The Effect of Pour Time and Head Height on Air Entrainment

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Introduction.

Oxide macroinclusions have been a special area of study for SFSA for many years. SFSA Research described early work on the ceroxide defect (1,2,3). This work pointed out the need for quality refractories. The formation of ceroxides was reviewed in 1970 (4). Ongoing customer concerns about inclusions were identified by the SFSA Quality Assurance Task Force in the early 1980's. This led to a series of recent projects sponsored by SFSA on the production of clean steel (5,6).

The first two clean steel projects identified reoxidation as a major contributor to inclusion formation in steel casting production. This is similar to the findings in the wrought steel industry in continuous casting production. They have used water modeling to understand steel flow in tundish operation. Water modeling appeared to hold promise for the evaluation of pouring operations in steel casting production.

In the first year of the current clean steel program, our understanding of fluid flow has been greatly improved. The literature survey reviewed the usefulness of water modeling in steel handling and the amount of air entrainment in water systems (7). It suggested that the amount of air entrained was influenced directly by the velocity of the pouring stream and inversely by the diameter of the stream. In simple terms this suggested that the higher the stream velocity and the smaller the diameter of the stream the greater the amount of air entrained. The literature survey also confirmed that these results should be applicable to steel.

One of the major sources of reoxidation is thought to be the entrainment of air during pouring. Measurement of air entrainment in typical foundry pouring systems was part of this water modeling project. The greater the amount of air entrained, the greater the number of oxide macroinclusions will form. The results of the water modeling study are presented in another paper at this conference (8).

Watermodeling allows an analysis of air entrainment. In particular, a relationship can be developed between the amount of air entrained and the pouring time. This should be quite useful since pouring times are commonly measured and recorded in commercial casting production.

Pouring Time.

Pour fast and cold is the normal advice given for the production of good castings. Fast pouring times are normally thought to be advantageous to the reduction of inclusions. The shortest practical pouring time will normally produce the best casting. Short pouring times decrease the exposure of molding sands to moving metal and minimize the time available for reoxidation. The average pouring time (seconds) for most castings is equal to the square root of the weight (pounds) seen in Figure 1:

$$PT=(Wt)^{0.5} \quad \text{--------------------} \quad A$$

It is possible to reduce this pouring time to 2/3 of the time given in Equation A. Both AFS and SCRATA proposed more complex expressions for pouring time (9). While short pouring times are a well established practice, little technical confirmation has been published.

Pouring time is controlled by the mass flow rate in the pouring operation. The velocity and crosssection of the stream normally determine the mass flow rate. It is well known that:

$$V = (2gh)^{0.5} \quad \text{------------------------------} \quad B$$

where, V = velocity
g = gravitational acceleration
h = head height

The pouring time is related to velocity and the diameter of the stream which gives the expression:

$$PT = k_1* 1/(h^{0.5} * D^2) \quad \text{------------------} \quad C$$

where, PT = pouring time
k_1 = constant
D = diameter of the stream

In the first clean steel effort, several foundries produced a test plate that were evaluated for inclusion levels. The pour times for these plates was recorded and this data was evaluated. The pouring times and ratings for a single foundry are shown in Figure 2 and all the available data is plotted in Figure 3. The scatter in the data indicates that some factors beyond pouring time are important.

A new bottom pour nozzle design was developed by SFSA and evaluated in a large industrial trial (10). These trials were reevaluated as part of the current clean steel efforts to try and estimate the heat to heat effect. As a part of that evaluation, pouring time and casting quality were plotted In Figure 4. This chart is similar to Figure 3, indicating increased inclusions with longer pouring times, but without a simple relationship between pouring time and quality.

Air Entrainment

The literature review of watermodeling suggested that the velocity and diameter of the stream also have a significant effect on the amount of air entrained (7). This implies that it should be possible to relate air entrainment directly to pouring time. This relationship is not simple, it must be derived from the different relationships that air entrainment and pouring time have to the height and stream diameter.

The water modeling data included both pouring time and air entrainment shown in Figure 5. This is similar to the casting results in Figures 3 and 4 which shows significant scatter with some results at low pouring times and low air entrainment or inclusion level, some results showing rapid increase in air entrainment with pouring time, and some results show only a modest rise in air entrainment with increased pouring times. Some of these results show higher inclusion levels for shorter pouring times. This highlights the need to develop a more complex relationship between pouring time and air entrainment based on stream height and diameter.

The literature review (7) reported in equation 2.10 that:

$$k_2 = q_{ae}/(V^3/g) \text{ ------------------------- D}$$

where, k_2 is a constant
          q_{ae} is the air entrainment per stream width.

This results in equation 2.13:

$$B_e = k_3 \ h/D \text{ ---------------------------- E}$$

where, B_e is a measure of entrainment.

Equation E is for air entrainment per stream width. If the air entrainment rate is used instead, dimensional analysis leads to a different result:

$$k_4 = Q_{ae}/(V^5/g^2) \text{ ----------------------- F}$$

where, k_4 is a constant
          Q_{ae} is the rate of air entrainment.

The total amount of air entrainment is:

$$AE = Q_{ae} \ PT \text{ ---------------------------- G}$$

where,   AE is the amount of air entrained.

Substituting equation B into F and solving for Q_{ae} results in a relationship between pouring time and air entrainment:

$$AE = k_5 \ h^{2.5} \ PT \text{ ----------------------- H}$$

This proposed relationship between pouring time and air entrainment is shown in Figure 6. This plot includes all the water modeling results except the sprueless data where the air supply was shrouded from the stream. It includes lip pour, quadrant trials, throttled and open bottom pour. With a wide variation in pouring conditions and systems, the air entrainment remains nicely related to the pour time and pour height.

The use of dimensional analysis to develop equation H should be verified from the data. Additional plots were made using logarithmic scales. Figure 7 shows the relationship between the logarithm of the pouring height, Ln (h), and the logarithm of the air entrainment divided by the pouring time, Ln (AE/PT). This verifies the expression in equation H, especially the exponent of 2.5 on h. The slope of the line in Figure 7 is 2.5.

Discussion

The expression for air entrainment and pouring time given in equation H may be useful in understanding and controlling air entrainment in steel casting pouring systems. The powerful effect of height suggests the need to engineer pouring systems which minimize the height difference between the ladle and the casting.

Some information does suggest that head height may be a significant factor in practice. In the first project, the test plates results were plotted versus the ladle size as shown in Figure 8 (5). The increase in inclusions with larger ladles would be the result of greater head height. Ladles normally have a height to diameter ratio of 1 to 1.5 so that larger ladles inevitably have greater head height at the beginning of pouring.

This equation also shows why the first castings from a bottom pour ladle even with shorter pouring times are normally more prone to inclusions than the last castings poured, the reduction of total height in the pour system. It also suggests that the results of casting trials in Figures 3 and 4 may be due to variations in pour height. Since the pour height is not available for these trials, no correlation with equation H is possible. This points out the need to record all of the normal operating parameters when doing trials of this sort.

More data analysis is needed on casting trials especially those from the nozzle trials (10). The equation H does begin to give the steel casting industry an engineering approach to reduce air entrainment and inclusion formation.

Reducing the pouring time will reduce air entrainment if not offset by the effect of higher head heights. The only practical way to do this in bottom pouring is through the use of larger nozzles. If the larger nozzles are throttled this will increase air entrainment (8).

The amount of air entrainment in steel pouring is fundamentally related to the velocity of the pouring stream. Any design that is intended to minimize air entrainment must reduce the pouring stream velocity. This is the basic design criteria in any pouring system to reduce air entrainment.

References

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8. C. Wanstall, J. Griffin, and C. Bates, "Water Modeling of Steel Pouring Practices", SFSA 1993 T&O Conference Proceedings

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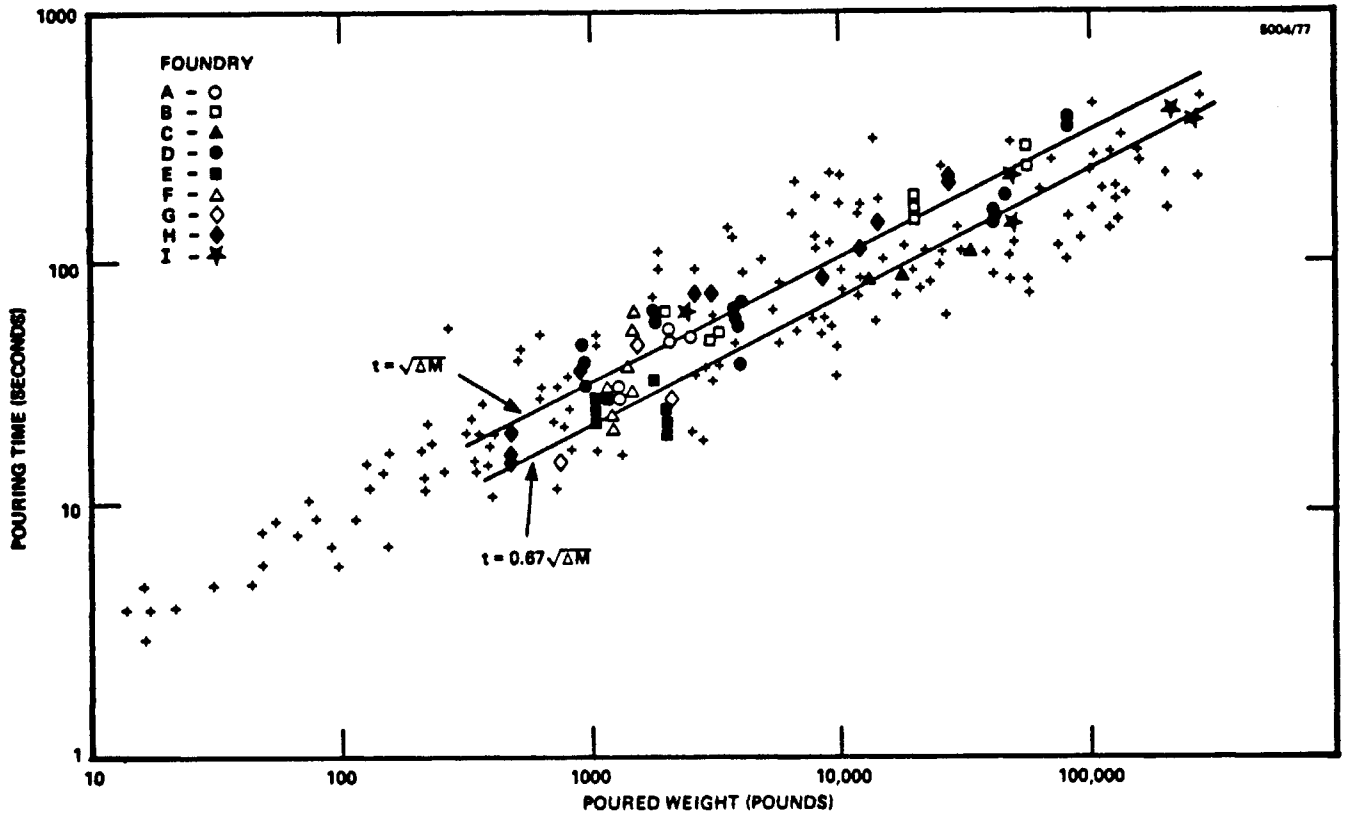
Fig. 1 Industrial survey of pouring times and weights in steel casting production. (9)
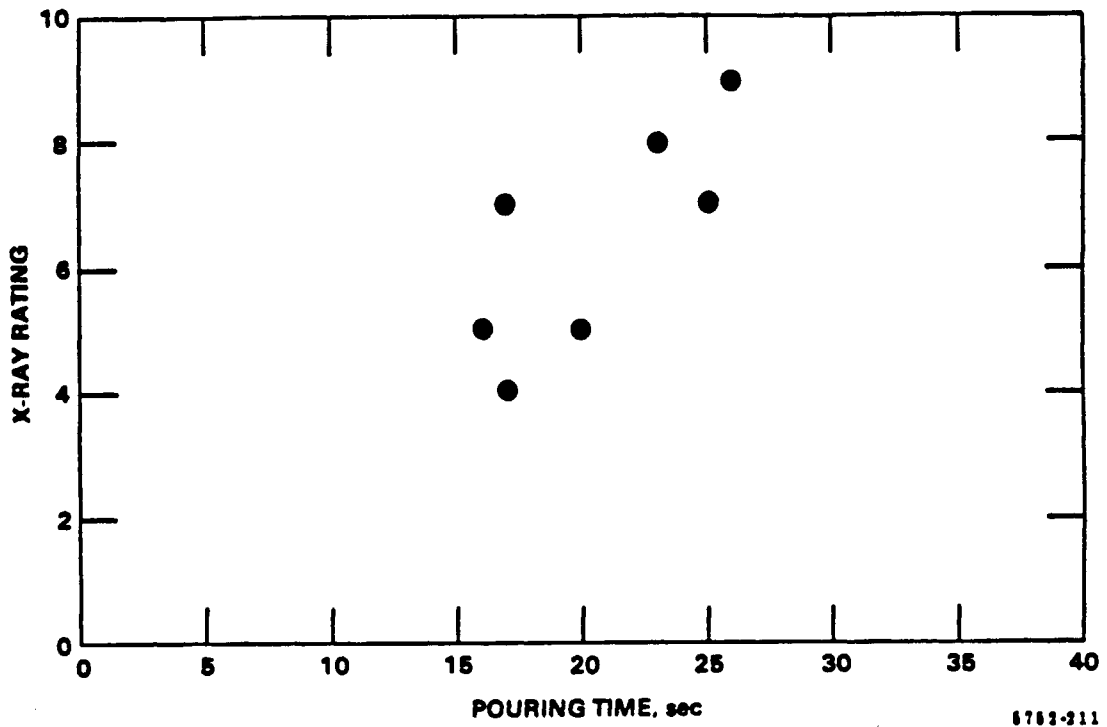

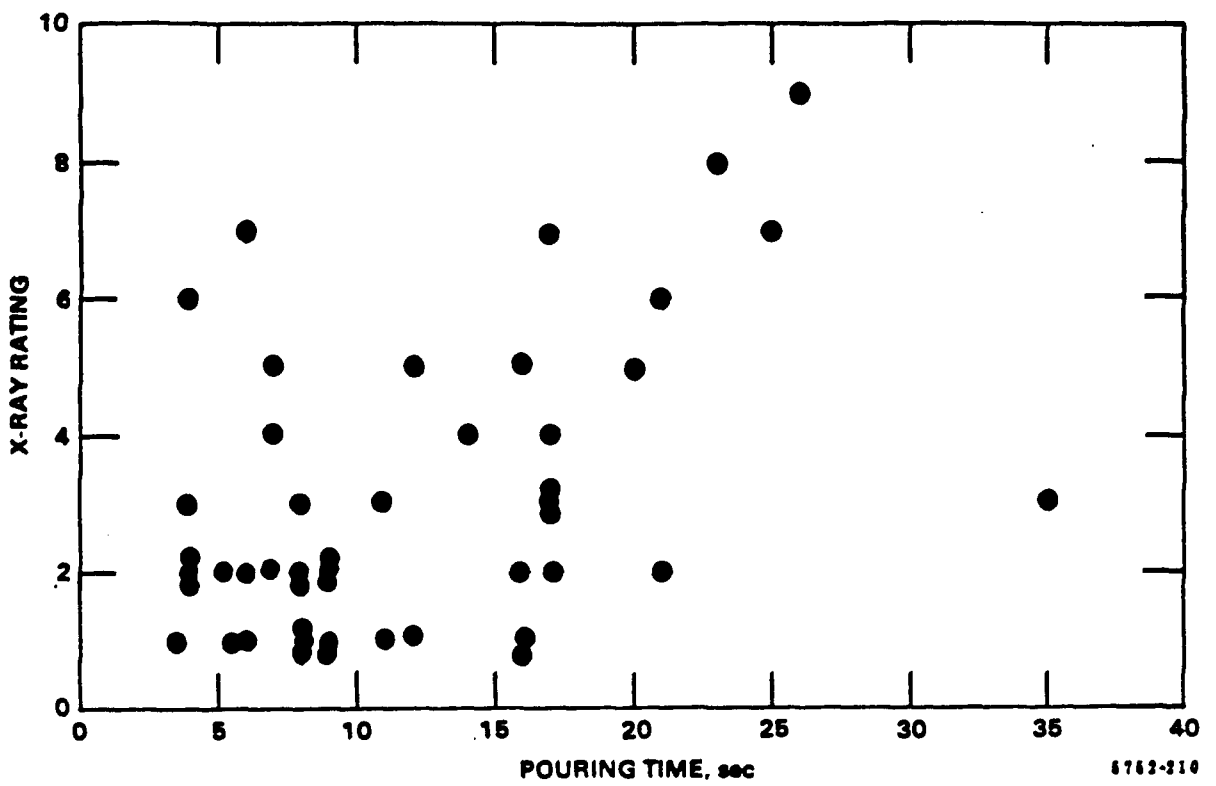Fig. 2 Pouring time and cleanliness rating in a single plant. (5)

Fig. 3 Pouring time and cleanliness rating for all participants. (5)
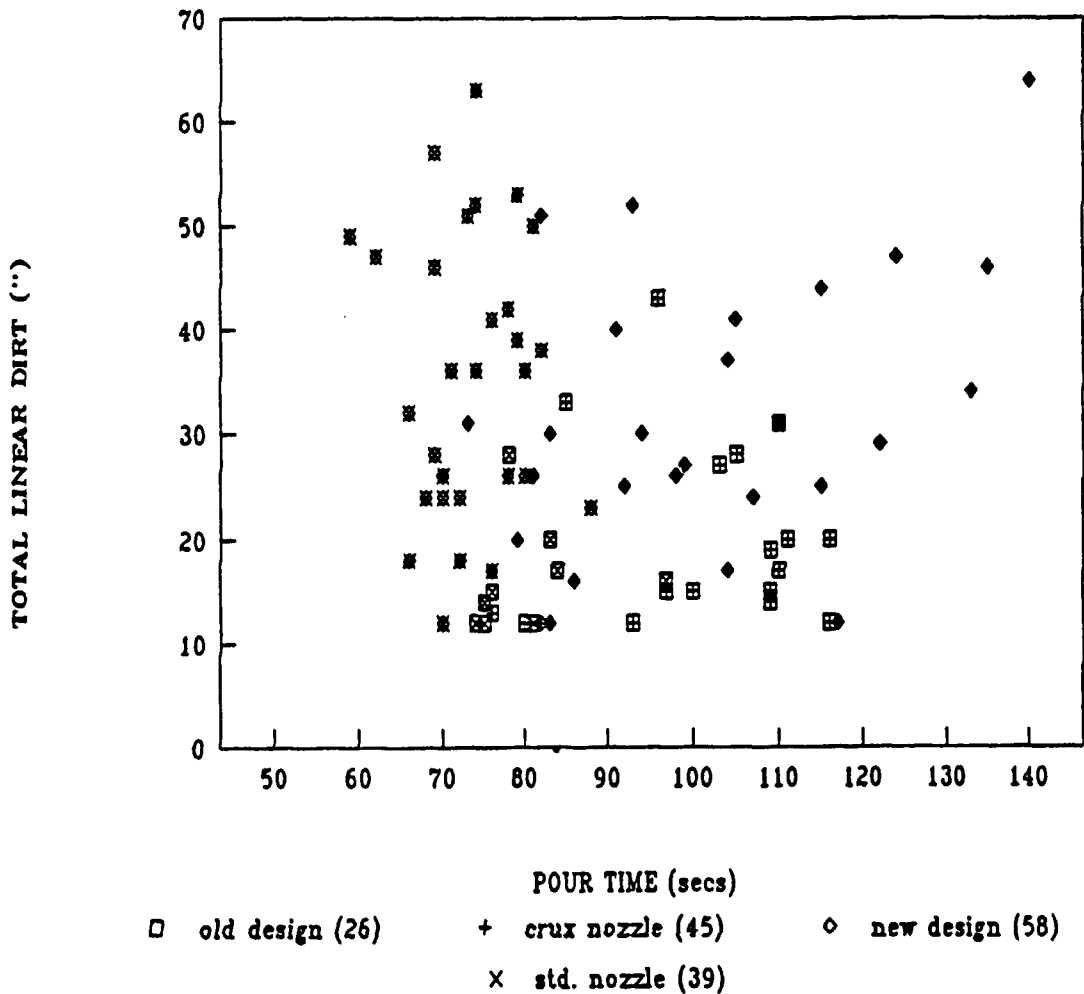

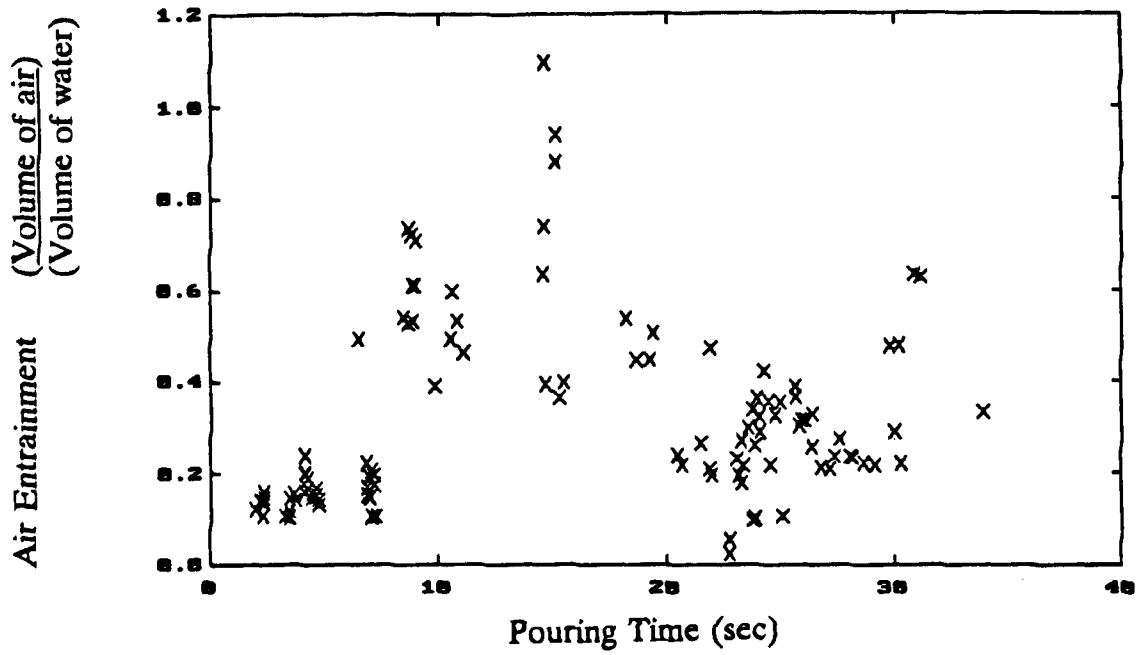Fig. 4 Total "Dirt" length and pouring time for transmission case castings.

Fig. 5 Pouring time and air entrainment from water modeling trials. (8)
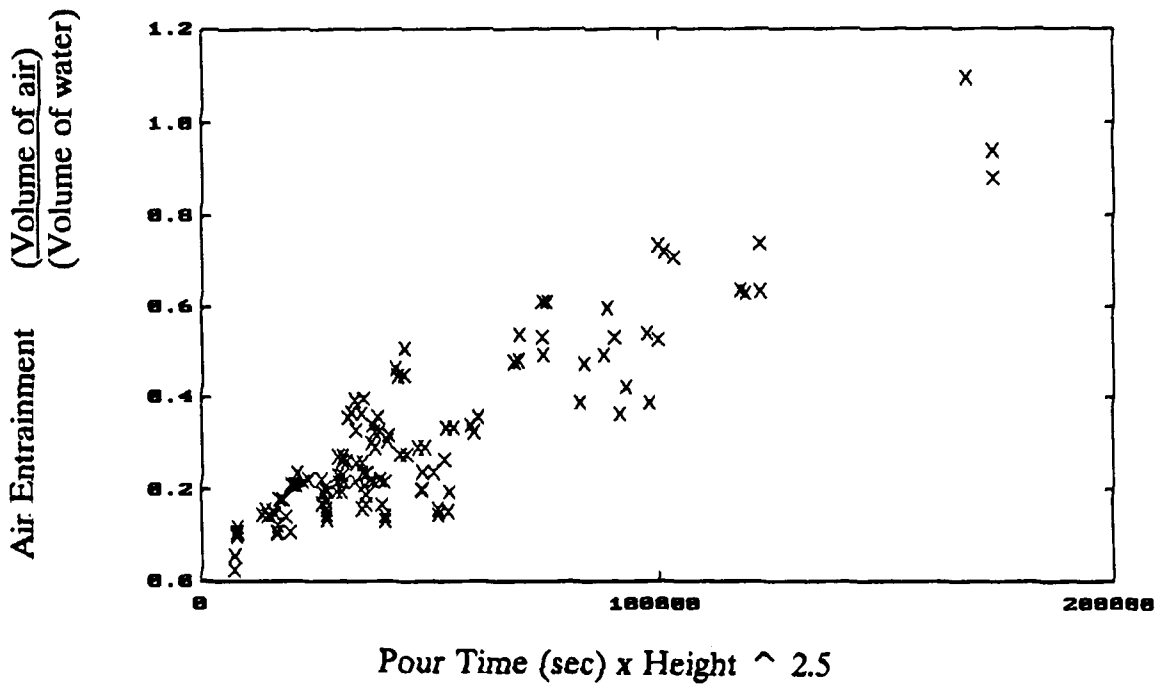

Fig. 6 Equation H plotted for water modeling results.
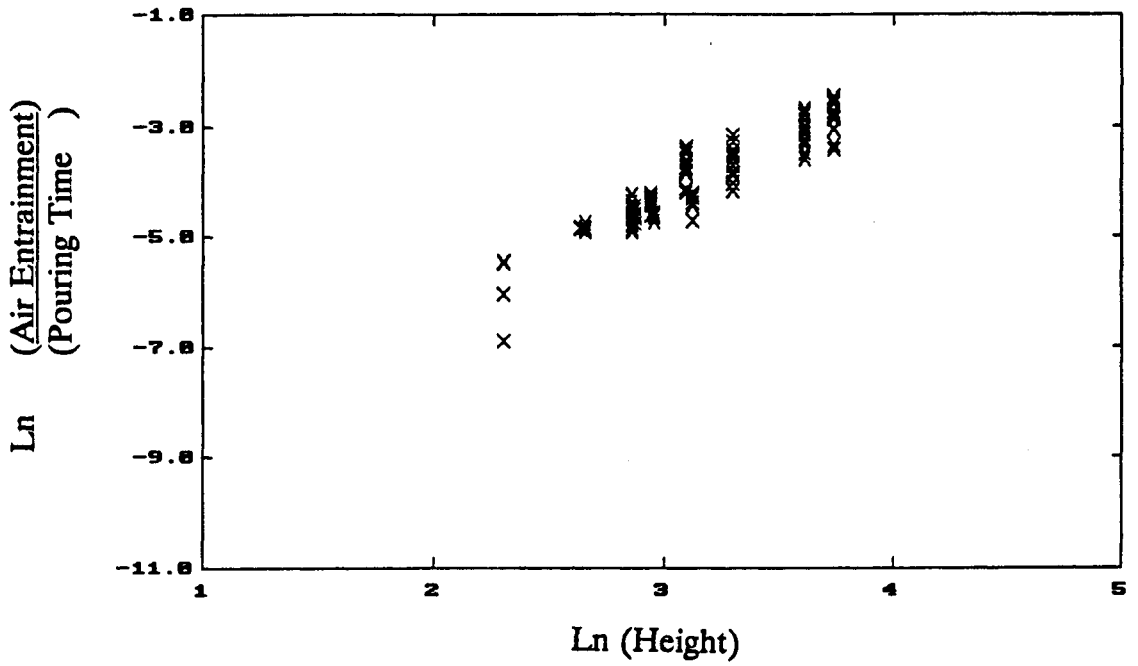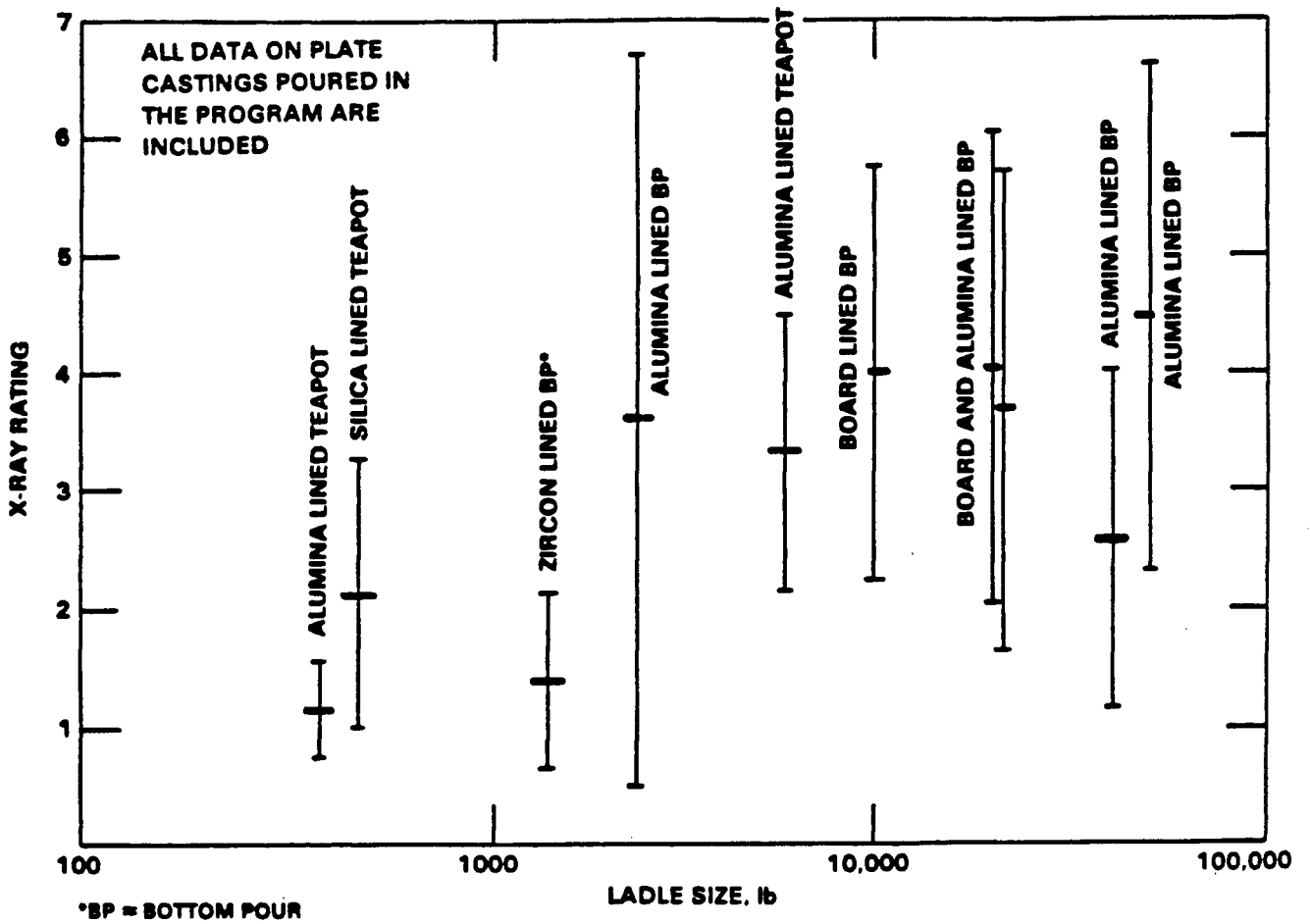
Fig. 7 Confirmation of exponent on height in equation H.

Fig. 8 Effect of ladle size on test plate cleanliness.