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The Current State of Casting Yield: Results from the 1997 Steel Founders' Society of America Casting Yield Survey

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Abstract

The results of a casting yield survey of steel foundries taken in the first quarter of 1997 are presented. Data collected in the survey includes the average, best case, and worst case castings yields for steel castings, and statistical data on the factors which influence casting yield. The average casting yield was found to be 53.3%, and the average best and worst case casting yields were found to be 72.7% and 33.2% respectively, based on a per response average. The response rate for this survey was 40% of the North American steel foundries contacted. Production, end-use, steel type, geometry, and risering methodology factors were identified and ranked in importance affecting casting yield. The following were statistically identified as important positive factors on casting yield, where yield increases with their increase: tons produced per pattern, amount of railroad and wear resistant end-use production, average section thickness, and use of risering rules developed in-house. A negative impact on yield was found to be related to pump and valve end-use production, and corrosion resistant steel production. The quantitative contributions of these factors on casting yield are presented. Unconventional yield improvements were rated very low relative to methods currently in use. Induction heating, compressed air cooling and stacking of castings were indicated as unconventional methods which had been attempted in foundries.

INTRODUCTION

It is commonly believed that the average metal yield in the steel casting industry is approximately 50 to 55 percent. A primary goal of conducting the casting yield survey is to determine the yield with statistical accuracy for steel casting foundries. Regardless of the precise average yield, it can be safely assumed that most foundries must melt about twice as much steel as will be shipped as finished products. The resulting negative consequences of lower casting yield include additional costs in remelting scrapped steel (estimated to account for 7% of the total casting cost), the need for increased capacities for melt furnaces and melt handling, and increased costs associated with additional labor, molding and sand use. Increasing casting yield is therefore a major research priority for the Steel Founders' Society of America (SFSA).

As part of that research plan, the SFSA is currently supporting a research project to achieve increased casting yield through new directional solidification techniques. The present casting yield survey was developed and conducted with the goals that it would assess the current yield performance among SFSA member companies, provide quantitative data on the casting process variables which affect yield (and to what extent), and poll the membership on promising yield improvement methods. From operational experience, it is understood that casting yield depends on factors such as type of casting (i.e. size, shape complexity, weight, and section thickness), alloys used, molding media and methods, and foundry practice (i.e. risering methods). The survey was designed to produce quantitative data on the relative importance of these factors. Finally, to further support the ongoing research project, it is hoped that the survey results will help identify types of castings and foundry practices as good candidates for application of the yield improvement techniques being developed as part of the project.

Important objectives for the survey are summarized below:

- Obtain quantitative data on the current level of casting yield in steel foundries.
- Obtain data on the current methods of risering and yield improvement used.
- Acquire input from steel foundries on best yield improvement methods to pursue and important issues to consider in research.
- Use acquired data to correlate casting yield with casting variables.
- Use survey results in identifying and prioritizing yield improvement techniques.

SURVEY DESCRIPTION

The survey questionnaire was developed with input from the SFSA and SFSA member foundries. The result was a compact survey considering the amount of information collected. Following its development and approval, the survey was mailed from the SFSA to a pool of 93 foundries located in the U.S. and Canada. The response rate for the survey was 40%.

The survey was divided into four sections; a general information section for contact data, and three sections of questions. The three question sections include general foundry characterization questions (section II with questions 1 through 9), current yield information questions (section Ill with questions 10 through 13), and questions regarding yield improvement methods (section IV with questions 14 through 18). The general foundry characterization questions covered information on tonnage, number of units of production, molding methods, typical casting geometry, and type of steels cast. For geometry data, participants were asked to give the minimum, maximum and average section thicknesses and the maximum dimensions for their typical castings' length, width, and height for a typical casting they produce. Annual energy usage for melting, and melting practice by weight percent of tonnage was also requested.

Participants were directly asked for their average casting yield, which can be checked with the computed yield in the previous section for answer consistency. They were also asked to provide their highest possible yield on a "best case" casting and their worst yield on a "worst case" casting. The questions in the final section were developed to collect data on issues dealing with yield improvement; identifying obstacles and looking for solutions. Causes of lowered casting yield and defects which limit yield were rated for importance, and conventional and unconventional methods of increasing casting yield were rated for effectiveness. Data in the SFSA Directory of Steel Founders and Buyers Guide was used to collect the foundries' end-use as percentage of their tonnage.

RESULTS FOR THE SURVEY OF STEEL CASTING YIELD

Data from the survey was entered into an Excel spreadsheet "database", and selected data from the spreadsheet was analyzed using the SAS statistical. The SAS program was used to produce the linear regression, ANOVA analysis (single and multivariate). Results from the survey's general foundry characterization section (section II) were also compared with results from two previous studies undertaken by the SFSA, the 1995 Capacity Study and the 1995 End-Use Survey, to confirm that the pool of respondents is representative of the industry. Extensive detail of the survey results is given in the survey report submitted to the SFSA (Steel Founders' Society of America 1997 Casting Yield Survey).

Survey Production Data and Sample Pool Comparisons

Data for the respondents' yearly production in tonnage and units produced per casting weight class are summarized in Table I. The weight class with the most tonnage produced is the 1000 to 5000 Ib class. Also note the 25 to 50 Ib class has a marked drop in percentage of the overall tonnage; otherwise, the distribution of tonnage is fairly uniform over the weight. The smallest weight class range has the majority of the unit production with 62% of units produced in the 0 to 25 Ib class. Comparing the survey casting size distribution with the SFSA 1995 Capacity Study required combining the two lowest yield survey classes into one 0 to 50 Ib class. This weight class was 10% of the total production in the capacity study as compared to 26% in the yield survey indicating that the survey results may be biased slightly to smaller casting weights.

Table I Tonnage and unit production distribution by casting weight for the most recent year

Weight Classes (pounds)	Tonnage Produced in each class	Units produced in each class
0 to 25	19.33%	61.80%
25 to 50	7.50%	12.70%
50 to 250	15.58%	9.73%
250 to 1000	14.63%	5.71%
1000 to 5000	25.68%	6.65%
over 5000	17.28%	3.40%
Total	100.00%	100.00%

The percentage of tonnage produced by steel type and molding method is presented Table II. Again, comparisons were made with the SFSA 1995 Capacity Study, and the comparisons showed that the survey sample pool is similar in distribution to the capacity study. One main difference appeared in the carbon and low alloy classes where the survey results appeared to have an almost exact opposite distribution, and the yield pool is dominated by the plain carbon steel type producers. The comparison between the survey production breakdown by molding method and that from the 1995 Capacity Study is good, and the survey response pool appeared the same here.

Product end-use data collected from the survey responses in combination with data in the SFSA Directory was used to produce the data given in Table III. The end-use of castings by total tonnage of participants in the 1995 End-Use Survey is also given in Table III. The main differences between them appear in the mining, construction and railroad categories. It appears that the yield survey pool is biased more heavily to mining and construction, and much less to the railroad category. Note that the yield survey sample pool appears to under represent the railroad producers by about 20%. Although, it is clear that railroad is the

Table II Tonnage production distribution by steel type and molding method from yield survey

Steel Type Produce by wt% of Total Tonnage		**Molding Practice Used in Foundries by Percent of Total Tonnage**	
Class of steel		Molding Type	
Carbon	41.67%	Green sand	51.50%
Low Alloy	29.28%	No bake organic	28.33%
Corrosion Resistant	3.18%	Shell molding	5.63%
Heat Resistant	0.53%	Other	14.54%
Wear Resistant	25.09%		
Other	0.25%		

Table III Comparison of yield survey end-use pool with SFSA end-use survey

End Use Description	Percentage SFSA End-Use	Percentage Yield Survey
Ordnance & Accessories	0.79%	2.09%
Pumps, Valves & Pipe Fittings	5.48%	6.99%
Construction Equipment	9.81%	14.36%
Mining Machinery & Equipment	14.06%	20.76%
Oil Field Machinery	1.14%	1.27%
Motor Vehicles	5.23%	2.74%
Railroad Equipment	51.60%	30.57%
Others	11.89%	21.23%
Total	100.00%	100.00%

dominant end-use market represented in the yield survey pool.

A summary of averages and standard deviations from the section I survey data discussed above is given in Table IV. In all categories in Table IV the wide range of responses (as reflected in the minimum and maximum ranges, and large standard deviations) demonstrate the diverse production circumstances under which respondent steel foundries operate. The average casting weight showed a wide range with a large disparity between the mean and median average casting weight. In addition to examining factors directly requested in the survey, several possible yield contributing factors were derived by combining survey answers; the distribution of total units shipped to number of different patterns ratio, the tonnage per pattern ratio, the typical casting box volume to casting weight ratio, and the average casting box modulus.

Casting Geometry Data

The reported minimum, maximum and average section thickness data (in inches) for a typical casting are plotted in Figures 1, 2, and 3 respectively. The minimum section thickness data has many samples in the 0.15 to 0.45 in range. The distributions of the minimum and average thickness are much more skewed to the lower values than the maximum thickness. The maximum thickness is more balanced and Gaussian. The data for section thickness is summarized in Table V. The maximum typical casting dimensions for length, width and height are also summarized in Table V. These geometry distributions show good variation with relatively few outliers. The average values for each thickness and length category are summarized graphically in Figure 4 along with error bars indicating ± one standard deviation.

Table IV Summary of average data from the yield survey for total tonnage, number of units, number of different patterns cast, and average casting weight during the last year

	Total Tonnage (tons)	Total Number of Units	Number of patterns	Average Casting Weight (lbs)
Average	12521	206181	1980	926
Standard Deviation	16067	402920	2662	1240
Median	5298	81270	1100	184
Maximum	80000	1839000	14259	4062
Minimum	200	2000	6	8

Table V Summary of casting geometry data; section thickness and maximum dimensions (in)

	Casting Section Thickness (in)			Maximum Casting Dimensions (in)		
	Minimum	Maximum	Average	Length	Width	Height
Minimum response	0.075	0.800	0.125	15.0	11.5	2.0
Maximum response	3.000	30.000	12.000	252.0	220.0	120.0
Average	**0.524**	**12.210**	**2.889**	**111.0**	**66.0**	**42.8**
Standard Deviation	0.536	8.375	2.791	72.3	44.0	32.6

Energy Use, Melting and Pouring

The survey respondents' melting practice as a percentage of total was compared with the melt practice data reported in the 1995 SFSA Capacity Study. This showed the yield survey sample to be somewhat more highly skewed to the electric arc melting. The average reported energy (kW-hr) used per ton of metal melted was found to be 592 kW-hr per ton, and from the reported tonnage of castings shipped, the energy used per ton of metal shipped was found to be 1219 kW-hr per ton shipped. The average energy usage per ton of castings shipped is remarkably close to the value of 1300 kW-hr/ton as reported by McNaughton (1977), and is about 6% less. Also, there was a statistically significant relationship (found by ANOVA testing at the 0.15 level) between decreasing power usage per ton for foundries with increasing total tonnage; this data and its linear regression are shown in Figure 5. The average percentage of metal lost in the pouring process was found to be 9.43%.

Responses to Yield Improvement Questions

In the yield improvement section of the survey, respondents were asked to evaluate reasons for lower yield, relative importance of various defects to casting yield and various conventional and unconventional yield improvement techniques. In Table VI the averages and standard deviations of the responses to the questions concerned with defects and reasons for lower yield are given. The respondents were asked to rate them from 1 (of lesser importance) to 4 (of the most importance). Unsurprisingly, since it is the reason risers, for the most important defect limiting casting yield (the most important obstacle) according to respondents was internal shrinkage and voids. The standard deviation shows that there is very little disagreement on that defect. Microporosity and cracks are the next most important with nearly identical responses, and this is followed by macrosegregation (for which there is the most disagreement). Overly conservative rules did not rate high as a reason for lower yield, but it was statistically shown that the risering rules are a significant factor effecting yield. Yield improvement methods performing poorly are not an important factor in low yield. Apparently yield improvement methods can only do so much, and are not a reason for casting yields being low.

The evaluation of conventional and unconventional yield improvement techniques are presented in Tables VII and VIII. This feedback identified worthwhile yield improvement methods. Respondents were also

Table VI Summary of ratings for defects limiting casting yield and causes of lower casting yield, rated on a scale from 1 (of lesser importance) to 4 (of the most importance).

Defects limiting high yield	Average response	Standard Deviation
Internal shrinkage and voids	3.57	0.77
Microporosity	2.30	1.20
Cracks	2.30	1.22
Macrosegregation	1.89	1.31
Inclusions	1.51	1.19
Non-inclusion surface defects	1.30	1.20
Poor dimensional control	1.16	1.01
Other (pressure tightness):	4.00	0.00
Reasons for lower casting yield		
Complex casting and section thickness	3.38	1.09
High quality standards required	3.08	0.92
Large number of hot spots	2.97	0.87
Rangy casting	2.84	0.99
Part is not casting friendly	2.70	1.00
Use of side risers	2.08	1.28
Overly conservative rules	1.89	0.94
Yield Improvement methods performing poorly	1.30	1.05
Lack of shrinkage and property data	1.08	1.06

asked to indicate whether or not their foundry had used a given technique. For unconventional yield improvement methods, only induction heating of risers, compressed air chilling, and stacking were indicated as having been used by 1, 2, and 6 foundries respectively. The conventional improvement method evaluations are given in Table VII for all respondents and for only the respondents who used a given technique. The average responses are out of a possible high rating of 4. The use of computer simulation, insulating riser sleeves and changing the part design to make it casting friendly are all highly ranked, but with noticeably more disagreement on computer simulation. Improvement of feeding rules, although being ranked somewhat lower, shows a larger disagreement; and when the response pool is limited to those who have tried them it ranks remarkably higher. In fact, this technique ranks higher than insulated risers and design changes for those who had tried them. Another technique which increases upon trying appears to be exothermic mold materials, although the overall rating remains only sixth best. Techniques which had a decrease in rating with respondents who had tried them are tapered risers and specialty sands (both rated lower to begin with), and chills are rated in the lower half, and appear unchanged in the “tried” response list.

The ratings for unconventional yield improvement methods are presented in Table VIII. By definition, these are methods which have not been tried much and when tried they appear to have given mixed results. The vast majority of respondents unfortunately did not respond to this question, and whether that is an indication of lack of knowledge preventing a response attempt, or disinterest, can only be guessed. These methods are viewed with a great deal of skepticism since all rank low. Only vertical/horizontal stacking of castings has a favorable rating though still only 2.27, but there was disagreement among foundries which had tried it. Water-cooled chills and induction heating of risers rank next, but then again there is disagreement. Methods for which there is general agreement that they are poor prospects are water cooled molds, arc heating of risers and direct water spraying; and it should be noted that these are perhaps the most radically unconventional techniques in the list. This response is probably not surprising, but indicates a hurdle to overcome in implementing unconventional yield improvement methods.

Table VII Summary of ratings for conventional yield improvement techniques for all respondents and only respondents who have tried a given technique, rated from 0 (least effective) to 4 (very effective).

Conventional Yield Improvements - Average Rating and Standard Deviation		
All respondents	**Average**	**Standard Deviation**
Computer simulation for risering	3.18	1.19
Insulating riser sleeves	3.00	0.86
Change part design, make it casting "friendlier"	3.00	0.97
Improve feeding rules	2.63	1.36
One riser for several castings	2.52	1.18
Tapered risers	2.35	1.17
Chills (not actively cooled)	2.21	1.23
Exothermic mold materials	2.14	1.33
Specialty sands (zircon and chromite)	2.00	1.03
Respondents Who Have Tried a Given Method		
Computer simulation for risering	3.64	0.84
Insulating riser sleeves	3.00	0.86
Change part design, make it casting "friendlier"	3.00	0.97
Improve feeding rules	3.18	0.87
One riser for several castings	2.81	0.91
Tapered risers	2.08	1.16
Exothermic mold materials	2.67	1.07
Chills (not actively cooled)	2.18	1.24
Specialty sands (zircon and chromite)	1.88	0.72

Casting Yield Data

The reported (average yield as reported directly in the survey) and computed (from the tonnage shipped and melted) casting yields averaged per survey response were 53.3% and 52.1%, respectively. They are remarkably close, as they should be. This serves as a check on this critical figure reported in the survey. The distribution of the reported average yield is given in Figure 6, and there is very little skew to the data and only no outliers. In Table IX is given a summary of the average, minimum and maximum casting yields averaged on a per response basis, on a per ton shipped basis and per unit shipped basis, The distributions for the reported minimum and maximum yields are shown in Figures 7 and 8 respectively. Note that the average and maximum casting yield on a per ton basis is about 10% greater than the per response average since this figure is dominated by the railroad suppliers, who will be shown to have a statistically much higher yield. The per units averaged yield figures will be dominated by those producing smaller castings in the 0 to 25 Ib range. Hence, the average and minimum casting yields determined by a per unit weighted average are smaller; the average yield by just a few percent, and the minimum yield by about 15%. How one determines the averaging basis for the casting yield effects the resulting average casting yield. In Figure 7 the minimum yield is slightly skewed toward the low side, and the opposite skewness is seen in the maximum reported casting yield in Figure 8. The average, minimum (worst case) and maximum (best case) casting yield averaged per response are compared in Figure 9. There was a good correlation between minimum and average casting yields as shown in Figure 10. This indicated that if the worst case yield is high, the overall average is higher. It is also remarkable that no such trend appears with the maximum yield; regardless of how good the very best yield is, the average yield is appears unaffected.

When yields are computed on the basis of steel tonnage produced by risering method as shown in Table X, it was found that tonnage produced by in house rules and the SFSA guidelines have high yields.

Table VIII Summary of ratings for unconventional yield improvement techniques from all survey respondents, rated from 0 (least effective) to 4 (most effective)

Unconventional Yield Improvement Technique	Average	Standard Deviation
Water-cooled mold	0.56	0.86
Water-cooled chills	1.11	1.37
Induction heated risers	1.16	1.26
Arc heated risers	0.88	0.99
Direct water chilling, spray cooling	0.63	0.81
Compressed air chilling	1.06	1.11
Heat pipe cooled chills	1.07	1.49
Vertical or horizontal stacking of castings	2.27	1.39

Table IX Minimum, maximum and average casting yields averaged per response, per ton shipped, and per units shipped

	Type of Casting Yield			
Method for Determining Yield	Minimum	Maximum	Average	Standard Deviation
Casting Yield Based on Average per Response	33.17%	72.72%	53.30%	12.68%
Casting Yield Computed from Tonnage Shipped and Melted per Response	39.41%	64.78%	52.09%	10.80%
Casting Yield Computed with Weighted Average per Ton	41.23%	76.52%	61.42%	
Casting Yield Computed with Weighted Average per Unit	26.61%	73.93%	49.50%	

Casting simulation is one of the lower resulting yields. This could be explained by the fact that casting simulation is generally used on the toughest parts a foundry casts, and the foundries which use it are casting difficult and complex parts. Hence, the comparison is not fair. Here, again, note that a high average yield appears to go hand-in-hand with a high minimum yield while the maximum yield appears to have little effect on the average yield. The average, maximum, and minimum casting yields averaged on a per tonnage produced by steel type, by molding method and for a given end use are also given in Table X. The weighting equation used to produce these averages is given below for the example of tonnage produced by plain carbon steel type

$$(\text{Average Yield})_{\text{by tons of plain carbon}} = \frac{\sum_{i=1}^{N} (\text{Average Yield}_i)\,(\text{Tonnage of Plain Carbon Steel}_i)}{\sum_{i=1}^{N} (\text{Tonnage of PlainCarbon Steel}_i)}$$

where N is the total number of respondents, and the subscript i refers to the i-th response. By examining the casting yields in Table X, comparisons can be drawn on which risering method, steel type, molding method, and product end-use categories produce on average higher or lower casting yields. Note that on a simple averaged comparison, interactions between categories cannot be discerned (i.e. the high yield of carbon

Table X Minimum, maximum and average casting yields averaged per given risering method, steel type, molding material, and product end-use

Averaged by tons produced by risering method	**Average yield**	**Maximum yield**	**Minimum yield**
SFSA publication "Risering Steel Castings"	63.28%	80.19%	45.69%
non-SFSA publications, give source	55.75%	78.31%	31.71%
rules developed "in house"	65.45%	76.25%	45.93%
rule-based software from a vendor	50.55%	70.10%	25.62%
rule-based software or spreadsheets developed "in house"	46.05%	59.35%	28.71%
casting simulation software	51.42%	74.64%	28.10%
Averaged by tons produced by steel type			
Carbon	64.57%	77.84%	48.02%
Low Alloy	56.55%	76.79%	36.53%
Corrosion Resistant	47.45%	71.25%	27.06%
Heat Resistant	53.86%	81.67%	36.15%
Wear Resistant	64.53%	75.16%	38.42%
Other	58.56%	60.70%	48.90%
Averaged by tons produced by molding method			
green sand	65.36%	79.69%	47.34%
no bake organic	56.56%	72.09%	34.61%
shell molding	55.14%	74.24%	32.35%
other	59.45%	74.84%	36.07%
Averaged by tons produced for end-use			
Construction	52.85%	77.55%	33.39%
Industrial	52.88%	73.29%	30.02%
Military	52.54%	68.70%	31.37%
Mining	61.32%	76.74%	37.67%
Oil	52.30%	72.62%	28.66%
Pumps & valves	49.42%	71.40%	26.42%
Railroad	71.60%	80.69%	56.74%
Trucks	64.76%	76.84%	45.11%
Other: Furnace, Stainless sleeves, Marine)	59.14%	71.95%	35.06%

steels and low yield of stainless are influenced not only by the steel grade, but also by the types of castings being produced. Some observations on these averages are:

For steel type

- Carbon and wear resistant steel show the highest average casting yields, and carbon in particular shows the highest worst case (minimum) yield.
- Heat resistant steel shows the highest maximum yield on average.
- Corrosion resistant steels show the lowest average casting yield, which is also indicated by its very low value of worst case yield.
- The maximum casting yield values vary by about 10% while the minimum (or worst case) casting yield show a 21% variation.

For molding type

- There is the least degree of variation between yields when averaged by tonnage produced by molding method. However, green sand casting molding tonnage produces on average a noticeably higher yield. It should be noted that, green sand casting shows a high correspondence with railroad end-use.

For casting end-use

- A dramatically higher casting yield is observed in railroad producers. As observed in Table IX, the casting yields average on a per ton basis are higher than those computed on a per response and per unit basis. This is due to rail producers dominating the end-use tonnage distribution. The higher average yield of the rail producers does not appear to be due to their best case casting yield, but is probably due to the fact that even their worst case castings have high yields (see minimum yield data in Table X).

- The next highest yields appear in the mining and truck producing categories. These categories also revealed to have the next highest minimum observed yields. This is more evidence that higher average yield is achieved by increasing the yield of worst case castings (rather than getting the best possible yield out of best case castings).

- The lowest average and worst case (minimum) casting yields were noted in the pump and valve categories, and the oil, military, construction and industrial categories were not much better.

- The military production best case (or maximum) observed yield is the lowest of any category. This may not be too surprising owing to the standards which are required.

In Figure 11 a plot is shown of the tonnage of steel produced by various risering methods according to the survey responses. Rules developed in-house predominate as the most used risering methodology with 50% use on a tonnage basis. The next highest methods used are the SFSA publications with about a 20% share. The actual usage of the SFSA guidelines is perhaps even higher than the plot would indicate as they are typically the starting point from which in-house rules were derived. Non-SFSA publications (Wlodawer, Heine, FOSECO and Exomet were mentioned) were used on about a 10% share of the tonnage. Computer simulation of casting solidification was used on about 8% of the reported tonnage, and rule-based software was used on about 5% of the tonnage.

ANALYSIS OF FACTORS INFLUENCING CASTING YIELD

In the yield survey results of the previous section the relative importance and interactions between factors affecting casting yield were not statistically prioritized or identified. By using the analysis of variance (ANOVA) and multivariate ANOVA analysis technique, the data gathered in the survey regarding casting geometry and production data are added to the analysis to search for the most important factors affecting casting yield. In ANOVA analysis, the possible sources of variation of a variable (say casting yield in our case) are tested for the significant factors contributing to its observed variation. If a factor or source of variation is found to be a statistically important contribution to that variation, the ANOVA analysis produces two figures of merit which signify the factor's importance. One of these, the F-ratio (or Fisher ratio) is a measure of the statistical significance of a factor; the higher the F-ratio is, the greater the probability that a given factor has a significant effect on the variation of casting yield. The second figure, the significance (or p-value), is an indicator of how random the effect of a given factor is on the variation in the variable of interest. A high significance indicates a high probability that a factor has a random effect, and the lower the significance the greater the probability that the factor's effect is not random. The ANOVA analysis also provides the contribution to the variation in the variable of interest due to a given factor. In this case, the ANOVA analysis gives the contribution in percentage of the variation in casting yield due to factor of interest. The ANOVA analysis is used here with linear regression to indicate the manner and degree to which the casting yield is effected by a given factor. Here the dependence of casting yield on a factor is prescribed to be linear, and ANOVA analysis will be used to detect which of the hypothesized effects (or their interactions) are statistically significant.

The results of the one-way ANOVA tests with no interactions on factors affecting average, minimum, and maximum casting yield are given in Table XI. In this table the results are presented by the type of casting yield (average, worst case or best case) with variables organized into various headings such as overall production data and steel composition. The tables also include, under the Statistical Evidence column, the assessment from the SAS program as to whether a given factor has more than simply a random effect on the casting yield. SAS bases this assessment on the significance (p-value) which is the probability that the variation in results observed is not the results of random chance alone. The following p-value ranges are assigned at the 95% level to the following five categories of Significance in Table XI:

p-value > 3/10	means **no evidence** of difference from random effect
3/10 > p-value > 1/10	means **not much evidence** of difference from random effect
1/10 > p-value > 1/20	means **weak evidence** of difference from random effect
1/20 > p-value > 1/100	means **appreciable, or yes there is, evidence** of difference from random effect
1/100 > p-value	means **strong evidence** of difference from random effect

and the above categories are indicated in Table XI using the terms: no, not much, weak, yes and strong respectively.

The effect of a variable's influence on increasing or decreasing yield can be determined by the regression formula given in the final column of each table. The linear regression formulas contain the SAS variables V1, V2, and V3 for average, maximum and minimum yield respectively. The independent variable is the variable being considered in that table row. Tables in the complete survey report also detail all variables considered which were found not to have a statistical effect on yield. For consistency the ANOVA table results given here were computed without discarding any observations.

Results of ANOVA for Average Casting Yield

Variables with the strongest statistical influence on average casting yield are summarized below (in order of significance):

Factors of Strong Significance on Average Yield
1, Tonnage per pattern (yield increases with its increase)
2. Percentage of pump and valve production (yield decreases with its increase)
3. Percentage of rail production (yield increases with its increase)
4. Percentage use of in-house risering rules (yield increases with its increase)
5. Percentage of industrial production (yield decreases with its increase)
6. Percentage of corrosion resistant production (yield decreases with its increase)
7. Minimum section thickness (yield increases with its increase)
Factors of Significance on Average Yield
8. Average section thickness (yield increases with its increase)
9. Percentage of wear resistant production (yield increases with its increase)
10. Typical casting "box" volume/average casting weight (yield decreases with its increase)

The most significant factor influencing average casting yield is a variable related to mass production, tonnage per pattern. This variable does not distinguish between many casting made of a single smaller pattern, or fewer castings made of larger/heavier patterns. In both cases foundries are able to refine and optimize their process leading to higher yields. The number of units per pattern did show a weak statistical significance when all observations were included, and average casting weight (formed by the tonnage per pattern divided by the number of units per pattern) showed no statistical influence on casting yield. However, when one influential observation was discarded, the number of units per pattern was found to be significant

Table XI One-way ANOVA table for factors influencing average, minimum (worst case) and maximum (best case) casting yields (factors that have no influence are left out)

Variable Heading	Variable	Statistical Evidence	S.S. and M.S.V.	F-Ratio	Significance	Contribution to Variation (%)	Regression Formula
Effect on Average Casting Yield							
Overall Production Data	Tonnage/Pattern	strong	1540	20.47	0.0001	37.60%	$V1 = 50.505 + 0.0522*V12$
	Number Units/Pattern	weak	441.2	4.101	0.0508	10.80%	$V1 = 51.01 + 0.0108*V13$
Steel Composition	% Corrosion Resistant	strong	836.8	8.688	0.0057	19.90%	$V1 = 55.96 -0.172*V7$
	% Wear Resistant	yes	568.5	5.467	0.0252	13.50%	$V1 = 51.45 + 0.121*V9$
Derived Variables	Casting Box Volume/Casting Weight	yes	548.6	5.247	0.0281	13%	$V1 = 55.21 -64E-5*V27$
	Average Shape Factor	weak	446.8	4.043	0.0524	10.60%	$V1 = 57.97 - 0.046*SF_{ave}$
	Minimum Shape Factor	strong	1098	12.01	0.0015	26.10%	$V1 = 60.65 - 0.014*SF_{min}$
Casting Geometry	Minimum Section Thickness	strong	821.8	8.495	0.0062	19.50%	$V1 = 48.63 + 8.914*V18$
	Average Section Thickness	yes	621	6.059	0.0189	14.80%	$V1 = 49.00 + 1.488*V20$
End Use by Weight %	% Industrial	strong	899.4	9.515	0.004	21.40%	$V1 = 57.50 -0.359*V29$
	% Military	not much	218.1	1.913	0.1754	5.18%	$V1 = 54.71 -0.560*V30$
	% Mining	not much	171.7	1.489	0.2305	4.08%	$V1 = 52.10 + 0.0911*V31$
	% Oil	weak	418.1	3.861	0.0574	9.94%	$V1 = 55.15 -0.879*V32$
	% Pumps and Valves	strong	1496	19.32	0.0001	35.60%	$V1 = 57.94 -0.262*V33$
	% Rail Products	strong	1325	16.09	0.0003	31.50%	$V1 = 50.16 + 0.188*V34$
Risering Methodology	SFSA Guidelines	not much	273.4	2.432	0.1279	6.50%	$V1 = 55.22 -0.079*V4$
	In House Rules	strong	1073	11.98	0.0014	25.50%	$V1 = 46.97 + 0.142*V6$
	Rule based software, in house	not much	223.1	1.96	0.1703	5.30%	$V1 = 53.97 -0.339*V8$
	Casting simulation software	not much	152.9	1.32	0.2584	3.63%	$V1 = 54.36 -0.098*V9$
Effect on Minimum Casting Yield							
Overall Production Data	Number of Different Castings/Year	weak	692.9	3.758	0.0606	9.70%	$V3 = 36.30 -0.002*V11$
	Tonnage/Pattern	strong	3074	33.76	0.0000	49.80%	$V3 = 28.77 + 0.0738*V12$
	Number Units/Pattern	strong	1148	7.777	0.0086	18.60%	$V3 = 29.09 + 0.0174*V13$
Steel Composition	% Corrosion Resistant	not much	238.1	1.206	0.2796	3%	$V3 = 34.59 -0.092*V7$
Derived Variables	Average Modulus	not much	234.9	1.648	0.2079	4.62%	$V3 = 29.72 + 12.47*V26$
	Casting Box Volume/Casting Weight	yes	682.2	5.273	0.0279	13.40%	$V3 = 34.12 -72E-5*V27$
	Minimum Shape Factor	strong	1271	7.414	0.0101	12.90%	$V3 = 40.95 - 0.015*SF_{min}$
	Maximum Shape Factor	weak	725.3	3.86	0.0579	10.50%	$V3 = 24.48 + 0.483*SF_{max}$
Casting Geometry	Minimum Section Thickness	strong	1909	12.42	0.0012	26.80%	$V3 = 23.37 + 21.73*V18$
	Average Section Thickness	weak	519.3	3.87	0.0573	10.20%	$V3 = 27.90 + 1.370*V20$
End Use by Weight %	% Industrial	yes	692.1	5.362	0.0268	13.60%	$V3 = 35.76 -0.319*V29$
	% Military	not much	190.1	1.322	0.2583	3.74%	$V3 = 33.29 -0.525*V30$
	% Oil	yes	714.4	5.562	0.0242	14.10%	$V3 = 34.43 -1.153*V32$
	% Pumps and Valves	strong	1242	11	0.0022	24.40%	$V3 = 36.31 -0.241*V33$
	% Rail Products	strong	1872	12.42	0.0012	26.20%	$V3 = 29.44 + 0.224*V34$
	% Other End Use	not much	318.1	2.27	0.1411	6.26%	$V3 = 31.02 + 0.235*V35$
Risering Methodology	In House Rules	yes	1174	6.878	0.0128	16.40%	$V3 = 26.55 + 0.148*V6$
	Rule based software from vendor	not much	246.1	1.248	0.2715	3.44%	$V3 = 34.17 -0.130*V7$
End Use by Weight %	% Industrial	yes	692.1	5.362	0.0268	13.60%	$V3 = 35.76 -0.319*V29$
	% Military	not much	190.1	1.322	0.2583	3.74%	$V3 = 33.29 -0.525*V30$
	% Oil	yes	714.4	5.562	0.0242	14.10%	$V3 = 34.43 -1.153*V32$
	% Pumps and Valves	strong	1242	11	0.0022	24.40%	$V3 = 36.31 -0.241*V33$
	% Rail Products	strong	1872	12.42	0.0012	26.20%	$V3 = 29.44 + 0.224*V34$
	% Other End Use	not much	318.1	2.27	0.1411	6.26%	$V3 = 31.02 + 0.235*V35$
Risering Methodology	In House Rules	yes	1174	6.878	0.0128	16.40%	$V3 = 26.55 + 0.148*V6$
	Rule based software from vendor	not much	246.1	1.248	0.2715	3.44%	$V3 = 34.17 -0.130*V7$
Effect on Maximum Casting Yield							
Overall Production Data	Casting Weight	no					
	Number of Different Castings/Year	not much	74.3	1.165	0.2879	3.22%	$V2 = 71.69 + 0.0005*V11$
	Tonnage/Pattern	yes	347.2	6.093	0.0188	15.20%	$V2 = 71.66 + 0.0248*V12$
Steel Composition	% Corrosion Resistant	weak	217	3.633	0.0649	9.40%	$V2 = 74.07 -0.088*V7$
	% Heat Resistant	not much	119.1	1.905	0.1763	5.16%	$V2 = 72.13 + 0.348*V8$
	% Other Composition	not much	173.1	2.838	0.1009	7.50%	$V2 = 73.13 -0.192*V10$
Molding Practice	% Green Sand	not much	155.5	2.529	0.1208	6.74%	$V2 = 70.96 + 0.0539*V14$
Casting Geometry	Maximum Section Thickness	weak	196.7	3.262	0.0795	8%	$V2 = 69.39 + 0.283*V19$
Risering Methodology	Rule based software, in house	strong	405.7	7.467	0.0098	17.60%	$V2 = 73.62 -0.457*V8$
	Other	not much	80.24	1.261	0.2691	3.48%	$V2 = 72.29 + 0.0806*V10$

with p = 0.0011, and was associated with a positive effect on yield with its increase.

It was already shown in Table X that pump producers and rail producers have the lowest and highest production weighted yields respectively. In the ANOVA analysis it is demonstrated that the influence of the production rate for these end-uses have a statistically strong influence on average yield. The rate of pump and valve production having a high negative influence on yield and accounting for about 36% of the variation in yield, and rail production accounts for about a 32% of the average yield variation and has a high positive effect on yield. The use of in-house risering rules ranks as the next most important effect on average yield, accounting for 25% of the variation. This result may be influenced by the use of in-house rules by railroad producers; the two highest railroad producers also reported 100% and 90% in-house rule use (see the final report for more details). The use of in-house rules is also an indication that foundries have directed efforts in refining and tailoring their process themselves, and therefore its association with increased yield is understandable. The industrial end-use category is also associated with a strong negative impact on yield, and this is followed by corrosion resistant steel production which is also has a negative influence on yield.

Since corrosion resistant steel production showed a strong statistical association with both pump and valve production (p-value = 0.0015), it remains to be determined whether this is due to the type of steel itself or a dependence on the end use of many corrosion resistant steel castings. An analysis using induction melting showed a strong statistical correlation with corrosion resistant steel (p-value = 0.0010) and weak association with pumps and valves (p-value = 0.0506), and was shown to have no effect on yield. This is evidence that the deleterious effect of corrosion resistant steels is due to their association with pump and valve castings rather than the inherent properties of corrosion resistant steel. However, the results of Varga et al. (1958) among others show clearly the additional difficulties involved with feeding castings of increasing alloying elements. On their face the survey results directly support the poor casting yield/feeding characteristics of corrosion resistant steels.

Two thickness variables appear next in the list; minimum thickness which has a strong significance with average yield and average section thickness which has an effect, but in the statistical class below “strong”. Note that minimum thickness appears to be more important than the average thickness, and that these geometric variables, though identified as important, are less important than “production” related variables. Maximum thickness was not identified as a significant effect on average casting yield.

Following percentage of wear resistance production in the list, is a variable derived from responses to geometric questions as to casting size and weight. By taking the reported typical casting’s length, width and height and then multiplying them to create a casting “box” volume, and then dividing this volume by the foundry’s average casting weight, a specific volume for the casting’s rangyness was formed. For castings whose dimensions were large, but the average weight was small; this factor has a large value, and it is assumed that such a casting is rangier than a casting whose overall box dimensions are smaller and whose weight is higher. It was found that this derived variable proved a statistically significant factor, and that its effect is as one would logically expect, when its value increases (i.e. a rangier casting) it is associated with a slight decrease in average casting yield.

It is also important to note the factors which do not have an influence on casting yield, according to the survey responses. Average casting weight had no influence, and only a weak influence was observed with the number of different casting patterns produced each year. Molding practice had no discernable effect. In the risering rules category, only “in-house rules” was found to have an important influence and it was positive. All other risering methodologies either had “no effect” or “not much”, and when the effect was found it was negative (for SFSA Guidelines, in-house rules based software and casting simulation). Variables which might be expected not to have an effect on yield by themselves such as casting length, width and height, and melting practice; did not.

Minimum and maximum casting yield data were also analyzed for factors influencing them. Unlike average yield and minimum yield few statistically defendable factors influencing maximum casting yield were found. The dependence between the three reported yields were also examined, and the only dependence found was between average and minimum reported casting yields. As shown in Figure 10, this dependence appears excellent and has a strong statistical significance (p-value = 0.0000). According to the ANOVA analysis between average yield and minimum yield, 65% of the variation in average casting yield can be accounted for by the variation in minimum yield. One possibility for this relationship could be that foundries adapt a level of conservatism in their methoding practice based on the worst case scenario they might experience. Furthermore, the results for best case casting yield show statistical evidence of a statement often heard in foundries; that great casting yields can be had by any foundry if they are willing to put in the effort and expense of achieving them.

Results of ANOVA for Minimum Casting Yield

A number of the factors which were found to have a strong influence on average yield appeared as strong factors on minimum casting yield. The factors influencing minimum casting yield are listed below in order of significance:

Factors of Strong Significance on Minimum Yield
1. Tonnage per pattern (yield increases with its increase)
2. Minimum section thickness (yield increases with its increase)
3. Percentage of rail production (yield increases with its increase)
4. Percentage of pump and valve production (yield decreases with its increase)
5. Number of units per pattern (yield increases with its increase)

Factors of Significance on Minimum Yield
6. Percentage use of in-house risering rules (yield increases with its increase)
7. Percentage of oil end-use production (yield decreases with its increase)
8. Percentage of industrial end-use production (yield decreases with its increase)
9. Typical casting “box” volume/average casting weight (yield decreases with its increase)

As with average yield, variables dealing with mass production and production end-use appear to be the most important variables effecting minimum casting yield. The tonnage per pattern is the most important factor contributing to minimum casting yield accounting for 50% of the variation in minimum casting yield. This variation is substantially greater than the 38% variation effect this variable had on average yield. Although the fifth variable in the list, units produced per pattern appears as a strong factor on minimum yield. Its effect on the variation is a noticeable step down from the top four factors in the list. This factor was not of importance in average casting yield unless one influential observation was removed. Here it is determined to be a strong factor, but again not as strong as the tons produced per casting. In any event, the effect of mass production on increasing casting yield is statistically demonstrated.

The second variable in this list, minimum section thickness, has a stronger influence on minimum yield than it had on average yield, and average section thickness has only a weak statistical effect on minimum. This demonstrates an important correlation between minimum section thickness and corresponding minimum casting yield. As was the case with average yield, there is no observable influence from maximum section thickness. Rail and pump and valve production are again shown to have a strong statistical influence. In this case, with minimum yield, rail has a slightly stronger effect, but both are shown to have a similar effect on the variation of minimum casting yield; 26% and 24% of the variation in minimum yield accounted for by rail and pump and valve production respectively. Minimum section thickness is only slightly higher than this with 27% of the variation in minimum yield owing to its effect.

Factors which were found to influence minimum yield, though not strongly, were the use of in-house rules (strong effect on average yield), oil end-use production (weak effect on average yield), industrial end-use production (strong effect on average yield), and effective casting “box” volume to weight ratio. This last factor in the list above, the "rangyness "factor, has a 13% effect on the variation for minimum yield. Of the other factors appearing to have some statistical influence, the number of different casting patterns made per year has a negative effect on casting yield which is reasonable. However, it is remarkable that this apparently does not have more of an effect on casting yield.

Results of ANOVA for Maximum Casting Yield

In the case of maximum reported casting yield, the lack of statistical evidence on factors which are of influence was remarkable. The factors influencing maximum casting yield are listed below in order of significance (again, see Table XI):

Factors of Strong Significance on Maximum Yield
1. Percentage use of risering software based on in-house rules (yield decreasing with its increase)
Factors of Significance on Maximum Yield
2. Tonnage per pattern (yield increases with its increase)
Factors of Weak Significance on Maximum Yield
3. Percentage of corrosion resistant production (yield decreases with its increase)
4. Maximum section thickness (yield increases with its increase)

These results demonstrate that there are probably many varied factors which determine the maximum yield reported in foundries, and therefore few standout in this analysis. In particular the lack of correlation with any of the end-use categories is noticed, while end-use influences appeared as dominant factors in the average and minimum yields. Percentage use of “in-house risering rule based software” is shown to have a strong (and the strongest) effect, but accounts for only 18% of the variation. This variation is modest by comparison with important factors for the minimum and average casting yield categories. Tonnage per pattern, the dominant factor in the other yields, has only a 15% variation effect on maximum reported yield.

In part, because effects on maximum yield are so few, the above list also includes weak influences on maximum yield. Percentage of corrosion resistant steel production showed a weak effect (accounting for 9% of the maximum yield variation). The maximum section thickness appears as a variable of importance affecting maximum yield. It did not previously appear to be of consequence in the minimum and average yields. The statistical dependence of minimum yield on minimum thickness, and maximum yield on maximum thickness has been shown here, in which the “type” of casting yield increases with increasing “type” of thickness for both cases.

SUMMARY OF FACTORS INFLUENCING CASTING YIELD

The variables which were identified by the survey as having the greatest effect on casting yield are summarized below. Summaries of the analysis are discussed below by the following topics; production related, end-use factors, steel type, casting geometry, and risering methodology related factors. Results of multivariate analysis, interactions and common factors acting along with the topics which were identified as significant are also discussed below.

Production Related Factors

- The tonnage per pattern was identified as a significant factor for all categories of casting yield. Figures 12 and 13 provide plots of this data for average and minimum yield respectively for which it ranked as the strongest influence on yield. This indicates that mass production in tonnage per pattern is very advantageous in increasing casting yield, and demonstrates that if the process can be refined with accompanying mass production, then higher yields are statistically possible if not expected.

- The number of units per pattern was statistically demonstrated to be an important factor for minimum casting yield (strong significance) and average yield (weakly significant). The data for these two cases are given in Figures 50 and 51 for minimum and average yield respectively. In both figures a higher number of units produced per pattern is associated with increasing casting yield. This provided additional evidence of the advantage of mass production in making the casting process more efficient from the standpoint of casting yield.

- The number of different patterns used by foundries produced a logical but only weakly significant effect on casting yield. For average and minimum casting yield, an increasing number of different patterns used per year was statistically related to decreasing casting yield. In other words, the more, different castings a foundry produces, the lower the casting yield; this is the opposite of mass production.

End-use Related Factors

- End-use categories of pump and valve, rail, oil and industrial were shown to be significant and strongly significant factors affecting average and minimum casting yield. No end-use factors were identified as having any influence on maximum casting yield.

- Pump and valve production was strongly associated with decreasing the average and minimum reported casting yields as shown in Figures 16 and 17, respectively. Pump and valve production was also statistically associated with a decrease in average and minimum section thickness. As shown in Figure 18 for the case of average section thickness, 17.5% of its observed variation was attributable to variations in pump and valve end-use production with $p = 0.0099$ (strongly significant). For the case of minimum section thickness $p = 0.0296$ accounting for 12% of the variation.

  Pump and valve production was also strongly correlated with corrosion resistant steel, and induction melting as well. The product of corrosion resistant and pump and valve did have a stronger significance ($p = 0.004$) than corrosion resistant alone, but not as strong as pump and valve alone. This is evidence that the decreased yield associated with more pump and valve casting is due to the type of castings (geometry) rather than the type of steel used. Pump and valve casting was also significantly related ($p < 0.05$) to an increase use of no bake molding materials.

- Railroad end-use castings have a strong significant positive effect on average and minimum yield as plotted in Figure 19 for the average yield. The reason for this is related to mass production in combination with casting geometry factors.

  Increased railroad end-use shows a corresponding increase in minimum section thickness ($p < 0.05$) as shown in Figure 20. Rail castings also showed a strong statistical association with increased mass production with tons per pattern ($p = 0.0012$); number of units per pattern $p = 0.0246$; and the product of the two having a significance of $p = 0.0045$ and all having an increase associated with an increase in railroad production. Railroad casting end-use data showed strong statistical evidence of association with an increase in carbon steel castings ($p = 0.0072$), and some statistical evidence of an association with increased green sand use ($p = 0.03$) was observed.

- An increase in the production rate of industrial castings is strongly associated with a decrease in average casting yield and significantly related to a decrease in minimum casting yield. The main, statistically evident, reasons for this appears to be the significance of minimum section thickness decreasing with increasing industrial production ($p = 0.031$). Some statistical evidence (but not much) exists to show that an increase in industrial casting production is associated with a decrease in mass production by the number of units produced per pattern ($p = 0.26$).

- Minimum casting yield decreases with increasing oil end-use casting production. This was statistically significant with $p = 0.0268$. However, an increase in oil end-use production was found to be statistically related ($p = 0.0051$) to an increase in pump and valve production. This was evidence of a secondary relationship affecting minimum casting yield for this case as oil end-use production was never more than 15% of a foundry's tonnage.

Steel Type Factors

- Corrosion resistant steel shows a negative effect (yield decreasing with its increase) on average casting yield (strongly significant) as shown in Figure 21, and on minimum casting yield (weakly significant). It is believed that this is due to the strong association between increased corrosion resistant steel use in pump and valve end-use castings as well as the feeding characteristics of the steel itself.

- Wear resistant steel use shows a significant ($p = 0.0252$) association with increased casting yield with its increased use in castings. While there is no evidence from the survey to clarify this, foundries casting these steels are generally interested in surface quality and centerline shrink is usually not the primary concern. As a result, increased casting yield occurring with its increased use is logical. This data is plotted in Figure 22.

Geometry Factors

- Increased minimum section thickness was strongly correlated with increased average and minimum casting yield as shown in Figures 23 and 24 respectively.

- Average section thickness showed a significant (but not strong) effect on increasing average casting yield as plotted in Figure 25.

- Maximum section thickness showed a weakly significant effect on increasing maximum casting yield. No other section thickness category was shown to be significant for maximum yield. There was also a wider spread in the maximum section data when compared with the minimum and average section thicknesses.

- While certain classes of castings (i.e. pump and valve end-use) showed relations with section thickness. There do not appear to be any other combined factors with the section thickness data to explain the increased casting yield with increased minimum and average section thickness. It is therefore surmised that the effect of section thickness is primarily important on its own.

- The derived variable used to describe casting "rangyness", casting box volume divided by casting weight, was shown to be significant in the cases of average and minimum reported casting yield. A high value of this ratio is associated with a rangier casting than one having a smaller value. The actual number associated with this ratio has a relative meaning. The minimum casting yield is plotted in Figure 26, and the average yield plot is quite similar. Logically, in both yield categories, a decrease in casting yield is associated with an increase in this ratio.

- The casting box modulus (volume/surface area) was shown to be significant for the case of minimum casting yield only ($p = 0.2079$). Casting yield was shown to increase with its increase.

- The casting "box" dimensions in length width and height did not show any statistical influence on yield by themselves.

Risering Methodology Factors

- The increased use of in-house risering rules showed a strong statistical significance with increased average casting yield, and a significant effect in increasing minimum casting yield. This data is plotted in Figure 27 for the case of average casting yield.

- A strong statistical significance was found between increasing use of in-house developed risering software and maximum casting yield. This was one of a relatively small number of factors (compared to average and minimum yield) found to be of significance in examination of the maximum yield data.

- Not much significance was associated with the effects of increased SFSA risering guideline use. Only for the case of average casting yield was an effect shown to be of any significance ($p = 0.1279$), and unfortunately the increased use of SFSA guidelines is related to a decrease in average yield.

Combined Effects

This section includes factors which were found to contribute to casting yield when examined using ANOVA in combination with other factors.

- Casting weight was not found to be a statistically significant factor on casting yield by itself. When combined with the production variables, tons per pattern and units per pattern in a multivariate ANOVA analysis, it was found to be significant. When the product of average weight and tons per pattern was analyzed it was found to be significant (p = 0.0122). Its increase was associated with an increase in casting yield when analyzed on its own. When used in a multivariate analysis with casting weight, tons per pattern, and their product; tons per pattern was not significant, and the product turned out to be quite strongly significant (p = 0.0086), and casting weight also was significant (p = 0.0972). In this analysis all factors had the effect of increasing casting yield with their increase. This indicated that casting weight in combination with other mass production variables has more of a relationship with casting yield than casting weight alone.

- The product of tons per pattern and units per pattern gave a strong significant effect on the average yield (p = 0.0007). This demonstrates the importance of mass production when a large tonnage and a large number of castings are being produced of a given pattern. This effect is not as great as tons per pattern alone, but it is of much greater significance than units per pattern alone.

ADDITIONAL RESULTS FROM END-USE CATEGORIES

The following results indicate that, depending on the type of casting, it can be more or less useful to develop and use improved feeding rules.

- There was weak statistical evidence (p = 0.1139) of increased use of in-house rules by railroad casting producers as shown in Figure 28.

- Oil end-use production was significantly related (p = 0.0327) to decreasing use of in-house risering rules.

The respondents' answers to the questions regarding the reasons for lower casting yields were analyzed by end-use category. This reveals not only the issues of importance for a given type of casting producer, but also insight into reasons for higher or lower casting yields.

- Railroad producers responded significantly lower (from ANOVA analysis with p = 0.0021) to the question of whether complex castings were an issue of importance. Pump and valve producers were shown to respond that this was an issue of increasing concern, but with somewhat less significance (p = 0.1694).

- With increasing railroad production, the use of side risers (p = 0.0125) and the issue of internal voids (p = 0.0214) were indicated to be of decreasing importance in affecting casting yield.

- There was statistical significance (p = 0.02) associated with increasing level of importance of dimensional control in rail castings. Other issues were shown to be of decreasing importance in railroad end-use.

- Pump and valve production did not demonstrate any significant relationships with the level of response to the "issues affecting casting yield" questions.

- Analysis of the "issues" questions with average casting yield revealed that a lower casting yield was significantly related (p = 0.0478) to a higher level of response to the importance of complex castings in limiting casting yield.

- The importance of quality as an issue limiting casting yield was shown to be weakly significant ($p = 0.1464$) in being associated with a decrease in average casting yield with an increasing level of its reported importance. Combined with the previous finding, this indicates that the complexity of a casting may be more of a constraint on casting yield than quality requirements, and both are related to decreased casting yield when they are of greater concern.

CONCLUSIONS

Casting yield and yield improvement issues were investigated using the survey responses from steel foundries. The primary goals of this study were to determine the current state of casting yield, determine factors which influenced casting yield, and identify prospective methods of yield improvement. It was also a goal to identify opportunities for improving casting yield by pinpointing problem areas where large improvements in yields are possible. As a means of verifying the sample pool, a profile of foundries that responded to the questionnaire data on the sample pool was also collected and is presented in this report. Overall, the sample pool profile was found to be representative of the steel casting industry.

Depending on how the casting yield is averaged for the survey responses, one ends up with different results for the average yield. Weighted on a per response average, the worst case, average and best case casting yields were found to be 33%, 53%, and 73% respectively. If the casting yield averages are determined on a per ton basis, a higher set of yields was found: 41%, 61% and 77% for the worst case, average and best case casting yields, respectively. It was found that high best case casting yields could be had by most foundries , and there was a drop off in factors contributing to maximum casting yield. For the case of minimum/worst case casting yield, there were a number of contributing factors which could be identified. Also, there was a strong statistical relationship between a foundry's reported average and worst case casting yields.

Casting yield was shown to be related to several variables which reappeared in the analysis of the minimum, average and maximum casting yields. Mass production related variables, tons per pattern and number of units cast per pattern, were shown to be strongly significant in relation to increasing casting yield with their increase. Several end-use categories (which reflect both casting type and quality requirements) were also shown to be strongly related to casting yield. In the case of pump and valve castings, their increased production was associated with a drop in casting yield. The opposite was found in railroad castings which was shown to be strongly related to casting yield increases. Section thickness, primarily minimum and average section thickness, was revealed to be strongly related to increasing casting yield with their increase. Maximum thickness did not reveal such a relationship indicating that very thick section should not be expected to continue the trend to higher casting yields. Indeed very thick sections have their own challenges for foundrymen to overcome. Higher yields were also statistically related to the use of risering methods/rules developed in-house. This is an indication of the benefit of improved feeding rules, and the advantages of study and experimentation with the casting process.

The survey questions addressing the reasons for lowered casting yield showed complex casting and section thickness followed by high quality standards to be of the highest concern. When average casting yield was compared with these responses, a relationship between increasing level of response to these questions and lower casting yield was shown. Microporosity, for which the existing SFSA feeding rules were developed, was ranked as an important defect limiting casting yield, and examination of this defect limiting casting yield makes sense, To pursue this, additional research for the project for which this survey was conducted has been performing computational studies (Beckermann et al., 1997) in re-evaluating those rules using the Niyama criteria for microporosity prediction.

The conventional yield improvement methods were rated higher than all of the unconventional yield improvement methods but one, vertical and horizontal stacking of castings. Computer simulation, insulating sleeves, changing the design of parts to make them casting friendlier, and improved feeding rules were all rated high by respondents in the conventional yield improvement category. The methods classified as unconventional did prove to be that, as few had been attempted by respondents. Along with stacking castings, methods of active heating by induction showed the next highest level of promise, followed by water cooled chills. From these responses, it is clear that casting trials, extensive testing, and demonstrations of success will be required to convince respondents of attempting unconventional methods.

When attempting to apply new or unconventional methods to steel shape casting with the goal of improving casting yield, the survey results lead to several conclusions. Depending of the type of casting and its end-use there will probably have to be different approaches taken to achieve higher yields. In the case of rail castings, yields are already quite high, and so is the tonnage produced. A small increase in yield could mean large energy/capacity savings due to the tonnages involved. In this category, methods which take advantage of the mass production already existing in this sector should be examined, Since these castings (approximately 0.60 $/lb) are not as costly as pump and valve castings (which can be 10 to 15 $/lb) the monetary savings would not be great unless implemented on a mass scale. In the case of pumps and valves, a sector which has quite a different outlook from railroad castings as far as yield goes, the yields and tonnages are certainly lower. The possibility of energy and tonnage/capacity savings are not as great due to the smaller tonnage produced. However, the opportunity to increase yield is excellent due to the current lower yields. Due to their higher costs, increased casting yields for these more complex castings (with generally thinner sections) leads to higher profits. Indeed, the cost of an active, unconventional yield improvement method is more easily justified for these types of castings. Furthermore, if such methods could be extended, with cost savings, to mass production scaled operations, they could also be justified for the type of castings exemplified in the railroad end-use category.

The use of improved risering and feeding rules seems to hold great promise according the survey responses. If this course is pursued, the survey results indicate that issues related to thin sections and complex castings will need to be considered in reformulating less conservative feeding rules if the lowest yields are to be increased while maintaining casting quality level, and consideration of the level of quality required of a casting might also be examined in developing improved and, where possible, less conservative risering guidelines.

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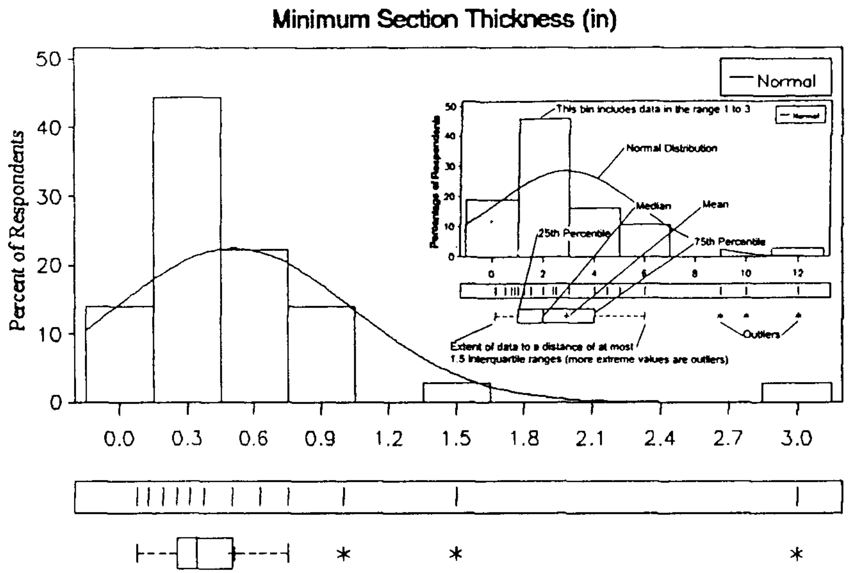

Figure 1 Distribution of minimum casting section thickness (in) from yield survey respondents

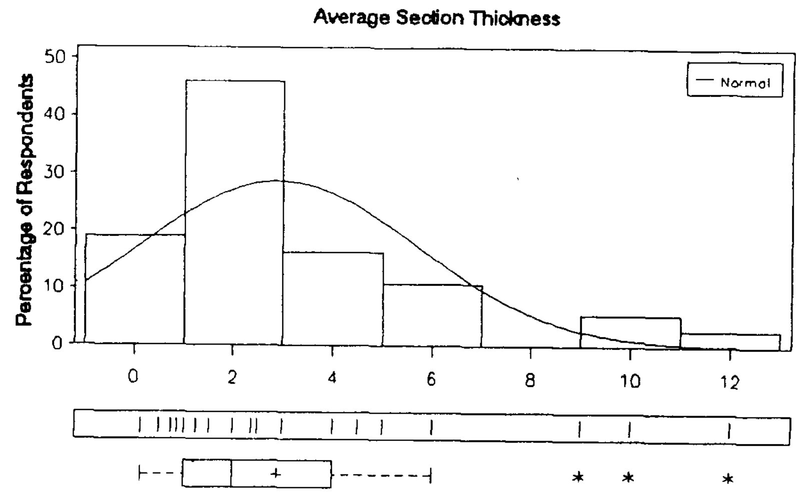

Figure 3 Distribution of average casting section thickness (in) from yield survey respondents

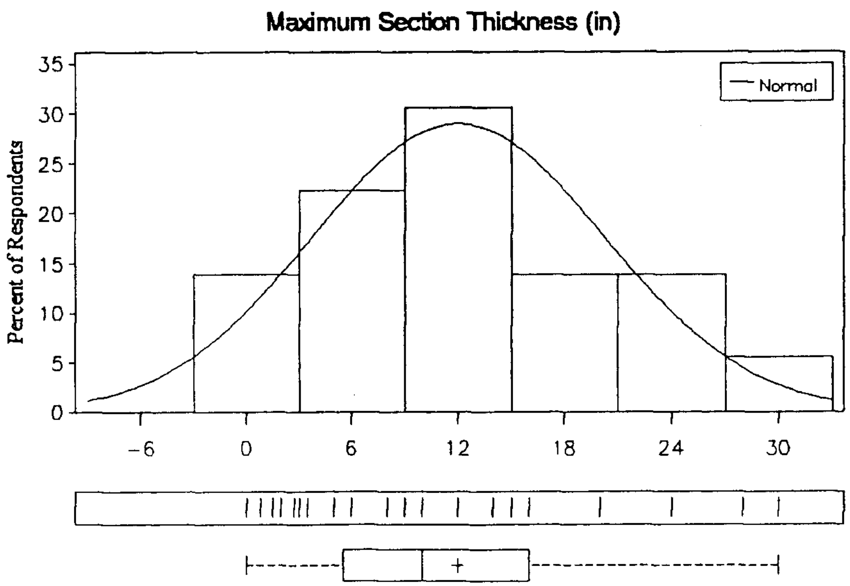

Figure 2 Distribution of maximum casting section thickness (in) from yield survey respondents

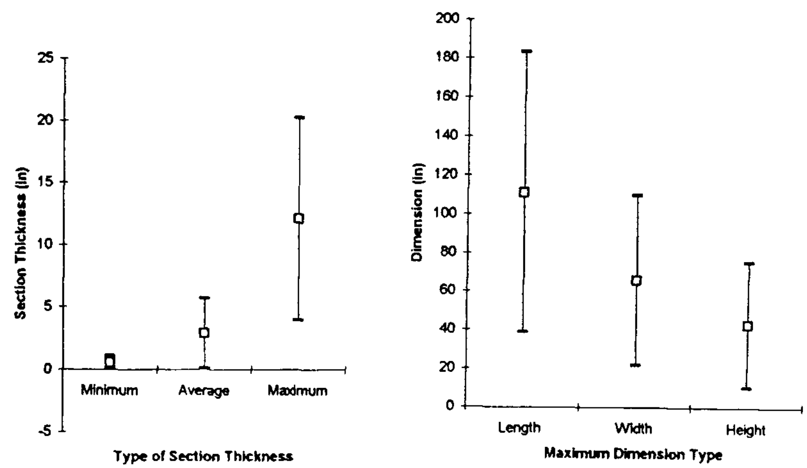

Figure 4 Average section thickness and maximum casting length data (average value indicated with + and - one standard deviation error bars)

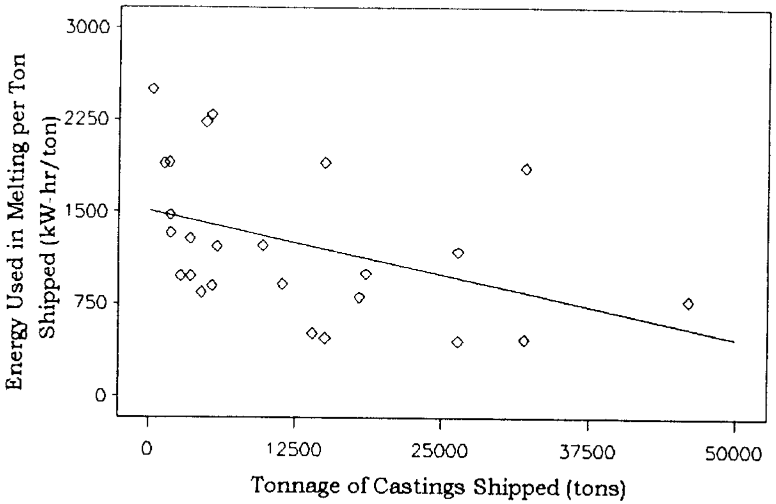

Figure 5 Dependence energy used in melting per ton shipped on total tonnage shipped per year

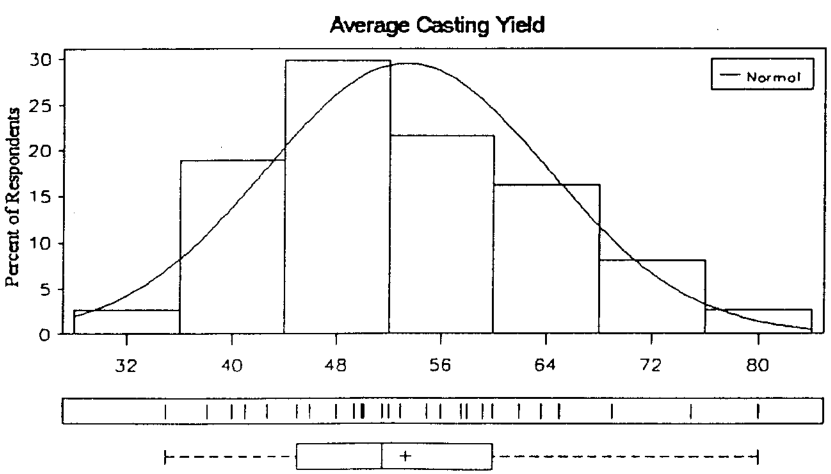

Figure 6 Distribution of average casting yield reported by survey respondents

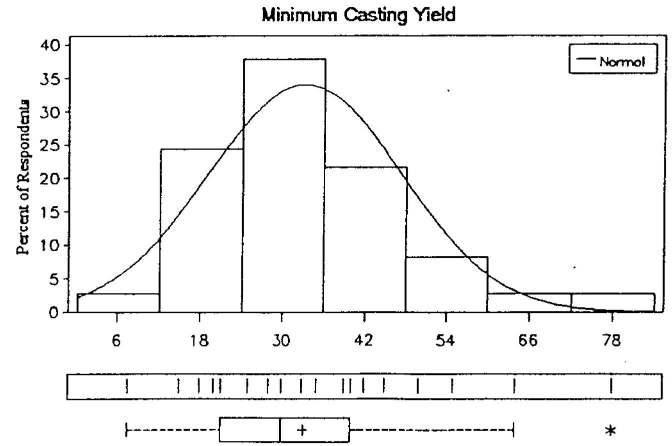

Figure 7 Distribution of minimum (or worst case) casting yield reported by survey respondents

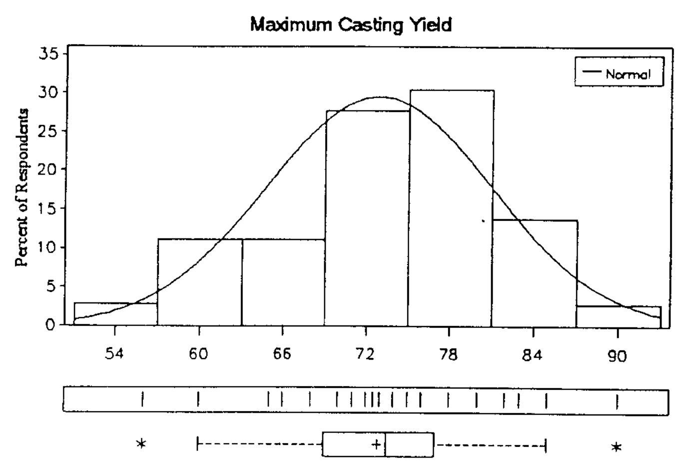

Figure 8 Distribution of maximum (or best case) casting yield reported in survey averaged per response

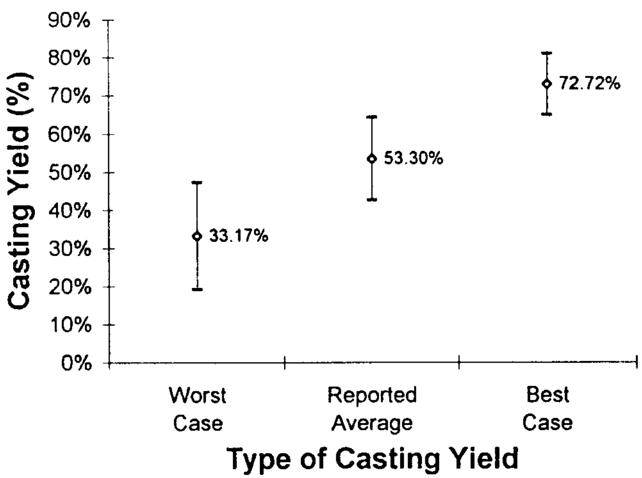

Figure 9 Summary of minimum, average and maximum casting yield reported in survey average per response

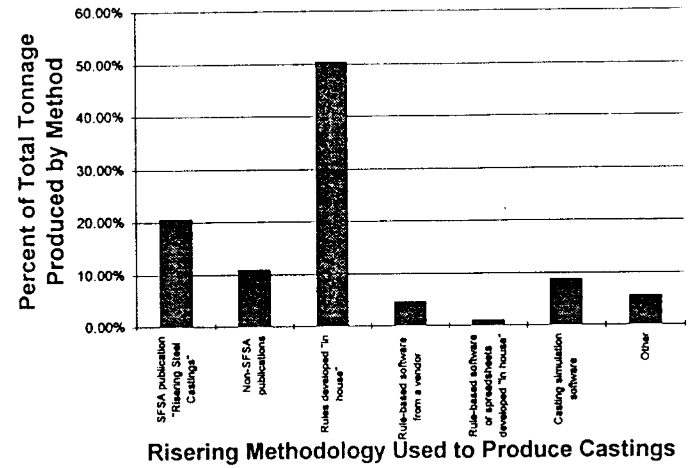

Figure 11 Percentage of total tonnage produced by various risering methodologies

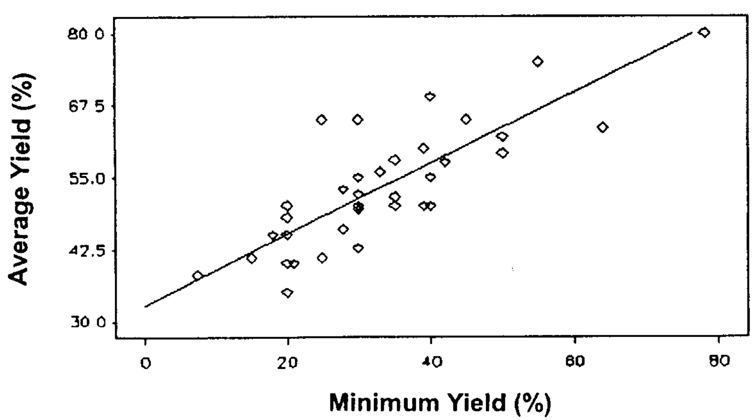

Figure 10 Dependence of average casting yield on minimum reported yield

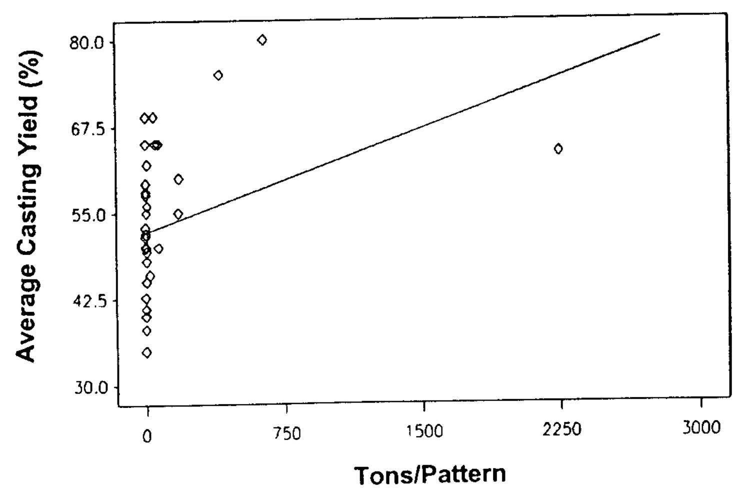

Figure 12 Average casting yield versus tons per patterns

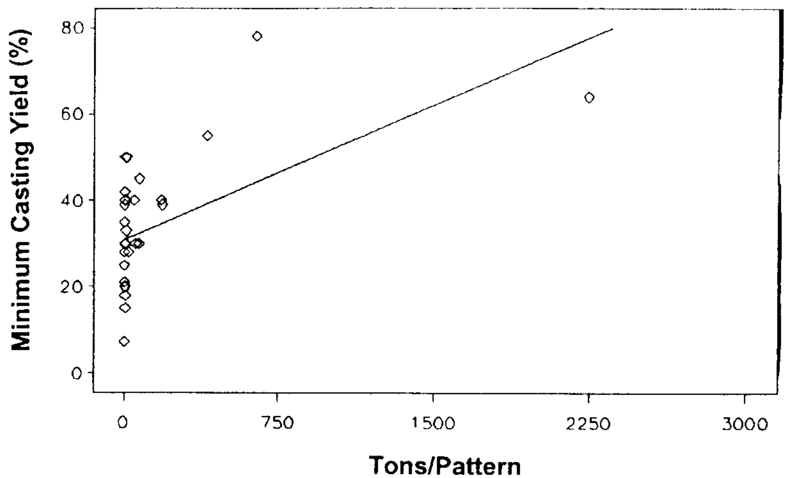

Figure 13 Minimum yield versus tonnage produced per pattern

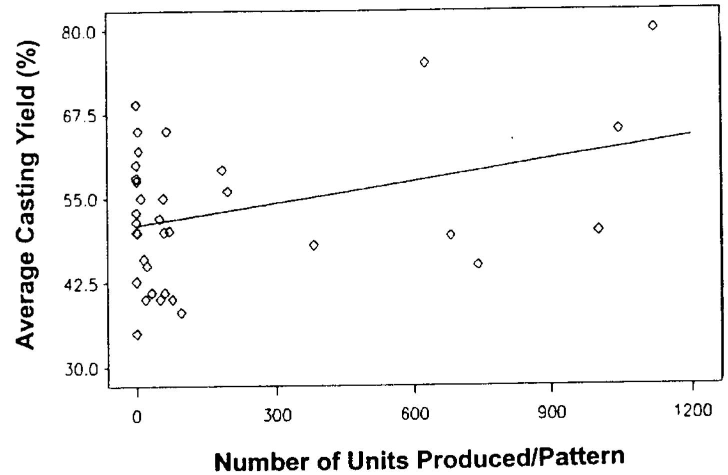

Figure 15 Average yield versus number of units produced per pattern

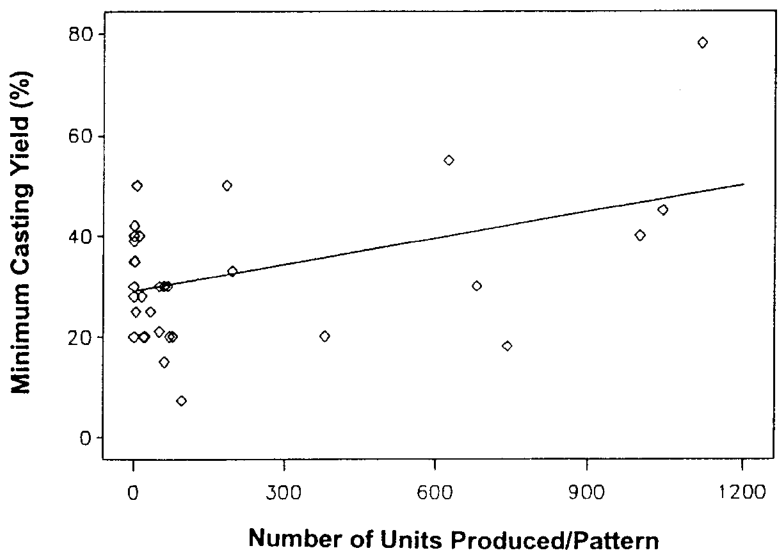

Figure 14 Minimum casting yield versus number of units produced per pattern

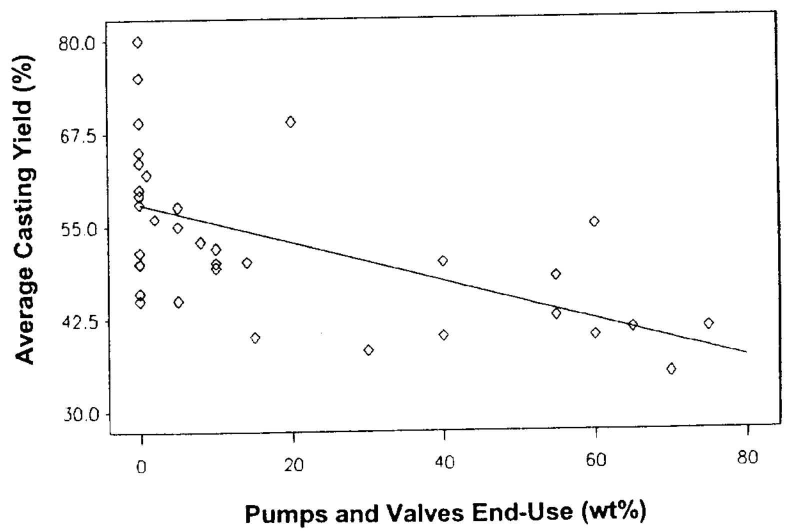

Figure 16 Average yield versus weight percentage of castings produced for pump and valve end-use

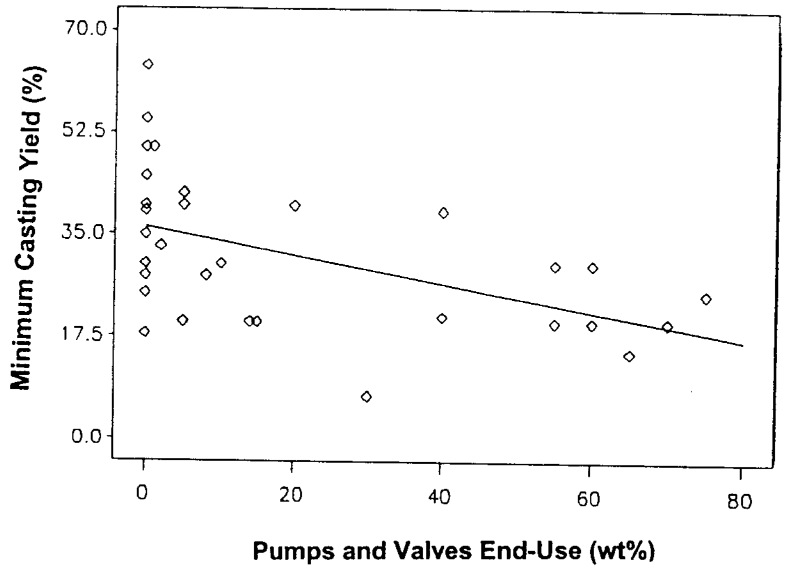

Figure 17 Minimum yield versus weight percentage of castings produced for pump and valve end-use

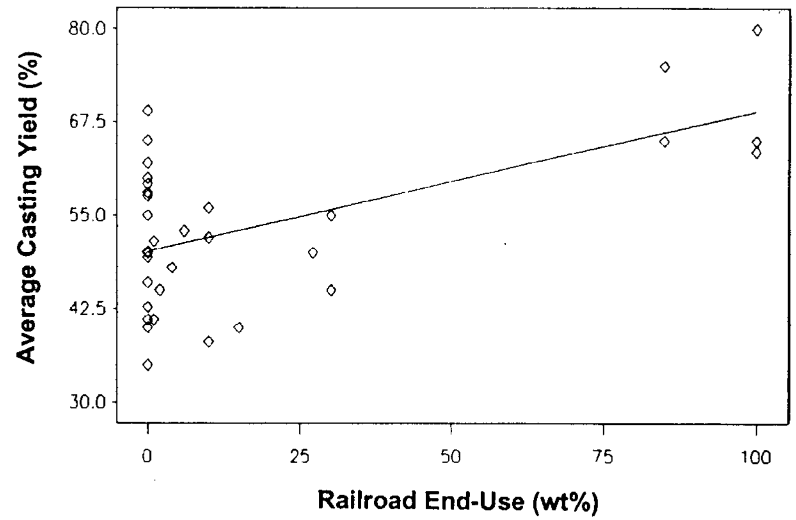

Figure 19 Average casting yield as a function of percentage of casting weight produced for railroad end-use

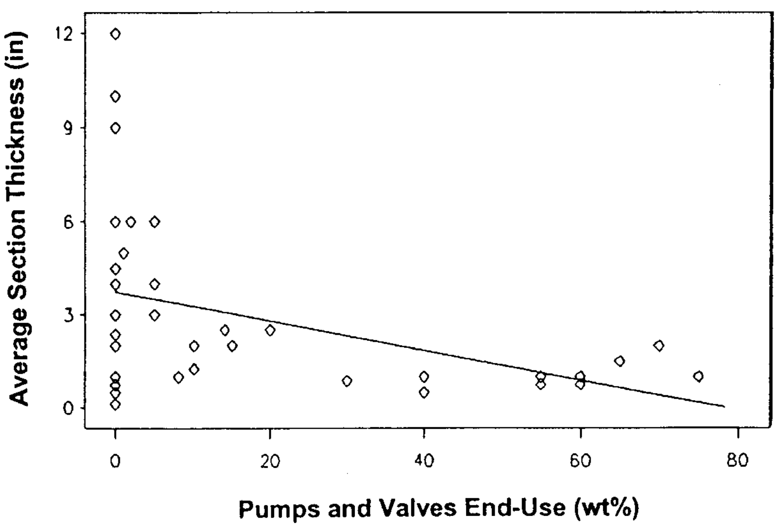

Figure 18 Average section thickness versus weight percentage of castings produced for pump and valve end-use

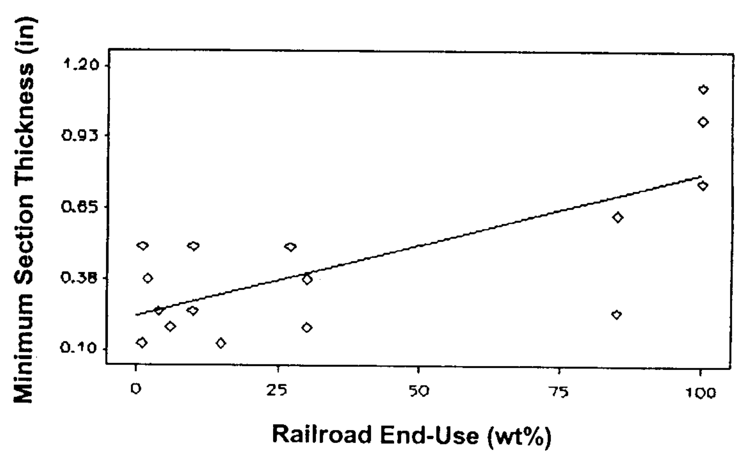

Figure 20 Minimum section thickness versus percentage of casting weight produced for railroad end-use

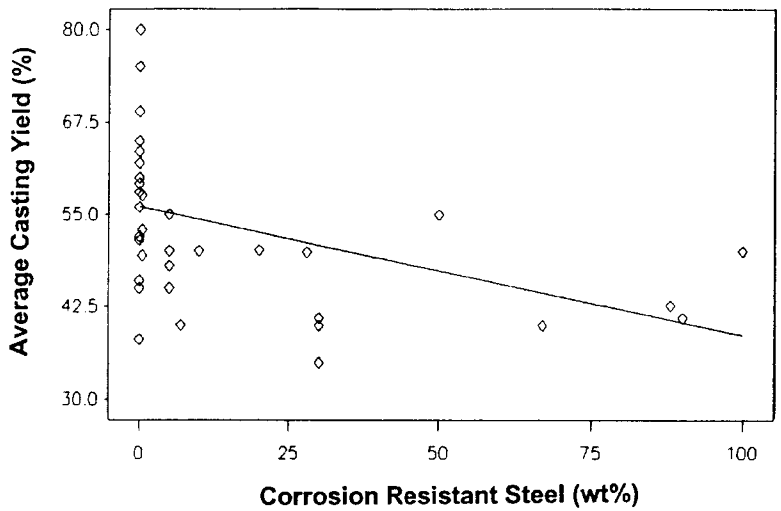

Figure 21 Average casting yield versus weight percentage of corrosion resistant castings produced

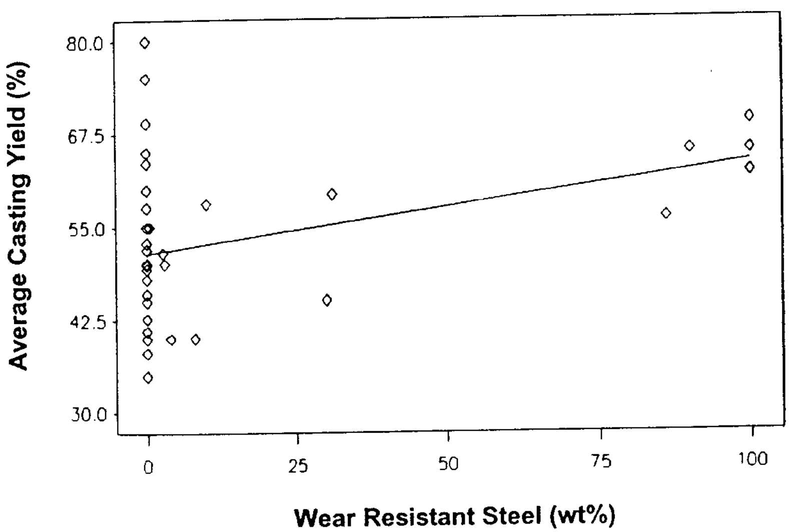

Figure 22 Average casting yield versus weight percentage of wear resistant castings produced

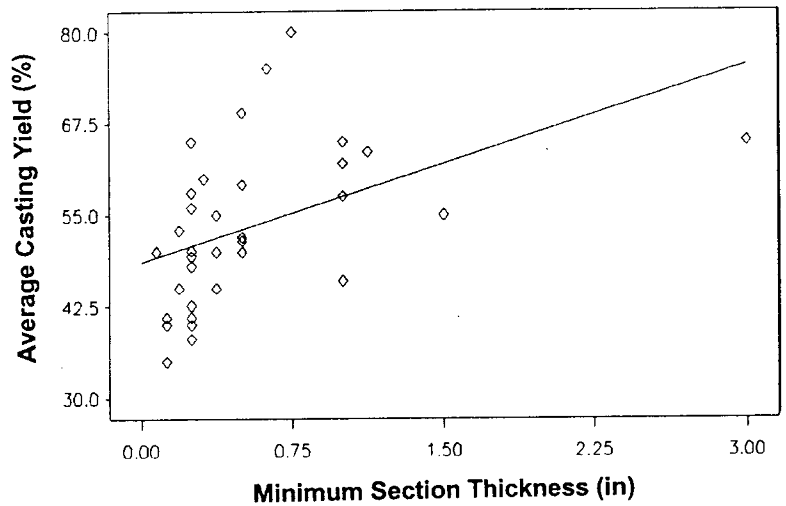

Figure 23 Average casting yield versus minimum casting section thickness

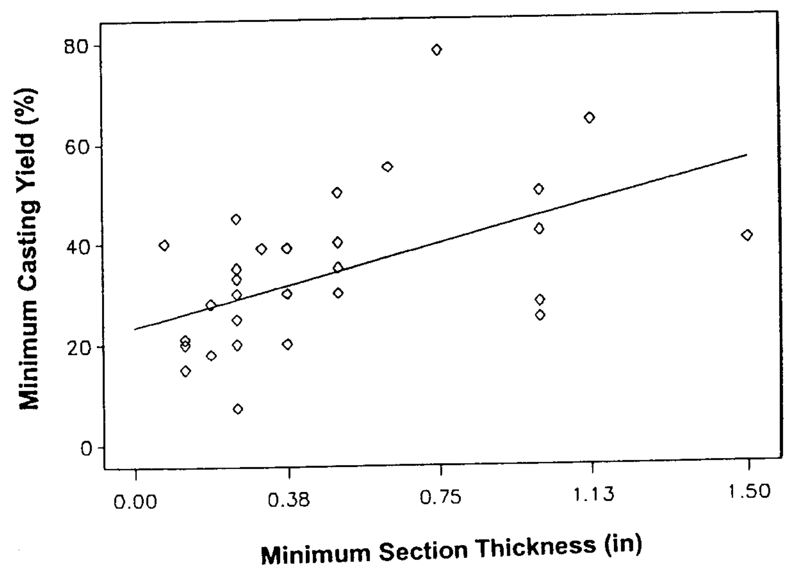

Figure 24 Minimum casting yield versus minimum casting section thickness

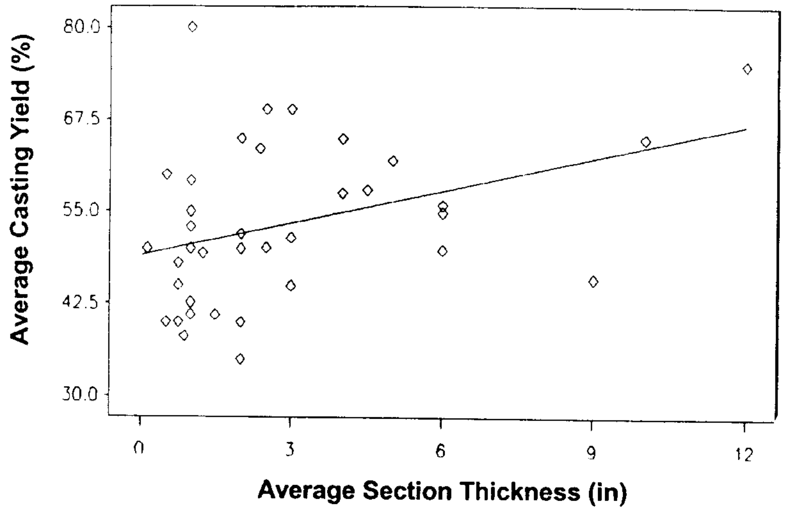

Figure 25 Average casting yield versus average casting section thickness

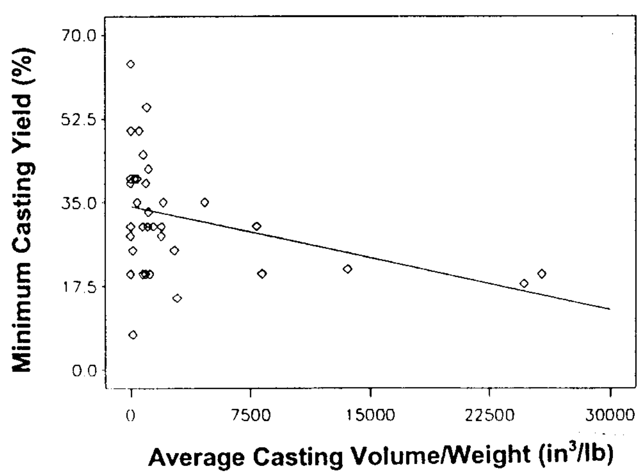

Figure 26 Minimum casting yield versus average casting volume to weight ratio

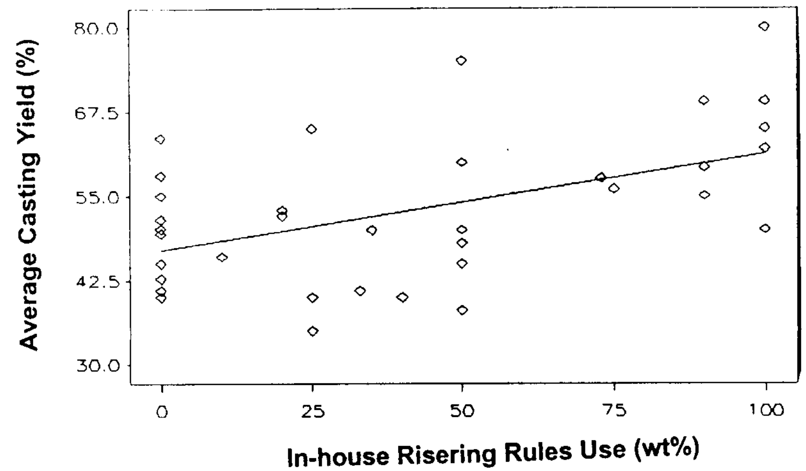

Figure 27 Average casting yield versus weight percentage use of in-house risering rules

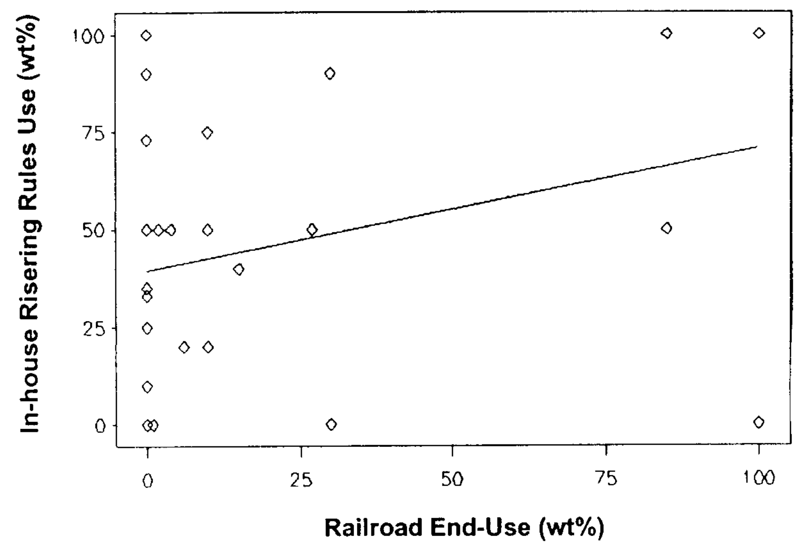

Figure 28 Usage of in-house risering rules by weight percent as a function of weight percentage castings produced for railroad end-use