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YIELD IMPROVEMENT CASE STUDY: STACKED SPRING CAPS

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ABSTRACT

This paper summarizes the findings of a yield improvement study performed for a 3" spring cap cast from WCB steel. The original mold assembly used horizontal stacking with vertical parting lines, and had a yield of 46.3%. About 25% of the caps cast from this design required welding for shrinkage defects, and all caps had some reoxidation inclusions. The casting simulation software package MAGMAsoft was utilized to simulate alternate mold assemblies, and promising designs were then sent to the foundry that produces this part for casting trials. Several different vertical stacking arrangements with horizontal parting lines were utilized in the casting trials. A maximum yield of 73.0% was achieved for a 3-layer stacking arrangement that was poured through the riser. Caps produced from this design were similar to the original caps in terms of welding required, but had significantly more inclusions. The quantity of inclusions was somewhat reduced through the use of a thin, rectangular bottom gating system. 3-layer and 4-layer vertical stacking arrangements were designed and cast with this bottom gating system, resulting in yields of 67.5% and 69%, respectively. These caps also required a similar amount of welding as the original caps. They had fewer inclusions than the vertical stacking assemblies that were poured through the riser, but still more inclusions than in the original horizontal design. The results of the casting trials indicate that the ability to improve the yield for this casting through vertical stacking will be impeded by the failure to develop a gating system that produces clean castings. There is still a possibility for yield improvement, however, using an optimized horizontal assembly. Simulation results indicate this optimized arrangement should produce caps of similar soundness to the original caps, with a 62.9% yield. Although casting trials have yet to be performed for this design, the similarity between this design and the original assembly leads to optimism that the caps will contain a similar amount of inclusions to the original caps.

1. Description of Case Study

The case study described in this report investigates the potential yield improvement offered by different mold box stacking arrangements. In this paper, 'yield' is defined as the total weight of the castings produced by a mold assembly divided by the total weight of the melt poured to produce the castings. The casting analyzed in this stacking case study is a 3" spring cap for gas valves (see Figure 1), which operates at pressures up to 300 psi. The diameter of the cap is 9.5" (8.5" between the flat edges), and the total height is 1.7". The cap is cast from WCB steel in a no-bake sand mold, with a final casting weight of about 6.5 kg. A brief summary of the quality requirements for this production casting is as follows:

- No visible defects after machining
- Must pass a hydrostatic test (after machining) at twice the anticipated working pressure
- Limited surface inclusions
- No x-ray requirements

This spring cap is a good candidate for stacking, since it is a flat, small casting that is produced in large quantities. The foundry that casts this part was initially using the horizontal stacking assembly with vertical parting lines shown in Figure 2 (1/4 of the assembly is shown). Five mold boxes were stacked on either side of a mold section containing the downsprue. Each mold box contained the pattern for a riser and two spring caps (one on each side of the riser), and a section of runner. When the mold boxes were stacked together, the continuous bottom runner seen in Figure 2 was formed. The quarter-symmetry views shown in Figures 2 – 4 only show half of each mold box (i.e. one spring cap and half of the riser), and only show the five mold boxes on one side of the downsprue. Thus, the complete mold assembly is obtained by mirroring the quarter-symmetry view across the risers, and then mirroring the resulting half-symmetry view across the downsprue. So while only 5 spring caps are shown in the results, there are actually 20 spring caps cast in this arrangement.

Unfortunately, the yield for this assembly was relatively low (46.3%), and the resulting castings frequently had shrinkage defects on the inside rim of the cap (see Figure 1). Because of this shrinkage, about 25% of the caps that were produced required welding along the inside rim. The castings also had some reoxidation inclusions. The primary objective of this case study was to improve the yield without increasing the shrinkage problem or the amount of inclusions.

Alternate stacking arrangements were developed and analyzed with the aid of the commercial casting simulation software package MAGMAsoft. First, a base case was established by simulating the mold filling and solidification processes for the original stacking assembly, using actual casting conditions. Then, each alternate assembly was simulated with the base case casting conditions, the yield was computed and the casting soundness was examined[1]. If the yield was an improvement over the base case and the casting soundness was at least as good as in the original design, the alternate stacking design was sent to the foundry as a prospect for casting trials. If the design was cast, the actual casting conditions were used to re-simulate the process, so the simulation results would be consistent with the casting trial results. All simulations were performed using MAGMA's WCB steel and furan sand property databases.

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[1] The casting soundness was evaluated in terms of feeding percentage and the Niyama criterion. Feeding percentage is a local quantity that indicates if sufficient feed metal is available to feed solidification shrinkage in that location throughout solidification. Feeding percentage indications considerably less than 100% (for example, less than 85%) indicate the presence of significant macroshrinkage, such as a cavity. The smaller the percentage, the more macroshrinkage is present. The Niyama criterion (Ny) is a local thermal criterion for porosity formation, defined as

$$Ny = G/\sqrt{\dot{T}}$$

where G is the temperature gradient (K/mm) and $\dot{T}$ is the cooling rate (K/s). Small values of Ny indicate the possible presence of porosity (micro- or macro-) in that region. It has been found that if the minimum Niyama value in a casting is greater than about 0.1 $(K\ s)^{1/2}mm^{-1}$, the casting will be sound (ASTM shrinkage x-ray level 1 or better) [1].

2. Simulation and Casting Trial Results – Horizontal Stacking

The original horizontal stacking arrangement with vertical parting lines was simulated using the casting conditions listed in Table 1. The simulation results for this original assembly are shown in Figures 2 - 4. The feeding percentage plot given in Figure 2 shows that the risers contain mostly sound metal, indicating that the risers used in the original rigging were too large. The feeding percentage plots in Figure 3 illustrate that there are minimal feeding percentage indications inside the spring caps (about 95% or higher), occurring on the inner rim of the caps where shrinkage defects were found. Figure 4 contains Niyama value plots, which clearly show that each cap has a region of low Niyama values (the blue area) that runs through the center of the cap. This indicates the possibility that shrinkage defects may form in this area. However, since there are no x-ray requirements for these caps, it is acceptable to have shrinkage defects in the center of the caps. Also, notice that this blue region comes very close to the inner rim of the caps, where shrinkage defects were found. Thus, the simulation results agree with the results of the casting trials for the original mold assembly.

In an attempt to improve the yield of the original stacking arrangement, the sizes of the risers, the downsprue and the pouring cup were reduced. The height of the downsprue and pouring cup in the original rigging were 16” and 8”, respectively. These heights were reduced to 12” and 2”, respectively. The original risers were 14” high (10” plus a 4” taper into the runner), 2.5” wide (1.6” wide at the bottom of the taper) and 3” thick (only half of the thickness is shown in the quarter-symmetry view). The modified risers, which were resized using the modulus method [2], have dimensions 9.6” (no taper) x 1.5” x 3”. As seen in Table 1, the simulation results indicate that these changes increase the yield from 46.3% in the original design to 62.9% in the optimized horizontal assembly (a 16.6% improvement).

The geometry of the optimized horizontal stacking assembly is given in Figure 5, along with the riser feeding percentage plot for this configuration. This feeding plot shows that there is less sound metal in the resized risers, downsprue and pouring cup, and hence increased yield. Figure 6 shows that the feeding percentage indications inside the spring caps are about the same as in the original assembly (Figure 3), again having slight indications near the inner rim of some of the caps. The Niyama value plots in Figure 7 look similar to those of the original assembly (Figure 4), only with slightly higher values (indicating slightly more sound castings). However, there are still low-Niyama (blue) regions near the surface of the inner rim. In any case, the simulation of the optimized horizontal assembly indicates that this arrangement should produce spring caps at least as sound as the original castings, and with a higher yield. Casting trials have yet to be performed for this arrangement, but will be done in the near future.

Finally, it should be noted that the vertical downsprue used in the horizontal stacking simulations (see Figures 2 - 4) is slightly different than what was actually used in the foundry. The actual arrangement has the downsprue angled 24° from vertical and curving at the bottom to an almost horizontal alignment where it meets the runners. This allows the incoming metal to flow smoothly down the side of the downsprue and into the runners, instead of falling the entire length of a vertical downsprue and impinging near the runners. The foundry used this angled downsprue to reduce turbulence and thus minimize inclusions. Since the simulations did not include the prediction of inclusions, the vertical downsprue was added to allow the use of quarter-symmetry rather than half-symmetry. This considerably reduced the required simulation time, and did not significantly affect the casting yield or soundness predictions.

3. Simulation and Casting Trial Results – Vertical Stacking

Next, the effects of changing to a vertical stacking arrangement with horizontal parting lines were investigated. The advantage vertical stacking has over horizontal stacking is that the vertical mold assembly can be designed with one common central riser that feeds castings in all stacking layers. The use of a single common riser instead of several individual risers indicates definite potential for yield improvement. An example of this idea is illustrated in Figure 8, which depicts a central riser that feeds two castings in each layer. This is termed an “I-pattern”. Another possible arrangement is a “cross-pattern”, shown in Figure 9, where the riser feeds four castings in each layer. Figure 9 shows that the cross-pattern is not an ideal arrangement for the spring caps. Because of their geometry, the caps cannot be placed very close to the riser with a cross-pattern, and rather large riser necks are required to connect them to the riser. This additional rigging reduces the potential yield. Furthermore, for simplicity and ease of modification, the foundry wanted to continue to use the existing casting mold boxes that formed the individual layers of the original horizontal stacking assembly. This led to the use of the I-pattern assembly shown in Figure 8.

Ideally, the riser size and distance between castings (inter-casting distance) should be chosen in such a way that upon solidification, the castings are sound and there is a minimal amount of sound metal left in the riser. The use of the existing casting mold boxes, however, fixed the inter-casting distance. Because of this, a constant-diameter riser would lead to a reduced yield; if the riser had a diameter large enough to feed the castings, a significant amount of metal would solidify in the riser between castings. For this reason, the riser design shown in Figure 8 was employed. A cylindrical riser with a relatively small diameter runs through all the casting layers, and larger riser blocks branch off from the cylindrical riser in each layer and connect to the castings. Figure 8 also illustrates the modular design of the I-pattern. The desired number of casting mold boxes are stacked on top of a layer that closes the bottom of the riser, and an additional mold box containing the pouring cup is placed on top to complete the assembly.

The four variations of the I-pattern that were used for casting trials are shown in Figure 10 (half-symmetry views). As in the optimized horizontal assembly, the riser blocks were sized using the modulus method [2]. The riser block dimensions and casting conditions are listed in Table 1. For the upper two designs shown in Figure 10, the melt simply enters the mold assembly through a pouring cup that channels the metal into the riser, sequentially filling the castings and riser blocks from the bottom up. Both of these designs have three casting layers, each containing two castings, and thus produce six spring caps at a time. The only difference between these two arrangements is that one has the spring caps oriented with the flanges facing upward (“3 up, poured through riser”), and the other has the flanges facing downward (“3 down, poured through riser”). The lower two designs in Figure 10 are similar to the “3 down, poured through riser” assembly, but they employ a bottom gating system. The melt flows from the pouring cup into the downsprue, and then through a thin, flat section of gating at the bottom of the assembly. Finally, the metal flows up the riser, again sequentially filling the castings and riser blocks from the bottom up. One of these designs has 3 casting layers (“3 down, bottom gating”), and the other has 4 layers (“4 down, bottom gating”). The casting mold boxes used in the bottom gating assemblies are the same as those used in the “poured through riser” assemblies, except they also contain a section of the downsprue. The bottom gating is added by modifying the extra bottom mold layer shown in Figure 8, and the larger-diameter riser head on top of the riser is added to the pouring cup mold box.

The simulation results for the two “poured through riser” designs are given in Figures 11 and 12. By comparing these simulation results with the results for the horizontal assemblies discussed in the previous section, it is seen that the predicted casting soundness in all of these cases is similar. There are only slight differences in the feeding percentage plots, and the Niyama plots are similar as well. The Niyama plots in Figures 11 and 12 again have low values (i.e. potential for shrinkage defects) in the center of the caps, and again these low Niyama regions pass very near the inner rim of the spring caps. Thus, the potential for inner-rim surface shrinkage defects remains. The low Niyama (blue) regions in Figure 12 (“3 down, poured through riser”) appear to be a little smaller than in the “3 up, poured through riser” assembly and the horizontal assemblies, which indicates that the “3 down, poured through riser” caps may be slightly more sound.

The results of the casting trials for the “poured through riser” I-patterns are in good agreement with the simulations. Figure 13 provides a comparison between x-ray results and Niyama values for one of the spring caps cast in the “3 down, poured through riser” configuration. The x-ray image (top left) was digitized and treated with the image analysis software package Transform, resulting in the bottom left image in Figure 13. Simulation results are shown for three cross-sections of the spring cap, displaying only Niyama values less than 0.1 (where shrinkage defects that are visible on x-ray can be expected). Comparing the two bottom images, the location of the shrinkage defects that appear on the x-ray corresponds quite well with the Niyama prediction. Figure 14 shows a comparison between the predicted and actual shrinkage cavities in the risers of both “poured through riser” I-patterns. In the feeding percentage plots, the light purple regions represent areas where there is no metal. Comparing these regions with the holes seen in the photos, the riser shrinkage cavities are predicted quite well.

In terms of inclusions, both “poured through riser” arrangements produced caps with a significantly larger number of inclusions than the original horizontal assembly. In addition, the “3 up, poured through riser” design produced caps that had an excessive number of inclusions on the flange surface. This was unacceptable to the foundry, because the flange surface must be as smooth and flat as possible. It is not surprising that this design resulted in excessive inclusions on the flange surface, since inclusions tend to rise in the melt and deposit on the cope surfaces of castings.

According to the foundry, about the same amount of welding repair work was required along the inner rim for caps produced with the two “poured through riser” I-pattern assemblies as in the original assembly. As shown in Table 1, the yield for these two I-patterns was 73.0%. However, even though the yield was improved by 26.7% and the caps had comparable soundness to those produced by the original assembly, these I-pattern assemblies were rejected due to the significant increase in the number of inclusions.

The bottom gating designs shown in Figure 10 were developed in an effort to reduce the quantity of inclusions in the spring caps produced by the “poured through riser” configurations. Both of these bottom gating designs have the caps oriented with the flange side facing down. The foundry opted to add a sleeve to the riser head atop the cylindrical riser in the “3 down, bottom gating” design, but not in the “4 down, bottom gating” design. The simulation results for the bottom gating arrangements are given in Figures 15 and 16. Both the feeding percentage indications and Niyama values are similar to those of the other assemblies presented in this paper. Thus, the simulation results for these bottom-gated I-patterns indicate that the castings produced should be of about the same quality (in terms of soundness) as in the original configuration. Note that these results also indicate that the use of a sleeve on the riser head does not affect the soundness of the resulting castings.

Figure 17 shows a comparison between simulated Niyama values and dye penetration results for a spring cap cast in the “4 down, bottom gating” configuration. Notice that the locations of the shrinkage defects in the casting fall along the ring of low Niyama values predicted in the simulation. Figure 18 compares the simulated and actual riser shrinkage cavities for the “4 down, bottom gating” I-pattern. The predicted cavities are very similar to those seen in the pictures. The simulation did not predict that the cavity in the top layer would be connected to the cavity in the riser head, but the region between the two does have a low feeding percentage. These two figures provide further confidence in the predictive capabilities of the simulations.

As with every other design cast, the caps produced by the bottom-gated assemblies required about the same amount of weld repairs along the inner rim as for the original arrangement. The foundry reported that the use of bottom gating did reduce the amount of inclusions on the surface of the caps somewhat, but the improvement was not as drastic as expected. There were still more inclusions on the caps than in the original assembly. It is interesting to note that the cope surfaces of the castings in the top stacking layer had fewer inclusions than the castings in the bottom layer.

As seen in Table 1, the yield for the “3 down, bottom gating” case was 67.5%, and the yield for the “4 down, bottom gating” case was 69.0%. The change from three stacking layers to four, then, only increases the yield by 1.5%. The addition of layers beyond four would have a small impact on the casting yield. Similar conclusions can be made for the “poured through riser” designs. Comparing the “3 down, bottom gating” and “3 down, poured through riser” results, bottom gating reduces the yield by 5.5% and slightly reduces the amount of inclusions. However, the inclusion reduction is not significant enough to warrant the extra rigging required or the reduction in yield. The foundry may do just as well to use the “poured through riser” design, and possibly add one or more filters to reduce the amount of inclusions.

Unfortunately, the 21.2% yield improvement from the “3 down, bottom gating” assembly and the 22.7% yield improvement from the “4 down, bottom gating” assembly are offset by the increase in the number of surface inclusions on the caps. Unless a gating system can be designed for these vertical stacking arrangements that produces castings at least as clean as the caps from the original assembly, these yield improvements will not be realized. However, there is still the possibility of a 16.6% yield improvement through the optimized horizontal assembly. Because the rigging in this optimized design is similar to the original rigging, the resulting castings may have a comparable number of inclusions to the original caps.

This issue will be clarified when the casting trials for the optimized horizontal assembly are performed in the near future.

As a final note, although none of the alternate stacking designs used in the casting trials removed the shrinkage defects along the inner rim of the spring caps, some additional simulation work was done to investigate this problem. One simulated vertical 3-layer design did solve the problem. However, it required the use of a riser that passed through the center of the spring caps, riser blocks on top of the caps, and strategically placed chills on the caps. The additional cost in rigging and in the cleaning room rendered this design infeasible in practice.

4. Summary

A vertical stacking arrangement called the "I-pattern" was utilized in this study to increase the yield of 3" spring caps cast with WCB steel from 46.3% to a maximum of 73.0%. The original assembly used horizontal stacking, and the resulting castings contained some reoxidation inclusions. In addition, 25% of the original caps required welding for shrinkage defects on the inside rim of the caps. Alternate stacking designs were investigated using simulation software, and promising candidates were cast by the foundry that produces this part. A 3-layer "poured through riser" I-pattern design produced caps of comparable soundness to the original caps, with a 73.0% yield. However, caps produced from this design had significantly more surface inclusions. In an attempt to reduce the amount of inclusions, a thin, rectangular bottom gating system was used instead of pouring through the riser. A 3-layer I-pattern that used this bottom gating system produced caps of similar soundness compared to the original caps and a 67.5% yield. There were fewer inclusions than in the "poured through riser" design, but still more inclusions than in the original caps. Adding a fourth layer to this design increased the yield to 69.0%. However, unless a gating system can be designed for the I-pattern that can produce clean castings, the yield improvement possible with vertical stacking will not be realized. An optimized horizontal stacking design with a yield of 62.9% will be used in casting trials in the near future, and quite possibly may produce caps of comparable overall quality to caps from the original design.

ACKNOWLEDGMENTS

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REFERENCES

[1] 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*, 1999.

[2] Wlodawer, R. *Directional Solidification of Steel Castings*, Pergamon Press, 1966.

Table 1 Summary of different stacking arrangements for 3" spring cap stacking study.

Name	No. Layers/ No. Castings Per Assembly	Mold Size Per Layer (inches)	Riser Dimensions (inches)	Pouring time/ temperature (s/°C)	Yield (%)	Potential Quality Concerns
Original horizontal stacking	10 / 20	15.5 H x 24.8 W x 5.8 T	14 H x 2.5 W x 3 T	54 / 1620	46.3	Low yield, weld repairs, some inclusions
Optimized horizontal stacking*	10 / 20	15.5 H x 24.8 W x 5.8 T	9.6 H x 1.5 W x 3 T	54 / 1620	62.9	N/A*
I-pattern, 3 up, poured through riser	3 / 6	5.2 H x 24.8 W x 15.5 T	1.7 H x 3 W x 2.7 T	9.9 / 1566	73.0	Weld repairs, many inclusions on flange surface
I-pattern, 3 down, poured through riser	3 / 6	5.2 H x 24.8 W x 15.5 T	1.7 H x 3 W x 2.7 T	11 / 1613	73.0	Weld repairs, many inclusions
I-pattern, 3 down, bottom gating	3 / 6	5.2 H x 24.8 W x 15.5 T	1.7 H x 3 W x 2.7 T	18 / 1588	67.5	Weld repairs, more inclusions than original
I-pattern, 4 down, bottom gating	4 / 8	5.2 H x 24.8 W x 15.5 T	1.7 H x 3 W x 2.7 T	20 / 1588	69.0	Weld repairs, more inclusions than original

* This design was simulated, but the casting trials have yet to be performed.

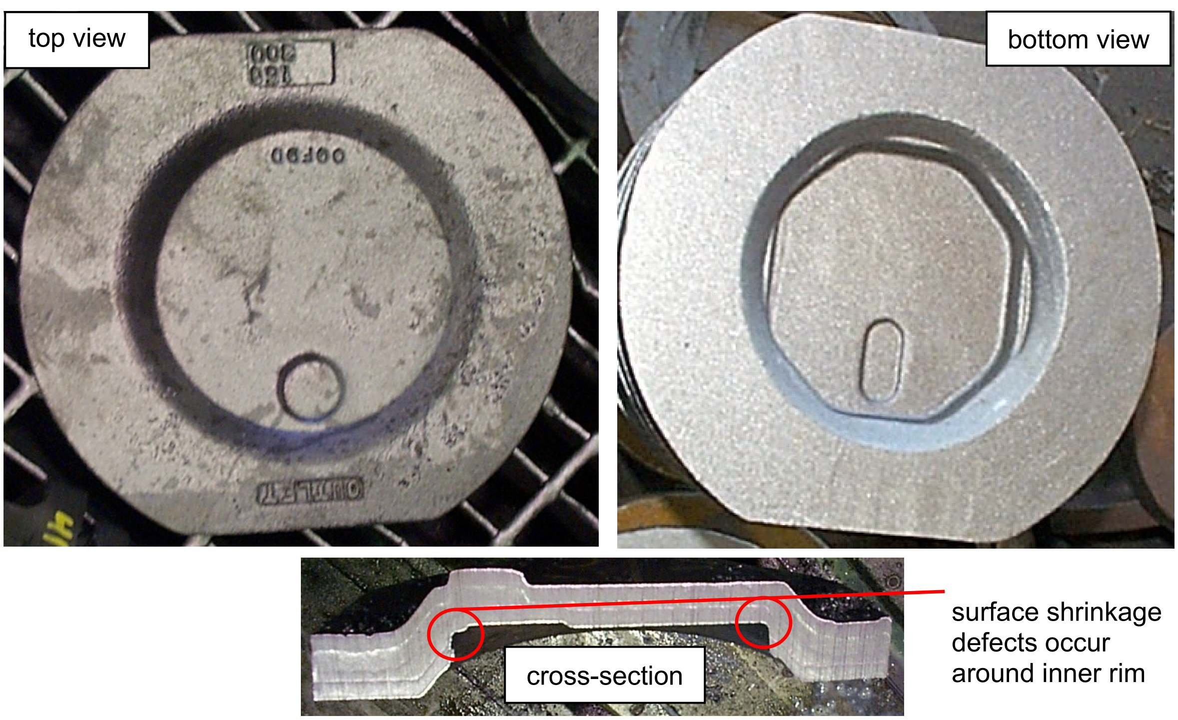


Figure 1 3” spring cap investigated in this stacking case study; the red circles show the location of surface shrinkage defects.

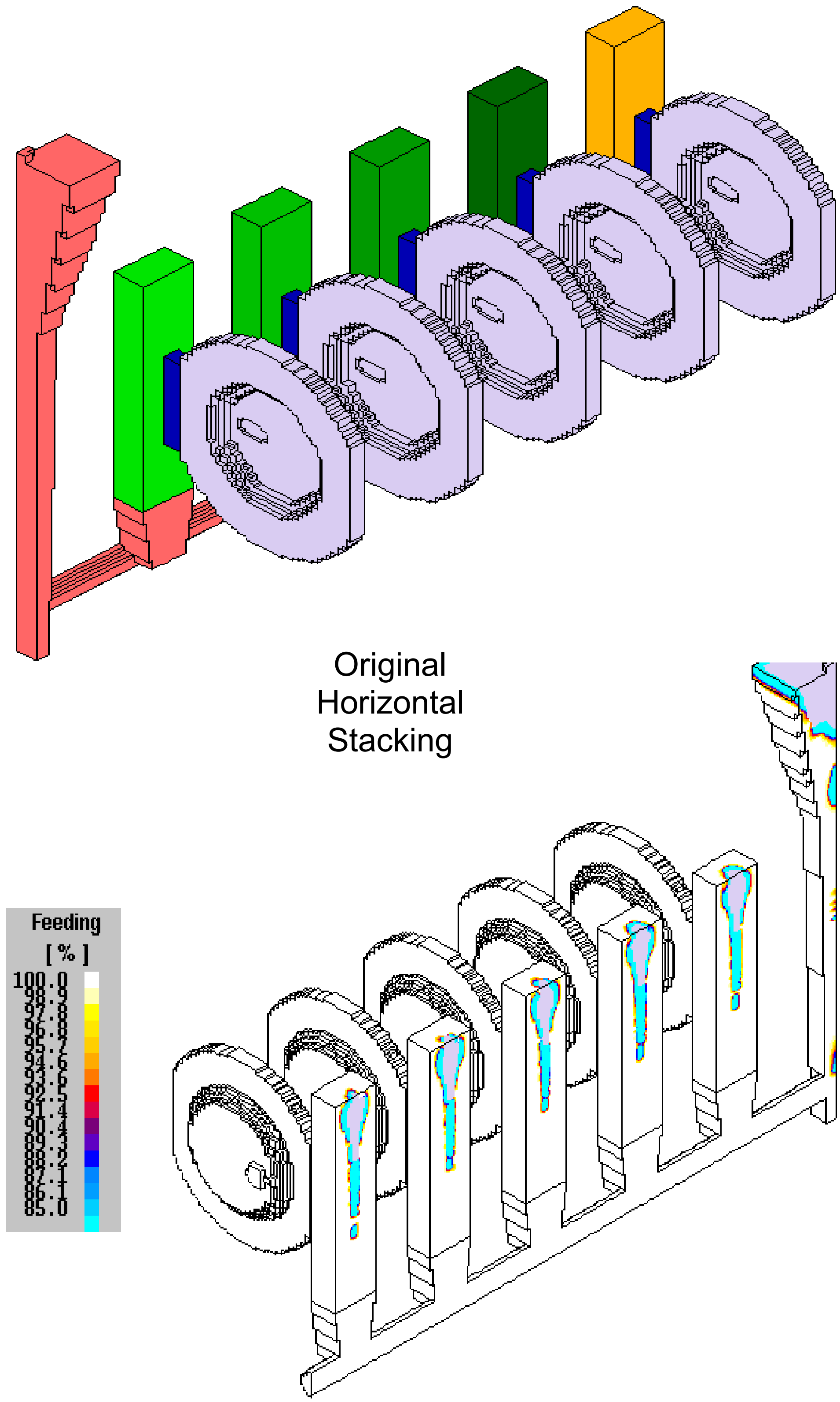


Figure 2 Original horizontal stacking assembly for 3” spring caps, with simulation results showing feeding percentage indications in risers (quarter-symmetry views shown).

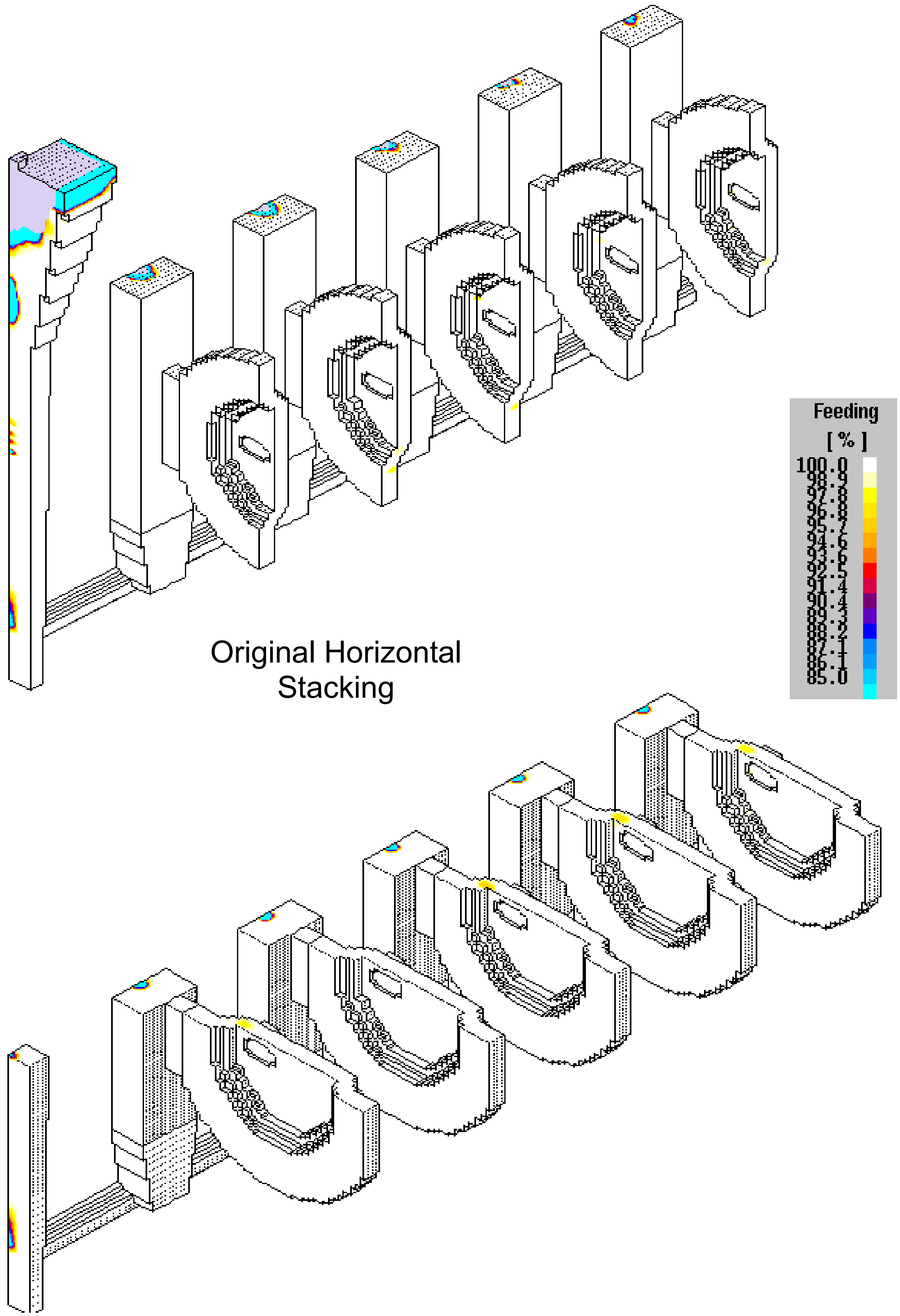


Figure 3 Simulation results for original assembly – feeding percentage in spring caps.

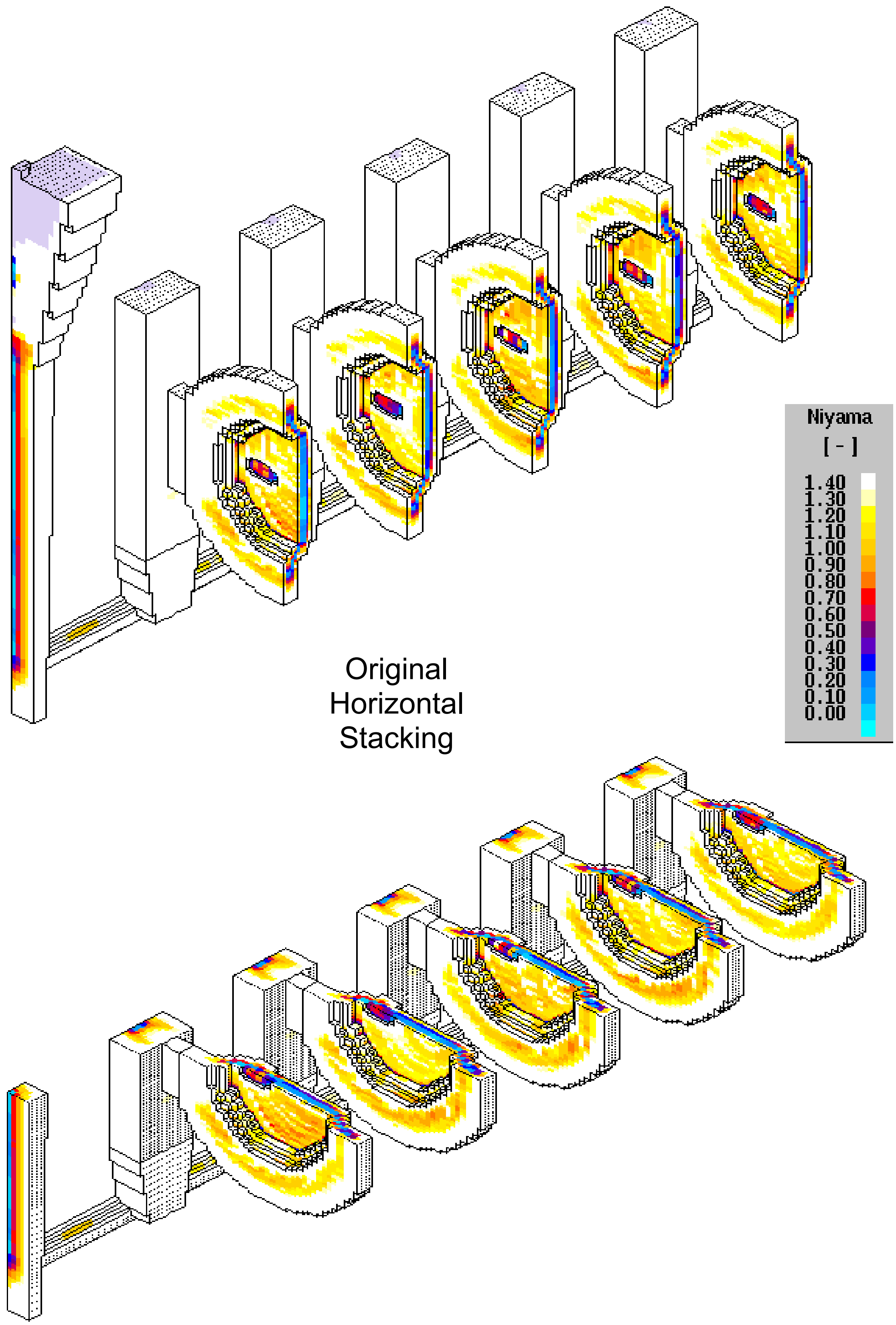


Figure 4 Simulation results for original assembly – Niyama indications.

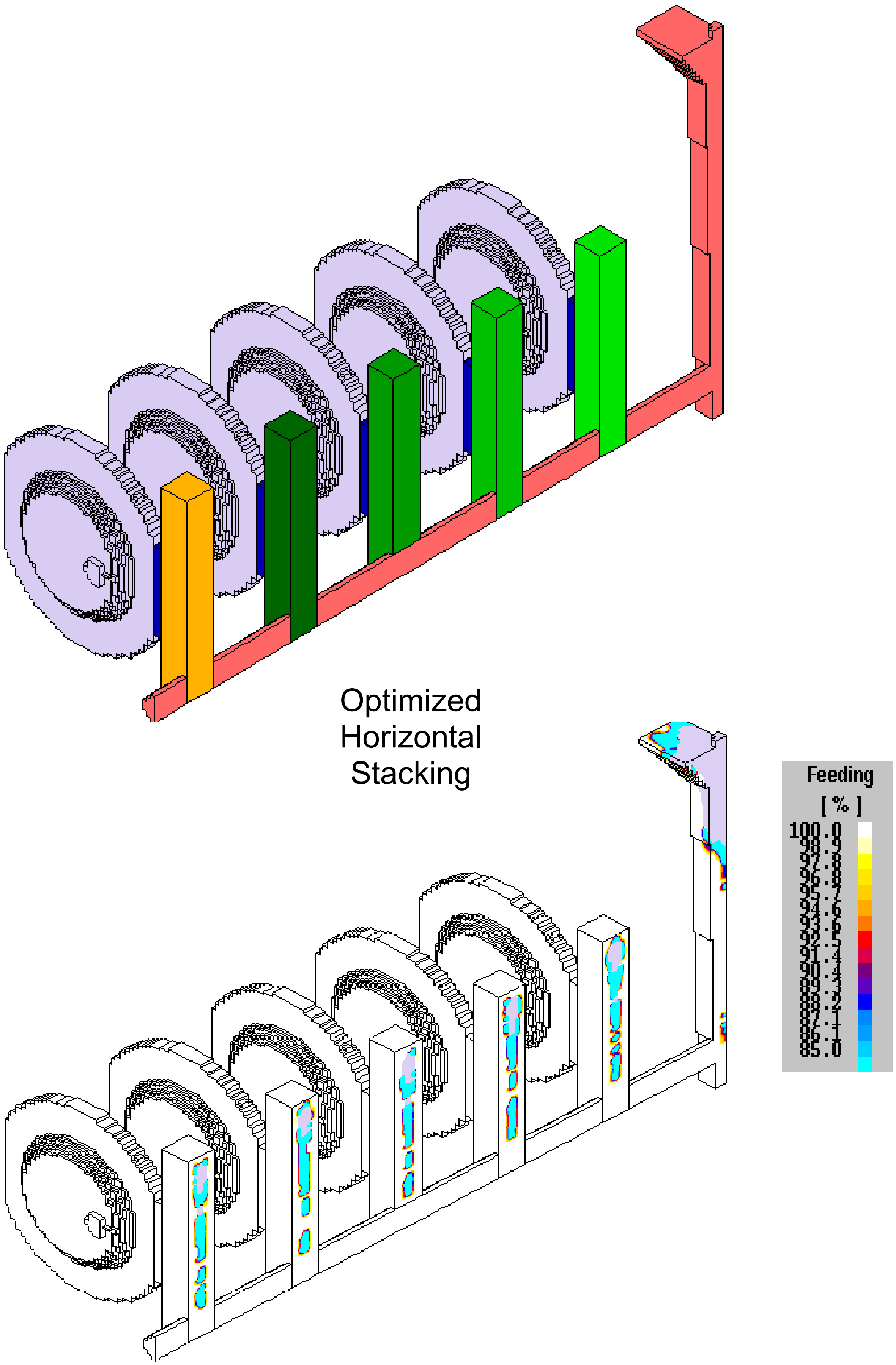


Figure 5 Optimized horizontal stacking assembly for 3” spring caps, with simulation results showing feeding percentage indications in risers (quarter-symmetry views shown).

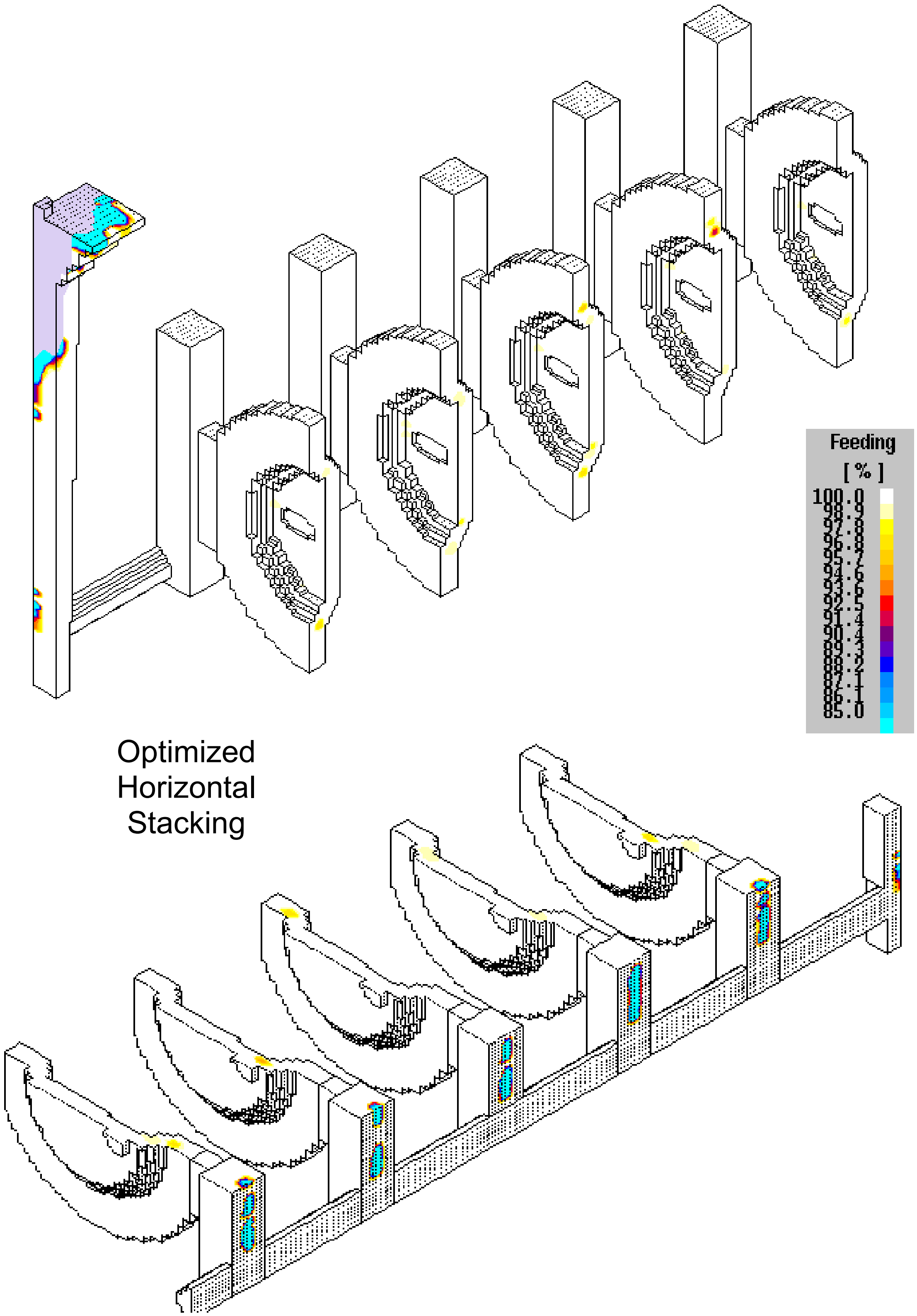


Figure 6 Simulation results for optimized horizontal assembly – feeding percentage in spring caps.

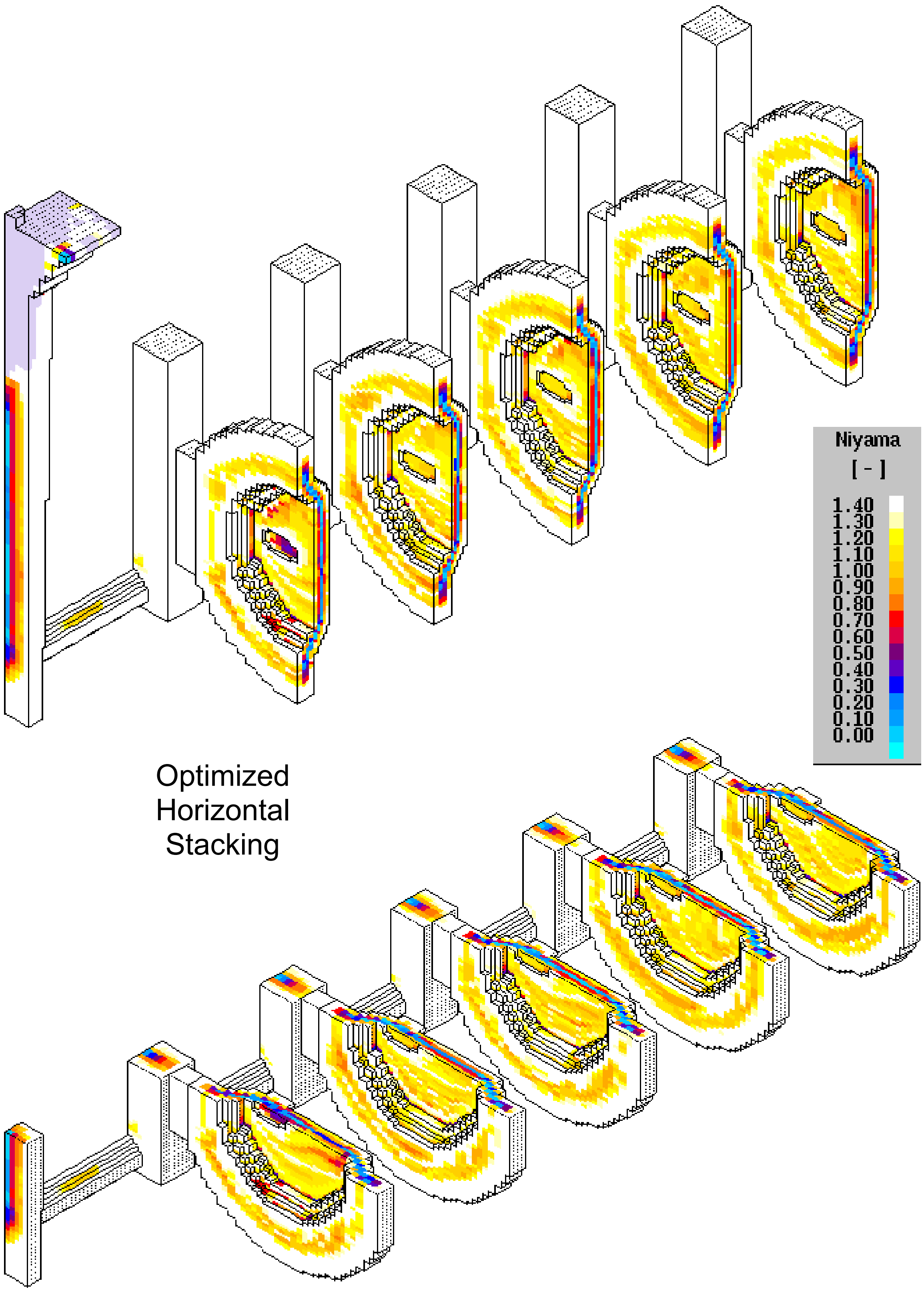


Figure 7 Simulation results for optimized horizontal assembly – Niyama indications.

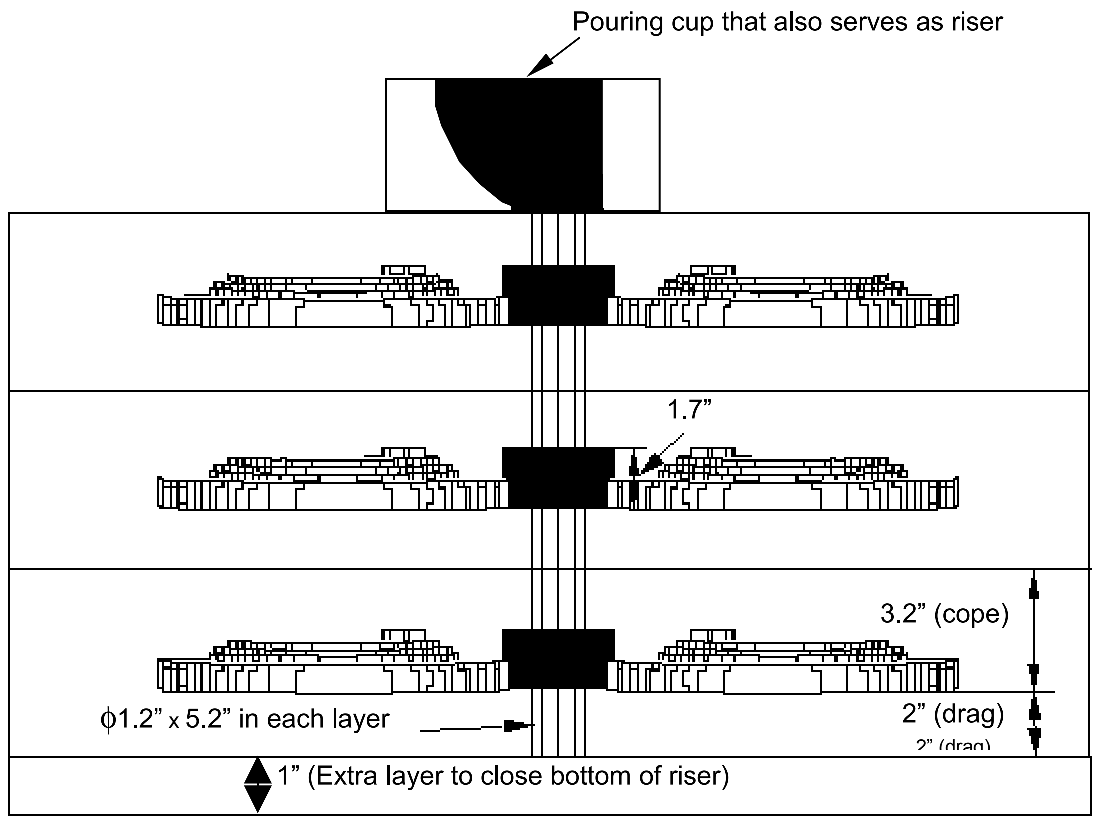


Figure 8 Sketch showing vertical stacking of casting mold boxes for I-pattern assembly.

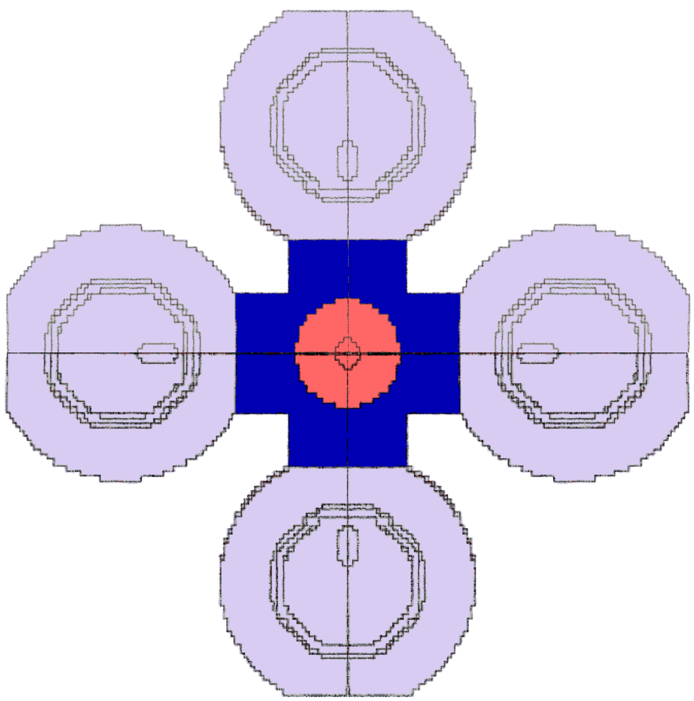


Figure 9 Top view of cross-pattern vertical stacking arrangement.

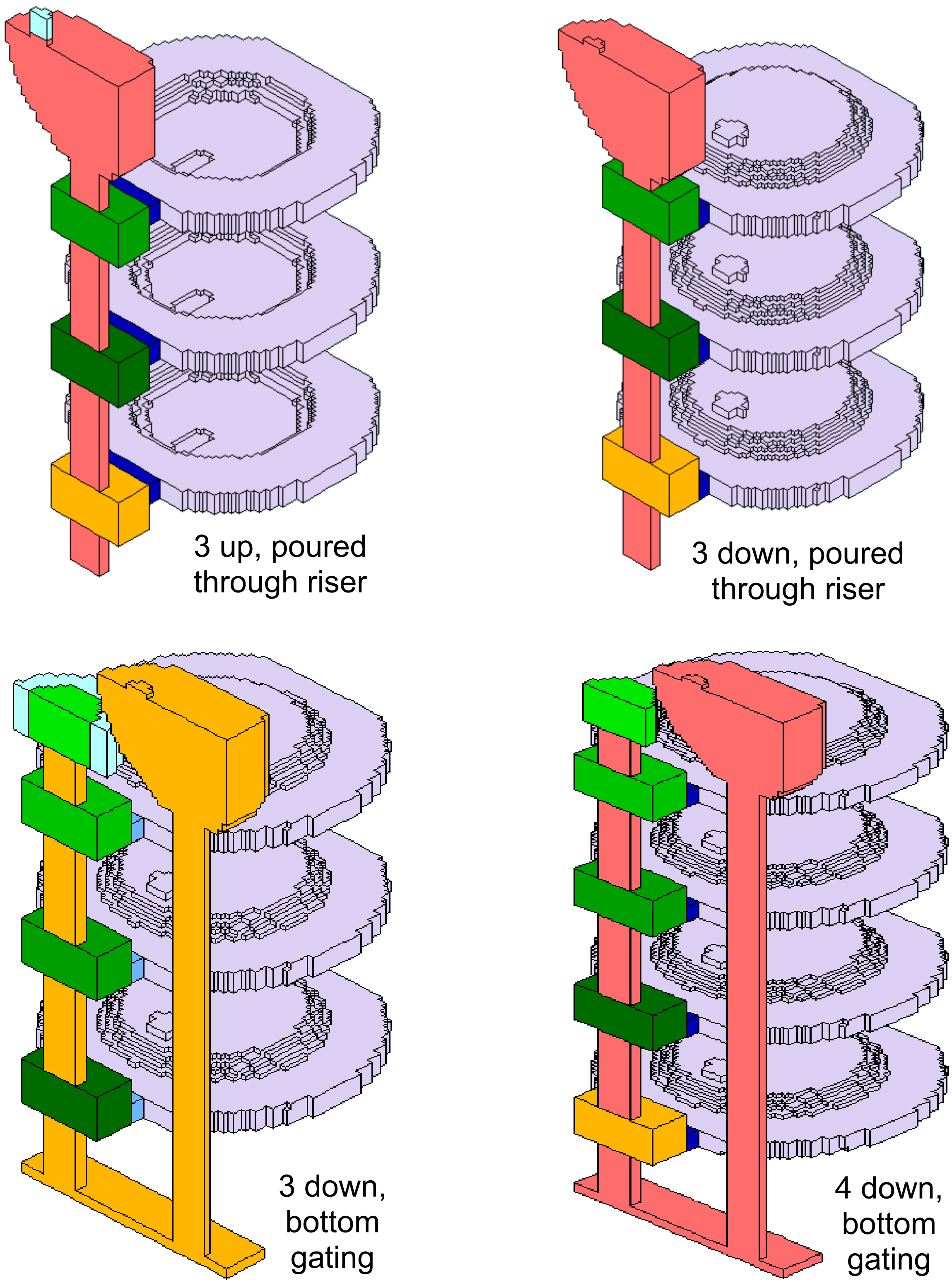


Figure 10 Four variations of I-pattern assembly used in casting trials (half-symmetry views shown).

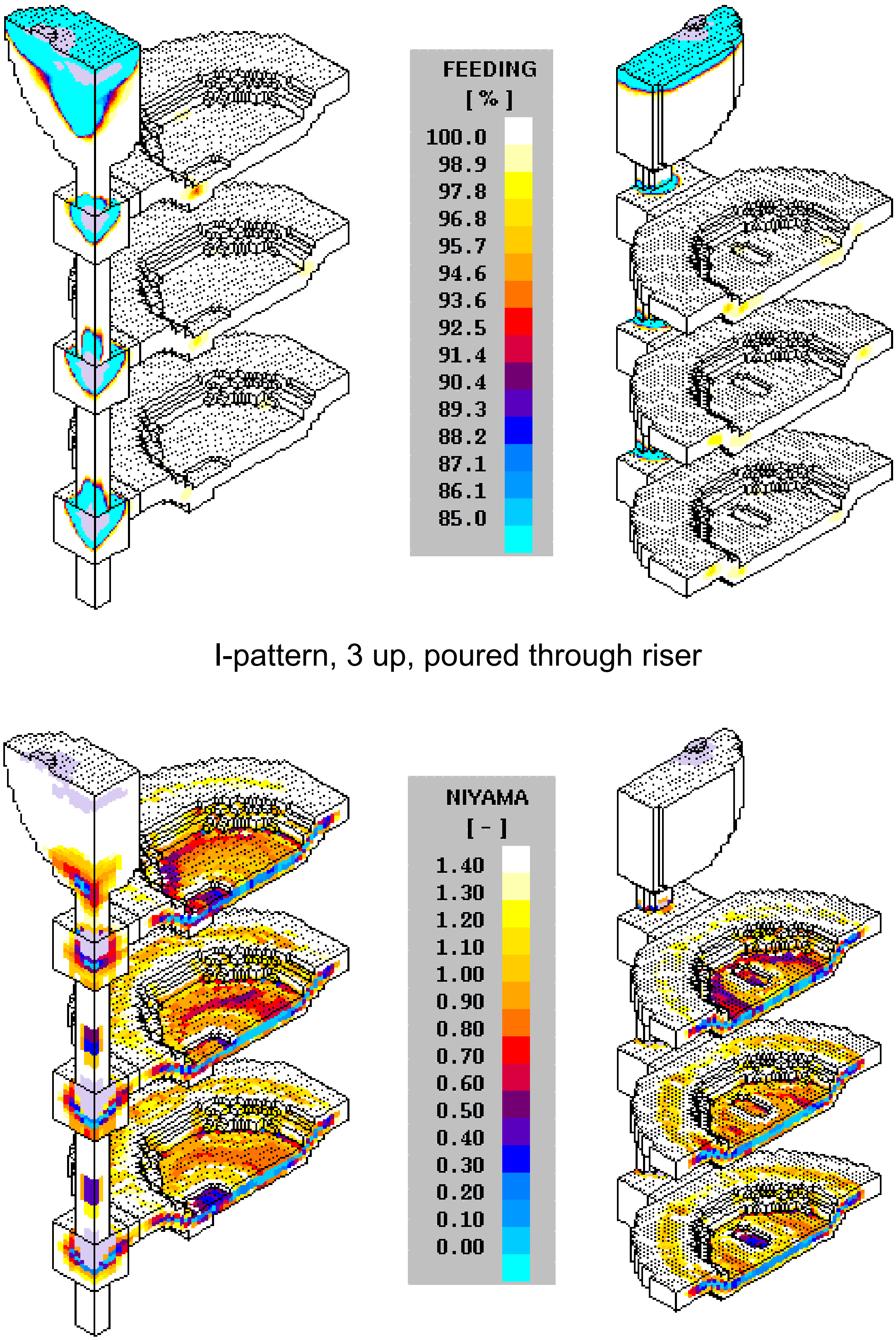


Figure 11 Simulation results for I-pattern with 3 stacking layers, flange-side up, poured through the riser.

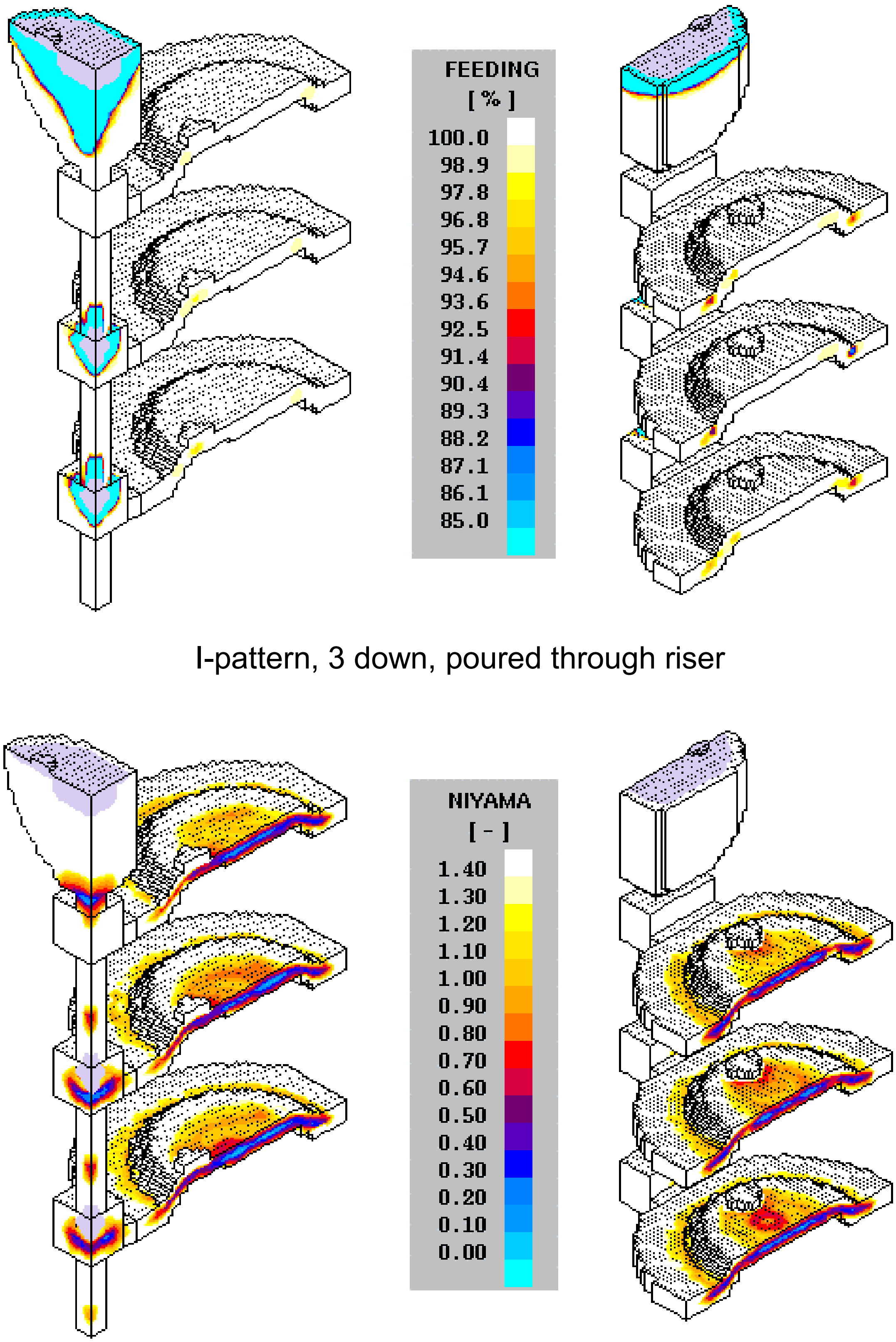
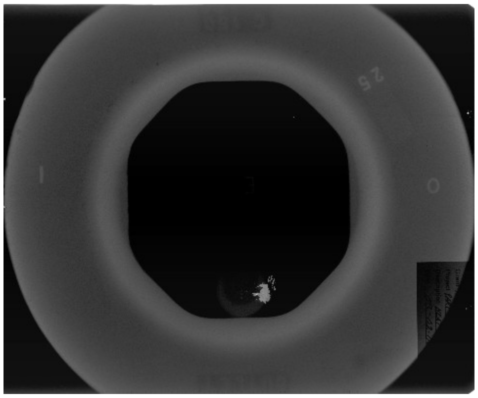


Figure 12 Simulation results for I-pattern with 3 stacking layers, flange-side down, poured through the riser.

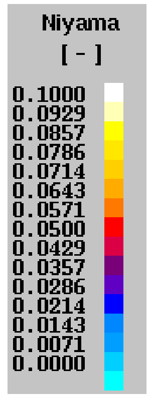
I-pattern, 3 down, poured through riser

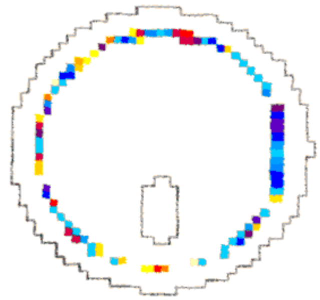
<u>Casting Trial Results</u>



X-ray film after scanning

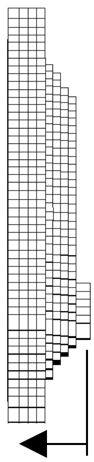
<u>Simulation Results</u>



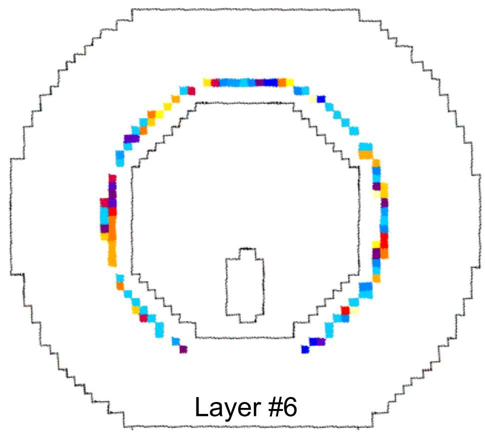


Layer #5

<u>Note</u>: In the color image below, the red and yellow areas in the interior of the spring cap correspond to shrinkage on the x-ray. The red/yellow/blue/purple areas near the inner and outer edges of the cap are merely edge effects, not shrinkage. Treatment of the scanned x-ray image with image analysis software (Transform) was necessary to bring out the defects, because the scanned x-ray image above is too dark to see the defects.



Layer # count



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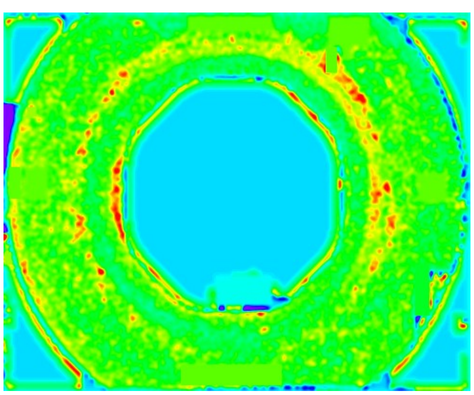
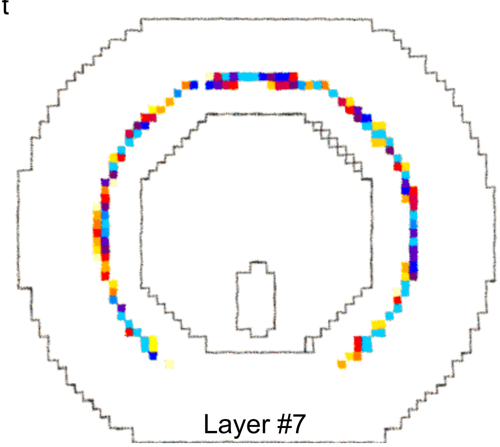


After handling with *Transform*



Layer #7

Figure 13 Comparison of casting trial results and simulation results for I-pattern with 3 stacking layers, flange-side down, poured through the riser.

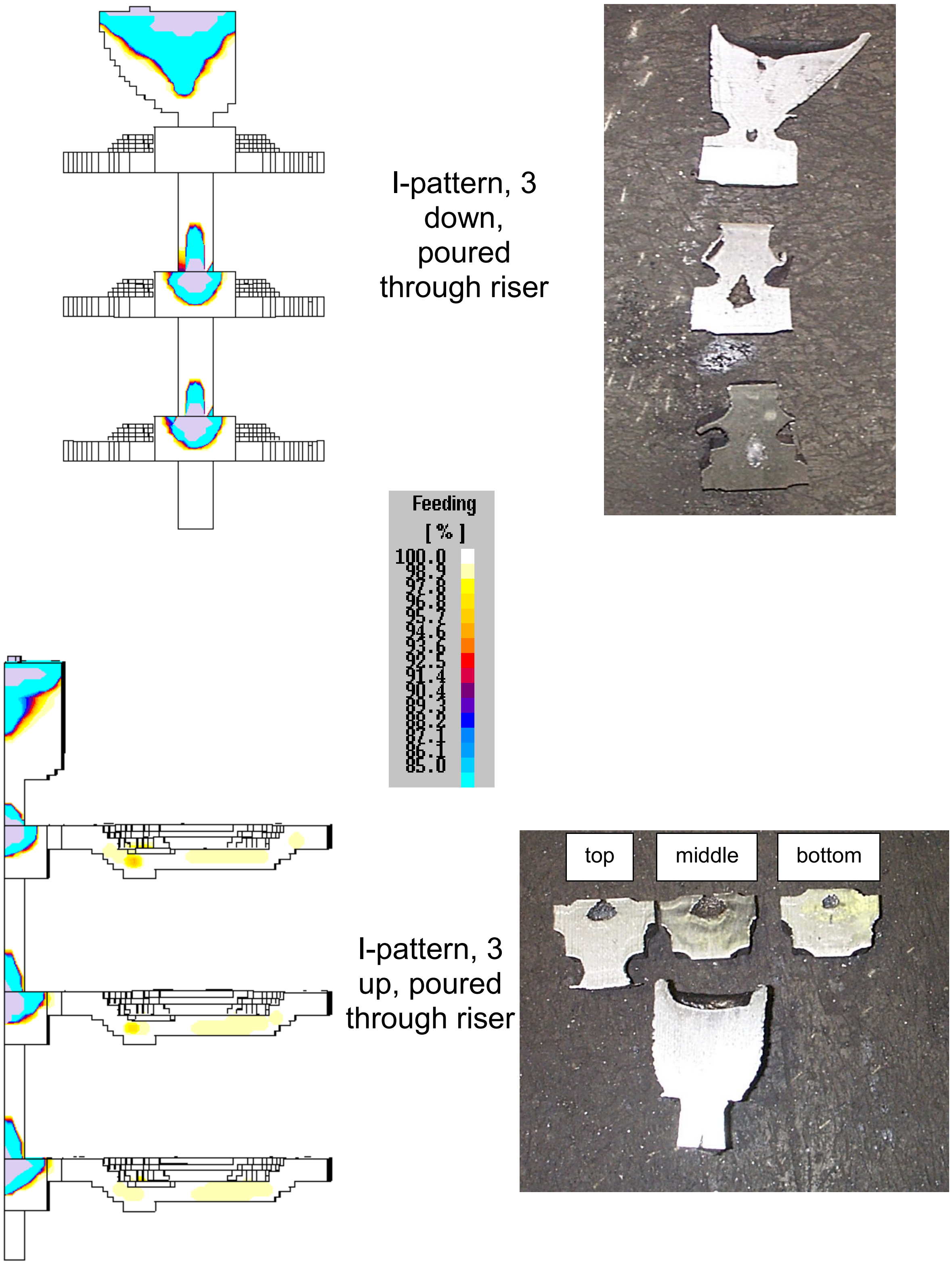
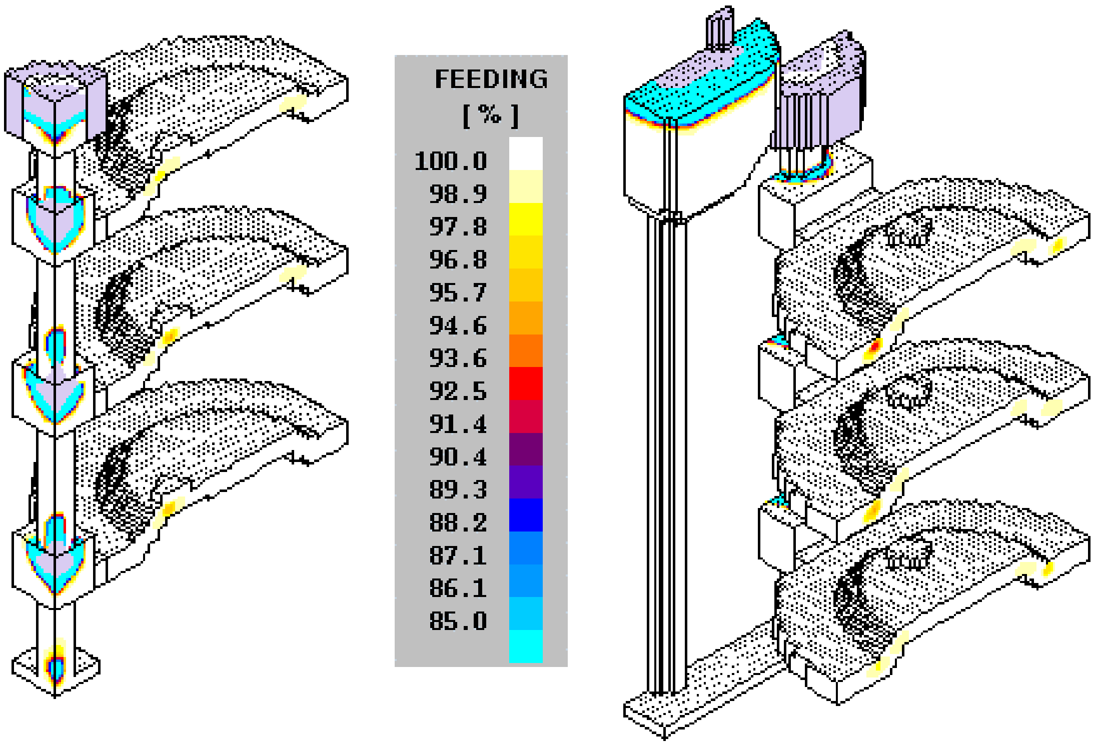


Figure 14 Comparison between simulation results and casting trial results of riser shrinkage cavities for both I-pattern assemblies poured through the riser.



I-pattern, 3 down, bottom gating

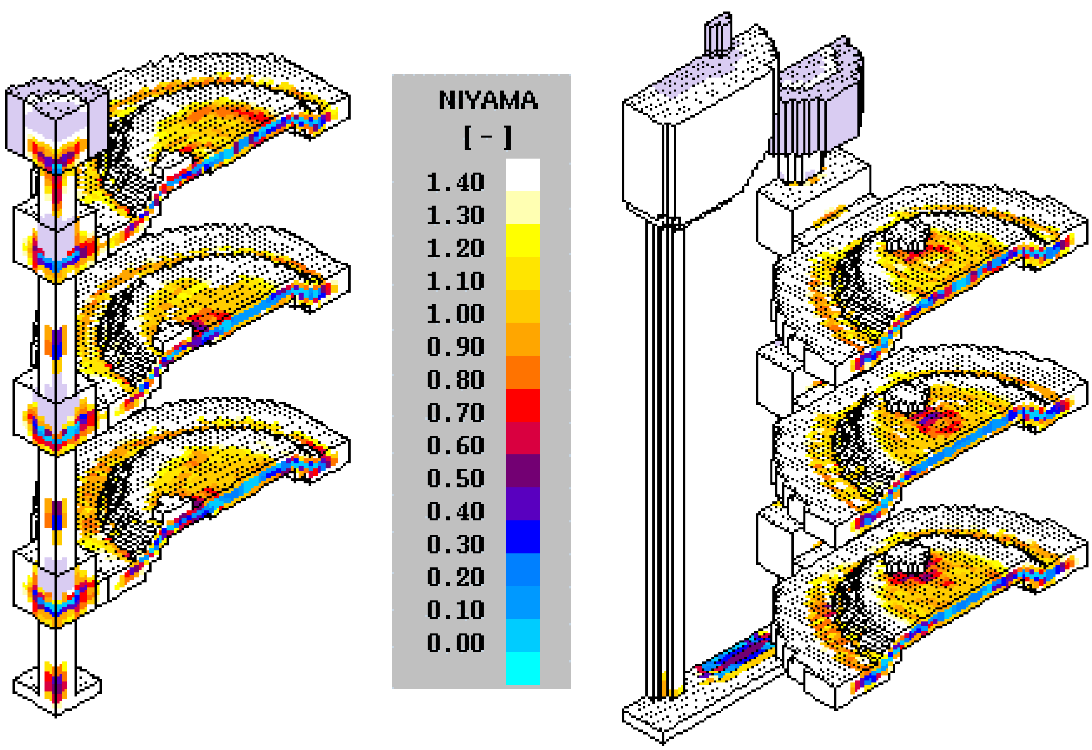


Figure 15 Simulation results for I-pattern with 3 stacking layers, flange-side down, and bottom gating.

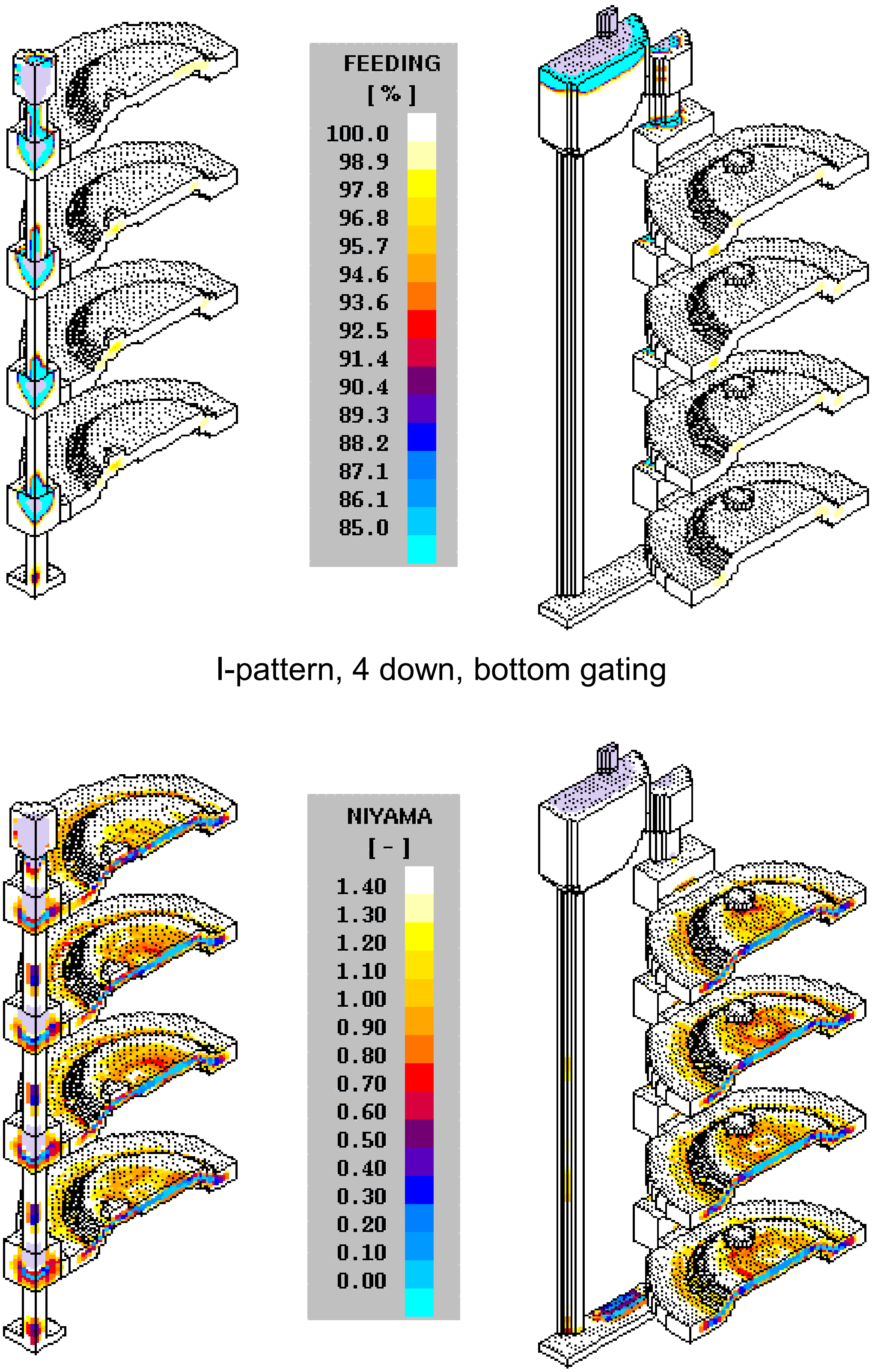


Figure 16 Simulation results for I-pattern with 4 stacking layers, flange-side down, and bottom gating.

I-pattern, 4 down, bottom gating

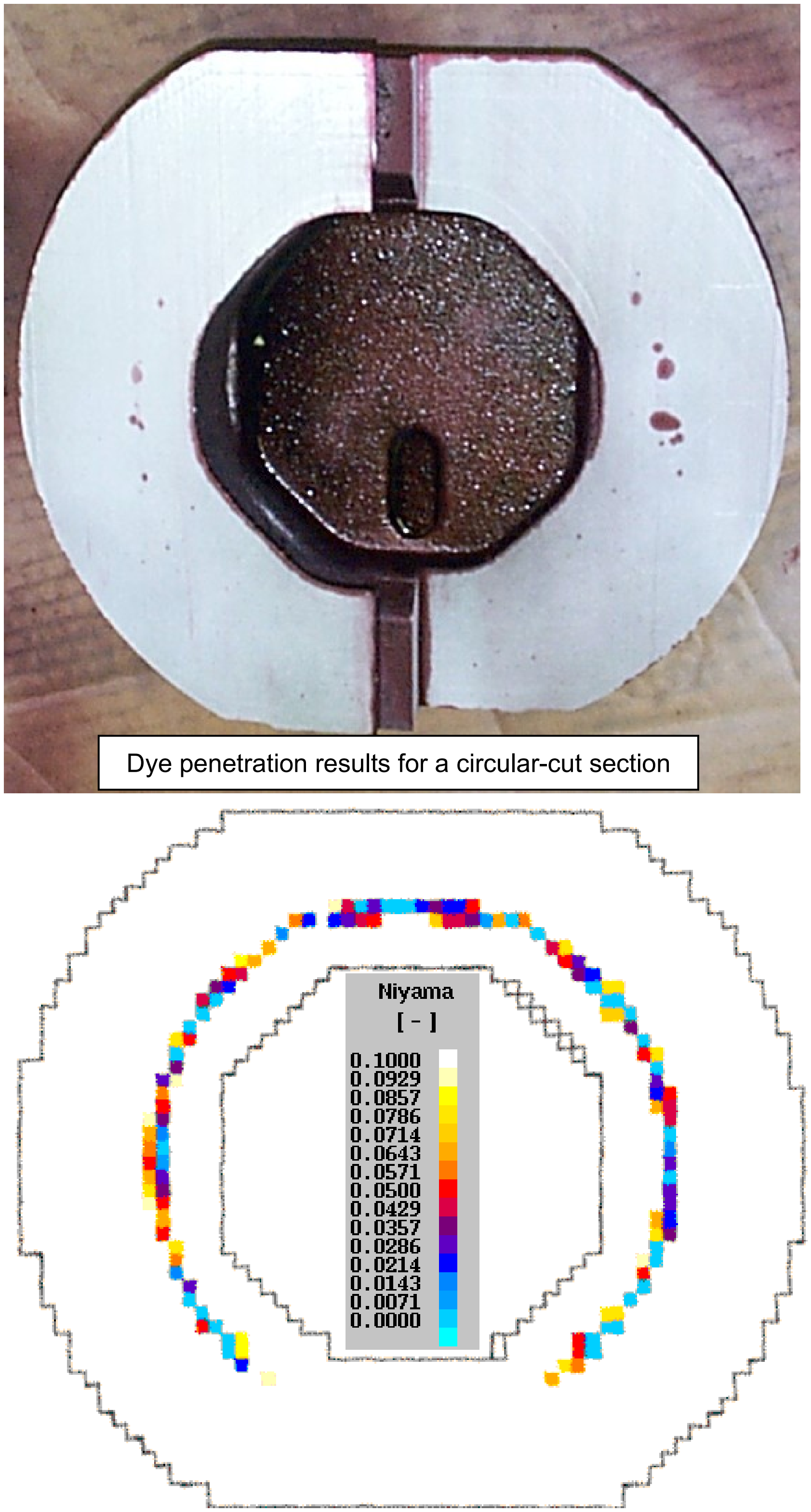


Figure 17 Comparison of casting trial results and simulation results for I-pattern with 4 stacking layers, flange-side down, and bottom gating.

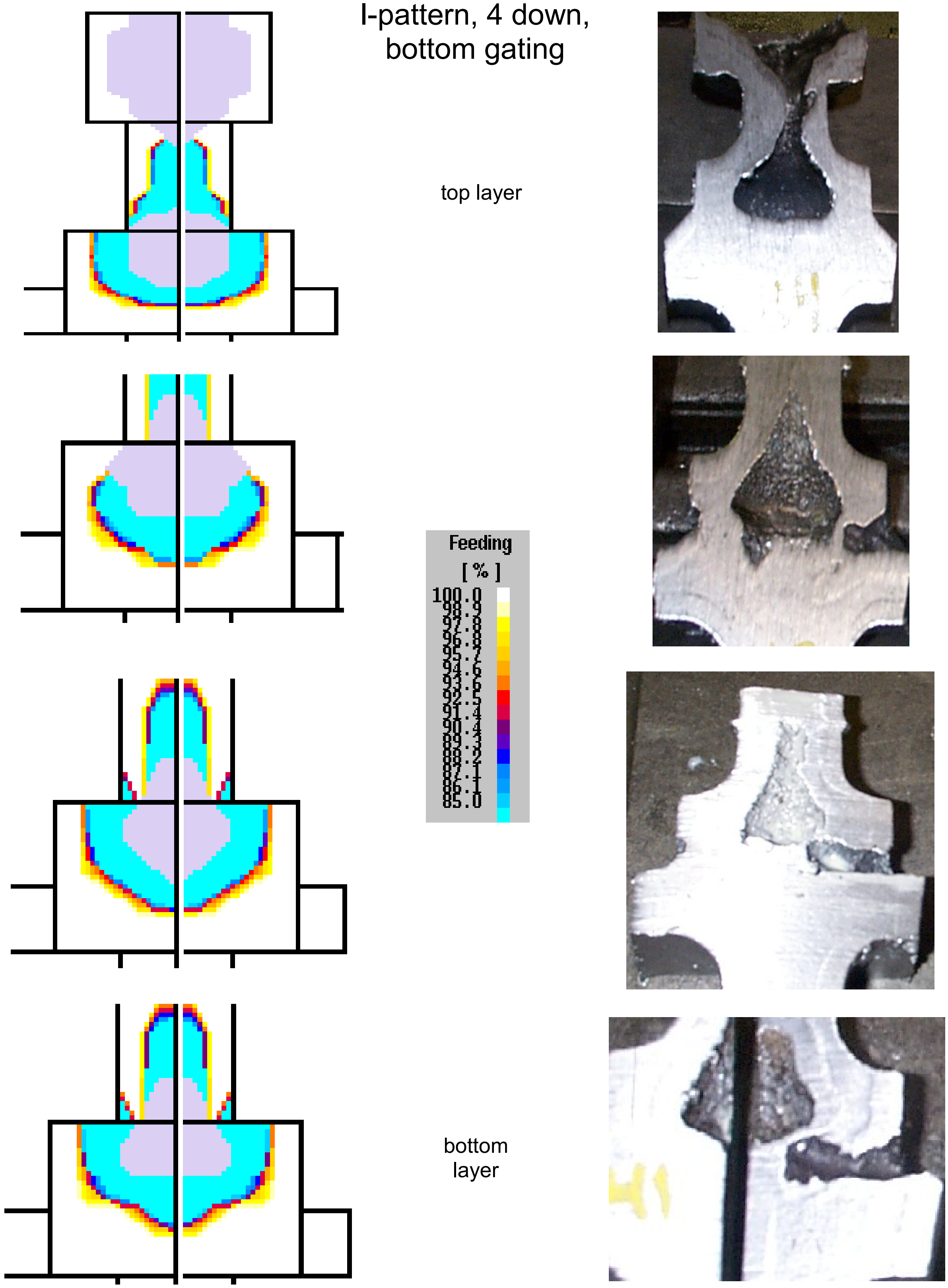


Figure 18 Comparison between simulation results and casting trial results of riser shrinkage cavities for I-pattern with 4 stacking layers, flange-side down, and bottom gating.