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Relationship between Casting Simulation and Radiographic Testing: Results from the SFSA Plate Casting Trials

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Abstract

Casting trials have been conducted in order to acquire a statistically meaningful set of experimental data on the feeding length of cast sections. The data establish a relation between the section length (L), width (W), and thickness (T) and the ASTM radiographic testing shrinkage level for various casting configurations. While some of the data agree with traditional feeding rules, it is shown that for certain cases the rules are overly conservative. Simulations of the trials were performed using data for the casting trial conditions recorded by the foundries. The trial results for shrinkage severity are quantitatively compared with simulation predictions for shrinkage based on the Niyama criterion. For the horizontal plates cast in these trials, a relationship is shown to exist between the radiographic testing results for shrinkage and both the minimum Niyama criterion value, and the amount of area with a Niyama criterion value below a critical value. For simple horizontal plates with a single top riser, it is found that the Niyama criterion can be used to predict the extent of macroporosity as measured by the x-ray level. For lateral feeding between several top risers feeding the same section (no end effect), it is demonstrated that the Niyama criterion breaks down due to symmetry of the temperature field at the centerline between the risers. However, a methodology is presented that allows for the prediction of the lateral feeding length, as measured in the casting trials, using the Niyama criterion in a special way. Altogether, these results allow for the establishment of improved feeding rules, tailored to the casting conditions. Also, a listing of additional trials from this ongoing study on feeding and yield improvement in steel casting is presented.

1. INTRODUCTION

Under sponsorship by the Steel Founders' Society of America (SFSA) through the Cast Metals Coalition (CMC), a program in steel casting yield improvement is being conducted at the University of Iowa. This research program has had substantial industry guidance, participation, and in-kind support. While a substantial part of the effort during this program has been in the development of improved feeding rules, the program has also provided the SFSA with studies on the current state of casting yield and unconventional techniques for improving yield in the steel casting industry [1,2].

In the early part of this project, SFSA members attending the project kick-off meeting and the early project review meetings requested that the project team investigate the feeding rules for risering of steel casting as currently published by the SFSA [3]. There was substantial feedback and anecdotal evidence at these meetings that these "Red Book" feeding rules were overly conservative. A consensus of the attending members indicated that these rules were overly conservative for both the ASTM x-ray shrinkage Level 1 soundness for which they were developed, and for higher ASTM radiographic testing (RT) levels, which are commonly stipulated by the customer. It was decided that an initial series of casting trials would be conducted with the goal of determining if the rules were conservative and if so, to what degree.

The initial casting trials conducted by five SFSA member foundries for the project demonstrated that the current feeding rules were conservative for some cases and agreed with the trial results for others [4,5]. Subsequent casting trials at larger plate width-to-thickness ratios (W/T) demonstrated a strong trend that the current feeding rules were increasingly conservative at larger W/T. Consequently, a large part of the research program has focused on investigating and predicting feeding and shrinkage for the purpose of developing improved rules, which are consistent for a wide range of W/T and plate thickness. The trial results demonstrate where the current feeding rules are applicable, and where they can be substantially improved. The primary goal of this paper is to present the results of the casting trials for the low alloy plates cast for the research project, focusing on the results for plates with end-effect and for lateral feeding. Also, the RT shrinkage severity levels in the trial plates are quantitatively compared with simulation predictions for shrinkage based on the Niyama criterion. A relationship exists between them, which can be justified based on analyses presented in the casting literature.

2. USE OF THE NIYAMA CRITERION AND THE SELECTION OF TRIAL PLATE GEOMETRY AND FEEDING LENGTHS

Results from a computational study [2] provided insight and laid the groundwork to establish a methodology to determine feeding distances using a commercial casting code. This methodology was based on the prediction of shrinkage defects in simulations of the trial plates using the commercial casting software package, MAGMAsoft. This methodology was needed to establish the geometry of plates for the casting trials, and was subsequently used to develop the new feeding rules [4,5]. It was found that this methodology could be used to consistently establish the feeding lengths for a wide range of plate trial castings. As described in detail elsewhere [4,5], this methodology uses the Niyama criterion to predict shrinkage porosity formation in plate castings. This criterion is a well-known indicator of porosity formation, and is used in many casting modeling software programs. A review of this criterion is provided below.

2.1 Overview of the Niyama Criterion

The discussion provided below focuses on the principal question of whether the Niyama criterion can be used to predict shrinkage porosity large enough to be detected by radiographic testing. While the Niyama criterion has been shown to be a reliable shrinkage porosity predictor for plate castings, the reader should exercise care in extending the results of this study to more complex castings. In such cases the formation of the shrinkage porosity is also influenced by phenomena not taken into account by the Niyama criterion.

The Niyama criterion is defined as $G/\sqrt{\dot{T}}$, where G is the temperature gradient in K/mm and $\dot{T}$ is the cooling rate in K/s. Both quantities are evaluated at the end of solidification, although the exact method needs to be carefully defined to be reproducible. Also note that the temperature gradient is generally a vector. When evaluated in casting simulations, only the absolute value of this vector is taken (i.e., the component in the direction of the heat flux vector). Niyama et al. [6] use the symbol R for the cooling rate – here we will reserve R for the solidification speed (in mm/s), as is commonly done in the recent casting literature. In steady directional solidification, $\dot{T} = R \times G$. Niyama et al. [6] suggest a critical value of

$$G/\sqrt{\dot{T}} = 1.0\ K^{1/2}\ min^{1/2}\ cm^{-1} = 0.775\ K^{1/2} s^{1/2} mm^{-1}$$

below which shrinkage defects occur (the latter combination of units is typically used in casting simulation software). In planning the initial casting trials, a Niyama criterion value of 0.7 ($K^{1/2}$ $s^{1/2}$ mm^{-1}) was used to determine the plate length where shrinkage defects should begin to form.

There has been some controversy regarding the use of the Niyama criterion for shrinkage prediction. This controversy stems from the fact that certain users of casting simulation software use the Niyama criterion only to predict what they call *microporosity*. Since this microporosity cannot be detected by radiographic testing, they conclude that the Niyama criterion is not suitable for judging if a casting will pass radiographic standards. Another consequence would be that the Niyama criterion cannot be used to develop feeding rules, which provide the distance a cast section can be fed without developing shrinkage porosity detectable by x-ray testing. While the Niyama criterion does indeed need to be used with *extreme care* and will fail in certain casting geometries, the following review of the literature indicates that it can in fact be used to predict both microporosity and shrinkage porosity large enough to be detected by radiographic testing. The original paper by Niyama et al. [6] is reviewed first, and is followed by a recent study by Sigworth and Wang [7].

2.2 Review of Niyama et al. [6]

Niyama et al. [6] state that "gross" shrinkage generally appears in an area enclosed by an "equisolidification time line" - such areas are the so-called "hot spots." Their study, however, focuses on centerline shrinkage that is formed in areas of shallow temperature gradients, not necessarily enclosed by equisolidification time contours. Rules for determining feeding distances in cast sections are concerned with the formation of this centerline shrinkage.

Niyama et al. [6] present experimental results for cast vertical cylinders of different diameters with a top riser and molds made from furan-bonded silica sand. They examine five different steels ranging from regular carbon/low alloy steel to high alloy (e.g., CF8) steel and investigate superheats ranging from 50 K to 100 K. The castings were tested and sectioned along the vertical centerline. The shrinkage was detected using dye penetrant (on the cut section), x-ray, and ultrasonic testing. The latter two methods were used to examine production castings. Photographs of some of the sectioned cylinders are shown (Fig. 2 in Niyama et al. [6]), and the shrinkage porosity appears to be several millimeters in diameter.

Niyama et al. [6] use two-dimensional simulations to determine the temperature gradient and cooling rate. In the simulations the cast-mold heat transfer coefficient was taken as infinite, and the temperature gradient was evaluated in an approximate way, as the maximum local value among eight directions at the end of solidification. The cooling rate was approximated as the difference between the liquidus and solidus temperatures, temperatures, $T_l - T_s$, divided by the total solidification time t_f. Because of these approximations, the actual values of the thermal parameters computed by Niyama et al. should be viewed with caution, especially when comparing them to values from modern three-dimensional casting simulation codes. The key finding of Niyama et al. is that the critical temperature gradient G at which porosity forms is proportional to $1/\sqrt{t_f}$. Since $\dot{T} = (T_l - T_s)/t_f$, this finding can also be expressed as the usual Niyama criterion $G/\sqrt{\dot{T}} > const.$ for the casting to be sound, where the constant is determined from experiments.

The following additional observations are also worth noting from Niyama et al [6]. The same critical Niyama value applies to all alloys, superheat values, and casting section thickness dimensions, within the ranges studied. The size of the shrinkage regions and the porosity size both correlate with $G/\sqrt{\dot{T}}$. *Radiographic* testing of production castings reveals that the Niyama criterion not only predicts the centerline shrinkage, but that hot spots and the corresponding gross shrinkage are also characterized by low $G/\sqrt{\dot{T}}$ values. The Niyama criterion could be evaluated at a temperature higher than the solidus temperature, which would result in lower critical Niyama values. However, the functional correspondence between this parameter and shrinkage porosity remains the same (note that some modern casting simulation codes do in fact evaluate the Niyama value at a somewhat higher temperature, which explains the lower critical values observed here). The Niyama criterion is a purely local thermal parameter; in reality, certain shrinkage will depend on the solidification behavior of other parts of the casting (however, this is immaterial when determining feeding rules for simple sections).

In an appendix, Niyama et al. [6] attempt to provide a theoretical justification of the Niyama criterion based on Darcy's law for interdendritic flow. Their analysis shows that the pressure drop is proportional to $(G/\sqrt{\dot{T}})^{-2}$. If the pressure drop exceeds a certain value, porosity will form. While the general concept of Darcy's law is always applicable to mushy zones, Niyama et al. do not carefully analyze the physical processes responsible for centerline porosity in a plate or cylinder. The analysis in the appendix is strictly only valid for *unidirectional solidification*, where the feeding flow is in the same direction as the heat flow (i.e., across the plate thickness from the centerline toward the outer solid shell). In this situation, the pressure drops to a value low enough for porosity to form only when the solid fraction is very large (close to unity) and the permeability of the mush is very small. That porosity is thus limited to small spaces between the dendrite arms – in other words, this porosity can safely be called microporosity or dispersed porosity. It cannot be detected by regular radiographic testing. Hence, the Niyama criterion can most likely be used to predict microporosity.

This microporosity is not the same as centerline shrinkage porosity in plates. That porosity can be much larger in size and, hence, must be forming at lower solid fractions. Niyama et al. do not consider that the feeding flow during solidification of a plate is primarily *along* the plate centerline (from the riser to the opposite end of the plate), whereas the solidification is mainly *toward* the centerline. If this feeding flow is "cut off," by bridging of mush across the centerline, centerline shrinkage porosity will develop. In fact, Niyama et al. observed that the centerline shrinkage is associated with V-segregates, indicating that such bridges were in fact present. This does not mean that Darcy's law is not valid. However, the analysis of Niyama et al. would need to be modified to account for the direction of the flow and the presence of bridging across the centerline.

2.3 Review of Sigworth and Wang [7]

Sigworth and Wang [7,1993] re-examined the issue of pressure drop due to interdendritic flow, making particular reference to the case of solidification of a plate and the question of feeding distance. They conclude that Darcy's law does not apply to the calculation of feeding lengths, because the calculated pressure drops are too small. This conclusion may be premature, because of certain assumptions made in their analysis. However, the "geometrical" model proposed by Sigworth and Wang in the following part of their paper is still worth considering, because it directly addresses the main physical process responsible for centerline shrinkage in plates.

Sigworth and Wang derive a model for centerline shrinkage of the type found in these present casting trials based on geometric arguments. They argue that "pinching off" of liquid areas along the plate centerline due to uneven solidification causes the shrinkage in plates. These isolated areas solidify without feeding and will exhibit shrinkage as shown in Figure 1(a). The presence of a gradient in the feeding direction serves to open up a channel, by effectively providing a taper to the inner liquid channel as shown in Figure 1(b). Assuming that feeding occurs as long as the tapered channel has an angle greater than a certain critical angle θ_c, the critical ratio of the temperature gradient along the plate, G_x, to the one across the mush in a direction perpendicular to the centerline, G_y, is given by

$$\frac{G_x}{G_y} = \tan\theta_c$$

The thermal gradient across the mush is given by $G_y \approx (T_l - T_s)/l$, where l is the thickness of the mush. According to Flemings [8], the thickness of the mush grows as $l \sim \sqrt{t}$. Following the derivations of Sigworth and Wang, the final expression for the critical temperature gradient is then given by

$$G_x = \frac{T_l - T_s}{2\sqrt{\pi k_M}}\sqrt{k_m \rho_m c_m}\, tan\,\theta_c \frac{1}{\sqrt{t_f}} = \frac{A}{\sqrt{t_f}}$$

where k_m, ρ_m, and c_m are the thermal conductivity, density, and specific heat, respectively, of the mold, and k_M is the thermal conductivity of the metal. Substituting appropriate values for the properties, and taking measured critical temperature gradients from Pellini's experiments (Pellini used radiographic testing to measure shrinkage), Sigworth and Wang estimate a critical angle θ_c for steel plates between 2 and 5 degrees, which appears reasonable.

The most important conclusion, however, is that this alternative derivation results in the same functional dependence between the temperature gradient and the solidification time as that found experimentally by Niyama et al. Note that substitution of the cooling rate for the solidification time results in the usual Niyama parameter $G/\sqrt{\dot{T}}$ (see the previous section). Niyama et al., as well as casting simulation codes, do not use the thermal gradient G_x along the plate centerline. Therefore, the constant A in the above equation would be different, and its exact value depends on how the thermal parameters are evaluated.

The above review shows that the Niyama criterion can be used to predict centerline shrinkage in steel plates that is detectable by radiographic testing. The evidence is in the form of experiments and analysis. The results of the present casting trials support this conclusion. The critical Niyama value found through the casting trials is lower than the one reported by Niyama et al., but this difference can be attributed to how the thermal parameters are evaluated in the casting simulation software used. Note that the Niyama criterion can fail to provide meaningful guidance on the formation of shrinkage porosity, for example in lateral feeding between two risers (due to symmetry, which creates a zero temperature gradient). However, this does not detract from the general usefulness of the Niyama criterion in determining feeding distances for simple plates. Finally, it is apparent from the literature that the Niyama criterion can also be used to predict microporosity that cannot be detected by radiographic testing.

2.4 Selection of Trial Plate Dimensions Using Niyama Criterion

The selection of the plate cross section dimensions cast in the trials was made considering the typical section thickness of castings produced by SFSA member foundries [1], and the pool of data already available from the large number of castings produced in earlier studies [9-15].

Extensive experiments over many years in the 1950's and 1960's led to empirically-based feeding rules. Most notably, there is the substantial body of experimental work from the Naval Research Laboratory (NRL) by Pellini, Bishop, Myskowski et al. for determining feeding distances [9-13] and adequate riser dimensions [14]. In these studies, castings were considered sound only if there was no evidence of shrinkage detected by radiography at 1.5% sensitivity. Plate sections of thickness ½", 2", and 4" with width to thickness ratios of 2, 3, 4, and 5 were cast for these studies, as well as bar-shaped cases (W/T = 1) with 6" and 8" sections. The castings were made of plain carbon steel of 0.25 to 0.30 weight percent carbon content, and a pouring temperature of approximately 2950 °F. In addition, the SFSA conducted comprehensive casting trials involving about 50 foundries of member companies [15]. In the SFSA studies, the feeding distance required to cast a section to commercial soundness (better than or equal to Class 2 ASTM RT soundness) was determined for ½", 1", 2", 4" plate and bar sections. The steel cast in the SFSA studies was reported as a carbon steel of 0.20 to 0.23 weight percent carbon that was cast with pouring temperatures between 2850 °F and 2950 °F, and the mold material used by the foundries was green sand.

It is assumed that these excellent studies are still valid, and should be considered along with the present trials, and therefore it was decided that cases from these trials would not be repeated. The geometry chosen for the initial plate casting trials was selected based on the recommendations of SFSA members, and results from the survey [1] that indicated the average section thickness for steel castings was about 2.5". A plate 3" thick (T) by 6" wide (W) was chosen for the first trials, and five lengths of this cross section were cast. The five initial plate lengths were chosen based on the current SFSA rule for feeding distance, and computer simulations of the plate lengths corresponding to Niyama criterion values of 1.0, 0.7, 0.2, and below ($K^{1/2}$ $s^{1/2}$ mm^{-1}). The current SFSA rule feeding length for this case (T = 3", W/T = 2) corresponded to a Niyama criterion value of about 0.4 ($K^{1/2}$ $s^{1/2}$ mm^{-1}). Castings were made and tested at four foundries for this initial trial case. One foundry also volunteered to cast 1" thick by 5.5" wide plates with the lengths chosen to coincide with the SFSA "Red Book" feeding length, and longer lengths corresponding to various Niyama criterion threshold values. A similar process was used for all subsequent casting trials. However, as experience was gained, and it was found that in many cases the SFSA "Red Book" feeding rules were conservative, the casting trial plate lengths were chosen based on minimum Niyama criterion values that were found to give the desired level of soundness.

3. CASTING TRIAL PROCEDURES AND ANALYSIS OF TRIAL RESULTS

A goal of the present trials was to include the normal variations that are possible in foundry practice when executing the trial results. These variations would also be considered in the analysis of the results. Therefore, detailed information was collected on the casting process for the trial plates, and all information was recorded in detailed data sheets that were filled out by the participating foundries. These data sheets were created by the investigators with substantial input from the SFSA and participating foundries. Results from the RT were included in the data sheets and the films were sent to the investigators. Following completion of the trials the results were sent to the project investigators, who analyzed the results and performed simulations in order to predict the casting soundness.

3.1 Data Collected by Participating Foundries

Since a goal of the casting trials was to establish a correspondence between x-ray level and Niyama values that occur in simulation, these plates must be simulated using conditions that are as close as possible to the actual casting conditions as recorded in the data sheets. The casting parameters that were taken into account in these plate simulations were: pouring temperature, mold material, actual casting rigging and mold-box geometry, steel chemistry and pouring time. Foundries cast the plates in different mold materials, with the details of the mold composition recorded for future reference and use in the computer simulations of the trials. The steel composition and pouring temperature (giving the superheat) would also be recorded for use in generating accurate computer simulations as will be described shortly. Rigging and gating configurations were recorded by the foundries in sketches, and together with the filling time, this provided information from which the filling process would be simulated. Data sheets included additional information on melt shop and ladle practice. Unfortunately, the level of detail of information given in the present trial data sheets is not available in the reports of the casting trials performed by the NRL and the SFSA. Precise simulations of these earlier trials do not appear possible, but comparisons with the experimental results are still meaningful.

Considering that the previous work [9-15] did not distinguish levels of soundness, it was decided that in the present trials that the ASTM RT rating for each trial plate would be determined so that a range of soundness data could be collected. More information than whether a plate was sound or unsound was desired. Each plate was examined by RT using ASTM E94 procedures (E186 for 3" thick plates, and E446 for 1"). Films from the RT were requested by the investigators for all plates cast, and these serve as a record of the casting trials and as a source to double check the RT results[1]. For the initial 3" trials, the plates were sectioned longitudinally through the center mid-width and were tested using magnetic particles. The magnetic particle testing was performed primarily to confirm casting soundness, and to help explain anomalies in the x-ray results. For the sectioned castings, the locations of regions of gross defects (visible to the observer) were also requested on the data sheets. In is envisioned that a more quantitative measure of casting soundness than is provided for in the current ASTM Standards will be possible from the results of the authors' investigations into digital analysis of the x-ray films[2].

3.2 Casting Trial Plate Geometry and Nomenclature

The general configuration for the horizontal plate casting trials is shown in Figure 2. Plates were cast for a given width to thickness ratio at several feeding lengths (FL) that were chosen to provide a range of soundness data. Since they are often confused, the feeding distance (FD) and the feeding length (FL) are clearly defined in the context of the present work to avoid confusion:

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[1] A gage R&R of the X-ray films from the trials is underway and will be included with the final report on the trials to the SFSA.

[2] The results of the quantitative analysis of x-rays, using digital processing, will be presented final project report to the SFSA.

Feeding Distance: The feeding distance (FD) is the distance from the riser to the furthest point in the casting over which the riser can provide feed metal resulting in a sound casting. In the case of the SFSA guidelines [3], soundness is defined as "Class I soundness at 2% radiographic sensitivity."

Feeding Length: As given in Figure 2 for the casting trial cases, the feeding length (FL) is the distance from the riser to the furthest point in the casting. It is the length to be fed. It is purely geometrical, and implies nothing as to the soundness of the casting being fed.

3.3 Simulations of the Trials

From the trial data sheets, simulations were performed for each trial plate for which unique casting data was available. In some cases, a set of plates with a given length was said to have identical pouring temperatures and times and individual simulations could not be run. In these instances, one simulation was performed for the entire set.

The simulations provide the distribution of the Niyama criterion throughout the trial castings. From this distribution, the minimum value of the Niyama criterion, and the amount (or area in a central-thickness cross section) below a critical value of the Niyama criterion will be shown to correlate well with casting soundness. The term "minimum Niyama criterion" is used to refer to the smallest value of the Niyama criterion in a distribution of values as shown in Figure 3. In this figure, the minimum Niyama criterion value is 0.3 ($K^{1/2}$ $s^{1/2}$ mm^{-1}). The scale shown is from 0 to 1.4 ($K^{1/2}$ $s^{1/2}$ mm^{-1}), and this scale is used to resolve the value to the nearest tenth. Unless otherwise stated, this scale is used throughout this work. Thus, when a minimum Niyama criterion value is referred to as 0.3 it could be as low as 0.3, and its value lies somewhere between 0.3 to 0.4 ($K^{1/2}$ $s^{1/2}$ mm^{-1}).

Steel chemistry was taken into account in these detailed simulations, and it has an effect on the Niyama criterion. The variations in the steel chemistry between the foundries produce differences in the Niyama criterion results. This is due primarily to slight changes in the liquidus and solidus temperatures (T_l and T_s, respectively) for slightly different chemistries. These changes will affect the temperature at which the temperature gradient and cooling rate are computed. In the software used in the present study, these quantities are evaluated at a default temperature equal to T_s plus 10% of the solidification temperature interval (T_l - T_s), which changes as the steel chemistry varies. Since the Niyama criterion is evaluated at a consistent temperature relative to the solidification process, the effect of steel chemistry on the simulation results is computed in a consistent manner. It should be pointed out that these effects are relatively small for the range of plain carbon steel chemistries cast in the trials presented here. Nonetheless, they appear to cause some variations in the simulations of trial results, and should also influence the experimental results.

The effect of chemistry on T_l, T_s, and the other thermophysical properties of the steel was computed using the interdendritic solidification computer software (IDS) developed by Miettinen et al. [16,17]. For a given chemistry, this model will predict thermal conductivity, density, specific heat, thermal expansion, viscosity, enthalpy, and solidification path (temperature and solid fraction relationship during solidification) using equilibrium and non-equilibrium calculations. The non-equilibrium calculations require a specified cooling rate. The austenite decomposition model in the IDS program computes solid-state phase transformations as well and their heats of transformation.

For each chemistry recorded for a given plate, computational runs were made using IDS in the non-equilibrium calculation mode, and the cooling rate specified was a representative cooling rate found by preliminary simulations of the trial cases near the plate's center. After the properties and the solidification temperature range were determined from IDS, the resulting values were compared with those for the appropriate steel from the property database in the MAGMAsoft program. T_l, T_s and the other thermophysical were checked for large disparities between the IDS program and the database. In most cases, they were found to agree quite well. Liquidus temperatures were generally within 5 °C and solidus temperatures within 10 °C. The thermophysical properties were generally in good agreement also, but where the differences were large enough to effect the results, the IDS property values were used. In such cases, the new properties from the IDS results were added to the database and were used in the simulations for that trial. Because of space limitations, the details of properties and trial conditions used in these simulations will be given in the final report on the trials, which is now in preparation.

4. CASTING TRIAL RESULTS

The results of the casting trials for the low alloy plates with end-effect and lateral feeding are presented in separate sections below. An overview of the other casting trials performed for the Yield Improvement Project, which will be given in detail in the final report on the trials, is presented at the end of this section. The experimental results are presented by plotting the RT rating for each trial plate versus feeding length. Comparisons are also made between the experimentally determined soundness (ASTM RT level) and the soundness predicted from the simulations based on the Niyama criterion. Both the minimum Niyama criterion, and the area of computational cells having a Niyama criterion value below 0.1 ($K^{1/2}\ s^{1/2}\ mm^{-1}$) will be compared with the experimental soundness results.

The data from the casting trials, the present SFSA feeding rules, and the data from trials conducted by the SFSA and NRL (data taken from [15]), are compared using the feeding shape factor in the plots that follow. The feeding shape factor was developed as part of this project for establishing improved feeding rules for the SFSA, and a more detailed discussion of the FSF is given elsewhere [4,5]. The feeding shape factor showed an excellent correlation with the simulations performed to establish feeding distances based on the Niyama criterion. This factor is defined as (referring to the diagram in Figure 4):

$$FSF = \frac{L_{FD} + W}{T}$$

where: L_{FD} = plate length corresponding to the simulation feeding distance
W = plate width

T = plate thickness

It was demonstrated previously that all the simulation results collapse on a single FSF line regardless of plate thickness when the FSF is plotted versus W/T [4,5]. The SFSA guidelines produce curves that vary with plate thickness. This indicates that the FSF is a sound dimensionless parameter for correlating the feeding behavior of castings. Note that a similar shape factor, (L+W)/T, is used in the SFSA rules for determining riser sizes [3], but the current application to feeding lengths is new. Note that the length in the definition of the FSF (see Figure 11) is not the feeding distance, defined as the distance from the riser to the corner of the plate, but the total length of the plate that can be fed with a single top riser.

4.1 Casting Trial Results, Part I: Horizontal Low Alloy Plates with End-Effect

The experimental results for the 3" by 6", 1" by 5.5", and 1" by 10" casting trials are shown in Figures 5 through 7. These will be referred to as the W/T = 2, 5.5 and 10 cases, respectively. In these figures, the rating from the RT is plotted versus feeding length for all plates cast. The numbers inside or near the symbols indicate the number of plates which were rated at a given RT severity level for a given feeding length. The mean x-ray rating is shown for each feeding length with the upper and lower 95% confidence intervals indicated by the error bars.

For all W/T ratios, there is a strong trend of increasing mean RT ratings as the feeding length is increased. There is some scatter in the data once defects begin to appear in the W/T=2 and 5.5 trials. However, for the W/T=10 trials, the shortest feeding length selected for the trials was too long. The reader will note this from the scatter in x-ray ratings at the shortest feeding length in Figure 7. For this recently completed trial, there was an intentional effort not to be overly conservative in selecting the plate lengths. The assumed superheat used in establishing the matrix turned out to be too high compared with the actual pouring temperature. A shortest length of between 7" and 7.5" should have been selected in order to produce a set of castings that would be expected to be Level 1 (given the casting conditions used in the actual trials).

Aside from the overly ambitious feeding lengths for the W/T=10 trials, it is clear that the various level of soundness can be determined as a function of feeding lengths for these trials. There are several possibilities upon which this relationship could be based:

1. The most conservative relationship is to examine only the worst case ratings for the trial at given feeding lengths. The shortest feeding length where a given RT severity level is first observed would be the feeding length corresponding to that RT level.
2. A rational, but still somewhat conservative worst case soundness rating at each feeding length, might be based on the upper 95% confidence level from the plots rounding to the nearest x-ray rating level.
3. The least conservative approach would be to select the mean x-ray rating and round up or down to the closest rating level for a given feeding length

Using these three methods, the longest plate lengths that were cast to a soundness better than or equal to a given RT level can be determined for the horizontal plate trials. This information is presented in Table 1. Selection methods 2 and 3 above, result in similar plate lengths. Choosing the least conservative method would appear to be reasonable. The chosen method of selection will affect the determination of the boundaries of the feeding rules that are designed to meet a given casting soundness. The mean value of the RT results will be used as the indicator of casting soundness here. While considering the comparisons that follow, it should be kept in mind that RT and x-ray film rating is both a science and an art. The rating is subjective, and studies of the repeatability of film evaluation have shown that the uncertainty in the rating can be as large as ±1 x-ray level [18].

Comparing the trial results with the present SFSA feeding rules [3] and Niyama criterion-based rules, note that the Niyama criterion-based rules are as accurate in the case of Figure 5, and more accurate in the case of Figure 6. The new Niyama criterion-based feeding rule plotted in Figures 5 through 7 was designed for RT level 1, as will be described shortly. In one case (Figure 5) the SFSA rule is only slightly less conservative than the new rule, but 2 out of 21 castings did not meet the RT level 1 rating for which the SFSA rule was developed. On the other hand, as shown in Figure 6, 21 castings were produced at RT level 1 for feeding lengths longer than the SFSA rule feeding distance. In the 1"T by 5.5"W trials, the new feeding distance rule is 48% longer (6.7" versus 4.5" for the SFSA rule), and no castings of RT level greater than 1 were produced up to the new rule feeding distance. Note also that 21 RT level 1 castings were produced at feeding lengths longer than the new rule. Such variations are possible given the many variables involved in the steel casting process.

For the 1"T by 10"W trials, as shown in Figure 7, the initial break from sound (level 1) to unsound was not determined. However, it should be noted that one of the four foundries participating in the trials produced 15 plates without shrinkage defects for the three cases up to 11" (5 plates at each case/feeding length). The gas porosity that was evident in many of the 1"T by 10"W castings might be affecting whether or not shrinkage porosity formed. Because of the desire not to be overly conservative in choosing the trial lengths, these trials were performed at longer feeding lengths than even the Niyama criterion-based rule, which for these trials was 75% longer than the SFSA rule (7.9" versus 4.5" for the SFSA rule). Considering that for the W/T=5.5 cases only RT level 1 plates were cast at lengths only slightly shorter than the new rule feeding distance, a 7.75" feeding length case should have been included in these trials (and perhaps should be cast by at least one foundry for confirmation). The new feeding rule is not disproved by these results, and once again the present SFSA feeding rule appears much too conservative.

The measured casting soundness for all data is plotted versus the predicted casting soundness, as reflected by the minimum Niyama criterion computed for each plate, in Figure 8. The data in Figure 8 were computed for all the plate cases (geometry) and using the casting conditions (i.e. pouring temperature, mold material etc.) from the trials. The number of plates which fell in various Niyama criterion and RT soundness ranges is indicated in the plot. For instance, 34 of 39 plates with a minimum Niyama criterion value above 0.2 ($K^{1/2}$ $s^{1/2}$ mm^{-1}) were ASTM level 1 or better. The most conservative border for the departure from level 1 would be about 0.26 ($K^{1/2}$ $s^{1/2}$ mm^{-1}), where the first non-level 1 plates occur. Between minimum Niyama criterion values of 0.1 and 0.2 ($K^{1/2}$ $s^{1/2}$ mm^{-1}) a noticeable increase in the frequency of level 2 rated castings occurs, and below 0.1 the frequency of RT level 3 castings begins to increase. The 0.1 ($K^{1/2}$ $s^{1/2}$ mm^{-1}) minimum Niyama criterion values could reasonably be taken as the threshold below which RT level 3 plates occur. Similarly, near minimum Niyama criterion value 0.05 ($K^{1/2}$ $s^{1/2}$ mm^{-1}) could be taken as the threshold below which RT level 4 and 5 plates occur.

A more statistically sound method of determining the breaks between the RT level is to use the mean and 95% confidence intervals for the minimum Niyama criterion values at each RT level. These results are shown in the upper right hand corner of Figure 8. Using the upper 95% confidence limit as the value below which an RT severity level is likely to occur, a number slightly less than 0.1 ($K^{1/2}$ $s^{1/2}$ mm^{-1}) appears to be a good choice for the value below which level 2 castings would occur. The confidence intervals for level 2 and 3 have considerable overlap, as do the intervals for the level 4 and 5 ratings, which could be due to the nature of x-ray reading and the closeness of these levels in the film readers' ratings. A good conservative value below which a trial casting will have an RT level worse than level 2 is approximately 0.03 ($K^{1/2}$ $s^{1/2}$ mm^{-1}) based on the confidence intervals. The reader must understand that magnitudes of these Niyama criterion values and their relationship to the casting trials' RT levels are meant to be used to calibrate the model predictions to the trial results for the purpose of feeding rule development. Extending these values and their associated shrinkage severity levels to general casting applications, other alloys, other model properties and other Niyama criterion evaluation temperatures is not advised.

Given the results discussed above, the value of the minimum Niyama criterion appears to work best as an indication that there is a risk of a given shrinkage severity occurring in a trial plate, since numerous level 1 castings are produced at Niyama criterion values below 0.1. This could be due to the fact that other physical phenomena play a role that are not considered in the Niyama criterion (i.e. dissolved gas content and gas porosity formation instead of shrinkage). Also, if the recorded data was not accurate, the simulations would predict a different minimum Niyama value than what the actual casting would have experienced. For instance, if the superheat was higher than reported (all other factors being the same) the minimum Niyama criterion values would shift to the right. More importantly, it was observed that not only the minimum value of the cells, but also the area of cells having low Niyama values was important in determining if shrinkage defects form. For example, many of the level 1 castings having minimum Niyama criterion values below 0.1 had only a small area (in the mid-thickness plane of the casting) of cells below 0.1.

An attempt was also made to correlate the x-ray levels with the area of Niyama criterion values below a threshold value of 0.1 ($K^{1/2}$ $s^{1/2}$ mm^{-1}). Plots for this area in the mid-thickness plane for the three W/T trials are given in Figures 9 through 11. The trend in the mean values in these plots indicates that x-ray level increases with area of Niyama criterion below the threshold value. For the area of Niyama criterion, the number of "good" plates is greatly reduced as the area of low Niyama values increases. In the case of the minimum Niyama criterion, it was noted above that numerous level 1 castings are produced at minimum Niyama criterion values below 0.1, including a substantial number of castings below 0.05. The area of Niyama criterion analysis method appears to be a much better indicator of "good" and "bad" plates than the minimum Niyama method. In short, the "area of Niyama criterion" method of soundness prediction greatly reduces the number "good" plates found where "bad" plates are predicted. Unfortunately, a good method has not yet been devised to non-dimensionalize this area indicator for a given casting geometry. It is an area of continued investigation.

Data for the feeding shape factor (FSF) versus width to thickness ratio are plotted for all of these trials in Figures 12 and 13. In Figure 12, the present trial results are plotted as symbols for each case with the mean RT level given in the symbol. In this figure, the present results are compared with the experimental results from the previous experiments by Pellini et al. and the SFSA as summarized in [15]. The previous results are plotted as cases for level 2 soundness (commercial soundness) and for completely sound (not even level 1 type shrinkage). The present trials agree well with the previous experimental results, and delineate the range of soundness at each W/T.

Note that the sound plate at W/T=2 from Pellini et al. is a 2"T by 4"W plate, which appears to be the only sound plate which does not agree well with the trend in the present trial results. This difference is not large enough to be of concern. The main difference in the level 2 casting soundness data also occurs for the W/T = 2 ratio, where there are three data points for the SFSA data. The main point of concern is the FSF = 25 point at W/T=2 in Figure 12, which is for a 2"T by 4"W plate. This point should be compared with the two lower values of FSF≈19.5 at the same W/T=2; one is for a 1"T by 2"W plate and the other is for a 4"T by 8"W. The concept of the FSF works well at these two points, since it demonstrates the feeding shape factor is a function of W/T for the same set of casting conditions and desired soundness. The FSF for the 2"T case at the same W/T is noticeably different from the 1"T and 4"T cases. If the effect of T were systematic (following the present SFSA feeding rules), the FSF value for 2"T would lie between 1"T and 4", but it does not. Therefore, its validity is questionable. The cluster of data at W/T=1 for level 2 and level 1 casting soundness appears to be within the uncertainties of RT ratings and variation in casting conditions. Considering this comparison of experimental data for many thickness values over a range of W/T, the FSF versus W/T analysis appears to collapse the experimental data regardless of plate thickness. Finally, it is very important to understand that as the casting conditions vary (alloy, superheat, etc.) the FSF value where a given soundness is achieved will vary. Such variations in the earlier experiments [15] can explain some of the scatter in Figure 12.

Figure 13 is provided to compare the results of the casting trials with the new feeding rules [4,5] and the currently published SFSA rules [3]. The new feeding rule shown in this figure is based on a minimum Niyama criterion value between 0.1 and 0.2 ($K^{1/2}$ $s^{1/2}$ mm^{-1}), a superheat of 60C, plain carbon steel of 0.25 wt.% carbon, and a chemical no-bake (furan) mold. The rule of Pellini is defined in terms of a so-called forward feeding distance (riser edge to farthest casting edge distance), whereas the SFSA rules [3] state the feeding distance is defined as the distance from the riser edge to the farthest point in the casting to be fed (in this case the corner of the plate). At W/T=2, the trials and all rules appear to be in good agreement, but at larger W/T the feeding rules begin to disagree. This disagreement between the rules increases as W/T increases. Referring back to Figure 12, it can be observed that the new Niyama criterion-based rules agree better with the current and previous trials for the entire range of W/T.

4.2 Casting Trial Results, Part II: Horizontal Low Alloy Plates with Lateral Feeding

The lateral feeding distance (LFD) is the farthest distance a riser can soundly feed a casting in the absence of the end-effect, as shown in the diagram in Figure 14. The well-known concept of a riser feeding zone and an end feeding zone illustrated in Figure 14 are used to establish the feeding distance between two risers using the Niyama criterion.

Due to the symmetry involved with lateral feeding, a point will always exist between two risers where the temperature gradient approaches zero. This results in a minimum Niyama criterion value of 0, no matter how close one places the risers next to each other. Taken at face value, the Niyama criterion value would always predict that shrinkage defects form between two risers. Therefore, the Niyama criterion cannot be used directly as a predictor in such cases; it breaks down. By increasing the plate length for a given W/T, one will arrive at the threshold minimum Niyama criterion value corresponding to a value where defects will begin to form. The distance from the riser edge to the point of this threshold value is the riser zone length for this minimum Niyama criterion value. Since this is the distance the riser can feed without the end-effect, it is also the lateral feeding distance.

Casting trials were performed for lateral feeding on the 3"T by 6"W casting sections. Three cases at different lateral feeding lengths (approximately 5.6", 7", and 8.4") were chosen and were cast at one foundry. As can be seen in Figure 15, the shortest of these feeding lengths corresponds to the "Red" Book rule [3], and the longest was determined from a minimum Niyama criterion rule when the first cell becomes less that 0.1. Three plates were cast at each length, and all plates at each length were rated at Level 1 or better in the initial trials. For these trials, the SFSA rule was shown to be overly conservative when compared to the trials and the Niyama-based rule. The Niyama-based rule was shown to be quite accurate, since all initial plates were sound. Following the initial trials a second foundry offered to cast plates, and slightly longer plate lengths were chosen for these trials (approximately 9", 11", and 13"). As shown in Figure 15, the results from the second series of trials were consistent with the initial trials. Two of the three plates cast at the 9" length were level 1, but one plate was rated at level 3. As the length increases, the shrinkage ratings become increasingly worse, and appear to systematically increase as observed by consideration of the mean ratings. The scatter is due in part to the inexactness of the RT rating process.

The scatter in the data for these trials is also a reflection that the level of severity of the shrinkage defects in lateral feeding is more sensitive to changes in feeding length than in the case of end-effect feeding. For lateral feeding, the trials demonstrate that for a change in feeding length of less than 3", the trial results go from all plates rated Level 1 (8.4" lateral feeding length, LFL) to the first Level 5 plate (at 11" LFL). Comparing this to Figure 5 for the 3"T by 6"W plates with end-effect, note that it took an increase in feeding length of over 12" between the length where all plates were sound to the length where the first level 5 plate appeared.

In Figure 16, a plot of the minimum Niyama criterion resulting from simulations of the lateral feeding trials is given. Simulations of the trials were performed using the casting conditions specified in the trial data sheets. These simulations were performed using a plate in end-effect, where the plate length was changed until the minimum Niyama criterion value occurred at the lateral feeding length of the trial plate. Eventually, if the simulated plate is made long enough, the distribution of the Niyama criterion in the riser feeding zone remains constant, and with increasing length only the region between 0 and 0.1 becomes longer. In this case, one should resort to an area below a given threshold Niyama criterion to distinguish between RT rating levels as shown in Figure 17.

The area of Niyama criterion below 0.1 ($(\mathrm{K\ s})^{1/2}$/mm) is plotted in Figure 17 for the lateral trials. Observe that the trial castings become worse than RT level 1 at about 15 cm^2 for the lateral feeding trials. At about 50 cm^2 the lateral trial castings have a mean RT level of 3, and at 65 cm^2 the mean RT level is 5. This shows a good trend; with an increasing amount (or area) of low Niyama values, the shrinkage defects become progressively worse. These values and trend also agree with the observations made earlier for the data for plates with end-effect. Also, note that the values of the area at the breaks between RT levels for the lateral plates agree remarkably well with those in Figure 9 for the 3"T by 6"W plates with end-effect. The break between RT level 1 and 2 is at approximately 13 cm^2 at the 95% confidence level in Figure 9. Also, at 50 cm^2 in Figure 9 there is overlap between RT level 3 and 4, which is also certainly the case in Figure 17 for the lateral trials. Finally, in Figure 9 for the end-effect plates, the 95% confidence intervals for RT levels 4 and 5 overlap at 65 cm^2, and at this area for the lateral plates the same RT range was measured. These quantitative observations are significant for the 3"T by 6"W horizontal plate sections cast in the trials, but the values would change depending on the section thickness (compare Figures 9, 10, and 11 for example). If the area of low Niyama criterion values has any physical meaning or correspondence to the degree of shrinkage formed, the quantities of areas corresponding to various RT levels should agree for the end-effect and lateral feeding, and they do as demonstrated by these trial results.

Comparison between trial results, the current SFSA rule and the Niyama criterion-based rule for lateral feeding are shown in Figure 18. Although more data might be desirable to demonstrate the agreement at large W/T ratios, the Niyama criterion-based rule agrees better with the trial results and is less conservative than the SFSA rule.

Remember that a special technique was used to simulate the lateral feeding cases based on the riser feeding zone concept. A second riser was not used, due to the zero temperature gradient that would always occur between two risers. Unfortunately, this problem cannot be overcome in applying the Niyama criterion to actual castings where lateral feeding is involved. Consider, for example, a casting case study performed as part of this project, shown in Figure 19. As shown in the top part of this figure, the casting is tub-shaped; and only one-half required modeling due to symmetry. The casting has twelve risers and lateral feeding occurs between them. According to the MAGMAsoft feeding percentage predictions, no defects form between the risers. Note in the Niyama criterion plot (shown in the lower part of Figure 19, and viewed from beneath the casting) that large regions of low values appear between the risers. These regions between the risers are misleading because taken at face value, they predict that defects will form in sound regions of the casting. This demonstrates that the Niyama criterion cannot be used as a reliable shrinkage predictor between risers in actual castings. However, note that both the Niyama criterion and Feeding Percentage indicate the formation of shrinkage in the "corners" of the part, and shrinkage defects at these locations were observed for this rigging as the part was originally cast in the foundry. An improved rigging has been recommended as a test of the new feeding rules, but as yet no casting trial results for the new rigging are available.

It is therefore inappropriate to use the Niyama criterion to predict shrinkage defects in many applications. Nevertheless, through use of the riser feeding zone concept, lateral feeding rules can be developed using the Niyama criterion that have been demonstrated in these trials to be better and more accurate that the current SFSA rules [3].

4.3 Casting Trial Results, Part III: Overview of Additional Trials Conducted

Due to space limitations, the results and analysis of the following trials are not presented here. These results will be presented in detail in a report being prepared for the SFSA on the plate casting trials and their analysis performed as part of the Yield Improvement Project. The trials that have been completed are:

- Horizontal High Alloy (CF8M) Plate Trials, Three W/T Cases
    - 1" thick by 8" wide, 4 cases with plate lengths from 9" to 15", data for 10 plates at each length from 2 foundries (40 plates total)
    - 0.5" thick by 6" wide, 5 cases with plate lengths from 4.4" to 9.2", data for 10 plates at each length from 2 foundries (40 plates total)
    - 0.5" thick by 1" wide, 4 cases with plate lengths from 3.3" to 6.8", data for 5 plates at each length from 1 foundry (20 plates total)
- Vertical Low Alloy (WCB) Plate Trials
    - 1" thick by 5.5" wide, 5 cases with plate lengths from 7" to 18", data for 5 plates at each length from 1 foundry (25 plates total)
- Vertical High Alloy (CF8M) Plate Trials
    - 1" thick by 5.5" wide, 5 cases with plate lengths from 7" to 18", data for 5 plates at each length from 1 foundry (25 plates total)

5.0 Conclusions and Future Work

Casting trials were conducted and then simulated using the precise casting conditions as recorded by the participating SFSA foundries in order to acquire a statistically meaningful set of experimental data on soundness versus feeding length. The following important conclusions were observed:

- For the casting trials with end-effect, the minimum Niyama criterion value corresponding to the departure from RT level 1 soundness was approximately 0.1 ($(K\ s)^{1/2}\ mm^{-1}$), based on the upper 95% confidence limit.

- For the lateral feeding trials, a minimum Niyama criterion value of 0.1 ($(K\ s)^{1/2}\ mm^{-1}$) corresponded to the break from RT level 1 as well. Breaks between other RT levels were also established in this way according to the casting trial results.

- Area of Niyama criterion indications was found to better distinguish higher RT levels than the minimum value, but the area is difficult to non-dimensionalize for arbitrary section thickness. For predicting the onset of shrinkage, the minimum value appears to be a very good indicator.

- It was observed that the area of computational cells below 0.1 ($(K\ s)^{1/2}\ mm^{-1}$) for the same measured RT levels was the same for both the end-effect and lateral feeding cases.

Comparisons between the present casting trials and casting trials performed over forty years ago by Pellini and the SFSA are quite good and appear reasonable. Comparisons between the current SFSA feeding rules and feeding rules based on the minimum Niyama criterion reveal that the Niyama-based rules are generally less conservative. The Niyama-based rules also agree better with the trials presented here, and the casting trials performed by Pellini and the SFSA. Furthermore, the use of the Niyama criterion to predict centerline shrinkage for horizontally fed plate sections has a theoretical basis according to the casting literature reviewed here. Taken altogether, these results strongly support the use of improved feeding rules for horizontal plate sections based on the Niyama criterion, which can be tailored to the casting conditions for a given alloy and to a desired level of soundness.

As currently planned, future work on casting trials will focus on thicker plate sections, where there is a large discrepancy between the current SFSA rules and the Niyama-based feeding rules. Trials in this thickness regime (T=6" and greater) will provide further evidence of the power of using the Niyama criterion to develop feeding rules. It would also be desirable to perform casting trials on other shapes besides plate castings, and explore other fundamental shapes to determine whether the Niyama criterion based rules can be applied. Finally, more emphasis needs to be placed on performing case studies with SFSA member foundries that would test the application of the new feeding rules to castings in the industry.

ACKNOWLEDGMENTS

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Table 1 Longest plate lengths corresponding to soundness better than or equal to ASTM RT levels 1 through 5 cast in the horizontal plate trials as selected by three methods

X-ray Level Plate Should be Equal to or Better Than	Selection Method 1: Most Conservative	Selection Method 2: Somewhat Conservative	Selection Method 3: Least Conservative
Longest Plates Cast to X-Ray Level at Left for 3" T by 6" W Trials (in)			
1	11.8	11.8	11.8
2	13.3	13.3	19.7
3	14.7	19.7	22.7
4	22.7	22.7	> 22.7
5	25.7	> 22.7	> 22.7
Longest Plates Cast to X-Ray Level at Left for 1" T by 5.5" W Trials (in)			
1	6.6	8	8
2	8	8	9.4
3	8	9.4	9.4
4	9.4	12.3	12.3
5	12.3	> 12.3	> 12.3
Longest Plates Cast to X-Ray Level at Left for 1" T by 10" W Trials (in)			
1	< 8.6	< 8.6	< 8.6
2	< 8.6	9.9	9.9
3	8.6	11	11
4	9.9	14	14
5	11	> 14	> 14

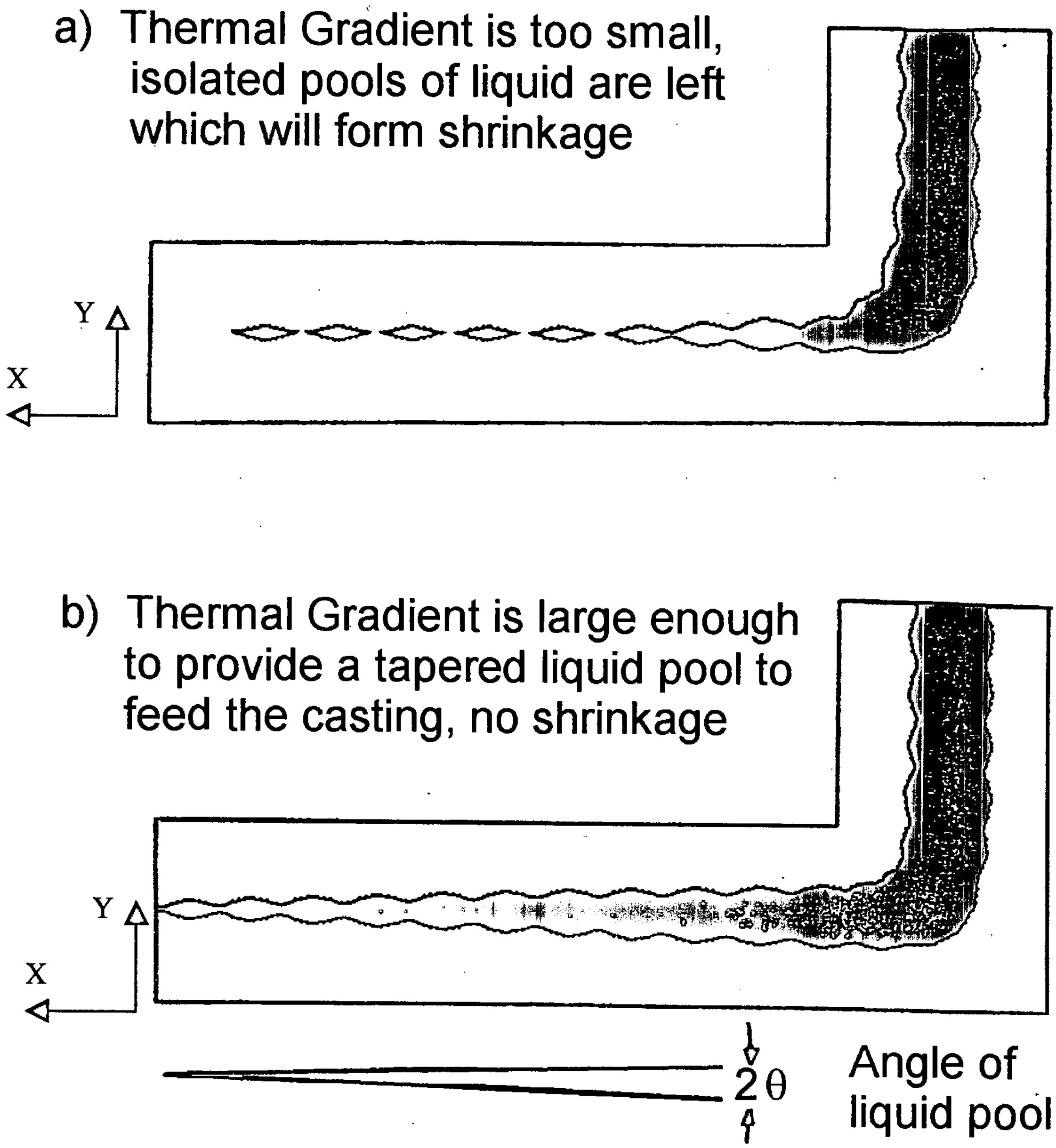


Figure 1 Diagram of a plate-like casting with (b) and without (a) an adequate thermal gradient to prevent formation of shrinkage porosity (adapted from [7])

Mold for Casting Trials

- casting material: steel (carbon or low alloy)
- mold material: silica

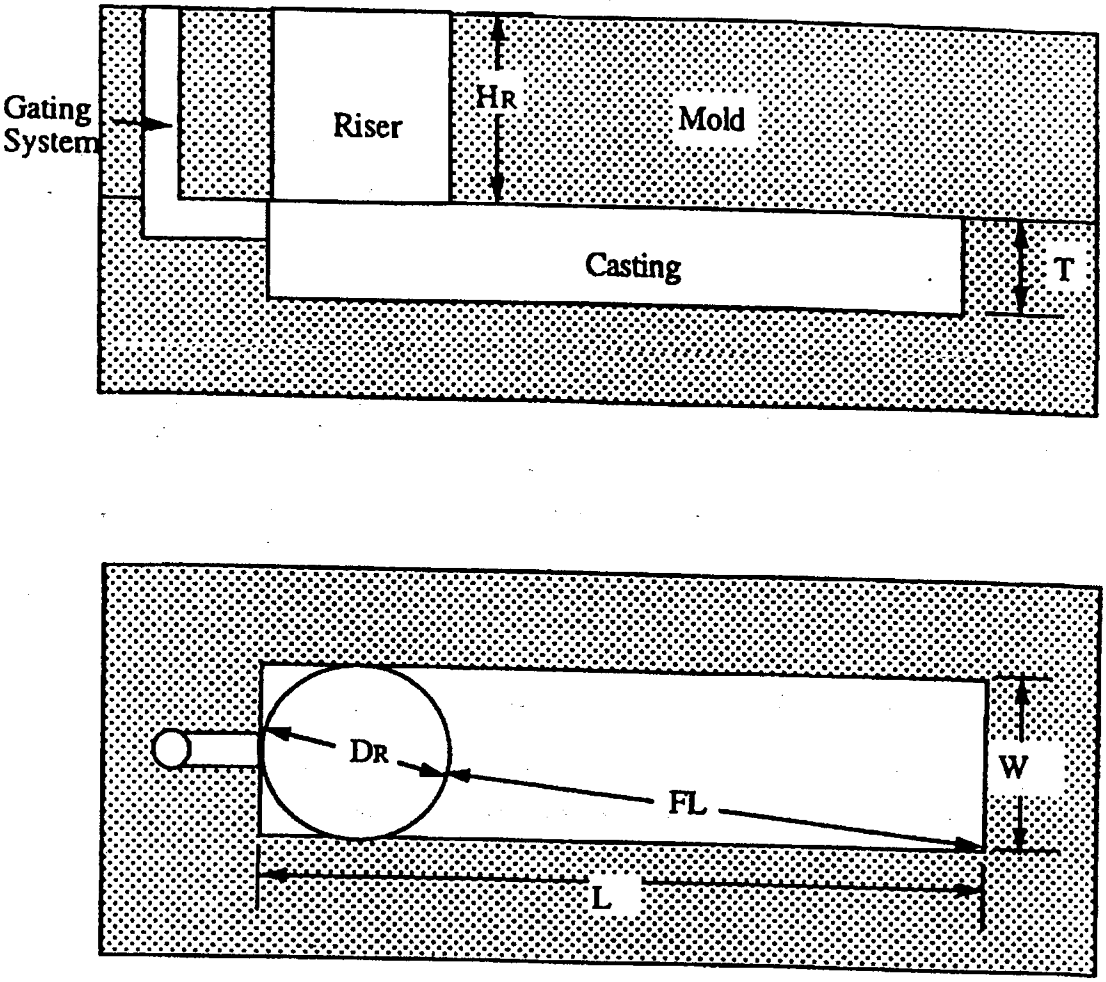


Figure 2 General configuration and nomenclature for the horizontal plate casting trials

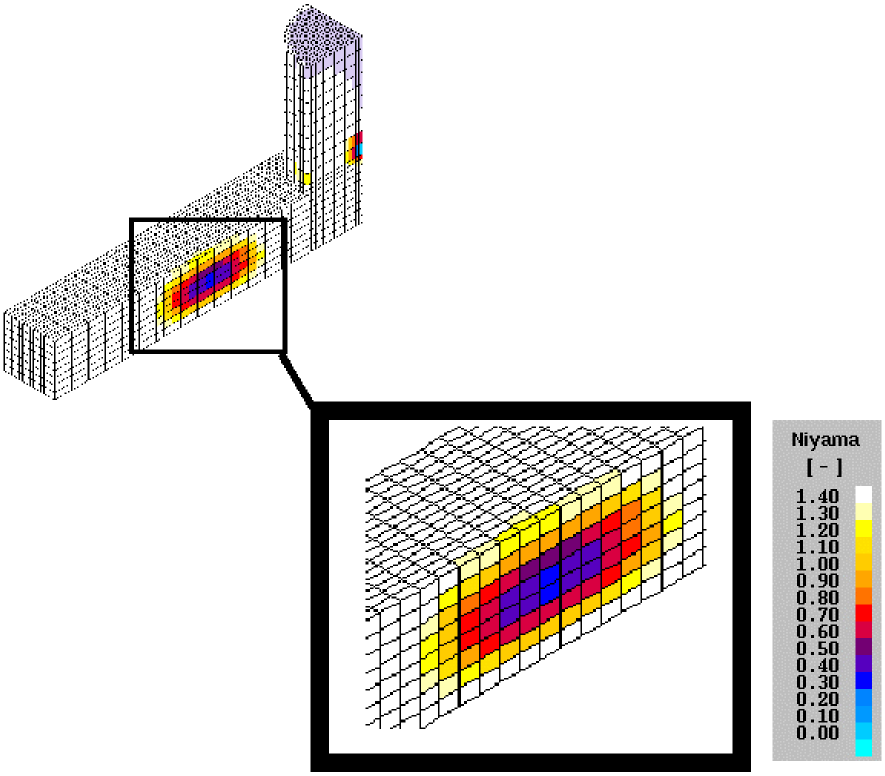
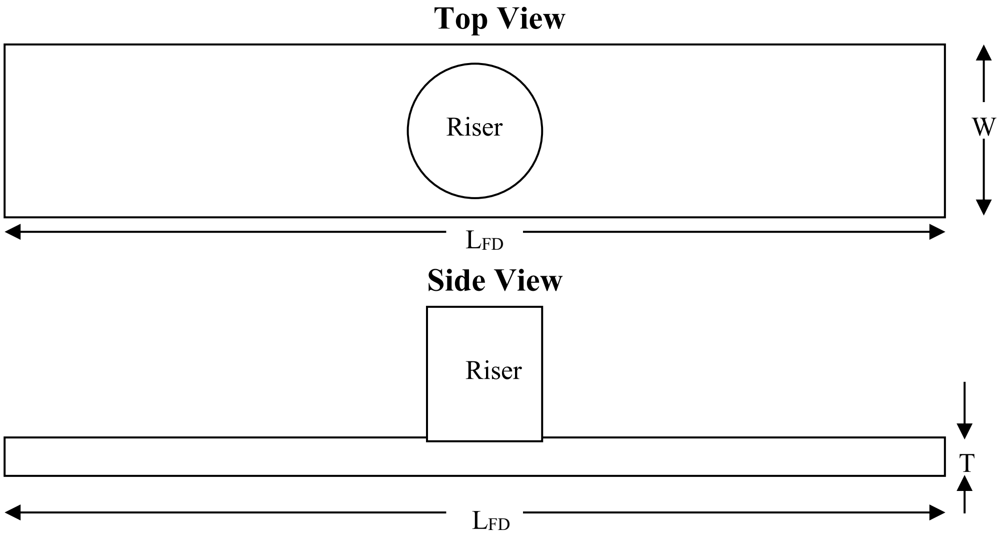


Figure 3 Example of Niyama criterion distribution in a plate casting having a minimum value of 0.3 $K^{1/2}$ $s^{1/2}$ mm^{-1} (the actual smallest value is between 0.3 and 0.4)



$$FSF = \frac{L_{FD} + W}{T}$$

Figure 4 Definition of the Feeding Shape Factor (FSF)

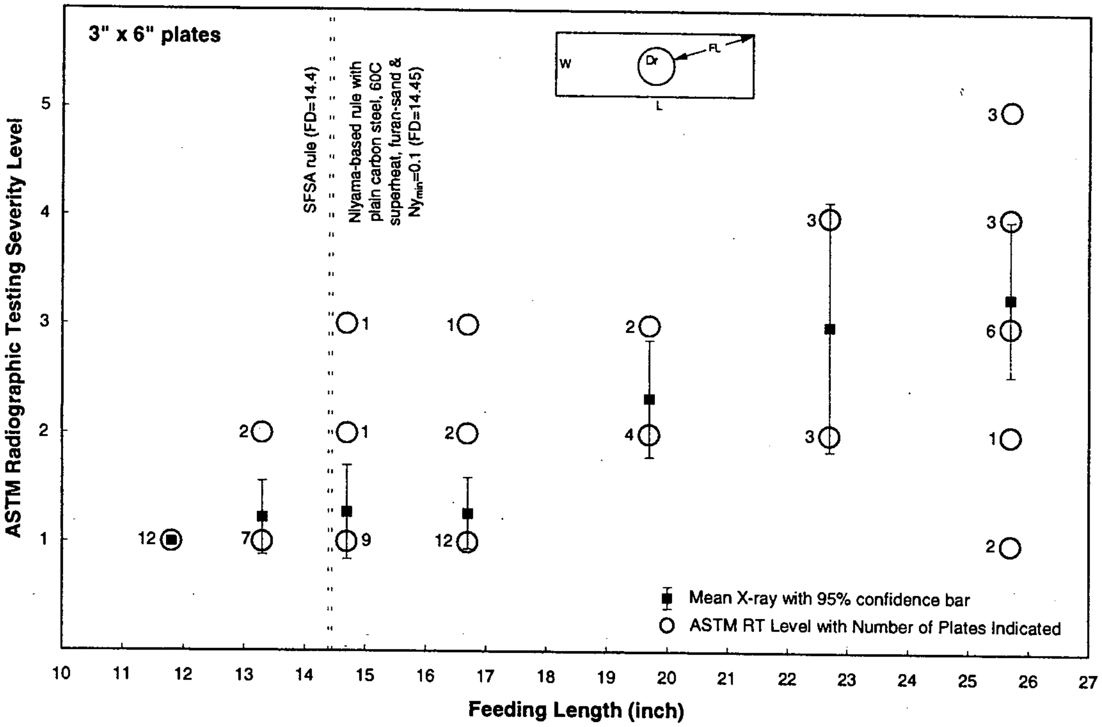


Figure 5 Casting trial results for 3" T by 6" W: Soundness versus Feeding Length

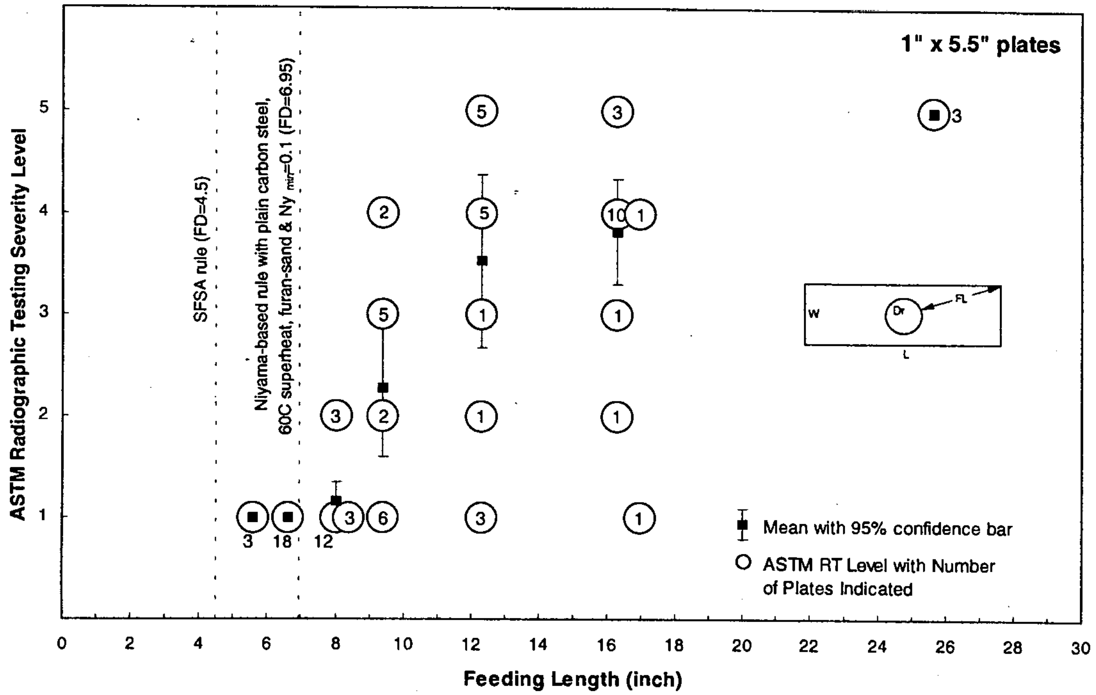


Figure 6 Casting trial results for 1" T by 5.5" W: Soundness versus Feeding Length

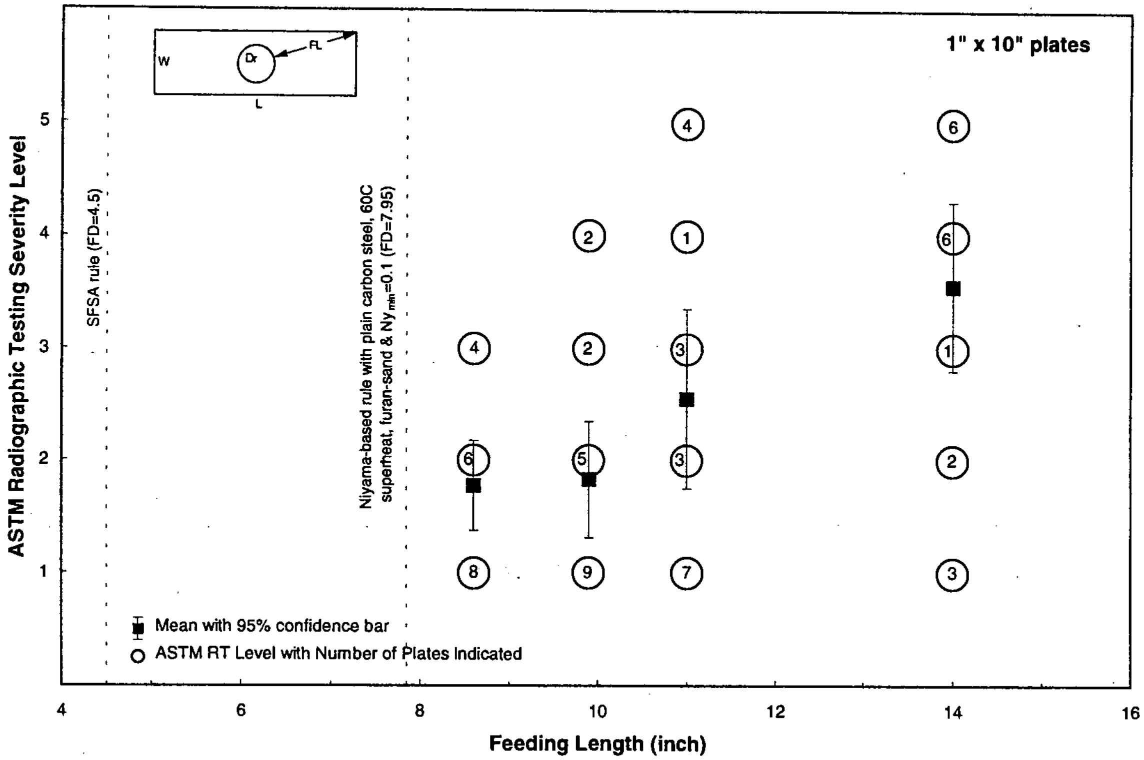


Figure 7 Casting trial results for 1" T by 10" W: Soundness versus Feeding Length

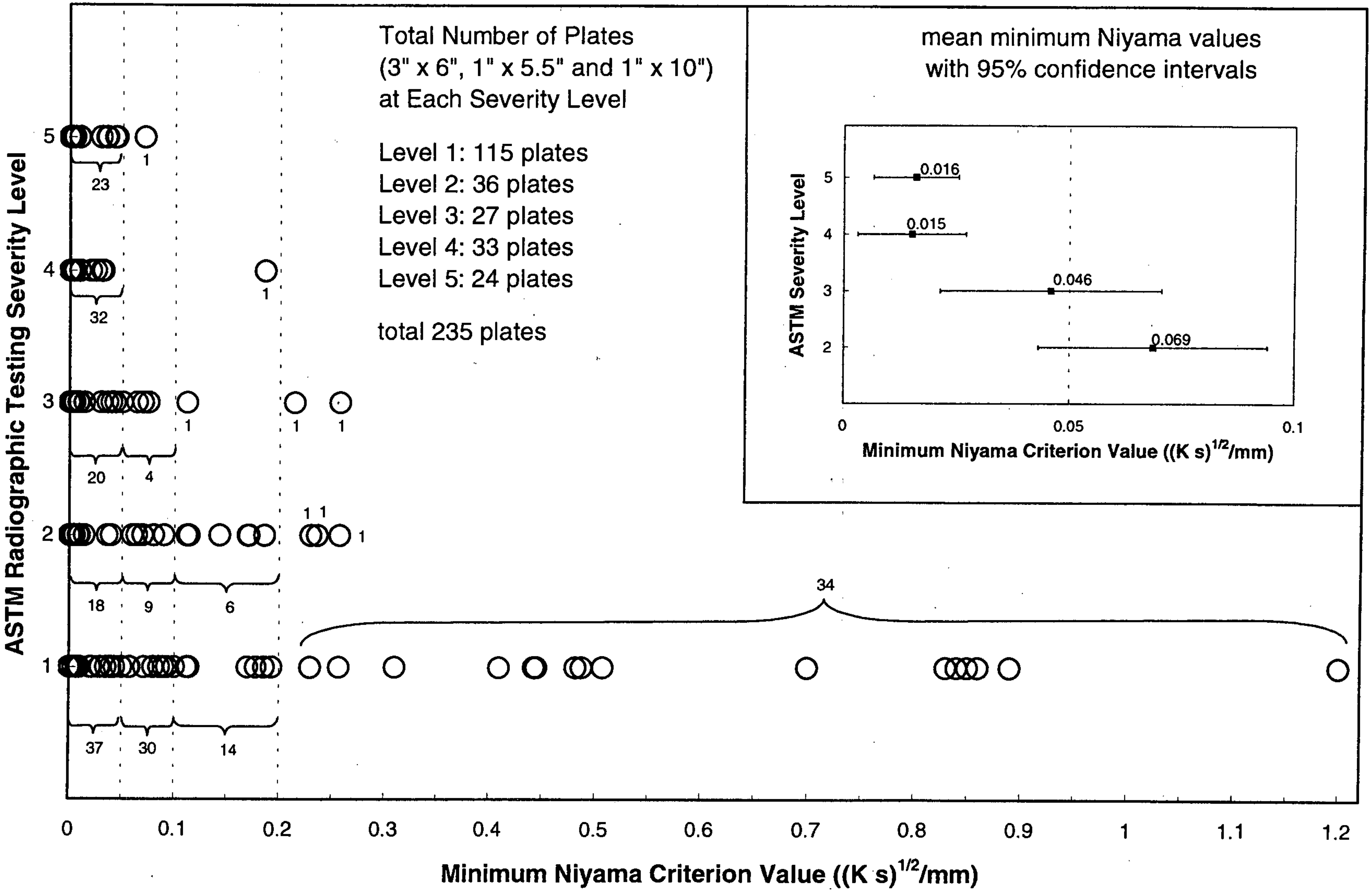


Figure 8 ASTM RT soundness level versus minimum Niyama criterion value for all horizontal low alloy plates with end-effect

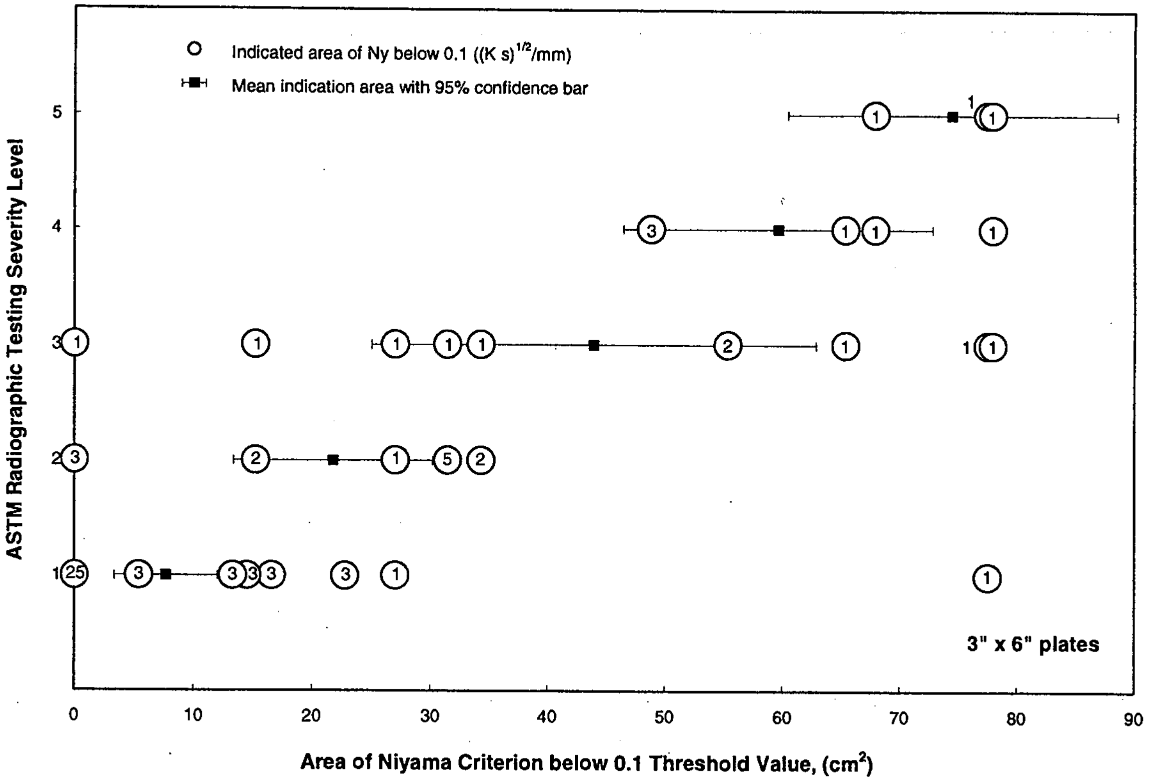


Figure 9 Casting soundness versus area of cells below Niyama criterion threshold value of 0.1 ((K s)$^{1/2}$/mm), for 3" T by 6" W low alloy horizontal plate trials with end-effect

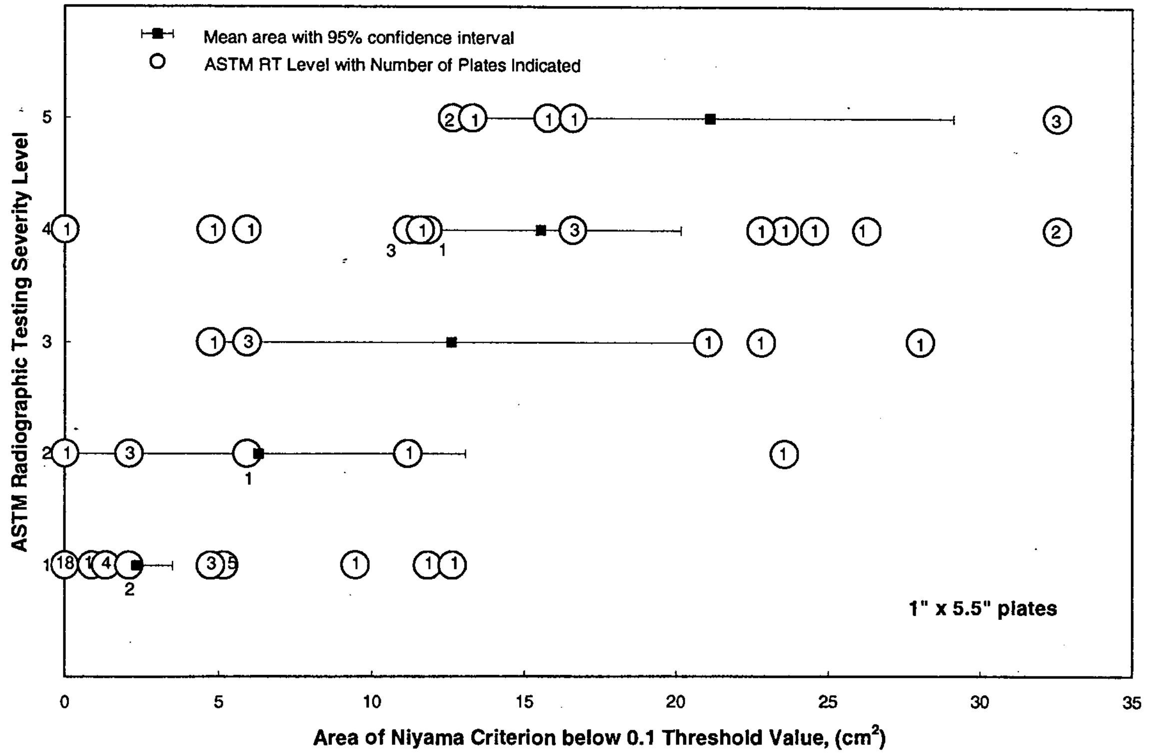


Figure 10 Casting soundness versus area of cells below Niyama criterion threshold value of 0.1, for 1" T by 5.5" W low alloy horizontal plate trials with end-effect

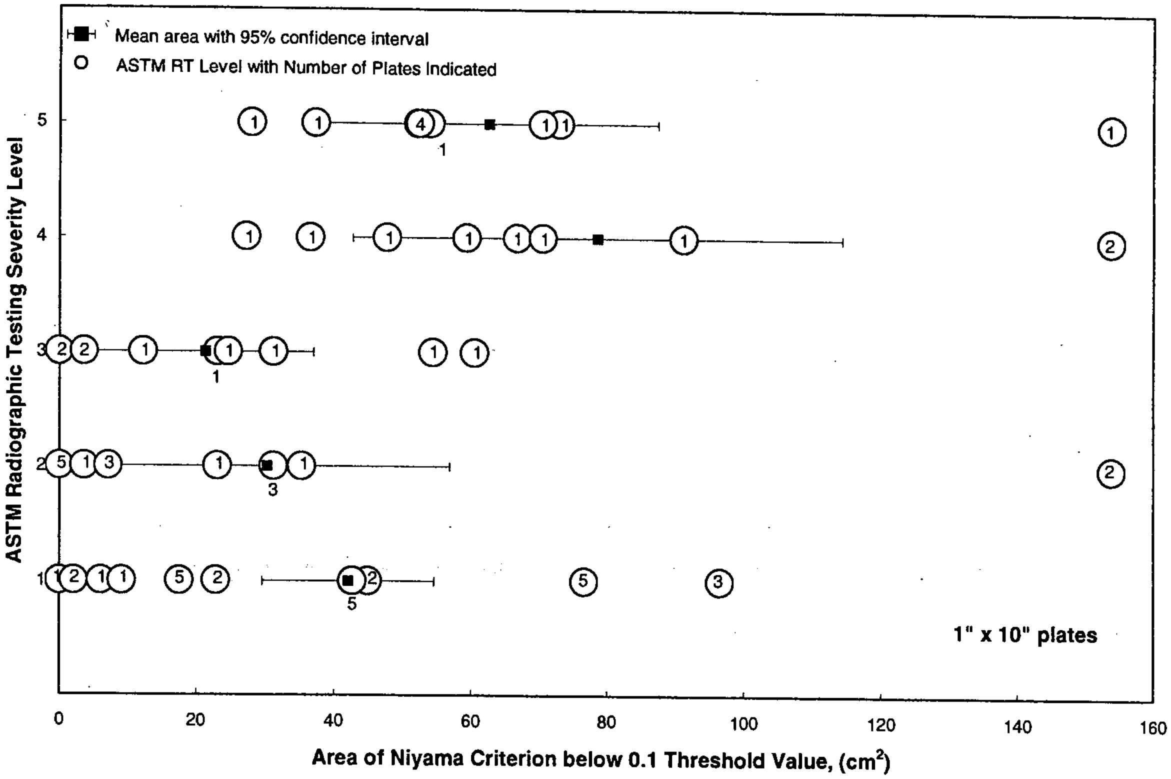


Figure 11 Casting soundness versus area of cells below Niyama criterion threshold value of 0.1, for 1" T by 10" W low alloy horizontal plate trials with end-effect

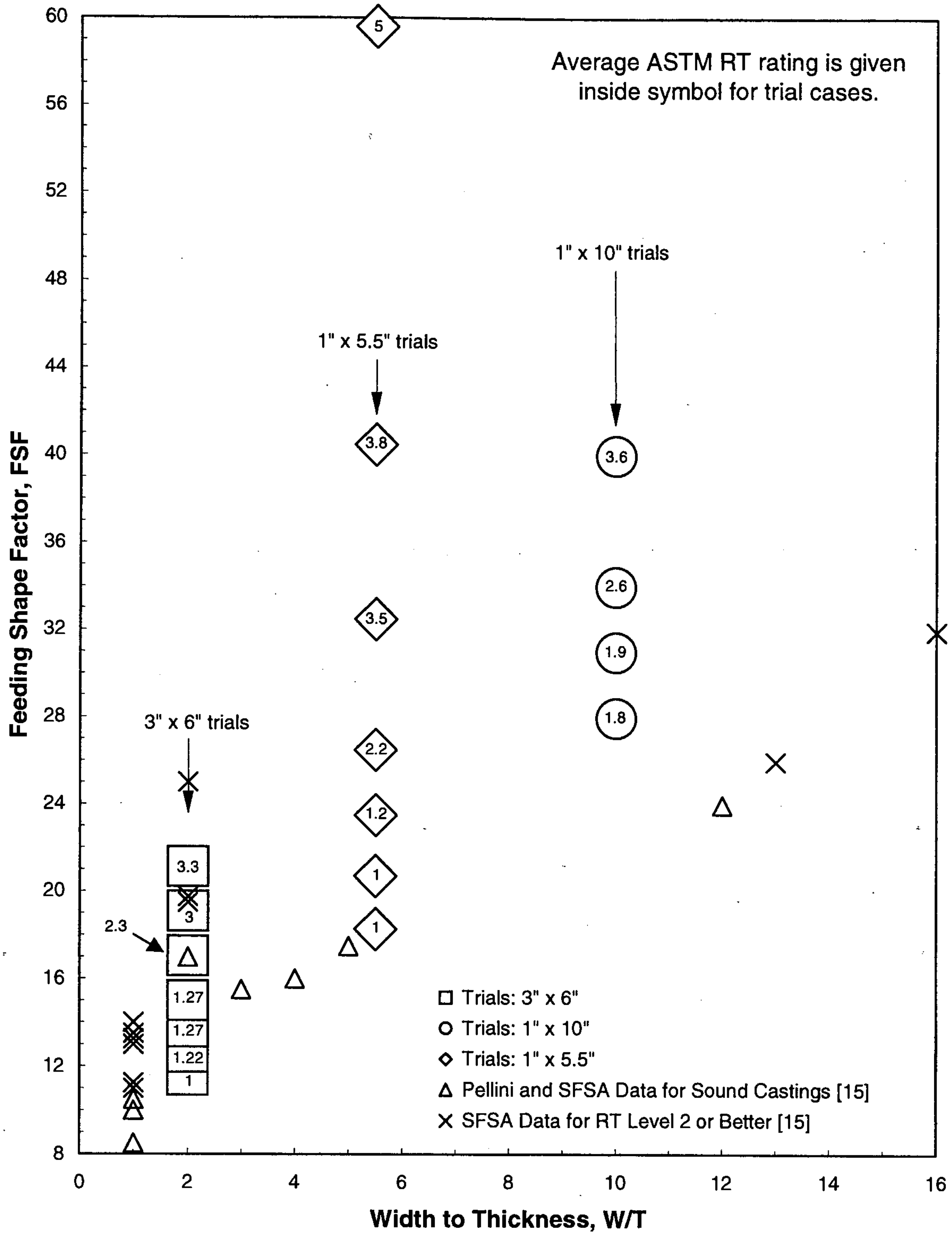


Figure 12 Comparison between previous trials [15] and present casting trials for FSF versus W/T

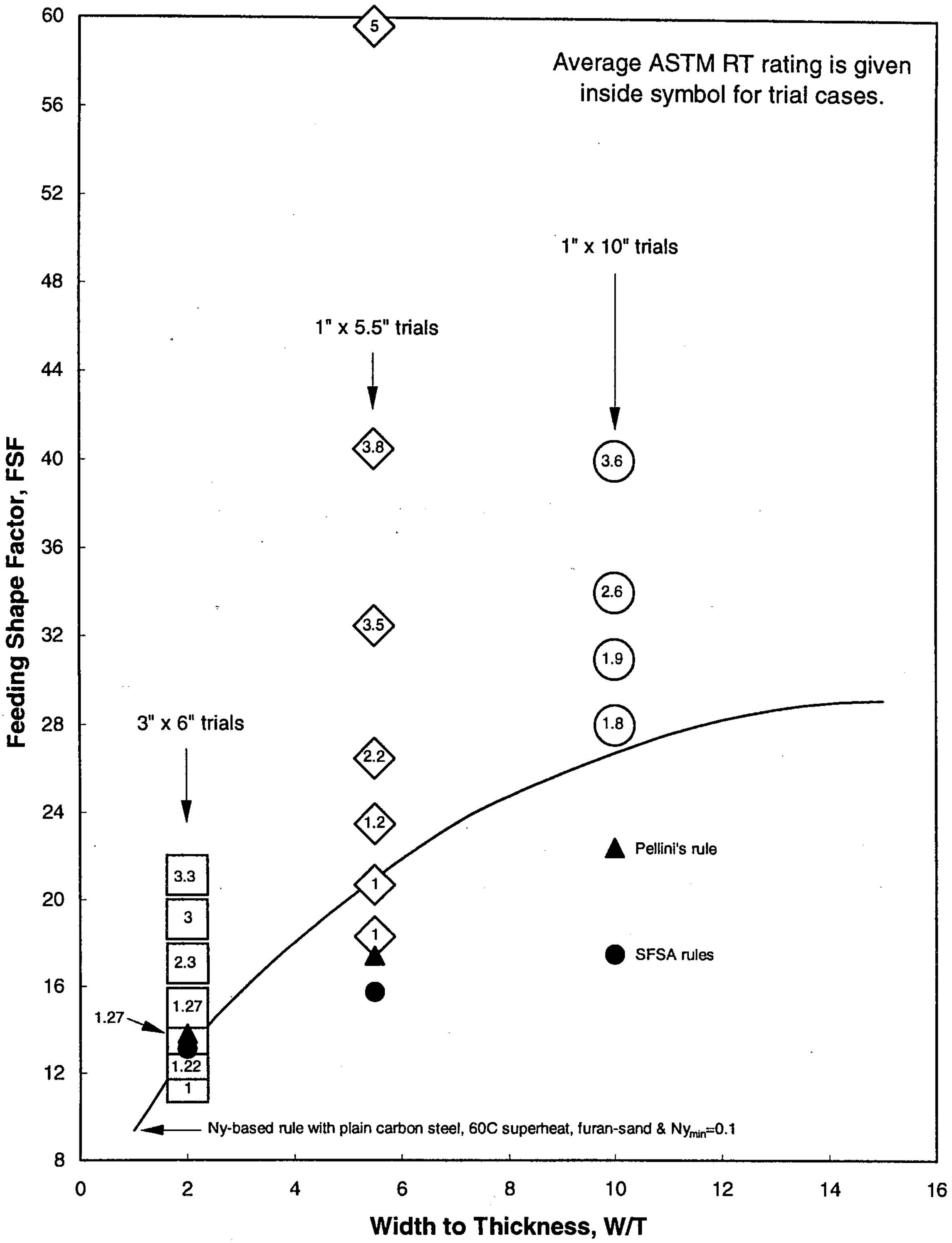
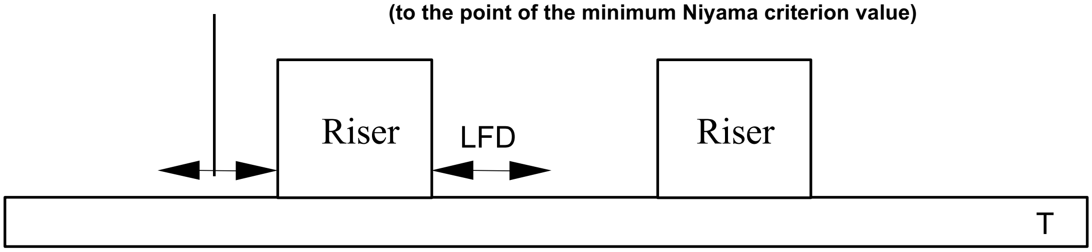


Figure 13 Comparison of FSF versus W/T for present casting trial data, new feeding rule, and feeding rules from Pellini [9,10] and SFSA [3] for end-effect

Lateral Feeding Distance (LFD) between two risers

Lateral Feeding Length = Riser Feeding Zone Length
(to the point of the minimum Niyama criterion value)



The LFD is equivalent to the longest riser zone length the riser can soundly feed between the two risers.

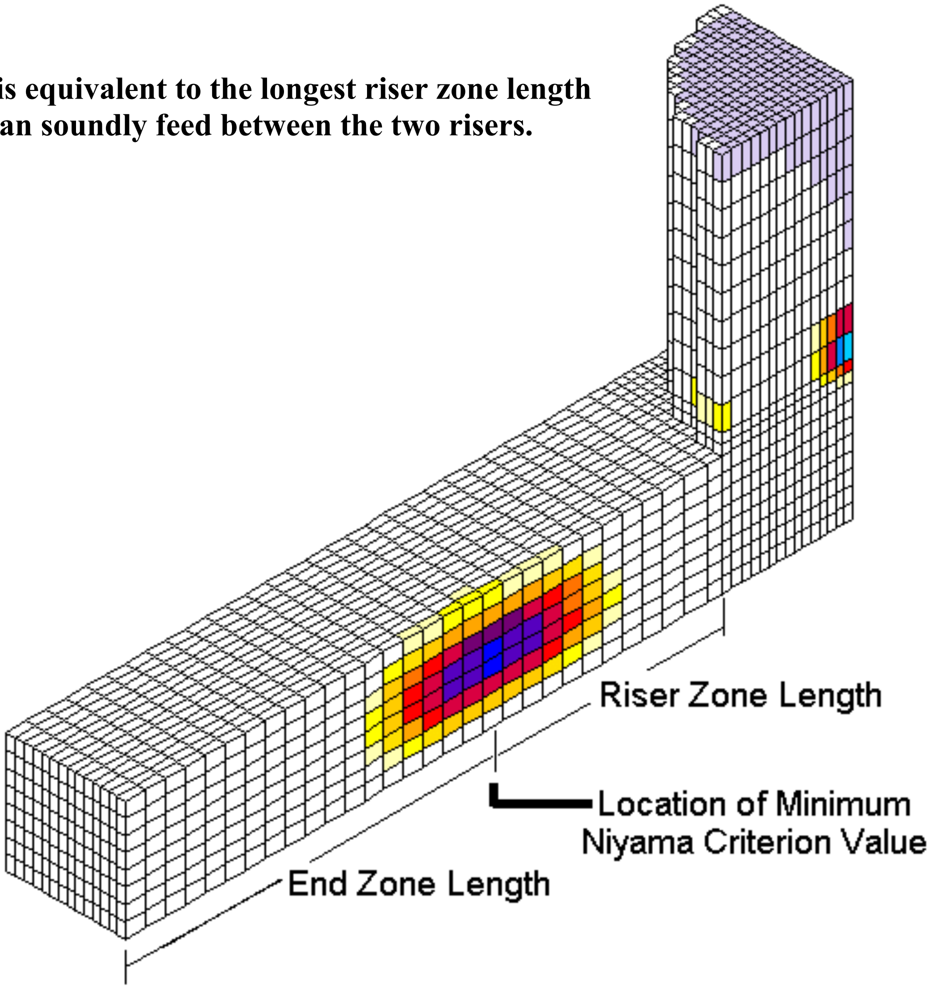


Figure 14 Diagram of the lateral feeding distance (LFD) and the riser zone length concept used to determine the LFD by the Niyama criterion

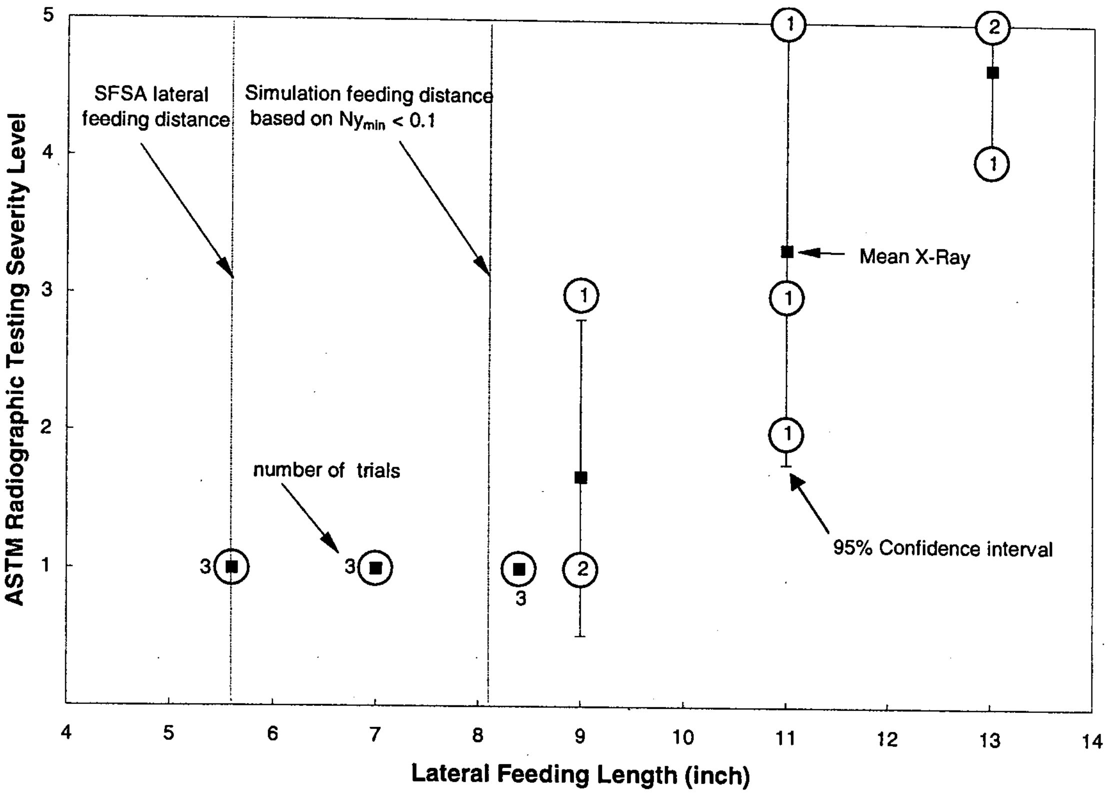


Figure 15 Casting trial results for 3" T by 6" W: Soundness versus Lateral Feeding Length

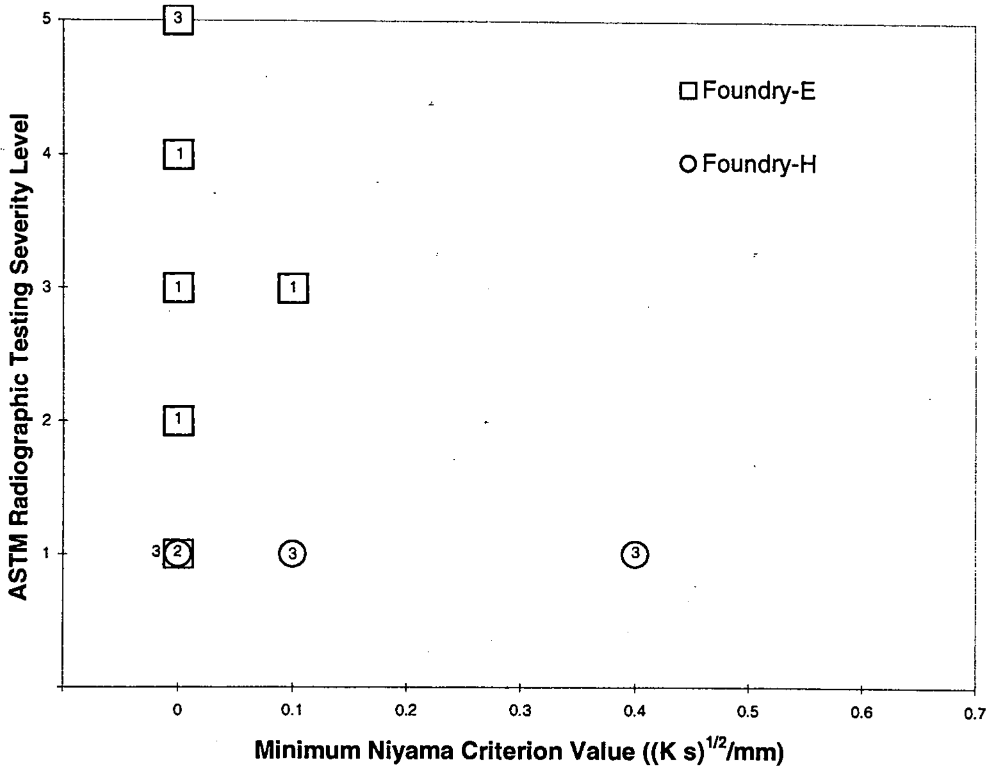


Figure 16 ASTM RT soundness level versus minimum Niyama criterion (where 0 denotes Niyama$_{min}$ < 0.1, and 0.1 denotes 0.1 < Niyama$_{min}$ < 0.2 etc.) for lateral feeding trials

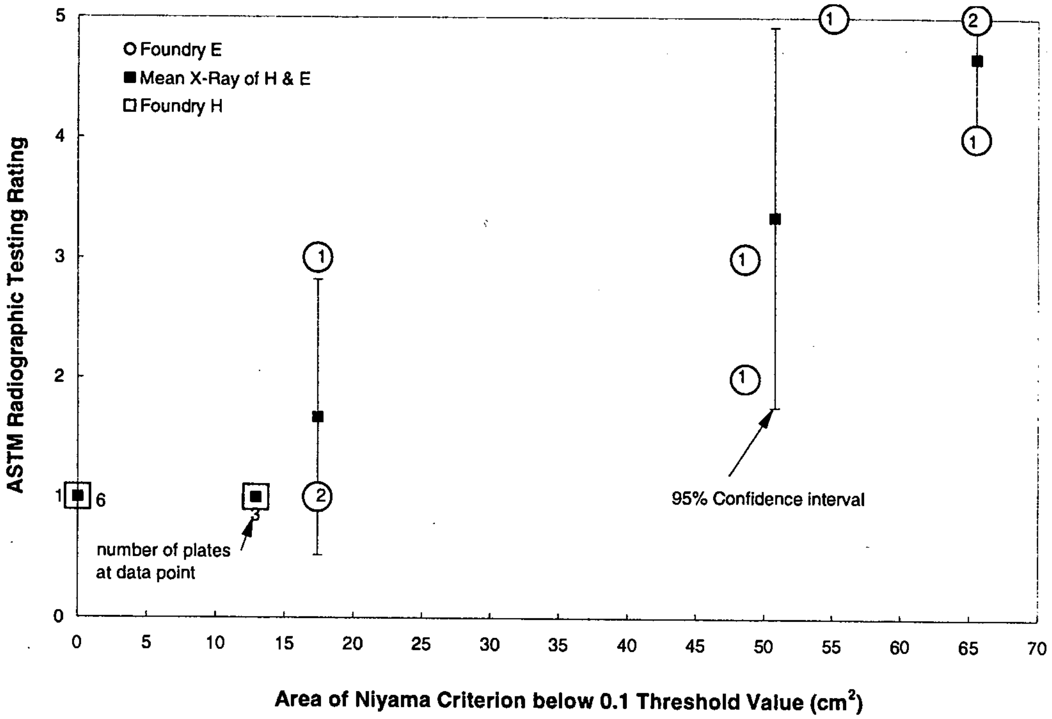


Figure 17 Casting soundness versus area of cells below Niyama criterion threshold value of 0.1 $((K\ s)^{1/2}/mm)$, for 3" T by 6" W low alloy horizontal plate trials with lateral feeding

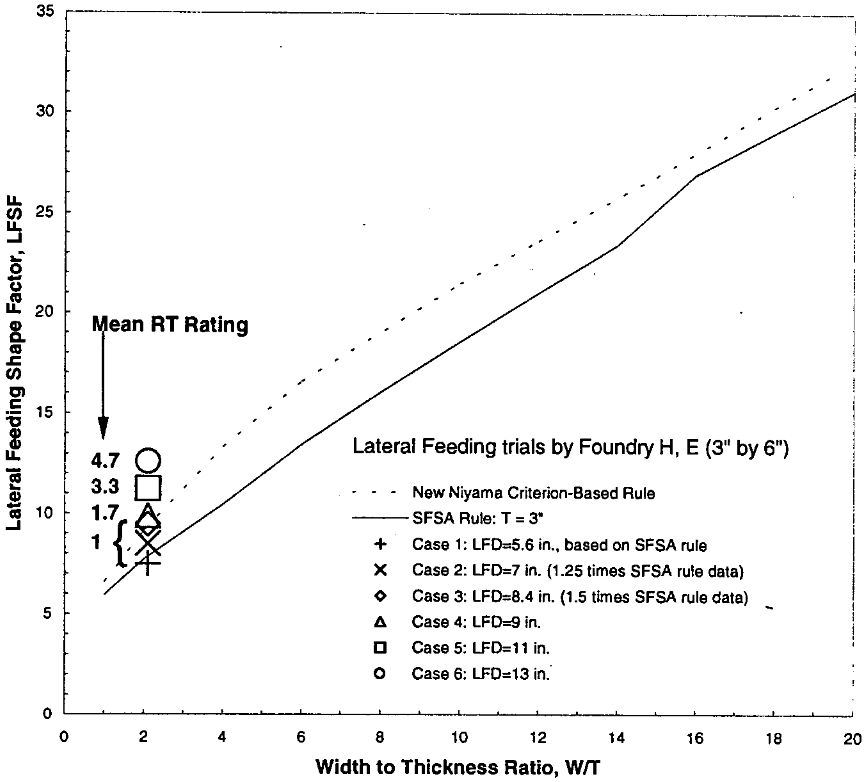
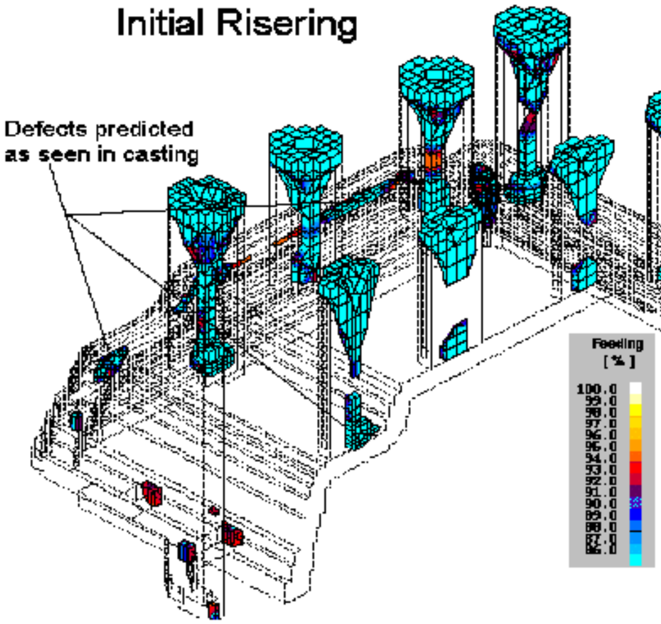


Figure 18 Comparison of FSF versus W/T for lateral casting trials, new feeding rule based on Niyama criterion and feeding rules from SFSA "Red Book"[3]

Feeding Percentage



Niyama Criterion Viewed from Below Casting

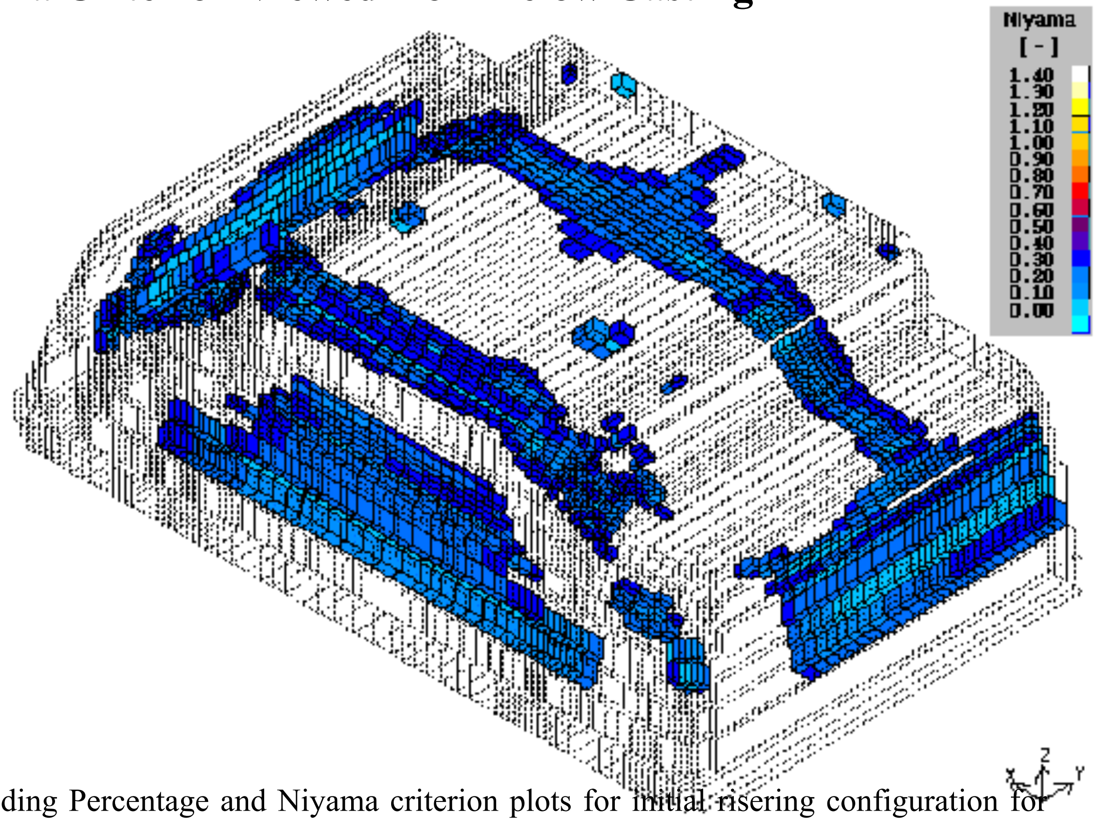


Figure 19 Feeding Percentage and Niyama criterion plots for initial risering configuration for case study of lateral feeding rules

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