DIS Research Project #34 Executive Summary

1) A Taguchi design investigation has been made into the relationship between shrinkage and process variables, microstructure, and thermal analysis parameters in ductile iron castings. The most important process parameters to reduce or eliminate the formation of remote area (un-fed) shrinkage were determined.

2) The designed experiments used a standardized experimental procedure that consisted of 7 factors at two different levels, the factors being: tap temperature; silicon content; graphite type; magnesium alloy type; time after magnesium treatment (holding time); method of addition of inoculant; in-mold inoculation (yes or no). Carbon content was kept constant.

3) The shrinkage test castings utilized in this study included a boss-plate, a step-plate, and a chill wedge, produced in CO_2 bonded silica sand molds. The test mold had two identical sets of castings on either side of the sprue, with two inoculation chambers in the runner to study the effect of different in-mold inoculants. Shrinkage and surface sink evaluation of the boss-plate castings was done by visual comparison, titration, grid, and x-ray (selected castings) methods. Microstructure evaluation was done on ½" and 1/8" thick sections of the step-plate casting and from the shrinkage/porosity areas of selected boss-plate castings. Microprobe and SEM analysis was performed on selected boss-plate castings to investigate the segregation pattern, and image analysis was used to examine the distribution of graphite nodules. In addition to acquiring thermal analysis data from the boss and step-plate castings, ten thermal analysis cup samples were poured from each melt to collect data from the base and final iron after inoculation and at the end-of-pour for three types of inoculants.

4) Analysis of the results from the designed experiments using Taguchi software showed that the only significant factors affecting the shrink and surface sink are final silicon content and tap temperature.

5) Regression analysis of the data resulted in predictive equations for shrinkage and surface sink. Using the 7 factors at two different levels in the Taguchi designed experiments, final silicon content and tap temperature were the most significant factors. Shrink–titration showed the effect of additional factors such as graphite and magnesium alloy type. All of the regression analysis results obtained using the variables from the Taguchi designed experiments were in good agreement with the results from Taguchi analysis. Shrinkage prediction equations using an individual data set for chemistry showed that an increase in silicon and oxygen content increased the shrink. Nodule count was one of the most significant factors in the microstructure; shrinkage increased with an increase in the nodule count. Thermal analysis parameters TAL and TEU showed the main effect on shrinkage. Regression equations for shrinkage prediction using all the combined experimental data sets from chemistry, microstructure, and thermal analysis showed that increases in silicon, oxygen, TAL, and TEU led to increased shrink, whereas an increase in pour temperature led to decreased shrink. Surface sink increased with an increase in silicon, oxygen and TEU, whereas increases in pour temperature resulted in a decrease in sink.

6) Analysis of all the data using traditional methods showed the following: -
   a. *Chemistry:* Shrinkage and surface sink increased with an increase in silicon and magnesium content. High silicon promoted more surface sink than low silicon. Lower residual magnesium led to decreased shrinkage. Shrinkage and surface sink also

increased with an increase in oxygen level of the base and final iron, whereas there was little correlation between shrinkage and cerium level in the final iron

b. *Process Variables:* Shrinkage and surface sink decreased with higher tap temperature but the overall shrinkage showed only a slight decrease with an increase in pouring temperature. Special magnesium alloy and crystalline graphite produced a slight decrease in shrinkage. Variations in time after magnesium treatment (holding time) and method of addition of inoculant did not show much effect. Non in-mold inoculated iron showed a decreased shrinkage tendency compared to in-mold inoculated iron. The in-mold inoculant containing Zr and inoculation filter with Zr inoculant produced the highest shrinkage. Duplicate molds did not show any difference in shrinkage tendency compared to the original molds. This corresponds with the observation that changes in pouring temperature and time after treatment had little effect on shrink and sink.

c. *Microstructure*: Shrinkage increased with an increase in nodule count in both the 1/2" and 1/8" thick step plates, whereas an increase in the amount of pearlite showed a decreased shrinkage tendency as a result of decreased nodule count. Comparison of the effectiveness of different in-mold inoculants on the average nodule count and carbide in ½" thick section showed that the Zr containing inoculation filter showed the highest nodule count and lowest amount of carbides, and non in-mold inoculated iron the lowest nodule counts and highest amount of carbides. On the other hand, in 1/8" thick sections, Zr containing inoculation filter resulted in lower nodule counts and highest amount of carbides, and foundry-grade 75%FeSi in the highest nodule count and lowest amount of carbides. Non in-mold inoculated iron in 1/8" thick section resulted in the lowest nodule counts but showed less amount of carbides than Zr containing inoculation filter. Zr containing inoculation filter was more effective in eliminating the carbides in the ½" thick section than the 1/8" thick section.

d. *Thermal Analysis Parameters (TAL, TER, and TEU):* In general, shrinkage and surface sink increased with an increase in selected thermal analysis parameters (TAL, TER, and TEU) from the boss-plate castings. Thermal analysis parameters increased with an increase in silicon and magnesium content, but did not show much effect from variations in oxygen level, holding time after magnesium treatment, or method of addition of inoculant. An increase in cerium content, higher tap temperature, the use of special magnesium alloy or crystalline graphite, all led to a decrease in TAL, TER, and TEU. In-mold inoculated iron, especially with Zr-containing inoculants, showed the highest values of TAL, TER and TEU and resulted in the highest shrinkage compared to other in-mold inoculants. Lower values of TAL, TER and TEU, and decreased shrinkage tendency were associated with non in-mold inoculated irons. Shrinkage tendency increased with an increase in nodule count in both the ½" and1/8" thick step plates with a corresponding increase in TAL, TER, and TEU values.

7) Image analysis results showed a heterogeneous distribution of nodule size and number (i.e., large, small and mixed population of nodules) in different areas of microstructure close to shrinkage/porosity. No particular trend was observed relating overall shrinkage tendency to variations in nodule size distribution and number close to shrinkage/porosity areas.

8) Microprobe analysis (X-ray maps for Si, Mg, Ce, C, P, S, V, Mn, Ti, and Mo) of intercellular segregation close to shrinkage/porosity areas showed the high silicon iron to have more segregation of carbide promoting elements in last to freeze intercellular areas compared to low silicon irons. In addition, high silicon iron showed more depletion of silicon in the intercellular regions than low silicon irons. The intercellular areas of both high and low silicon samples showed localized concentration of Mg, Ce, P, and Si due to the presence of

inclusions and/or carbides. SEM analysis close to shrinkage areas also showed the presence of micro porosity in intercellular areas associated with carbides containing Mo, Cr, Mn, etc., and inclusions of P, Ce, Mg, Si, etc.

9) That shrinkage decreases with an increase in tap temperature and increases with silicon content are both contrary to expectation. The tap temperature effect has not previously been reported in the literature. The current finding that lower magnesium content leads to less shrinkage is in accord with earlier work. High nodule count was associated with increased shrinkage tendency in this investigation. In past work on nodule count effects, conflicting results in this area have been presented.

10) Another important finding in this investigation was the high silicon iron showing more surface sink than low silicon irons. This is probably associated with a wider mushy zone forming at higher silicon contents. The wider mushy zone and increased thermal conductivity of the iron results in a thin or weak casting wall that cannot resist the internal pull and collapses to compensate for the shrinkage/porosity in the later stage of solidification, and the volume loss is transferred to the surface of the castings in the form of surface sink. The wider mushy zone at high silicon content results in more intense intercellular segregation in the last to freeze areas, leading to increased shrinkage/porosity. This is in accord with the current microprobe and SEM examination of intercellular segregation close to shrinkage/porosity areas showing the high silicon iron to develop more segregation of carbide promoting elements in last to freeze areas compared to low silicon irons.

11) The observation that high tap temperatures decrease both shrinkage and surface sink considerably is probably associated with the probability that superheating and holding an iron melt at or above 2800^{o}F purifies the melt of harmful inter-metallic compounds/inclusions/slag that might play a role in shrink formation. Also, holding the melt above 2800^{o}F reduces its nucleation potential and so leads to lower nodule counts (low nodule counts were associated with decreased shrinkage tendency in this work). High tap temperatures may also give rise to more rapid magnesium fade after treatment, and consequently lower the residual magnesium level in the iron, and so reduce shrinkage.

12) A higher base and final iron oxygen content led to more shrinkage in this investigation. Oxygen levels in the iron are directly related to the molten metal processing conditions such as tap temperature, holding time, melt oxidation and composition, treatment and inoculation practices. The effect of oxygen content is complex. Oxide-forming elements are concentrated in the last areas to freeze, at the same locations where porosity is observed. The oxides formed at these locations probably act as nuclei for the porosity, hence higher oxygen content will lead to more porosity. Alternatively, we may be looking at the effect of dissolved oxygen, rather than at the presence or absence of oxides.

13) Shrinkage remains a problem in ductile iron foundries. Irons with very similar composition and treatment often show different shrinkage behavior. We need to understand better why shrinkage varies, and couple that with microstructures and thermal analysis parameters. For a clearer understanding of the causes of shrinkage/porosity, further experimentation is needed involving a few of the most influential variables (including as tap temperature and silicon content) in new designed experiments. A better understanding may be obtained from factorial-design experiments involving the variables shown to be significant in the present work, with the ultimate aim of finding how shrinkage is related to microstructure and thermal analysis parameters.