Application of New Feeding Rules To Risering of Steel Castings

Doug Smith[1], Tony Faivre[2], Shouzhu Ou[3], Kent Carlson[3],
Richard Hardin[3] and Christoph Beckermann[4]

[1] Manager - Manufacturing Engineering , ABC-NACO TECHNOLOGIES, Lombard, IL
[2] Project Engineer - Casting Simulation, ABC-NACO TECHNOLOGIES, Lombard, IL
[3] Research Engineers, [4] Professor, DEPARTMENT OF MECHANICAL ENGINEERING,
UNIVERSITY OF IOWA, Iowa City, IA

ABSTRACT

New feeding rules that have been developed for the SFSA are applied to three castings, and comparisons are made between these new rules and the feeding rules presently published by the SFSA. The feeding lengths used in the three production castings are compared with these feeding distances. The effectiveness of the feeding rules are evaluated by comparing the level of tested and predicted shrinkage porosity in the castings to the expected level of porosity based on the new feeding rules. The methodology used to establish the new feeding rules is checked by examining the predicted Niyama Criterion values in the castings, and comparing it to what is expect given the feeding distance computed by the new rule. This comparison shows that the new feeding rules accurately estimate the level of the Niyama Criterion values computed in the actual castings. For the case of feeding a circular, ring-shaped, section with a single riser it is found that it is not appropriate to use the lateral feeding rule. Depending on the casting conditions considered in the new rules, the rule comparisons demonstrate that the new feeding rules are sometimes similar to, but are generally less conservative than, the current SFSA feeding rules. If the new rules are evaluated using the casting conditions for which the current SFSA rules are developed (green sand mold and plain 0.3% carbon steel), the new rules are always less conservative than current rules. Also, based on the results of this study, there exists a good likelihood that these new feeding rules can be made even less conservative.

1. INTRODUCTION

The importance of investigating and improving the guidelines for risering and feeding steel castings is clear, from anecdotal evidence and the experiences of foundrymen, from foundry trials of plate castings [1] and from insight gained from the application of modern casting software to production castings [2]. In some casting trial cases (for example 3" thick by 6" wide plates with end-effect [1]), the present feeding rules [3] appear to be acceptably accurate. In other casting trial cases, for lateral feeding and plates with larger width to thickness ratios [1], the need for an improvement to the present rules was keenly demonstrated, and the current rules were shown to be too conservative. Therefore, two of motivations for developing new feeding rules for the SFSA are to create rules and guidelines that are: 1) valid for a wide range of simple plate geometries, and 2) more accurate and less conservative. Other motivations are to develop rules that accurately account for more casting variables than do the present rules (alloy, mold type, amount of superheat), and to allow the foundry engineer to increase casting yield by tailoring the casting soundness to customer requirements. The use of these rules will lead to casting yield increases throughout the foundry industry.

A brief listing of the current SFSA rules for determining the feeding distances in this work is given in Appendix A. These SFSA rules are intended to be used down to 2" thick sections, and in the present work they are extrapolated to thinner sections. This is commonly done in practice. Feeding distances of sections down to 0.5" thick are presented here. The SFSA rules are developed to predicted feeding distances for castings produced using green sand and plain 0.3% carbon steel "when Class 1 soundness at 2% radiographic sensitivity is desired" [3]. These conditions should be kept in mind, because the new rules are designed to consider numerous casting process variables. A fair comparison between the new and current SFSA rules would actually involve using these "old-rule" casting conditions when evaluating the new feeding rules.

An overview of the new feeding rules used to determine the new rule-feeding distances is given in Appendix B. Please be aware that these are preliminary rules, and may be subject to "tuning" as the guidelines for applying the new feeding rules are being prepared for final publication. The methodology for the development of the new rules was established using the casting simulation software MAGMAsoft [4] and the Niyama Criterion [5]. The rules presented in Appendix B are based on increasing the required feeding length of a casting until the Niyama Criterion value first drops below 0.1 ($C^{1/2}s^{1/2}mm^{-1}$) for any computational cell in the casting[1]. This is termed a minimum Niyama Criterion value of 0.1. Therefore, when the first Niyama Criterion value below 0.1 appears, the feeding distance is reached. Casting trials were performed for vertical and horizontal plate castings with end effect and lateral feeding. From the results of these SFSA plate casting trials [1], the new feeding rules in Appendix B have been demonstrated to always produce castings to Level 1 soundness or better. In these trials, there were also sound plates cast at feeding distances corresponding to minimum Niyama Criterion values below 0.1, or longer than the new rule feeding distance. However, it was observed in these cases that the area of Niyama Criterion below 0.1 was small. While it still remains to be finalized, it should be possible to develop less conservative feeding rules than those given in Appendix B that are based on the area of Niyama below 0.1.

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[1]Considering the units of the Niyama Criterion, $C^{1/2}s^{1/2}mm^{-1}$ should be taken for all Niyama Criterion values given in this paper. For the remainder of this paper, unit specification for the Niyama Criterion values is omitted for ease of presentation.

New guidelines are being prepared to replace the "Red Book" of current SFSA feeding rules [3]. These new guidelines should contain clear recommendations and procedures covering the best methods to apply the feeding rules. This includes the operations involved in representing the actual casting as one or more basic plate-like shapes. This is a very important step since it defines the section to which the rules are applied. In the current "Red Book" of SFSA feeding rules (see Figure 1 taken from page 4 of [3]), the manner in which this is done is given too brief a discussion, and a more thorough discussion for this procedure is planned for the new guidelines. The approaches discussed in the literature which address this operation can involve using the true section dimensions when appropriate, as shown in Figure 1. However, in the case of junctions, changes in section thickness, and more complicated cross-sections, a "substitution" plate geometry is determined to represent the section to be fed. In such cases, the dimensions of the "substitution" plate are sometimes determined based on the size of the hot-spot. For example, a hot spot section thickness is sometimes used [2]. Clearly since this procedure is an important part of determining the feeding distance, the new guidelines should address this procedure and provide recommendations.
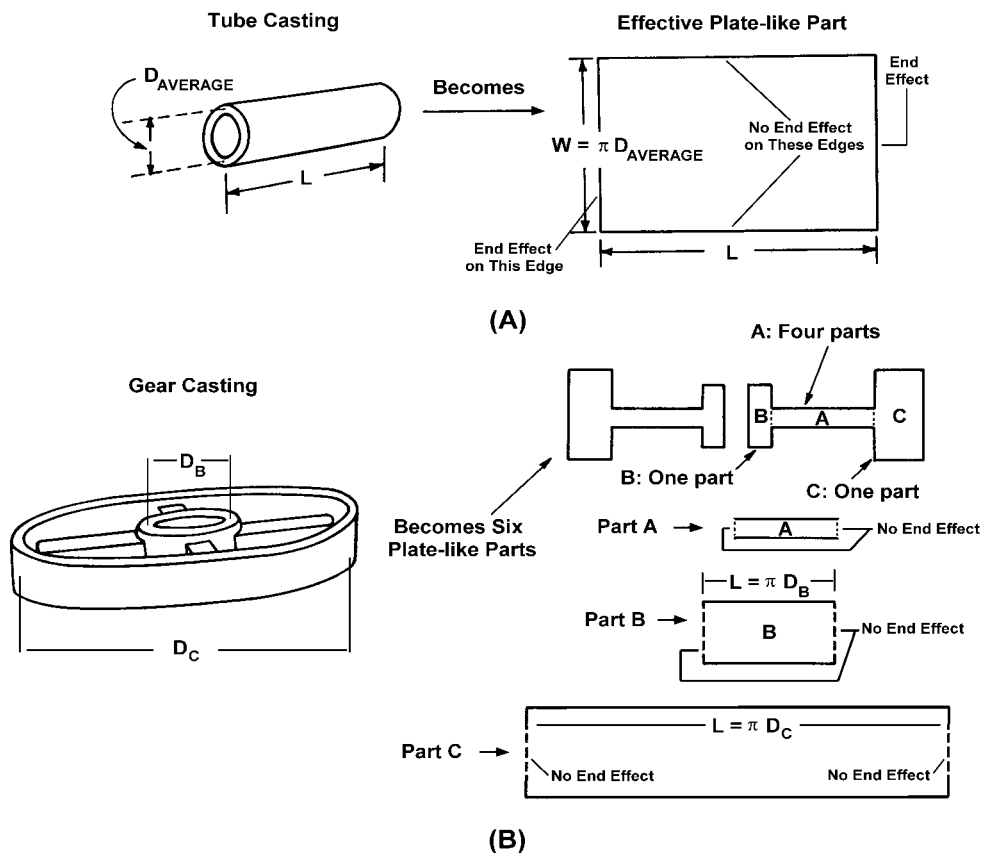
Figure 1   Examples for representing castings as simple plate-like parts taken from [3]: (A) a tube casting is represented as a plate, and (B) a gear casting becomes six plate-like parts

Casting simulation represents the best, most accurate approach yet devised to optimize the rigging of a casting and the resulting casting yield. Yet rules for risering remain an important first step in rigging castings, even when simulation might be applied later to optimize the process. When state-of-the-art casting simulation is applied to castings, and compared with the

rigging one would have gotten by applying risering rules, the inadequacies of the feeding rules can often be demonstrated. Also, as will be discussed here, insight gained from simulating casting can be used to apply feeding rules more accurately. In the case of the new feeding rules, the results of the Niyama Criterion from the simulation can be directly compared to what would be expected from the feeding distance. The primary goal of this paper is to compare the feeding distances determined using the new rules and the current SFSA rules with each other, and the results from casting simulations and radiographic testing (RT).

In this paper, casting simulation results and RT data were provided by the authors at ABC-NACO TECHNOLOGIES. Three castings are analyzed to answer the following questions:

- Are there differences between the required feeding lengths used in the production castings and feeding distances recommended by the present SFSA rules [3] and the proposed new rules?

- How do the predicted shrinkage porosity in the castings, the shrinkage porosity found in RT, and the expected porosity level based on the feeding rules compare?

- How do the tested porosity and the predicted porosity level from the casting simulations compare with the Niyama Criterion-based methodology that is used to establish the new feeding rules?

The three castings are analyzed in separate sections below. They are:

Casting #1: a small valve casting weighing 51.8 lb. cast from AISI 1020 steel
Casting #2: a hub casting weighing 445 lb. cast from AISI 4135 steel.
Casting #3: a large valve body weighing 678 lb. cast from AISI 1020 steel

In this work, the casting simulations were performed by the authors working at, ABC-NACO TECHNOLOGIES. The production of castings and the RT of the castings were done by foundries affiliated with ABC-NACO. The analysis of the required feeding lengths and distances were done by the authors at the University of Iowa, and the interpretation of the casting simulation results was done by all.

2.0 RESULTS FROM FEEDING RULE APPLICATIONS, CASTING SIMULATIONS AND RADIOGRAPHIC TESTING OF PRODUCTION CASTINGS

For each of the castings investigated, the following issues are addressed:

- Regions of the casting are simplified as simple plate-like geometries and are analyzed according the current and newly developed SFSA feeding rules.
- According to the feeding rules, an assessment is made whether or not the section could be fed to ASTM RT Level 1 or better.
- The rule assessment is compared with the simulation and RT results.

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2.1 RESULTS FOR CASTING #1

Casting #1 is ball valve casting that was used as an example in evaluating methoding rules several years ago [2]. The process details are:

- Casting configuration: Rough dimensions, 12.25"L x 5.5"W x 5.5" H (Figure 2)
- Casting alloy: AISI 1020, gross weight 51.8 lb.
- Pouring temperature: 1579°C
- Pouring time: 24 seconds
- Gating system & feeding system (Figure 2)
- Sleeve: Foseco Kalmin 70
- Topping materials: Foseco Ferrux 746
- Riser configuration: 6" Diameter x 8" Height
- Sand mold: Pepset-Isocure (Furan mold properties are used when simulating this)
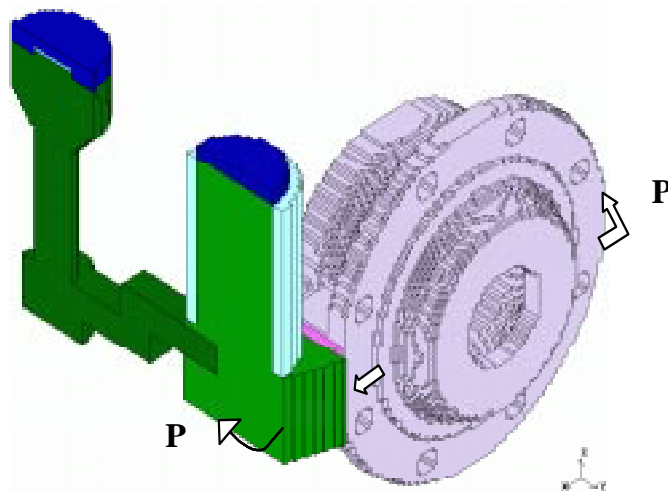

Figure 2   Casting #1 down sprue, gating and riser (note section P-P)

The feeding rule analysis of the casting geometry proceeds by identifying the regions requiring feeding. Consider a cross section P-P shown in Figure 2. Regions A and B in section P-P (shown in Figure 3) become the cross-sections of two simple plates to be analyzed.

- The simple plate geometry used in the analysis for region A becomes section C-C (shown in Figure 4). It is analyzed as a ring-shaped plate of thickness, T=1.3"; width, W=5.5"; and required feeding length, FL=12.2". This is half of the circumference, from the riser contact to the end of the required feeding length. Including riser contact and two such required feeding lengths, the entire circumference is reduced to a plate of length, L=27.7".

- The simple plate geometry used in the analysis for region B becomes section D-D (shown in Figure 5) and it is reduced to a ring-shaped plate of thickness, T=1.4"; width, W=1.5"; and required feeding length, FL=10.8". Including riser contacts and two required feeding lengths, the entire circumference is a plate of length, L=23.9".
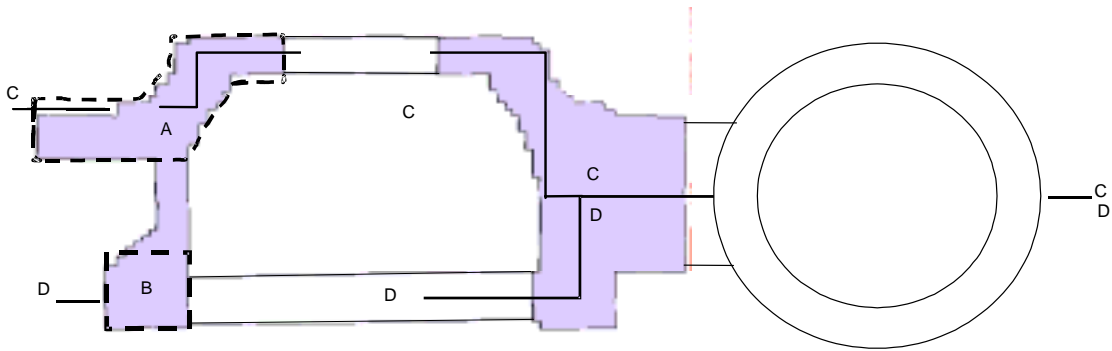
Figure 3   Cross-Section P-P: regions A and B, and sections C-C and D-D used for feeding distance analysis

feeding length for section C-C
FL = ((1.6+5.3/2)x2x3.14 - 2.35)/2=12.2"
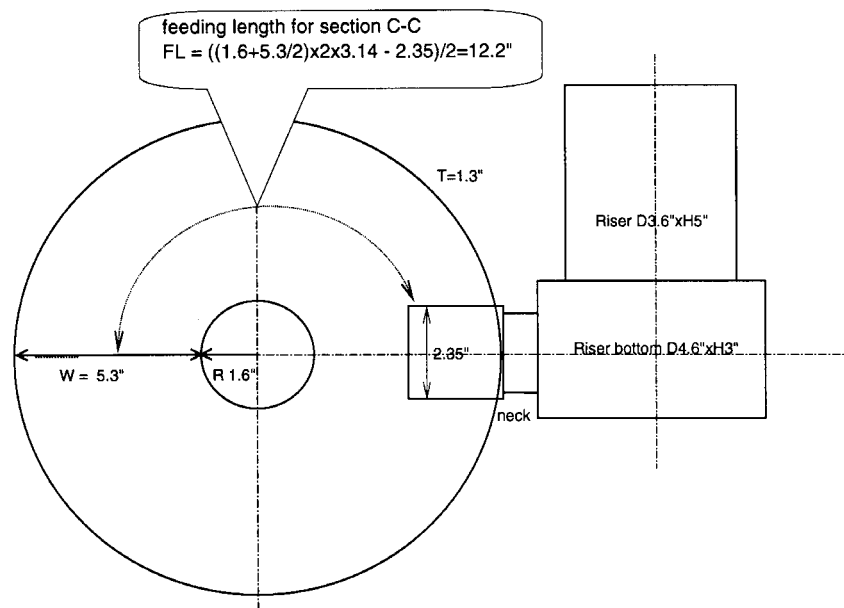
Figure 4   Required feeding length for section C-C

feeding length for section D-D
FL = ((3.1+1.5/2)x2x3.14 - 2.35)/2=10.8"
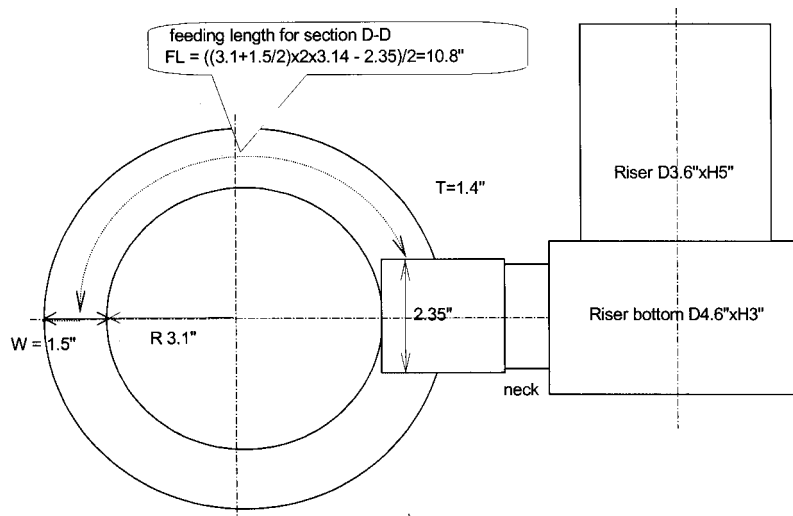
Figure 5   Required feeding length for section D-D

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For such ring-shaped sections fed by a single riser (as shown in Figures 4 and 5) it is usually assumed that there is no end effect, and lateral feeding rules are applied. By performing a series of simulations and using the methodology on which the new feeding rules are based, it was determined that there is an "end effect" acting when there is one riser placed on such a ring-shaped section. This effect is not as strong as that for a part with a true end effect, but it is enough to be important, and it makes the estimation of feeding distance by using the lateral feeding rules far too conservative [2]. For these ring geometries with one riser it was found that the feeding rule with end effect was closer to the feeding distances found for simulations of ring-shaped sections. If one has two or more risers on a ring-shaped casting section, the lateral feeding rules are still recommended.

The feeding distances computed according to the current SFSA rules and the new feeding rules are outlined in Table 1. The new feeding rules consider that the casting section should be ASTM RT Level 1 sound (using a minimum Niyama Criterion value of 0.1), and use multipliers to consider the following conditions as being different from the new rule base case: superheat of 70°C (see Appendix B for multipliers and new rule). Note that for these sections lateral feeding $FD_{old} \approx FD_{new}$ is coincidental for the present T and W, for the T=3" x W=6" plate trials $FD_{new} \approx 2\ FD_{old}$. From the results in Table 1, the rule for lateral feeding is far too conservative and no analysis using this rule is given. From Table 1, the new rule feeding distance is slightly more than the current rule feeding distance. Both rules say, the casting requires two risers since the required feeding length is 12.2" for section C-C, and 10.8" for section D-D. More discussion of the rule application for end effect is provided in the conclusion section below.

**Table 1** Feeding rules results compared for sections A and B in Casting #1

Feeding Rule Results for Region A, Section C-C: T = 1.3", W = 5.3"	Feeding Distance Based on Current SFSA Rule	Feeding Distance Based on New Rule
Lateral Feeding	2.9"	3.6"
End Effect	7.4"	8.9"
Feeding Rule Results for Region B, Section D-D: T = 1.4", W = 1.5"	**Feeding Distance Based on Current SFSA Rule**	**Feeding Distance Based on New Rule**
Lateral Feeding	2.7"	2.7"
End Effect	5.0"	5.7"

Results from the Foundry Castings and Simulations for Casting #1

The rigging with one riser used in the simulations (as shown in Figure 2) was cast. The casting soundness was determined by radiographic testing according ASTM E446 at Keokuk Steel Castings to CB-1 and CD-1 (Level 1 soundness). The simulation results of the predicted Niyama Criterion in the casting are given in Figure 6 for section C-C and Figure 7 for section D-D. According to the feeding rule methodology, these plots indicate that the casting, particularly in section D-D, might be worse than Level 1 shrinkage since there are several cells below the 0.1 Niyama Criterion value. Since the area below 0.1 is not too large the casting might also be Level 1. The casting is borderline Level 1 soundness. The interpretation that this amount of area is approximately Level 1 soundness is based on the methodology used to develop the new feeding rules, and is based on the experience gained in analyzing the SFSA plate casting trials [1].
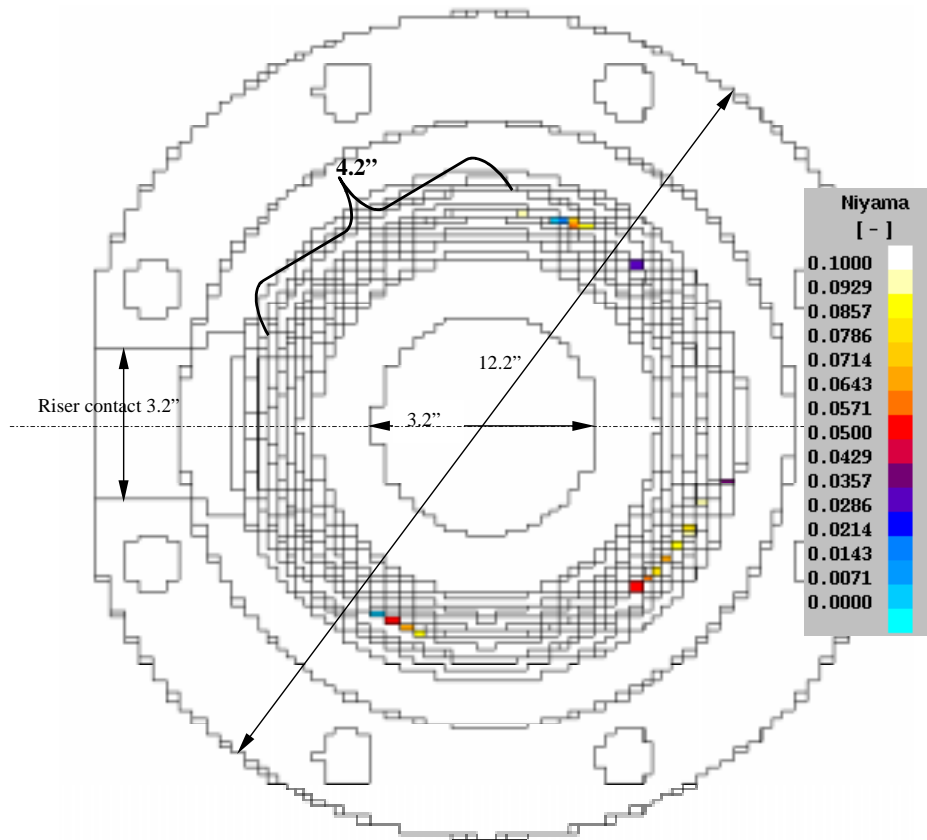
Figure 6 Niyama Criterion plot for section C-C in Casting #1, riser zone length in cope is shown to be 4.2"
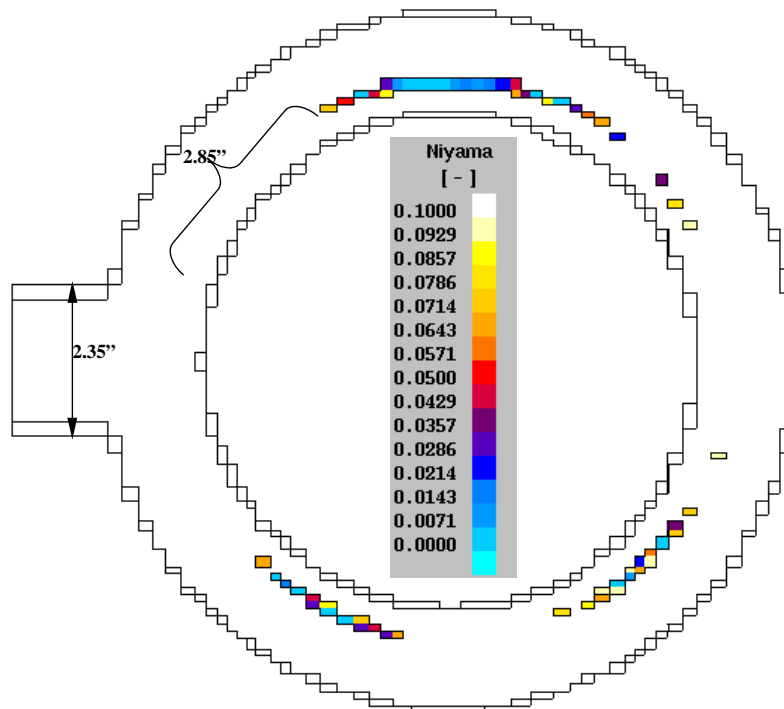
**Figure 7** Niyama Criterion plot for section D-D in Casting #1

Conclusions for Casting #1

- The use of lateral feeding rules for ring-shaped sections having one riser needs to be examined. It appears to be far too conservative, and probably is not applicable.

- Feeding distance based on new rule (Table 1) using as-cast conditions is exceeded by the required feeding distance:

  For section C-C: Required feeding length = 12.2", $FD_{old\ rule}$= 7.4", and $FD_{new\ rule}$= 8.9"

  For section D-D: Required feeding length = 10.8", $FD_{old\ rule}$= 5.0", and $Fd_{new\ rule}$= 5.7"

- The feeding distance based on the new rule is only slightly more than the old rule (Table 1). In general, for sections with $W/T \approx 1$ at thickness up to about 4" the difference between the old and new feeding rules is small.

- The current feeding rules are for green sand molds, which have a multiplier of 1.108 in the new rules (Appendix B). A fairer comparison between the rules would be to consider the new rule for green sand: for section C-C $FD_{new\ rule}$= 9.4" and for section D-D $FD_{new\ rule}$= 6.4".

- From the simulation results, the predicted Niyama Criterion distributions agree with the feeding rules in both sections. Since the new feeding rules are exceeded in both sections, the minimum Niyama Criterion is expected to be below 0.1, and it is as seen in Figures 6 and 7. Based on experience from the casting trials [1], section C-C is noticeably less sound given the area of Niyama Criterion, and it is borderline Level 1 soundness.

- Recalling the relationship between the riser feeding zone and the lateral feeding distance, the lateral feeding distance in the new rules is the distance between the riser and the first point of Niyama Criterion below 0.1. This distance is indicated in Figure 6 for section C-C and it defines the riser feeding zone to be 4.2" long, which is quite close to the 3.6" lateral feeding distance determined for this section with the new feeding rule. This confirms that the new feeding rules for the simplified section geometry are consistent with the simulation results for the actual casting.

- For such ring-shaped sections, the actual feed path shifts toward the core and shortens the actual required feeding length. This had been mentioned previously [2] and is apparent here from Figures 6 and 7, where the lowest Niyama Criterion values (defining the thermal centerline of the sections) are shifted toward the core. This is an effective decrease in the required feeding length because it will always be less than the geometric mean circumference for a ring-shaped section. This could be important to consider in applying feeding rules to ring-shaped sections and could be contributing to the casting meeting the Level 1 soundness requirements.

- When filling is simulated, the first region to solidify is near the top of the section, which means the required feeding length for the bottom part of the ring is actually longer than the top [2]. This asymmetry is apparent in Figures 6 and 7.

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2.2   RESULTS FOR CASTING #2

Casting #2 is a hub casting. The casting process details are:

- Casting rough dimensions are 24"L x 19.2"W x 19.2"H
- Casting alloy: AISI 4135
- Casting weight = 454.2 lbs (206.2 kg)
- Pouring temperature: 1565°C
- Pouring time: 23 seconds
- Gating system & feeding system: see Figure 8
- Sand mold: Pepset-Isocure
- Yield: 57.5%
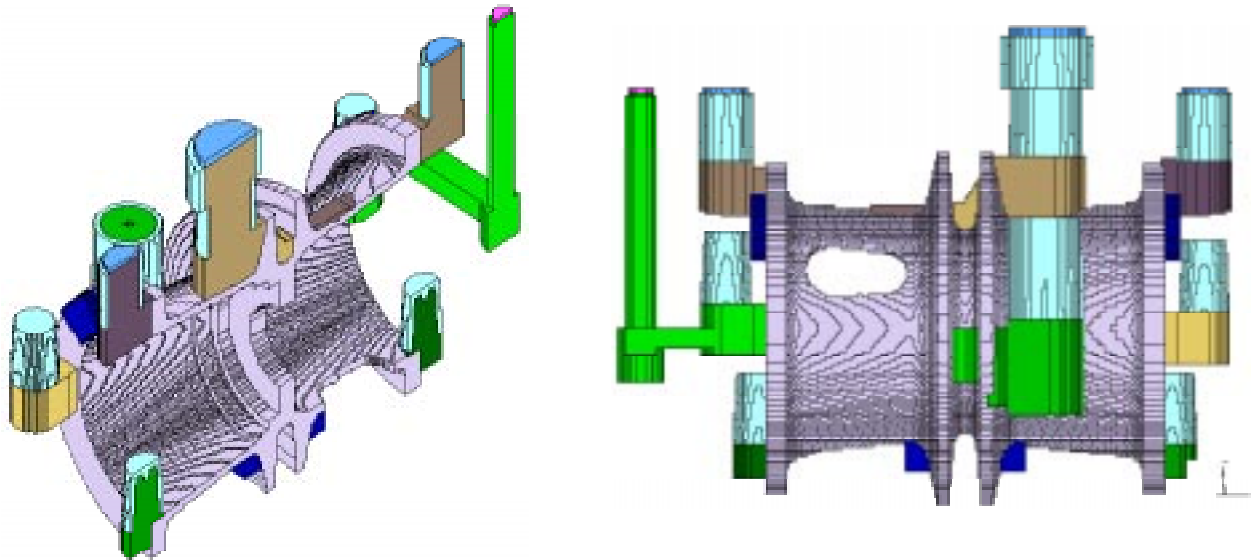
Figure 8   Half section (at left) and side view of rigging used on the hub casting (Casting #2)

The feeding rule analysis of this casting examines the regions requiring feeding. These are the ring-shaped sections at sections A through E in the cross section shown in Figure 9. The feeding rules are also compared in the region of the thin-walled body of the hub.

Feeding Distance Analysis for Sections A and B

Sections A and B are rigged nearly identically as shown in Figures 10 and 11, respectively. The only noticeable difference between them is that the risers contacting along the parting line are lower for section A than section B. This makes the required drag chill feeding length in the cope 0.5" longer for section A than section B, and the required lateral feeding length in the drag longer for the case of section B than section A. If chills are not used in the cope, the foundry RT results showed that Level 3 (CB-3) shrinkage formed in the cope side. When cope chills are used, the casting tests to the ASTM E446/E186 RT Acceptance Standard at Level 1 or better. Other observations for sections A and B are:

- For these sections, mold type, alloy, and superheat, the extrapolated SFSA rules give longer feeding distances than the new rules by 0.2" for lateral feeding and by 0.7" for the drag chill. These values are essentially equal. See Figures 10 and 11.

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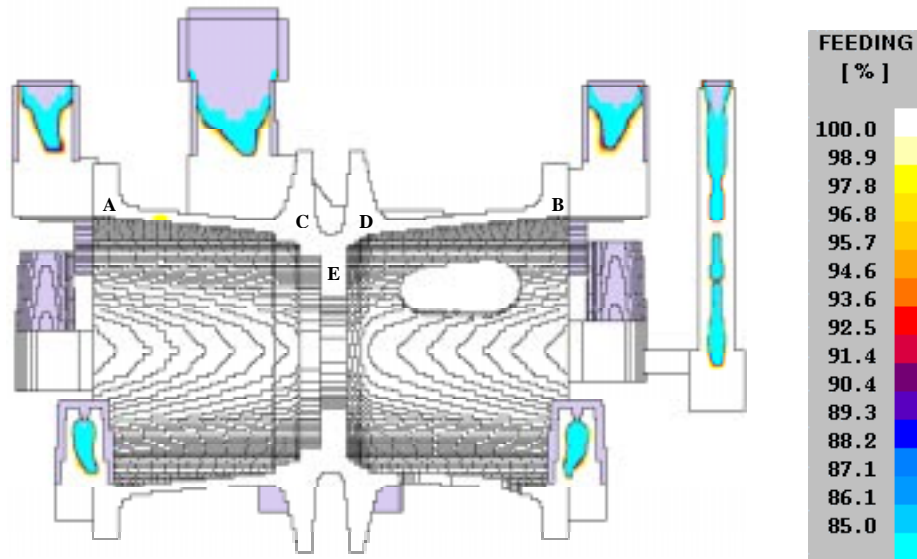
Figure 9   Cross section of Casting #2 showing feeding percentage and sections where feeding distance rules will be applied
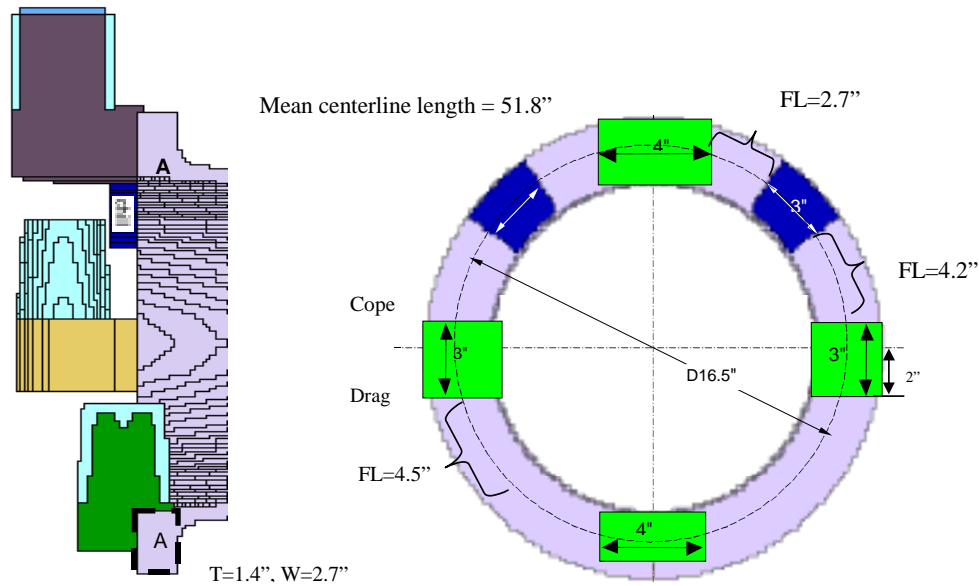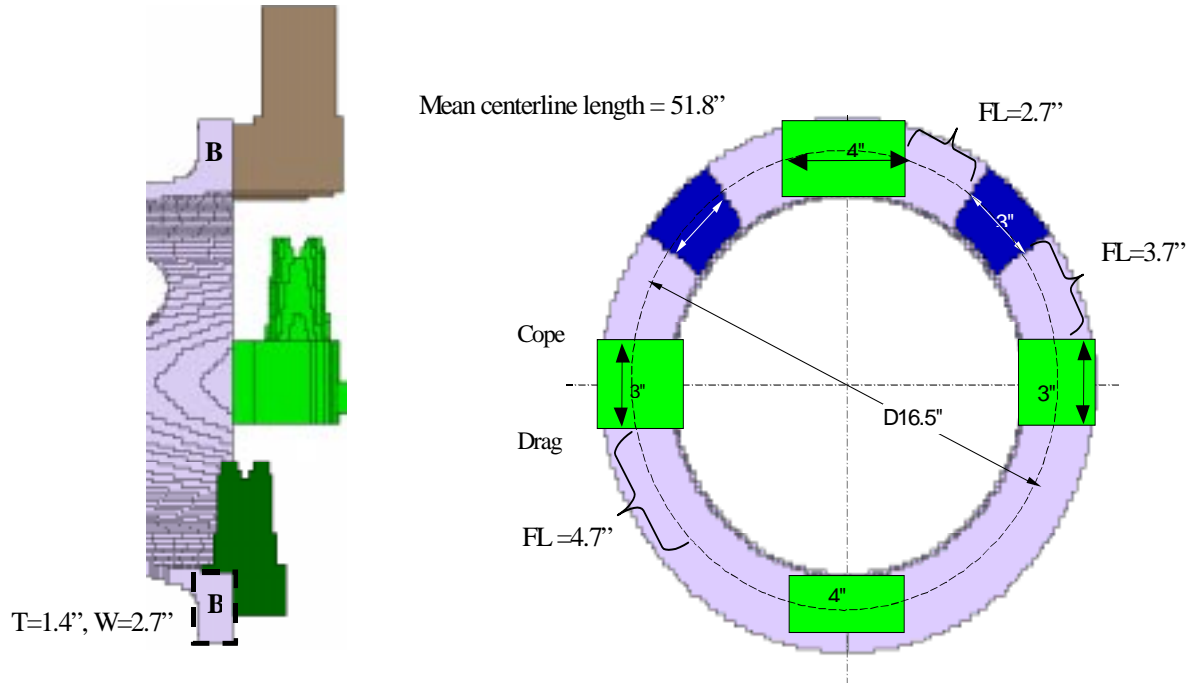

In section A the region to be fed is represented by a plate: 1.4"T x 2.7"W x 51.8"L
Required Feeding Lengths (FL): Mean Centerline Length = 51.8"
  Required Drag Chill Feeding Length in cope = **4.2"**
  Required Drag Lateral Feeding Length = (51.8"/2 – 4"-2(2"))/4 = **4.5"**
  Drag Chill CT=1", CW=3"
Calculated Feeding Distance (FD) by current SFSA rules [3]:

$$FD_{Lateral} = 3.38\sqrt{T} + 0.84\sqrt{W} - 2.34 = 3.38\sqrt{1.4} + 0.84\sqrt{2.7} - 2.34 = 3.05",$$

$$FD_{DragChill} = 0.88T - 0.76W - 1.91\sqrt{T} + 10.8\sqrt{W} + 0.35\sqrt{CT} + 0.21\sqrt{CW} - 7.04 = 8.3",$$

Calculated Feeding Distance (FD) by new feeding rules: $FD_{Lateral}$ = **2.85"**, $FD_{Drag\ chill}$ = **7.6"**
Assessment: By current SFSA rules lateral feeding length cannot be fed, FD is 1.45" smaller than FL
  By new feeding rules lateral feeding length cannot be fed, FD is 1.65" smaller than FL
  By current SFSA rules drag chill feeding length can be fed, FD is 4.1" larger than FL
  By new feeding rules drag chill feeding length can be fed, FD is 3.4" larger than FL

Figure 10   Simplified geometry, feeding percentage, Niyama Criterion predictions, and feeding distance analysis for section at section A in Casting #2

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Mean centerline length = 51.8"

FL=2.7"

FL=3.7"

Cope

Drag

FL =4.7"

D16.5"

B

T=1.4", W=2.7"

In section B the region to be fed is represented by a plate: 1.4"T x 2.7"W x 51.8"L
Required Feeding Lengths (FL): Mean Centerline Length = 51.8"
                                     Required Drag Chill Feeding Length in cope = **3.7"**
                                     Required Drag Lateral Feeding Length = (51.8"/2 – 4"-2(1.5"))/4 = **4.7"**
                                     Drag Chill CT=1", CW=3"
Calculated Feeding Distance (FD) by current SFSA rules [3]:

$$FD_{Lateral} = 3.38\sqrt{T} + 0.84\sqrt{W} - 2.34 = 3.38\sqrt{1.4} + 0.84\sqrt{2.7} - 2.34 = 3.05",$$

$$FD_{DragChill} = 0.88T - 0.76W - 1.91\sqrt{T} + 10.8\sqrt{W} + 0.35\sqrt{CT} + 0.21\sqrt{CW} - 7.04 = 8.3",$$

Calculated Feeding Distance (FD) by new feeding rules: $FD_{Lateral}$ = **2.85"**, $FD_{Drag\ chill}$ = **7.6"**
Assessment: By current SFSA rules lateral feeding length cannot be fed, FD is 1.65" smaller than FL
                         By new feeding rules lateral feeding length cannot be fed, FD is 1.85" smaller than FL
                         By current SFSA rules drag chill feeding length can be fed, FD is 4.6" larger than FL
                         By new feeding rules drag chill feeding length can be fed, FD is 3.9" larger than FL

Figure 11   Simplified geometry, feeding percentage, Niyama Criterion predictions, and feeding distance analysis for section at point B in Casting #2

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- Both of the chill rules indicate that the cope section can be easily fed. The lateral feeding rule indicates that the drag section is not quite fed, and that feeding distance is about 1.5" short. Given that the RT results for this casting were Level 1, both the new rule and the current rule appear to be a little conservative for this case.

Feeding Distance Analysis for Sections C, D and E

- In section C and D, as seen in Figure 12, the new rule lateral feeding distance is 3.6" and is longer than the current SFSA rule by 0.5". The new rule lateral feeding distance is shorter than the required feeding length by 1.6", but there are no shrinkage indications found in the RT.

- Also seen in Figure 12 in section C and D, the new rule for drag chill feeding distance is 9.5" and is longer that the current SFSA rule by 0.8". The feeding distances for both rules are longer than the required feeding length, and there are no shrinkage indications found in the RT.

- The middle section, section E in Figure 12, is also a section with lateral feeding. In this case the new rule feeding distance, 3.05", is less than the current SFSA rule FD by 0.25". There was no shrinkage found by RT. The feeding distance was found to be adequate to feed the cope section, but in the drag section the new rule feeding distance is 0.55" short of the required lateral feeding length.

Feeding Distance Analysis for Thin Wall Section of the Hub Body

- This section of the casting is shown in Figure 13. The required lateral feeding length between flanges A and D is 5.6".

- The feeding distance found using the new rule is 2.85", and is 0.65" longer than the current SFSA rule. The feeding distance is 2.75" less than the required length.

- This region of the casting was not radiographically tested. Given the large region of Niyama Criterion predicted below 0.1 there are certainly shrinkage defects there at Level 3 or worse.
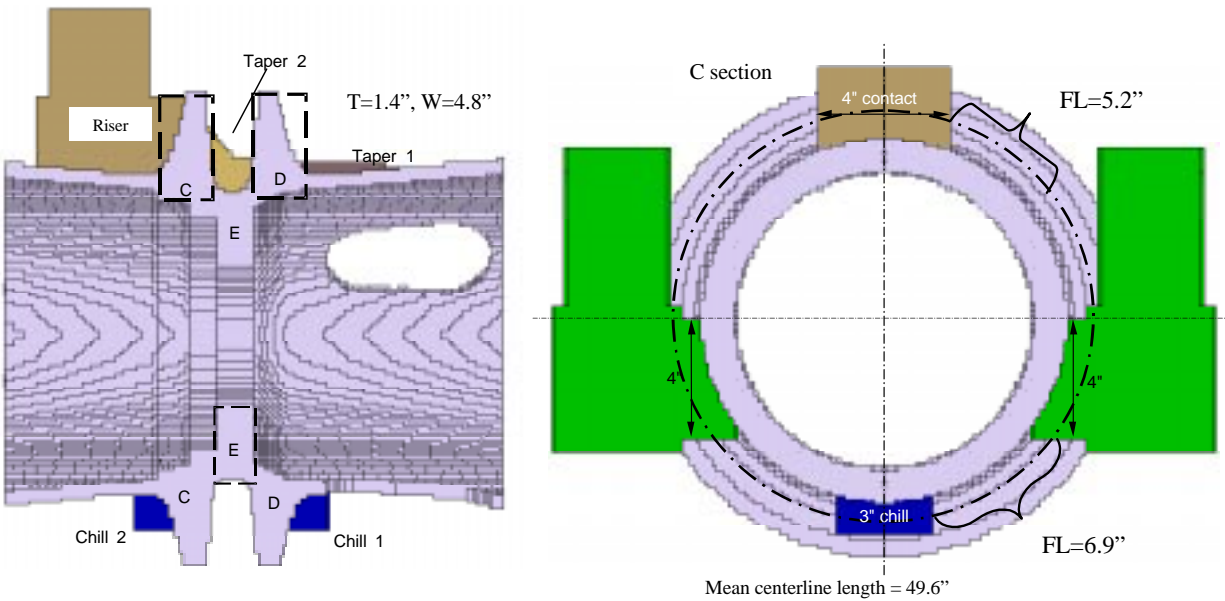
In section C and D the region to be fed is represented by a plate: 1.4"T x 4.8"W x 49.6"L

Required Feeding Lengths (FL): Mean Centerline Length = 49.6""

Required Cope Lateral Feeding Length = (49.6"/2 – 4")/4 = **5.2"**

Required Drag Chill Feeding Length = (49.6"/2 – 2(4") – 3")/2 = **6.9"**

Drag Chill CT=1.8", CW=3"

Calculated Feeding Distance (FD) by current SFSA rules [3]:

$$FD_{Lateral} = 3.38\sqrt{T} + 0.84\sqrt{W} - 2.34 = 3.38\sqrt{1.4} + 0.84\sqrt{2 \cdot 1.4} - 2.34 = \mathbf{3.1"}, \text{ for W>2T plate cases W=2T [3]}$$

$$FD_{DragChill} = 0.88T - 0.76W - 1.91\sqrt{T} + 10.8\sqrt{W} + 0.35\sqrt{CT} + 0.21\sqrt{CW} - 7.04 = \mathbf{8.7"}, \text{ for W>2T plate cases W=2T}$$

Calculated Feeding Distance (FD) by new feeding rules: $FD_{Lateral}$ = **3.6"**, $FD_{Drag\ chill}$ = **9.5"**

Assessment: By current SFSA rules lateral feeding length cannot be fed, FD is 2.1" smaller than FL

By new feeding rules lateral feeding length cannot be fed, FD is 1.6" smaller than FL

By current SFSA rules drag chill feeding length can be fed, FD is 1.8" larger than FL

By new feeding rules drag chill feeding length can be fed, FD is 2.6" larger than FL

In section E the region to be fed is represented by a plate: 1.6"T x 2.6"W x 26.4"L

Required Feeding Lengths (FL): Mean centerline length = 26.4", Riser contact lengths - 4"in cope, 3" in drag

Required Cope Lateral Feeding Length = (26.4"/2 – 4")/4 = **2.3"**

Required Drag Lateral Feeding Length = (26.4"/2 – 2(3"))/2 = **3.6"**

Calculated Feeding Distance (FD) by current SFSA rules:

$$FD_{Lateral} = 3.38\sqrt{T} + 0.84\sqrt{W} - 2.34 = 3.38\sqrt{1.6} + 0.84\sqrt{2.6} - 2.34 = \mathbf{3.3"}$$

Calculated Feeding Distance (FD) by new feeding rules: $FD_{Lateral}$ = **3.05"**
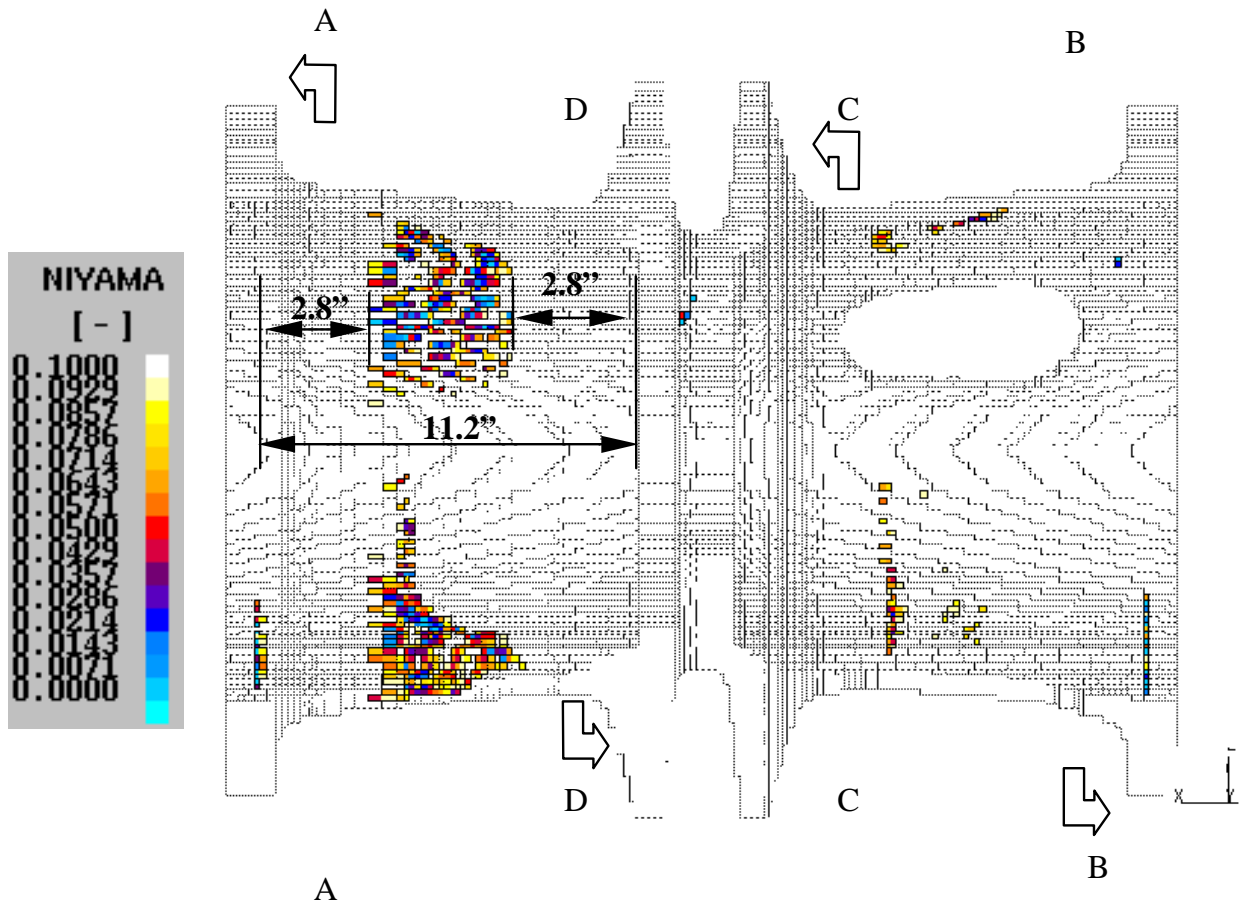
Assessment: By current SFSA rules cope lateral feeding length can be fed, FD is 1" larger than FL

By new feeding rules cope lateral feeding length can be fed, FD is 0.75" larger than FL

By current SFSA rules drag lateral feeding length cannot be fed, FD is 0.3" smaller than FL

By new feeding rules drag lateral feeding length cannot be fed, FD is 0.55" smaller than FL

Figure 12   Simplified geometry, feeding percentage, Niyama Criterion predictions, and feeding distance analysis for section at sections C, D and E in Casting #2

In section to be fed between two flanges A and D is represented by a plate: 1"T x 5"W x 11.2"L

Required Feeding Length (FL) = 11.2"/2 = **5.6"**

Calculated Feeding Distance (FD) by current SFSA rules [3]:

$$FD_{Lateral} = 3.38\sqrt{T} + 0.84\sqrt{W} - 2.34 = 3.38\sqrt{1} + 0.84\sqrt{2} - 2.34 = 2.2", \text{ for W>2T plate cases W=2T [3]}$$

Calculated Feeding Distance (FD) by new feeding rules: $FD_{Lateral}$ = **2.85"**,

Assessment: By current SFSA rules lateral feeding length cannot be fed, FD is 3.4" smaller than FL

                    By new feeding rules lateral feeding length cannot be fed, FD is 2.75" smaller than FL

Figure 13   Simplified geometry, Niyama Criterion predictions, and feeding distance analysis for thin wall section in Casting #2

Conclusions for Casting #2

- Lateral feeding distance based on new rule is found to be slightly shorter than the required feeding length in the drag half at sections A and B, and in the cope half at sections C and D. The Niyama Criterion predictions in sections A and B are shown in Figure 14 and are consistent with the new rule feeding distance being exceeded since there is an area of values below 0.1. Its is possible to have some castings meet Level 1 RT requirements with such indications. In the cope half the feeding distance was not exceeded and there are no indications below 0.1.

- When the new rule feeding distance is smaller than current SFSA rule, there is only small difference. The new rule takes into account casting conditions that are not considered in the current rules which can decrease its value. As discussed for Casting #1, these multipliers reduced the new feeding distance in this case below the current SFSA rule.

- The size of the region of Niyama Criterion below 0.1 in the regions where the feeding distance is exceeded indicates that the new feeding distance rule agrees with the simulations results, but there may not be a large enough area of Niyama below 0.1 to form shrinkage worse than RT Level 1.

Niyama Criterion - Section A   **Niyama Criterion - Section B**
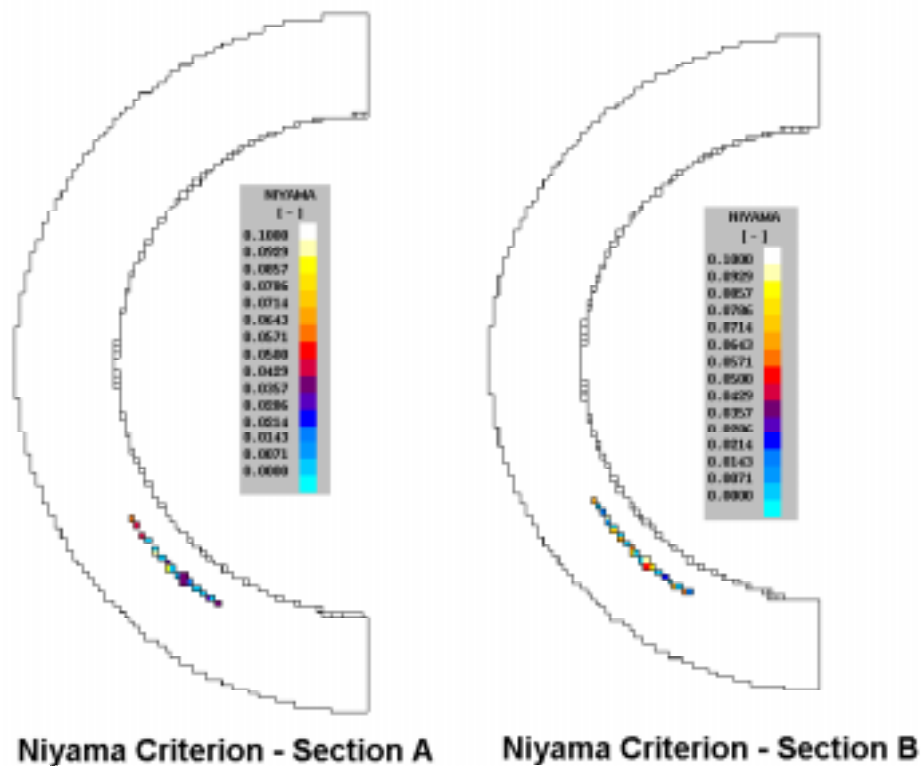
Figure 14   Niyama Criterion plot of sections A and B in Casting #2 with chills in the cope as shown in Figures 10 and 11

2.3   RESULTS FOR CASTING #3

Casting #2 is a valve casting shown in Figure 15. The casting process details are:

- Casting rough dimensions are 28.2"L x 19.0"W x 16.3"H
- Casting alloy: AISI 1020
- Casting weight = 678 lbs (308 kg)
- Pouring temperature: 1565°C
- Pouring time: 23 seconds
- Gating system & feeding system: 6 risers/sleeves , 3 chills, see Figure 17
- Sand mold: Pepset-Isocure
- Casting yield 50.6%
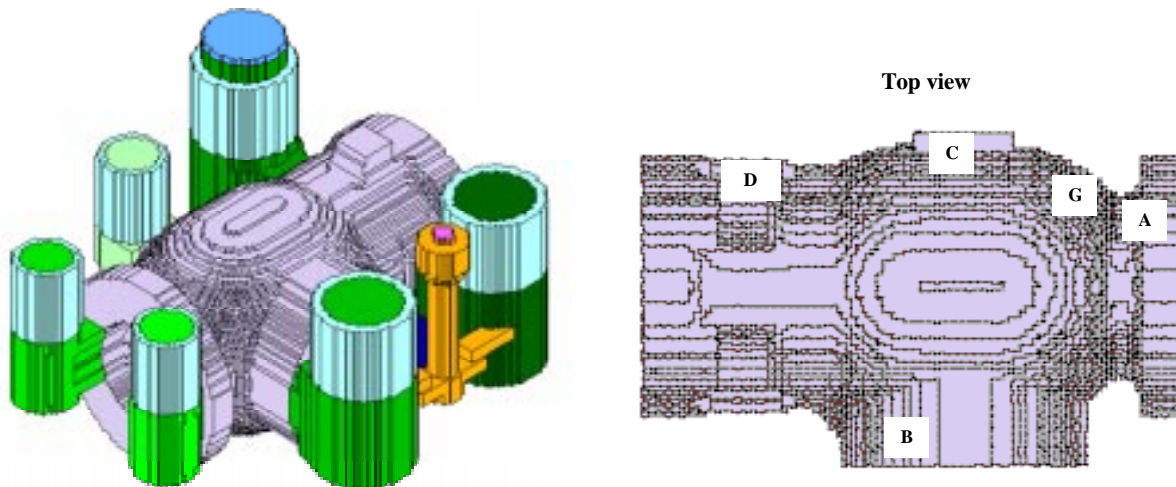
Figure 15   Rigging for Casting #3 (left above) and points of interest for feeding distance and shrinkage prediction (right above)
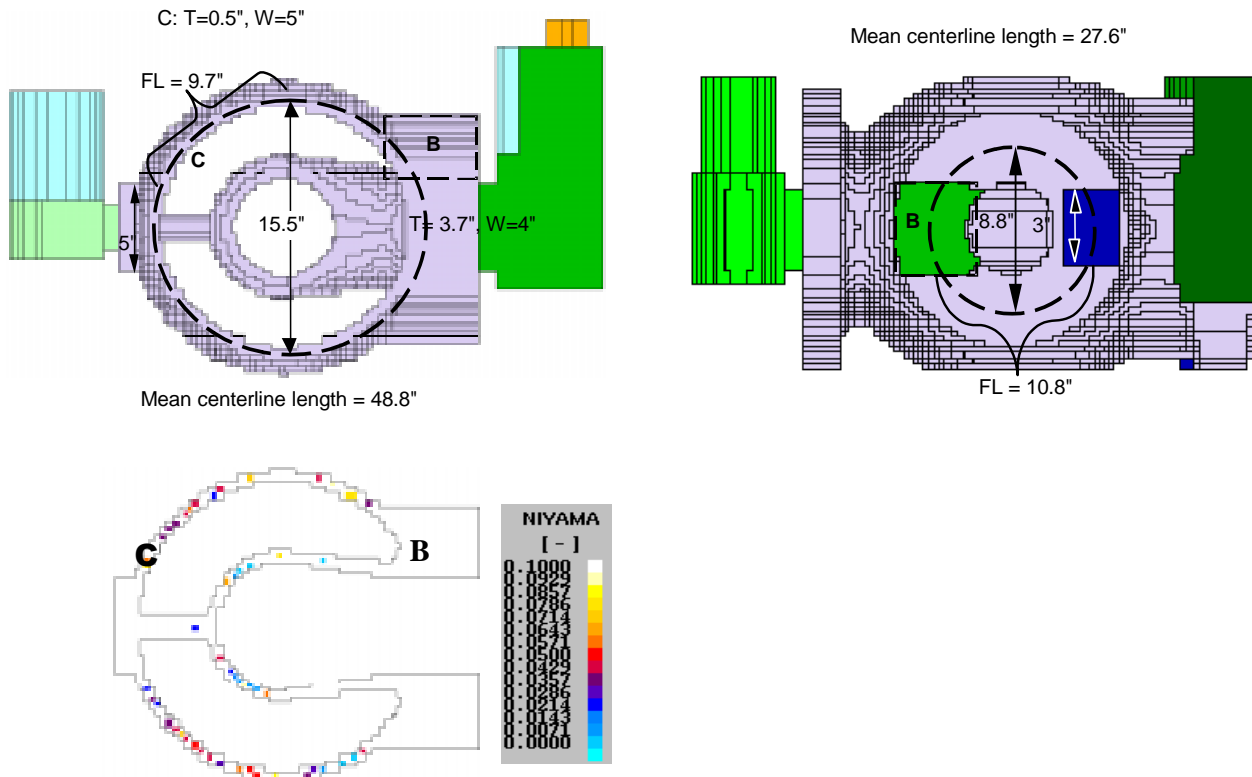
Feeding Distance Analysis for Casting #3

Sections B, C, and G in Figure 15 were chosen for example feeding distance calculations. The results of the predicted Niyama Criterion and example feeding distance calculations for sections B and C are shown in Figure 16 These results are shown for the section at G in Figure 17

Section B in Figure 16:

- The section is predicted to be quite sound. The required feeding length is 10.8", by the new drag chills rule the feeding distance is 16.9". The SFSA rule gives 11.9". Both rules say it can be fed but the new rule gives feeding distances which are substantially longer.

Section C in Figure 16:

- The applicable case is lateral feeding. The required feeding length is 9.7" for this 0.5" thick section. This section thickness is well below the application range of the SFSA rules. The new rule feeding distance is 1.55" and the current SFSA rule gives 0.9".

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C: T=0.5", W=5"

FL = 9.7"

C

15.5"

B

T = 3.7", W=4"

5"

Mean centerline length = 48.8"

Mean centerline length = 27.6"

B

8.8" 3"

FL = 10.8"

C

B

NIYAMA
[-]
0.1000
0.0929
0.0857
0.0786
0.0714
0.0643
0.0571
0.0500
0.0429
0.0357
0.0286
0.0214
0.0143
0.0071
0.0000

In section B the region to be fed is represented by a plate: 3.7"T x 4"W x 27.6"L
Required Feeding Lengths (FL): Mean Centerline Length = 27.6"
Required Drag Chill Feeding Length = (27.6"-3"-3")/2 = **10.8"**
Drag Chill CT=2", CW=3.2"
Calculated Feeding Distance (FD) by current SFSA rules [3]:

$$FD_{DragChill} = 0.88T - 0.76W - 1.91\sqrt{T} + 10.8\sqrt{W} + 0.35\sqrt{CT} + 0.21\sqrt{CW} - 7.04 = 11.9",$$

Calculated Feeding Distance (FD) by new feeding rules: $FD_{Drag\ chill}$ = **16.9"**
Assessment: By current SFSA rules drag chill feeding length can be fed, FD is 1.1" larger than FL
By new feeding rules drag chill feeding length can be fed, FD is 6.1" larger than FL
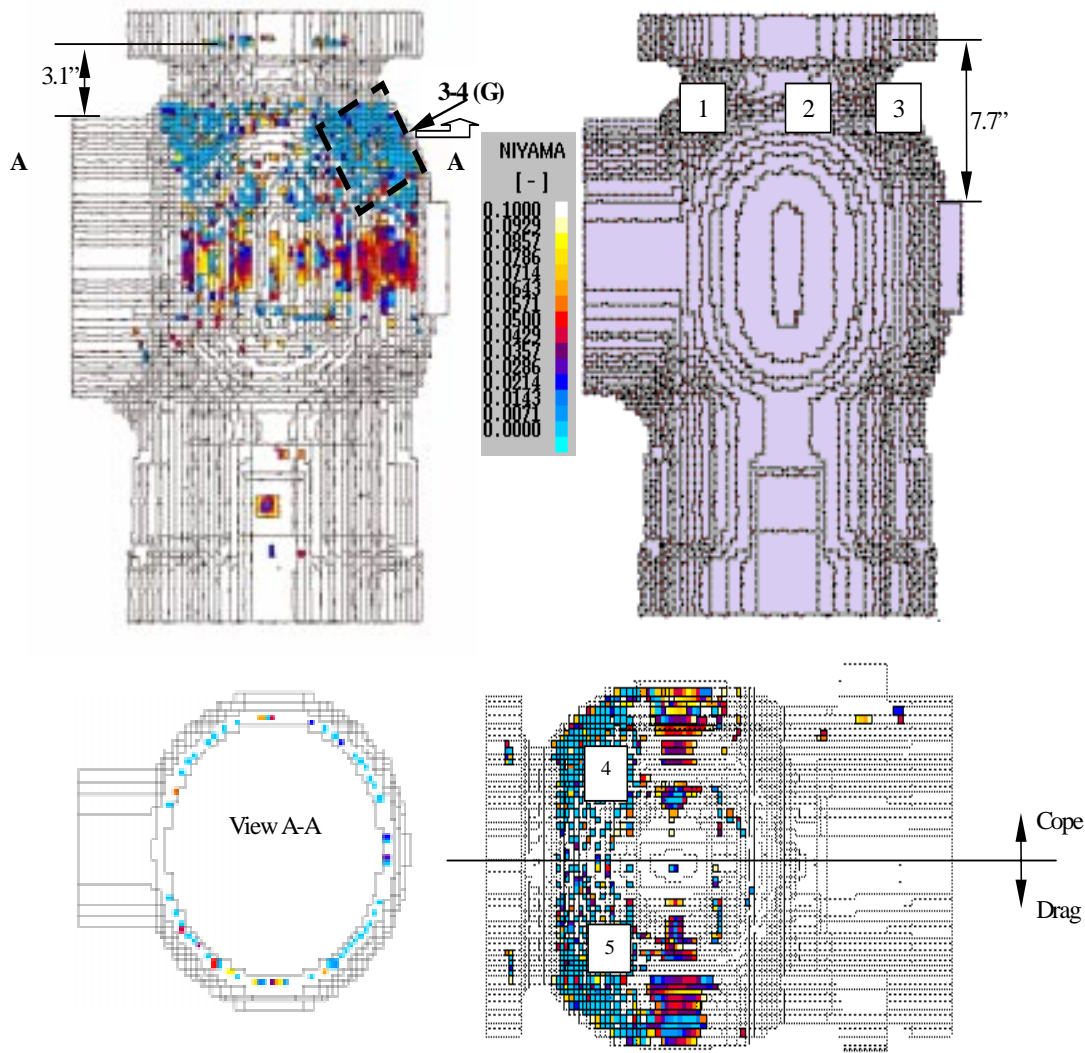

In section C the region to be fed is represented by a plate: 0.5"T x 5"W x 48.8"L
Required Feeding Lengths (FL): Mean Centerline Length = 48.8"
Required Lateral Feeding Length = (48.8"/2– 5)/2 = **9.7"**
Calculated Feeding Distance (FD) by current SFSA rules [3]:

$$FD_{Lateral} = 3.38\sqrt{T} + 0.84\sqrt{W} - 2.34 = 3.38\sqrt{0.5} + 0.84\sqrt{2 \bullet 0.5} - 2.34 = 0.9",\ \text{for W>2T plate cases W=2T}$$

Calculated Feeding Distance (FD) by new feeding rules: $FD_{Lateral}$ = **1.55",**
**Assessment:**   By current SFSA rules lateral feeding length cannot be fed, FD is 8.8" smaller than FL
By new feeding rules lateral feeding length cannot be fed, FD is 8.15" smaller than FL

Figure 16   Cross sections at sections B (top right) and C (top left), Niyama Criterion and Feeding Percentage for section shown at top left, and feeding distance calculations for Casting #3

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In section G the region to be fed is represented by a plate: 0.6"T x 8.4"W x 7.7"L
Required Feeding Length (FL): = 7.7"
Calculated Feeding Distance (FD) by current SFSA rules [3]:

$$FD_{Lateral} = 3.38\sqrt{T} + 0.84\sqrt{W} - 2.34 = 3.38\sqrt{0.6} + 0.84\sqrt{2 \cdot 0.6} - 2.34 = 1.2", \text{ for W>2T plate cases W=2T}$$

Calculated Feeding Distance (FD) by new feeding rules: $FD_{Lateral}$ = **1.75"**,
Together with FD from section C: 1.2"+ 0.9" = **2.1"** for old rules, 1.75"+1.55" = **3.3"** for new rules
Assessment: By current SFSA rules lateral feeding length cannot be fed, FD is 5.6" smaller than FL
By new feeding rules lateral feeding length cannot be fed, FD is 4.4" smaller than FL

Figure 17   Top (top left), cross section A-A (lower left), and side views (lower right) of Niyama Criterion distribution in wall of valve with region at G indicated (top left). G corresponds to position 3-4 (shown above) from the RT reader sheets where Level 3 shrink was found. Feeding distance calculations for section also shown.
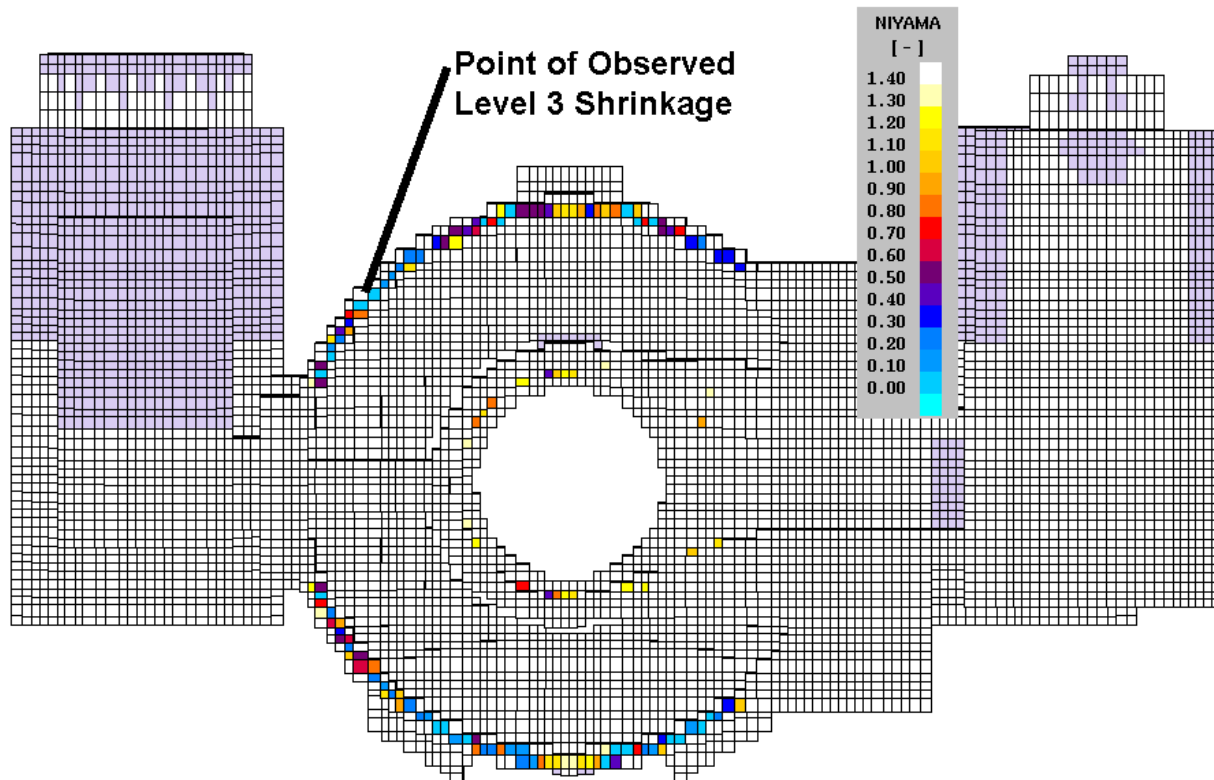
Figure 18   Niyama Criterion plot of section with Level 3 shrinkage

Section G in Figure 17:

- The case considered is lateral feeding. The total required feeding length across this region is 7.7". The section is 0.6" thick. The new rule feeding distance is 3.3" and the current SFSA rule is 2.1". The feeding distance is exceeded.

Conclusions for Casting #3

- In section B there are no cells with Niyama Criterion below 0.1. Therefore the simulation results for the casting are consistent with the new rule for this section since the feeding distance was not exceeded. If the feeding distance is not exceeded there should be no cells below the 0.1 Niyama Criterion value.

- In sections C and G a Level 3 shrink was found in this region based on the RT reader sheets from NACO Inc.'s Richmond Foundry. This is not surprising since the feeding distance is greatly exceeded. Coinciding with the new feeding rules, there is a large region of Niyama Criterion below 0.1. The new rule is consistent with the simulation results.

- The position of the Level 3 in the wall of the valve in sections C and G is shown in the Niyama Criterion plot in Figure 18. The vertical section through the casting wall in Figure 18 shows concentrated region of Niyama values below 0.1.

3.0 CONCLUSIONS

The results from this study are summarized in Table 2. In this table, for a given casting and section, the required feeding length, the current rule and new rule feeding distances (based on actual casting conditions), the new rule feeding distance corresponding to the casting conditions of the current SFSA rules (green sand mold and plain 0.3% carbon steel), and RT results are given. Note that:

- The new feeding rules are based on the feeding distance determined by the first appearance of a minimum Niyama Criterion of 0.1. For all sections of the castings considered here, where the new rules said the casting section could be fed, there are no computational cells having Niyama Criterion values below 0.1. In these cases there was also no shrinkage found worse than Level 1 found by RT. Furthermore, for all sections where the new rules were exceeded computational cells having Niyama Criterion values below 0.1 were found.

- When the required feeding length is substantially larger than the feeding distance the RT is worse than Level 1; Level 3 as shown in Table 2. There is also a very large region of Niyama Criterion less than 0.1 in such cases.

- When the new feeding rule is exceeded and the casting is still rated by RT as Level 1 or better, there is not a large area of Niyama less than 0.1.   This was observed in the plate casting trials [1] in some cases. For these cases the feeding distance was not exceeded by much. In some cases it is desirable to have the feeding distance rule for RT Level 1 (or better) be on the conservative side, but in other cases a less conservative rule is preferred. Considering that the new rules are still preliminary, it might be advisable to make still less conservative rules based on the area of Niyama Criterion below 0.1.

- Comparing the current SFSA rules [3] with the new rules in Table 2, sometimes the new rule gives a smaller feeding distance that the current rule. In these cases, the difference is small and the two rules are more or less equal. There are situations when the rules agree. It is often the additional factors considered by the new rules that decrease their

Table 2   Summary of comparisons between required feeding lengths, feeding distances and RT for castings studied

Case and Section	T (inch)	W (inch)	Rule Applied	FL (inch)	FD_{Old} (inch)	FD_{New}, Based on Actual Casting Conditions (inch)	FD_{new}, Based on Current Rule Casting Conditions (inch)	RT Level
Casting # 1: Section A	1.3	5.5	End Effect	12.2	7.4	8.9	9.4	0
Casting # 1: Section B	1.4	1.5	End Effect	10.8	5	5.7	6.4	1
Casting # 2: Section A Drag	1.4	2.7	Lateral feeding	4.5	3.05	2.85	3.26	1
Casting # 2: Section A Cope	1.4	2.7	Drag Chill	4.2	8.3	7.6	8.98	0
Casting # 2: Section B Drag	1.4	2.7	Lateral Feeding	4.7	3.05	2.85	3.26	1
Casting # 2: Section B Cope	1.4	2.7	Drag Chill	3.7	8.3	7.6	8.98	0
Casting # 2: Section C/D Cope	1.4	4.8	Lateral Feeding	5.2	3.1	3.6	4.13	0
Casting # 2: Section C/D Drag	1.4	4.8	Drag Chill	6.9	8.7	9.5	11.2	0
Casting # 2: Hub Wall Section	1	5	Lateral Feeding	5.6	2.2	2.85	3.36	No RT
Casting # 3: Section B	3.7	4	Drag Chill	10.8	11.9	16.9	19.9	0
Casting # 3: Section C	0.5	5	Lateral Feeding	9.7	0.9	1.55	3.48	3
Casting # 3: Section G	0.6	8.4	Lateral Feeding	3.8	1.2	1.75	2.2	3

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feeding distances below the current guidelines. The multipliers for PUNB (furan) mold, superheat and alloy decrease the new rule feeding distances in Table 2.

- Comparing the new feeding distance rules for the casting conditions corresponding to the new feeding rules and the current SFSA rules (determined using AISI 1020 steel properties, green sand mold and 60°C superheat), the new rules are always less conservative. Recall that the section thicknesses covered in the current SFSA rules go down to 2" thick so their accuracy in all but one entry in Table 2 is questionable. The new rules cover 0.5" to 12" thick sections.

It has been shown here that the application of lateral feeding rules to ring-shaped sections having one riser is not appropriate. If the inner ring diameter is small relative to the section thickness, there could be considerable effects on the required feeding length and feeding distance calculations due to the superheating of the core sand. While no strong effects were seen in the castings analyzed here (since the Niyama Criterion were consistent with the rules), one would expect the superheated core to cause; 1) a shifting of the feed path toward the core, shortening the required feeding length, and 2) the section to behave as if it were thicker, because heat transfer is reduced by the superheated core. This means that using the geometric mean circumference is not always applicable in determining the required feeding length, again depending on the ring inner diameter and section thickness. The second effect, the change in the effective thickness of the section, would require the development of rules or correction factors specific for ring-shaped sections. As the final guidelines for the application of the new rules are prepared, it would be beneficial to analyze more castings, and test all the steps involved in applying the feeding rules.

ACKNOWLEDGMENTS

REFERENCES

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[2] Smith, D. "An Evaluation of Conventional Method Rules Using Casting Simulation", 50th Technical and Operating Conference Proceedings, Steel Founders' Society of America, 1996.

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[5] Niyama, E., Uchida, T., Morikawa, M. and Saito, S., "A Method of Shrinkage Prediction and Its Application to Steel Casing Practice," AFS Int.l Cast Metals Journal, Vol 7 (#3), pp 52-63, Sep. 1982.

APPENDIX A: SFSA RULES USED IN FEEDING DISTANCE COMPARISONS

A-1 SFSA Rules for End Effect [3]

Equation from [3]

F- 2. **End Effect for Plates (W>2T)**
$$FD = 12.25 \sqrt{T} - 6.56$$

F- 3. **End Effect for Bars (T=W)**
$$FD = 8.47 \sqrt{T} - 5.03$$

F- 4. **End Effect for Semi-Plates (T<W<2T)**
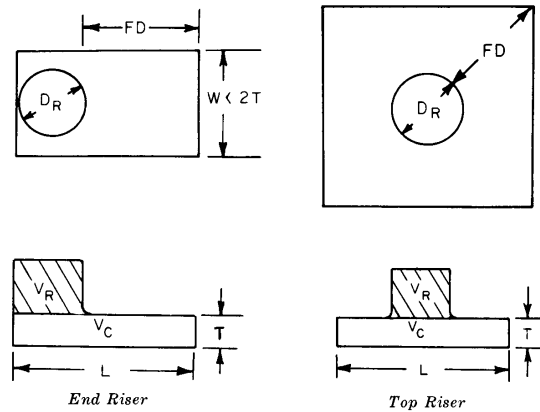$$FD = 7.24 \sqrt{W} + 1.51 \sqrt{T} - 5.67$$

Figure A-1 Example plates with end effect [3]

A-2 SFSA Rules for Lateral Feeding [3]

Equation from [3]

F-14. **Lateral Feeding for Semi-Plates (T<W<2T), and for Plates (W>2T) use W=2T**
$$FD = 3.38 \sqrt{T} + 0.84 \sqrt{W} - 2.34$$

F-16. **Lateral Feeding for Bars (T=W)**
$$FD = 4.26 \sqrt{T} - 2.45$$

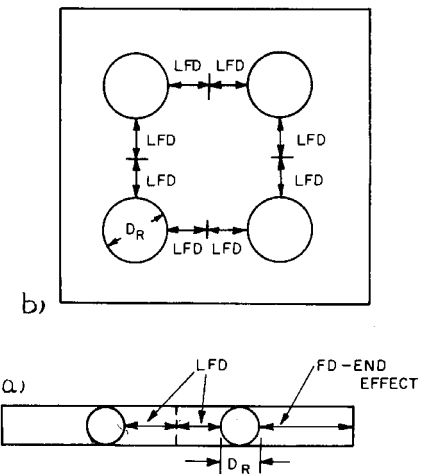**Figure A-2** Lateral Feeding examples [3]

A-3 SFSA Rules for Drag Chill [3]

Equation from [3]

F-11. **Drag Chill, for Plates (W>2T) use W=2T**
$$FD = .88\,T - .76\,W - 1.91 \sqrt{T} + 10.80 \sqrt{W} + .35 \sqrt{CT} + .21 \sqrt{CW} - 7.04$$
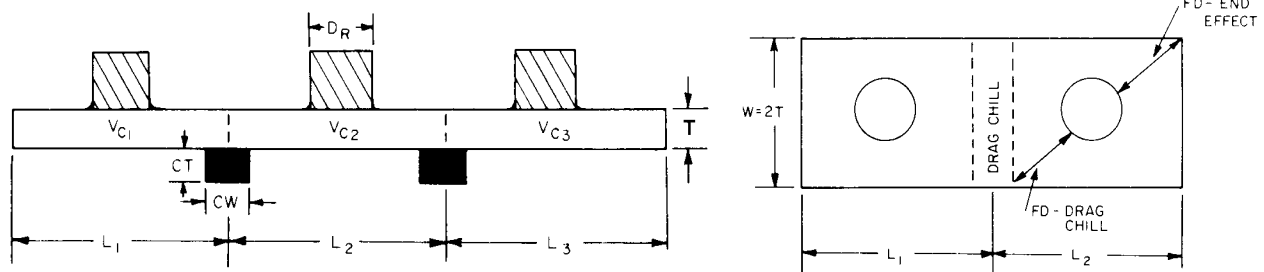

Figure A-3 Examples of drag chill applications from [3]

APPENDIX B: NEW FEEDING RULES

A plot of the new feeding rule base case is given in Figure B-1. The "base case" is taken at the following conditions: AISI 1025 steel, furan mold, superheat of 60°C, minimum Niyama criterion value of 0.1 $C^{1/2} s^{1/2} mm^{-1}$, and for section thickness from 0.5" to 12". Multipliers are used to modify the feeding rule to the actual casting conditions as follows:
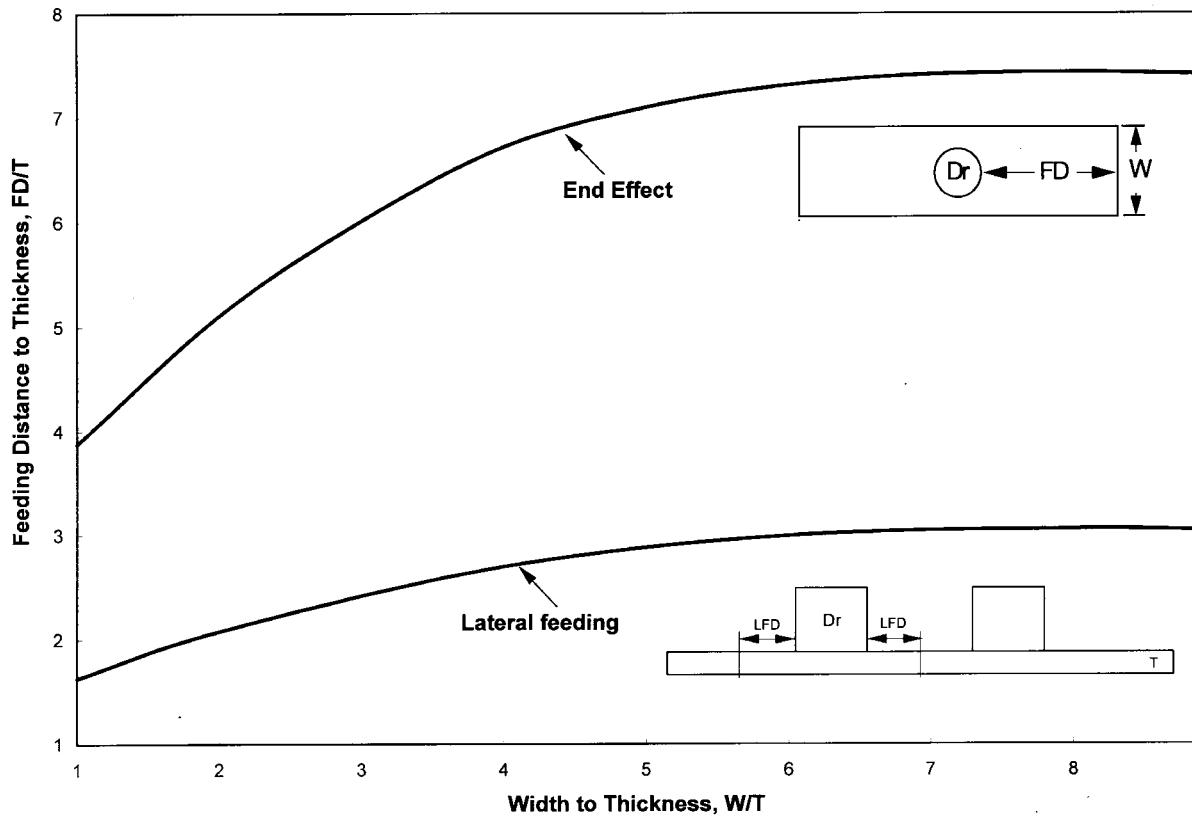
Figure B-1 New feeding rule plot for base case conditions: AISI 1025 steel, furan mold, superheat of 60°C, minimum Niyama criterion value of 0.1 $C^{1/2} s^{1/2} mm^{-1}$, and for section thickness from 0.5" to 12".

1. For End Effect conditions other than base case: multiply FD/T by these factors
   - Green Sand = 1.108, if green sand is used
   - AISI 4135 = 0.967, if AISI 4135 steel is poured
   - Superheat = 1.024, for every 10°C superheat above 60°C
2. For Lateral Feeding conditions other than base case: multiply FD/T by these factors
   - Green Sand = 1.075, if green sand is used
   - AISI 4135 = 0.955, if AISI 4135 steel is poured
   - Superheat = 1.018, for every 10°C superheat above 60°C
   - Drag Chill = 2.55, if drag chill is used