Pressurized Riser Casting Trials

Richard Hardin[1], Tim Hays[2], and Christoph Beckermann[1]

[1]Department of Mechanical Engineering,
University of Iowa, Iowa City, IA

[2] Harrison Steel Castings Company, Attica, IN

ABSTRACT

The application of higher than atmospheric pressure to the risers of steel castings has been reported in the foundry literature going back at least to the 1940's. In these reports, the application of pressure to risers resulted in increased feeding distances, increased casting yield, and improved casting soundness. Despite these encouraging reports, the technique never became a practical tool in steel foundries. A series of three casting trials were performed comparing 3" thick by 6" wide plate castings produced with and without riser pressurization. In each trial a slightly different technique or schedule was used to apply the pressure. Computer simulations were performed to assist in both the design of the trials and the analysis of the trial results. The results of the trials showed that a system capable of applying pressure to the riser could be developed from materials which many foundries already have at hand. Two systems, one with and one without a pressure cap, were developed for applying the pressure. Both were able to sustain a good degree of pressure tightness. When a pressure cap is not used, it is critical that the pressure delivery tube protrudes deep enough into the riser so that a pressure tight seal is formed between the tube and steel shell of the riser, and so that pressure is applied to the liquid in the riser. The application of pressure was found to give a noticeable improvement in casting soundness. The most dramatic improvement in casting soundness was found in the results of the third casting trial where the longest plates were cast. Since riser pressurization should result in longer riser feeding zone lengths, it is not surprising that one of the pressurized plates was produced having a riser feeding zone length over 4 times longer than that found for the non-pressurized risers.

1. INTRODUCTION

It is well known that the application of increased force on liquid feed metal during solidification assists feeding and reduces porosity in castings. The force on the liquid feed metal can be increased using centrifugal acceleration or by pressure, as in the case of squeeze casting, for example. There is substantial evidence in the literature that relatively low pressures can provide great improvements in feeding distances. Yet, it is an open question as to how much additional pressure is necessary to improve feeding and casting soundness, and to what degree and under what circumstances can feeding and soundness be improved.

This paper reports on recent efforts by the authors and Harrison Steel Castings Company to apply pressure to the liquid steel in a riser to demonstrate that a pressurized riser is able to feed a greater distance than a riser operating under normal atmospheric pressure. The primary goals of these trials were to begin to answer these questions, and to determine a simple, safe and reliable method which could be used to apply pressure to risers to enhance their feeding. In the case of applying pressure to blind risers, it may allow them to operate much more effectively and predictably throughout the solidification process. In addition to improved casting soundness, increased feeding distances will results in casting yield improvement by decreasing the number of risers. Additional benefits will include reduced cleaning room costs from a reduced number of risers and sounder castings requiring less rework.

Several configurations were tested to apply the pressure in these casting trials. All of the trials were cast at the Harrison Steel Casting Company. The trials tested the methods' capabilities to maintain pressure tightness and to deliver the desired force on the surface of the liquid steel in the riser. It was hoped that the following questions could be addressed: when has sufficiently strong metal skin formed at the casting surface so that pressure may be applied without rupturing the casting or mold penetration, and what is the maximum solid fraction through which the liquid can be forced along the centerline of a casting section. Substantial guidance in planning the trials was taken from reports in the casting literature addressing riser pressurization dating back to the 1940's.

2. OVERVIEW OF PREVIOUS WORK

Literature has been found describing techniques for riser pressurization in steel casting going back as far as 1945 [1]. Jazwinski and Finch [1] reported using gas producing cartridges in blind risers to improve their feeding capability. Their pressure releasing cartridge was placed in the riser before filling, and it was designed to release the pressure quickly after a time delay that was sufficient for a shell to form around the riser. They also reported that an increase in casting yield would result because of the shorter, flat-bottomed, shrinkage cavity observed in the pressurized risers. Their finding was that pressurized risers would not have to be as tall as conventional atmospheric risers, and the riser size could be reduced. However, their method suffered from its lack of control, and the method never gained acceptance. These results [1] were so encouraging that Taylor [2] performed an extensive series of blind riser pressurization trials.

Taylor [2] used a tank of nitrogen as a pressure source and an L-shaped tube that protruded into the riser mold cavity to deliver the pressure as shown in Figure 1. He packed dry sand into the end of the tube to avoid metal flowing into the tube. By using this pressurization

method he was able to control the critical variables of riser pressurization: the amount, time of application, and "sequences of the varying amounts of pressure with time" [2]. We term this last variable the "pressure schedule". The range of pressures applied was 3 to 135 psig, the starting times of application were 30 s to 2.5 minutes after pouring. Taylor attempted seven blind riser trial configuration, which he cast without and with varying degrees of pressure and pressure application schedules. The castings studied were fairly small, 1" plates, 3.5" bars, 4" cubes and bars, and 6" by 10" castings. His findings were disappointing and discouraged the use of the technique. His main conclusions were:

- he found no dependable improvement in casting quality or casting yield

- application of pressures 3 to 50 psig were more beneficial than higher pressures in the isolated cases where there was success

- the rate and schedule of pressure application was critical to prevent the casting from being enlarged, mold penetration, and forcing metal out of the gating system

- pressure capsules will not work due to the critical nature of the pressure schedule

- he believed the flat-bottomed shrinkage pipes resulting from the pressure would not offer any yield improvement

- the effect of temperature gradients are of the utmost importance in making sound castings with or without the application of high pressures (i.e. you can feed a hot spot with the pressurized riser technique)

- he found mold penetration to be especially troublesome when using green sand molds with pressure.

Despite reporting the shortcomings of using pressurized riser in [2], Taylor participated in another study several years later attempting commercial application of the technique [3]. Taylor and Briggs [3] applied controlled pressure and the gas cartridge method again with disappointing results. Again, one problem might have been that they were attempting the technique on relatively small castings. Taylor's effort to study the technique again is an indication that there was considerable interest and were also reports of success with riser pressurization at the time.

Reports of success with the technique were coming primarily from the former Soviet Union, but there were also Western European foundries that reported using the technique successfully. Russian work on pressurized risers is presented by Kononow [4] and Desnizki [5]. They describe application of the riser pressurization technique to large castings using compressed air. Table I, taken from Kononow (1955, [4]), presents a comparison of casting yields obtained with and without using pressurized risers. Yields as high as 89% are reported with riser pressurization. A schematic diagram of the method used to apply pressure to the riser is shown in Figure 2. Compressed air was applied to the riser through a steel tube into which another tube made of molding sand, or chamotte refractory material, containing small 3 mm diameter channels was inserted. The ends of the channels were covered with a thin layer of slurry to prevent the channels from filling with steel and freezing closed during mold filling. The riser was molded in a sand with a low gas permeability. Kononow says the riser could be

3

pressurized by up to 5 atmospheres after a sufficient time elapses to form a solid skin. At first a low pressure was applied, and the pressure was increased with the progress of solidification as the solidified skin could support higher pressures. The pressurization schedule was varied depending on riser size and section thickness. Casting yield is said to be increased from the decrease in the height of the risers and number of risers required. It is mentioned that castings with a 9 inch section might be fed up to 11 feet by this technique. Using the old "rule of thumb", 4.5 times thickness, the feeding distance is about 3.5 feet. Castings were said to be appreciably more sound with riser pressurization. It was also stated that the method is only successful if the solidification progresses towards the risers, and that it cannot be used to feed hot-spots soundly ("a thick section fed through a thin one").

An experiment using pressurized riser feeding for a 3 m long plated is described by Desnizki [5] as shown in Figure 3. The plate cast was approximately 2.5" thick x 15" wide and about 10 ft long. Note that the plate was tilted with the riser feeding "uphill", and a thick section was added 0.3 m from the end of the plate. A chill was placed on the thick section. Cr-Mo steel was used, and the pouring time for the plate shown in Figure 3 was 30 seconds. Desnizki gives the pressurization schedule as 0.2 atm (2.94 psig) after 4 minutes, and then increased by 0.2 atm every two minutes until a maximum pressure of 5 atm (73.5 psig) is reached. This would mean the maximum pressure was reached at 52 minutes after the pour; this is shown in Figure 4. The pressure was maintained for 1.5 hours. Shrinkage was found in the thick section showing again that pressurized risers cannot feed hot spots. Sections A-6 and B-6 were found to be sound, which might be due to the end effect rather than the pressurized feeding. The author claims this to be evidence of the method working, but the stronger evidence of this is that the plate appeared sound up to the thick section. No abnormal increase in oxidation or inclusions was found in test specimens cut from the plate.

After considering the Russian literature [4,5], one is justified in viewing the claims of higher casting yield with skepticism. It is not known how much the riser height can be reduced through riser pressurization, and neither is it known by how much the feeding distance can be increased. Yet, both must play a role if the increase in yield is so great. Criticism of these claims of higher yield begins with the fact that the thermal requirements of the riser will remain the same, regardless of the pressure assistance. Therefore if the yield is increased, one is left supposing that it must be from reducing the number of risers required by substantially increasing the feeding distance. From description of the technique and these considerations, it may be that the technique will find application in castings requiring numerous risers and in lateral feeding applications where the feeding distances are shorter.

Another method for riser pressurization was used at a foundry in Europe (Cie Carels, Ghent, Belgium) as outlined in [6] and as shown in Figure 5. Note the use of a vent, and observe that the compressed air pressure is applied both to the top of the liquid steel through the cover and also down into the riser itself through a tube. The sealing of the riser is said to be improved by using a grey iron cover on the riser top, and an exothermic sleeve is used to increase the riser's thermal modulus and further improve yield. The pressurization tube was made from a moldable exothermic material with metal rods used to reinforce its strength. Casting yield as high as 85% on iron and steel castings up to 10 tons were achieved, and 2 atm of pressure could be applied within 30 seconds of filling the mold. This process was said to be under European and British patent rights at the time, and it is not known whether a patent was ever applied for in the United States. This method improves the riser performance in both the thermal and the feeding requirements, and is a concept in optimized riser efficiency since it

minimizes both the size and number of risers a casting would require.

Berry et al. [7-9] have applied the technique to aluminum casting risers with demonstrated success in reducing and eliminating interdendritic shrinkage porosity. Berry and Watmough [7] demonstrate how pressurization may be applied using a plaster-of-paris cap as shown in Figure 6. Other applications that they cite for aluminum castings use steel caps to retain the pressure. They chose two castings for their experiments, 2 inch square bars 14 inches long and 4 inch square bars 26 inches long. Both castings will have shrinkage porosity if produced without the pressure technique. They found that a delay in the application of pressure was necessary to prevent metal penetration into the mold; a 30 second and 2 minute delay should be used for the 2 inch and 4 inch bar, respectively. Also, a colloidal silica mold wash was applied to assist with preventing metal penetration. By using pressures of 10 or 20 psig, they found that significantly less porosity developed, and there were substantial differences in riser pipes between the castings produced with and without pressure. In a more recent study, Shenefelt et al. [8], present some preliminary evidence that a pressure of 52 psig could reduce the porosity content from 1.5% (in non-pressurized castings) to 0.5% in pressurized castings. It was noted in [8] that the porosity shape of the porosity in the non-pressurized castings was irregular and appeared to be shrinkage driven. Whereas the pressurized castings contained primarily spherical gas porosity, having smaller sized pores than the non-pressurized castings. In [9], Berry and Taylor present a theoretical background to the principles behind riser pressurization including a derivation of the beneficial effect of pressure on the liquid feed metal based on the Niyama Criterion. This derivation shows that the Niyama Criterion value associated with a porosity level formed under atmospheric pressure feeding might be shifted lower by a factor of 1.5 if the local pressure applied were increased to 15 psig.

If there is skepticism that riser pressurization is not a practical technique for increasing riser effectiveness, the reader should consider the development and application of the technique for ductile iron castings in an industrial setting [10]. Aagaard et al. [10] describe a process developed over a period of about 5 years at Georg Fischer Disa A/S in Denmark as shown in Figure 7. Through industrial trials and MAGMAsoft simulations a process was developed for applying pressure using compressed air to blind risers in vertically parted green sand molds. The system is able to operate on up to 1/2 meter of metal head. Here the goal is not only to increase feeding distances, but to allow the placement of risers anywhere on the casting. The additional pressure can allow them to feed over a larger vertical distance than atmospheric risers. One example application of this technique is shown in Figure 8, for a disc casting produced using a pressurized riser. For this casting Aagaard et al. (2000) applied pressure of 0.15 bar (about 2.2 psig) after 30 seconds from filling which was maintained for 5 minutes.

Based on the literature surveyed, the advantages and disadvantages of using riser pressurization are summarized below.

Advantages and Reasons to Develop and Study Pressure Assisted Feeding:
- Improved yield from increased feeding distance and reduced number of risers, yield increase of 30% often reported
- Reduced cleaning room time and cost can result
- Castings can be appreciably more sound, increased performance
- Required equipment is relatively inexpensive, in some cases already in-house
- Offers a solution for difficult "tall" castings with large vertical dimensions that

gravity driven risers cannot adequately feed
- Trials will also provide data on physical mechanisms of feeding and the effect of pressure on feeding.

Disadvantages and Problem Areas of Pressure to Assisted Feeding:
- Cannot assist in feeding a thick section through a thin one
- If a leak forms in the riser pressurization system, the gas/air might act as a cooling agent in the riser, the riser must be properly sealed
- Successful application of pressurization depends upon: rate of pressure increase and pressurization schedule, size and shape of casting, position of risers, gating system, rate of mold filling
- Taylor's 1961 SFSA report [2] says centerline shrink cannot be eliminated, and that the method is not dependable
- Technique is probably not 100% reliable when used without experience and/or simulation to design the correct pressurization schedule, but its use in production [10] indicates difficulties in application can be overcome.

3. CASTING TRIAL BACKGROUND AND PREPARATION

The metallostatic pressure resulting from riser head height is given in Figure 9. A pressure of 1 atmosphere is about 14.7 psi, which is equivalent to about 53 inches of liquid steel head, assuming a density of 7010 kg/m^3 in Figure 9. Each additional 1 psig of pressure applied to a riser would be equivalent to an additional 4 inches of riser head height. With the additional pressure applied to the riser and casting, it should be kept in mind that if the gating system is still open and liquid enough, each additional 1 psig on the riser will push the metal about 4 inches higher, resulting in an over flow if it is not contained. Therefore, one of the first considerations in designing the pressurized riser trials would be to determine if additional gating system height would be used to accommodate a small amount of pressure applied early in the process (as used in [7] and [10]), or if a time delay would allowed to elapse for the gating system to solidify sufficiently. The trials performed here in this use a time delay approach, and the gating is allowed to solidify sufficiently before sustained pressure is applied. The plate geometry chosen for these trials was a 3" T x 6" W section. According to the current SFSA feeding distance rules the feeding distance for this section is 14.4". This section was chosen since previously performed casting trials for feeding rule development had produced numerous plate lengths for comparison. The alloy poured was equivalent to a AISI 1030 steel.

The method for riser pressure delivery and containment for the trials needed to be determined. Given the variety of methods used previously, there is apparently more than one way to accomplish this.   Unfortunately the literature does not provide all the details and possible pitfalls of the various methods. For the first trials, rather than rely on the solidified skin of the riser to contain the pressure (as was used in [2], [4] and [10]), in the interest of safety it was decided that a riser cap would first be used. This approach was used in [7]. One advantage of this pressure containment system is that it could be pressured tested before the casting trial was poured to confirm its integrity. Based on the results of the first trials, it was decided that a pressure cap was not necessary, either for safety reasons or for the success of the technique, and subsequent trials did not use a cap. When a cap is not used, it is critical that a good pressure-tight seal is formed at the interface between the pressurization tube and the riser metal, since the metal shell of the riser is relied upon for pressure containment.

6

The method of pressure delivery to the riser was studied. It was decided that the tube would protrude into the riser about 2" to deliver the pressure to the liquid metal. There was a fear that a steel tube might melt, burn off or allow the gas line to get too hot. There are reports in the literature of steel tubes being used, but here we took guidance from those that used pressure delivery tubes made from fireclay refractories and mold material. It was decided to use a fused silica tube, based on the experience that Harrison Steel Castings Company has using this material. The fused silica tube used was a "Fusil" tube obtained from Industrial Ceramic Products Inc. (ICP), 3/4" ID and 1 3/8" OD.

The pressurization schedule was determined based on MAGMAsoft simulations depicted in Figure 10. These were used to indicate when a sufficient shell thickness had formed and when the gating system was adequately solidified, and also how much time could elapse before the pressure tube might freeze off. It was determined that a small initial pressure should be applied to clear the tube, and activate the pressure system. Guidance as to the critical maximum solid fraction for pressure assisted feeding was taken from MAGMAsoft simulations of the experiments presented in the literature [5], as was shown in Figure 11. If the trials were successful as reported in [5], the simulation Niyama Criterions results that are shown in Figure 11 A) indicate that one would expect centerline shrink beyond the riser feeding zone up to the point of the chill when no pressure in applied. At the chill, the Feeding Percentage indications in Figure 11 B) indicate the hot spot of the thickened section at the chill would form a large region of macroshrinkage. This would form regardless of the pressure applied to the riser. If the plate was fed soundly up to the chill as reported, then the simulations indicate that the fraction solid for the cut-off of pressure feeding could be as high as 0.7 solid fraction. In reality, one would expect this value to vary with the casting conditions (pressure and alloy composition for example).

Taking 0.7 solid fraction as the maximum solid fraction through which the casting might be fed under pressure, MAGMAsoft simulations shown in Figure 12 indicate the casting should be sufficiently solid to prevent penetration through the shell at thirteen minutes from the pour. For mold penetration, this is conservative since it would be expected that the mold itself offers resistance to the metal flow. Based on these simulations in Figure 13, the centerline is still at least a solid fraction of 0.7 at 21 minutes from pouring. The results indicate a window of pressurization from 13 to 21 minutes for the casting trial geometry. The actual pressurization schedule used for each trial will be discussed in the next section of this paper.

MAGMAsoft could not be used as a tool to design the amount of pressure to be applied and the pressure schedule. The current modeling in MAGMAsoft does not model pressure assisted feeding and the physics related to it, such as: pressure driven liquid flow, nucleation and growth of gas porosity, shrinkage porosity formation and shrinkage driven flow in the mush. At the time of this writing, algorithms are being implemented in MAGMAsoft under the direction of one of the authors (CB) to give it this capability. To facilitate this implementation and to experiment with various algorithms and the fundamental physics involved, a 2-D model with these improved feeding calculations has been developed. Even though this model has yet to be validated, it still can provide useful data and guidance in the design of these casting trials. This 2-D model indicates that not much difference is seen in feeding enhancement between 1 atm and 5 atm of riser pressurization It is interesting that this was also a conclusion from the studies in the literature. Therefore, the range of riser pressurization should probably be limited to 30 psig max, and that pressures 60 psig or higher are probably not necessary.

4. DESCRIPTION OF CASTING TRIALS WITH RESULTS AND DISCUSSION

Following the trial design studies, the first of three casting trials was executed. The alloy poured for all trials was equivalent to a AISI 1030 steel.   In Table III, all casting trial plates are summarized, and are presented in the order they were cast by a plate identifier (ID). The plate ID uses a "T" followed by a number to indicate the trial number the plate is from, then number of the plate in order it was cast in the trials followed by an "X", and then, if the plate was cast using a pressurized riser, a "-P" is appended to the plate identifier for clarity in presenting the pressurized results.   So "T1-1X" is the first plate poured in trial 1, and "T1-3X-P" is the third plate cast in trial 1, and pressure was used. A description of the three trials is given below:

Trial #1: Five plates were cast. The plate geometry chosen for the first pressurized riser trials was a 3" T x 6" W section of length 31.5". A 6" diameter riser by 8" high riser was used, and the distance from the edge of the riser to the end of the plate was then about 26". The in-gate was made at the riser. A vent was used at the end of the plate opposite the riser so that the mold gases during pouring are not allowed to build up in the system. The rigging used in the first trial is shown in Figure 14.   According to the current SFSA feeding distance rules, the feeding distance is 14.4". Fifteen plates like this were cast in earlier feeding distance rule development casting trials, and the typical result from radiographic testing was ASTM Level 3. Therefore it was expected that we would see unsoundness in a non-pressurized plate. Two of these five plates were cast without pressure applied, and three were cast with pressure applied. A flow-off riser was used to sight the fill level of the riser. This was an effort to try and prevent too much metal filling the tube and the shutting off of the pressure tube that might result. A riser cap was used to contain the pressure. The material chosen for the cap was a Harbison-Walker castable ceramic (Kruzite), which contains about 75% alumina and 20% silica. Gas line from the argon tank was then press-fitted into the Fusil tube, and was sealed and fixed to the gas line using an Aremco high temperature ceramic adhesive. The Fusil tube was then integrally cast with the Kruzite cap. This assembly is shown in Figure 15. The patterns used for these first trials are shown in Figure 16.

Trial #2: A second series of plate trials followed with the plate length extended to 39" as indicated by the rigging shown in Figure 17. **No pressure cap was used. It was decided to test that the steel shell in the riser is pressure tight and safe for pressure containment by itself.** Two castings were made without pressure, and one with pressure. The in-gate was made at the riser.

Trial #3: In the third series of casting trials, four 50" long plates were cast. **No pressure cap was used.** Pressure was contained using the riser steel shell, and the seal formed between the pressurization tube and the riser metal. This trial used a gating system placed at the end of the plate opposite the riser. This was done to eliminate interference between the pressurization and pouring equipment. A drawing of the rigging is given in Figure 18 and the cope pattern is shown in Figure 19. Two non-pressurized and two pressurized castings were produced in this trial configuration at the time of writing this paper.

A discussion of the trials and results for each of the three trial configurations is presented below. All trials were conducted at Harrison Steel Castings Company, Attica, Indiana. The pressurization equipment assembled by Harrison for the trials consisted of an

argon tank, pressure regulator and pressure line.

4.1 Pressurized Riser Trial Configuration #1 Results and Discussion

A brief description of each casting poured in the first trial configuration is given below.

For the **first heat**, temperature at mid-pour is 2875 °F (1579 °C):

Casting T1-1X - poured first in series from the first heat, Kruzite sleeve used, no pressure applied, pouring time about 16 s. A violent reaction occurred when the casting was poured. Kruzite sleeve reacted violently; this Kruzite was not baked and probably contained too much water content still even though it was air-cured according to guidelines.

Casting T1-2X - poured second in series from the first heat , no sleeve used, no pressure, pouring time about 16 s.

Casting T1-3X-P - poured third in series from the first heat, Kruzite sleeve used and pressure applied, pouring time greater than 16 s. Pressurization pipe position resulted in a higher than desired metal release height and funnel cup had to be added. **Pressure schedule used** - 2 psig applied after 6 minutes, 15 psig at 13 minutes, pressure off at 20 minutes. **Observations** - Argon tank flow very noticeable, cold at regulator, some bubbling noticeable at the vent, also crack observed at top of fusil tube at press-fit to steel tube that could be cause of leak.

For the **second heat**, temperature at mid-pour is 2847 °F (1564 °C):

Casting T1-4X-P - poured fourth in series from the second heat, Kruzite sleeve used and pressure applied, pouring time about 15 s. Again, pressurization pipe position resulted in a higher than desired metal release height, funnel cup was added. **Pressure schedule used** - 15 psig at 13 minutes, pressure off at 30 minutes. **Observations** - Argon tank flow **not** noticeable, pressure appears to hold, small crack observed at top of fusil tube at press-fit to steel tube

For the **third heat**:

Casting T1-5X-P - poured fifth in series from the third heat, Kruzite sleeve and pressure used, pouring time about 10 s, a chill used at ingate so initial pressure might me applied sooner. **Pressure schedule used** - 15 psig at 10 minutes, increased pressure to 30 psig at 13 minutes pressure off at 30 minutes. **Observations** - Pouring height is less than other castings, appears to be 3" from top of overflow reservoir casting, ingate appeared to freeze off due to the chill that was added there and also the pouring was being done more slowly and carefully for this casting, argon pressure appears to hold at the start, then a gas leak forms, possibly escaping near the downsprue.

Plate T1-1X had quite a poor soundness due to a problem with Kruzite sleeve and could be considered as valid data. The results of the radiographic testing were interesting. From the standpoint of feeding distance, the non-pressurized plate T1-2X was fairly sound, and shrinkage was rated at ASTM-Radiographic testing Level 2 even though the feeding distance of

9

about 14.5 inches was exceeded by 12 inches. It was hoped that this plate would have been quite unsound for comparison, but is an indication that plates of this soundness can be cast at fairly long feeding lengths. In the pressurized casting T1-3X-P, an interesting indication on the x-ray near the vent and a hole near the contact between the casting and vent was found that was evidence of an argon leak. A section of the cavity caused by the leak is shown in Figure 20. The solid fraction was determined to be about 0.3 at the surface of the casting at the location of the leak when the 2 psig was applied at 6 minutes. This indicated the riser was pressurized, and the pressurization tube was not blocked, which was a concern. This results also serves to establish that a surface solid fraction of 0.3 or less should be avoided when applying even 2 psig pressure. Pressure appeared to be well maintained for plates T1-4X-P and T1-5X-P, and plate T1-5X-P was the most sound of the pressurized plates and had an excellent surface appearance as well. Radiographs of the most sound non-pressurized plate T1-2X and the most sound pressurized plate T1-5X-P are compared in Figure 21.There is virtually no difference in the soundness of the plates in Figure 21. Observing the x-rays closely, the soundness of the pressurized plate T1-5X-P was judged to be only slightly better than the non-pressurized T1-2X.

4.2 Pressurized Riser Trial Configuration #2 Results and Discussion

Based on the results of the first trials, it was decided that the second trial would use a plate with a longer feeding length. A 39 inch long plate was used, which exceeds the feeding distance by about 19 inches. Refer to Figure 17 for this trial plate length and rigging. One goal was to not cast any non-pressurized plates as sound as plate T1-2X. It was also decided that the next trial would not used a sleeve/cap to contain the pressure. A simpler riser pressurization system would be tested that would be easier and less costly to apply in practice. This simpler system also presents fewer opportunities for leaks to develop and possibilities for failure. Like in the first trial, a Fusil tube would be used to pressurize the riser. However, in these trials the argon line to Fusil tube connection was simplified to prevent the thermal expansion related cracks and leaks that developed in the first trials. High temperature rubber hosing clamped on the outside of the Fusil tube would be used to deliver the pressure to the riser as shown in Figure 22.

Three plates were cast in these second trials. Two plates were not pressurized (T2-1X and T2-2X) and one was pressurized (T2-3X-P). Casting T2-1X was poured at a temperature of 2873 °F. The mold took 12 seconds to fill. Castings T2-2X and T2-3X-P were poured at a temperature of 2870 °F. Casting T2-2X took 13.2 seconds to pour, while casting T2-3X-P took 16 seconds. A pressure of 1 to 2 psig was applied to casting T2-3X-P approximately 90 seconds after pouring. At the start of pressurization the argon regulator indicated 1,130 psi on the high side in the tank.   It appeared that system held pressure fairly well.   The pressure was increased after 10 minutes to 15 psi. At which point, the pressure apparatus was blown off the Fusil tube. The clamps were immediately re-installed and tightened, and the apparatus was held at 15 psig for 10 minutes. At the 20 minutes after pouring mark, pressure was increased to 20 psig, and the apparatus again blew off the Fusil tube again. After re-attaching the coupling hose, the pressure was set and maintained at 18 psig until 30 minutes after pouring. After this 30 minutes, a drop of about 130 psi in the tank high side pressure was noted when the tank was shut off. It is believed that most of this loss came from the two times the gas line coupling slipped off the Fusil tube.

Castings T2-1X and T2-2X (non-pressurized castings) definitely had observable

10

shrinkage in the Radiographic testing x-rays, with casting T2-2X being more severe. The pressurized casting T2-3X-P was by far the best of the three castings in the trial, and the radiographer rated it as ASTM Class 1. The x-rays from plates T2-2X and T2-3X-P are shown in Figure 23, and the pressurized plate T2-3X-P is more sound, although this is difficult to see in the x-rays reproduced here. In Figure 23, the brightness and contrast of areas with indications were adjusted to try and get them to better show the x-ray indications. The result of this trial was very encouraging since a remarkably sound plate was produced at a feeding length of nearly three times the normal feeding distance. If the pressurized riser feeding is working, it should result in longer riser feeding zone lengths than for the same plates with non-pressurized risers. Here the riser zone length is defined as the distance between the outside edge of the riser and the first region of centerline shrinkage. In this trial it was found that the riser zone lengths were virtually 0" for T2-1X since a region about 4.5" long starts from the riser, and about 9.2" inches from the riser to the first indication for T2-3X-P. A somewhat larger region starts also at 15".

4.3 Pressurized Riser Trial Configuration #3 Results and Discussion

The third trial configuration was a 50" long plate gated at its far end (away from riser) as shown in Figure 18. It should be noted that this plate does not have the proper "end effect" due to the gating. A hot spot is located in the end region of the plate similar to Desnizki's trial ([5], shown in Figure 3). It would not be expected that this hot spot could be fed. The lack of a good end-effect, combined with the very long feeding length (about 44"), makes this trial configuration a good test of the technique, and provides a good basis for comparison of pressurized versus non-pressurized risers. Here the feeding distance is exceeded by about 29.5 inches, or the feeding distance is 3 times the SFSA rule feeding distance of 14.5".

As in the second trials, a pressure cap was not used. Four plates were cast, and two of these were   pressurized (plates T3-2X-P and T3-4X-P). On the riser of one of the non-pressurized plates (T3-3X) an exothermic sleeve was used to increase the riser thermal modulus and demonstrate that shrinkage in the non-pressurized plates was not due to secondary riser shrinkage. In the pressurized plates, the end of the fusil tube was positioned to protrude about 1/8" distance into the top of the riser. Also, a graphite wash was used on the end of the tube to help prevent metal freezing and blocking the end of the tube. Plates T3-1X and T3-2X-P were cast in one heat, and T3-3X and T3-4X-P in another heat some days later.

4.3.1 Plates T3-1X and T3-2X-P:

The pressurization schedule used on plate T3-2X is shown in Figure 24, and a table of events and observations made during casting of this plate is given in Table III. The casting process of this plate is presented in more detail because it was the most successful demonstration of the technique presented here. The pour temperature taken following the first two test plates was 2863 degrees F. Casting T3-1X was poured in 9 s, and casting T3-2X was poured in 11 s. For the pressurized casting T3-2X, the starting argon tank pressure was 1000 psi. As outlined in Table III, an initial pressure of 2 psig was briefly applied to the system 41 s after pouring. The rise of metal from the gating system at the far end of the casting confirmed that the Fusil tube was clear of metal and confirmed that the pressurization system was operating.   At 1 min 43 s the 2 psig was again applied, and since no observable flow was observed it was maintained. The riser cross sections of castings T3-1X and T3-2X are shown in Figure 25. Here note the unique features of the pressurized riser section. In particular note

the region at the top of the casting formed after the initial pressure application, and then observe longer vertical sides of the riser indicating a relatively fast metal loss from the riser. Based on the thickness on the riser shell observed here (in Figure 25) and simulations, this long vertical drop in the riser metal height must have occurred at the 2 psig pressure application at 1:43. Since good pressure tightness was observed this quick metal loss must have pushed the liquid metal into the gating system, since not ruptures of the casting were found. The rest of the pressure schedule and observations can be found in Figure 24 and Table III.

The riser cross sections in Figure 25 show risers from the pressurized casting T3-2X-P, and the non-pressurized riser for plate T3-1X. The pressurized riser appears to have three distinct zones: the small top region about 0.5" in height, which appears to be about 1.5" long below it (where the quick loss of metal discussed above occurred), and the lower region which is most of the riser. This lowest region of the shrinkage pipe has a much wider throat (or bore, or diameter) than the non-pressurized riser and is good evidence of the pressure applied.

Four Radiographic testing x-rays were made for each casting for trial 3, covering the entire casting length. These are shown in Figure 26 for T3-1X and T3-2X-P. Note the end region in both castings which shows shrinkage and is unaffected by the pressurization as expected. The non-pressurized T3-1X casting has severe centerline shrinkage starting from the riser (with what appears to be secondary shrinkage) and extending to a distance of about 25.3" from the riser. Over the same region the pressurized casting has only a few slight indications that were determined to be Class 1. Riser pressurization has resulted in a riser feeding zone length (sound length from riser edge) of 29" long, at Class 1 soundness. Considering the approximate rule for riser feeding zone length (2 times plate thickness, or 6"), riser pressurization extends the riser feeding zone by nearly a factor of 5. Figure 27 is provided to show a more detailed comparison of the pressurized and non-pressurized Radiographic testing results near the end of the plate, and Figure 28 shows the more detailed comparison near the riser.

4.3.2 Plates T3-3X and T3-4X-P:

The second set of plates cast for trial configuration #3 were cast using an exothermic sleeve on the non-pressurized riser (plate T3-3X) and a different riser pressurization schedule for the pressurized plate (plate T3-4X-P) . A very small initial pressure was applied briefly at the start to confirm the pressurization was active on the casting, as was done with plate T3-2X. Pressurization was applied at 10 minutes using 15 psig. However, because the pressurized casting was poured approximately one half inch below the top of the riser in an effort to prevent the tube from filling with metal, a good pressure tight seal between the Fusil tube and the riser steel shell did not form. This seal between the steel and the pressure tube is critical to the success of the technique. Pressurization on T3-4X started with a full tank of argon (2,400 psi) and by the end of the process 1,750 psi of argon was used. It is believed that this substantial flow of argon served to chill the riser, and reduced both the effectiveness of the pressure and the thermal modulus of the riser. This experience demonstrates the importance of containing the argon with a good metal seal around the tube, and that the riser should be either filled completely or the tube should be submerged into the riser cavity in order to pressurize the top of the liquid metal. The tops of risers from these two castings are shown in Figure 28. The effect of pressurization can be seen where the pressure deforms and tears the top of the riser in casting T3-4X.

The non-pressurized plate with the exothermic sleeve (T3-3X) was slightly more sound that the non-pressurized plate without a sleeve (T3-1X). The soundness of plates T3-3X and T3-4X-P from the riser to the plate mid-length can be compared in Figure 30, and in Figure 31 the whole plate lengths can be compared. The pressurized plate T3-4X-P is more more than T3-3X from the riser to about 16.3" from the riser. Plate T3-4X-P is not as sound as the pressurized plate produced in T3-2X-P. This probably is due to the undesired flow of argon chilling the riser top. Also, once a sufficient skin formed on the riser top, it is believed the pressure was no longer effectively applied to the liquid metal in the riser. Nevertheless, it is still interesting to see the effects of a short pour, and the pressure did have a noticeable effect on casting soundness over first 16.3" from the riser   In plate T3-3X, there is a slight indication close to the riser edge, and a long region of shrink extending from 4" to about 33" from the riser edge, as can be seen in Figure 31 where x-rays for the entire plate lengths are compared.

4. CONCLUSIONS AND RECOMMENDATIONS

It has been shown that the numerous reports of this casting technique's success in the literature have some basis to them. Based on the results of the pressurized riser casting trials, there is clear evidence that the technique can increase casting soundness by forcing liquid feed metal over remarkable lengths to feed centerline shrinkage in the 3" x 6" plates cast. In the case of T3-1X and T3-2X, it is found that the riser feeding zone length can be extended by a factor of at least 4 with a casting soundness rated at ASTM radiographic testing Class 1. This has important implications, particulary for applying the method in lateral feeding situations. Also, given the centerline porosity eliminated in T3-2X, our findings refute the statement that centerline shrink cannot be eliminated [2] by the method. It can be, up to a point that has yet to be determined.

It was determined that sustained riser pressures in the 15 to 28 psig range were found to improve casting soundness. The trials showed that a special pressure cap is not necessary to achieve good pressure tightness. Proper sealing of the pressurization tube can be achieved using the solid steel shell of the riser alone, but this sealing between the pressurization tube and the riser metal is all important. An adequate time delay must be used before pressure is applied; here it was found that when the minimum surface solid fraction is about 0.7 (determined by simulation) pressure can be applied without mold penetration. A more foolproof method of filling the mold to the required height, and method to avoid tube clogging during filling (given the time delay required) should be devised. Compressed air rather than argon might also be used in future casting trials to demonstrate that this common resource may be used as a pressure source.

Numerous questions remain following the trials that could be answered by additional trials. The primary questions are: how much sounder can a casting be made by the technique, and at what solid fractions and pressures is the technique effective? A perfectly sound plate has not been produced using the method. ASTM Class 1 is the best section soundness produced. Albeit, all the plate lengths cast exceed the rule feeding distance by considerable amounts. Presently, the first of these questions can only be answered by more casting trials and experimentation. Clues to the answer of the second question are found by comparing simulations and the trial results, and by more casting trials. These comparisons show that pressures in the range tested here (2 to 28 psig) can force liquid metal through centerline solid fractions in the 0.5 to 0.7 range. The development of new computer models that include consideration of the pressure forced liquid flow in the mush is necessary to study this issue

more thoroughly. Additional casting trials to explore these issues should and can be performed. These might include a casting set up with lateral feeding between two risers (one pressurized and one not) using a drag chill or reduced section asymmetrically placed between them to compare the longer feeding length that is possible using riser pressurization in the absence of end effect. Pressure would be applied at various levels when the centerline solid fraction at the chill (or reduced section area) attains certain threshold values determined using simulation. It can be observed directly whether and if there is liquid flow from the pressurized to the non-pressurized riser, and it such a trial the soundness of the pressurized and non-pressurized plate sections can be directly compared as parts of the same casting.

ACKNOWLEDGMENTS

REFERENCES

[1] S. T. Jazwinski and S. L. Finch, "A New Method of Feeding Applied to Castings Made in Static Moulds", *Foundry Trade Journal*, Nov. 29-Dec. 6, p. 269, 1945.

[2] Taylor, H.F., "The Pressure Feeding of Steel Castings at Pressures Higher than Atmospheric Pressure", *Final Report on SFSA Research Project No. 20*, SFSA, 1948.

[3] C. W. Briggs and H. F. Taylor, "Feeding of Castings at Greater-than-Atmospheric Pressures", *Proc. Inst. Brit. Foundrymen*, 1953, 46, A. 207.

[4] D. R. Kononow, "Compressed Air Risers", *Hochwertiger Stahlguss*, V.E.B. Verlag Technik, Berlin, p. 63, 1955.

[5] W. P. Desnizki, "The Application of Risers with High Atmospheric Pressure", *Iron & Steel*, Feb., p.51, 1958.

[6] Advertisement, *Foundry Trade Journal*, Mar., p. 15, 1957.

[7] Berry, J.T., and Watmough, T., "Factors Affecting Soundness in Alloys with Long and Short Freezing Range", *AFS Transactions*, vol. 69, p. 11-22, 1961.

[8] J. R. Shenefelt, R. Luck, and J. T. Berry, "The Case for Riser Pressurization", *1st International Conference on Gating, Filling and Feeding of Aluminum Castings*, Oct 11-13, Nashville, TN, pp. 227-237, 1999.

[9] Berry, J.T., and Taylor, R.P., "Improving Casting Performance by extending Feeding Action in Long-Freezing Range Cast Aluminum Alloys", *AFS Transactions*, vol. 107, p. 203-206, 1999.

[10] Aagaard, R., Schaefer, W., Hansen, P.N., and Rasmussen, N.W., "Active Feeding of Ductile Iron Castings", *Modeling of Casting, Welding, and Advanced Solidification Processes - IX*, Edited by Sahm, Hansen, and Conley, Shaker Verlag, 2000, pp. 861-867.

[11] Hardin, R. A., Ou, S., Carlson, K., and Beckermann, C., "Relationship between Casting Simulation and Radiographic Testing: Results from the SFSA Plate Casting Trials", *1999 SFSA Technical and Operating Conference Proceedings*, 1999.

Table I   Comparison of casting yields obtained with and without using pressurized risers, from [4]

Type of Casting	Dimensions of Casting in.	Weight of Casting	Yield with Usual Risers %	Yield with Pressure Risers %
Rudder	44½ × 72¾	3 tons	40	70
Housing	71 × 55 × 27½	1½ tons	50	78
Steam (Chest)	51 dia. × 22¼	17 cwt	44	84
Guide Wheel	47¼ dia. × 6	1¼ tons	40	83
Cog Wheel	84 dia. × 7½	2 tons	40	89.7
Bracket	86½ × 31½ × 8	15 cwt	34	72
Sleeve	20 dia. × 19½	5 cwt	50	88
Segment for Underground Railway (18 sizes)	67 × 59 × 32	5½ tons	60	83
Gear Wheel	23 dia. × 5	2 cwt	40	70
Ring	8½ × 62 × 8½	2¼ tons	60	75
Bed	71 × 16 × 8	1½ tons	50	80
Die Block	71 × 12 × 6	16 cwt	50	60
Die Block	71 × 16 × 6	1¼ tons	50	80
Chain Links (14 sizes)	From 40½ dia. × 5½ to 70 dia. × 8¾	2-8 cwt	45-50	75-80
Die Blocks (29 sizes)	From 59 dia. × 6¼ to 98½ dia. × 28	2 cwt-1¼ tons	45-50	65-75

Table II   Casting yields obtained using pressurized risers, from Desnizki (1958, [5])

Description	Gross Weight of Casting cwt	Weight of Riser cwt	Runner Weight kg	Yield of Molten Steel per Mould %
Bearer	28	5·2	2·8	77·7
Bed plate	50	8·4	2·0	83·0
Upper ring segment for rotor chamber	100	26·0	4·0	77·0
Bearer	174	35·0	9·0	80·0
Stretcher	30	4·0	2·4	82·5
Ball race for steam turbine	140	50·0[1]	8·0	70·8
Ring segment for chamber of water turbine rotor	150	64·0[1]	7·0	67·9

[1]The weight of the riser includes the weight of the technical material additions to the casting.

16

Table III   Summary of plates cast in the pressurized riser trials, all are cast using AISI 1030 steel, section is 3" T by 6" W

Plate ID	Casting Trial	Plate Length (in)	Distance from Riser Edge to End of Plate (in)	Pressure Used? (Yes or No)	Pressure Cap Used? (Yes or No)
T1-1X	1	31.5	25.5	No	No
T1-2X	1	31.5	25.5	No	No
T1-3X-P	1	31.5	25.5	Yes	Yes
T1-4X-P	1	31.5	25.5	Yes	Yes
T1-5X-P	1	31.5	25.5	Yes	Yes
T2-1X	2	39	33	No	No
T2-2X	2	39	33	No	No
T2-3X-P	2	39	33	Yes	No
T3-1X	3	50	44	No	No
T3-2X-P	3	50	44	Yes	No
T3-3X	3	50	44	No	No
T3-4X-P	3	50	44	Yes	No

Table IV   Events, observations, and pressurization schedule used in plate T3-2X-P

Event Description	Time from Start
Start pour	0:00:00
End Pour	0:00:12
Start touch up	0:00:14
Conclude touch up	0:00:16
Closed vent valve	0:00:40
Applied argon at 2 psi (Observation: Metal was pushed out of the sprue)	0:00:41
Argon valve closed	0:00:43
Applied argon at 2 psi	0:01:43
Applied argon at 6 psi	0:06:01
Increased argon to 13 psi (Observation: No noticeable loss in argon- tank pressure approx.1000psi)	0:10:01
Increased argon to 20 psi (Observation: noticed a quick 150 psi drop in tank pressure, but then it held)	0:14:31
Increased argon to 22 psi (Observation: noticed a quick 100 psi drop in tank pressure)	0:20:01
Increased argon to 24 psi (Observation: Tank pressure reads 600 psi)	0:21:01
Increased argon to 26 psi (Observation: Tank pressure 575 psi)	0:22:01
Increased argon to 28 psi (Observation: Tank pressure 400 psi ---- observed see gases being forced from the mold around the riser)	0:23:01
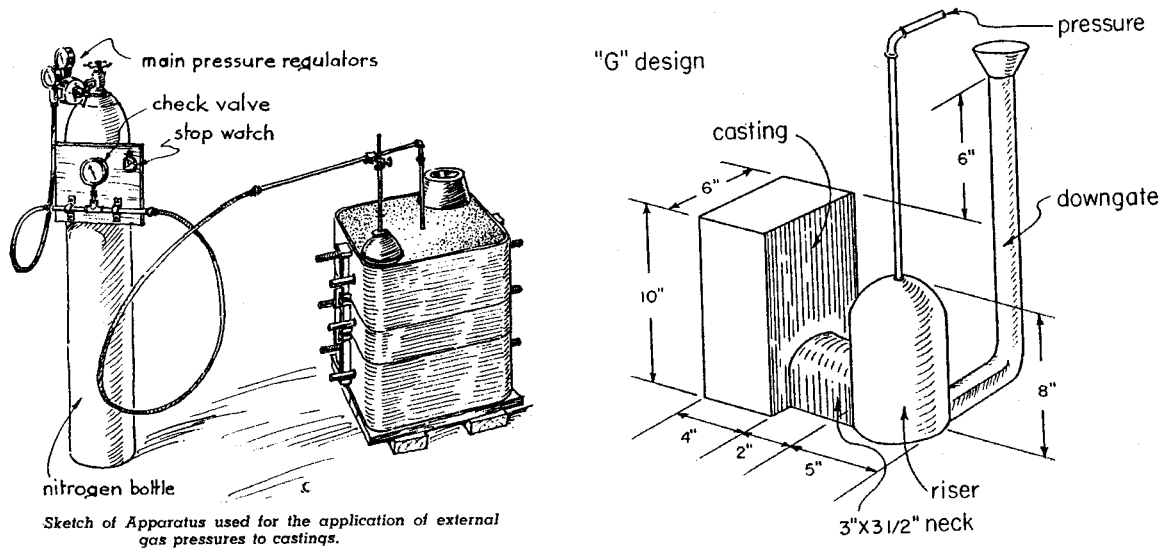
Figure 1 Apparatus used by Taylor [2] to pressurize risers (above left) and one of the numerous blind riser configurations tested, note the L-shaped pressure pipe inserted into the riser (above right), from [2]
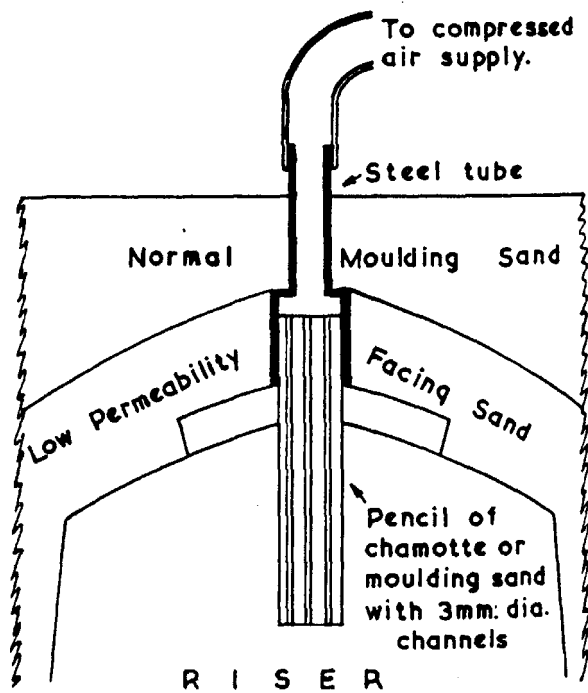
Figure 2 Russian method (Kononow, 1955 [4]) used to apply pressure to a riser

18
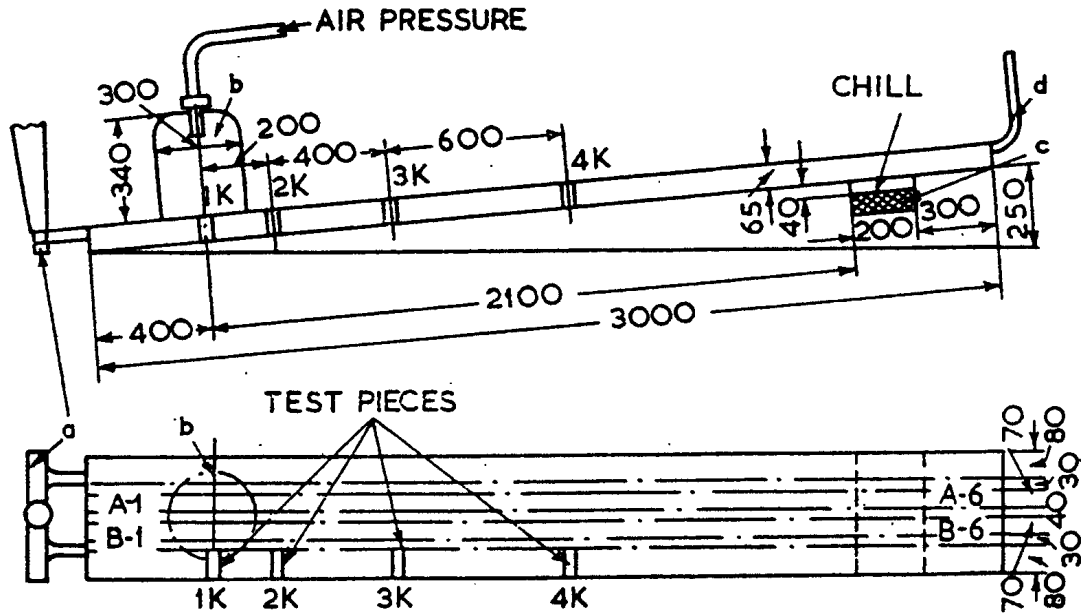
(a) Ingate;   (b) Riser under pressure;   (c) External chill in middle of bottom fillet; (d) Vent; A and B are strips which were cut out for the investigation of macrostructure; 1K, 2K, 3K, and 4K are specimens from the outside strip.

Figure 3   Experimental plate reported by Desnizki [5] to demonstrate pressurized riser feeding distance, plate is 3 m x 0.4 m x 65 mm
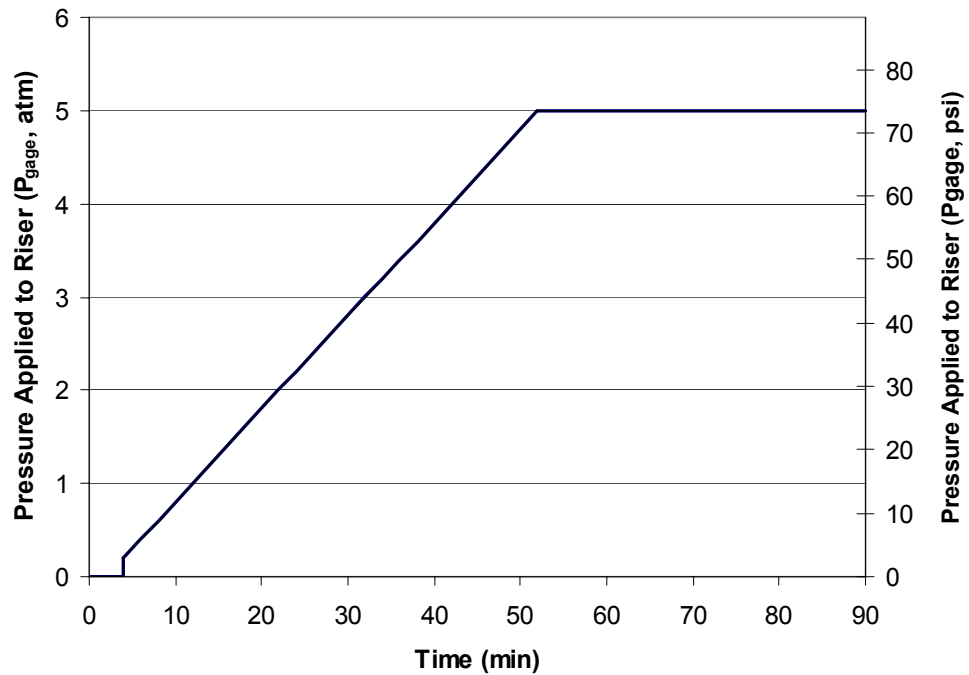
Figure 4   Pressurization schedule used by Desnizki [5] in the pressurized riser experiment shown in Figure 3

19
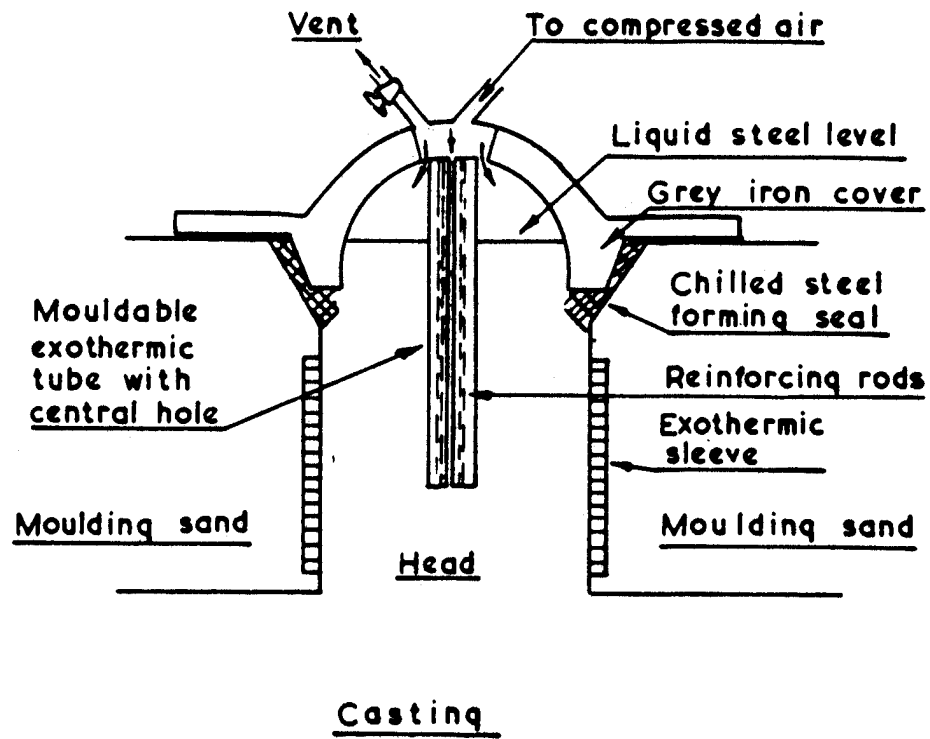
Figure 5   Diagram of riser pressurization technique used at a Belgian foundry ([6], 1957)
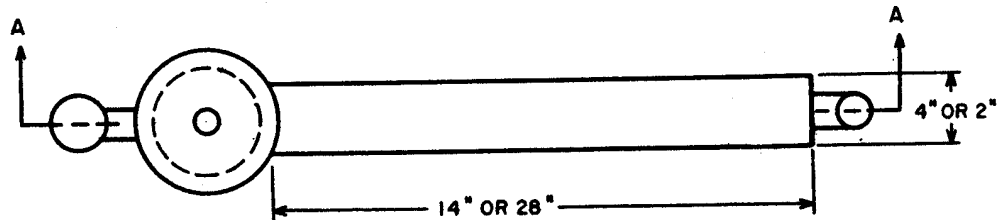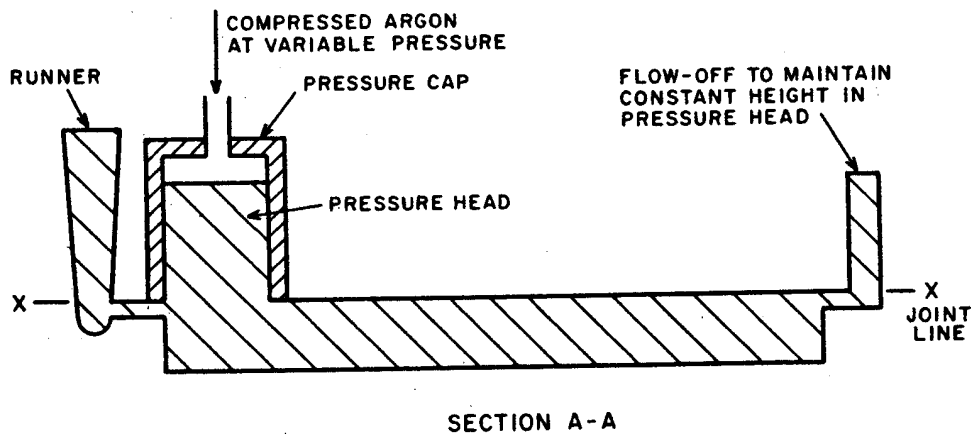
Figure 6   Pressure cap used by Berry and Watmough ([7], 1961)

1) A passage to the riser
   for the lance supplying
   the compressed air is
   built into the mold.

2) Lance is inserted through
   the passage to a point about
   15 mm from the riser top

3) Riser can be a blind riser,
   or a riser with a specially
   designed top (from graphite)
   for sealing the riser,
   and supplying the pressure.

4) Casting is poured,
   pressure lance is inserted
   into the riser

5) Gating system is closed

   Using MAGMA they determined the proper amount of time to wait before applying pressure

6) After a short delay, pressure is applied, at first equal to the metallostatic head,
   and then increasing to a maximum value as the casting solidifies

Figure 7   Diagram of pressurization technique used for active feeding of ductile iron
                  castings (Aagaard et al., 2000 [10])
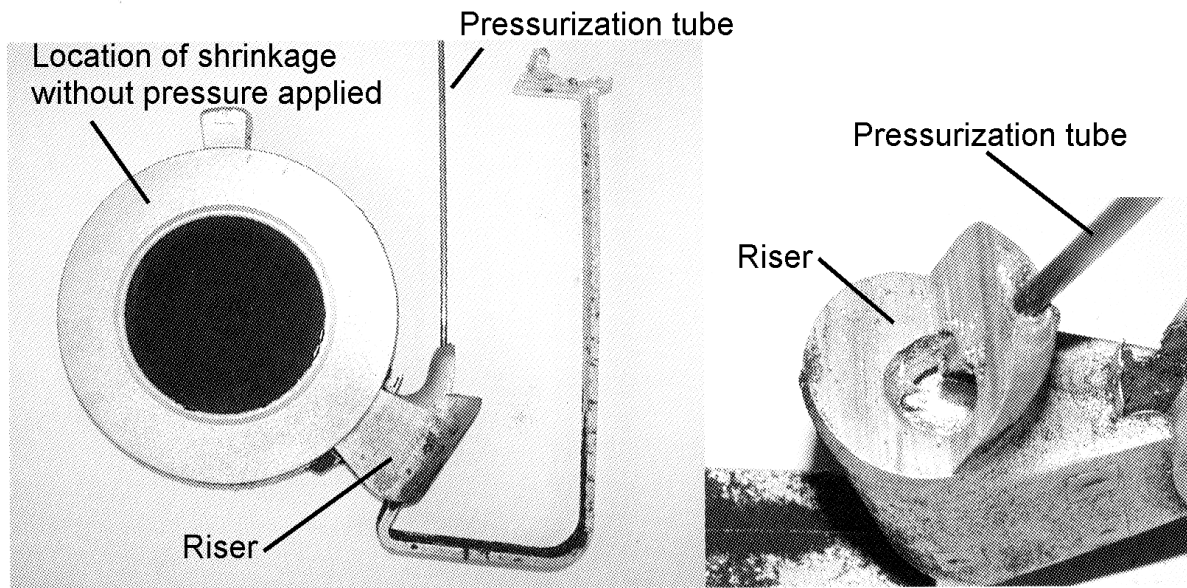
Figure 8   Photo from [10] showing disc casting produced using pressurized riser with
                  location of shrink formed when pressure not used (right), detail of riser cavity
                  with pressure tube (left)

21
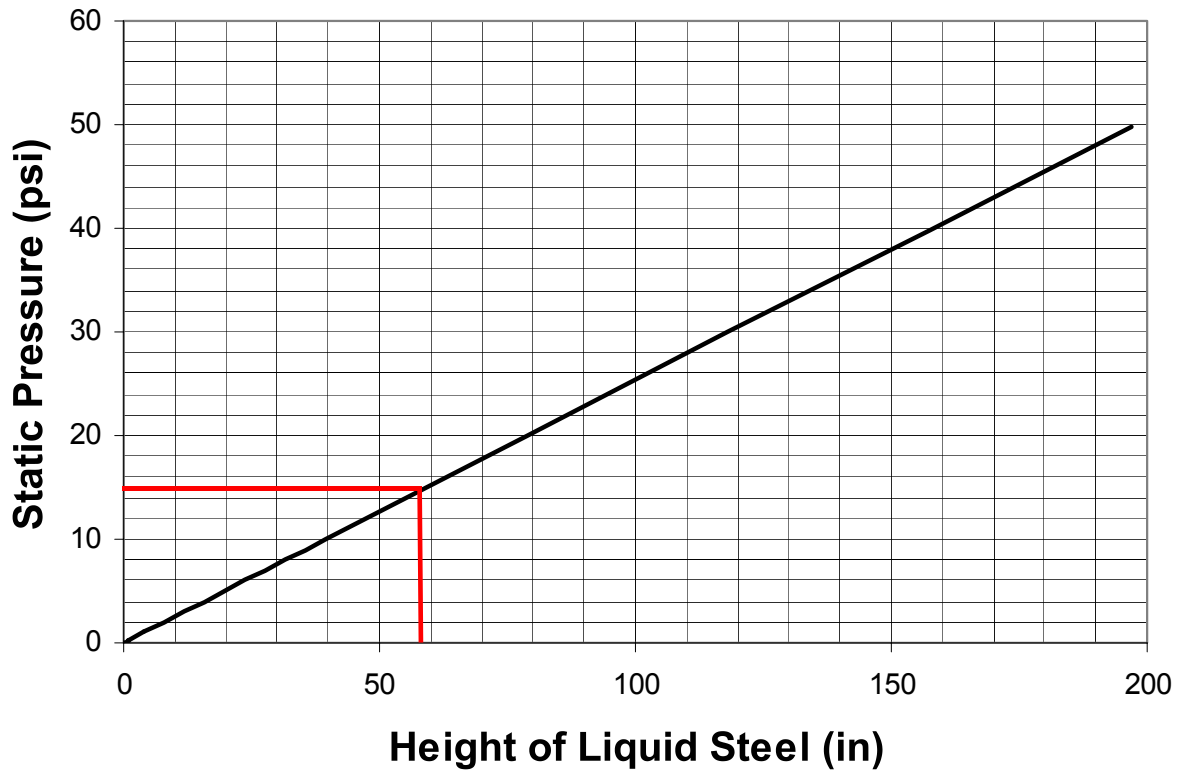
Figure 9   Relationship between pressure applied to a riser and metallostatic head height for liquid steel

Simulations were performed to:
1. Determine when shell is solid enough to pressurize

2. Determine if tube might clog
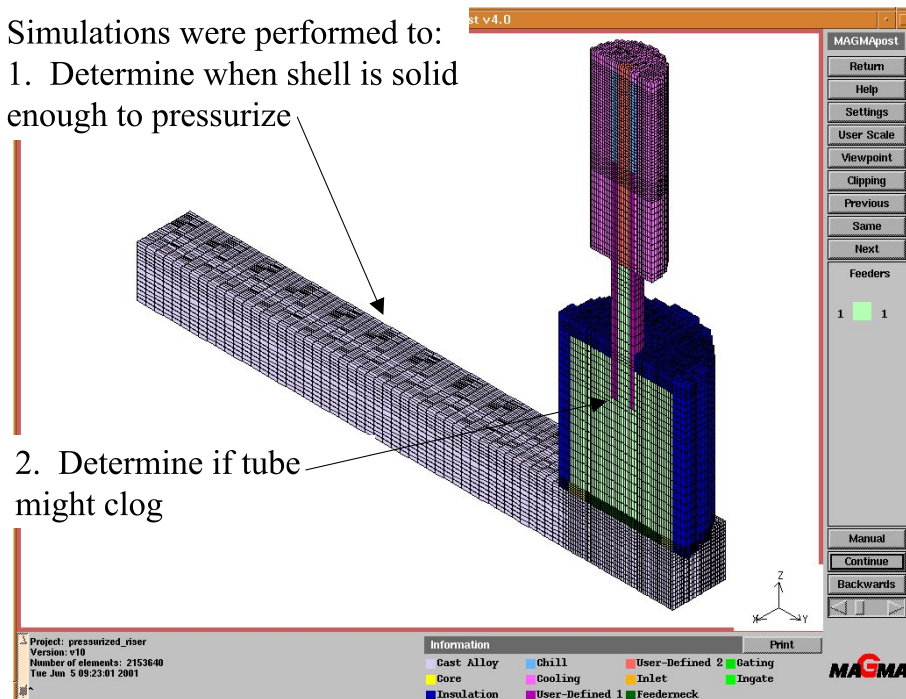
Figure 12   MAGMAsoft simulations were performed to establish the pressure schedule, and determine when the casting is solid enough to withstand the pressure and when the Fusil tube might solidify
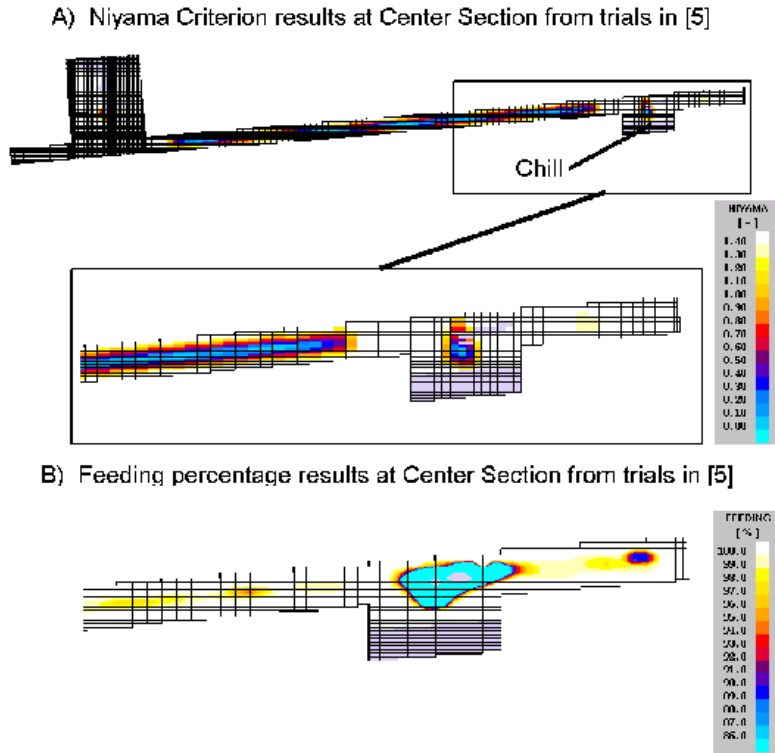
Figure 11 A) Niyama Criterion and B) Feeding percentage results from simulations of casting trial reported by Desnizki [5]

At 13 minutes, shell we believe shell is sufficiently solid and center sufficiently liquid to use pressurization
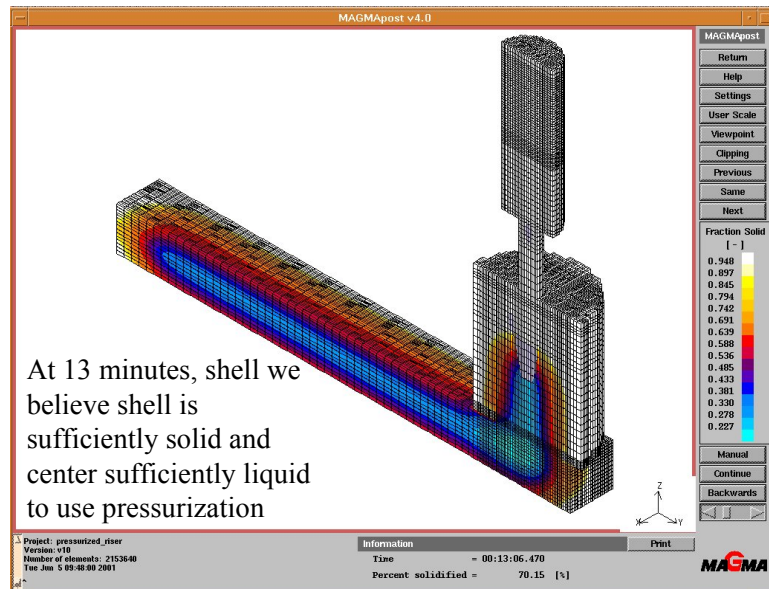
Figure 12 At 13 minutes the solid shell should be sufficient to prevent any mold penetration
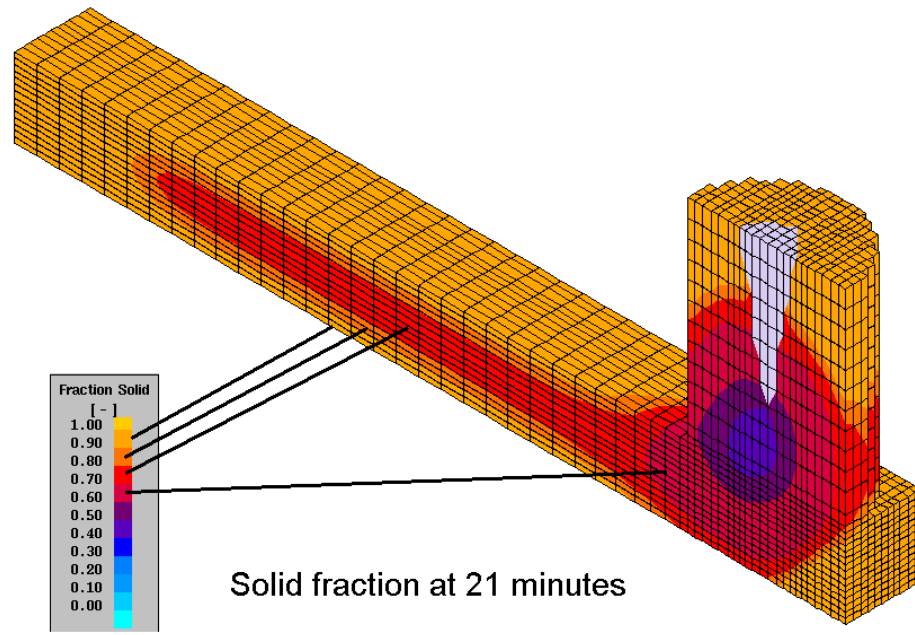
Figure 13   At 21 minutes from pour the centerline solid fraction is still 0.7, and pressurization might still be effective
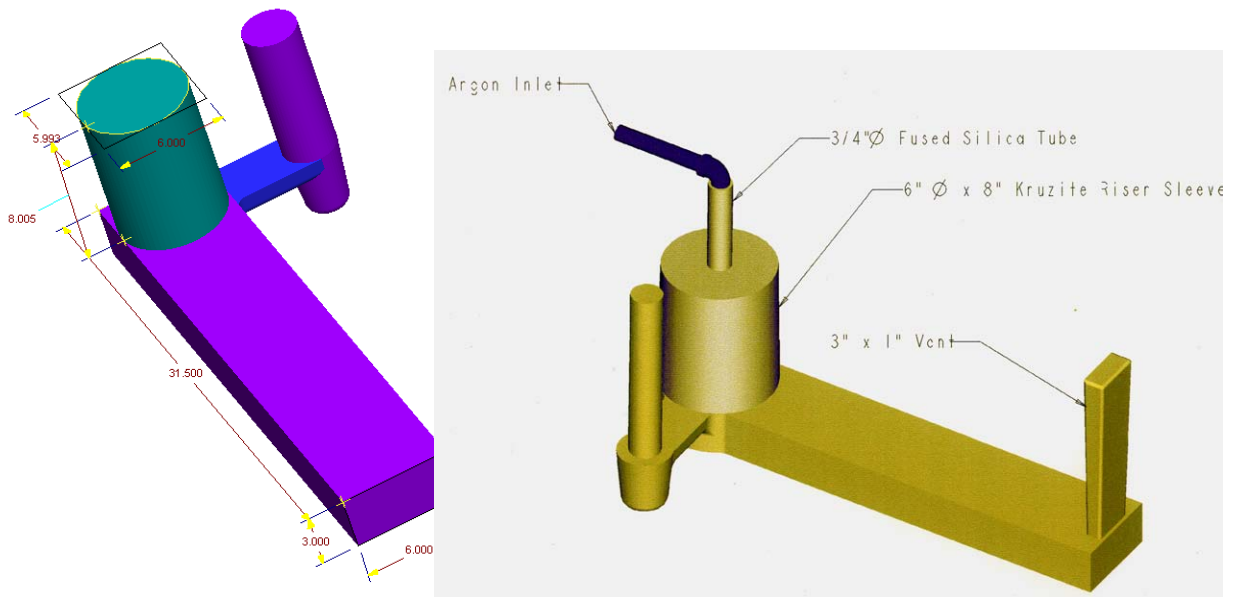
Figure 14   Rigging and plate geometry for first pressurized riser trials (above left) and CAD model with gas line (above right)

Figure 15   Pressure cap made from Kruzite castable ceramic with fused silica (Fusil) pressurization tube and gas line fittings with T-valve argon gas line
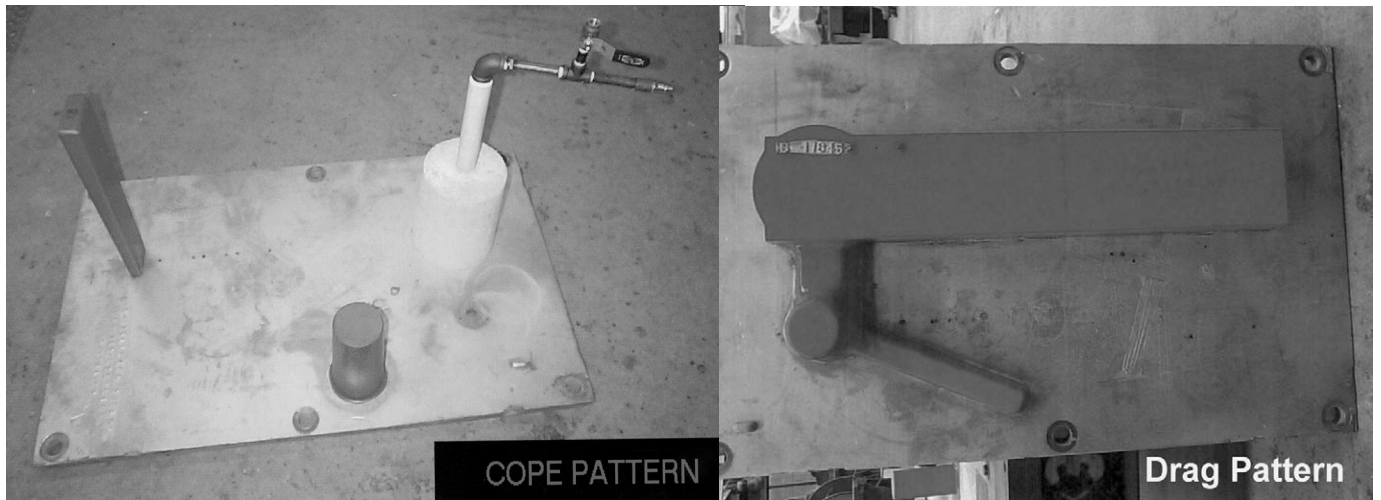
Figure 16   Cope pattern and drag pattern (above left and right, respectively) used in the first riser pressurization trials
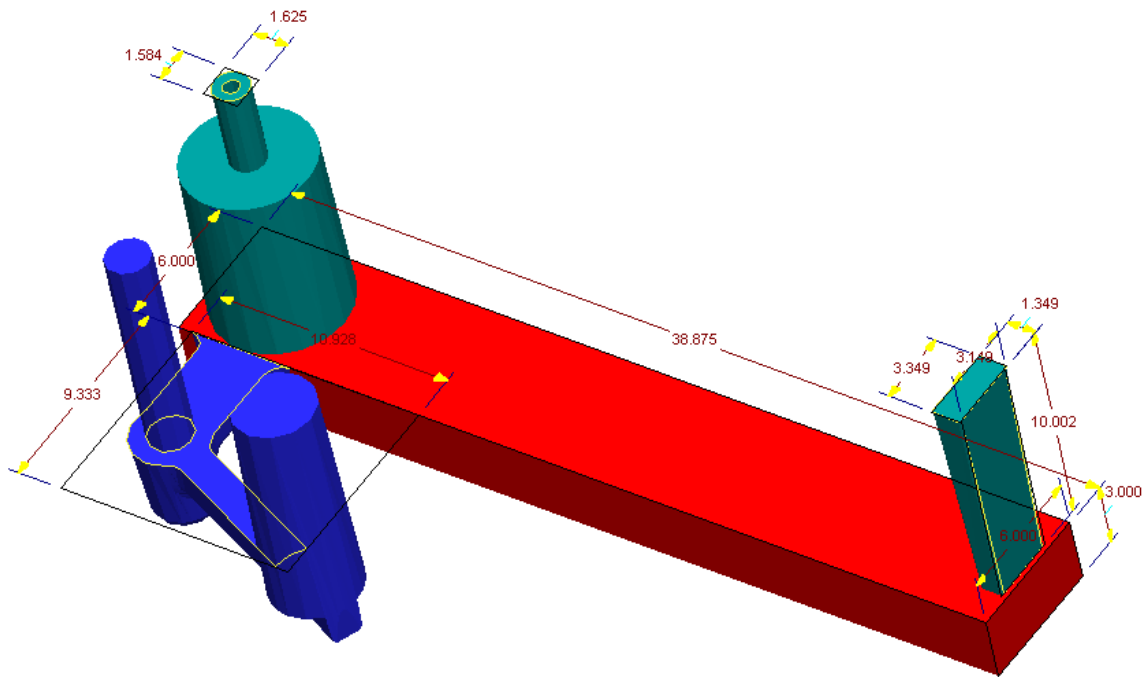
Figure 17   Casting geometry and rigging used in the second riser pressurization trials, plate length increased to 39" and no Kuzite cap is used
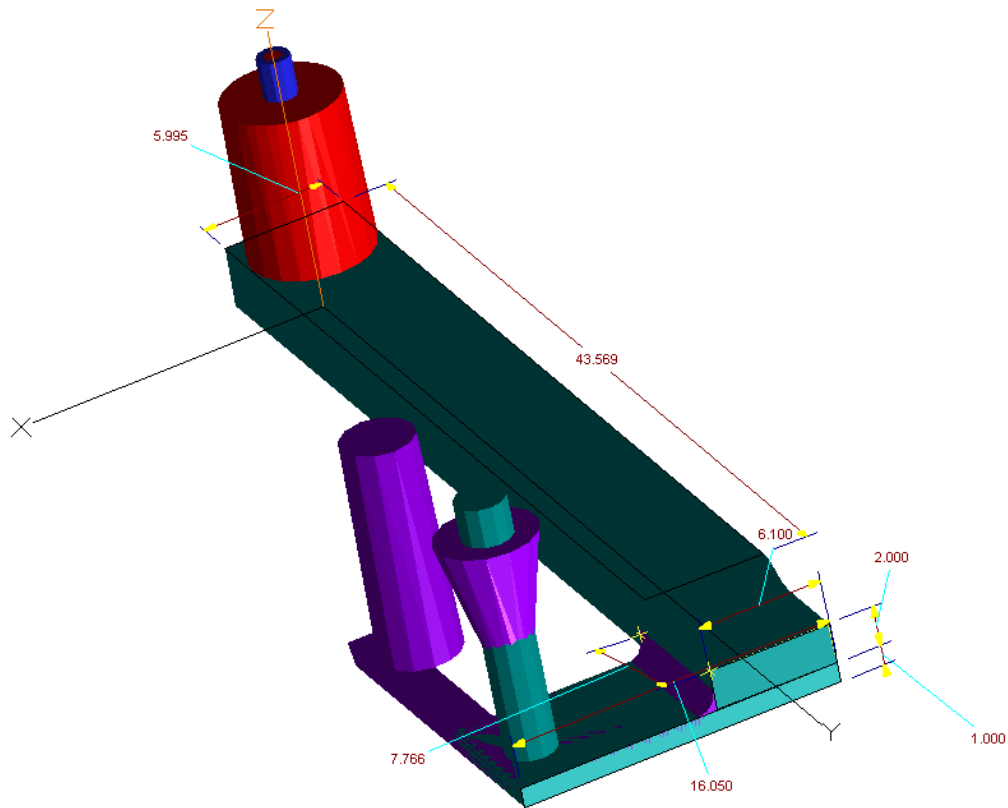
Figure 18   Casting geometry and rigging used in the third riser pressurization trials, plate length increased to 50" and no Kuzite cap is used
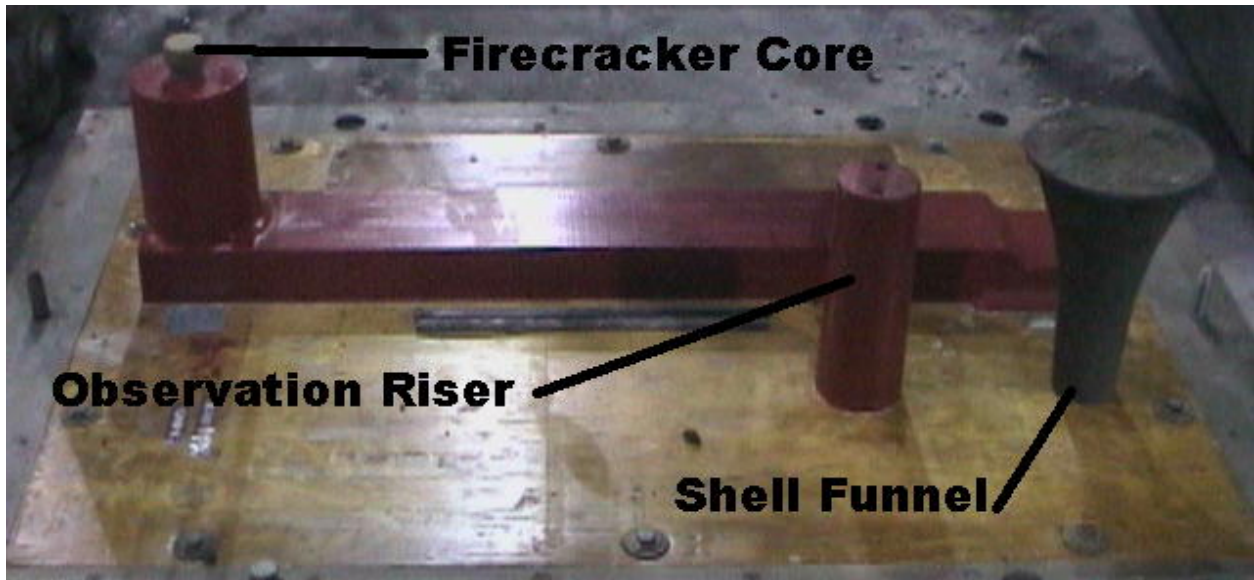
Figure 19   Cope pattern used in the third riser pressurization trials, firecracker core used in place of fused silica tube for non-pressurized plates

Figure 20   Section taken through plate T1-3X at the vent end shows the interior hole created by the argon leak

A) Without Pressure   B) With Pressure

End of Plate   End of Plate

Riser End   Riser End

Figure 21   No substantial difference in casting soundness was observed between the best non-pressurized and pressurized plate x-rays from the first trials, T1-2X (above left) and pressurized riser plate T1-5X (above right)
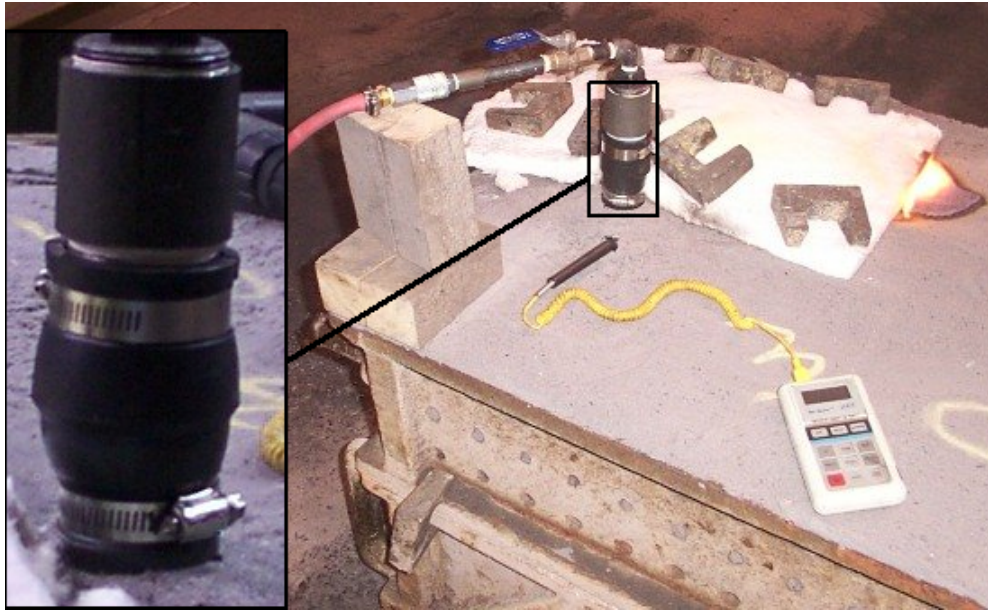
Figure 22   Photo of argon gas line hookup to Fusil tube used for riser pressurization in second casting trials
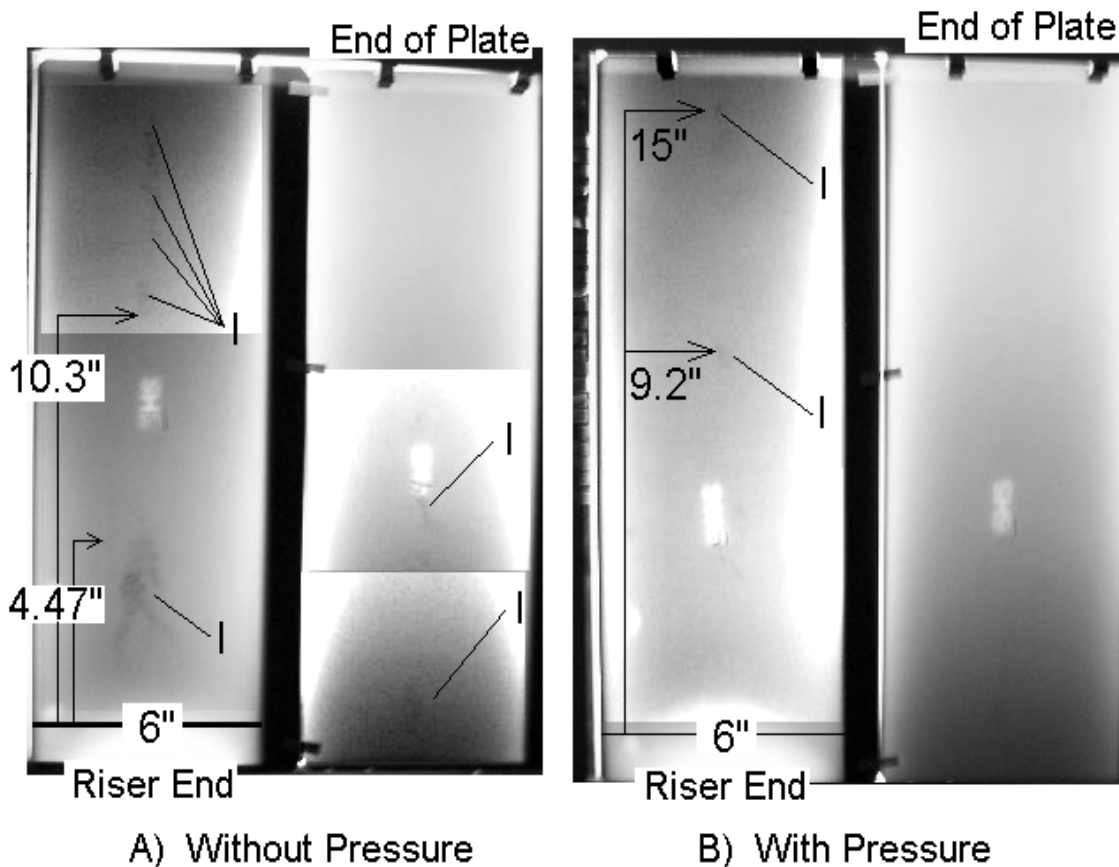
Figure 23   Comparison between RT x-rays from non-pressurized plate T2-2X (above left) and pressurized riser plate T2-3X (above right), left half from riser to mid-length and right half from mid-length to end, areas of the images with indications (I) are adjusted in contrast and brightness
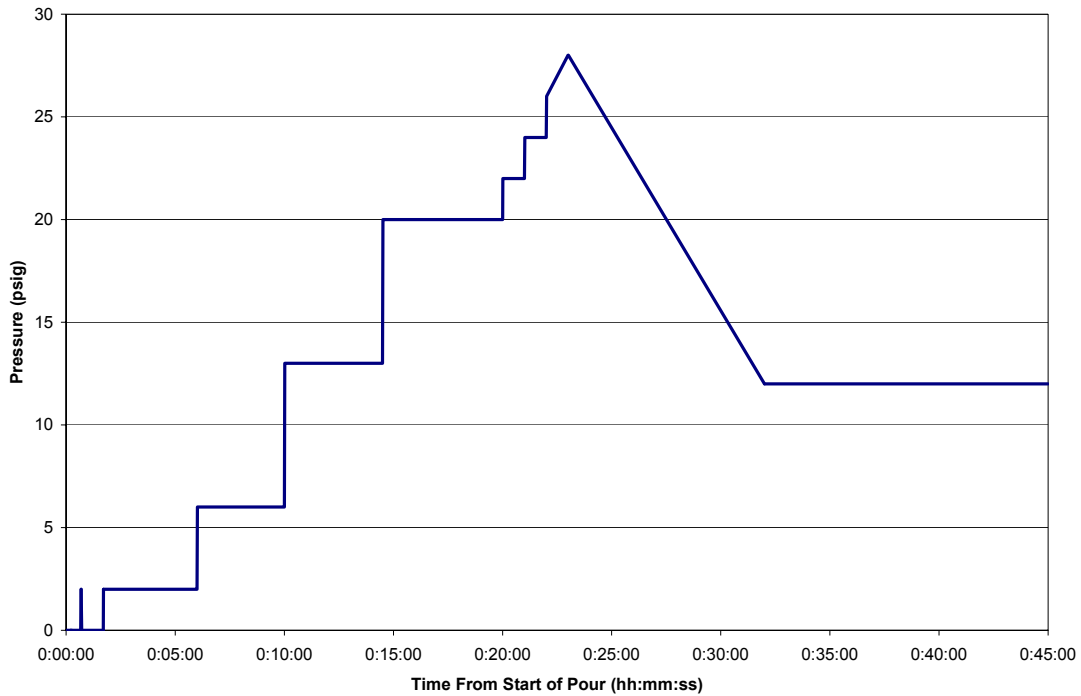
Figure 24 Pressurization schedule used for casting T3-2X from third trials using 3" T x 6" W x 50" L plates

This feature forms
after initial pressure application
41s from the start of the pour

This drop in riser height corresponds with the 2 psi applied at 1 min 43 s from end of pour

Casting T3-2X
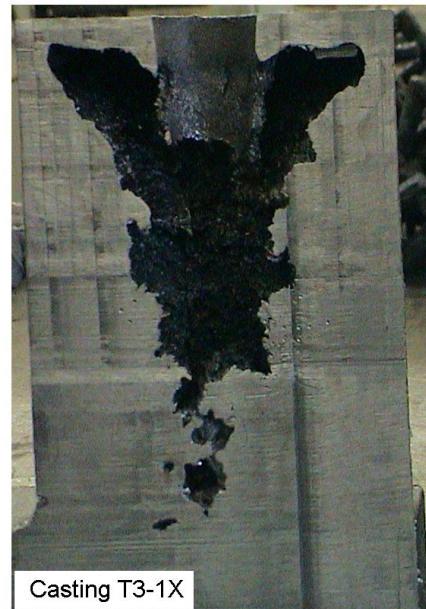
Pressurized Riser

Casting T3-1X

Non-pressurized Riser

Figure 25 Riser cross sections for castings T3-2X (pressurized, above left) and T3-1X (non-pressurized, above right) from third casting trials

30
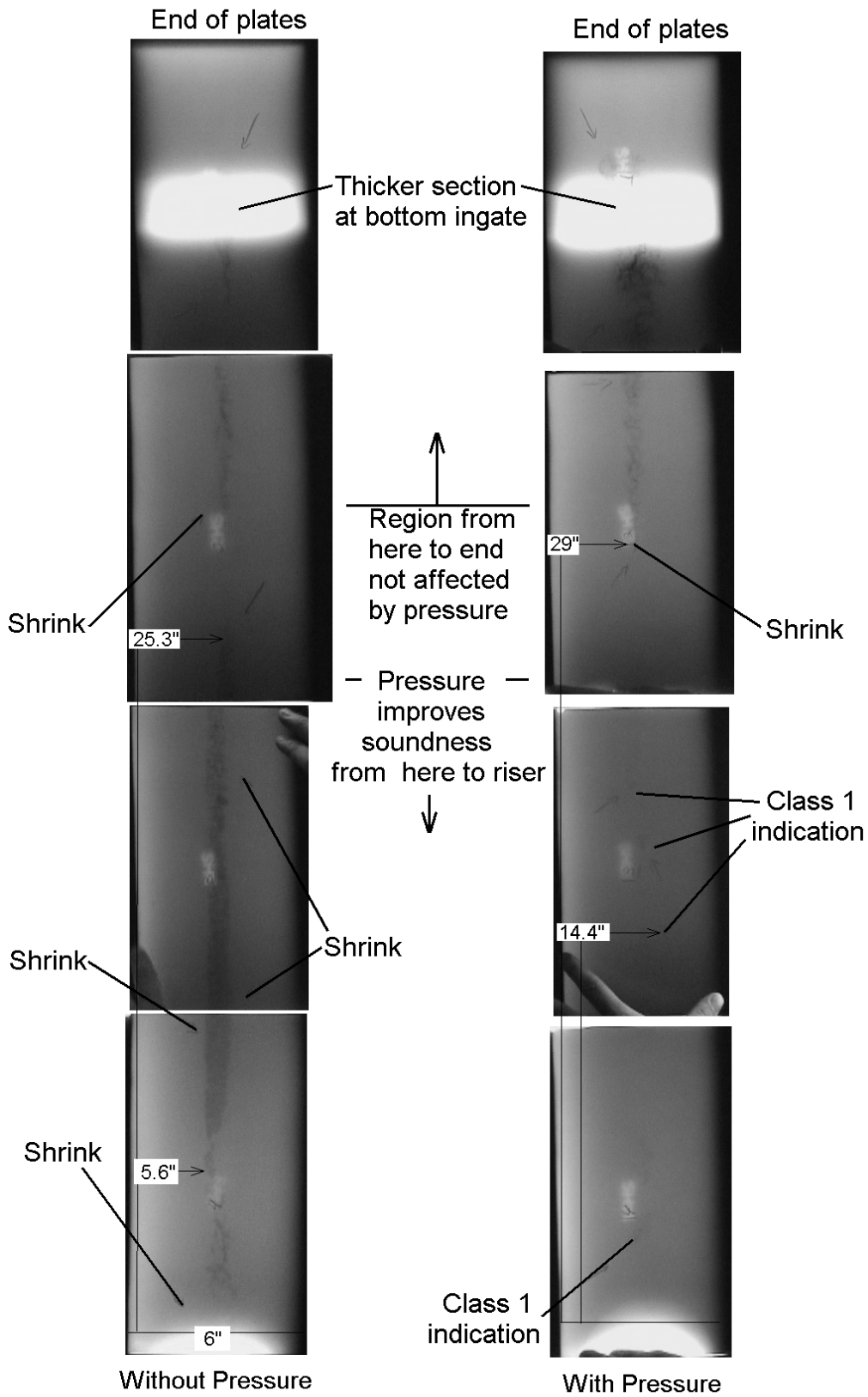
Figure 26 Radiographic testing x-rays from non-pressurized plate T3-1X (above left) and pressurized riser plate T3-2X (above right), entire casting length shown
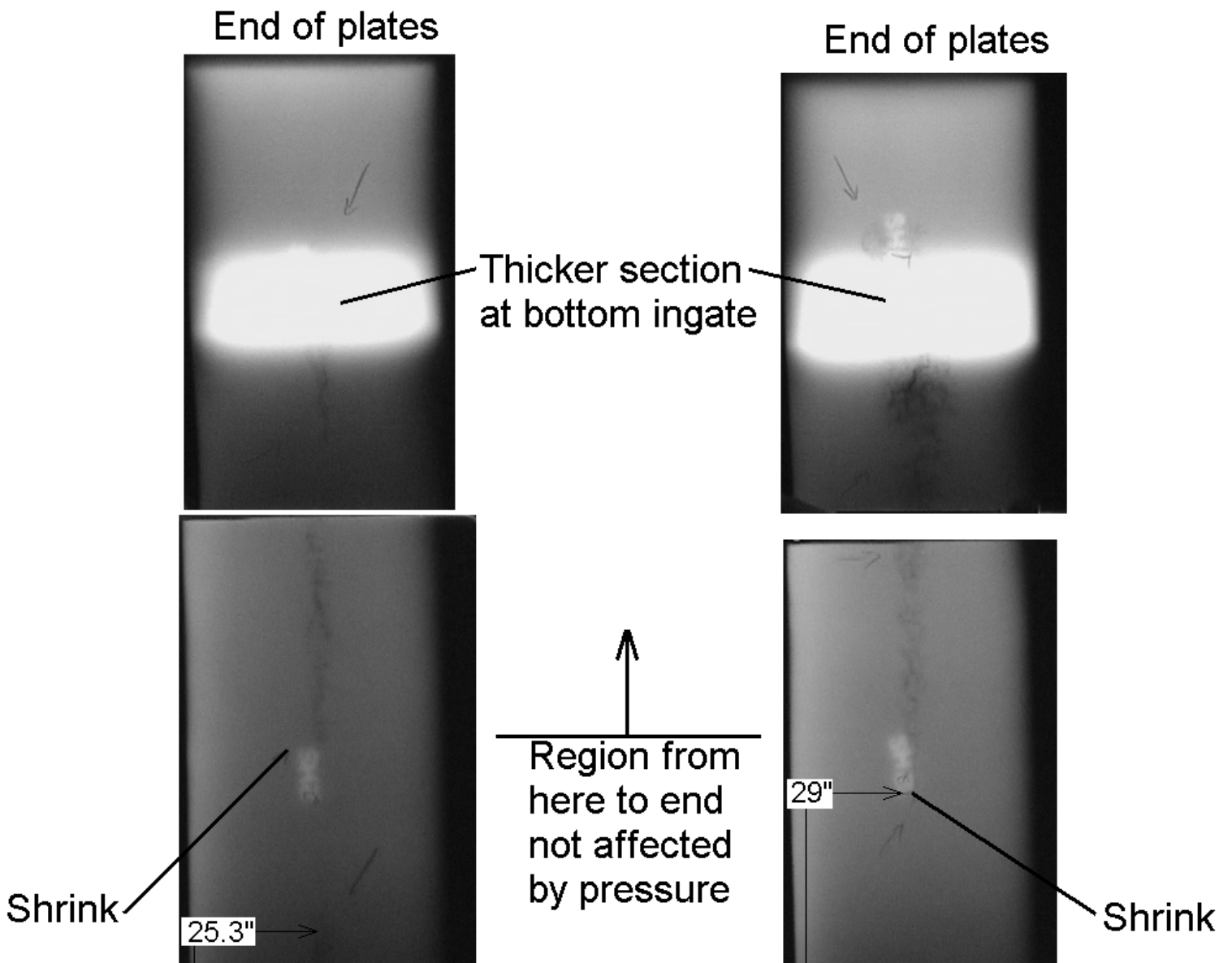
Figure 27 Comparison between RT x-rays from non-pressurized plate T3-1X (above left) and pressurized riser plate T3-2X (above right), dimensions shown are from edge of riser
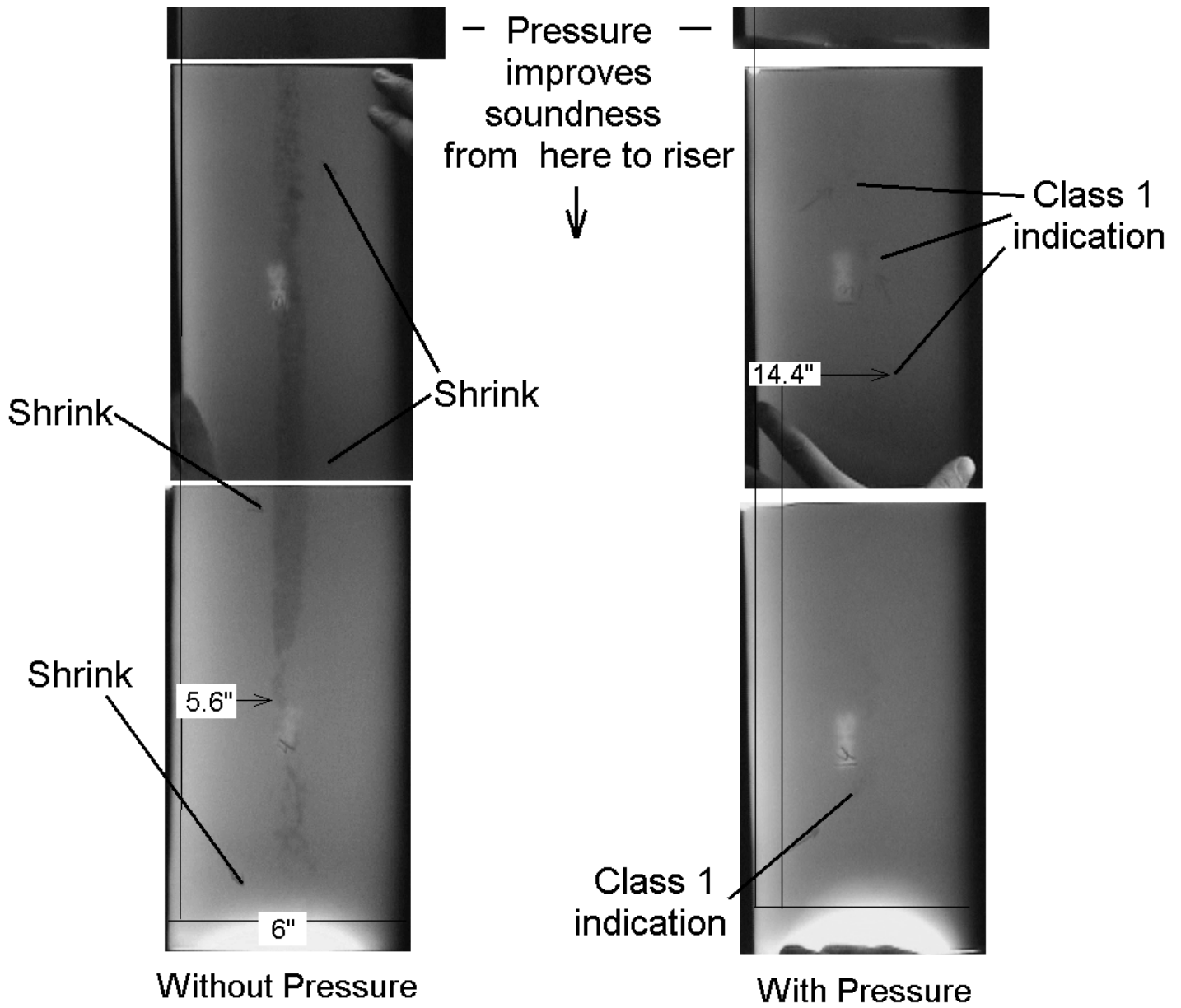
Pressure improves soundness from here to riser

↓

Class 1 indication

14.4"

Shrink

Shrink

Shrink

5.6" →

Class 1 indication

6"

Without Pressure

With Pressure

Figure 28   Comparison between RT x-rays from non-pressurized plate T3-1X (above left) and pressurized riser plate T3-2X (above right), dimensions shown are from edge of riser

Figure 29   Non-pressurized riser from plate T3-3X cast using exothermic sleeve (above left) and top of pressurized riser from plate T3-4X (above right)
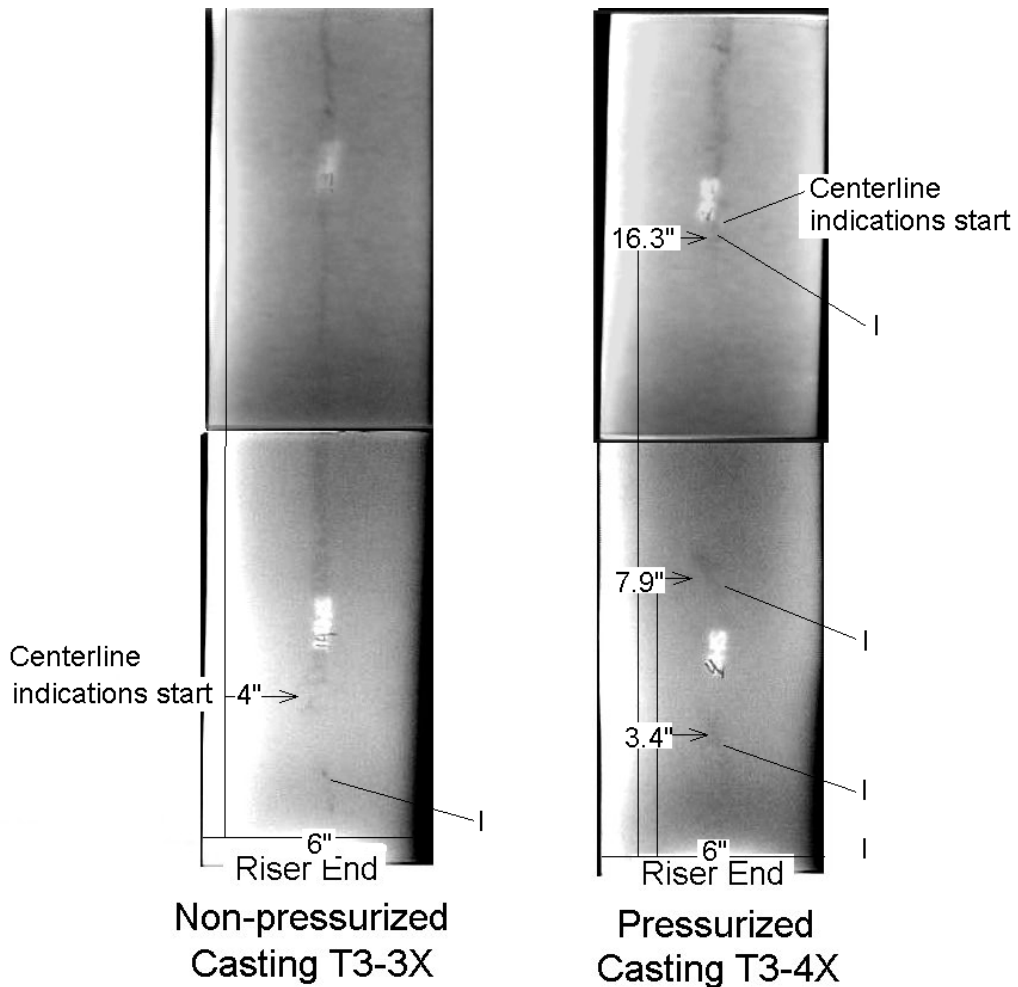

Figure 30   Comparison between RT x-rays from non-pressurized plate T3-3X (above left) and pressurized riser plate T3-4X (above right), dimensions shown are from edge of riser, indications visibly on x-ray noted using an "I"
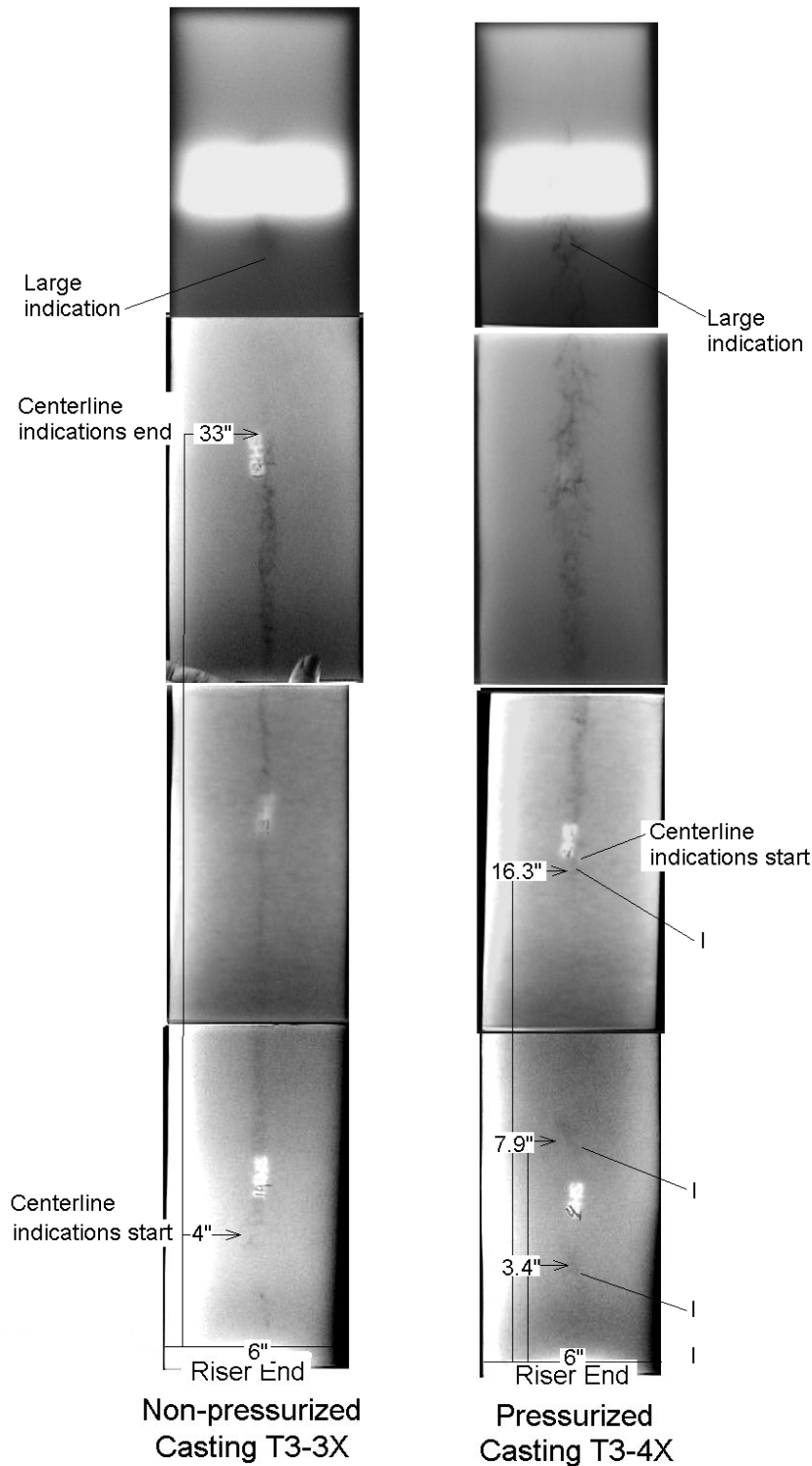
34

Figure 31 Comparison between RT x-rays from plate T3-3X (above left) and plate T3-4X (above right), dimensions shown are from edge of riser, indications visibly on x-ray noted using an "I"