \approx 0.48\left(\frac{FD}{T}\right)_{\text{end effect}} \qquad \text{for } W/T \leq 7 \qquad [1]$$

This equation is approximately valid to up to about $W/T = 7$. Note that division by the thickness *T* in the previous equation is not necessary, since *T* cancels out. It is simply included to make the aforementioned multiplier (0.48) easier to use with the various equations and figures where *FD*/*T* is correlated or plotted. It should be noted that there is a slight riser-diameter dependence in the *LFD*/*T* curve shown in Figure 19. The effect is small up to about $W/T = 7$. But, for larger values of *W*/*T*, this curve can be in error by a few percentages, depending on the riser diameter used. Again, the riser diameters used to develop this curve were chosen based on SFSA risering guidelines.[13] When there are no end effects in the lateral feeding region under consideration (for example, Figure 13, with four risers), the width is not relevant. For this special case, the lateral feeding distance is simply equal to the maximum riser-zone-length value of 3.05 *T*. This information is given in the sketch inset in the lower-right-hand portion of Figure 19.

Figure 20 provides a comparison between the new lateral feeding-distance rule and previously published rules. Analogous to the feeding-distance comparison shown in Figure 18, it was necessary to convert the previously published rules for the lateral feeding distance from *LFD** to *LFD*, where *LFD* and *LFD** are defined in Figure 3. The filled triangles at $W/T = 1$ are from Pellini.[4] Similar to the new rule for *FD*, the new rule for *LFD* (solid curve) at $W/T = 1$ agrees well with Pellini's value for $T = 7.62$ cm (3 in.). The SFSA lateral feeding-distance rule is shown for $T = 5.08$, 7.62, 15.2, and 30.5 cm (2, 3, 6, and 12 in.).[13,14,15] This rule indicates a slight decrease in *LFD*/*T* as *T* increases, much less pronounced than the decrease in the SFSA rule for *FD*/*T* as *T* increases, shown in Figure 18. Pellini's lateral feeding-distance rule, $LFD^* = 2\ T$,[4] is also shown; it lies between the SFSA curves labeled $T = 2$ in. and $T = 3$ in. Again, this rule is repeated by Cech[7] and Wlodawer,[8] who state that it is valid for $W/T \geq 5$, below which it branches

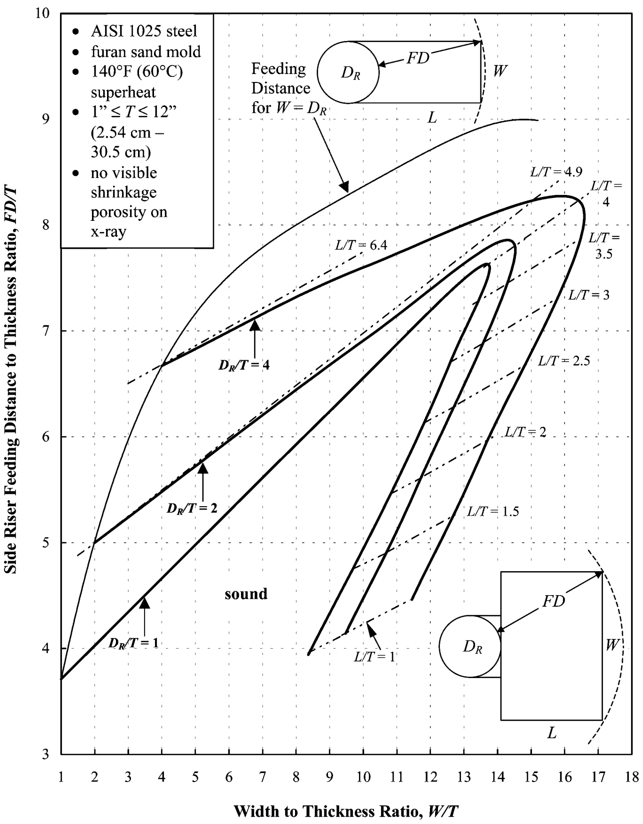


Fig. 21—Side-riser feeding distance, *FD*, as a function of D_R, *L*, *W*, and *T*.

out into curves for different thicknesses that decrease to slightly more conservative values at $W/T = 1$ than those shown in Figure 20. Quite similar to the trend seen for the new *FD* rule, the new *LFD* rule provides longer lateral feeding distances than previously published rules in almost every situation, regardless of whether the previous rules were designed to produce completely sound castings[4,7,8] or ASTM class 1 or better castings.[13,14,15] The improvement is on the order of 0.5 to 1 *T* over Pellini's rule and the SFSA rule for $T = 5.08$ cm (2 in.), with larger improvements over the SFSA rule as *T* increases.

C. *Side Riser With End Effect*

The normalized feeding distance, *FD*/*T*, for side-risered casting sections (Figure 2) is plotted in Figure 21 as a function of the width-to-thickness ratio. Note that, unlike *FD*/*T* for top risers shown in Figure 16, the feeding distance for side risers cannot be given by a single curve. Instead, *FD*/*T* in Figure 21 is also a function of the normalized riser diameter, D_R/T. This is due in part to the more complicated nature of feeding with a side riser, because the feed metal must turn corners at the riser/casting junction instead of simply moving along straight, radial paths. Another contributing factor is simply the geometric dependence of *FD* on the riser size. The curve in Figure 21 labeled "Feeding Distance for $W = D_R$" is an important limiting case. When $W = D_R$, the side-risered casting reduces to a top-risered casting with the riser placed at one end, as shown in the sketch at the top of Figure 21. In this limiting case, *FD*/*T* for side risers is the same as *FD*/*T* for top risers. In other words, the $W = D_R$ curve is simply the *FD*/*T* curve from Figure 16. The dash-dot-dotted lines shown in Figure 21 represent lines of constant normalized length. If the feeding distance, riser diameter, and casting-section width are known, the casting-section length can be calculated from

$$L = \sqrt{(0.5\,D_R + FD)^2 - 0.25\,W^2} - 0.5\,D_R \qquad [2]$$

These *L*/*T* lines are included to give some feeling of how the casting length changes with the other parameters involved in this plot.

The curves in Figure 21 for $D_R/T = 1$, 2, and 4 look complicated, but can be readily understood by following one of these curves, beginning from the limiting case just described. Consider, for example, the curve for $D_R/T = 2$. When $W/T = D_R/T = 2$, the value of *FD*/*T* is 5.0, just as it is for top risers when $W/T = 2$ (Figure 16). As *W*/*T* increases from this point, notice that the D_R/T curve is nearly parallel to the line representing $L/T = 4.9$. Thus, as *W*/*T* increases along the $D_R/T = 2$ curve, *L*/*T* remains nearly constant, and the casting section is simply becoming wider. The value of *FD*/*T* increases with *W*/*T* until *W*/*T* reaches its maximum of about 14.5, at which point the *FD*/*T* curve makes a sharp turn and *W*/*T* begins to decrease. The value of $W/T = 14.5$ represents the maximum section width that can be soundly fed by a riser with a diameter of $D_R/T = 2$. As the *FD*/*T* curve for $D_R/T = 2$ turns at $W/T = 14.5$ and begins heading down and to the left, notice that both *L*/*T* and *W*/*T* begin to decrease. This can be understood by considering that, as the section length is decreased, the width that can be soundly fed by a given riser will decrease as well. As *L* decreases, the end zone extending from the edge of the casting section opposite from the side riser causes a solidification front to begin advancing from that edge toward the riser zone extending from the riser. In addition, there are end effects on the sides of the casting next to the riser/casting junction that promote solidification of the casting in those regions. As the solidification fronts caused by these end effects move toward the middle of the casting, they begin to solidify the feeding path and force the feed metal to make sharper turns to feed tangentially. In essence, as *L* becomes smaller, it becomes harder for the feed metal to turn corners and feed tangentially into the casting section, and the feeding path solidifies sooner. Therefore, as *L* decreases, *W* must also decrease for the casting section to remain sound.

Notice the "sound" label in Figure 21. This indicates that any casting geometry that lies inside the "U" of the *FD*/*T* curves will be sound, while any geometry that falls outside this area is likely to contain shrinkage porosity. Consider, for example, a side-risered casting section with $D_R/T = 2$ and $W/T = 12$. The lower portion of the $D_R/T = 2$ curve crosses $W/T = 12$ at a value of $FD/T = 5.8$. The *L*/*T* value at this location is about 2.2. The upper portion of this curve crosses the $W/T = 12$ line again at $FD/T = 7.4$, where *L*/*T* is about 4.8. This can be interpreted as follows: if $D_R/T = 2$ and $W/T = 12$, a side riser can soundly feed casting sections with *L*/*T* ratios ranging from about 2.2 to 4.8. If *L*/*T* is larger than 4.8, the section is simply too large for the riser to feed. If *L*/*T* is smaller than 2.2, end effects will cause the difficulties in tangential feeding, and the feeding path will solidify prematurely.

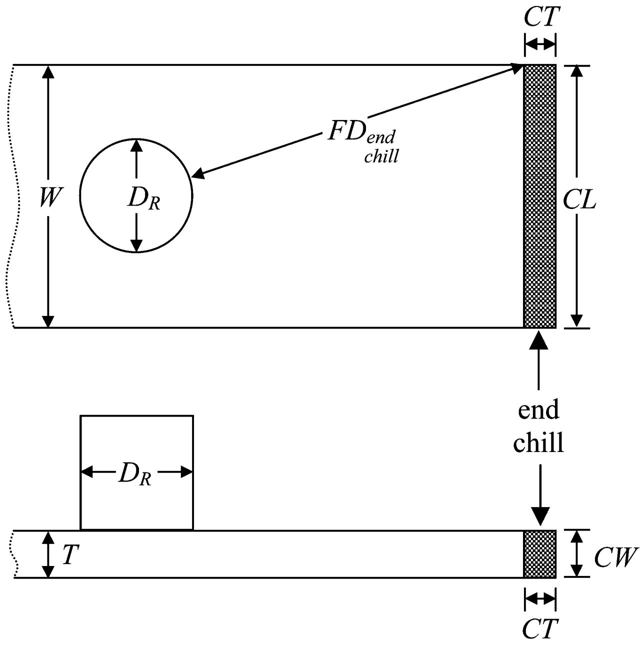


Fig. 22—End-chill dimensions for a top-risered casting section.

D. *Chills*

Chill blocks are inserted into the mold to enhance the feeding distance by creating a steeper temperature gradient. Chills are used at the end of casting sections (“end chills”) and as “drag chills” between two risers. Their use and effectiveness are described separately in the following text.

1. *End chill*

End chills increase the feeding distance by increasing the end-zone length. As shown in Figure 22, end chills have a chill thickness (CT) defined perpendicular to the casting/chill contact surface. The chill thickness should be between 1/2 and 2/3 T; larger chill thicknesses do not further increase the feeding distance. The end-chill multipliers given in Eqs. [3] and [4] were developed using a chill thickness of $CT = 2/3\ T$. The chill width (CW) and the chill length (CL) should be chosen to match the section geometry, *i.e.*, $CW = T$ and $CL = W$. The feeding distance, in this case, is defined the same as in the end-effect case, as the distance from the edge of the riser to the furthest point in the casting section (not including the chill). Although Figure 22 shows an example of an end chill used with a top riser, end chills can also be used in the same manner with side risers. In each case, end chills increase the end-effect feeding distance by about 19 pct, *i.e.*,

$$\left(\frac{FD}{T}\right)_{\text{end chill}} = 1.19\left(\frac{FD}{T}\right)_{\text{end effect}} \qquad [3]$$

An approximate feeding-distance multiplier, such as the one given in Eq. [3], can be computed for previously published rules by computing FD from those rules, with and without an end chill, and computing $FD_{\text{end chill}}/FD_{\text{end effect}}$. For Pellini’s rules,[4] this results in multipliers for bars ($W/T = 1$) varying with casting thickness from 1.23 for $T = 5.08$ cm (2 in.) to 1.46 for $T = 20.3$ cm (8 in.). Taking an average of the multipliers computed from Pellini’s plate rules from $W/T = 3$ to 15 yields average multipliers ranging from 1.29 for $T = 2.54$ cm (1 in.) to 1.03 for $T = 20.3$ cm (8 in.). The reason the multipliers for Pellini’s plate rules decrease with increasing thickness while they increase with thickness for Pellini’s bar rules is that the end-chill distance is not a function of thickness (add 5.08 cm (2 in.) to FD^*), while the bar-chill distance is a function of T (add T to LFD^*). Wlodawer[8] includes a figure for plates that lists Pellini’s rule for end-effect feeding distance and gives the end-chill feeding distance as $\sim 5\ T$. Computing an average multiplier from $W/T = 5$ to 15 yields 1.06, which is the same for all values of T. There is an error in Wlodawer’s figure for bars, because it lists the same feeding distance for end effect and end chill. The average (from $W/T = 1$ to 15) multipliers that result from the SFSA rules[13] vary from 1.14 for $T = 5.08$ cm (2 in.) to 1.30 for $T = 30.5$ cm (12 in.), while the average multipliers from Ruddle[14] over the same range of W/T ratios vary from 1.16 for $T = 5.08$ cm (2 in.) to 1.22 for $T = 30.5$ cm (12 in.). The reason for the variance between the multipliers from the SFSA’s rules and Ruddle’s rules is the deviation between the SFSA values and Ruddles’ values for end-chill feeding distances for plates, as mentioned in Section I. Based on the numbers from these previous rules, the multiplier 1.19, given in Eq. [3], seems very reasonable.

Since end chills only affect the end-zone length contribution to the feeding distance, the effect of an end chill can also be expressed in terms of how much it alters the end-zone length. Simulation results indicate that adding a chill increases the end-zone length by about 38 pct *i.e.*,

$$\left(\frac{EZL}{T}\right)_{\text{end chill}} = 1.38\left(\frac{EZL}{T}\right)_{\text{end effect}} \qquad [4]$$

where the subscript “end effect” refers to the curve for EZL/T in Figure 6.

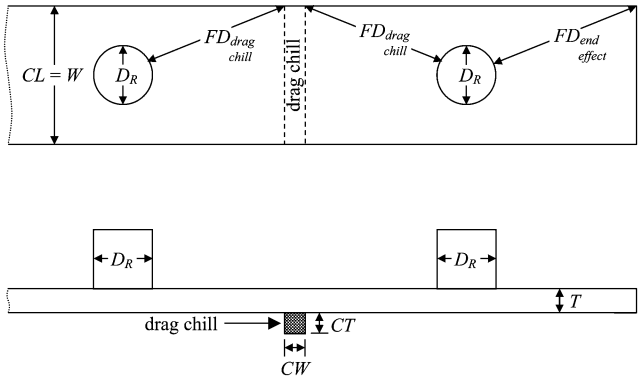


Fig. 23—Use of a drag chill for top-risered lateral feeding.

2. *Drag chill*

Figure 23 illustrates the placement of a chill in the drag between two top risers. This procedure increases the lateral feeding distance by essentially creating an end effect between the risers. As with end chills, the chill thickness is defined perpendicular to the chill contact surface and should be between 1/2 and 2/3 T. The chill width is defined parallel to the contact surface in the length direction and should also be between 1/2 and 2/3 T. Larger CT and CW values do not increase the feeding distance further. The drag-chill multiplier given in Eq. [5] was developed using

$CT = CW = 1/2\ T$, but there is little difference in this multiplier whether 1/2 or 2/3 T is used for CT and CW. The chill length is chosen to match the section geometry, *i.e.*, $CL = W$. As shown in Figure 23, the feeding distance with a drag chill is measured from the riser edge to the furthest point in the casting section that is not above the drag chill. Note that this feeding distance does not extend all the way to the symmetry line between risers (*i.e.*, the centerline of the drag chill), but rather only to the edge of the chill. Drag chills create a pseudoend effect between risers equal to about 95 pct of the end effect created when a casting section ends in the mold, *i.e.*,

$$\left(\frac{FD}{T}\right)_{\text{drag chill}} = 0.95\left(\frac{FD}{T}\right)_{\text{end effect}} \qquad [5]$$

In terms of lateral feeding, if one compares Eq. [1] and [5], it is seen that a drag chill nearly doubles the lateral feeding distance.

To compare with the multiplier given in Eq. [5], drag-chill multipliers for previously published rules can be computed in the same manner described for end chills, computing $FD_{\text{drag chill}}/FD_{\text{end effect}}$ for these rules. Using Pellini's[4] rules, the multiplier for bars varies with thickness from 1.12 for $T = 5.08$ cm (2 in.) to 1.23 for $T = 20.3$ cm (8 in.), and the multiplier for plates (averaged from $W/T = 3$ to 15) varies with thickness from 1.07 for $T = 5.08$ cm (2 in.) to 0.96 for $T = 20.3$ cm (8 in.). Both Cech[7] and Wlodawer[8] indicate that adding a drag chill produces the full end-effect feeding distance between the riser edge and the chill, and, thus, the drag-chill multiplier from these researchers has a value of 1.0 in all cases. Calculating the multiplier for the SFSA rules,[13] there is again some confusion about the definition of the feeding distance with a drag chill. If it is assumed that the distance used in Reference 13 is defined the same as in Ruddle,[14] the multipliers from the SFSA rules (averaged from $W/T = 1$ to 15) vary from 0.95 for $T = 5.08$ cm (2 in.) to 0.87 for $T = 30.5$ cm (12 in.). The values from Ruddle[14] are very similar, varying from 0.95 for $T = 5.08$ cm (2 in.) to 0.88 for $T = 30.5$ cm (12 in.). Again, in comparison with multipliers calculated for previously published rules, the value of 0.95 given in Eq. [5] seems quite reasonable.

E. *Other Casting Conditions*

The feeding distances presented in the previous subsections can be applied to casting conditions other than the stated base conditions through the use of multipliers. Table I contains a list of multipliers for alternate sand mold materials, cast alloy compositions, and pouring superheats. The feeding distance for casting conditions other than the base conditions is then computed with the equation

$$\left(\frac{FD}{T}\right)_{\text{different conditions}} = \left(\frac{FD}{T}\right)_{\text{base case}} \times C_{\text{superheat}} \times C_{\text{cast alloy}} \times C_{\text{sand mold}} \qquad [6]$$

where $(FD/T)_{\text{base case}}$ is the normalized feeding distance for the appropriate casting situation from the previous subsections. Again, the division by the thickness in the previous equation is not necessary, since T cancels out. Note that the multipliers for lateral feeding and chills introduced in the previous subsections could be multiplied into Eq. [6] if the base case corresponds to the end effect. For any conditions that are the same as the base casting conditions, a value of $C = 1$ is used. The multipliers supplied in Table I were originally developed for the end-effect feeding distance given in Figure 16, and they are valid for the entire range of this curve (*i.e.*, up to about $W/T = 15$). Through the use of Eq. [1], these multipliers can also be used for lateral feeding. However, they are only accurate up to about $W/T = 7$. Beyond this point, they are only approximate. In a similar manner, the multipliers can also be used for the riser- and end-zone lengths, which reach constant values at about $W/T = 7$. Finally, the multipliers are also approximately valid for side-riser feeding distances.

Table I. Multipliers Used to Apply Base Case Feeding Rules to Other Conditions; Base Case Conditions Are Listed with the Multiplier $C = 1$

Casting Parameter	Condition Description	Multiplication Factor C
Sand mold material ($C_{\text{sand mold}}$)	furan	1
	green sand	1.09
	zircon	0.96
	chromite	0.88
Steel alloy composition ($C_{\text{cast alloy}}$)	AISI 1025	1
	AISI 1522	0.97
	AISI 4125	0.98
	AISI 4135	0.97
	AISI 8620	0.96
	AISI 8630	0.95
	AISI 4330	0.97
	AISI 4340	0.86
Superheat ($C_{\text{superheat}}$)	30 °C	0.94
	60 °C	1
	90 °C	1.06
	120 °C	1.12

V. CONCLUSIONS

A new set of feeding-distance rules for risering of low-alloy steel castings is presented. The rules, which were designed to produce radiographically sound castings, were developed using a correlation between the Niyama criterion and radiographic casting soundness which was presented in Part I of this article. The correlation was developed by comparing extensive plate-casting trial results with corresponding simulation results, and the rules were then developed by performing further simulations covering a wide range of casting conditions and plate geometries. The current rules for both end-effect feeding distance and lateral feeding distance of top risers are shown to yield longer feeding distances in most instances than previously published rules. A feeding-distance rule for side risers is provided as well. In addition, rules for end-zone and riser-zone lengths are provided, with a detailed discussion of how they relate to the various feeding distances. The simulations performed to develop the current rules utilized AISI 1025 steel with section thicknesses ranging from 2.54 to 30.5 cm (1 to 12 in.), furan sand molds, and a superheat of 60 °C (140 °F). Multipliers are provided to tailor the feeding-distance rules to other steel alloys, sand-mold materials, and superheats.

In addition, multipliers are provided for the application of these rules with end chills and drag chills. The feeding-distance rules provided in this article are included in the SFSA special report, *Feeding & Risering Guidelines for Steel Castings.*[17]

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APPENDIX

This appendix contains fourth-order polynomial curve fits for various curves supplied in these guidelines. These curves are valid for casting sections with thickness, T, ranging from 2.54 to 30.5 cm (1 to 12 in.).

(1) The riser-zone length and end-zone length curves shown in Figure 6:

$$\frac{RZL}{T} = 2.803 \times 10^{-4}\left(\frac{W}{T}\right)^4 - 2.874 \times 10^{-3}\left(\frac{W}{T}\right)^3 - 0.0355\left(\frac{W}{T}\right)^2 + 0.5726\left(\frac{W}{T}\right) + 1.094 \qquad [A1]$$

$$\frac{EZL}{T} = -1.269 \times 10^{-3}\left(\frac{W}{T}\right)^4 + 0.02856\left(\frac{W}{T}\right)^3 - 0.276\left(\frac{W}{T}\right)^2 + 1.446\left(\frac{W}{T}\right) + 0.852 \qquad [A2]$$

Equations [A1] and [A2] are accurate up to $W/T = 7$, beyond which EZL/T and RZL/T take on constant values of 4.2 and 3.05, respectively.

(2) The end-effect feeding distance curve shown in Figure 16:

$$\left(\frac{FD}{T}\right)_{\text{end effect}} = -4.29 \times 10^{-4}\left(\frac{W}{T}\right)^4 + 0.0174\left(\frac{W}{T}\right)^3 - 0.266\left(\frac{W}{T}\right)^2 + 1.99\left(\frac{W}{T}\right) + 1.97 \qquad [A3]$$

Equation [A3] is accurate up to $W/T = 15$, beyond which FD/T has a constant value of 9.0.

(3) The lateral feeding distance curve shown in Figure 19:

$$\frac{LFD}{T} = -8.587 \times 10^{-5}\left(\frac{W}{T}\right)^4 + 3.408 \times 10^{-3}\left(\frac{W}{T}\right)^3 - 0.0533\left(\frac{W}{T}\right)^2 + 0.6967\left(\frac{W}{T}\right) + 1.019 \qquad [A4]$$

Equation [A4] is accurate up to $W/T = 15$.

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