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WESTINGHOUSE NON-PROPRIETARY CLASS 3

PA-MSC-1288 Statistical Assessment of PWR RV Internals CASS Materials

Materials Committee

PA-MSC-1288

November 2015

Westinghouse

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Statistical Assessment of PWR RV Internals CASS Materials

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November 2015

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	Surry 1 & 2 (W)	X	
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Centrales Nucleares Almaraz-Trillo	Almaraz 1 & 2 (W)	X	
EDF Energy	Sizewell B (W)	X	
Electrabel	Doel 1, 2 & 4 (W)	X	
	Tihange 1 & 3 (W)	X	
Electricite de France	58 Units	X	
Eletronuclear-Eletrobras	Angra 1 (W)	X	
Eskom	Koeberg 1 & 2 (W)	X	
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Nuklearna Electrarna KRSKO	Krsko (W)	X	
Ringhals AB	Ringhals 2, 3 & 4 (W)	X	
Shikoku	Ikata 1, 2 & 3 (MHI)	X	
Taiwan Power Co.	Maanshan 1 & 2 (W)	X	

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ACRONYMS AND ABBREVIATIONS

A/LAI	applicant/licensee action item
AMP	Acieries du Manoir Pompey
B&W	Babcock & Wilcox
BMI	bottom-mounted instrumentation
BWR	boiling water reactor
CASS	cast austenitic stainless steel
CE	Combustion Engineering
CEA	control element assembly
CMTR	certified material test record
CRGT	control rod guide tube
CSF	Canadian Steel Foundries
dpa	displacements per atom
EPRI	Electric Power Research Institute
GTAW	gas-tungsten arc weld
ICC	Investment Casting Company
IE	irradiation embrittlement
MRP	Materials Reliability Program
NRC	U. S. Nuclear Regulatory Commission
PF	Precision Founders
PFA	P.F. Avery Corporation
PWR	pressurized water reactor
PWROG	Pressurized Water Reactor Owner's Group
QACC	Quaker Alloy Casting Company
RAI	request for additional information
RT	room temperature
RV	reactor vessel
SAW	submerged-arc weld
SE	safety evaluation
SMAW	shielded-metal-arc weld
SPC	statistical process control
TE	thermal embrittlement
UHI	upper head injection
WC	Wisconsin Centrifugal

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1 EXECUTIVE SUMMARY

PA-MSC-1288 was developed to provide a more efficient and effective path for utilities seeking license renewal to address applicant/licensee action item (A/LAI) 7 from the NRC's safety evaluation (SE) of MRP-227-A [1] and follow-up requests for additional information (RAIs) from the NRC on plant-specific aging management plans developed per MRP-227-A. A/LAI 7 and the NRC RAIs address the potential for thermal embrittlement (TE) of cast austenitic stainless steel (CASS) reactor vessel (RV) internals components. The A/LAI and RAIs sought assurance that any components actually or potentially constructed from CASS would experience minimal TE or that the embrittlement would be adequately managed. A key step in the utilities' determination of the potential susceptibility of plant CASS components to TE was the search for plant-specific records of CASS chemical compositions to provide estimates of the ferrite content of the CASS. This would in turn be compared with established screening criteria to determine the potential for TE. The step was not only labor- and time-intensive but also not fully effective since often less than 100 percent of the required records were located. In such cases, the practice was to assume that such components would have to be considered susceptible to TE and accounted for in aging management processes and planned inspections. Because these processes and inspections would then incur unnecessary effort and irradiation exposure, PA-MSC-1288 was set up to provide a means to identify alternative, less burdensome approaches to identify the expected ferrite content of plant CASS components and, thereby, reduce the effort, expense, and potential personnel radiation exposures incurred by the original conservative approach.

The PA-MSC-1288 analysis used previously-generated RV internals CASS data to provide a statistical basis to determine an upper bound ferrite content for CASS RV internals components. CASS components in the RV internals of greater than 50 percent of the PWR plants had been analyzed prior to the program. The data generated covers a wide variety of PWR design variations, plant vintages, and component types, and so is representative of domestic operating PWRs. It was expected that trend analyses could be conducted on an industry-wide population or on other sub-populations of the data to provide more efficient predictions of the ferrite content of CASS components for the purposes of comparison with screening criteria used for aging management. Such identified trends would then be available for use by the utilities to more effectively determine the potential susceptibility of their CASS RV internals components to TE.

Under PA-MSC-1288, a complete survey of the estimations of the ferrite content and saturation toughness after TE was made for all the CASS components that had been evaluated by the industry to date. In alignment with the current practices used to respond the NRC RAI's, estimated ferrite contents of the CASS components were calculated from alloy chemical compositions in the plant-specific certified material test records (CMTR), using the Hull's Factors method as described in NUREG/CR-4513 [7]. Saturation fracture toughness after TE was also calculated using procedures outlined in that document. The data were then analyzed statistically, both on an overall basis and with respect to parameters that were expected to affect the ferrite content and the saturation toughness of the CASS, specifically, manufacturer, plant, vintage of production, and component.

A lognormal distribution was found to provide a reasonable fit to the overall distribution of ferrite content in static-cast Grade CF8 RV internals components. This allowed a 95/95 ferrite content upper bound of 17.5 percent to be calculated, below the 20 percent ferrite screening criteria established by the Grimes letter [4]. A 95/95 upper bound based on the mean ferrite content of material produced by each individual manufacturer was also calculated, and agreed well (17.4 percent) with the value calculated from the lognormal distribution. Further, for the Grade CF8 materials, it was demonstrated that for all compositions (including those with over 20 percent ferrite) fracture toughness greater than the screening criterion value was retained after TE effects had saturated.

While an assumption of lognormally distributed data was found to be viable for analyzing the complete population of the database, it was clear that the full population was made up of overlapping subsets of data that individually conformed better to normal or lognormal distributions. The parameter that had the strongest control of ferrite content and saturation fracture toughness was the component manufacturer. An overview of the results is provided in the body of the report: The complete analyses by manufacturer are given in appendices A.1 to A.12. Component datasets from every manufacturer that had contributed enough samples for statistically reliable analyses were modeled using normal or lognormal distributions from which mean and 95/95 upper bound ferrite contents could be determined. No other parameter had such a significant effect. Examining the data by plant or component did not result in datasets that could be modeled by normal or lognormal distributions, except in cases where a single manufacturer was the sole supplier of a given component or to a given plant. Production vintage had very little influence on ferrite content, indicating that individual manufacturers consistently employed their own preferred melt compositions to guarantee product reliability.

Analysis of the ferrite content by manufacturer identified some manufacturers that produced CASS with very low mean ferrite content and correspondingly low 95/95 confidence level ferrite content. One such manufacturer actually was responsible for over 40 percent of the total heats analyzed (50 percent of the Grade CF8 materials analyzed). This manufacturer provided low mean (6.2 percent) and 95/95 confidence limit (9.7 percent) ferrite content distributions. Other manufacturers provided materials with consistently low ferrite contents also. Thus, it was concluded that if the manufacturer of CASS RV internals components could be identified, statistics could be employed to predict expectations of the ferrite content of materials and components for which the plant records could not be located. Other similar trends, including limited manufacturers for some components, also provided a basis for predicting the expected ferrite content and saturation toughness after TE from incomplete plant records.

Based on the analysis of the existing data, PA-MSC-1288 has developed approaches for identifying the potential for assessing the ferrite content of plant-specific components for which plant records are not readily available. Essentially, these approaches employ statistical expectations of ferrite content based on manufacturer and/or component to identify expectations of the ferrite content and fracture toughness after TE. If the components can be associated with manufacturers whose production statistics displayed consistently low values of ferrite content then these components could be reasonably assured to have low ferrite content and would thus screen out from management and inspections for TE during the relicensing process.

Some data were found that produced ferrite contents above 20 percent, which means that a randomly selected component could not be guaranteed to have ferrite content below the current 20 percent criterion for TE. (This is even more so for ferrite content screening below the proposed 15 percent level proposed for combined TE and IE). Nevertheless, if restrictions on manufacturers or component distributions are taken into account, then very simple analyses can be based on incomplete plant records to provide reasonably assured expectations of plant RV internals component ferrite contents. The following three approaches are made available, based on the results of this program:

- Use of the ferrite upper bound based on the overall population
- Use of the ferrite upper bound based on a specific manufacturer
- Use of a ferrite upper bound for a specific component type, based on the limiting upper bound of the manufacturers who supplied that component

If the applicable distributions are found to be those that would predict low ferrite contents, then it would be reasonable to ask for exemption of these components from TE-driven aging management and inspection. These approaches would be useful in the cases where an incomplete number of records are discovered, when only manufacturer information is available, or when the component belongs to a set that were only manufactured by manufacturers that produced lower ferrite content compositions (e.g., lower core support columns were found to have been fabricated by manufacturers with ferrite content limits below 20 percent).

The results of the saturated fracture toughness calculations reveal that low-molybdenum, static-cast Grade CF8 compositions should have much higher toughness than the 255 kJ/m^2 criterion identified in the Grimes letter even at ferrite contents beyond the 20 percent screening level cited by the Grimes letter. These data may be taken to reflect the significant conservatism inherent in the Grimes letter approach and to call into question the need for more conservatism that is invoked by the recent NRC guidance of 15 percent ferrite content in consideration of combined TE and IE effects. The toughness data also reflect the lower toughness (with higher scatter) behavior of the higher molybdenum containing Grade CF3M.

The results of the PA-MSC-1288 analysis address only TE, and so do not provide a complete response to A/LAI 7, which also requests consideration of irradiation embrittlement and component functionality. A utility may also need to consider these factors in their A/LAI7 response. The utility may provide additional assurance of continued safe operation by demonstrating that components of concern are part of redundant assemblies, located in low fluence regions, have low operating stresses or have low consequences of failure.

2 INTRODUCTION

The MRP developed inspection and evaluation guidelines for managing long-term aging of RV internals components for pressurized water reactors (PWRs) in MRP-227-A [1]. In MRP-175 [2], a precursor document to MRP-227-A, the industry identified that CASS RV internals components could be susceptible to TE and provided a guidance criterion in accordance with the existing Nuclear Regulatory Commission (NRC) guidance, the 'Grimes Letter' [4]. In the NRC's safety evaluation (SE) of MRP-227-A [1], the NRC staff included A/LAI 7, which requests a plant-specific analysis of CASS RV internals components. CASS RV internals components are susceptible to TE which can result in a loss of fracture toughness. A/LAI 7 again also suggested the application of the screening criteria in [4], commonly known as 'the Grimes letter.'

The screening criteria in the Grimes letter are based on ferrite content, or the percentage of the CASS material that is the delta ferrite phase, as opposed to the austenite phase. This parameter was not measured for CASS RV internals components when they were manufactured, and would be difficult to measure in the field. Therefore, the ferrite content was calculated from the material's chemical composition, using an empirical correlation based on Hull's factors [5]. This approach required locating CMTRs for material, as well as documentation linking that CMTR to a specific plant.

This screening approach based on the Grimes letter was successful so long as the CMTRs could be located and traced to a plant. The vast majority of components for which records were located had ferrite contents far below the screening criteria, and screened out. However, it was often the case that CMTRs could not be identified for 100 percent of CASS RV internals components in a given plant. Without these CMTR data, it was conservatively assumed that the material was susceptible to thermal embrittlement and was screened in [6]; therefore, it required additional analysis or inspection. This report provides additional approaches that can be used in the screening process to relieve the necessity for making this assumption and so avoiding additional analysis or inspection.

To aid in determining appropriate aging management measures for CASS RV internals, the Pressurized Water Reactor Owner's Group (PWROG) developed the PA-MSC-1288 program. This program was intended to analyze available CASS RV internals manufacturing data on a fleet-wide basis, and to identify trends that could be used to predict ferrite content for components where CMTR data were not available. This report documents the development of and potential applications for a statistical approach to predict the ferrite content of CASS RV internals components for which limited manufacturing information is available (missing a complete set of CMTRs, for example). This is accomplished by recognizing that the 95/95 upper limit for ferrite content determined for static-cast Grade CF8 materials is below the NRC's screening criterion for that material. Utilities can, based on this conclusion, provide reasonable assurance to the NRC that a randomly selected CASS RV internals component is unlikely to have ferrite content greater than 20 percent, even when plant specific manufacturing records are incomplete or unavailable.

Alternatively, for utilities requested to provide plant-specific data, the statistical approach in this report can be used to supplement the plant-specific data. This is accomplished by recognizing that ferrite content approximates a normal or lognormal distribution for a given manufacturer, and from this determining a statistical tolerance limit (95/95 upper limit) for the ferrite content of a given manufacturer. Where the 95/95 upper limit for ferrite content for a given manufacturer is lower than the NRC's screening criteria, it can be stated with a high degree of confidence that no components from that manufacturer will exceed the criteria.

An additional benefit of analyzing the CMTR data on a fleet-wide basis is the ability to perform calculations to determine the saturated fracture toughness for these components using the NUREG/CR-4513 [7] methodology. This is the minimum remaining fracture toughness in the component after TE effects have saturated. This allowed the calculation of 95/95 lower limits by manufacturer for fracture toughness as well. Where the 95/95lower limit for fracture toughness is greater than the NRC's screening criteria (a resistance to fracture J of 255 kJ/m^2, at a crack extension of 2.5 mm), it can be stated with a high degree of confidence that no components from that manufacturer will fall below the criteria.

This report also documents the development of the statistical approach used herein by the inclusion of presentations given to the NRC (Appendices B and C). A PWROG expert panel was also used to develop and review the approach, as documented in [39].

All materials supplied by the manufacturers discussed in this document met the purchaser's chemical composition and quality assurance requirements and are in no way deficient or defective. Comparisons between manufacturers are only made to assist utilities in determining the properties of materials within their plant and are not a reflection of the quality of the product from these manufacturers.

The approach described in this report is currently only applicable to U.S. PWR RV internals. Application of the approach beyond U.S. PWR RV internals would require additional work to demonstrate applicability and is outside the scope of the current program.

3 BACKGROUND

Austenitic stainless steels are a common material choice in potentially corrosive, high temperature environments because of their good corrosion resistance and high fracture toughness, as well as (relative to nickel based alloys or other alternatives) low cost. Using CASS material is attractive when the alternative of manufacturing using wrought materials is large amounts of machining, welding, or forging operations. CASS has been used in the RV internals of PWRs to make components with complex geometries. The NRC has given these components special attention [1], [4] as the PWRs apply for license renewal. CASS components have the potential to become embrittled in the conditions found inside a PWR because of the high temperature (approximately 550°to 650°F or 288° to 343°C) and the neutron irradiation environment.

Current regulatory guidance relies on the calculated ferrite content (based on chemical composition) of a CASS component as a screening tool for TE-related issues. To support this approach, this study summarizes the available manufacturing data and proposes an approach to predict the ferrite content in the event that the manufacturing record for a CASS component is unavailable. The manufacturing data is also used to estimate conservative fracture toughness values for the materials studied when they have reached the saturation point for thermal aging effects. The data analyzed comes primarily from CMTRs and associated fabrication records applicable to CASS RV internals components that are in service in Babcock & Wilcox (B&W), Combustion Engineering (CE), and Westinghouse nuclear reactor designs. The CMTRs and associated fabrication records provide detailed manufacturing information including the chemical composition of the component, the manufacturer, the date of manufacture, heat treatment information, the quantity of parts produced from the heat, and tensile test properties.

3.1 CASS CHEMISTRY

Most PWR RV internals components are fabricated from rolled or forged Type 304 stainless steel. The CF8 grade is the cast equivalent of Type 304 stainless steel [8], however CASS typically contains between 5 and 15 percent delta ferrite, whereas rolled or forged stainless steel contains less than 4 percent delta ferrite. The austenite phase is approximately 18 percent chromium and 9 percent nickel, while the ferrite phase is approximately 28 percent chromium and 6 percent nickel [9]. The overall chemical composition of CASS differs from rolled and forged grades as depicted in Table 3-1.

Table 3-1 Chemistry Specification Difference between Bar, Forged, and Cast Austenitic Stainless Steel

Specification	Product Form	C	Mn	P	S	Si	Cr	Ni	Mo
Type 304 (A479 [10])	Bar	0.08	2.00	0.045	0.030	1.00	18.0-20.0	8.0-10.5	-
Type 304 (A182 [11])	Forging	0.08	2.00	0.045	0.030	1.00	18.0-20.0	8.0-11.0	-
Type 316L (A479 [10])	Bar	0.03	2.00	0.045	0.030	1.00	16.0-18.0	10.0-14.0	2.00-3.00
Grade CF8 (A351 [12])	Casting	0.08	1.50	0.040	0.040	2.00	18.0-21.0	8.0-11.0	0.50
Grade CF3M (A351 [12])	Casting	0.03	1.50	0.040	0.040	1.50	17.0-21.0	9.0-13.0	2.00-3.00

Note: Values in weight percents, as maximums unless otherwise shown.

Key differences in the chemical composition are:

- Increased Si to improve flow properties (decrease viscosity) during the casting process
- Reduced manganese to reduce hardening and to promote ferrite phase formation
- Increased Cr to compensate for segregation and to promote ferrite phase formation

Delta ferrite is encouraged to form in CASS because it prevents hot tearing during solidification. Hot tearing can occur in a casting when the mold is of a complex shape and is too rigid to allow contraction of the casting during cooling (especially problematic if there are long, thin sections adjacent to thicker sections). Even a very small amount of delta ferrite will significantly reduce the castings' susceptibility to hot tearing during solidification of the casting. Several theories for why this occurs are discussed in [13] and [14], though the specific details do not have a direct impact on this work. A certain amount of delta ferrite in CASS will also serve to increase the yield and tensile strength and improve the resistance to stress corrosion cracking [8].

The as-cast condition of a CASS component is similar to that of an austenitic stainless steel weld. Both CASS and austenitic stainless steel welds require a small amount of delta ferrite to prevent hot cracking or tearing during solidification [14]. For this reason, thermal aging research done on austenitic stainless steel welds can provide insight to how CASS might thermally age [15]. However, the failure mechanisms of thermally embrittled weld material may differ from that of thermally embrittled CASS material, so weld data must be used with caution if it is to be applied to CASS material as it may not be representative. Following the discussion in [15], submerged-arc welds (SAWs), shielded-metal-arc welds (SMAWs), and gas-tungsten arc welds (GTAWs) can fail by a dimpled rupture mechanism similar to CASS materials, but in the SAW and SMAW failure was initiated by decohesion of second-phase particles of manganese silicide and local rupture/decohesion of delta ferrite particles. This differs from the observed failure modes of CASS, where failure initiates by cleavage of the ferrite phase and shearing of the remaining austenite follows [16]. Thus SAW and SMAW weld data would present very conservative properties if used to represent CASS behavior.

Typically, CASS components are manufactured by melting down scrap metals of select compositions into a heat of molten metal, which is then cast into shaped molds. This can explain the origin and quantity of certain elements in material heats, such as cobalt. Cobalt-free stainless steel scrap would be difficult to procure; meaning that while no cobalt was intentionally added to the metal, small amounts of cobalt will invariably be present in the CASS chemical composition. Cobalt is not desirable for service in irradiation environments because when bombarded with neutrons cobalt readily forms ^{60}Co, which emits high levels of gamma radiation and has a half-life of 5.27 years. For PWR RV internals purposes, cobalt was typically required to be kept below 0.20 weight percent.

Molybdenum is also not intentionally added to Grade CF8 and Grade CF3 materials, such as the Grade CF8 heats examined in this study, but it is present in small amounts. Presumably this could be because small amounts of Type 316 stainless steel scrap were included in the melt. Molybdenum content would not have been measured during production and would generally not have been cited in the CMTRs. Molybdenum was set at 0.50 maximum for A351 Grade CF8 in the 1981 ASTM specification [17], but was not specified in prior specifications. For the A296 specification [18], no molybdenum limit was ever set (including in the specification that superseded A296 [18] once it was withdrawn, A743/743M [19]). The ASME Code set limits at 0.50 for molybdenum in Grade CF8, though the ASME Code was not applicable to many older plants when they were being constructed. Molybdenum content is included in screening for TE of CASS RV internals thus, an approach is required to accommodate such missing data in many product CMTR's. In the absence of available data it is considered to be conservative to include 0.5 percent as the molybdenum content in screening plant-specific CASS. Where CMTRs did report Mo content for Grade CF8 material, it was well below the 0.5 bound.

3.2 EFFECT OF FERRITE CONTENT ON THE EMBRITTLEMENT OF CASS

For the unaged cast stainless steels at operating temperatures of interest, the Charpy V-notch toughness is quite high, usually greater than 150 ft-lbs, often challenging the Charpy machine capacity of ~250 ft-lbs. Ferritic stainless steels exhibit about the same Charpy toughness. Thus, it is reasonable to assume that the contributions to the total energy by the austenitic matrix and the ferrite are approximately in proportion to the percent volumes of each component, perhaps 80 percent for the austenitic matrix and 20 percent for the ferrite. However, with aging, the ferrite, while increasing in strength and hardness, is embrittled. Thus, one constituent of the aggregate austenite-plus-ferrite microstructure will have lost considerable toughness while the remaining austenite would be considered to be essentially unaffected by the thermal exposure. The net effect of the thermal embrittlement of the ferrite on the aggregate's toughness depends on the amount of ferrite and its distribution. CASS toughness data after thermal aging were correlated with ferrite content as calculated by Hull's Equivalent Factors [7]. An EPRI study of the data [15] identified that ferrite contents greater than 20 percent were required to effect significant embrittlement of the overall CASS structures.

4 STATISTICAL APPROACH DESCRIPTION

In order to accurately predict component chemical compositions where precise manufacturing records are absent, data from available manufacturing records were analyzed on a fleet-wide basis to predict ferrite content and expected saturation fracture toughness. The results of the predictions were then analyzed using statistical techniques to determine the expectations for corresponding ferrite and toughness predictions for components for which CMTRs would not be available.

This following section describes the available data, the calculations performed with these data to compute ferrite content and fracture toughness values, and the statistical analysis that were performed using the results of those calculations. Overall, the approach combines calculations from NUREG/CR-4513 [7] and NUREG-1475 [20], and has many similarities to "Statistical Variation in Materials Properties" contained in [21]. Some comments are provided on the conservatisms of the approaches employed.

This statistical approach was reviewed by a PWROG expert panel (see [39]) and discussed with the NRC (see Appendix B and Appendix C) prior to the issuance of this report.

4.1 MANUFACTURING RECORDS DATA

The dataset used in this analysis includes information representing operating PWRs in the United States. This includes six (of six) operating B&W units, five (of 12) operating CE units, and 26 (of 47) operating Westinghouse units. A total of 14 different manufacturers are represented, with 1410 total unique heats of material analyzed. In this study, each unique material heat is considered a data point. 1598 total measurements are included; however CMTRs for some heats (187) include both product and ladle analyses. Additional statistical data is discussed in Section 5.0. An abridged dataset is included in Appendix E.

Data for B&W components were provided by AREVA [22]. Data for CE and Westinghouse components were gathered through efforts under PA-MSC-0983 [23] and other plant-specific record searches conducted as part of their aging management and NRC RAI response activities. These data are collected in [24].

It is important to note that many of these components (particularly for Westinghouse plants) were produced in a batch production mode – that is, components were often not fabricated for a specific plant. There are many cases where components from the same heat of material are installed in multiple different plants. Furthermore, not all plants have conducted plant-specific analyses of CASS RV internals components. A fraction of the components in these unanalyzed plants are, therefore, likely fabricated from material that has been included in this analysis. This concept is illustrated in Figure 4-1. This is a consequence of analyzing components produced in a batch mode on a plant-specific basis.

All of the data come from CMTRs – notarized test results, signed by a metallurgist employed by the material manufacturer. The various data parameters included on a CMTR typically include:

- Manufacturer
- Chemical composition
- Component type
- Manufacture date
- Heat treatment information
- Tensile test data

Previous analyses have only considered a single heat of material at a time, and used only chemical composition information to calculate delta ferrite content. The present analysis examines all the available data parameters for all operating U.S. PWRs.

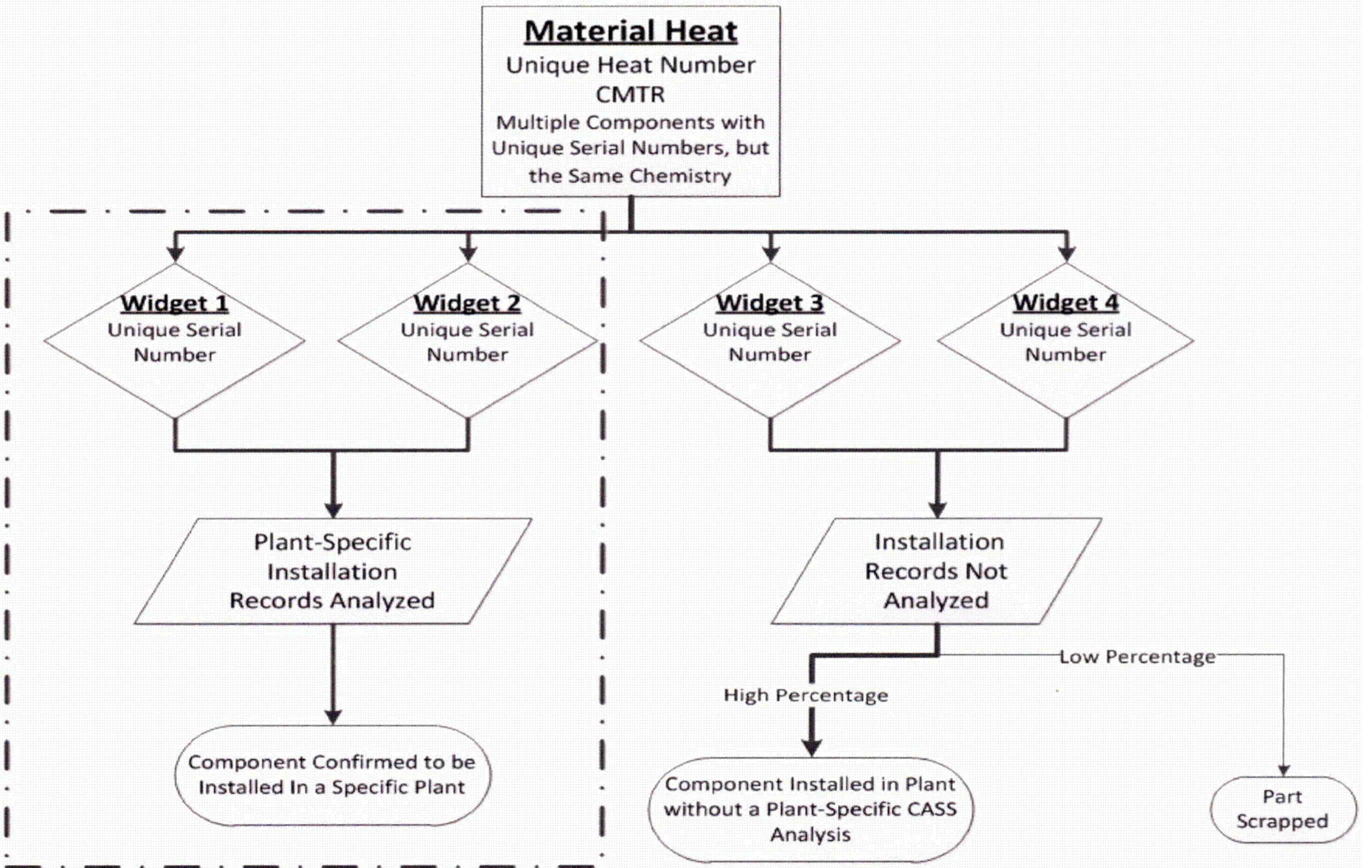

Figure 4-1. Batch Production of RV Internals

The dataset used in the statistical assessment includes data representing the following CASS RV internals components for B&W, CE, and Westinghouse-designed reactors (in MRP-189 [25] and MRP-191 [3] nomenclature as applicable):

- Mixing devices
- Column bases
- Upper head injection (UHI) flow column bases
- Brackets, clamps, terminal blocks, and conduit straps (conduit supports)
- Upper support plate assembly
- Bottom-mounted instrumentation (BMI) column cruciform
- Lower support column bodies
- Lower support casting
- Control element assembly (CEA) shrouds
- CEA shroud bases
- Modified CEA shroud extension shaft guides
- Flow bypass inserts (not identified in MRP-191 [3])
- Control rod guide tube (CRGT) spacer castings
- Outlet nozzles
- IMI Guide Tube Spiders
- Vent valve bodies and discs

The types of CASS material included in the data are statically-cast Grade CF8, centrifugally-cast Grade CF8, and statically-cast Grade CF3M. The majority of the material examined is static-cast Grade CF8, which was procured under a number of different (but equivalent) materials specifications, such as ASTM A296 [18], ASTM A351 [17], and ASME SA351 – all are Grade CF8 with equivalent chemical composition and strength requirements.

Centrifugally-cast Grade CF8 was used in CEA shrouds, CEA shroud bases, and for some UHI flow column bases. This material was procured under either ASTM A351, with centrifugal casting specified, or ASTM A451 [26] – both are Grade CF8 with equivalent chemical composition and strength requirements.

Statically-cast Grade CF3M was used exclusively in CRGT spacer castings for B&W plants, and was procured under ASTM A351, Grade CF3M.

The time period covered by the data set includes components fabricated from 1965 through 1979. It is important to note that these are the dates on the CMTRs, representing when the component casting was completed – these dates do not represent plant installation or the start of plant commercial operations. The time of fabrication can potentially reveal trends in a given manufacturer's material chemical composition over time (where sufficient data is available to develop a meaningful correlation).

For some manufacturers, both ladle and product analyses of the chemical compositions are provided on the CMTR. Since these data represent two separate measurements of essentially the same material, the single material heat is still considered only one data point. However, both analyses are used to calculate separate distributions for ferrite and fracture toughnesses.

This can be thought of as a check on the level of uncertainty in the final results from measurement uncertainty. In Appendix A.12, it is shown that the ladle and product analyses yield almost identical 95/95 limits on calculated saturated fracture toughness for that manufacturer (Wisconsin Centrifugal).

Overall, the data set used in this analysis represents a wide variety of plant designs, components, and vintages. Over half of the domestic operating PWRs contributed data.

4.2 FERRITE CALCULATIONS

Determining the amount of ferrite phase is important in understanding the mechanical properties of CASS, as well as for austenitic stainless steel welds. Because of the number of alloying elements present in austenitic stainless steel, there is no simple phase diagram that can be used to predict the amount of ferrite phase. Instead, empirical correlations were developed by dividing elemental alloying additions into two categories – austenite formers and ferrite formers [5]. These elements are each assigned an empirically determined coefficient that multiplies the elemental weight percent of the alloy, effectively 'weighting' them. The austenite promoters are so combined into a 'Nickel Equivalent' factor, and the ferrite promoters in a 'Chromium Equivalent' factor, which are in turn employed in an empirically-derived formula that estimates delta ferrite content as a percentage.

The NRC has recommended the use of these Hull's factors and the method of estimating ferrite content [1] in assessing the amount of delta ferrite in a CASS component of a PWR. This estimated delta ferrite value can then be compared to established screening criteria to determine if the component must be considered susceptible to thermal embrittlement [1].

Hull's factors [7]:

$$Cr_{(equivalent)} = Cr + 1.21(Mo) + 0.48(Si) - 4.99 \quad \text{Eq. 3.2.1 of [7]}$$

$$Ni_{(equivalent)} = Ni + 0.11(Mn) - 0.0086(Mn)^2 + 18.4(N) + 24.5(C) + 2.77 \quad \text{Eq. 3.2.2 of [7]}$$

The delta ferrite percent is then given by:

$$\text{Ferrite content, } \delta = 100.3(Cr_{eq}/Ni_{eq})^2 - 170.72(Cr_{eq}/Ni_{eq}) + 74.22 \quad \text{Eq. 3.2.3 of [7]}$$

Where:

Cr –	Chromium weight percent	Mo –	Molybdenum weight percent
Si –	Silicon weight percent	Ni –	Nickel weight percent
Mn –	Manganese weight percent	N –	Nitrogen weight percent
C –	Carbon weight percent		

The concentration of N is often not available in a CMTR; if not known, it is assumed to be 0.04 weight percent [7]. This is because Grade CF8 material is generally air cast, and the melt would absorb nitrogen from the air.

The units of the calculated value produced by the Hull's factors methodology is 'delta ferrite percent.' This is neither a weight percent nor a volume percent, but more like an estimated, average delta ferrite percent for the overall component. For most heats, the difference between the estimated ferrite content and a value of the ferrite content measured by microscopy methods is ±6 ferrite percent. The few heats for which the calculated ferrite content is significantly lower than the measured values generally contain ≥10 percent nickel [7].

Other methods of correlating chemical composition to delta ferrite content similar to Hull's factors have been developed as well [27], [28], and [29]. However, The NUREG/CR-4513 [7] thermally saturated fracture toughness estimation methodology is based strictly on Hull's factors as an input. Therefore it is not appropriate to use ferrite content calculated via the other methodologies as an input to the NUREG/CR-4513 [7] fracture toughness equations.

4.3 CONSERVATISM IN FERRITE CALCULATIONS

While the ferrite content calculated via Hull's factors is the appropriate input for the NUREG/CR-4513 [7] fracture toughness calculations, it is worth noting that there is some conservatism in this calculation. This conservatism originates from assuming a maximum value for molybdenum when it was not reported, and not accounting for the solution annealing effect on the ferrite content of the castings.

As discussed in subsection 3.1, molybdenum was often not reported on CMTRs for Grade CF8 material, as it was not a requirement of the specifications in place at that time. The ferrite calculations completed in this analysis assume 0.50 weight percent molybdenum for Grade CF8 material where it was not reported on a CMTR. As molybdenum is a strong ferrite former [5], assuming 0.50 weight percent molybdenum conservatively increases the calculated ferrite content by approximately 1 to 3 percent ferrite. The molybdenum content for Mo was included on CMTRs for the Grade CF3M material, so this is not a conservatism for that material type.

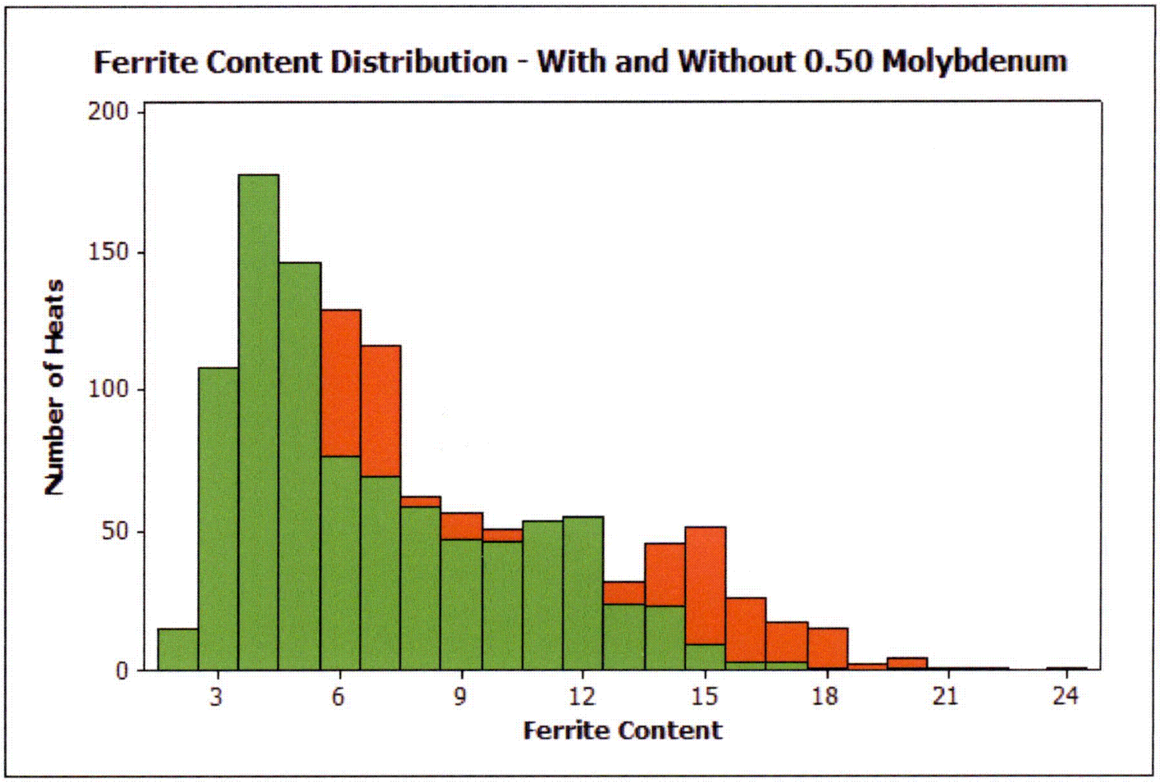

Figure 4-2. Effect of Molybdenum Assumption on Ferrite Content

The effect of assuming 0.50 weight percent molybdenum is illustrated in Figure 4-2. The green portion of the data represents the overall distribution of delta ferrite in static cast Grade CF8 material without the assumption of 0.50 weight percent molybdenum. The orange portion of the data is the same distribution, but with the inclusion of 0.50 weight percent molybdenum. Without the conservative assumption of 0.50 weight percent molybdenum, no heats of static-cast Grade CF8 exceed 20 percent delta ferrite.

A further conservatism is that, in practice CASS components would have been heat treated, using at least a partial solution treatment. During this heat treatment, at least some of the delta-ferrite would transform to austenite. Since Hull's factors predicts ferrite content after casting, the use of that method to predict ferrite content in heat treated components is also conservative. A methodology for predicting ferrite content in a heat treated CASS component has been developed by EdF [27]. Comparison of the predictions of ferrite content using the Hull's factors and the EdF method indicates that consistently lower values are obtained by the EdF method.

4.4 FRACTURE TOUGHNESS CALCULATIONS

The methods of NUREG/CR-4513 [7] as updated by NUREG/CR-7185 [30] employ the ferrite content as calculated by Hull's factors and other compositional parameters to develop predictions of the Charpy Impact Energy saturated fracture toughness data (C_{Vsat}). In turn, these predictions are used to develop predictions of the material's tearing resistance in the presence of a 2.5mm crack ($J_{2.5mm}$). The equations used to estimate the saturation fracture toughness values after TE are more complicated than those used to estimate ferrite content. A complete description of the equations is given in Appendix D.

A fracture toughness of 255 kJ/m^2 at a crack extension of 2.5 mm has been established as a screening criterion for potentially embrittled material [30]. That is, should a material fall below this fracture toughness, additional analysis or inspection of the relevant components may be required. The 255 kJ/m^2 criterion was developed for pressure boundary components by EPRI [15] and agreed to by the NRC in the Grimes letter [4]. This value is most likely overly conservative for CASS when employed in RV internals components. Additional analyses would need to be conducted to demonstrate this rigorously for all CASS RV internals such that the criteria could be relaxed [31]. However, a lower support column functionality analysis [32] demonstrated that even at very low fracture toughness values, a pre-service flaw significantly larger than the detection limit provided by the required radiographic or dye penetrant tests would have to be present for a failure to occur.

4.5 CONSERVATISTM IN FRACTURE TOUGNESS CALCULATIONS

The calculated saturated fracture toughness values are inherently conservative, as they are based on lower bound correlations from experimental datasets. NUREG/CR-7185 [30] explicitly states that these values are likely conservative for plant materials.

An assumption inherent in calculating saturated fracture toughness values for CASS is that the TE process has reached saturation. Even after a sixty-year life at reactor operating temperatures, this is a conservative assumption and underestimates the true toughness of the material, in particular for internals components operating at T_{cold} temperatures. The amount of margin in this conservatism will decrease as plants continue to operate and the TE process comes closer to saturation. The methodology for estimating the service-time and temperature fracture toughness properties and results of these calculations are documented in detail in Appendix D.1.

4.6 STATISTICAL APPROACH

The purpose of the statistical approach described in this section is to provide a basis for use of CMTR data beyond chemical composition (discussed in subsection 4.1) to identify trends in calculated ferrite content (subsection 4.2) and fracture toughness (subsection 4.4). The approach is to be used to provide estimates of ferrite content when complete manufacturing records are unavailable, and to assess the fracture toughness remaining in these materials after TE effects have saturated. The described approach applies statistical distributions to sample data to make reliable predictions about material properties for a larger population consistent with [20] and [21].

After preliminary analysis, ferrite content for a given manufacturer was found to approximate either a normal or lognormal distribution. That the ferrite content approximates such distributions for a given manufacturer is expected, as statistical process control (SPC) was a common practice when the CASS materials examined in this study were fabricated. That the distributions (i.e., the mean and the standard deviation) change with manufacturer was also expected. The amount of alloying additions required to maintain productivity for a given manufacturer would vary based on their casting practices. For example, a manufacturer could use more alloying additions (typically resulting in higher ferrite content) in lieu of developing specialized molds or temperature control during pouring. Parameters other than manufacturer examined (such as plant or component) do not show meaningful correlations, except in the case where a single manufacturer was the sole supplier of a given component or for a given plant.

The normal and lognormal distributions are well described in NUREG-1475 [20]. The lognormal distribution is essentially a normal distribution fit to the natural logarithm of a variable (in this case, ferrite).

To determine whether a given data set should be modeled using a normal or lognormal distribution, three tools were employed. The first of these was the Anderson-Darling parameter (A-D). This statistical parameter compares the cumulative distribution function for observed data with that for the fitted normal curve over the range of the data [37]. A smaller value of A-D indicates a better fit to the dataset.

A p value was also employed as the second tool to determine the validity of the application of the normal or lognormal distribution, with an acceptance criterion that p be greater than 0.05 (95 percent confidence).

The third tool employed in determining the appropriate distribution to apply was engineering judgment. This includes practical considerations, such as the effective minimum ferrite value at approximately 3 percent observed in the data sets. This minimum value eliminated the 'tail' for datasets with lower average ferrite values (for example, Kearsarge, see Appendix A.6). Another consideration was to implement distributions that were accurate or a conservative representation of the datasets.

For normally and lognormally distributed data, it is possible to calculate a statistical tolerance limit. For this analysis, one-sided statistical tolerance limits are calculated according to Section 9.12 of NUREG-1475 [20]. The tolerance limit used is a 95/95 tolerance limit; this equates to 95 percent confidence that at least 95 percent of the population is bounded by the tolerance limit (this is the most common specification for tolerance intervals at the NRC [20]). The statistical tolerance limits are calculated using the following equations taken from [20]:

$\bar{Y} + ks$ Upper tolerance limit (ferrite) Eq. 4-1

$\bar{Y} - ks$ Lower tolerance limit (fracture toughness) Eq. 4-2

Where $\bar{Y}$ is the sample mean, s is the sample standard deviation, and k is a tolerance limit factor (dependent on the number n of data points in the sample), available in Table T-11b of [20]. Statistical tolerance limits are developed for both ferrite content and fracture toughness for each manufacturer in Appendix A. The tolerance limits for each manufacturer are then compared to the screening criteria.

The factor k is dependent on the number of data points. This allows the k factor to account for uncertainty associated with small sample sizes. For a one-sided 95/95 limit, the factor k is 26.26 for two data points; it rapidly drops to 4.20 for five data points, and then slowly declines to 1.76 for 500 data points. The fact that the k factor is relatively high for two data points underscores the concept that it is difficult to draw any substantive statistical conclusions from a sample population of two data points. As shown in Appendix A, there are a few manufacturers for which data from only two material heats were available.

An assumption critical to this type of analysis is that the sample (the CMTR data) is representative of the entire population (all the CASS RV internals). Given that a significant fraction of the domestic operating PWRs contributed data to the study, and that this fraction covers a wide variety of plant designs and vintages (as discussed in subsection 4.1), it is expected that the data presented in this report is representative of domestic operating PWRs. Showing that there is no time or component dependence on ferrite content (shown in Appendix A) assures that the sample data available is representative of the population. Additionally, because some heats of material were found to have been used in more than one plant in the data analyzed to date, it is expected that some already analyzed heats will have been used in some of the plants that have not yet been analyzed; therefore, the analysis is applicable for the remaining plants.

The results of this statistical approach for ferrite content and fracture toughness can be used in instances where a plant may not have a complete set of manufacturing records down to the CMTR level for all CASS RV internals components available. The fleet-wide data available in this report can be compared to, or combined with, available plant-specific data to accurately predict the ferrite content or fracture toughness of CASS RV internals components for which a CMTR is not available. Additional discussion on the implementation of this approach, including specific examples, is given in Section 7.0.

4.7 CONSERVATISM IN STATISTICAL APPROACH

Using 95/95 criteria for this analysis may be too conservative. While the 95/95 criteria have precedence for acceptance within the NRC, many of the CASS RV internals components being considered are part of redundant structures (such as the lower core support columns discussed in [32]), for which a single failure would not be limiting.

Calculating the 95/95 lower limit for fracture toughness will be particularly conservative, as the fracture toughness values themselves have a significant amount of conservatism in them, as is discussed in subsection 4.3.

5 RESULTS

The results of the analysis of the calculated ferrite content and calculated saturation toughness values after thermal embrittlement are provided in this section. The ferrite contents were calculated using the CMTR data given in Appendix E and applying Hull's factors. The ferrite contents are, therefore, given in "percent ferrite". The fracture toughnesses given in this section are for fully saturated TE effects as calculated by the methodology outlined in Section 4 and using the equations given in Appendix D. The fracture toughness values are given as resistance to fracture J at a crack extension Δa of 2.5 mm, at a temperature of 554 degrees Fahrenheit (290 degrees Celsius), in units of kJ/m^2 to allow comparison of the saturated fracture toughness values to the established fracture toughness screening criterion at operating temperature.

The calculated ferrite contents and saturation fracture toughnesses were analyzed with respect to their distributions over the complete, currently-assessed database, and with respect to several potentially contributing control parameters such as vintage of manufacture, plant for which the components were manufactured, component, and individual manufacturer. As the individual manufacturers were found to have the most significant effect on the calculated ferrite content and toughness this effect was studied in the most detail. The analyses are therefore discussed in terms of a.) the overall distributions of the data over the whole calculated database, b.) the distributions with respect to subdivisions of the database, such as year of manufacture or plant in which the components were installed and, c.) the distributions with respect to individual manufacturers. These analyses are described and discussed in the following sections.

5.1 OVERALL POPULATION

The overall distribution of ferrite content in static-cast Grade CF8 materials, including contributions from all manufacturers who provided static-cast Grade CF8 RV internals material, is shown in Figure 5-1, with an associated normality test (based on lognormal statistics, Figure 5-2) in Figure 5-3, and descriptive statistics shown in Table 5-1.

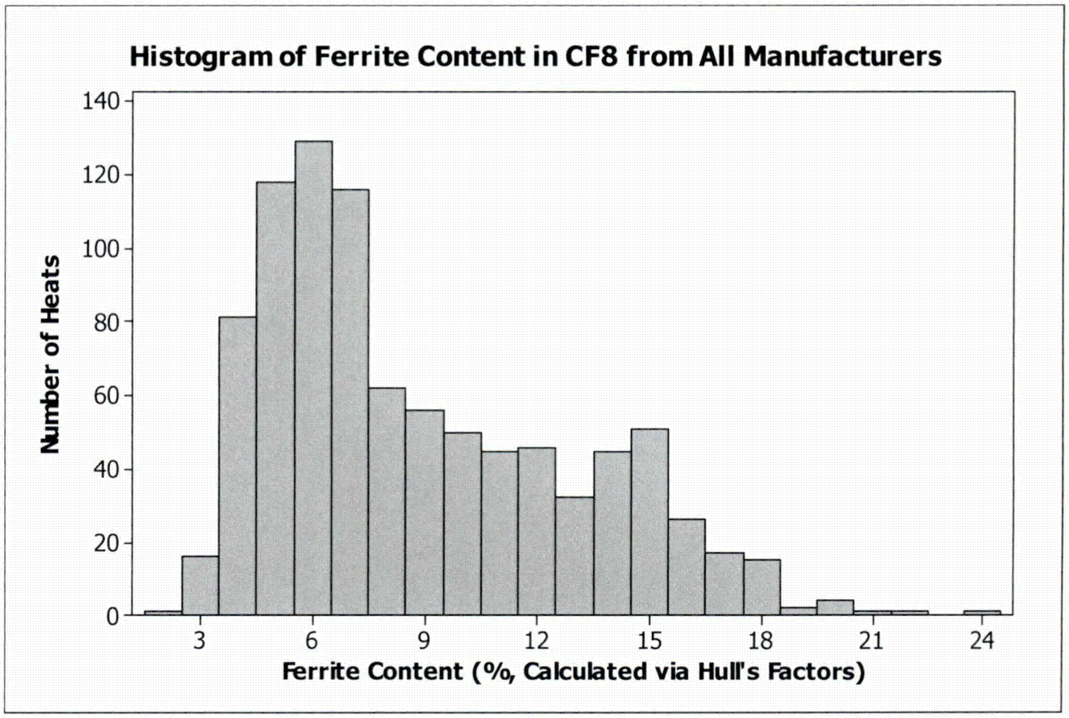

Figure 5-1. Distribution of Ferrite Content in Static-Cast CF8 Material from All Manufacturers

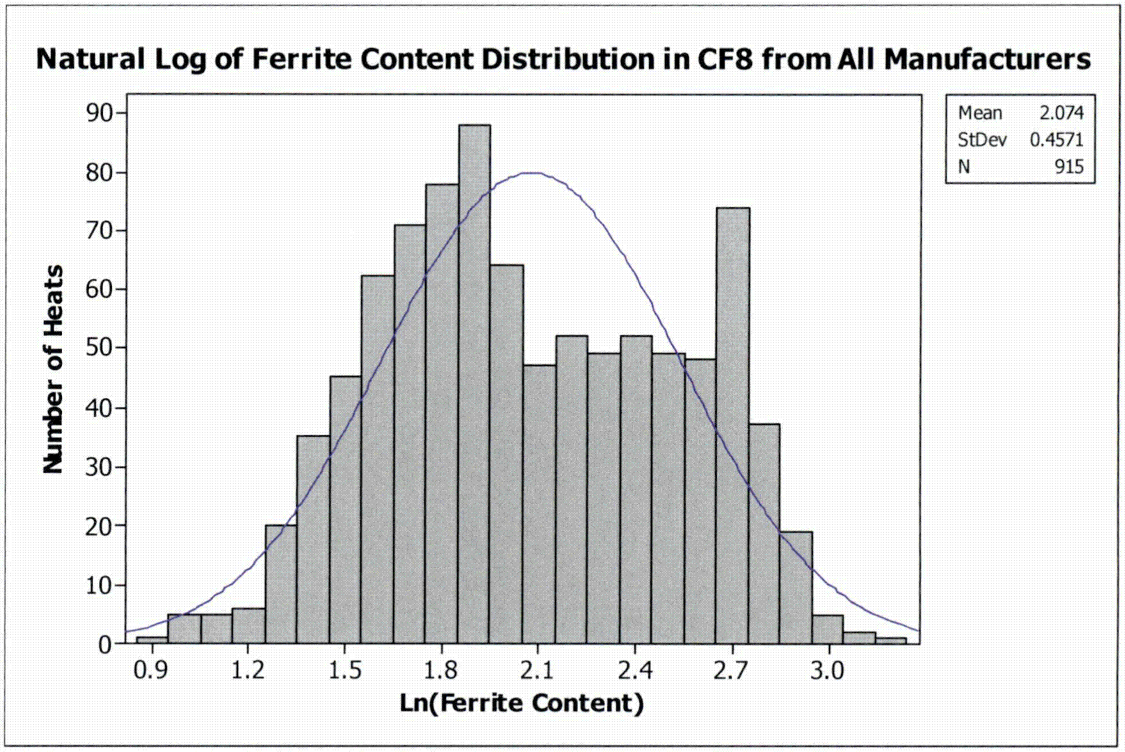

Figure 5-2. Distribution of the Natural Logarithm of Ferrite Content in Static-Cast CF8 Material from All Manufacturers

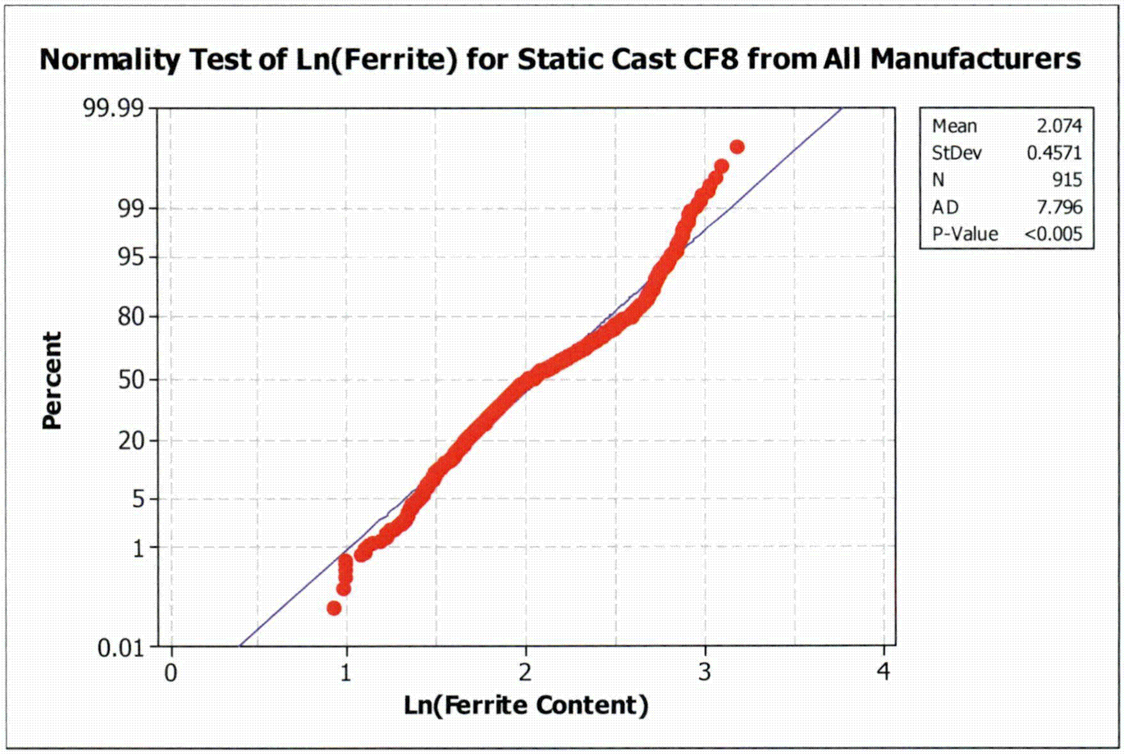

Figure 5-3. Normality Test for Ferrite Content in Static-Cast CF8 Material from All Manufacturers

Table 5-1 Summary Statistics for Static-Cast CF8 Material from All Manufacturers

Total	Mean	Standard Deviation	K (95/95)	95/95 Upper Limit	Minimum	Maximum	Over 15%	Over 20%
914	8.8	4.1	1.73	17.5	2.5	23.8	90	5

The distribution of ferrite content for all of the compositions identified to date, shown in Figure 5-1 has a distinctly extended "tail" towards the upper end of the ferrite contents. There are several reasons for the shape of this distribution. As will be shown in Section 5.3, the overall distribution is comprised of several overlapping, approximately normal or lognormal distributions with different means and standard deviations. These are essentially produced by distributions from the individual manufacturers. The peak at 6 percent ferrite is the result of contributions from a single, low-ferrite manufacturer (Kearsarge) that contributed 498 of the 914 static-cast Grade CF8 heats examined. The sharp drop-off at low ferrite contents (approximately 3 percent) is due to a calculational limit in the Hull's factors equations within the parameters of the ASTM A351 [17] chemical composition specifications.

Due to the shape of the distribution shown in Figure 5-1, a lognormal distribution was used to model the data as shown in Figure 5-2, with the resulting normality test shown in Figure 5-3. The p value calculated as part of the normality test fails the acceptance criterion. However, because the tail of the lognormal distribution bounds the higher-ferrite data points, the resulting 95/95 upper limit will be conservative. On this basis, the 95/95 upper limit for the overall population data is calculated as 17.5 percent ferrite. To credit the 95/95 upper limit of all data in the industrywide distribution, a utility must assume that the distribution of manufacturers of the castings in their plant is similar to the manufacturer distribution of data in the sample.

Additional assurance that a randomly selected CASS RV internals component will have ferrite content less than 20 percent can be demonstrated by calculating a 95/95 upper limit on the mean ferrite contents provided by each manufacturer. By taking the average ferrite content from each manufacturer and plotting these averages as a distribution (shown in Figure 5-4), a 95/95 upper limit can be calculated from the distribution of the averages. In this approach, the uncertainty (standard deviation) associated with each manufacturer is not represented, and the number of heats contributed by each manufacturer does not influence the result. This differs from modelling the overall data set with a lognormal distribution, where the number of heats provided by a given manufacturer varies and influences the result. The three manufacturers with two heats apiece (Hitchiner, ICC, PFA) are excluded from this analysis due to the lack of data associated with these manufacturers. The p value from the normality test shown in Figure 5-5 passes the acceptance criterion, so the distribution of the means can be reasonably represented by a normal distribution. Using the parameters shown in Table 5-2, a 95/95 upper limit of 17.5 results, which agrees well with the value calculated from the Figure 5-1 distribution.

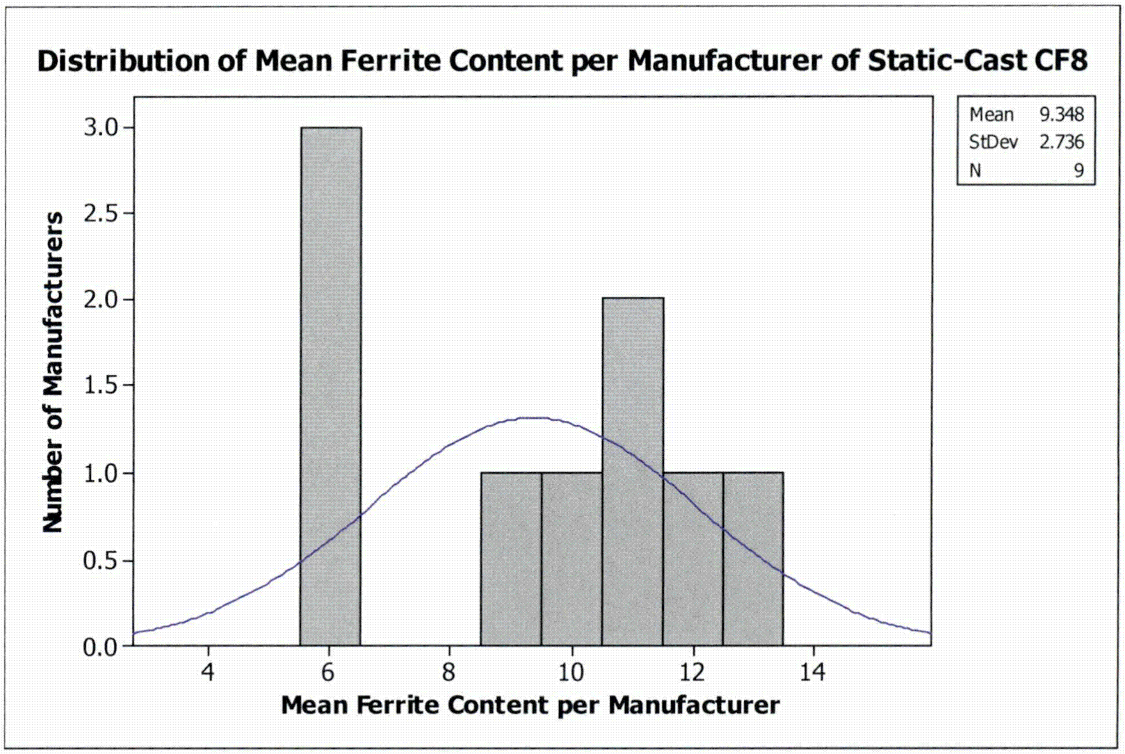

Figure 5-4. Distribution of Averages from Each Manufacturer of Static-Cast CF8 Material

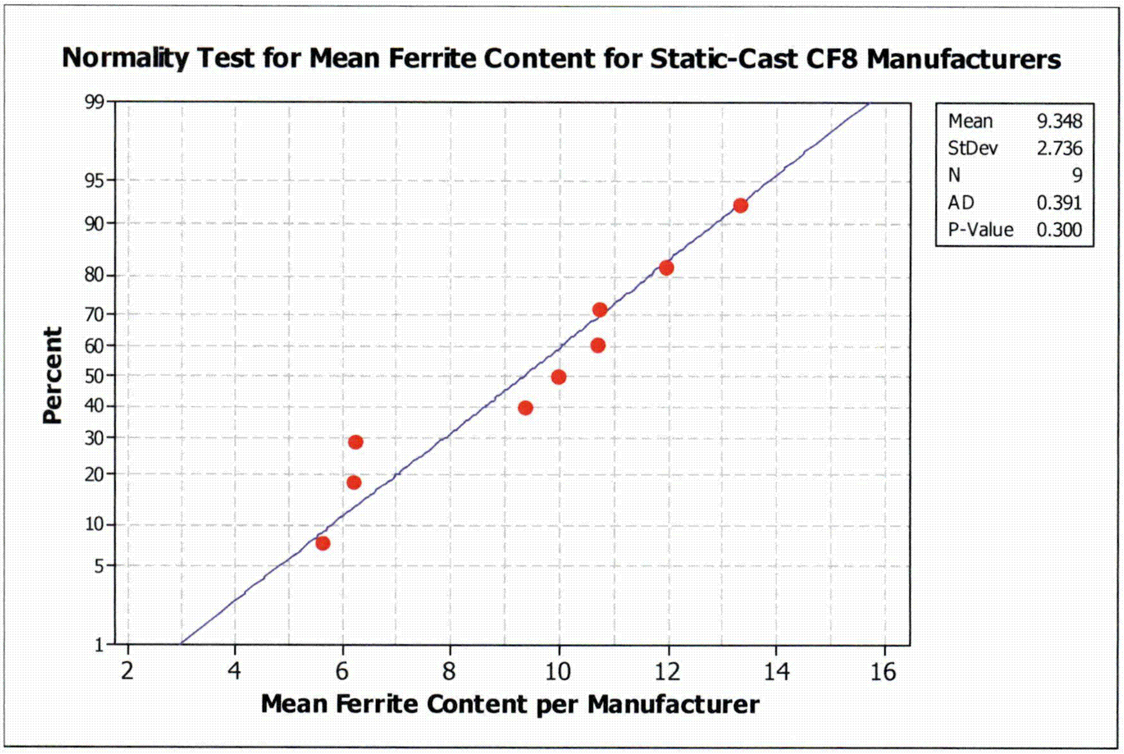

Figure 5-5. Normality Test for Averages from Each Manufacturer of Static-Cast CF8 Material

Table 5-2 Distribution of the Means

Average	9.3
Standard Deviation	2.7
Number of Manufacturers	9
k	3.03
95/95 Upper Limit	17.5

While these confidence levels for the random selection of components indicated that it can be stated with a very high level of confidence that a randomly-selected, static-cast Grade CF8 component from the domestic PWR fleet will have a ferrite content of less than 20 percent, it cannot be stated that no randomly-selected component would have a ferrite content that would exceed the criterion value of 20 percent. Furthermore, if the criterion would be reduced to 15 percent, then there is an increased probability that the ferrite content of a randomly selected component would exceed that value.

One result of the analysis does highlight the over-conservatism of the current industry processes for assessing the ferrite content of CASS. The previously-employed, conservative approach of assuming a component susceptible to thermal embrittlement in the absence of CMTRs was based on the possibility of setting the elemental compositions within the specification limit to generate the maximum ferrite content, i.e. maximum chromium equivalent, minimum nickel equivalent. The assumed elemental compositions were, therefore, set to the values shown in Table 5-3.

Table 5-3 Maximum Calculated Ferrite Content within CF8 Specification

C	Mn	Si	Cr	Ni	Mo	Ferrite
0.00	0.00	2.00	21.00	8.00	0.50	47.5

This conservative value of 47.5 percent ferrite should be compared with the ferrite levels presented in the current distributions, in which the maximum calculated ferrite content for Grade CF8 was only 23.8 percent and the expected values are much lower.

There are reasons that this fictitiously high ferrite content is not and cannot be observed in the industry data. The first, and perhaps most obvious, is that carbon is always present to some extent during steelmaking, and so the conservative assumption of carbon content being at zero is not physically possible. Similarly, manganese would also be present to some extent and would be non-zero as well. Further, manufacturers would want to avoid making material with compositions near these maximum allowable values (let alone exactly equal to them). Fluctuations in local material composition and measured values could cause such a material to be rejected as being 'out of spec' if these factors caused a measurement to be above the specified maximum. A manufacturer would want assurance that their material will be acceptable the vast majority of the time, and so would use SPC or similar methods to ensure that this is so. This would include avoiding manufacturing material compositions near the specified maximums.

The foregoing analysis is not repeated for the centrifugally-cast Grade CF8 and static-cast Grade CF3M materials. This is because the centrifugally-cast materials show a strongly bimodal distribution, due to only two manufacturers making centrifugally-cast material and these two manufacturers have significantly different ferrite content distributions (see Appendix A.6 and A.12). The static-cast Grade CF3M materials are provided by a single manufacturer, analyzed in Appendix A.13.

The calculated saturated toughness data are presented as a function of ferrite content in Figure 5-6. Figure 5-6 clearly reveals separate distributions as a function of material type. The three types of materials included in this study (centrifugally-cast Grade CF8, static-cast Grade CF8 and, static-cast Grade CF3M) each cover distinct areas of the plot. The data fall into three distinct regimes. Centrifugally cast Grade CF8 materials provide the highest levels of toughness after saturation of TE effects with values significantly above 255 kJ/m^2. This is in agreement with the Grimes letter that indicates that there is no need to screen on ferrite content for centrifugally cast Grade CF8 materials. The display of the data for the static cast Grade CF8 and Grade CF3M materials indicated that, although the data from these materials are often considered together, e.g. to set lower bound properties, the Grade CF3M materials display much more scattered toughness values and greatly reduced lower bound toughnesses compared to the Grade CF8 materials. Extension of the data trends for the static-cast Grade CF8 materials indicates that even above 25 percent ferrite content the material should retain toughness above the 255 kJ/m^2 criterion. This is also demonstrated by the minimum saturated fracture toughness calculation carried out for static-cast Grade CF8 in Appendix D.

Evident in Figure 5-6 are also “lines” of toughness vs ferrite content data within the same material dataset. These “lines” were found to correlate with the same levels of carbon content as reported in the CMTR’s for the Grade CF8 material. For these Grade CF8 materials, carbon content was, and still is, typically reported in increments of 0.01 percent, i.e. as 0.03, 0.04, 0.05, 0.06, 0.07, or 0.08. Carbon is not only an element that is critical to strength in steels but is also a strong “austenite stabilizer”. Identifying carbon content to only the 0.01 percent increment of precision, therefore, gives rise to these “lines” in the chart.

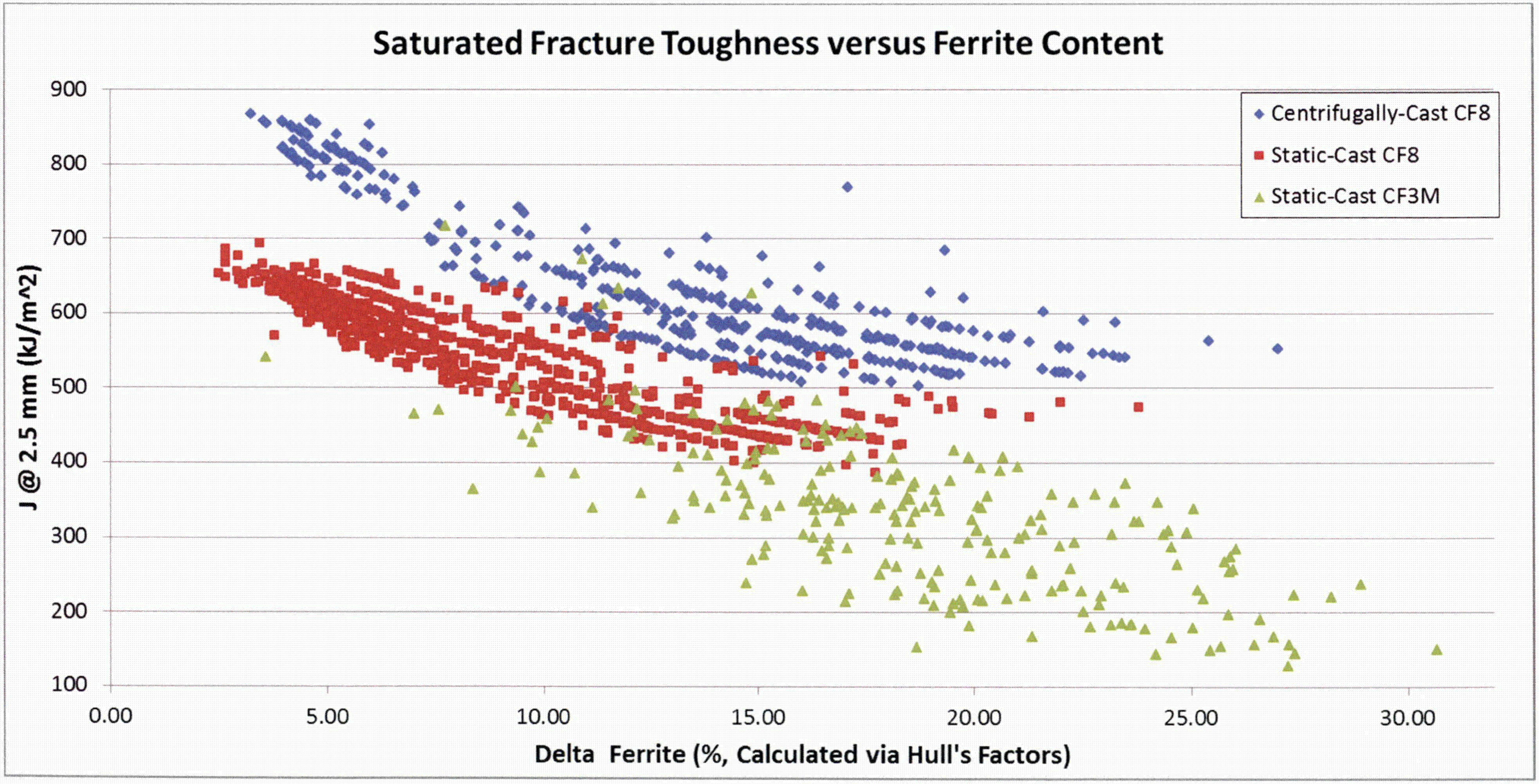

Figure 5-6. Saturated Fracture Toughness versus Ferrite Content

5.2 RESULTS BY SUBSETS OF POPULATION

Review of the complete dataset indicated that analysis of the data divided into subsets would probably identify the effects of significant control parameters. The data were therefore further analyzed according to subsets based on manufacturer, plant, component and vintage of production. Essentially the analysis by manufacturer showed the strongest trend and detailed presentation of the results per individual manufacturer is given in Appendix A, and a summary is presented in section 5.3. Thus, only a brief outline and an example case of the correlations are provided in this section. Analysis of the data according the other potential control parameters did not, as shown below, yield significant correlations. The fact that correlations with plant, component and vintage of production were not found provides support to the assumption that individual manufacturers would have had their defined melting and casting practices. That the ferrite content approximates a normal or lognormal distribution for a given manufacturer is expected, as SPC was a common practice when the CASS materials examined in this study were fabricated. That the distributions (i.e., the mean and the standard deviation) change with manufacturer was also expected. The amount of alloying additions required to maintain productivity for a given manufacturer would vary based on their casting practices. For example, a manufacturer could use more alloying additions (typically resulting in higher ferrite content) in lieu of developing specialized molds or temperature control during pouring.

An example of the ferrite content distribution approximating a normal distribution is shown for one manufacturer in Figure 5-7, with the accompanying normality test shown in Figure 5-8. Similar plots for each manufacturer are shown in Appendix A.

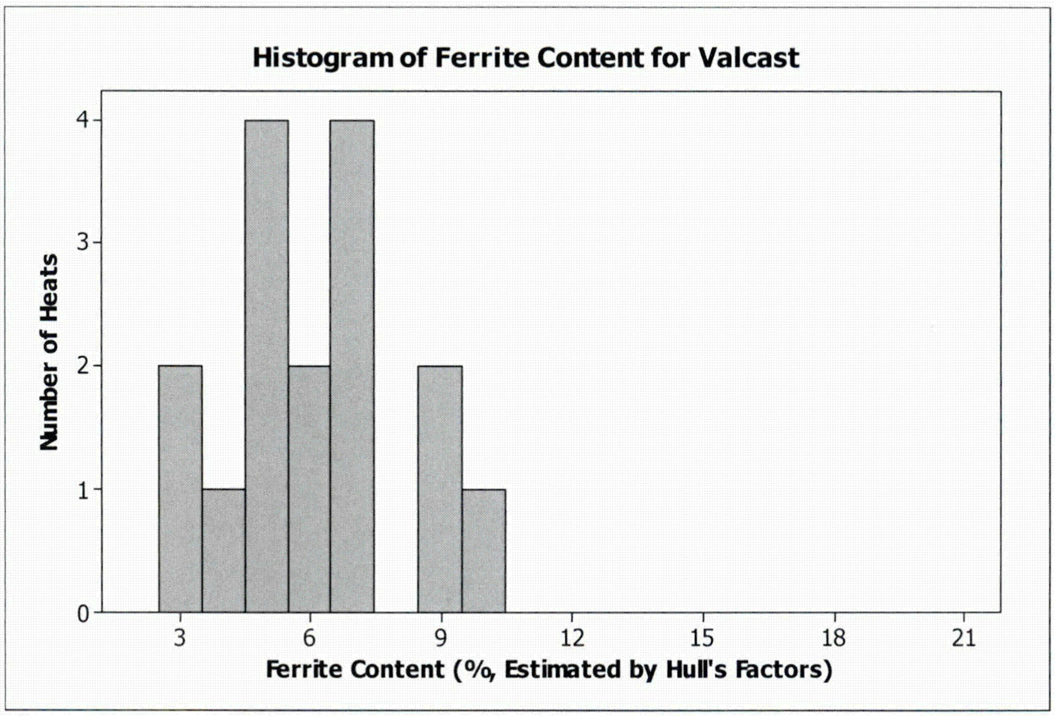

Figure 5-7. Ferrite Content Distribution for Valcast

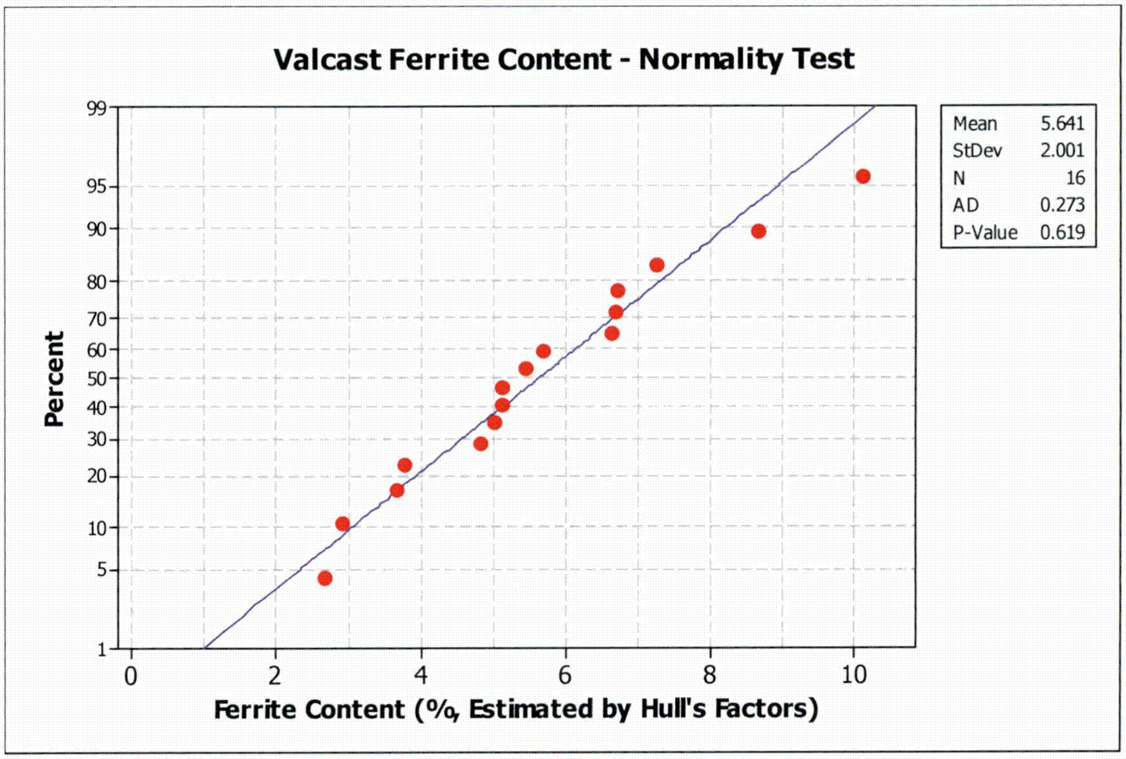

Figure 5-8. Normality Test for Valcast Ferrite Distribution

To demonstrate that the manufacturer is the controlling parameter, ferrite content is plotted in histograms representing an individual component and individual plants in Figure 5-9 through Figure 5-15. In these figures, the contribution from different manufacturers is shown in different colors to demonstrate the manufacturer dependence of ferrite content.

An example of the ferrite content distribution for a single component is given in Figure 5-9. This figure shows the ferrite content distribution for BMI column cruciforms. These components are used in Westinghouse-designed plants, and were provided by two manufacturers – Waukesha and Kearsarge. Figure 5-9 has been adapted from the original analysis to clearly show, by coloring, the contribution by manufacturer. It is evident that the contributions from each manufacturer are divided sharply at approximately ten percent delta ferrite and that each manufacturer has produced an approximately normal distribution of ferrite contents in their products.

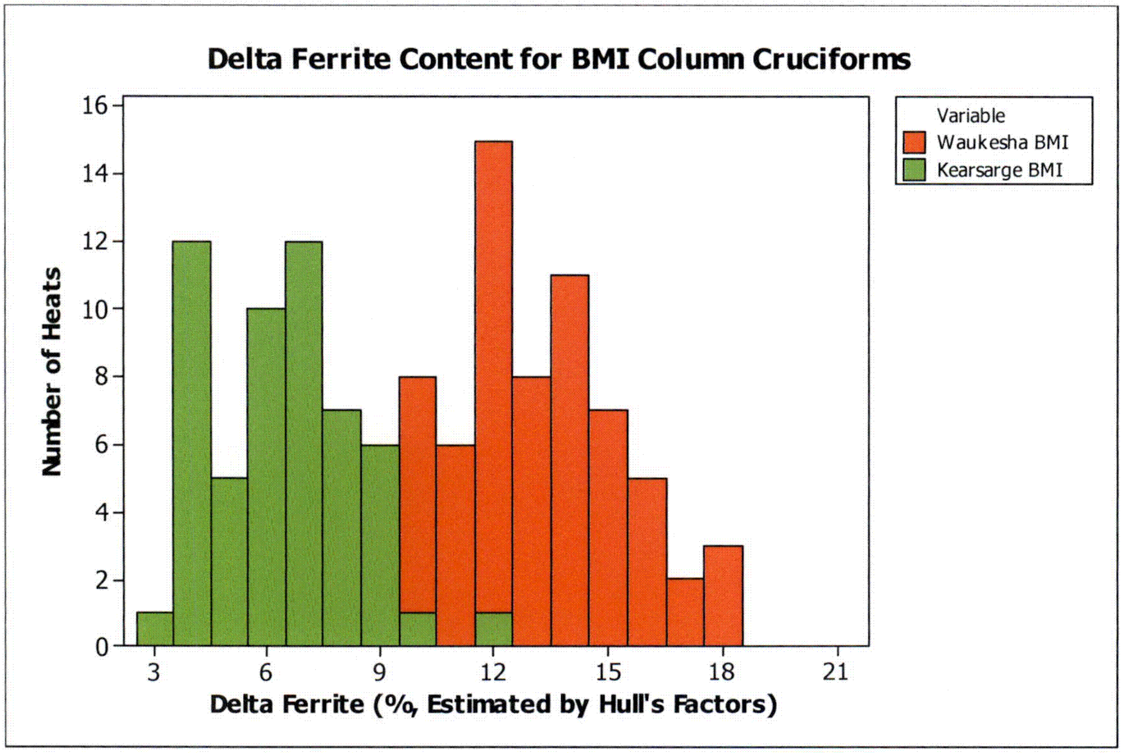

Figure 5-9. Ferrite Content Distribution for BMI Column Cruciforms

Examples of the ferrite content distribution for individual units and plants are given in Figure 5-10 to Figure 5-13. These data describe specific results from four units at two plant sites. Again the data reveal the existence of separated distributions and coloring of the plots highlights the strong dependence on manufacturer. Note that to some extent the analyses of ferrite content by plant is confounded by the lack of availability of the manufacturing records for some plants. More data were found for some plants than for others, and the amount of data found for a particular component was not constant amongst plants, either.

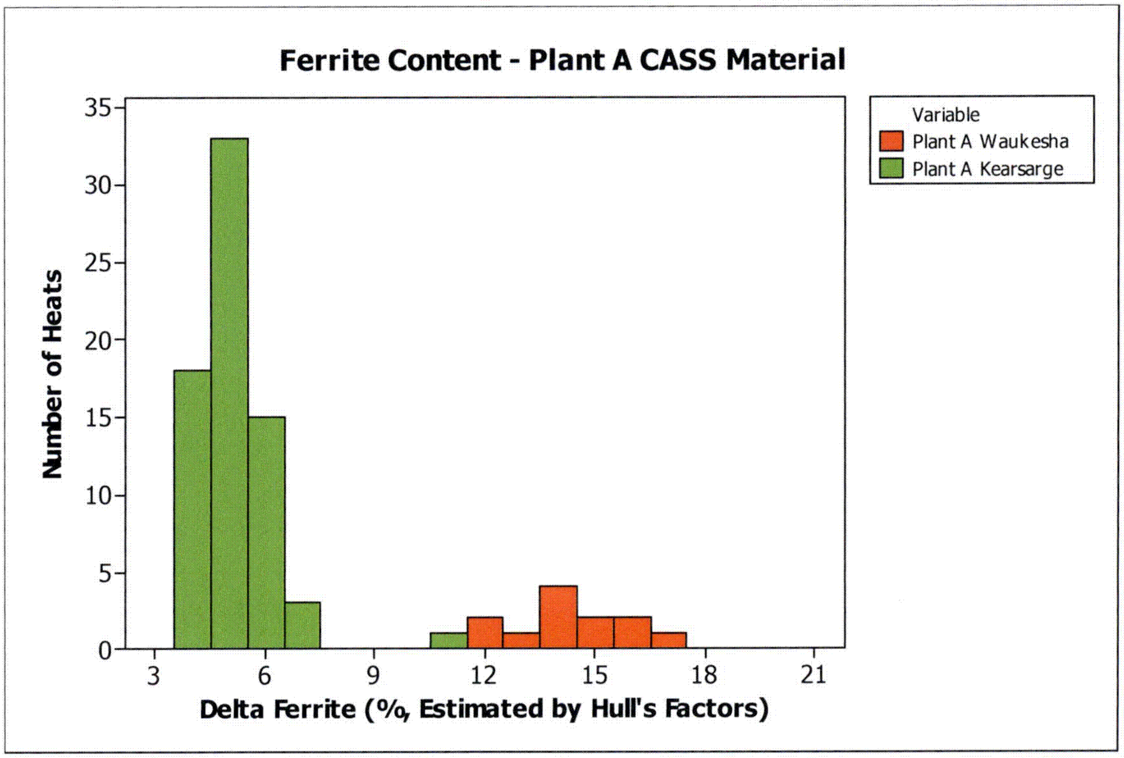

Figure 5-10. Ferrite Content for Plant A Components

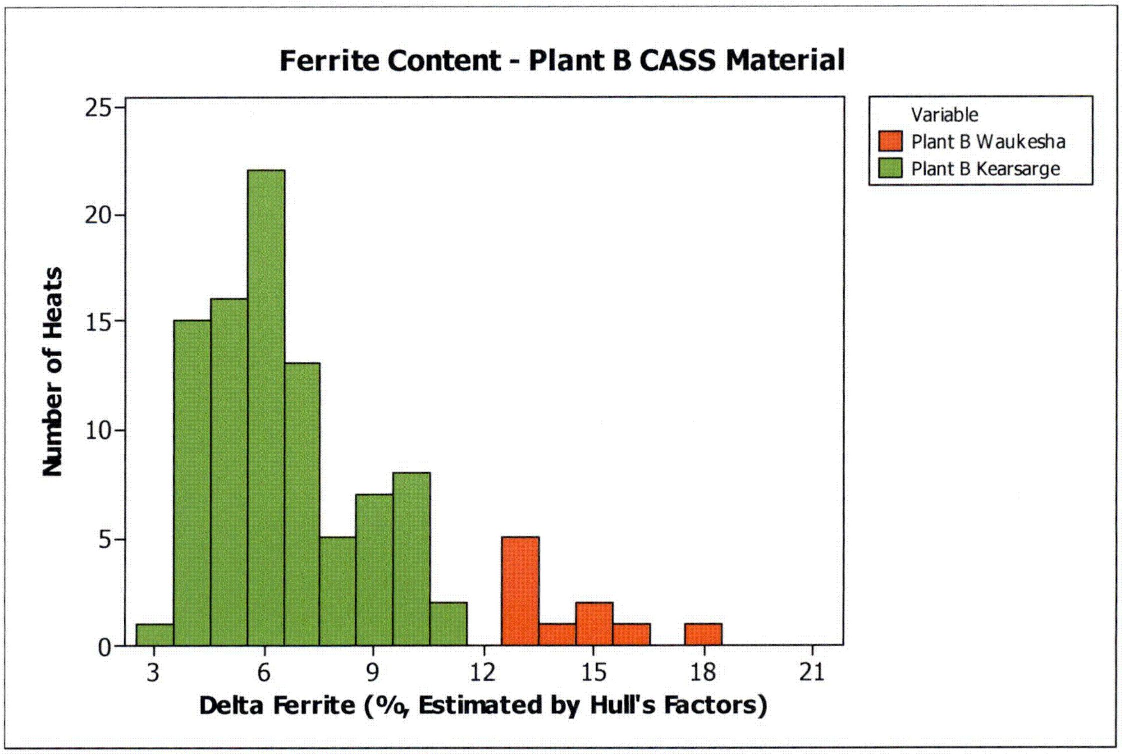

Figure 5-11. Ferrite Content for Plant B Components

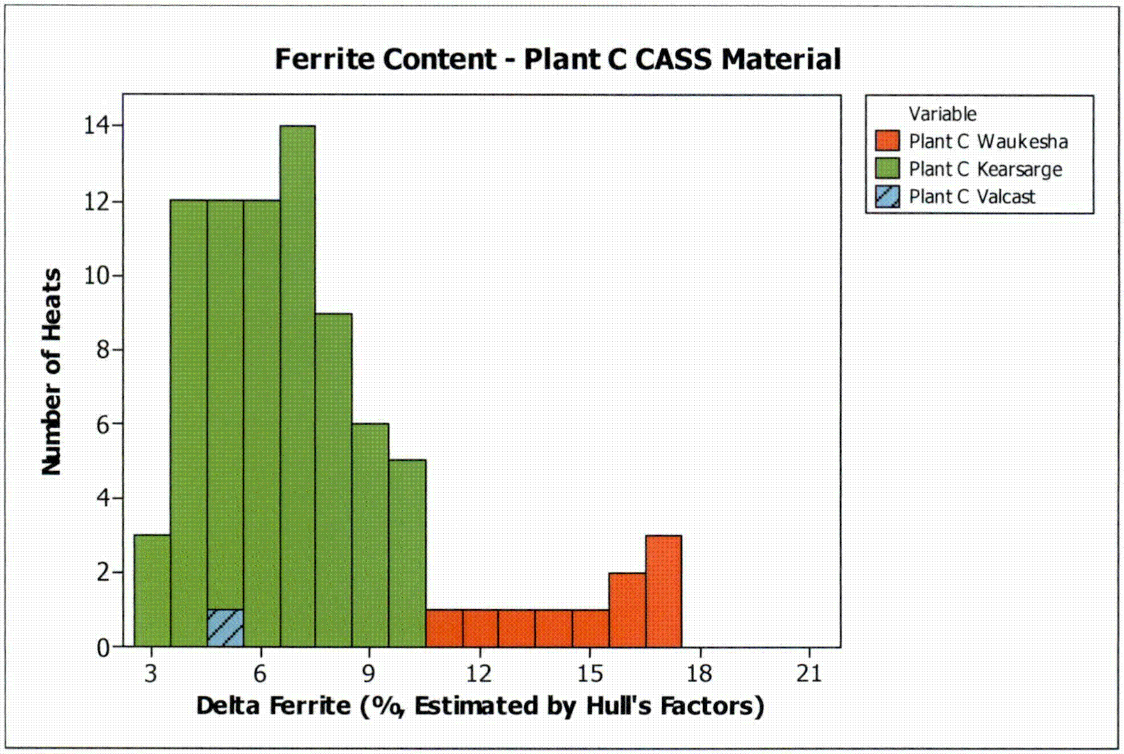

Figure 5-12. Ferrite Content for Plant C Components

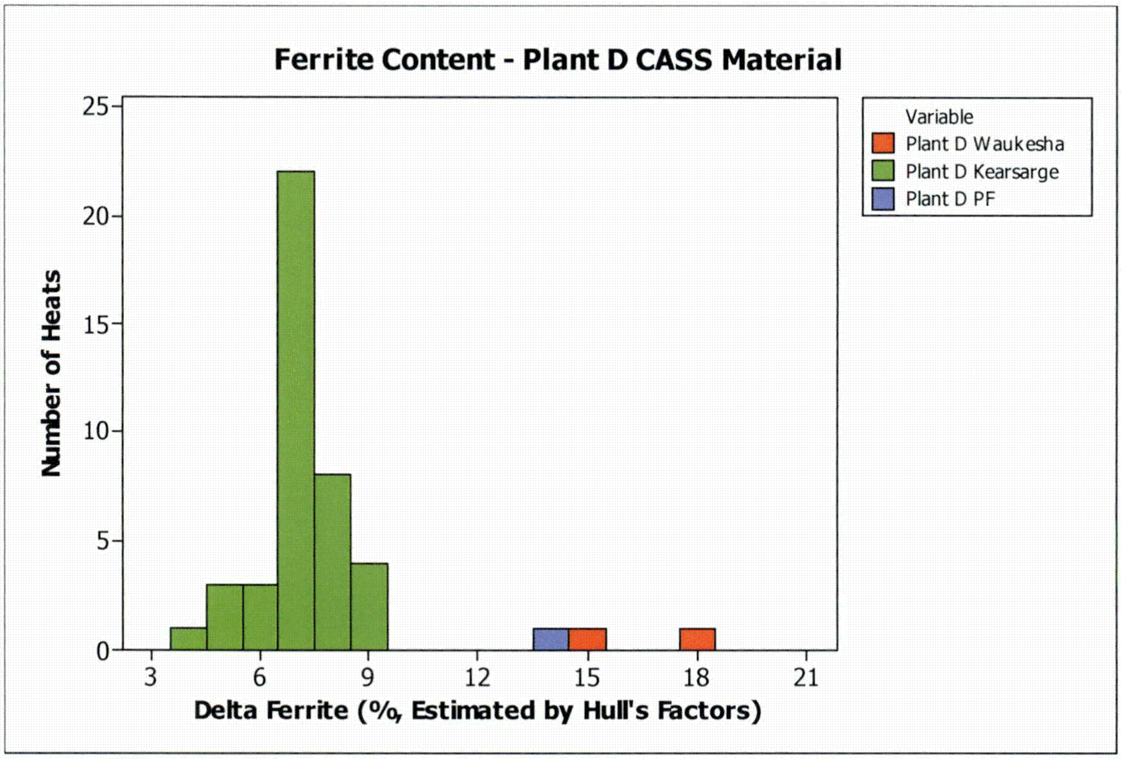

Figure 5-13. Ferrite Content for Plant D Components

The ferrite content data for Plants A through D could be considered to indicate that, for similar plants of similar vintage (or 'sister plants') the manufacturers used for CASS RV internals and ferrite contents would also be similar. This is true in many instances, but there are also exceptions. Figure 5-14 and Figure 5-15 show the ferrite content, separated by manufacturer, for Plant E and Plant F. These two units are at the same site - they have highly similar designs and went online within months of each other. The components represented in Figure 5-14 and Figure 5-15 are the same for both Plant E and Plant F; however, the same manufacturer was not necessarily used for both units – Plant E has components manufactured by Kearsarge, while Plant F does not.

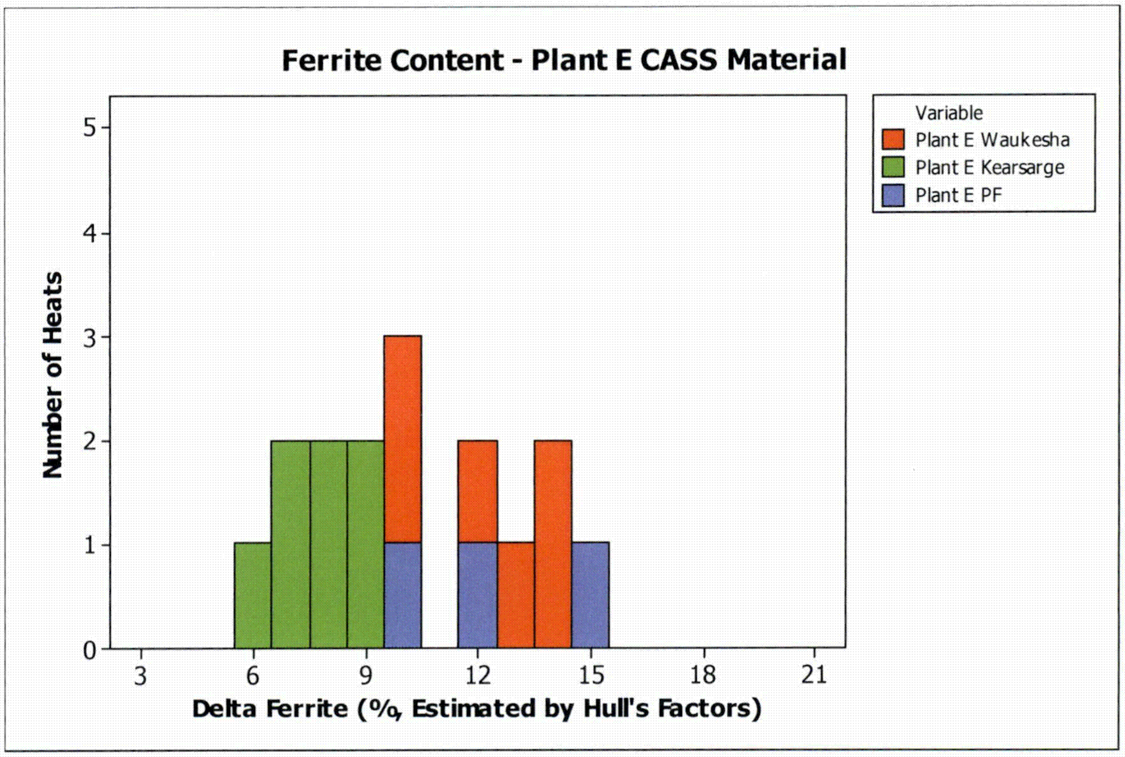

Figure 5-14. Ferrite Content for Plant E Components

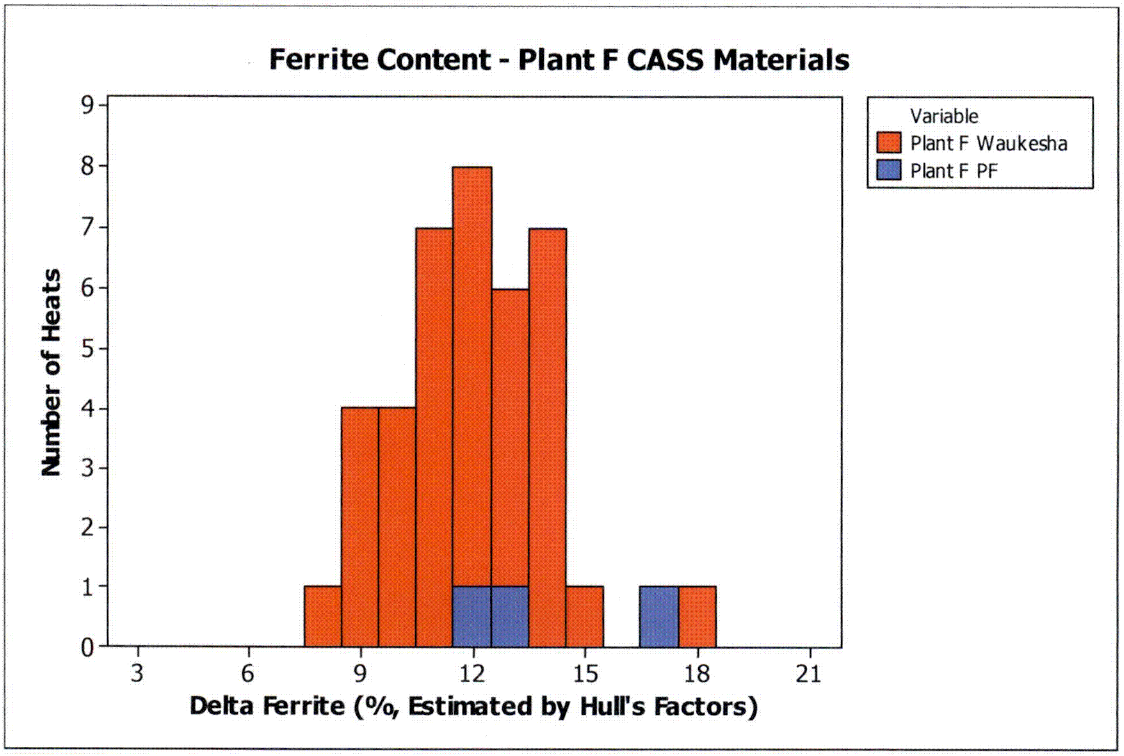

Figure 5-15. Ferrite Content for Plant F Components

5.3 SUMMARY OF RESULTS BY MANUFACTURER

Table 5-4 presents the statistics for ferrite content for each manufacturer. Table 5-5 presents the statistics for fracture toughness by manufacturer. For the ferrite content of static-cast Grade CF8, the 95/95 upper limits of two manufacturers exceeds the 20 percent ferrite screening criteria presented in [4]. The manufacturers Hitchiner, ICC, and PFA did not have sufficient data to produce meaningful 95/95 upper limits; however, none of the static-cast Grade CF8 material produced by these manufacturers has ferrite content exceeding the screening criteria.

The screening criteria in [4] indicate that for low molybdenum, centrifugally-cast materials, these components do not screen in at any ferrite level.

For static-cast Grade CF3M, the 95/95 upper limit for Wollaston exceeds the 14 percent ferrite screening criteria in [4].

For fracture toughness, the 95/95 lower limits of all of the manufacturers of static- and centrifugally-cast Grade CF8 are well above the established screening value of 255 kJ/m^2. The manufacturers Hitchiner, ICC, and PFA did not have sufficient data to produce a meaningful 95/95 limit; however none of the static-cast Grade CF8 material produced by these manufacturers has calculated fracture toughness below the screening criterion. The limiting manufacturer's fracture toughness for static-cast Grade CF8 materials is 364 kJ/m^2, and the limiting manufacturer's fracture toughness for centrifugally-cast Grade CF8 materials is 487 kJ/m^2.

The static-cast Grade CF3M components produced by Wollaston have a 95/95 lower limit for fracture toughness below the 255 kJ/m^2 screening criterion (141 kJ/m^2).

Table 5-4 Summary of Ferrite Content Statistics by Manufacturer

Manufacturer	Count	Mean	Standard Deviation	Minimum	Median	Maximum	Distribution	95/95
Static-Cast Grade CF8								
AMP	14	6.2	1.7	4.3	5.9	9.3	Lognormal	11.9
CSF	15	10.0	3.7	5.0	8.5	18.2	Normal	19.3
Esco	23	10.7	3.3	4.0	11.1	17.7	Normal	18.4
Kearsarge	498	6.2	1.7	2.7	6.0	12.0	Lognormal	9.7
PF	10	10.7	4.8	2.7	11.9	17.2	Normal	24.7
QACC	24	9.4	4.0	2.7	9.3	19.5	Normal	18.7
Valcast	16	5.6	2.0	2.7	5.3	10.1	Lognormal	13.4
Waukesha	263	13.3	3.0	2.6	13.6	21.3	Normal	18.7
Wollaston	39	12.0	4.5	5.2	11.2	23.8	Lognormal	24.5
Centrifugally-Cast Grade CF8								
Kearsarge	90	5.5	1.4	3.3	5.3	11.0	Lognormal	8.3
WC (Ladle)	185	16.2	3.5	7.1	16.2	23.4	Normal	22.7
WC (Product)	185	14.2	3.6	4.7	14.1	27.1	Normal	20.8
Static-Cast Grade CF3M								
Wollaston	227	18.4	4.7	3.6	18.2	30.7	Normal	27.0

Note: Delta ferrite content is calculated via Hull's factors and reported in percent ferrite.
Orange highlight indicates 95/95 limit exceeds criteria of [4].

Table 5-5 Summary of Fracture Toughness Statistics by Manufacturer

Manufacturer	Count	Mean	Standard Deviation	Minimum	Median	Maximum	Distribution	95/95
Static-Cast Grade CF8								
AMP	14	605	38.5	514	606	662	Normal	505
CSF	15	504	54.5	400	511	585	Normal	364
Esco	23	524	54.4	412	502	651	Normal	397
Kearsarge	498	592	36.9	475	593	684	Normal	527
PF	10	548	63.3	483	534	667	Normal	364
QACC	24	545	72.5	444	520	694	Normal	378
Valcast	16	593	38.1	524	589	656	Normal	496
Waukesha	263	462	35.4	387	454	675	Normal	398
Wollaston	39	544	45.1	471	542	653	Normal	448
Centrifugally-Cast Grade CF8								
Kearsarge	90	799	44.9	661	808	866	Normal	711
WC (Ladle)	185	581	50.7	507	569	769	Normal	487
WC (Product)	185	590	55.3	502	581	802	Normal	488
Static-Cast Grade CF3M								
Wollaston	227	327	101.7	127	333	717	Normal	141

Note: Fracture toughness is calculated via the NUREG/CR-4513 [7] equations, and reported as resistance to fracture J at a crack extension of 2.5 millimeters at a temperature of 554 degrees Fahrenheit (Units of kJ/m^2).
Orange highlight indicates 95/95 limit is below the established screening criterion.

From the analyses of the calculated ferrite contents and saturation fracture toughnesses it is clear that the manufacturer is the controlling parameter for the ferrite content of a given component, and that to predict ferrite content on the basis of component or plant alone is not appropriate. The assumption of normally or lognormally distributed data, supported by the statistical process control argument, has been further validated with normality tests for each manufacturer's data in Appendix A. For manufacturers with low average ferrite contents, the 'tail' of the distribution can be cut off at low ferrite values (approximately 3 percent) due to a calculational limit in the Hull's factors equations within the parameters of the ASTM A351 chemical composition specifications.

Further analyses of the individual manufacturer's data indicated that for manufacturers that produced numerous different components, histograms of ferrite content by component are shown to provide assurance that no statistically significant differences occur between the different component types. Moreover, as data given in the appendices show, a given manufacturer's ferrite content was found to be consistent over the period in which the CASS RV internals components in question were produced.

The statistical approach and the 95/95 criteria for each of the manufacturers for ferrite content and fracture toughness can be used in instances where a plant may not have a complete set of manufacturing records down to the CMTR level for all CASS RV internals components available. The fleet-wide data available in this report can be compared to, or combined with, available plant-specific data to determine bounding values of the ferrite content or fracture toughness of CASS RV internals components for which a CMTR is not available. Additional discussion on the implementation of this approach, including specific examples, is given in Section 7.0.

Table 5-4 demonstrates that all of the mean ferrite contents for the statically cast Grade CF8 materials were significantly below the original 20 percent screening criterion for TE and are even below the NRC proposed revised value of 15 percent to account for combined TE and IE. The 95/95 confidence limits, however, extend to higher values. There are several manufacturers whose 95/95 confidence level falls in the 15 to 20 percent range and two manufacturers whose 95/95 confidence limit falls above the 20 percent screening criterion. What is clear, however, is that for the most numerous manufacturer of static cast Grade CF8 there is a very low probability that missing CMTR's would have produced a ferrite value higher than 15 percent. Similarly, for most other manufacturers, it would be likely that missing CMTRs would not have produced ferrite values higher than 20 percent for static cast Grade CF8 components.

Note that for one manufacturer of centrifugal castings the mean and 95/95 confidence limits fall above the 15 percent and 20 percent levels, respectively, these values are not an issue because there is no ferrite content screening criterion for centrifugally-cast Grade CF8 material. Also, Table 5-4 indicates that higher values of ferrite content would be expected for the Grade CF3M materials and that these would exceed the lower screening values that are applied to this material. This material was only used in B&W plants and the component fabricated from this material is managed via inspection [1].

Table 5-5 presents the mean and 95/95 lower limits for the saturation fracture toughness values. It is readily apparent that for all of the Grade CF8 materials the saturation fracture toughness values are significantly above the criterion of 255 kJ/m^2. More importantly, the mean values are several standard deviations removed from this value, indicating an extremely low probability of a fully thermally-embrittled Grade CF8 component exhibiting fracture toughness after TE of below the 255 kJ/m^2 criterion. It is significant that even the lots from manufacturers Wollaston and Precision Founders (PF), which exhibited ferrite content 95/95 confidence limits above the 20 percent criterion, exhibit 95/95 confidence limits for saturation toughness well above the 255 kJ/m^2. (This is probably an indication of the conservatism that was taken into account in setting the ferrite content screening value in the original "Grimes letter"[4]).

In contrast to the Grade CF8 data, Table 5-5 indicates that for the higher molybdenum containing Grade CF3M material there is significant probability that the saturated fracture toughness after TE could be below the 255 kJ/m^2 criterion. Despite the mean value lying above the 255 kJ/m^2 criterion, the marked scatter for the calculated toughnesses for this material cause the 95/95 confidence limit at 141 kJ/m^2 to lie well below the 255 kJ/m^2 criterion. As noted earlier, for the B&W units, the component fabricated from Grade CF3M material is a "Primary" inspection item and is being addressed for license renewal. The large discrepancy between the

Grade CF3M and Grade CF8 data should however be pertinent to considerations of CASS embrittlement in general; it would appear that using high molybdenum data (Grade CF8M or Grade CF3M) to define a lower bound low for data from molybdenum materials (Grade CF8 or Grade CF3) would be excessively conservative.

The following results provide examples of the distributions of calculated ferrite content and calculated saturated fracture toughness for two of the highly utilized manufacturers (Kearsarge and Waukesha) and the two manufacturers whose confidence limits for ferrite content exceeded the guidance criteria (Wollaston and Precision Founders).

5.3.1 Kearsarge

Kearsarge provided numerous components for Westinghouse and CE plants, as shown in Figure 5-16. The Kearsarge-supplied CASS RV internals were all fabricated from low-molybdenum Grade CF8 material using both static and centrifugal casting methods. CMTR data were available for 498 individual heats of static-cast material and 90 heats of centrifugally-cast material supplied by Kearsarge. Kearsarge provided CASS RV internals components from 1969 to 1977, see Figure 5-17.

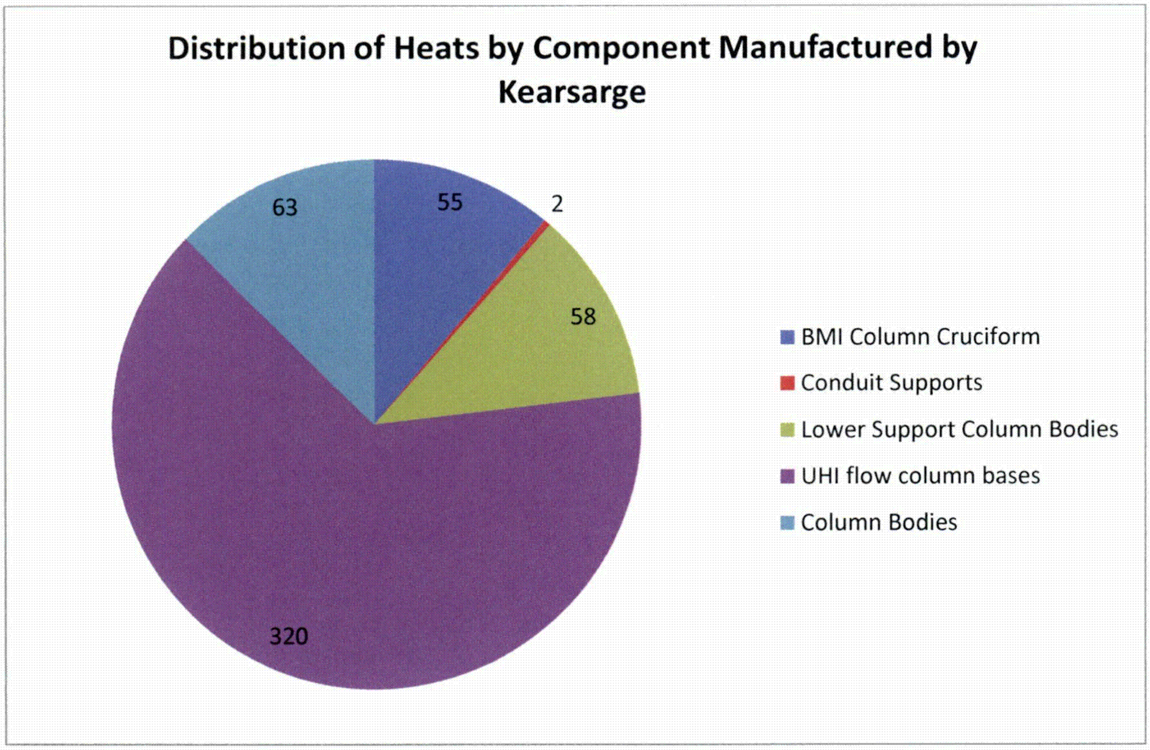

Figure 5-16. Static-Cast Components Provided by Kearsarge

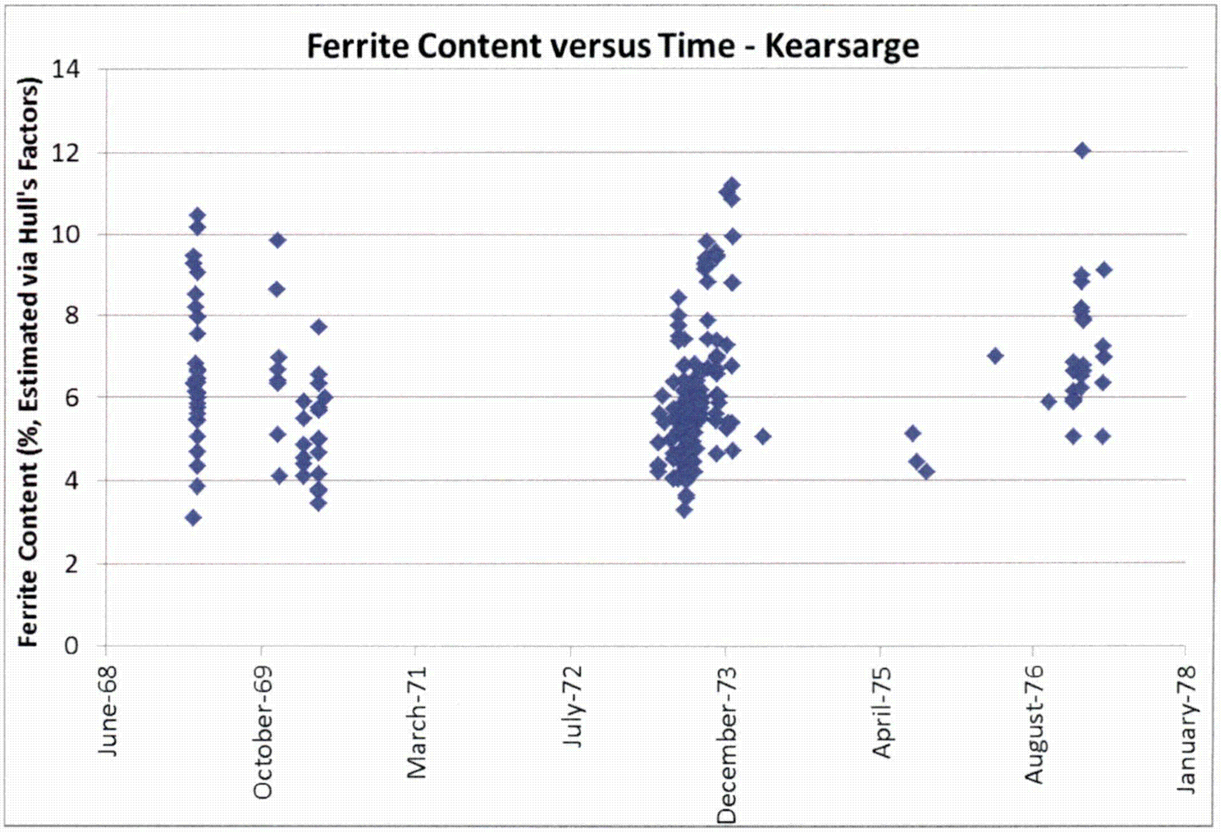

Figure 5-17. Ferrite Content over Time - Kearsarge

The distribution of ferrite content for centrifugally-cast components fabricated by Kearsarge is shown in Figure 5-18, with the accompanying normality test in Figure 5-19. A lognormal distribution was used to model the Kearsarge ferrite content distribution for centrifugally-cast material. The calculated p value (0.038) associated with applying the lognormal distribution does not pass the acceptance criterion, however the use of a lognormal distribution to model the dataset was judged to be appropriate as this fit provided the lowest A-D parameter. The centrifugally-cast components provided by Kearsarge were all UHI flow column bases.

The distribution of ferrite content for static-cast components fabricated by Kearsarge is shown in Figure 5-20, with the accompanying normality test in Figure 5-21. A lognormal distribution was used to model the Kearsarge ferrite content distribution for statically-cast material. The calculated p value (0.326) associated with applying the lognormal distribution passes the acceptance criterion. Figure 5-22 shows the ferrite content distribution for static-cast material separated by component for this manufacturer.

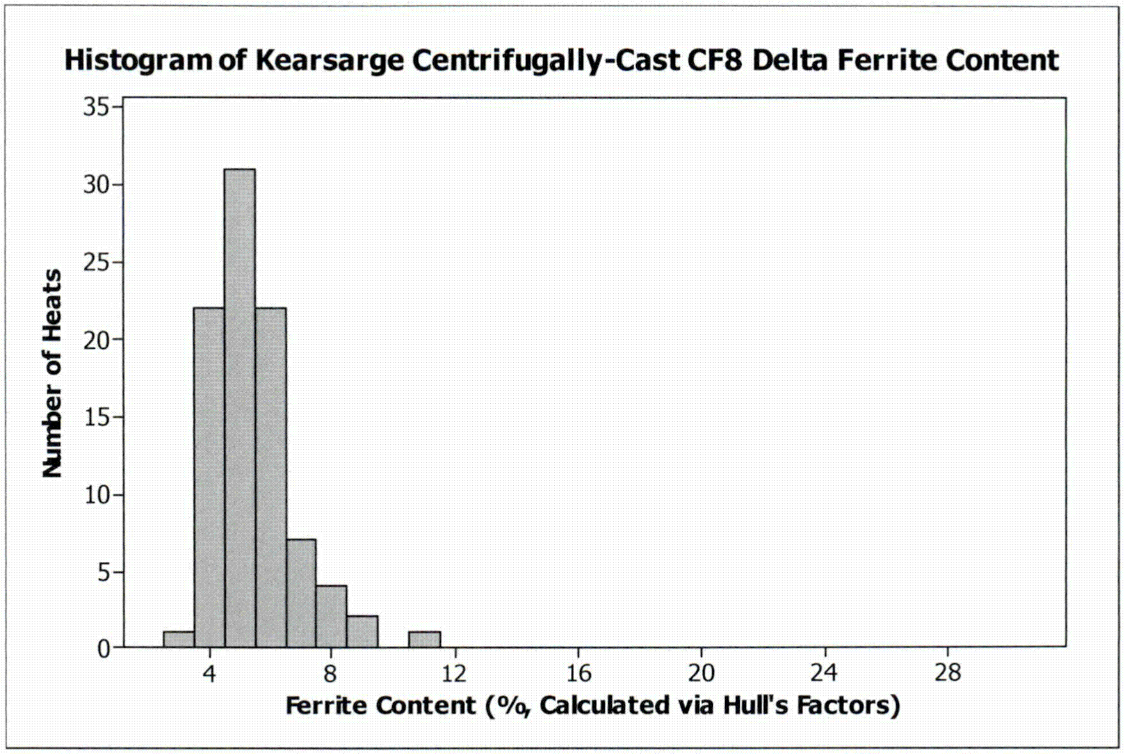

Figure 5-18. Histogram of Kearsarge Delta Ferrite Content (Centrifugally-Cast CF8)

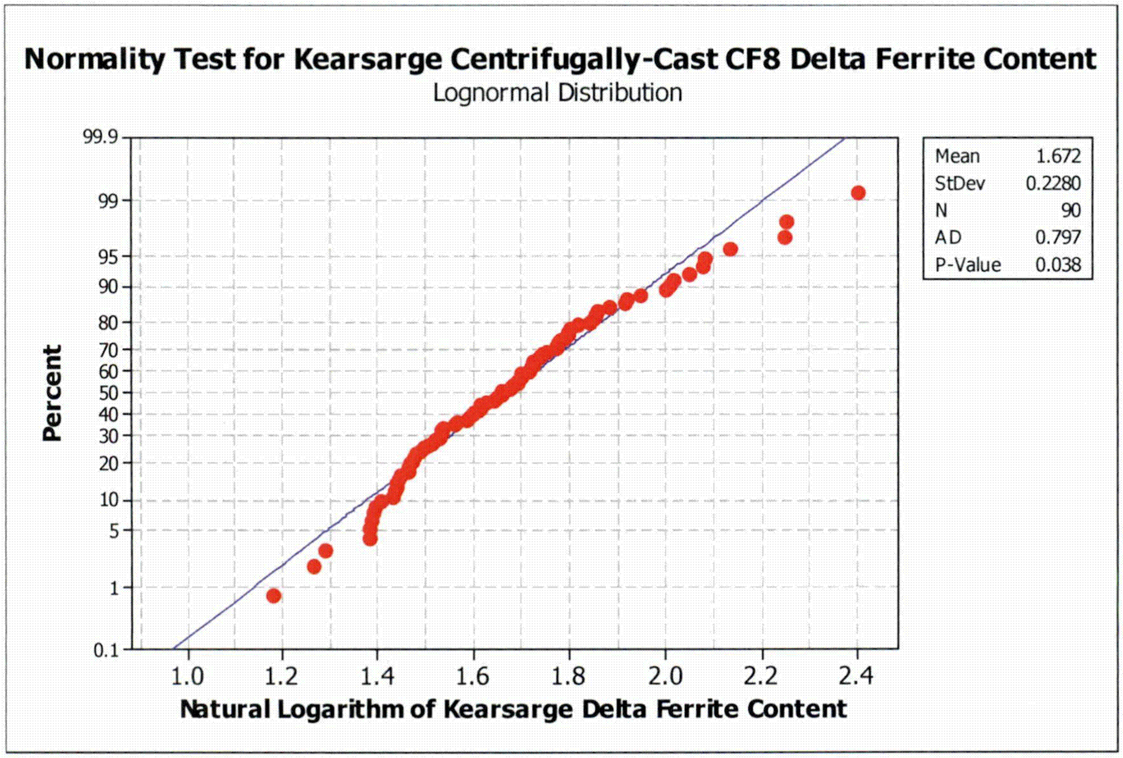

Figure 5-19. Normality Test for Kearsarge Delta Ferrite Content (Centrifugally-Cast CF8)

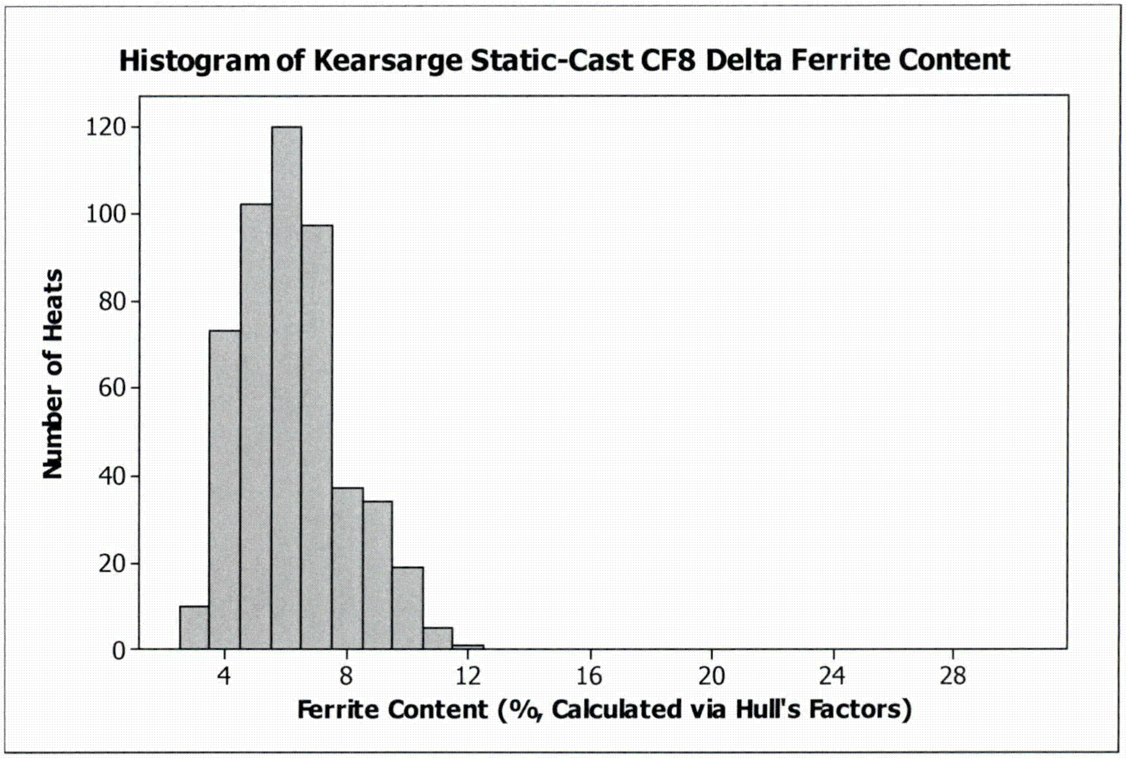

Figure 5-20. Histogram of Kearsarge Delta Ferrite Content (Static-Cast CF8)

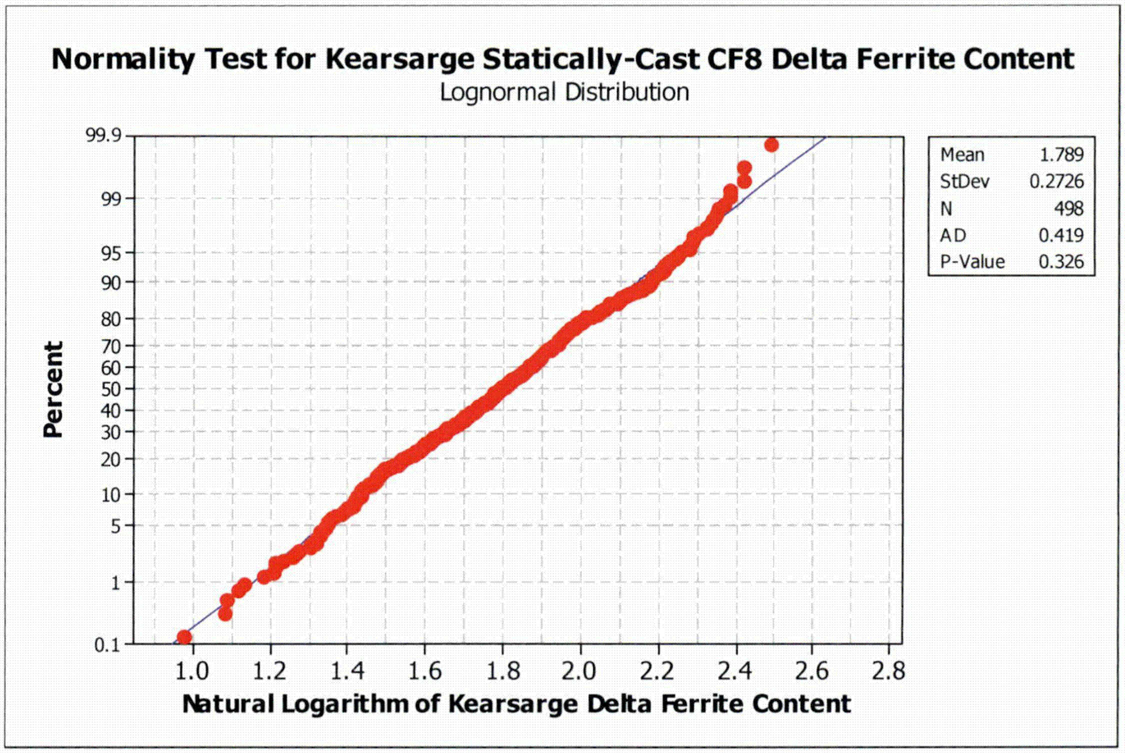

Figure 5-21. Normality Test for Kearsarge Delta Ferrite Content (Static-Cast CF8)

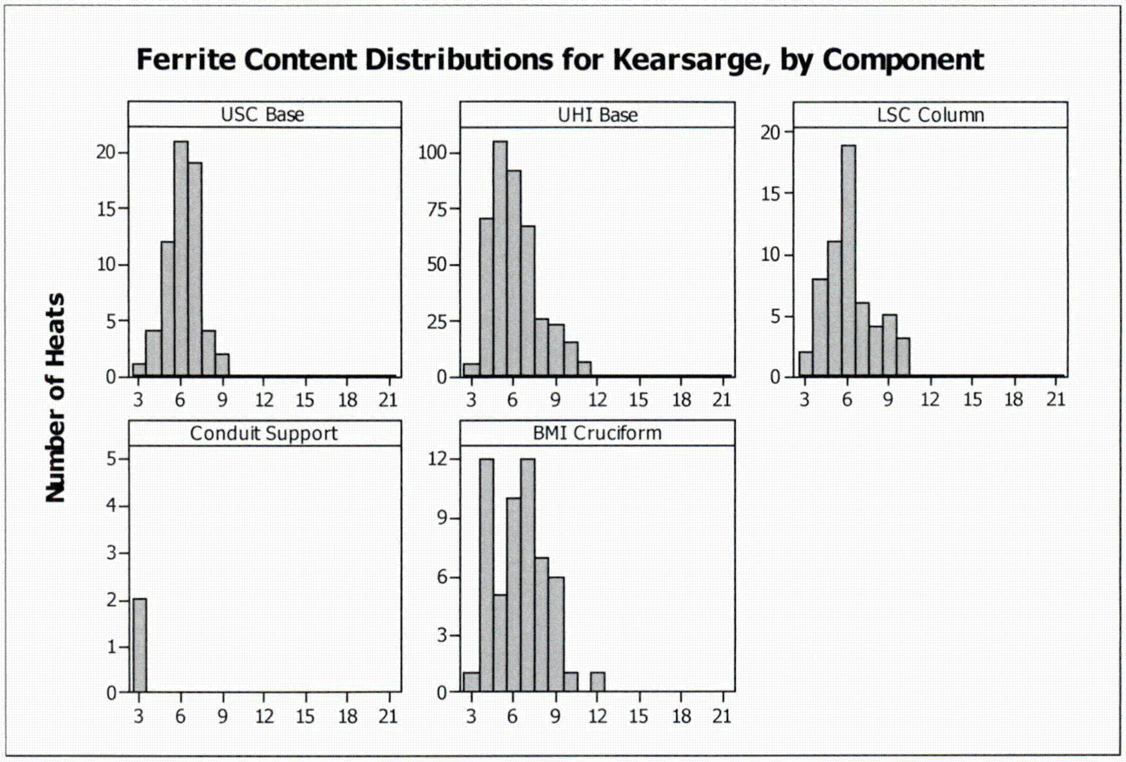

Figure 5-22. Ferrite Content Distributions by Component Manufactured by Kearsarge

Figure 5-18 and Figure 5-20 show that there are no heats of material produced by Kearsarge that exceed 15 percent ferrite content as estimated via Hull's factors. The average ferrite content for centrifugally-cast Kearsarge materials is 5.5 percent, and the standard deviation is 1.4 percent. The 95/95 limit for ferrite content for centrifugally-cast Kearsarge materials is 8.3 percent. The average ferrite content for static-cast Kearsarge materials is 6.2 percent, and the standard deviation is 1.7 percent. The 95/95 limit for ferrite content for centrifugally-cast Kearsarge materials is 9.7 percent.

The ferrite content distributions for the static-cast and centrifugally-cast materials are observed to be very similar in both mean and standard deviation. It is probable that Kearsarge used essentially the same alloy composition for both the static and centrifugal casting process. The UHI flow column bases were made by both processes at different time periods, so there may have been some overlap in materials resulting from that change as well.

Figure 5-23 shows the fracture toughness distribution for centrifugally-cast material heats made by Kearsarge, and Figure 5-24 is the normality test associated with that distribution. A normal distribution was used to model the Kearsarge saturated fracture toughness distribution for centrifugally-cast materials. The calculated p value (<0.005) associated with applying the normal distribution does not pass the acceptance criterion, however it provides a reasonable and conservative fit to the data. The average saturated fracture toughness for centrifugally-cast Kearsarge-supplied materials is 799 kJ/m^2 and the standard deviation is 44.9 kJ/m^2.

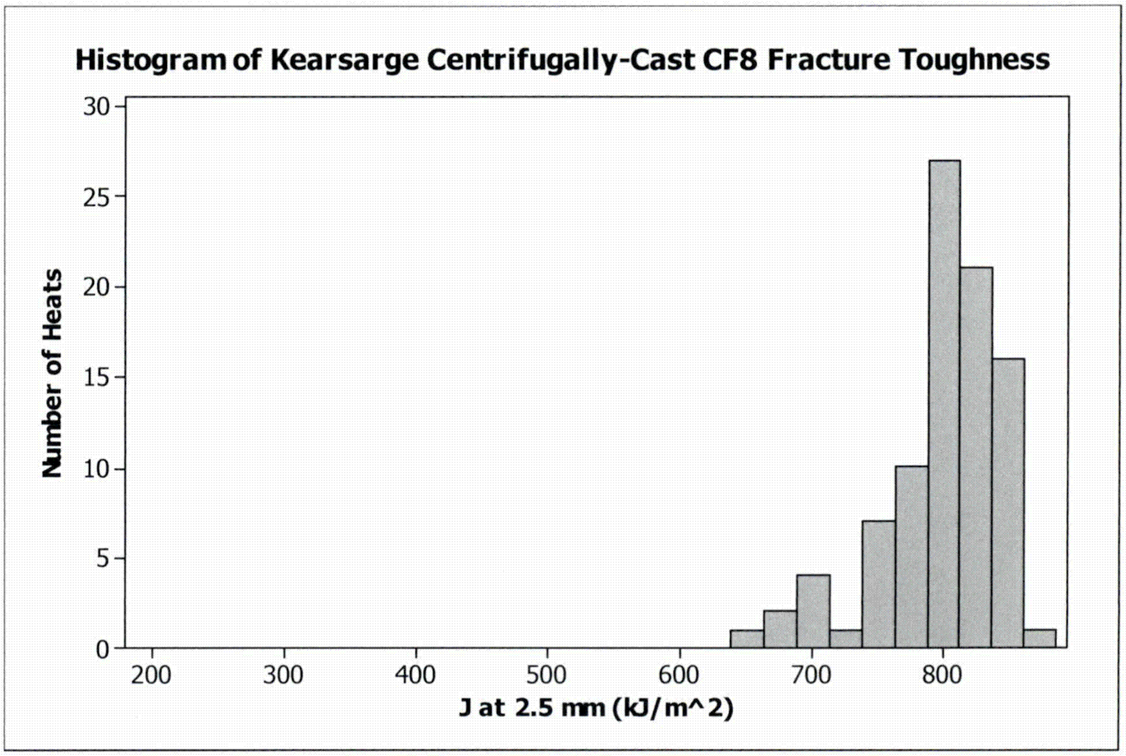

Figure 5-23. Histogram of Kearsarge Fracture Toughness (Centrifugally-Cast CF8)

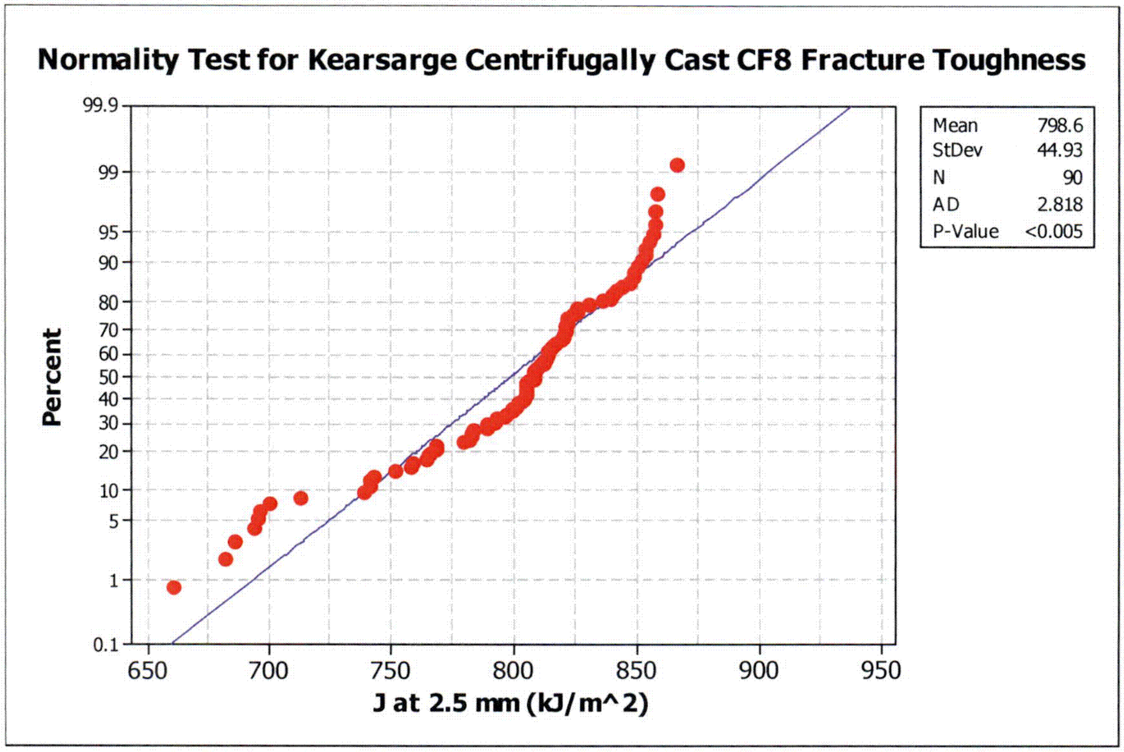

Figure 5-24. Normality Test for Kearsarge Fracture Toughness (Centrifugally-Cast CF8)

Figure 5-25 shows the fracture toughness distribution for static-cast material heats made by Kearsarge, and Figure 5-26 is the normality test associated with that distribution. A normal distribution was used to model the Kearsarge saturated fracture toughness distribution for statically-cast materials. The calculated p value (<0.005) associated with applying the normal distribution does not pass the acceptance criterion, however it provides a reasonable and conservative fit to the data. The average saturated fracture toughness for static-cast Kearsarge-supplied materials is 592 kJ/m^2 and the standard deviation is 36.9 kJ/m^2.

The 95/95 bound for fracture toughness for centrifugally-cast Kearsarge material is 711 kJ/m^2. The 95/95 bound for fracture toughness for static-cast Kearsarge material is 527 kJ/m^2. Thus, it can be stated with a high degree of confidence that no components fabricated by Kearsarge will have a saturated fracture toughness below 255 kJ/m^2.

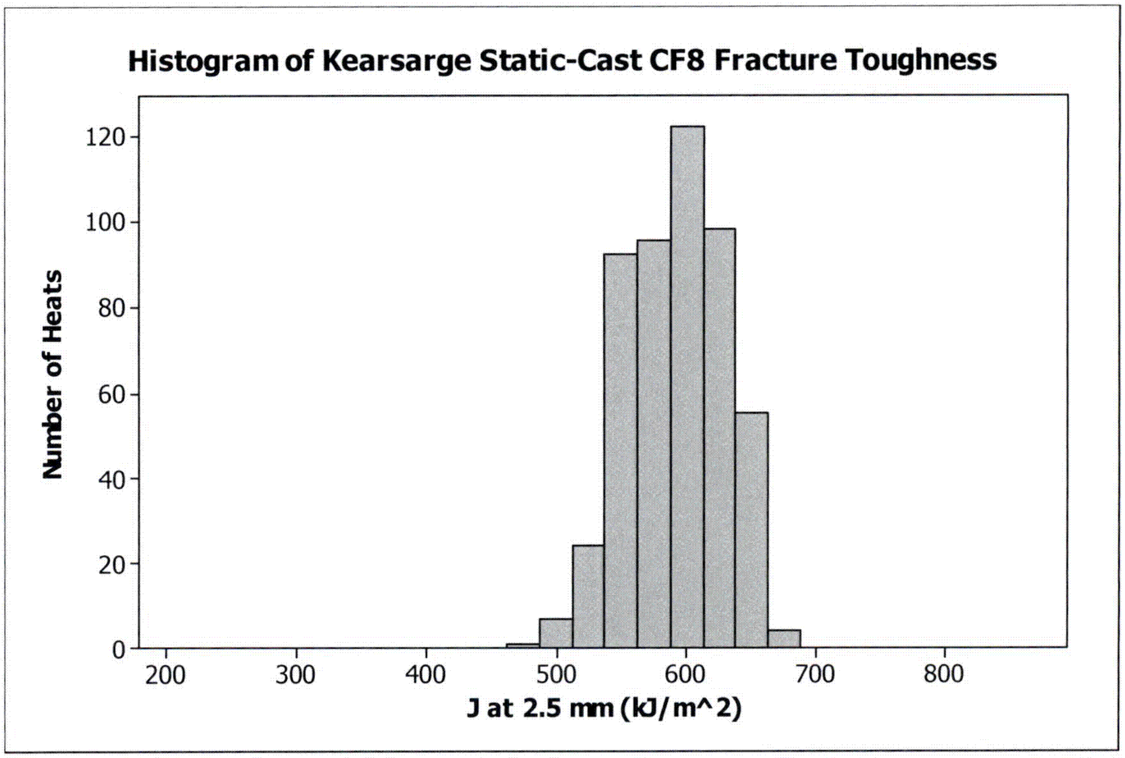

Figure 5-25. Histogram of Kearsarge Fracture Toughness (Static-Cast CF8)

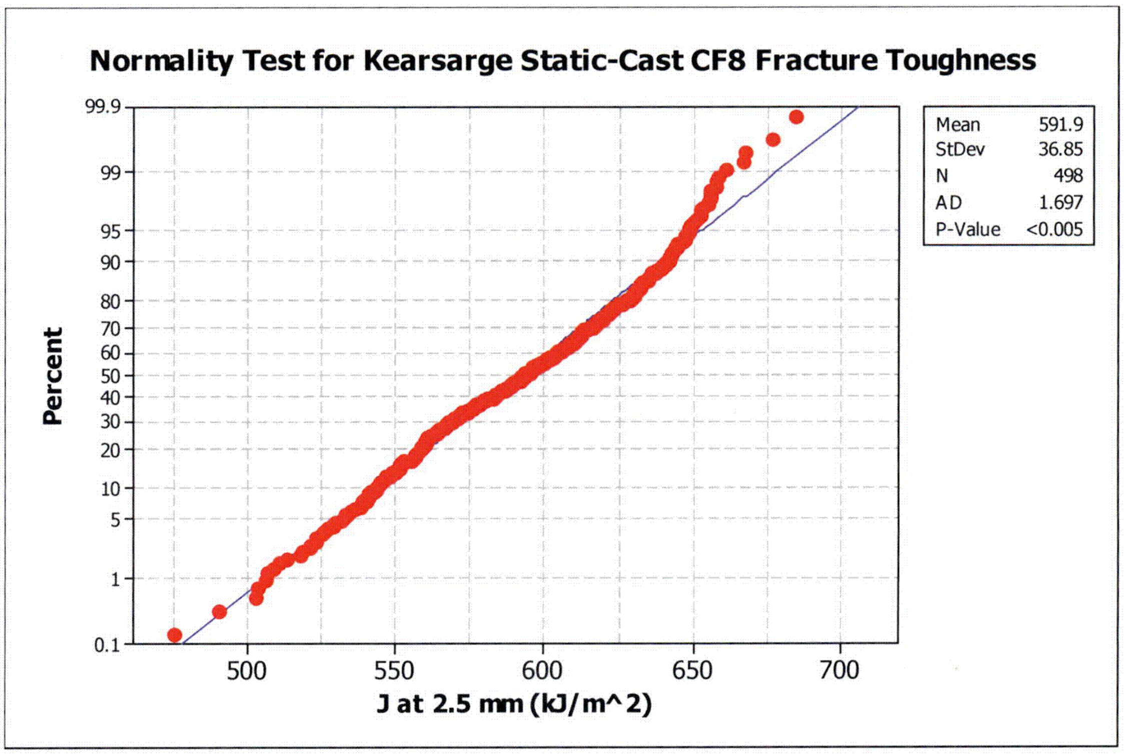

Figure 5-26. Normality Test for Kearsarge Fracture Toughness (Static-Cast CF8)

5.3.2 Waukesha

Waukesha supplied numerous CASS RV internals components for Westinghouse-designed plants, as illustrated in Figure 5-27. CMTR data were available for 263 individual heats of material supplied by Waukesha. The Waukesha-supplied CASS RV internals were all fabricated from static-cast, low-molybdenum Grade CF8 material. Data for this manufacturer includes heats made from 1968 to 1979. The ferrite content of material supplied by Waukesha over time is shown in Figure 5-28.

The distribution of ferrite content for components fabricated by Waukesha is shown in Figure 5-29 with the accompanying normality test data in Figure 5-30. A normal distribution was used to model the Waukesha ferrite content distribution. The calculated p value (<0.005) associated with applying the lognormal distribution does not pass the acceptance criterion, however it provides a reasonable and conservative fit to the data.

Figure 5-29 shows that there are a few heats of material produced by Waukesha that exceed 20 percent ferrite content, as estimated via Hull's factors, and a small but not insignificant fraction of heats that exceed 15 percent ferrite content. The average ferrite content for Waukesha materials is 13.3 percent, and the standard deviation is 3.0 percent. The 95/95 limit for ferrite content for Waukesha is 18.7 percent. Ferrite content distributions for each individual type of component are shown in Figure 5-31. Figure 5-31 shows that there is no significant difference in the estimated ferrite content between the different components made by Waukesha.

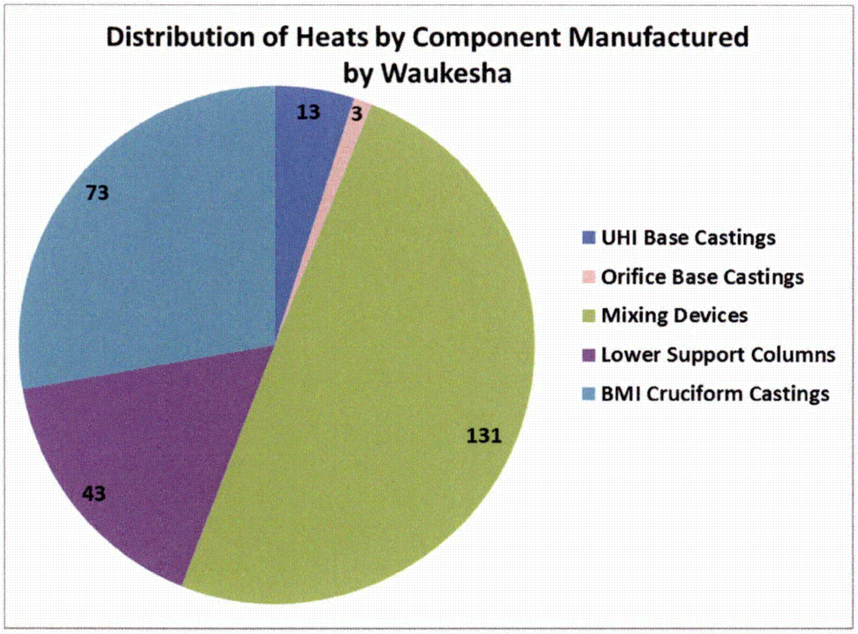

Figure 5-27. Static Cast Components Provided by Waukesha

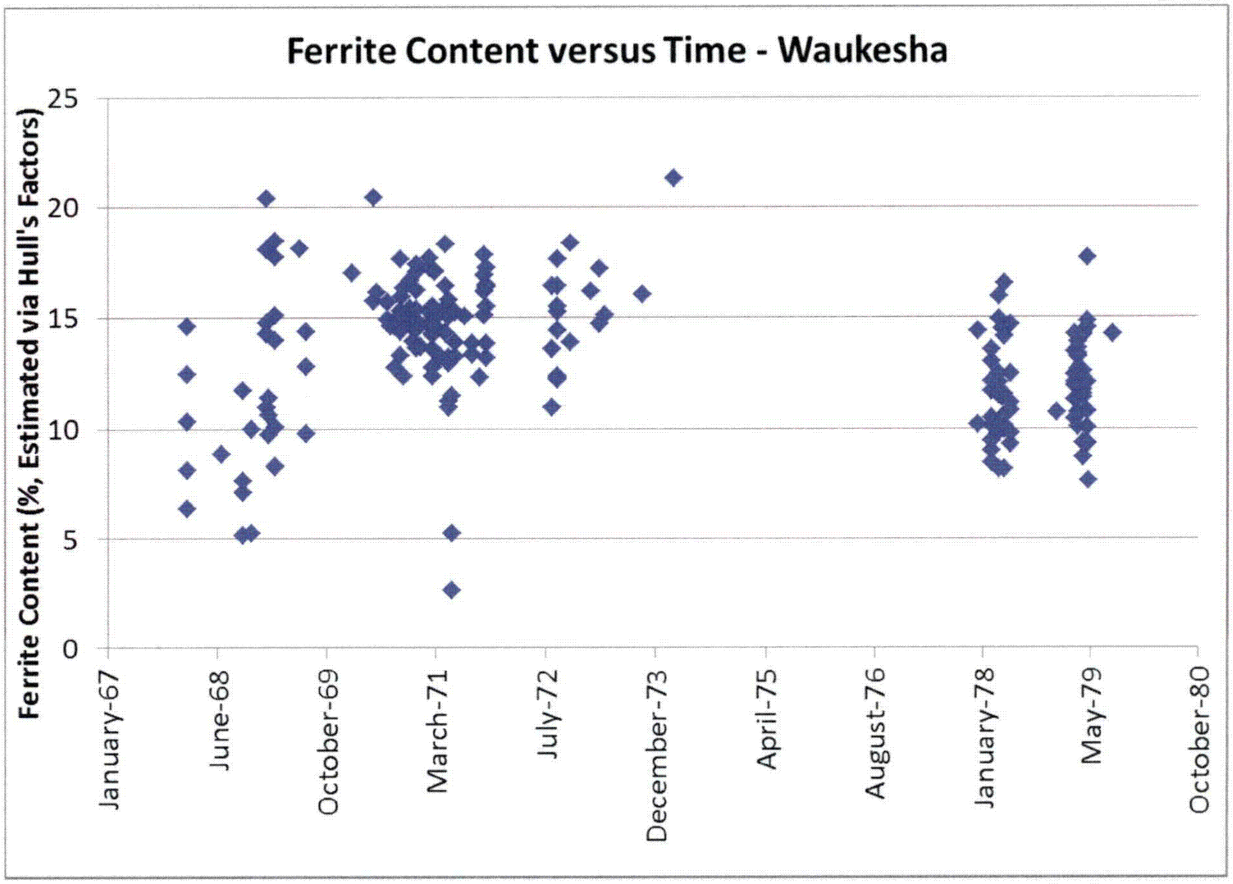

Figure 5-28. Ferrite Content over Time - Waukesha

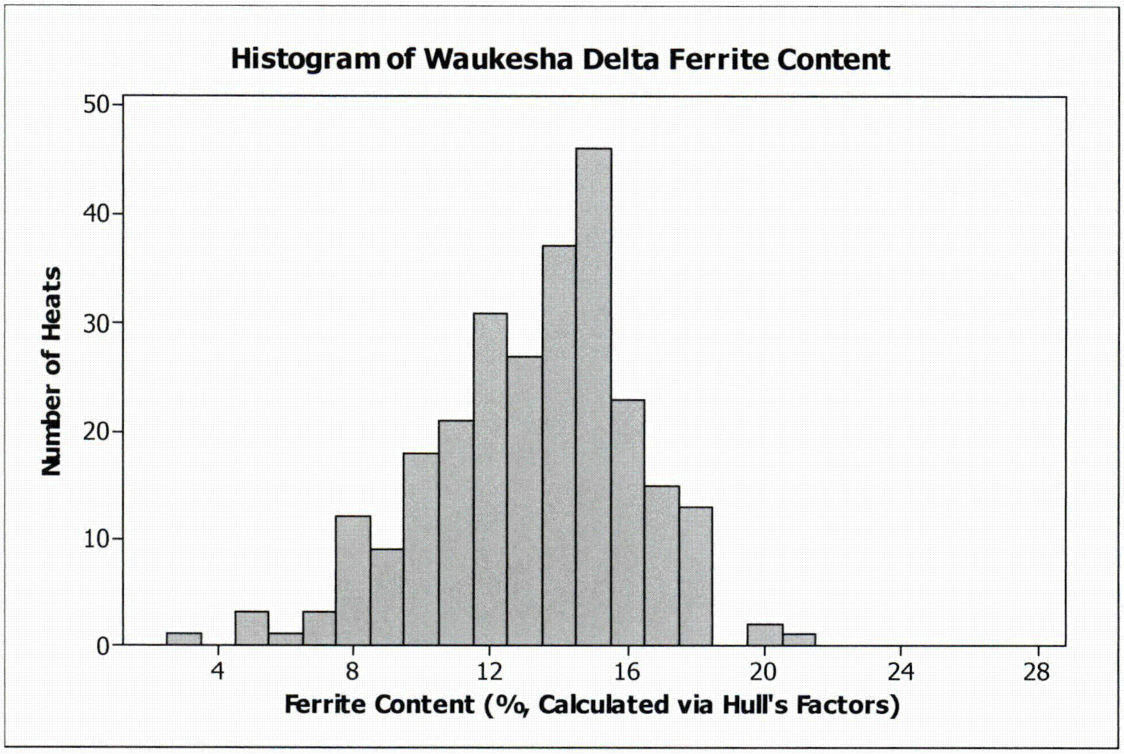

Figure 5-29. Histogram of Ferrite Content for Waukesha

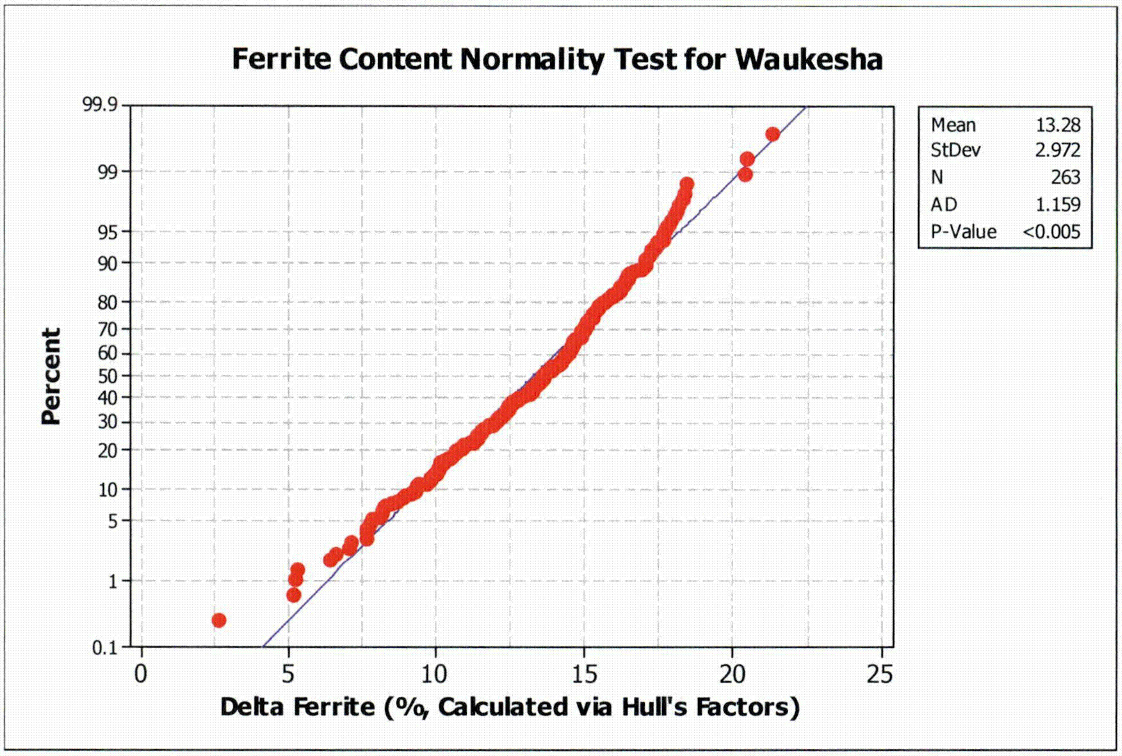

Figure 5-30. Ferrite Content Normality Test for Waukesha

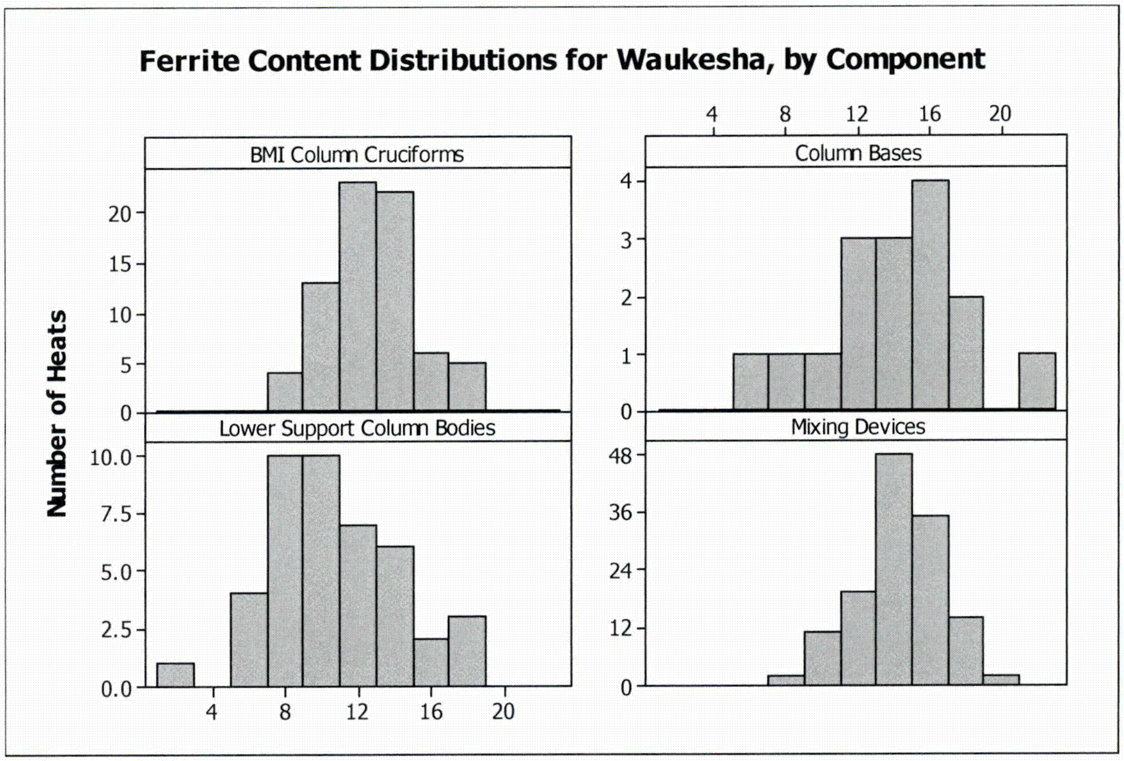

Figure 5-31. Ferrite Content Distributions by Component Manufactured by Waukesha

Figure 5-32 shows the fracture toughness distribution for material heats made by Waukesha, and Figure 5-33 is the normality test associated with that distribution. A normal distribution was used to model the Waukesha ferrite content distribution. The calculated p value (<0.005) associated with applying the lognormal distribution does not pass the acceptance criterion, however it provides a reasonable and conservative fit to the data. The average saturated fracture toughness for Waukesha-supplied materials is 462 kJ/m^2 and the standard deviation is 35.4 kJ/m^2. The 95/95 bound for fracture toughness for Waukesha is 398 kJ/m^2. Thus, it can be stated with a high degree of confidence that no components fabricated by Waukesha will have a fracture toughness below 255 kJ/m^2.

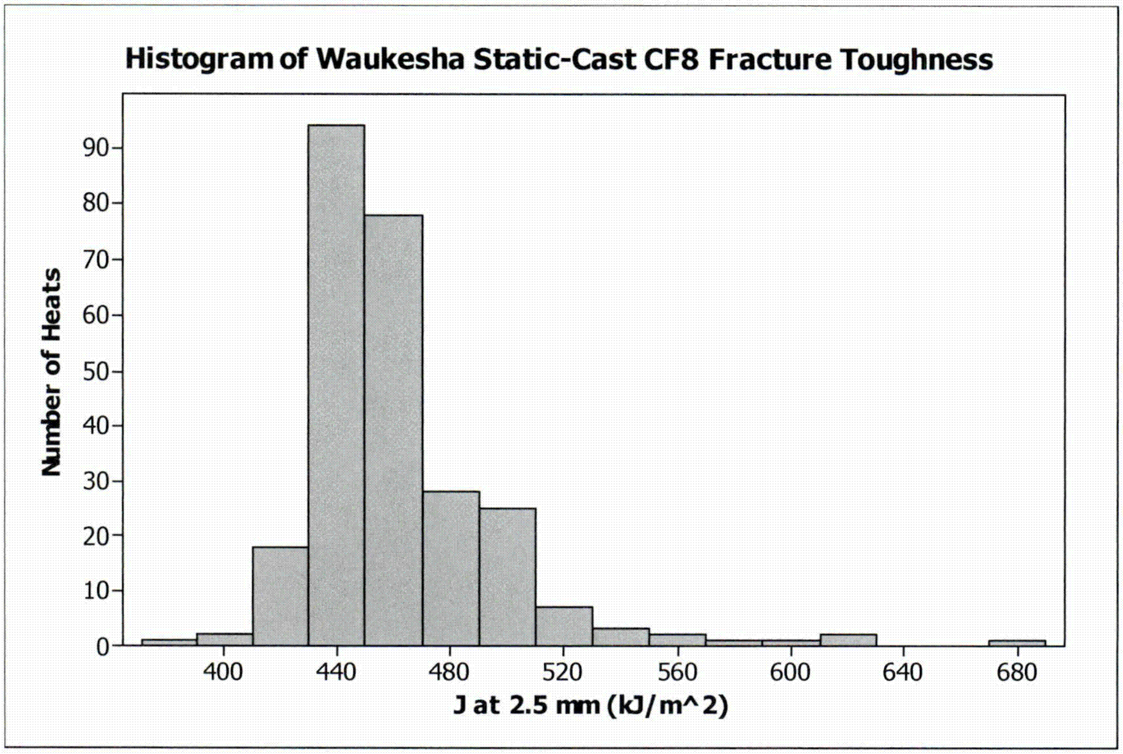

Figure 5-32. Histogram of Saturated Fracture Toughness for Waukesha

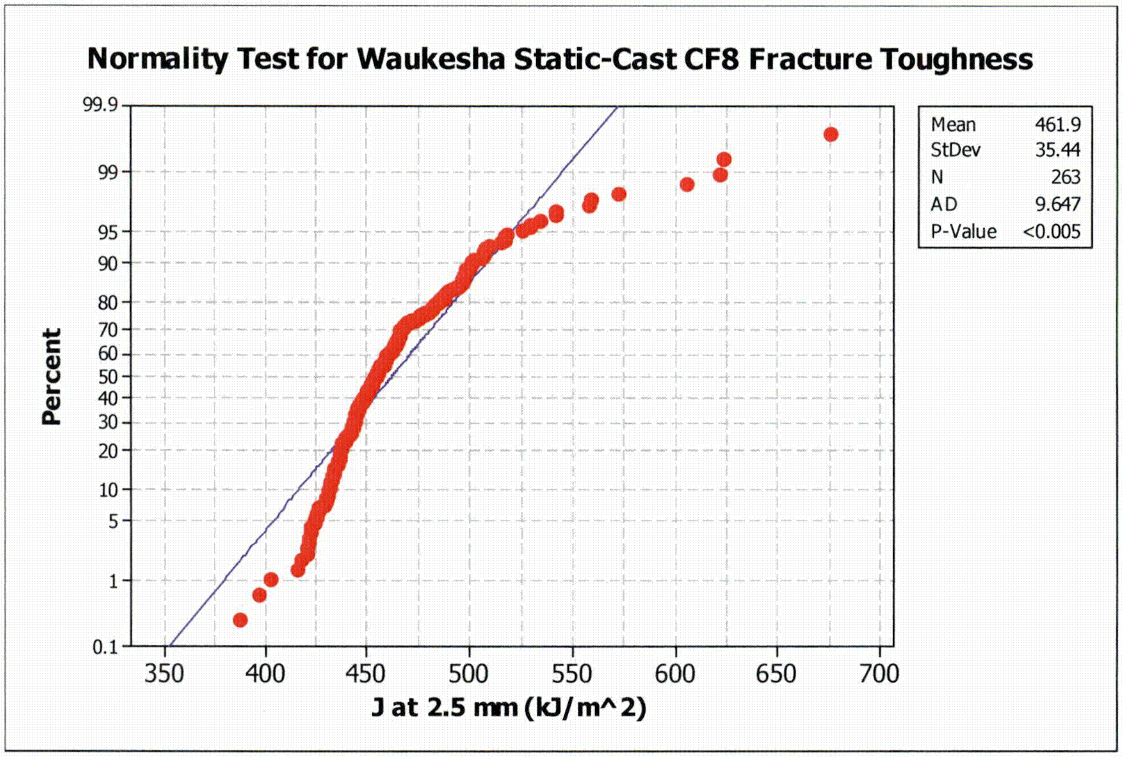

Figure 5-33. Saturated Fracture Toughness Normality Test for Waukesha

5.3.3 Wollaston Alloys

Wollaston Alloys (Wollaston) provided RV internals components for B&W plants. The Wollaston-supplied CASS RV internals components were fabricated from static-cast, low-molybdenum Grade CF8 material or static-cast, high-molybdenum Grade CF3M. The Grade CF3M material was used exclusively in the CRGT spacer castings, which are an MRP-227-A primary component [1]. CMTR data were available for 39 individual heats of static-cast Grade CF8 material and 227 heats of static-cast Grade CF3M material supplied by Wollaston. Wollaston provided CASS RV internals components from 1965 to 1970; however, there was not enough readily available information on the dates of manufacture to generate a meaningful distribution of ferrite content over time.

The distribution of ferrite content for Grade CF8 components fabricated by Wollaston is shown in Figure 5-34, with the accompanying normality test in Figure 5-35. A lognormal distribution was used to model the Wollaston Grade CF8 ferrite content distribution. The calculated p value (0.898) associated with applying the lognormal distribution passes the acceptance criterion. The average ferrite content for Grade CF8 Wollaston materials is 12 percent, and the standard deviation is 4.5 percent. The 95/95 limit for ferrite content for Grade CF8 Wollaston materials is 24.5 percent.

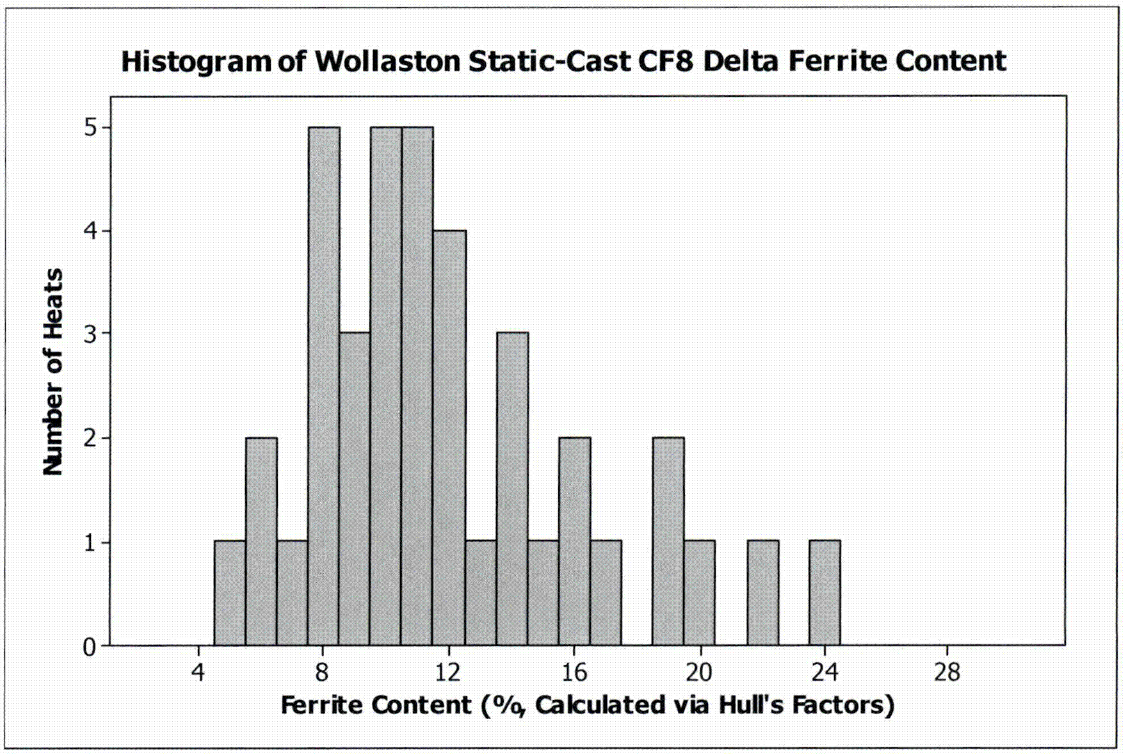

Figure 5-34. Histogram of Wollaston Delta Ferrite Content

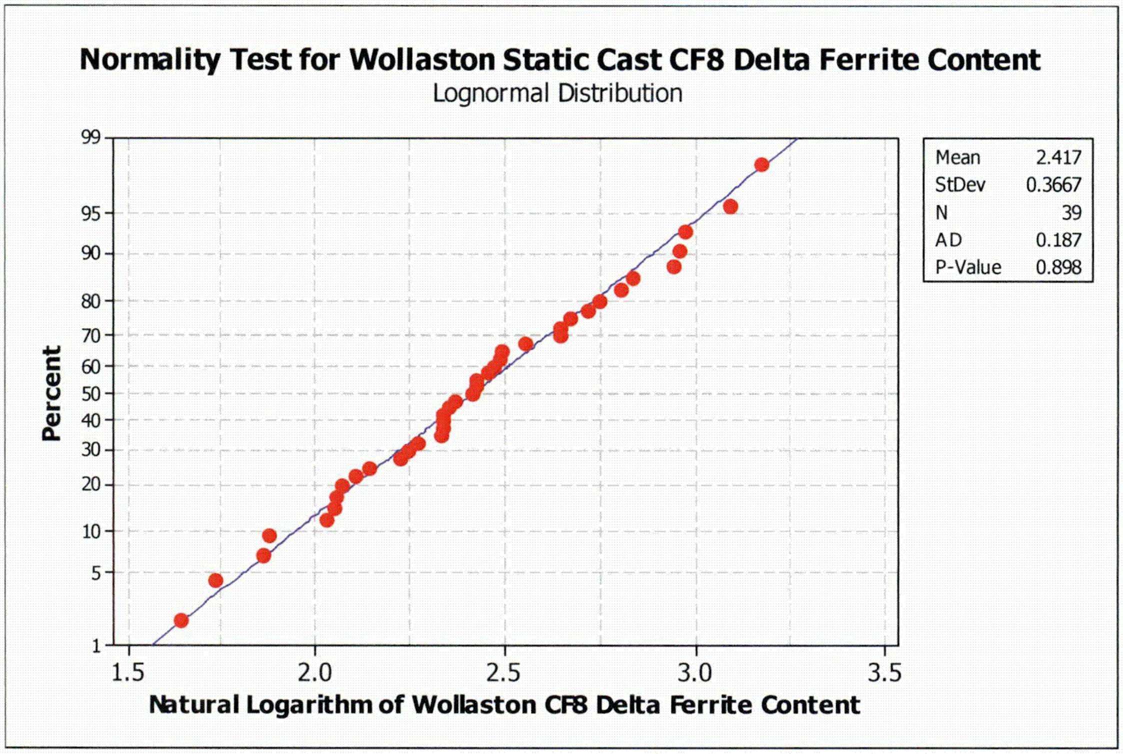

Figure 5-35. Normality Test for Wollaston Delta Ferrite Content (CF8)

Figure 5-36 shows the fracture toughness distribution for Grade CF8 material heats made by Wollaston, and Figure 5-37 is the normality test associated with that distribution. A normal distribution was used to model the Wollaston Grade CF8 saturated fracture toughness distribution. The calculated p value (0.519) associated with applying the lognormal distribution passes the acceptance criterion. The average saturated fracture toughness for Grade CF8 Wollaston-supplied materials is 544 kJ/m^2 and the standard deviation is 45.1 kJ/m^2.

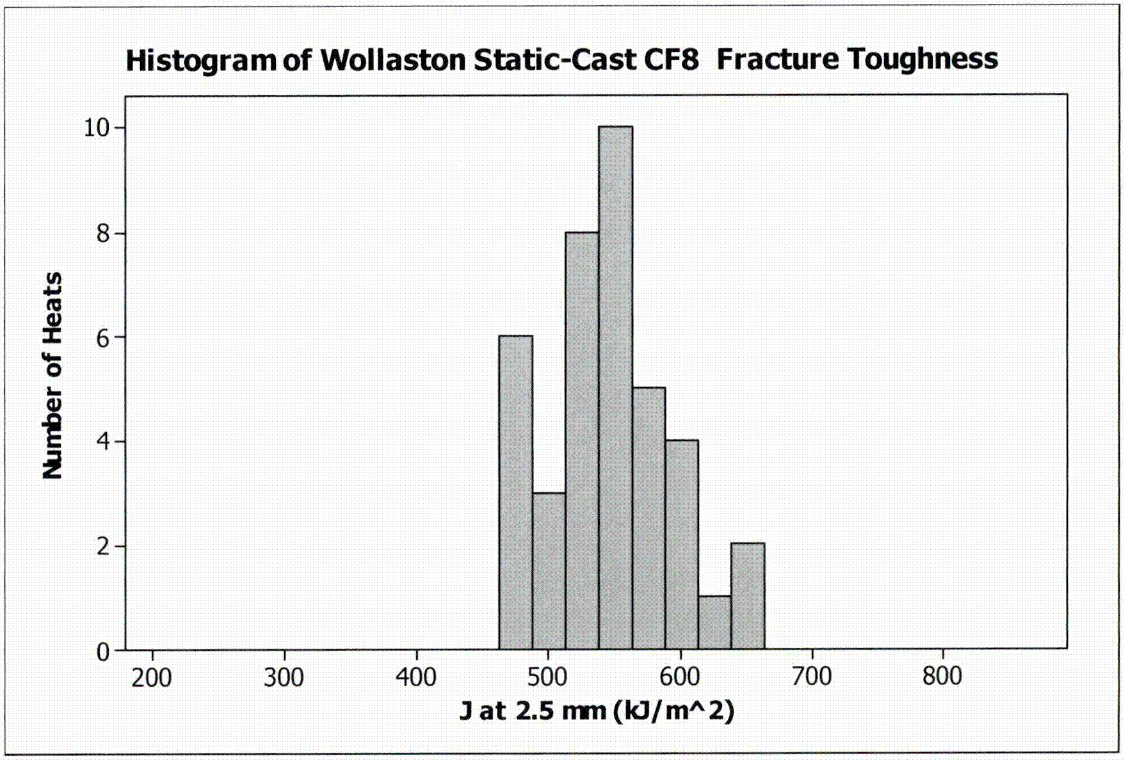

Figure 5-36. Histogram of Wollaston Fracture Toughness

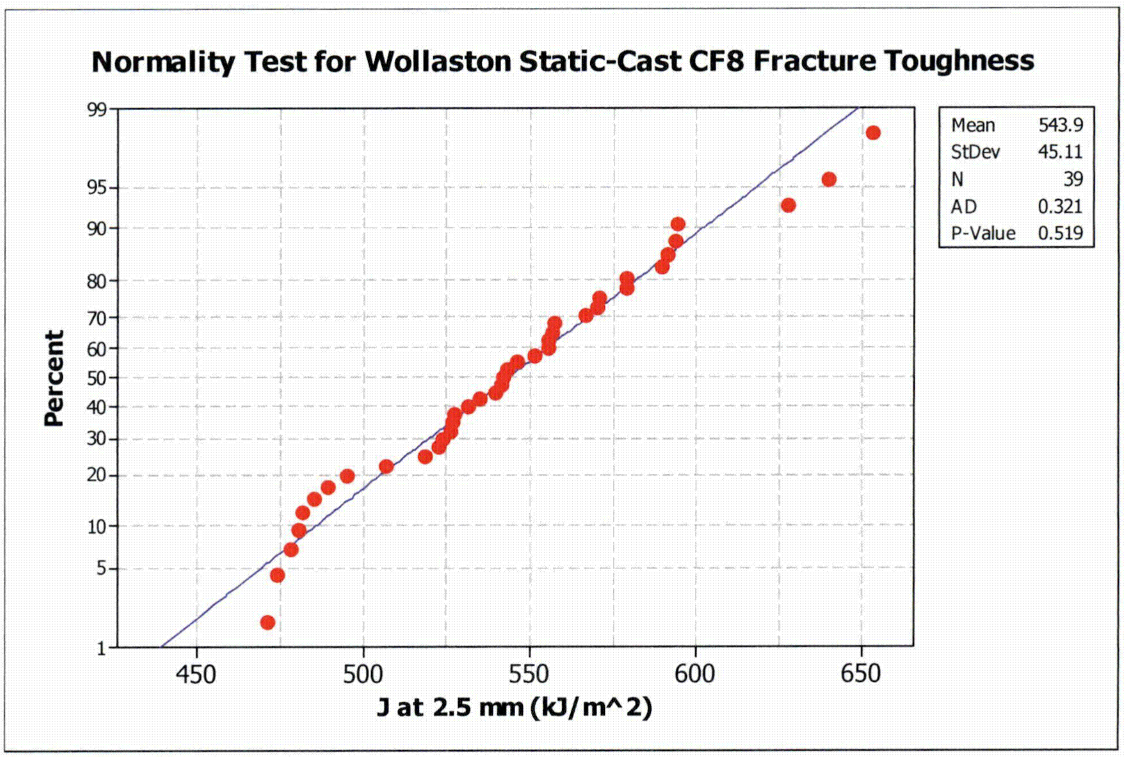

Figure 5-37. Normality Test for Wollaston Fracture Toughness (CF8)

The 95/95 bound for fracture toughness for Grade CF8 Wollaston material is 448 kJ/m^2. Thus, it can be stated with a high degree of confidence that no Grade CF8 components fabricated by Wollaston would have a saturated fracture toughness below 255 kJ/m^2.

The distribution of ferrite content for Grade CF3M components fabricated by Wollaston is shown in Figure 5-38, with the accompanying normality test in Figure 5-39. A normal distribution was used to model the Wollaston Grade CF3M ferrite content distribution. The calculated p value (0.441) associated with applying the normal distribution passes the acceptance criterion.

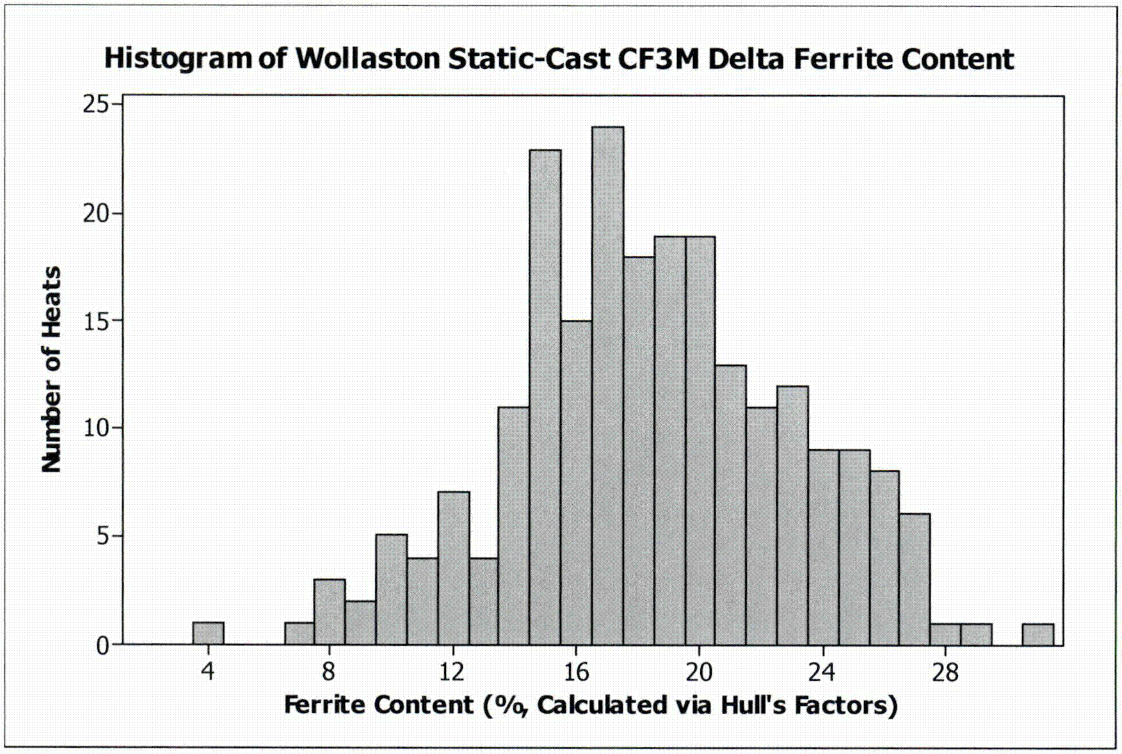

Figure 5-38. Histogram of Wollaston Ferrite Content (Grade CF3M)

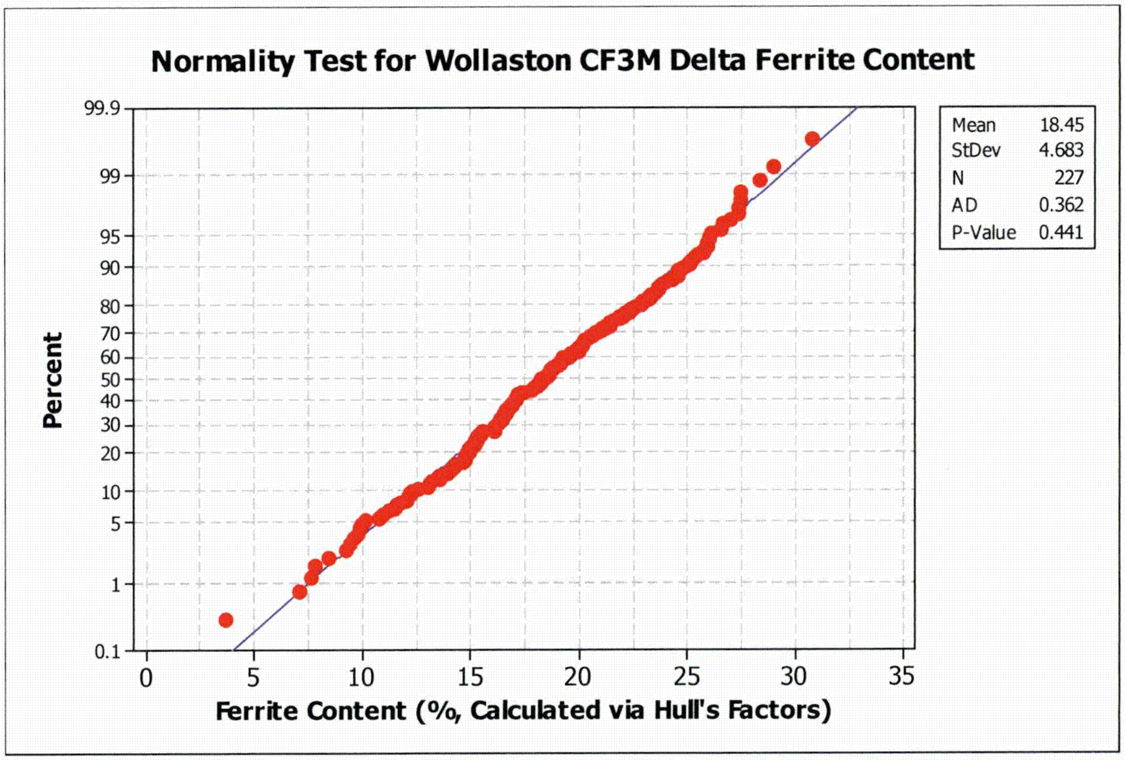

Figure 5-39. Normality Test for Wollaston Delta Ferrite Content (Grade CF3M)

Figure 5-40 shows the fracture toughness distribution for Grade CF3M material heats made by Wollaston, and Figure 5-41 is the normality test associated with that distribution. A normal distribution was used to model the Wollaston saturated fracture toughness distribution. The calculated p value (0.028) associated with applying the normal distribution does not pass the acceptance criterion, however it provides a reasonable and conservative fit to the data. The average saturated fracture toughness for Grade CF3M Wollaston-supplied materials is 327 kJ/m^2 and the standard deviation is 101.67 kJ/m^2.

The 95/95 bound for fracture toughness for Grade CF3M Wollaston material is 141 kJ/m^2. This is below the established screening criterion of 255 kJ/m^2. In the development of MRP-189-Rev. 1 [25], it was recognized that this material had the potential to lose enough fracture toughness that aging management would be required. This resulted in the spacer castings fabricated from the Grade CF3M material being categorized as an MRP-227-A [1] primary component, with inspection requirements appropriate to manage the potential loss of fracture toughness. This is a demonstration of the effectiveness of the MRP process in developing recommendations for aging management of RV internals components in the period of extended operation.

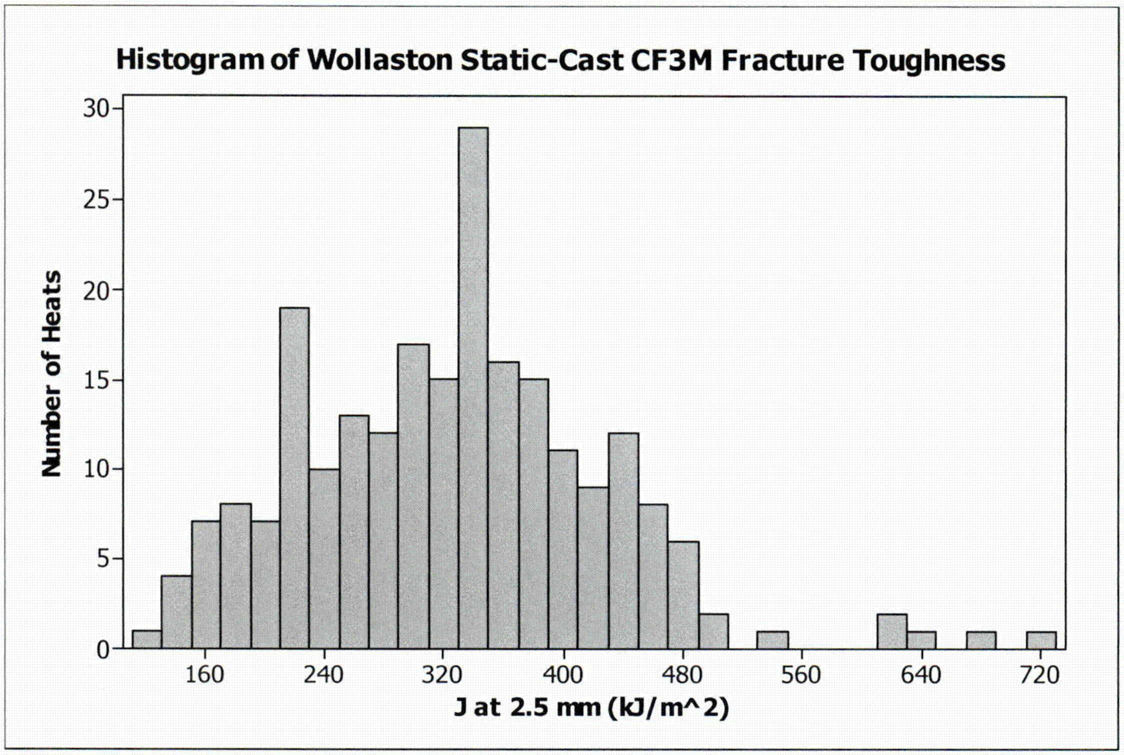

Figure 5-40. Histogram of Wollaston Fracture Toughness (Grade CF3M)

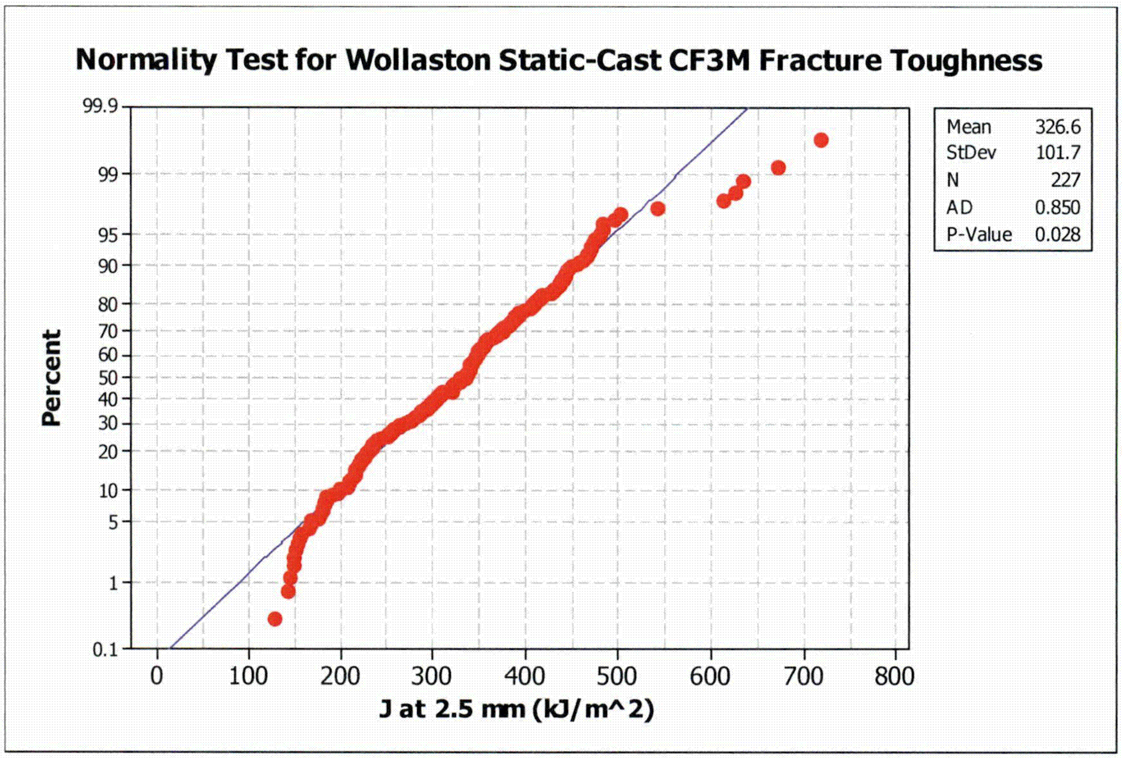

Figure 5-41. Normality Test for Wollaston Fracture Toughness (Grade CF3M)

5.3.4 Precision Founders (PF)

Precision Founders (PF) provided CASS BMI column cruciforms and conduit supports for Westinghouse-designed plants. CMTR data were available for 10 individual heats of material supplied by PF. The PF-supplied CASS RV internals were all fabricated from static-cast, low-molybdenum Grade CF8 material. PF provided CASS RV internals components in 1969 and from 1976 to 1978, as shown in Figure 5-42.

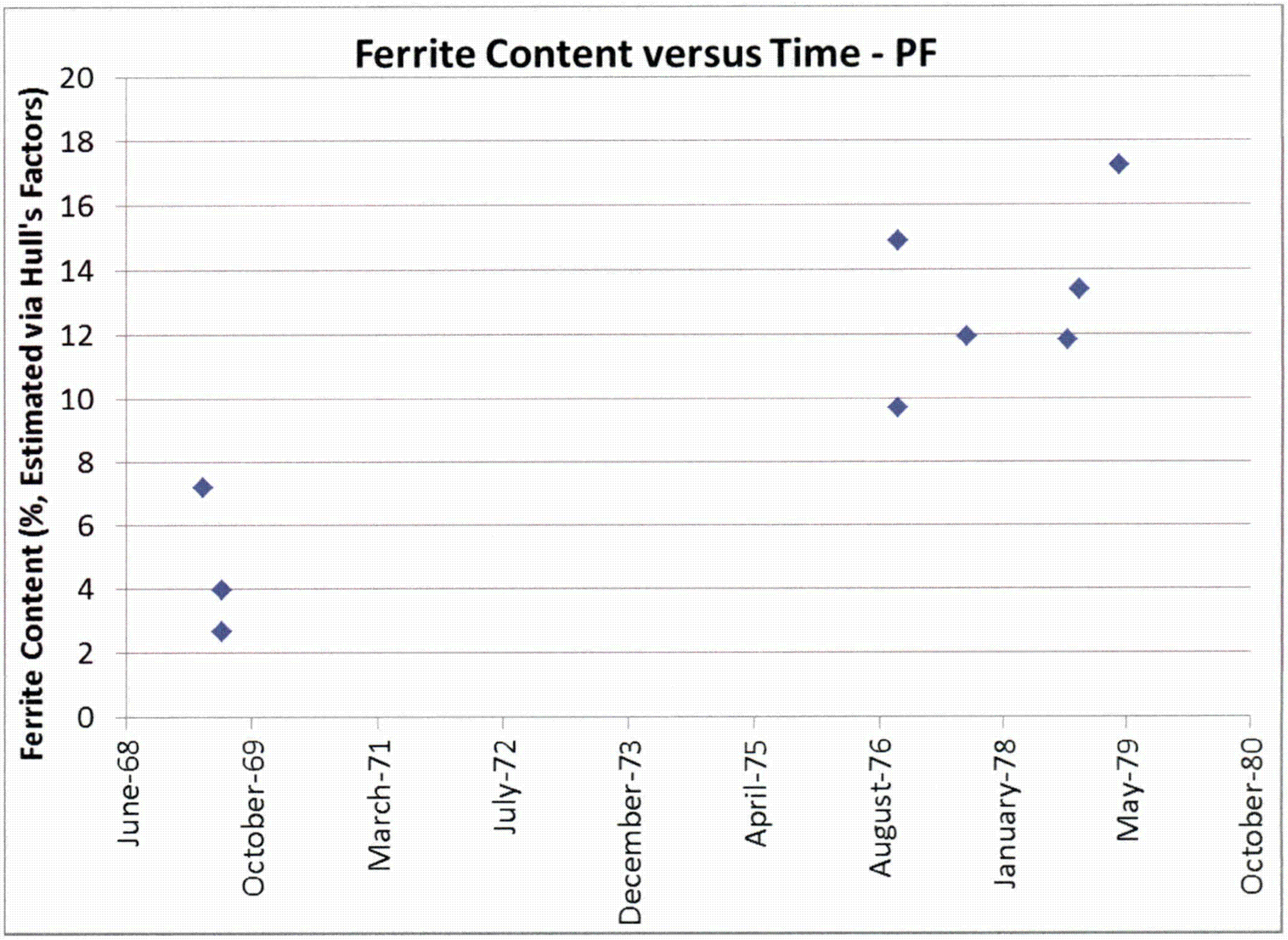

Figure 5-42. Ferrite Content over Time - PF

The distribution of ferrite content for components fabricated by PF is shown in Figure 5-43, with the accompanying normality test in Figure 5-44. A normal distribution was used to model the PF ferrite content distribution. The calculated p value (0.526) associated with applying the normal distribution passes the acceptance criterion. Figure 5-43 shows that there are no heats of material produced by PF that exceed 20 percent, and one heat that exceeds 15 percent ferrite content as estimated via Hull's factors. The average ferrite content for PF materials is 10.7

percent, and the standard deviation is 4.8 percent. The 95/95 limit for ferrite content for PF is, however, 24.7 percent, due to the small sample size evaluated.

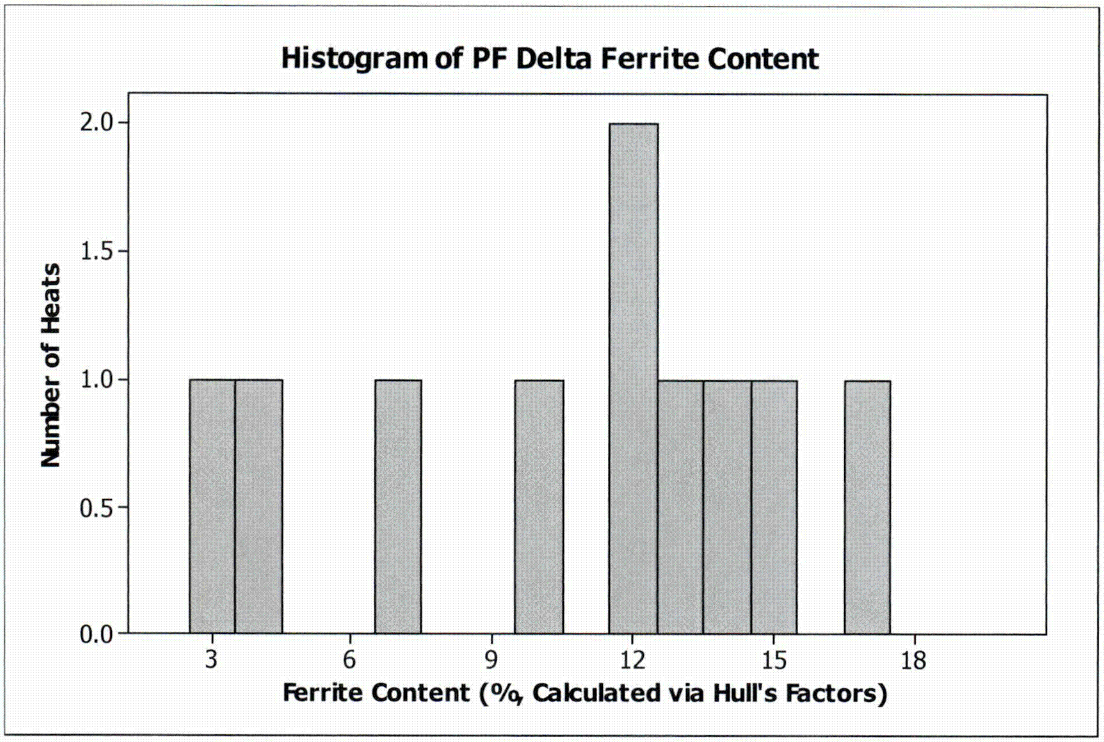

Figure 5-43. Histogram of PF Delta Ferrite Content

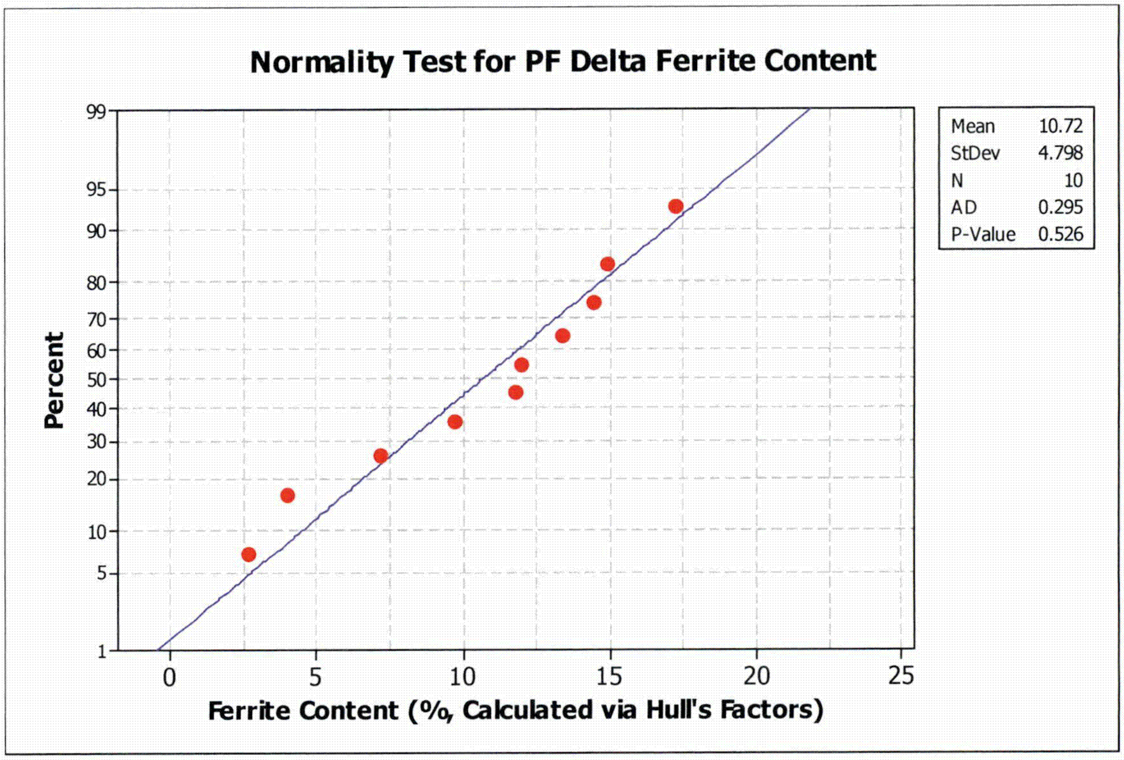

Figure 5-44. Normality Test for PF Delta Ferrite Content

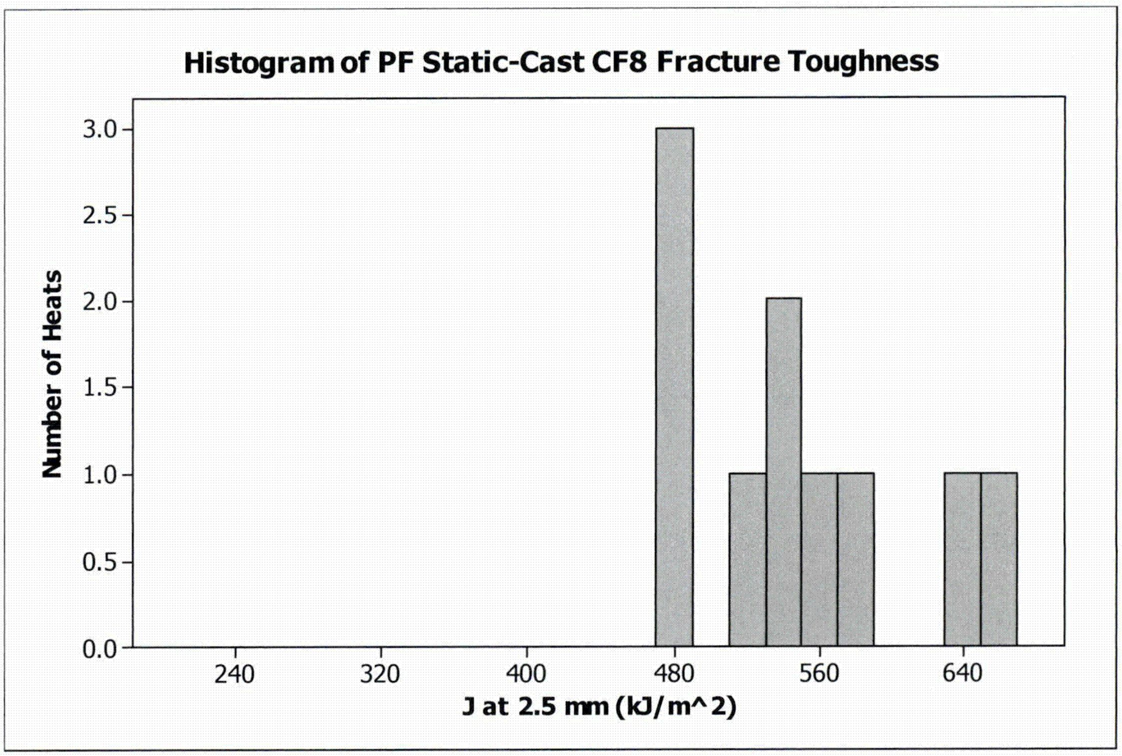

Figure 5-45. Histogram of PF Fracture Toughness

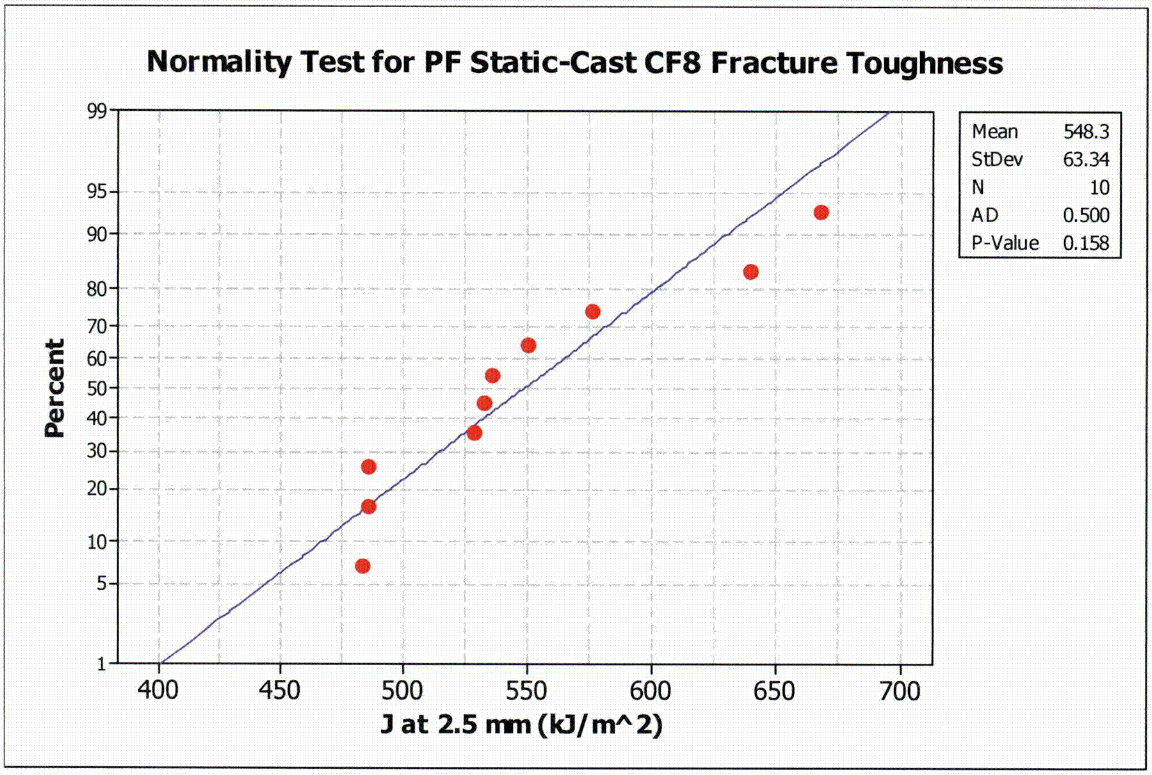

Figure 5-46. Normality Test for PF Fracture Toughness

Figure 5-45 shows the fracture toughness distribution for material heats made by PF, and Figure 5-46 is the normality test associated with that distribution. A normal distribution was used to model the PF saturated fracture toughness distribution. The calculated p value (0.158) associated with applying the normal distribution passes the acceptance criterion. The average saturated fracture toughness for PF-supplied materials is 548.3 kJ/m^2 and the standard deviation is 63.3 kJ/m^2. The 95/95 bound for fracture toughness for PF is 364 kJ/m^2. Thus, it can be stated with a high degree of confidence that no components fabricated by PF will have a saturated fracture toughness below 255 kJ/m^2.

6 CONCLUSIONS

6.1 FERRITE CONTENT

The ferrite content of U.S. PWR CASS RV internals has been shown to be dependent on material specification, casting method and, manufacturer. The ferrite content approximates a normal or lognormal distribution when separated by manufacturer. This behavior of the data provides a basis for the prediction of an upper bound ferrite content in instances where only limited manufacturing records may be available. The approach to using this basis is provided in Section 7.0. The calculated saturation fracture toughness after TE, which is based on the ferrite content and chemical composition, can be conservatively modeled by a normal distribution and so a lower bound can be predicted in a similar manner.

For static-cast Grade CF8 components, the ferrite content rarely exceeds the 20 percent screening criterion [4], as demonstrated by the 95/95 criteria for the overall distribution of this material type being below 20 percent. It cannot be stated that a randomly selected component would not have a ferrite content that would exceed 20 percent by using the overall distribution (Figure 5-1). Reducing the criterion to 15 percent to account for combined TE +IE would make it significantly more likely that a randomly selected component would have a ferrite content that would exceed the criterion. However, partitioning the database with respect to manufacturer has allowed the identification of manufacturers for whom the potential to exceed these criteria are reduced such that ***if the component manufacturer can be identified with reasonable assurance and if this manufacturer is one of the ones with demonstrated low ferrite content then it would be reasonable to assume that further components would have ferrite contents below the screening values.*** Such manufacturers of Grade CF8 components would be AMP, Kearsarge, Valcast and, Waukesha as a minimum. Note that these manufacturers contributed 94 percent of components to the existing database. This approach could be used in practice when plant-specific component CMTRs are missing, instead of the current practice of assuming the component screens in for TE based on the maximum possible ferrite content permitted by the materials specification. This study has confirmed that assumption to be overly conservative by showing that the vast majority of calculated ferrite contents for real heats of material are much less than the screening criterion.

Segregating the static-cast Grade CF8 data by component, plant, or vintage did not reveal any trends as significant as the dependence of ferrite content on component manufacturer (except in the cases where a manufacturer was the sole provider of a given component or to a given plant).

The 95/95 limits for centrifugally-cast Grade CF8 material are presented in Table 5-4, however there are no screening criteria for these components [4], as they are expected to retain adequate fracture toughness regardless of ferrite content.

A fraction of the static-cast Grade CF3M materials exceeds the 14 percent ferrite content screening criterion [4]. However, these components are "Primary" examination items for the B&W units and are adequately addressed for the extended period of operation.[1].

6.2 FRACTURE TOUGHNESS

All of the centrifugally-cast and static-cast Grade CF8 materials show saturated fracture toughness well above the established screening criterion. This is demonstrated by the 95/95 limits presented in Table 5-5. The assessment also demonstrated that Grade CF8 material at any ferrite content will have saturation fracture toughness significantly greater than 255 kJ/m^2. Again the saturated fracture toughness data show a strong dependence on manufacturer; manufacturers that produce low ferrite materials produce components with high saturated toughness after TE. The higher than 255 kJ/m^2 toughness of Grade CF8 materials with greater than 20 percent ferrite most probably reflects the conservatism that was taken into account when the NRC set the original ferrite content guidance of 20 percent for Grade CF3 and Grade CF8 materials in the Grimes letter. That the ferrite screening values were intended to be conservative is stated directly in NUREG/CR-4744 [36]: "Assessments based on the proposed delta-ferrite screening criterion must be very conservative or it may not be adequate for some steels, in particular Mo-bearing CF-8M steels."

The results presented here showing that Grade CF8 materials would have adequate fracture toughness after TE are consistent with conclusions drawn by the French nuclear industry [33]. This finding is also consistent with the conclusions of the industry and the NRC in pressure boundary CASS components with regard to the technical basis for leak-before-break considerations [34] and [35].

The statistical approach and the 95/95 criteria for each of the manufacturers for ferrite content and fracture toughness will be used in instances where a plant may not have a complete set of manufacturing records down to the CMTR level for all CASS RV internals components available.

While many of the Grade CF3M material heats examined in this study have a significant amount of toughness left after TE effects, this toughness was often below the established screening criteria. This was considered in the development of MRP-189 [25], so the components fabricated from Grade CF3M material are already included in the inspection scope of MRP-227-A [1]. This approach is expected to provide adequate aging management of these components. This analysis also demonstrates that low-molybdenum and high-molybdenum CASS will have significantly different aging behaviors, which is consistent with [7]. Therefore, it is important to note here that it is excessively conservative to use the much lower mean and significantly greater predicted scatter of the saturated fracture toughness of high molybdenum alloy (Grade CF3M and Grade CF8M) data to create bounding acceptance criteria for lower molybdenum-containing alloy variants (Grade CF3 and Grade CF8).

6.3 MRP-227-A APPLICABILITY

The statistical analysis of the CASS data completed in this report serves as an independent check on MRP-227-A [1] treatment of thermal embrittlement. This analysis provides reasonable assurance that no Grade CF8 components will fall below the established fracture toughness screening criterion due to TE effects. Moreover, given the results on fracture toughness, this analysis shows that a requirement for each plant to determine ferrite content of Grade CF8 components provides no meaningful increment of safety function assurance. This is especially the case when the safety function is redundantly distributed among multiple components, such as the case for CASS lower column supports [32]. The Grade CF3M components (spacer castings) that have the potential to fall below this screening criterion due to TE are already covered by MRP-227-A [1] inspection requirements to appropriately manage the potential loss of fracture toughness (as described in MRP-227-A [1]). Therefore, the results of this analysis support the level of aging management for RV internals CASS prescribed by MRP-227-A [1], and they provide additional assurance that CASS RV internals in domestic PWRs will continue to maintain functionality.

7 IMPLEMENTATION

This section discusses how the results of the statistical approach can be used in responding to A/LAI 7. The most efficient use of this work would permit a licensee to submit a response based on the generic conclusions in Section 6, and a discussion as to why the generic conclusions are applicable to that plant. Alternatively, for plants that are requested to provide plant specific data in responding to A/LAI 7, the outlined approaches can provide additional information and assurance when complete fabrication records are not available. In this case, the licensee would use the statistical approach on a case-by-case basis to predict the most likely extremes (highest ferrite content and lowest expected fracture toughness) of expected properties for the manufactured components.

The approach outlined below, based on the statistical analysis conducted in this program, would address the TE portion of A/LAI 7. A/LAI 7 requests responses for both TE and IE. Estimating ferrite content only provides a screening input for TE, since CASS of any ferrite content is potentially susceptible to IE, as indeed are wrought stainless steel internal components (but at the slightly higher criterion of 1.5 dpa rather than the 1.0 dpa for CASS components [3]). Nevertheless, a response to A/LAI 7, following the practices of MRP-227-A identified for CASS components, requires screening for TE before screening for IE. Conclusions drawn from this program can provide the basis for judging the potential for components to be screened in for TE (or not) in the absence of complete plant-specific component material records. Should the components be found to screen in then the approach would be combined with flaw tolerance assessments, structural redundancy arguments (such as [32] for the lower support column bodies), or other supporting information as applicable to provide a complete response to A/LAI 7.

The results of this program allow utilities to implement options for addressing TE as part of A/LAI 7 without an exhaustive fabrication records search or when records are not available. Previously, a component-specific CMTR would be used to calculate a delta ferrite content via Hull's factors for comparison to the screening criteria. If a CMTR was unavailable, then the component would be assumed to be susceptible to TE. This program adds the following three options:

1. Use of a ferrite upper bound based on the overall population
2. Use of a ferrite upper bound based on a specific manufacturer
3. Use of a ferrite upper bound for a specific component type, based on the limiting upper bound of the manufacturer(s) that supplied the component

The new options are summarized here. If no fabrication information is readily available for a given CASS RV internals component, the ferrite upper bound based on the overall population can be used. As the ferrite upper bound for the overall population (17.5 percent) is below the current screening value of 20 percent [4], this allows the components in question to be screened out.

Analysis of the overall industry data (Section 5.1) shows high confidence that the ferrite content of a randomly selected component is less than 20 percent, however there exists a small possibility of randomly encountering ferrite content above the current 20 percent criterion for TE and a greater probability of encountering ferrite content above the 15 percent criterion proposed to account for TE and IE effects. However, the second and third options are expected to yield benefits since the utilization of partial information to restrict the statistics to certain subsets would provide the opportunity to identify situations when reduced ferrite content should be expected. In such situations, the components would not be screened-in for TE, and burdensome inspections and overly conservative aging management would be avoided.

If the manufacturer of a component is known, then the ferrite upper bound for that manufacturer can be used for comparison to the screening criteria. The manufacturer of a component can potentially be determined from a number of fabrication records other than CMTRs, for example, a purchase order or radiographic inspection records. This requires the utility to assume that the manufacturer of the component was not changed after the records were issued.

As identified in the analysis, all of the manufacturers' products showed reasonably normally or lognormally distributed ferrite contents. Knowing the component manufacturer would then, as argued in the discussion, provide a reasonable assurance of the expected distribution of the ferrite contents for the components in question. If the supplier is known to be one with low mean and 95/95 confidence limit ferrite contents, it would be reasonable to consider comparison of these representative parameters with the screening criterion to determine whether to screen in these components for TE. For instance, if it is known that components were supplied by Kearsarge (ferrite content mean 6.2 percent and 95/95 confidence limit 9.2 percent), then it can be reasonably assumed that the ferrite content of the components would not exceed the TE screening criterion of 20 percent (or even the more recently proposed IE + TE screening criterion of 15 percent [31]).

A ferrite upper bound for a specific component can also be developed, if it can be determined that the given component was made by a subset of the manufacturers. In the case of B&W designed reactors, each manufacturer only provided a single component type. For Westinghouse and CE designed reactors, the manufacturer of a component can often be narrowed down to a subset of manufacturers. This approach would require the assumption that the manufacturers who provided a specific component were the only ones to do so. This assumption is considered valid because the dataset used in this study is a representative sample of the domestic PWR fleet as discussed in subsection 4.1.

In lieu of a search for and review of the complete set of manufacturing records for CASS RV internals the results of this program can be used to estimate the expected ferrite content of components for which complete plant records cannot be located. Two situations where this arises are when only incomplete records are readily available for a set of components and when the components in question were only manufactured by a limited subset of manufacturers. In the former case it is reasonable to assume that the remaining components in the set of components for the plant were supplied by the same manufacturer that supplied the other components. In that case, the missing ferrite contents would be expected to follow the same statistics as those of the identified manufacturer. In the latter case, when the missing plant records pertain to specific components which have only been manufactured by certain manufacturers, the expectation for ferrite content would be based on the "worst case" data for those manufacturers. An assessment of the possibility of the ferrite content exceeding the criteria could be made on the basis of that manufacturer's statistical distribution.

This process is only applied to components fabricated from static-cast Grade CF8 compositions, since there is no ferrite limit in the screening criteria [4] for centrifugally-cast Grade CF8 and the components fabricated from static-cast Grade CF3M have already been identified and are being managed by inspection [1]. Thus, the results of the program will be applicable to, and will be useful for, all remaining plants that have not yet responded to A/LAI 7 and that may have statically-cast Grade CF8 components in their RV internals.

While the current analysis of the ferrite content does not eliminate the possibility of encountering plant material with ferrite content greater than 20 percent, the analysis of the saturation fracture toughness data does provide a basis for alleviating the burden of screening Grade CF8 plant-specific components. The saturation toughness data for the Grade CF8 materials were all calculated to be well above the 255 kJ/m^2 criterion that has been applied (by the Grimes letter [4]) to assure providing adequate toughness. Examination of the data for the Grade CF8 material indicates that even at 25 percent ferrite content the Grade CF8 materials would be expected to have saturation toughness significantly greater than 255 kJ/m^2. It could be argued then that the criterion of 20 percent is too low. It is, however, most probable that this conservatism was taken into account in originally setting the 20 percent criterion for TE of static cast Grade CF8 in the Grimes letter. Nevertheless, the high saturated fracture toughness values calculated for the static-cast Grade CF8 materials examined in this study indicate that further reducing the criterion to 15 percent to account for combined TE and IE would be excessively conservative.

While A/LAI 7 also requests the applicant to address the combined effects of TE and IE, discussion of this topic is beyond the scope of this investigation. However it is noted that the use of IE data from high molybdenum Grade CF8M [30] to define a lower bound for IE effects for low molybdenum Grade CF3 and Grade CF8 materials should be analogous to using the Grade CF3M TE data in Figure 5-6 with lower mean toughness and excessive scatter to represent the TE of Grade CF8.

The above approaches have been discussed with the NRC to determine their acceptability for plant-specific analyses. The NRC has indicated, in the telephone conference call of May 27th, 2015, its willingness to consider such approaches. Additional discussions with the NRC were held on September 16th, 2015 where the details and results of the analysis were presented, and the NRC maintained their willingness to consider the approach in A/LAI responses.

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APPENDIX A DETAILED RESULTS BY MANUFACTURER

The data and approach described in Section 4 have been used to generate ferrite and fracture toughness distributions for available data [24], [22] for each manufacturer. Also developed are normality tests for the distributions, data on which components were fabricated by that manufacturer, and the timeframe that these components were manufactured. The exact extent of the analyses depends on the volume of available data. For some manufacturers, there is insufficient data to develop meaningful results for certain analyses.

The results of the normality tests vary based on manufacturer (specifically, the number of data points available for each manufacturer) however for this analysis the distributions for all manufacturers with sufficient data are assumed to be appropriately modeled by a normal or lognormal distribution. This is done because at present this is the best data available, and, should more data be added to a given manufacturer's data set the distribution should approach a normal or lognormal distribution (per the central limit theorem [20]). Additionally, a normal or lognormal distribution to model data of this type is expected from the implementation of statistical process control in materials fabrication [20]. Some deviation from normality is also expected due to minimum possible values of fracture toughness (see subsection 4.3.1) and ferrite content.

The fracture toughness values in this Appendix are given as resistance to fracture J at a crack extension Δa of 2.5 mm, at a temperature of 554 degrees Fahrenheit (290 degrees Celsius), in units of kJ/m^2.

A.1 AMP

Acieries du Manoir Pompey (AMP) provided CASS brackets, clamps, terminal blocks, conduit straps, mixing devices, and column bases for Westinghouse-designed plants. CMTR data were available for 14 individual heats of material supplied by AMP. The AMP-supplied CASS RV internals were all fabricated from low-molybdenum Grade CF8 material. Data for this manufacturer includes heats made from 1974 to 1975, as shown in Figure A-1.

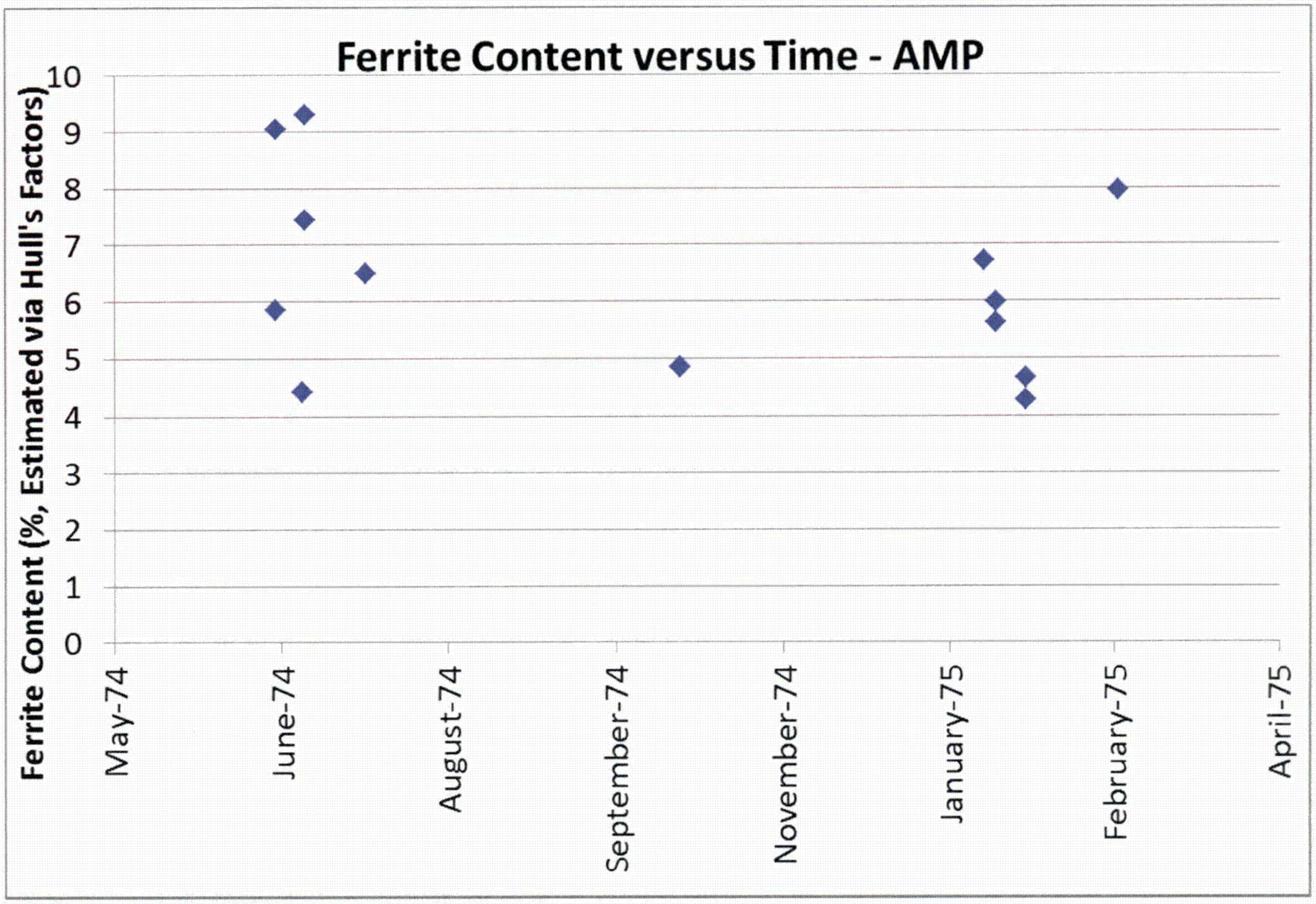

Figure A-1. Ferrite Content over Time - AMP

The distribution of ferrite content for components fabricated by AMP is shown in Figure A-2, with the accompanying normality test in Figure A-3. A lognormal distribution was used to model the AMP ferrite distribution; the calculated p value (0.593) associated with applying the lognormal distribution passes the acceptance criterion. Figure A-2 shows that there are no heats of material produced by AMP that exceed 15 percent ferrite content as estimated via Hull's factors. The average ferrite content for AMP materials is 6.2 percent, and the standard deviation is 1.7 percent. The 95/95 limit for ferrite content for AMP is 11.9 percent.

Figure A-4 shows the fracture toughness distribution for material heats made by AMP, and Figure A-5 is the normality test associated with that distribution. A normal distribution was used to model the AMP saturated fracture toughness distribution; the calculated p value (0.186) associated with applying the normal distribution passes the acceptance criterion. The average saturated fracture toughness for AMP-supplied materials is 605 kJ/m^2 and the standard deviation is 38 5 kJ/m^2. The 95/95 bound for fracture toughness for AMP is 505 kJ/m^2. Thus, it can be stated with a high degree of confidence that no components fabricated by AMP will have a saturated fracture toughness below 255 kJ/m^2.

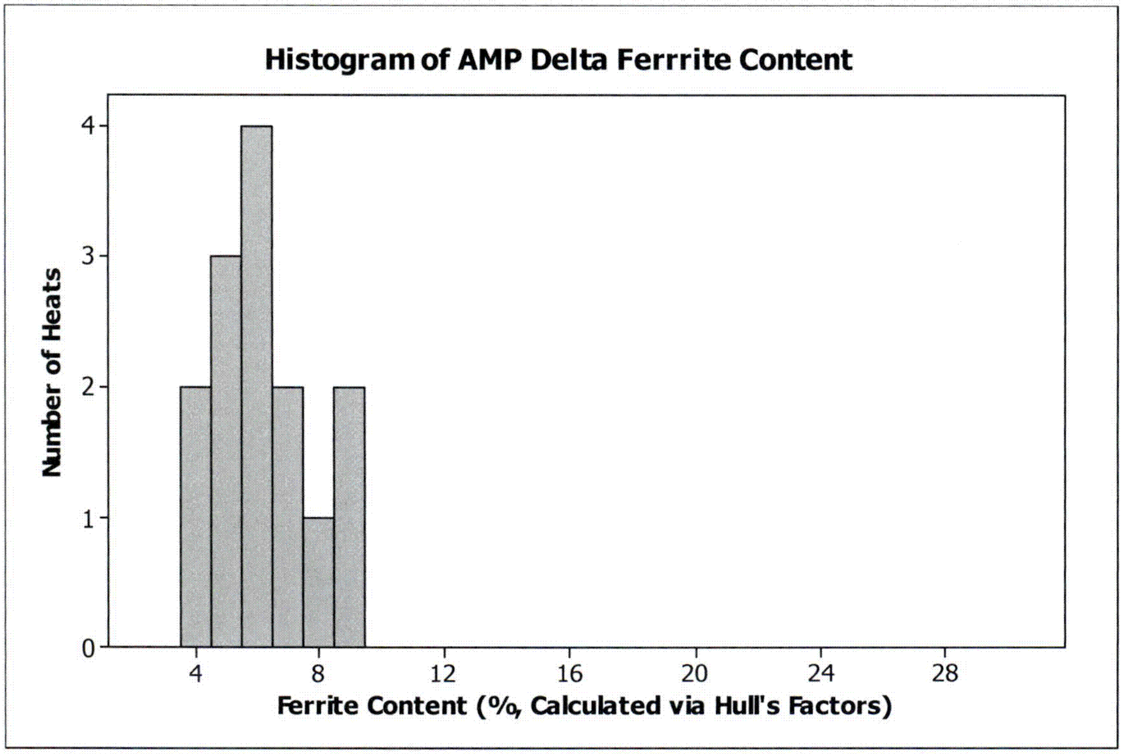

Figure A-2. Histogram of AMP Delta Ferrite Content

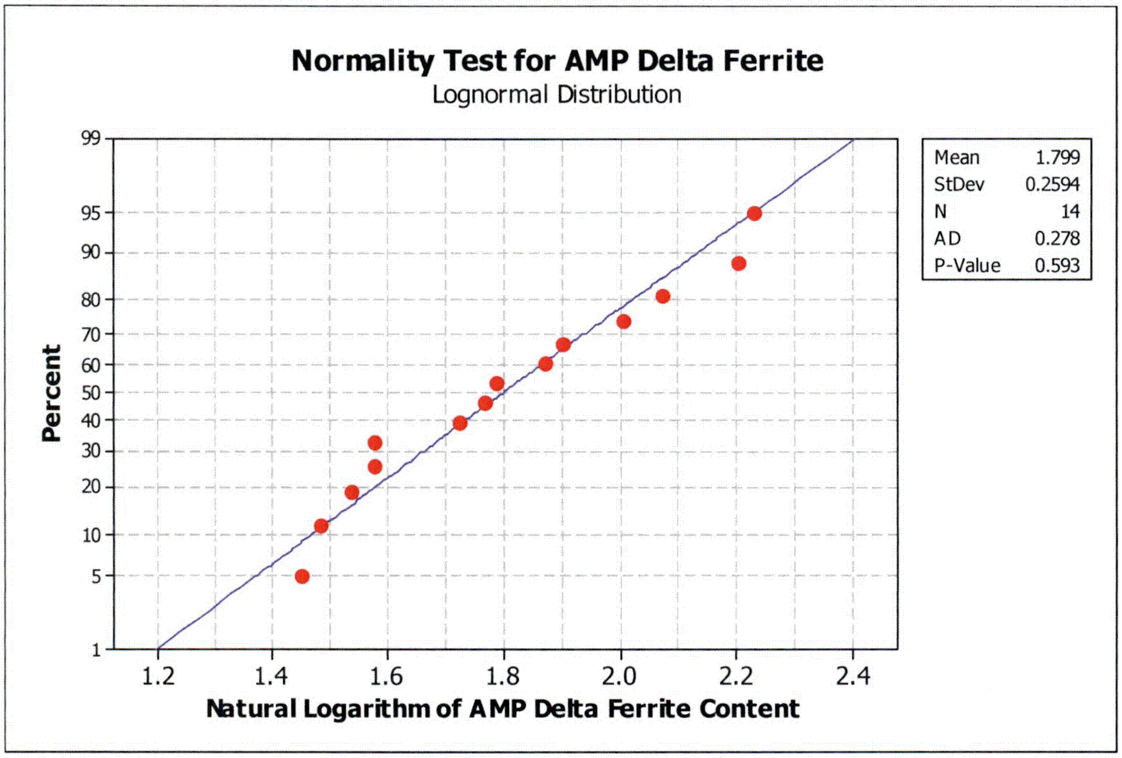

Figure A-3. Normality Test for AMP Delta Ferrite Content

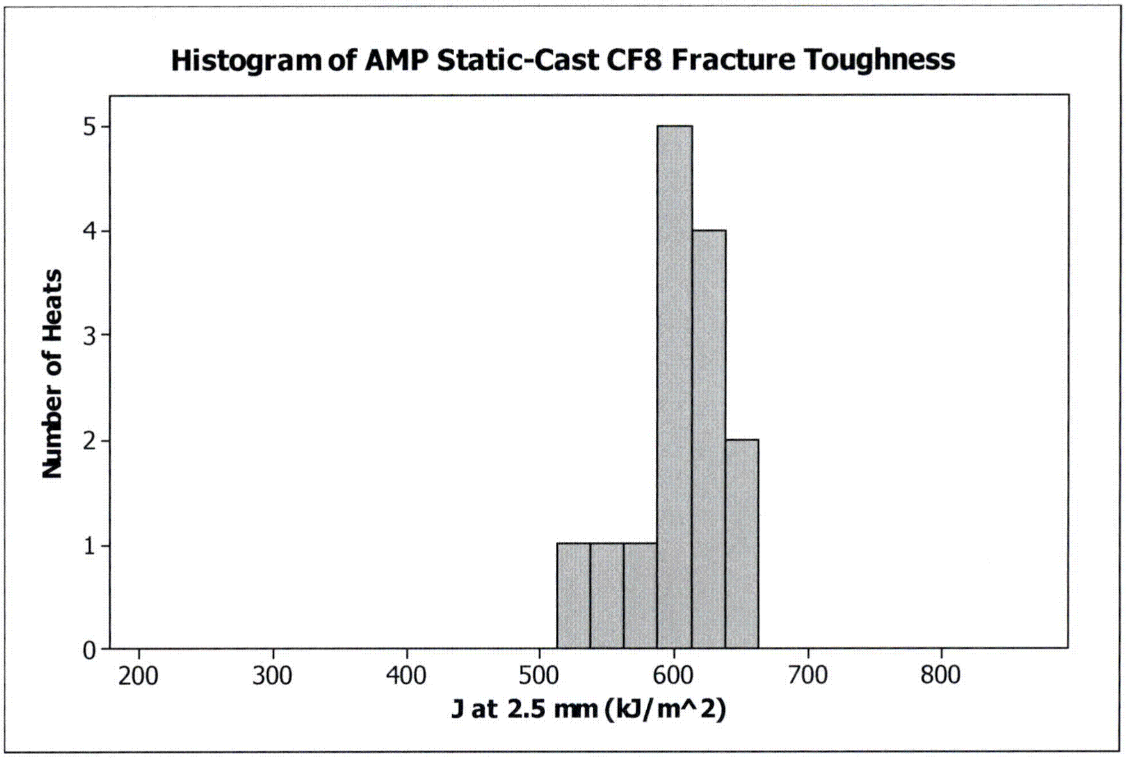

Figure A-4. Histogram of AMP Fracture Toughness

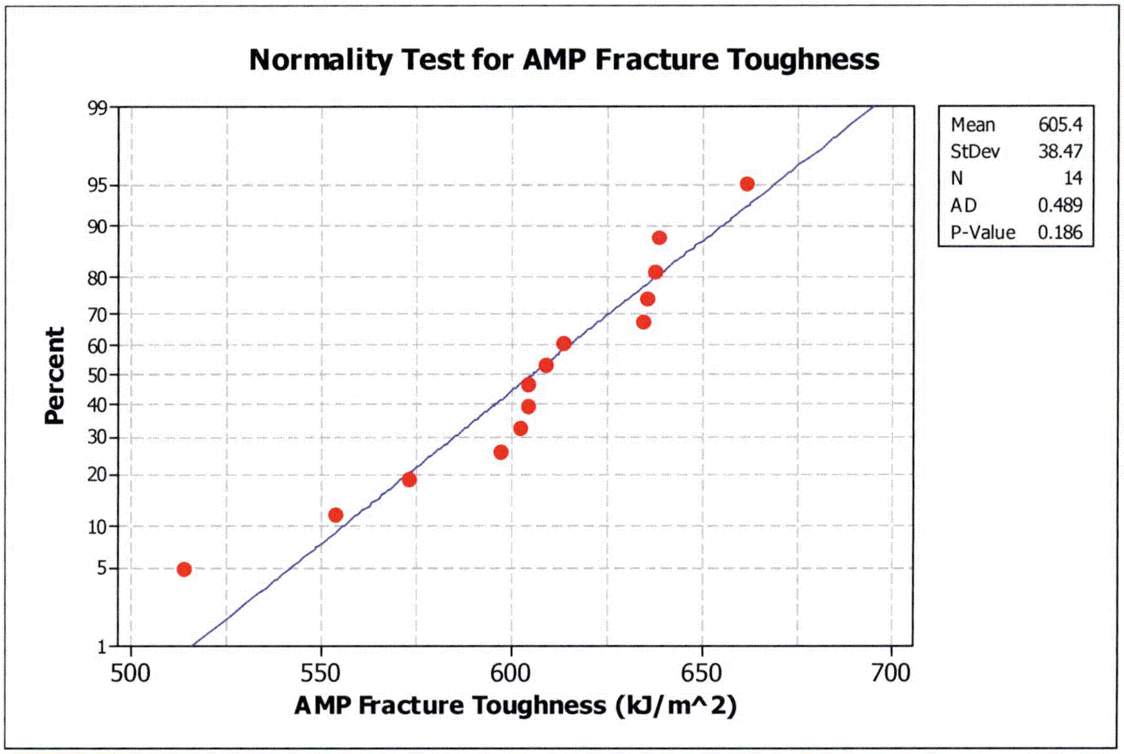

Figure A-5. Normality Test for AMP Fracture Toughness

A.2 CSF

Canadian Steel Foundries (CSF) provided CASS lower support castings and upper support castings for Westinghouse-designed plants. CMTR data were available for 15 individual heats of material supplied by CSF. The CSF-supplied CASS RV internals were all fabricated from low-molybdenum Grade CF8 material. Data for this manufacturer includes heats made from 1970 to 1971, see Figure A-6.

The distribution of ferrite content for components fabricated by CSF is shown in Figure A-7, with the accompanying normality test in Figure A-8. A normal distribution was used to model the CSF delta ferrite distribution; the calculated p value (0.265) associated with applying the normal distribution passes the acceptance criterion. Figure A-7 shows that there are no heats of material produced by CSF that exceed 20 percent, and only one heat that exceeds 15 percent ferrite content as estimated via Hull's factors. The average ferrite content for CSF materials is 10.0 percent, and the standard deviation is 3.7 percent. The 95/95 limit for ferrite content for CSF is 19.3 percent.

Figure A-9 shows the fracture toughness distribution for material heats made by CSF, and Figure A-10 is the normality test associated with that distribution. A normal distribution was used to model the CSF saturated fracture toughness distribution; the calculated p value (0.871) associated with applying the normal distribution passes the acceptance criterion. The average saturated fracture toughness for CSF-supplied materials is 504 kJ/m^2 and the standard deviation is 54.5 kJ/m^2. The 95/95 bound for fracture toughness for CSF is 364 kJ/m^2. Thus, it can be stated with a high degree of confidence that no components fabricated by CSF will have a saturated fracture toughness below 255 kJ/m^2.

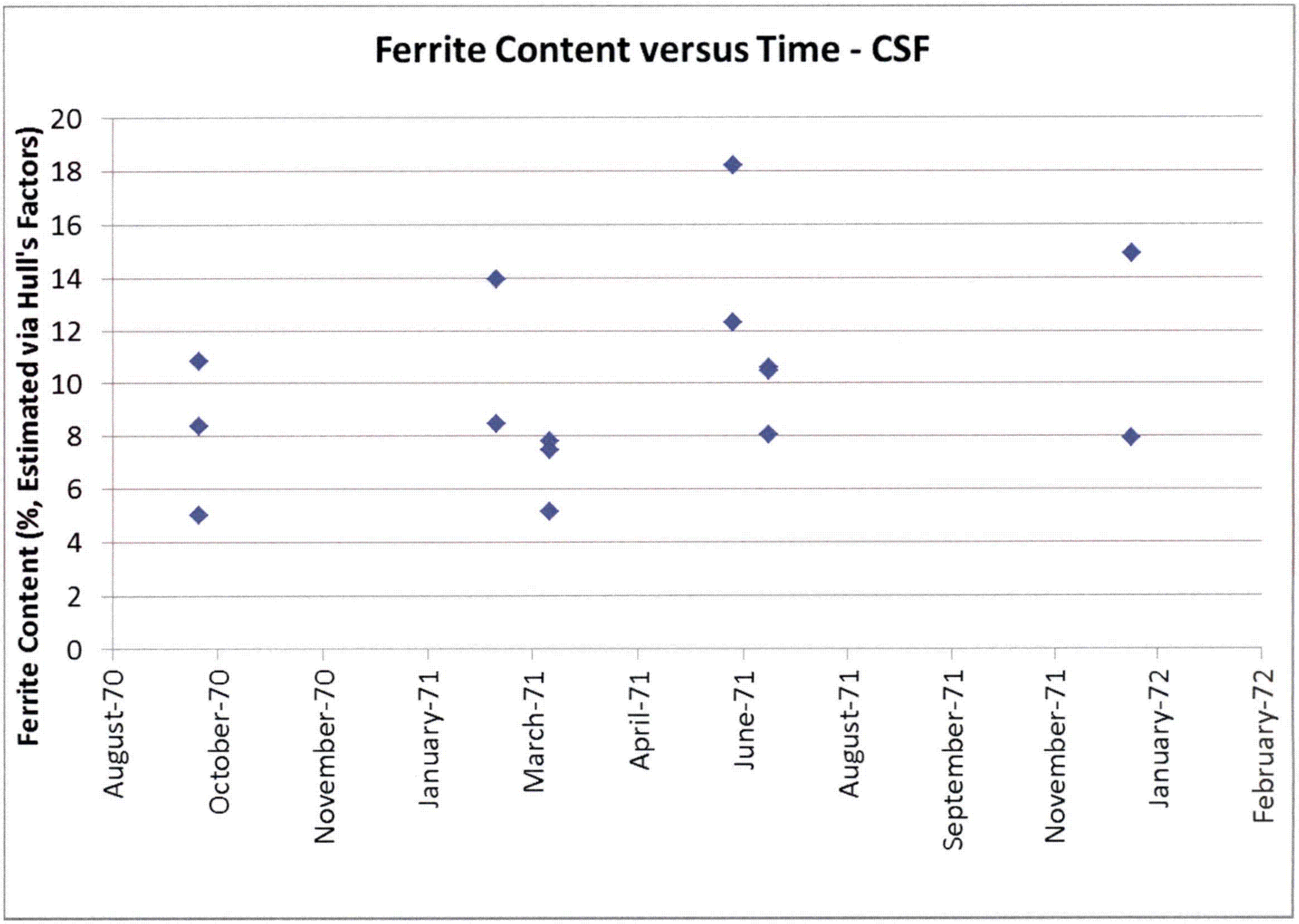

Figure A-6. Ferrite Content over Time - CSF

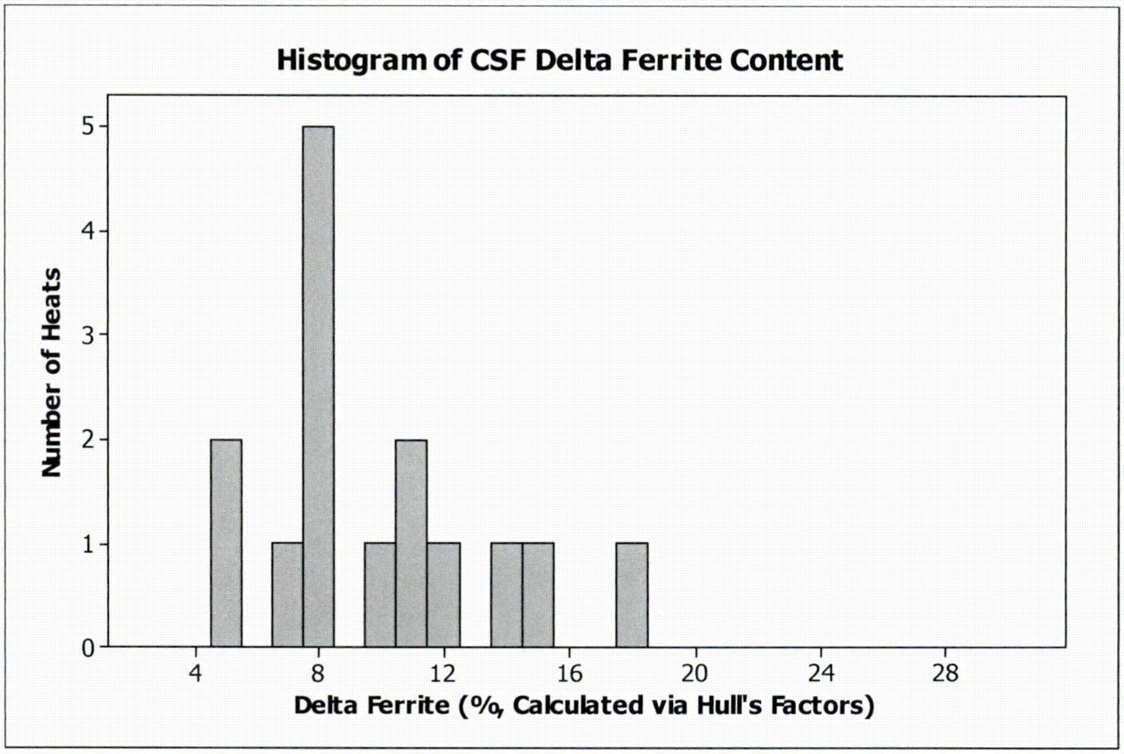

Figure A-7. Histogram of CSF Delta Ferrite Content

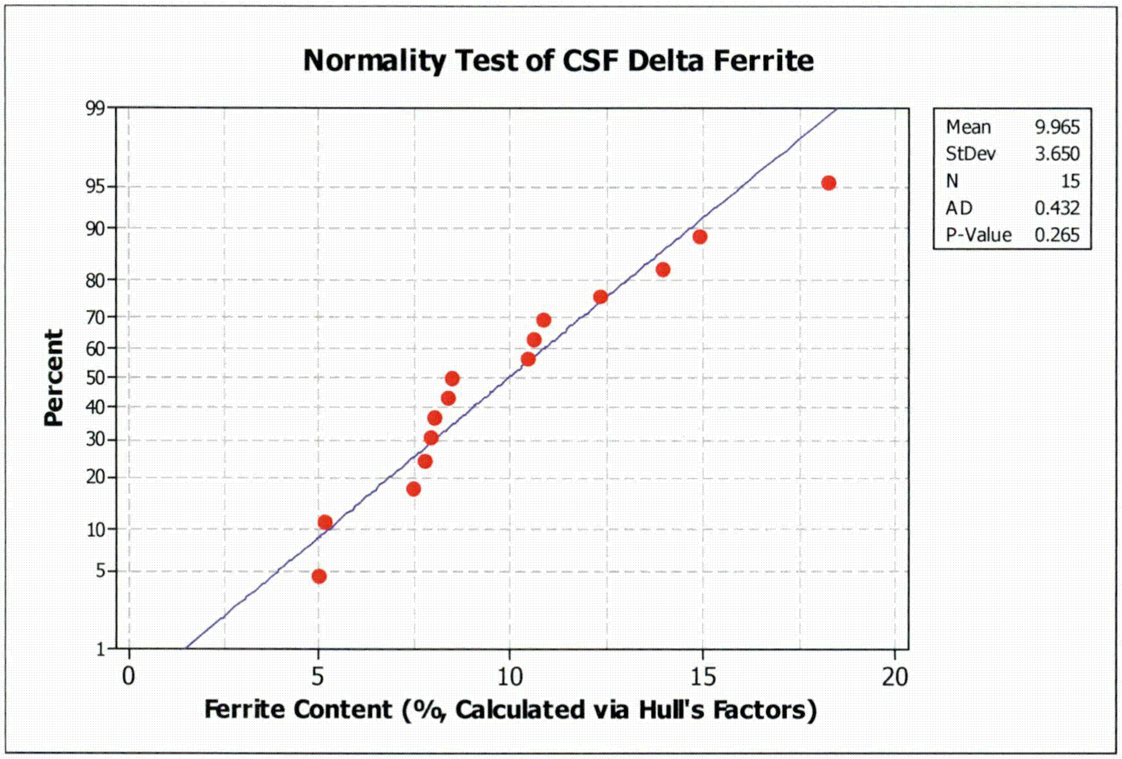

Figure A-8. Normality Test for CSF Delta Ferrite Content

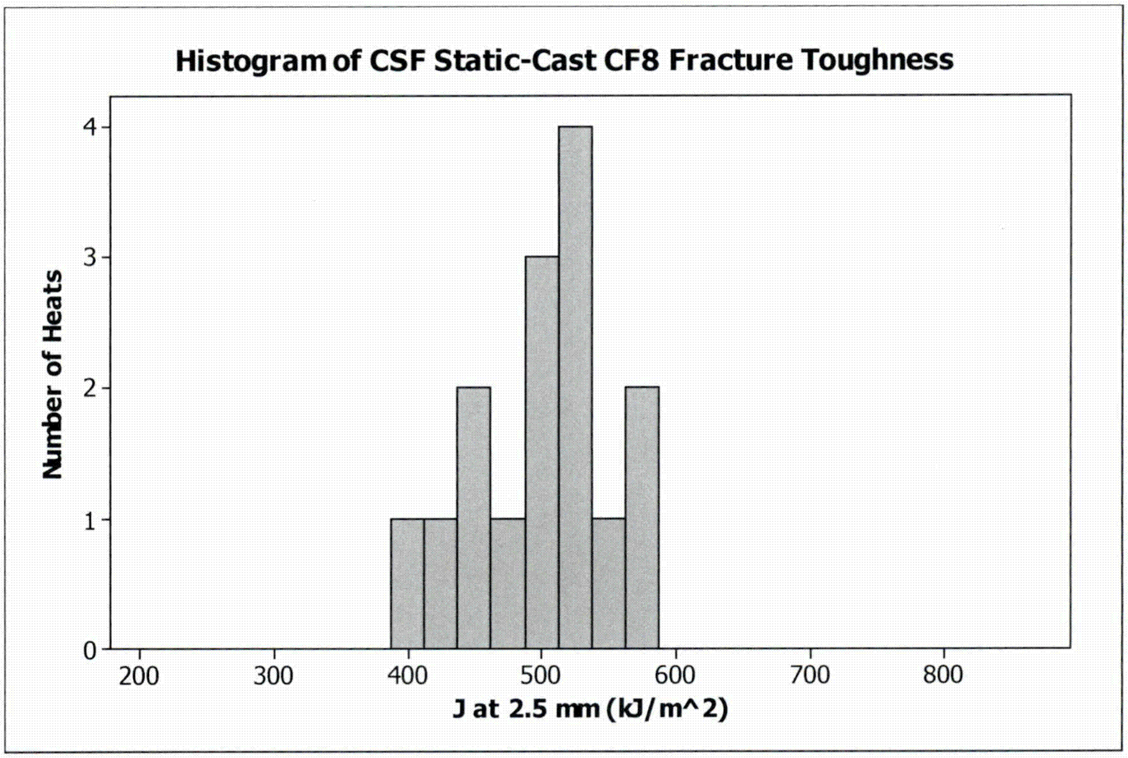

Figure A-9. Histogram of CSF Fracture Toughness

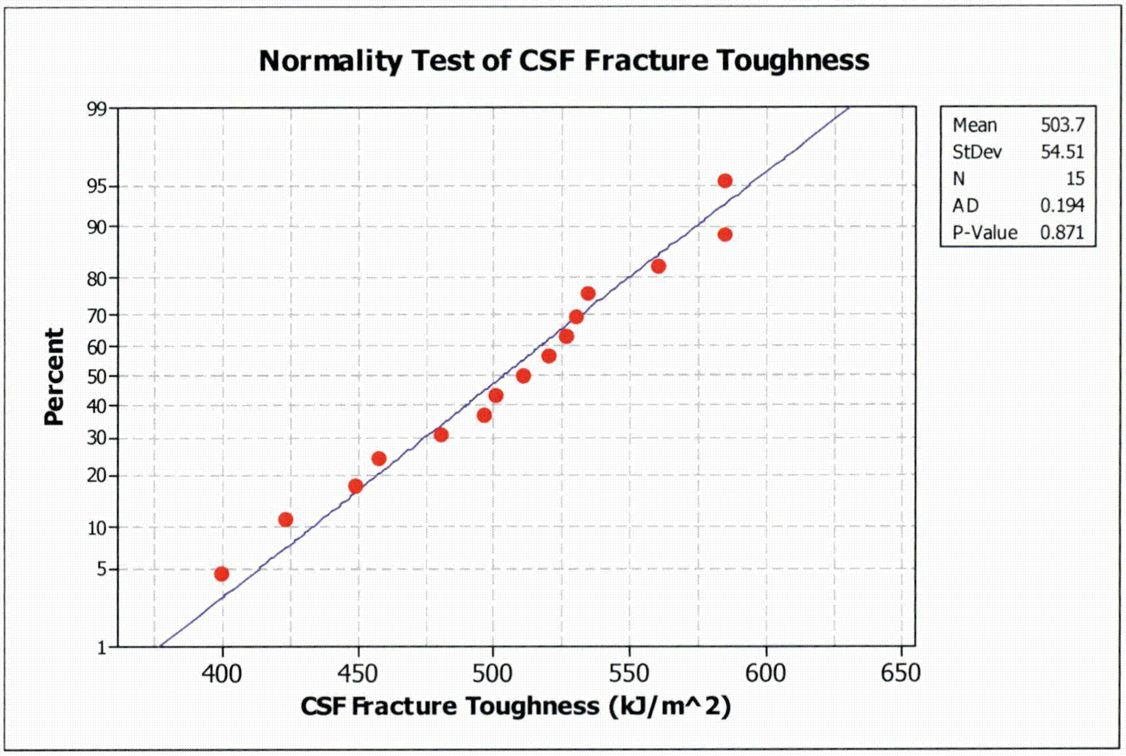

Figure A-10. Normality Test for CSF Fracture Toughness

A.3 ESCO

The Esco Corporation (Esco) provided CASS lower support castings for Westinghouse-designed plants as well as components for B&W plants. CMTR data were available for 23 individual heats of material supplied by Esco. The Esco-supplied CASS RV internals were all fabricated from low-molybdenum Grade CF8 material. Esco provided CASS RV internals components from 1965 to 1970; however, there was not enough readily available information on the dates of manufacture to generate a meaningful distribution of ferrite content over time.

The distribution of ferrite content for components fabricated by Esco is shown in Figure A-11, with the accompanying normality test in Figure A-12. A normal distribution was used to model the Esco delta ferrite distribution; the calculated p value (0.798) associated with applying the normal distribution passes the acceptance criterion. Figure A-11 shows that there are no heats of material produced by Esco that exceed 20 percent, and there are three heats that exceed 15 percent ferrite content as estimated via Hull's factors. The average ferrite content for Esco materials is 10.7 percent, and the standard deviation is 3.3 percent. The 95/95 limit for ferrite content for Esco is 18.4 percent.

Figure A-13 shows the fracture toughness distribution for material heats made by Esco, and Figure A-14 is the normality test associated with that distribution. A normal distribution was used to model the Esco saturated fracture toughness distribution. The calculated p value (0.037) associated with applying the normal distribution does not pass the acceptance criterion, however it provides a reasonable and conservative fit to the data. The average saturated fracture toughness for Esco-supplied materials is 524 kJ/m^2 and the standard deviation is 54.4 kJ/m^2. The 95/95 bound for fracture toughness for Esco is 397 kJ/m^2. Thus, it can be stated with a high degree of confidence that no components fabricated by Esco will have a saturated fracture toughness below 255 kJ/m^2.

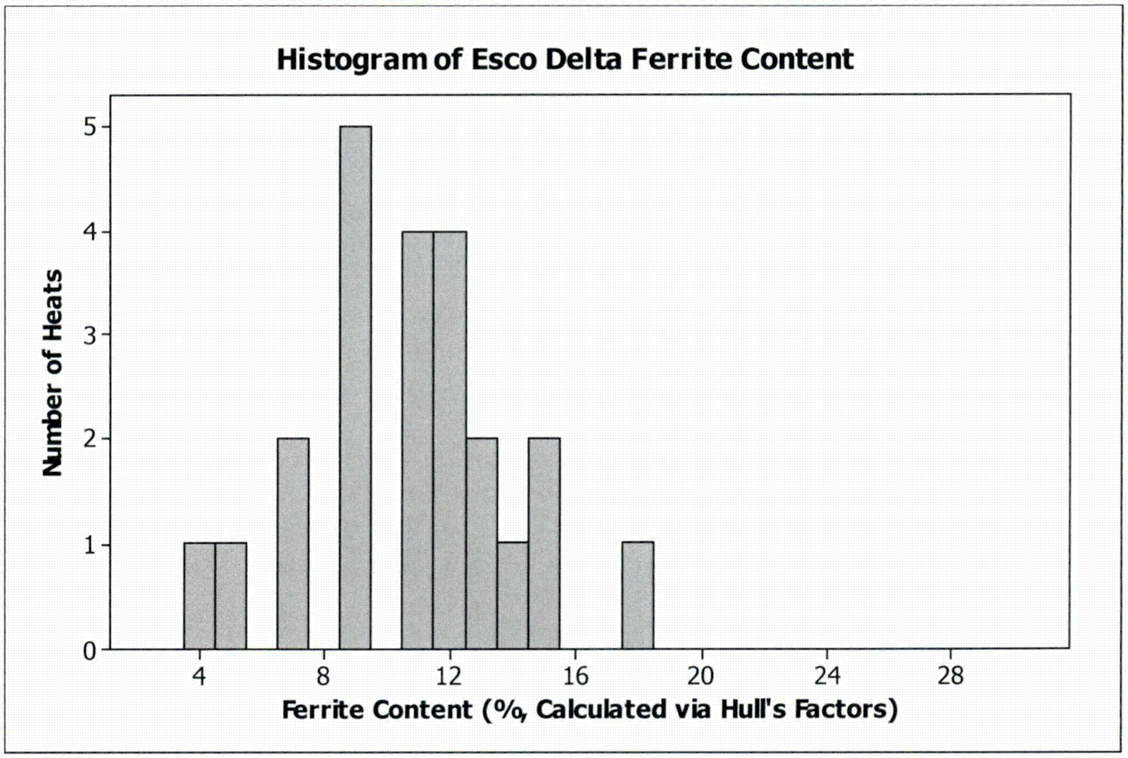

Figure A-11. Histogram of Esco Delta Ferrite Content

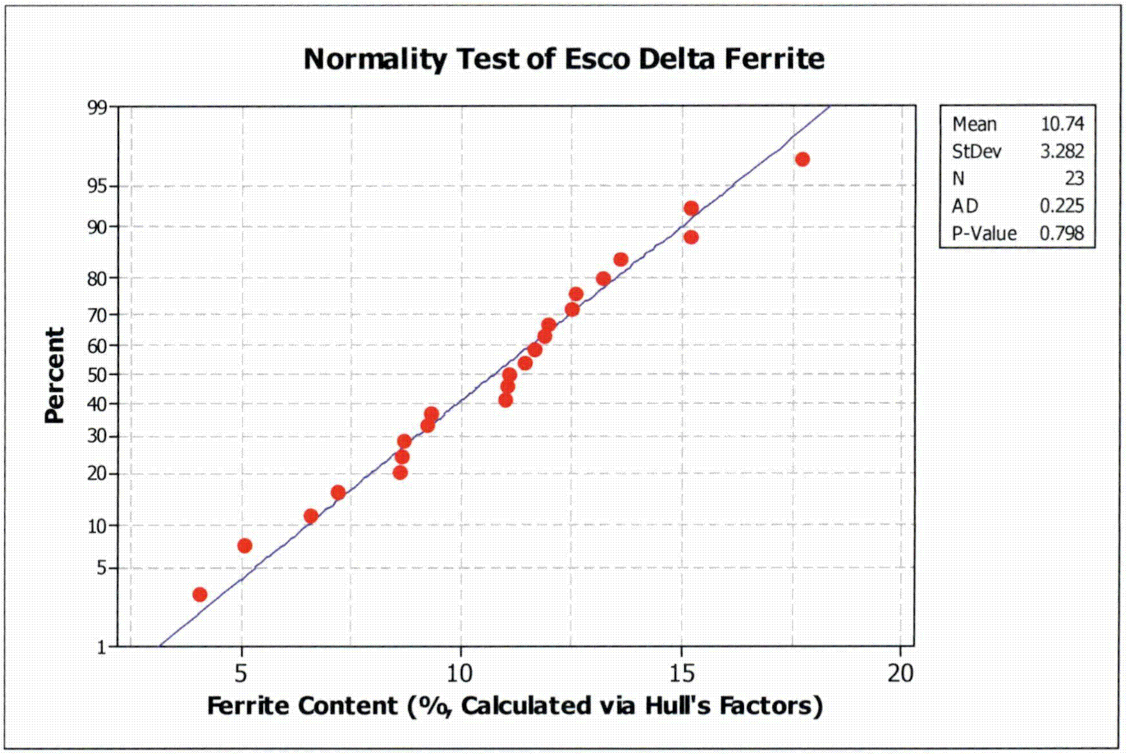

Figure A-12. Normality Test for Esco Delta Ferrite Content

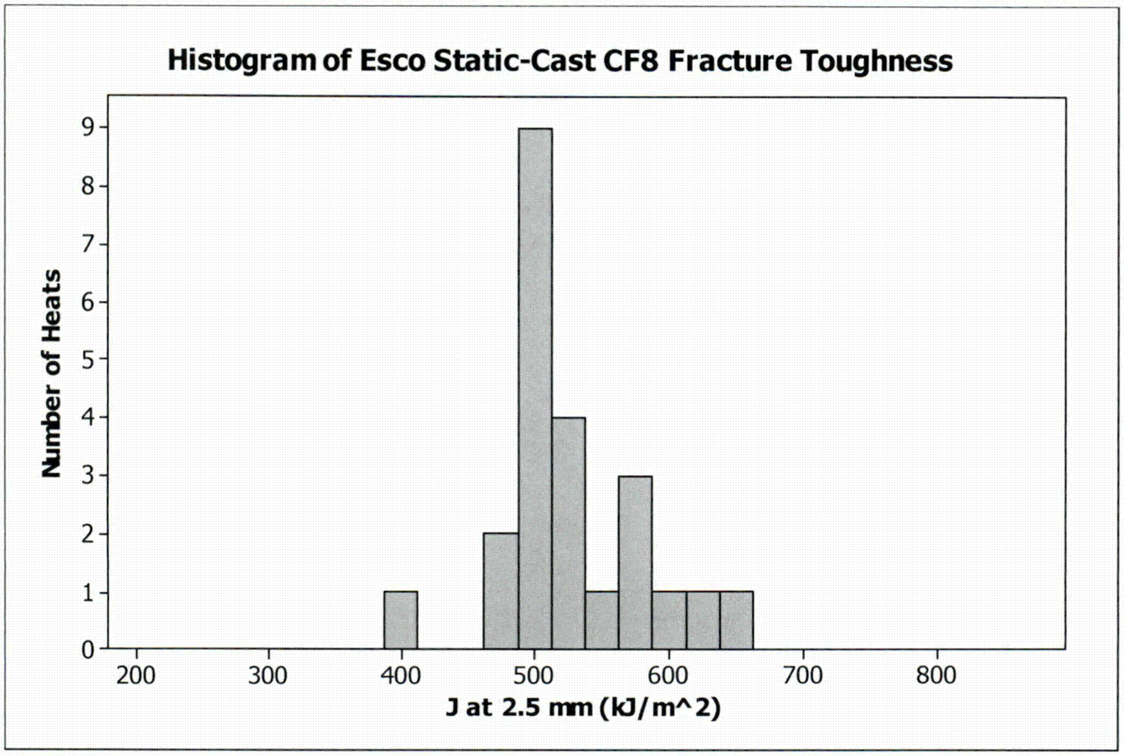

Figure A-13. Histogram of Esco Fracture Toughness

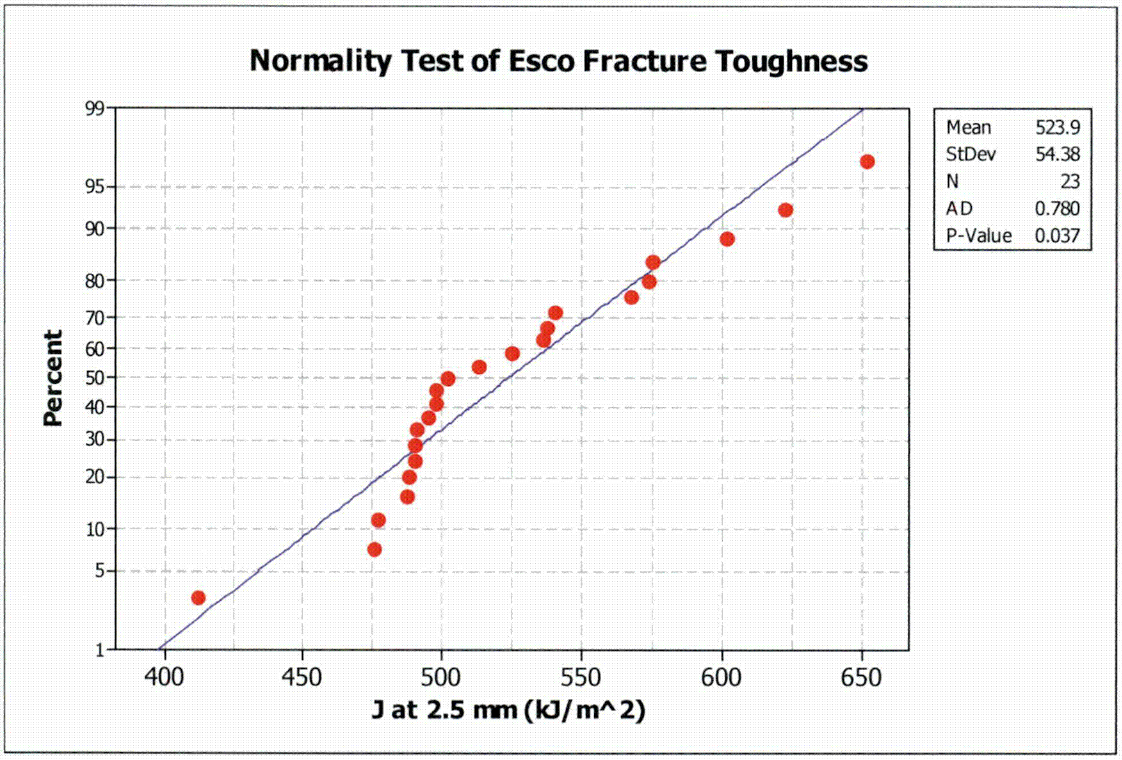

Figure A-14. Normality Test for Esco Fracture Toughness

A.4 HITCHINER

Hitchiner provided modified CEA shroud extension shaft guides for CE-designed plants. These components were fabricated from low-molybdenum Grade CF8.

Only two CMTRs were available from Hitchiner, so it is difficult to determine any meaningful statistical parameters for this manufacturer. The available manufacturing information is summarized in Table A-1. Both heats have low delta ferrite and correspondingly high fracture toughness.

Table A-1 Hitchiner Manufacturing Information

	Delta Ferrite (%)	Fracture Toughness J at 2.5 mm (kJ/m^2)
Heat 1	7.3	549
Heat 2	6.6	562
Average	6.9	555
Standard Deviation	0.5	9.6

A.5 ICC

Investment Casting Company (ICC) provided orifice base castings for Westinghouse-designed plants. These components were fabricated from low-molybdenum Grade CF8.

Only two CMTRs were available from ICC, and so it is difficult to determine any meaningful statistical parameters for this manufacturer. The available manufacturing information is summarized in Table A-2. Both heats have low delta ferrite, and correspondingly high fracture toughness.

Table A-2 ICC Manufacturing Information

	Delta Ferrite (%)	Fracture Toughness J at 2.5 mm (kJ/m^2)
Heat 1	4.12	650
Heat 2	2.49	653
Average	3.3	652
Standard Deviation	1.2	1.6

A.6 KEARSARGE

Kearsarge provided numerous components for Westinghouse and CE plants, as shown in Figure A-16. The Kearsarge-supplied CASS RV internals were all fabricated from low-molybdenum Grade CF8 material using both static and centrifugal casting methods. CMTR data were available for 498 individual heats of static-cast material and 90 heats of centrifugally-cast material supplied by Kearsarge. Kearsarge provided CASS RV internals components from 1969 to 1977, see Figure A-15.

The distribution of ferrite content for centrifugally-cast components fabricated by Kearsarge is shown in Figure A-17, with the accompanying normality test in Figure A-18. A lognormal distribution was used to model the Kearsarge ferrite content distribution for centrifugally-cast material. The calculated p value (0.038) associated with applying the lognormal distribution does not pass the acceptance criterion, however the use of a lognormal distribution to model the dataset was judged to be appropriate as this fit provided the lowest A-D parameter. The centrifugally-cast components provided by Kearsarge were all UHI flow column bases.

The distribution of ferrite content for static-cast components fabricated by Kearsarge is shown in Figure A-19, with the accompanying normality test in Figure A-20. A lognormal distribution was used to model the Kearsarge ferrite content distribution for statically-cast material. The calculated p value (0.326) associated with applying the lognormal distribution passes the acceptance criterion. Figure A-21 shows the ferrite content distribution for static-cast material separated by component.

Figure A-17 and Figure A-19 show that there are no heats of material produced by Kearsarge that exceed 15 percent ferrite content as estimated via Hull's factors. The average ferrite content for centrifugally-cast Kearsarge materials is 5.5 percent, and the standard deviation is 1.4 percent. The 95/95 limit for ferrite content for centrifugally-cast Kearsarge materials is 8.3 percent. The average ferrite content for static-cast Kearsarge materials is 6.2 percent, and the standard deviation is 1.7 percent. The 95/95 limit for ferrite content for static-cast Kearsarge materials is 9.7 percent.

The ferrite content distributions for the static-cast and centrifugally-cast materials are observed to be very similar in mean and standard deviation. It is possible that Kearsarge used essentially the same alloy composition for both the static and centrifugal casting process. The UHI flow column bases were made by both processes at different time periods, so there may have been some overlap in materials resulting from that change as well.

Figure A-22 shows the fracture toughness distribution for centrifugally-cast material heats made by Kearsarge, and Figure A-23 is the normality test associated with that distribution. A normal distribution was used to model the Kearsarge saturated fracture toughness distribution for centrifugally-cast materials. The calculated p value (<0.005) associated with applying the normal distribution does not pass the acceptance criterion, however it provides a reasonable and conservative fit to the data. The average saturated fracture toughness for centrifugally-cast Kearsarge-supplied materials is 799 kJ/m^2 and the standard deviation is 44.9 kJ/m^2.

Figure A-24 shows the fracture toughness distribution for static-cast material heats made by Kearsarge, and Figure A-25 is the normality test associated with that distribution. A normal distribution was used to model the Kearsarge saturated fracture toughness distribution for statically-cast materials. The calculated p value (<0.005) associated with applying the normal distribution does not pass the acceptance criterion, however it provides a reasonable and conservative fit to the data. The average saturated fracture toughness for static-cast Kearsarge-supplied materials is 592 kJ/m^2 and the standard deviation is 36.8 kJ/m^2.

The 95/95 bound for fracture toughness for centrifugally-cast Kearsarge material is 711 kJ/m^2. The 95/95 bound for fracture toughness for static-cast Kearsarge material is 527 kJ/m^2. Thus, it can be stated with a high degree of confidence that no components fabricated by Kearsarge will have a saturated fracture toughness below 255 kJ/m^2.

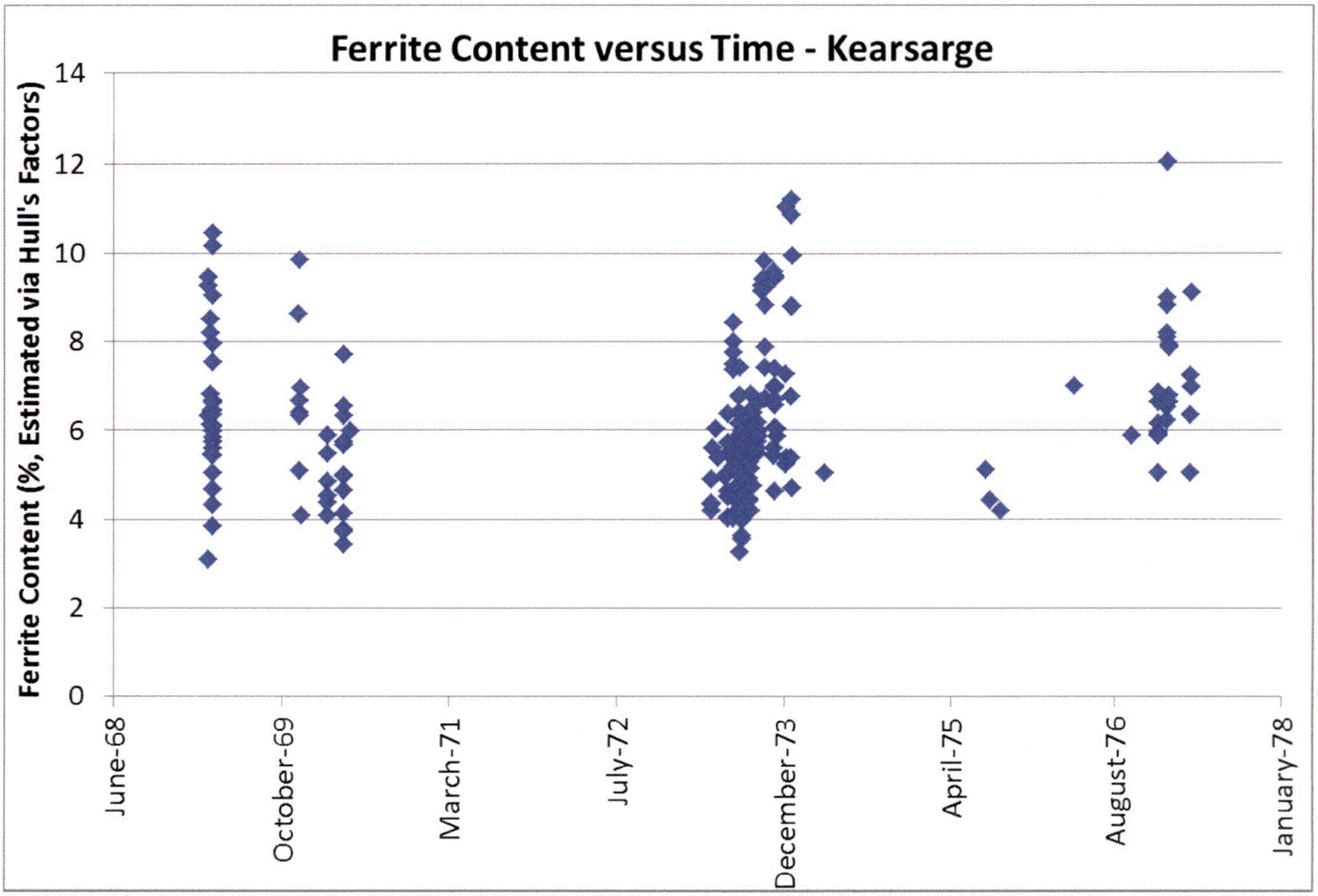

Figure A-15. Ferrite Content over Time - Kearsarge

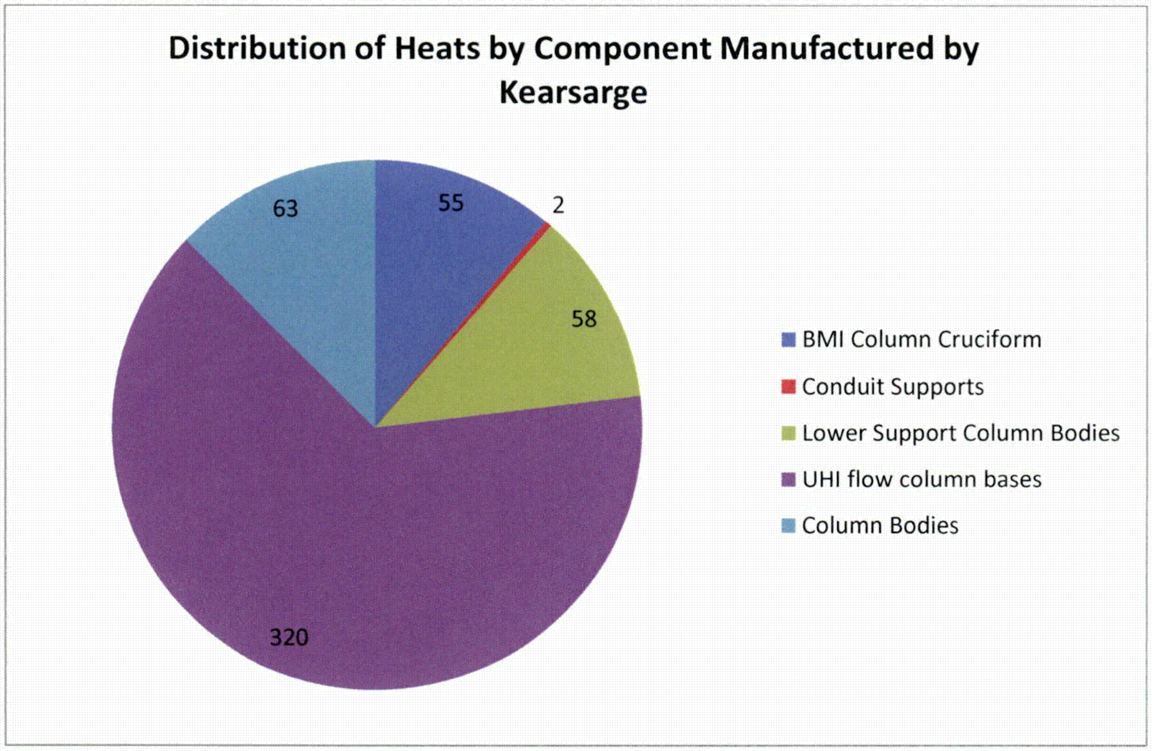

Figure A-16. Static-Cast Components Provided by Kearsarge

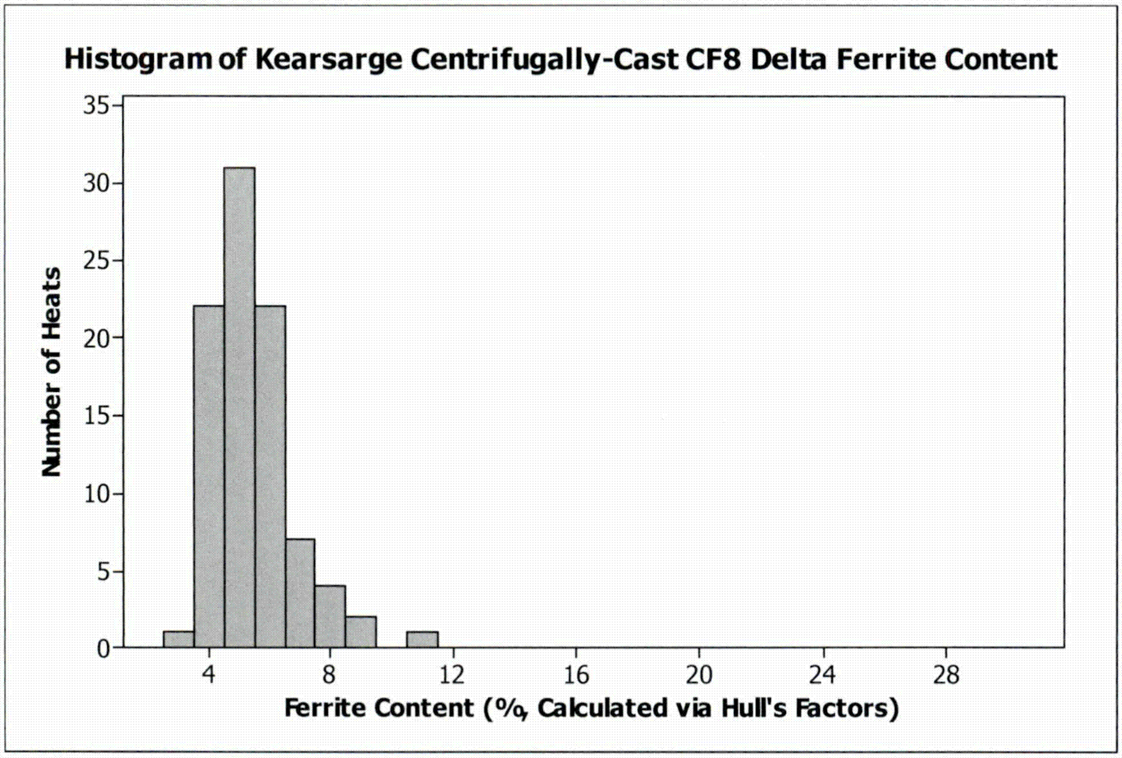

Figure A-17. Histogram of Kearsarge Delta Ferrite Content (Centrifugally-Cast CF8)

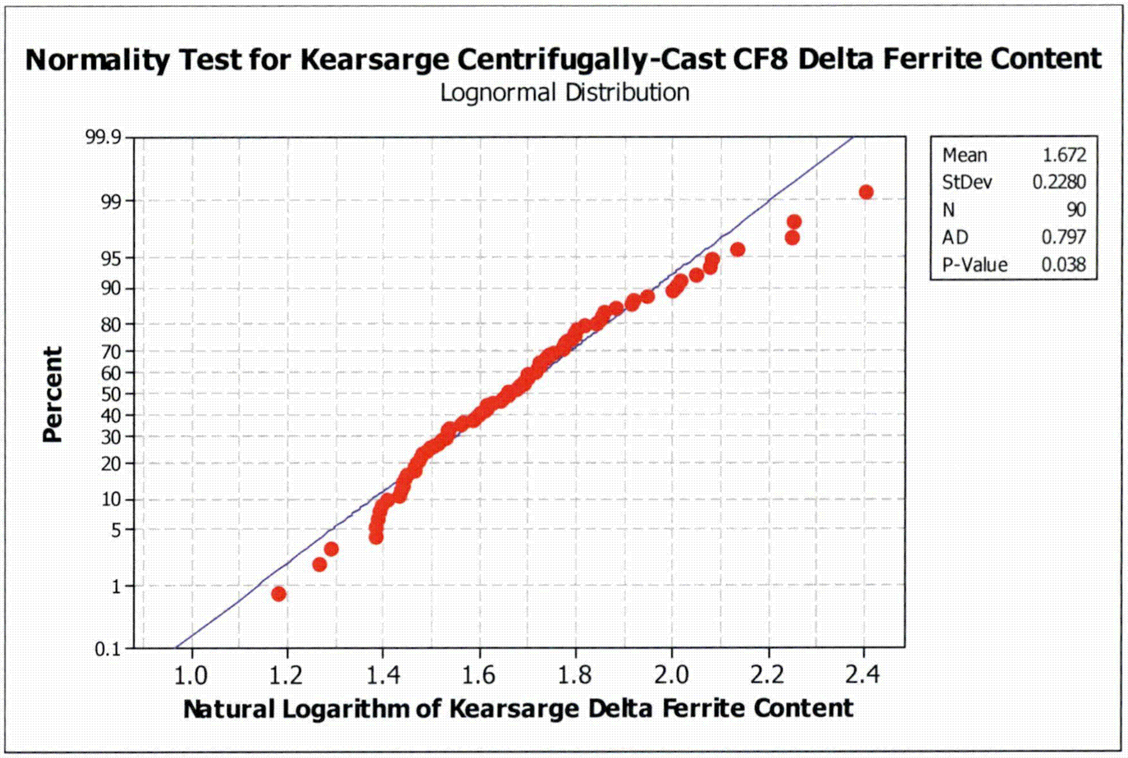

Figure A-18. Normality Test for Kearsarge Delta Ferrite Content (Centrifugally-Cast CF8)

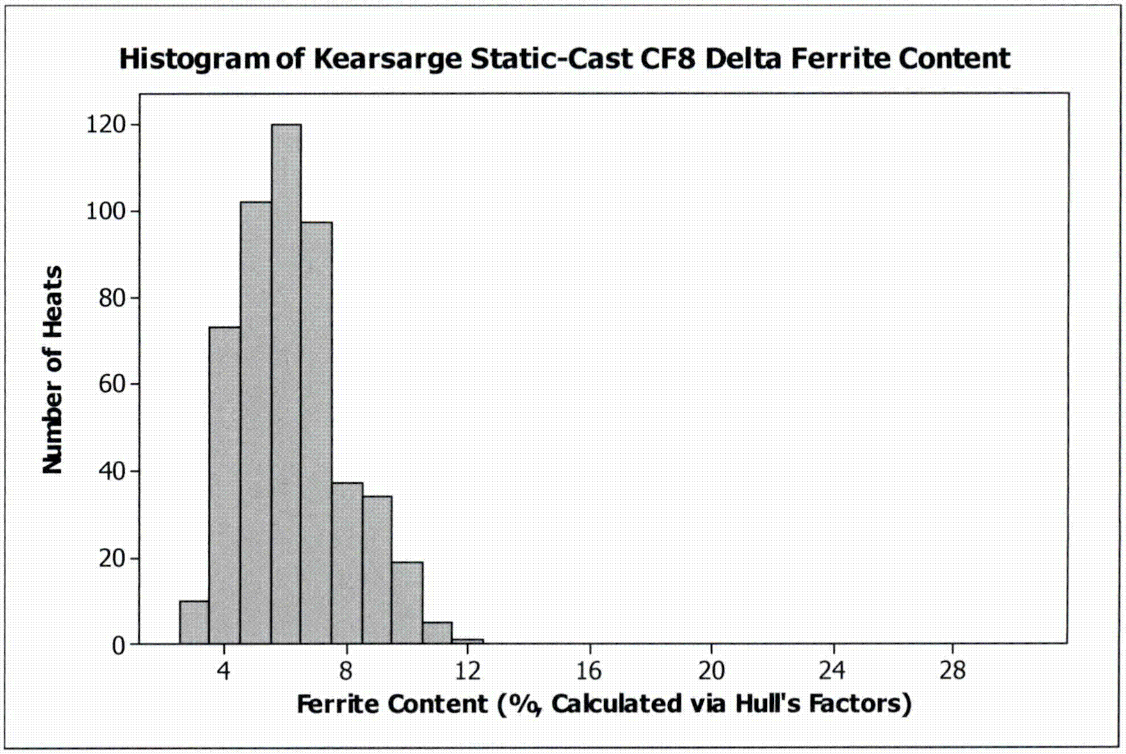

Figure A-19. Histogram of Kearsarge Delta Ferrite Content (Static-Cast CF8)

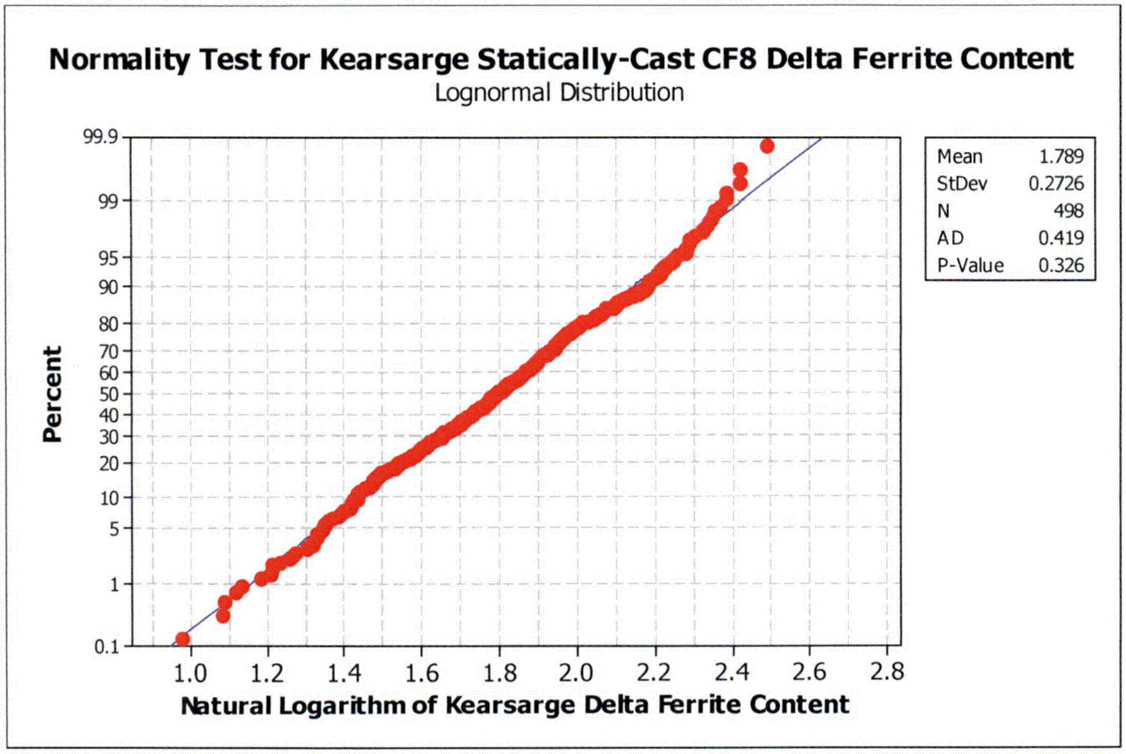

Figure A-20. Normality Test for Kearsarge Delta Ferrite Content (Static-Cast CF8)

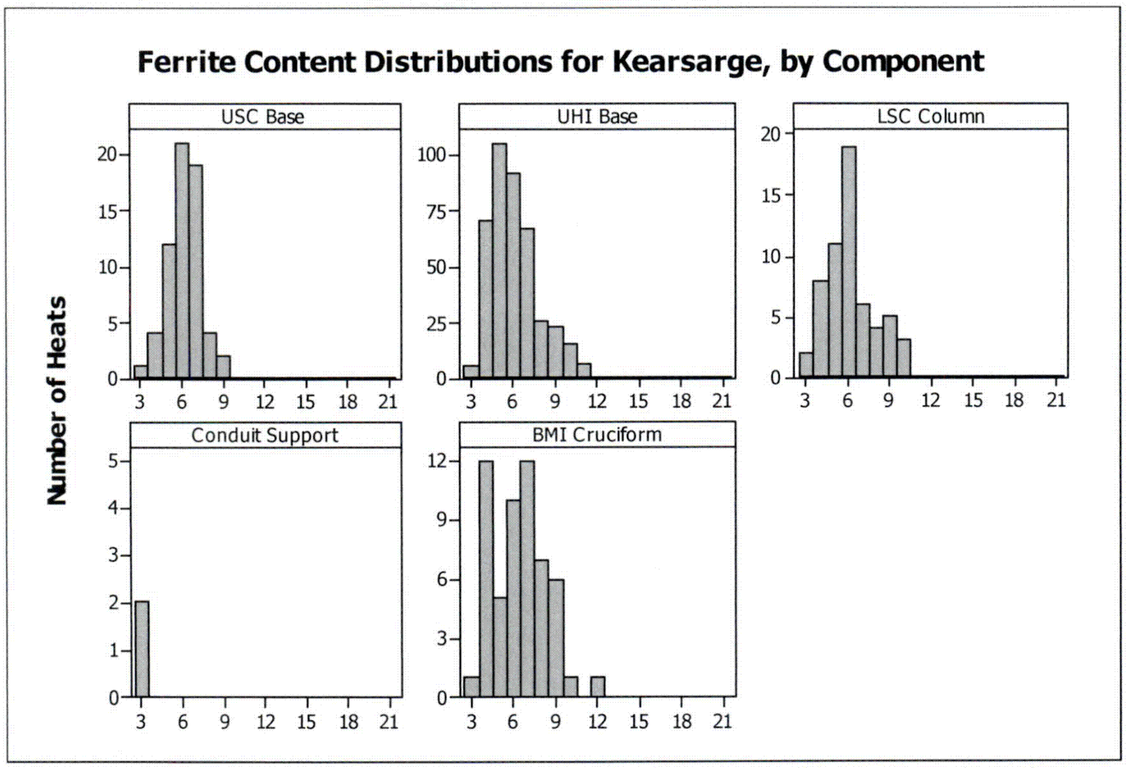

Figure A-21. Ferrite Content Distributions by Component Manufactured by Kearsarge

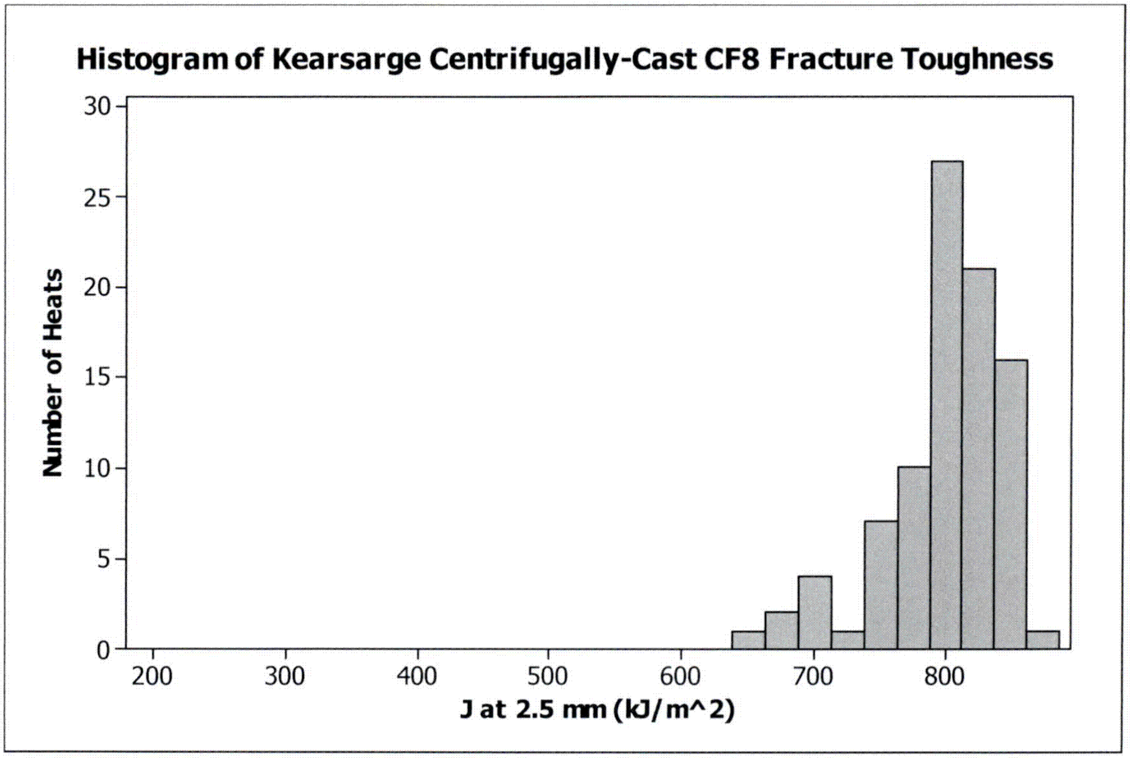

Figure A-22. Histogram of Kearsarge Fracture Toughness (Centrifugally-Cast CF8)

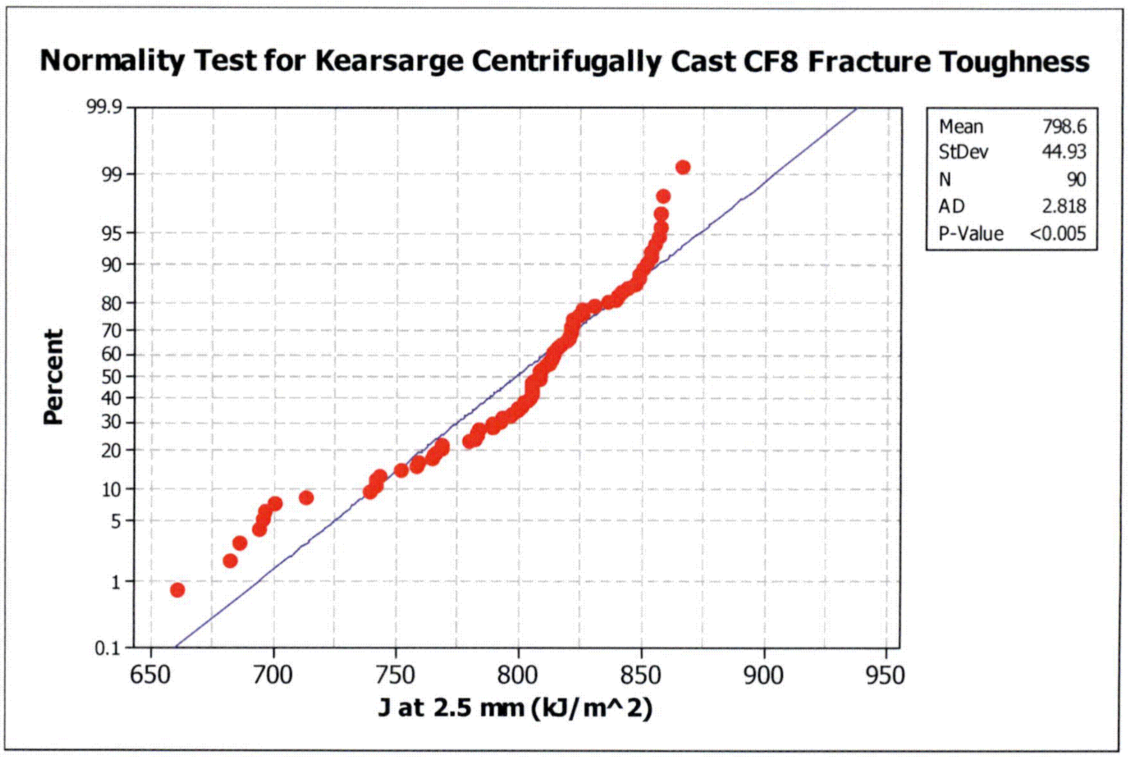

Figure A-23. Normality Test for Kearsarge Fracture Toughness (Centrifugally-Cast CF8)

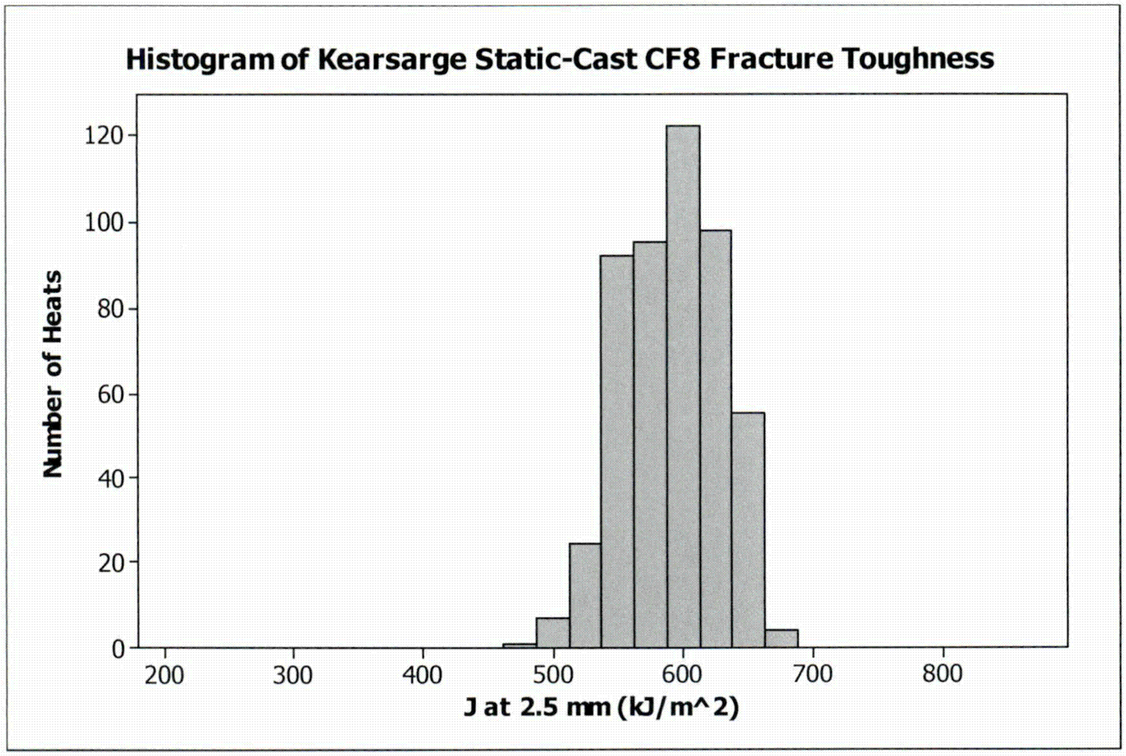

Figure A-24. Histogram of Kearsarge Fracture Toughness (Static-Cast CF8)

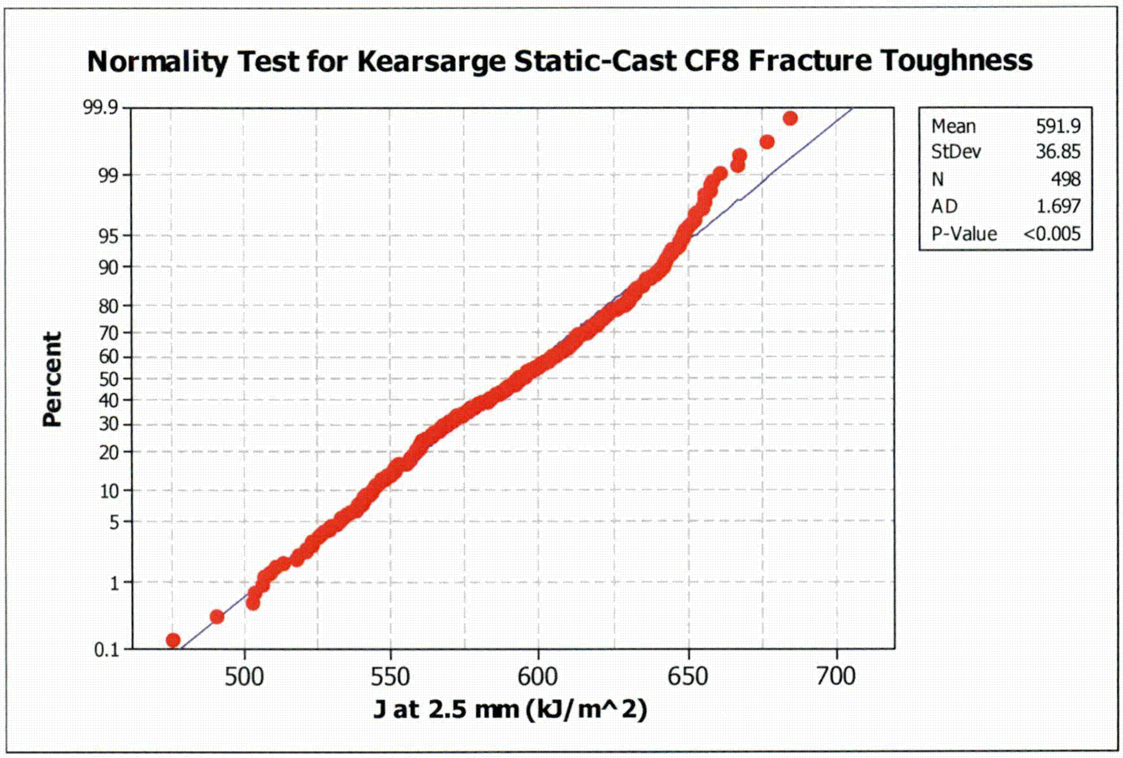

Figure A-25. Normality Test for Kearsarge Fracture Toughness (Static-Cast CF8)

A.7 PFA

The P.F. Avery Corporation (PFA) provided flow bypass inserts for CE-designed plants. These components were fabricated from low-molybdenum Grade CF8.

Only two CMTRs were available from PFA, so it is difficult to determine any meaningful statistical parameters for this manufacturer. The available manufacturing information is summarized in Table A-3. Both heats have low delta ferrite, and correspondingly high fracture toughness. The CMTRs for PFA-supplied material included both product and ladle analyses of the chemical composition and both are separately used to calculate ferrite contents and fracture toughnesses.

Table A-3 PFA Manufacturing Information

	Product Analysis		Ladle Analysis	
	Delta Ferrite (%)	Fracture Toughness J at 2.5 mm (kJ/m^2)	Delta Ferrite (%)	Fracture Toughness J at 2.5 mm (kJ/m^2)
Heat 1	10.1	553	9.6	565
Heat 2	11.0	608	10.5	615
Average	10.6	580	10	590
Standard Deviation	0.6	39.2	0.6	35.5

A.8 PF

Precision Founders (PF) provided CASS BMI column cruciforms and conduit supports for Westinghouse-designed plants. CMTR data were available for 10 individual heats of material supplied by PF. The PF-supplied CASS RV internals were all fabricated from static-cast, low-molybdenum Grade CF8 material. PF provided CASS RV internals components in 1969 and from 1976 to 1978, as shown in Figure A-26.

The distribution of ferrite content for components fabricated by PF is shown in Figure A-27, with the accompanying normality test in Figure A-28. A normal distribution was used to model the PF ferrite content distribution. The calculated p value (0.526) associated with applying the normal distribution passes the acceptance criterion. Figure A-27 shows that there are no heats of material produced by PF that exceed 20 percent, and one heat that exceeds 15 percent ferrite content as estimated via Hull's factors. The average ferrite content for PF materials is 10.7 percent, and the standard deviation is 4.8 percent. The 95/95 limit for ferrite content for PF is 24.7 percent.

Figure A-29 shows the fracture toughness distribution for material heats made by PF, and Figure A-30 is the normality test associated with that distribution. A normal distribution was used to model the PF saturated fracture toughness distribution. The calculated p value (0.158) associated with applying the normal distribution passes the acceptance criterion. The average saturated fracture toughness for PF-supplied materials is 548 kJ/m^2 and the standard deviation is 63.3 kJ/m^2. The 95/95 bound for fracture toughness for PF is 364 kJ/m^2. Thus, it can be stated with a high degree of confidence that no components fabricated by PF will have a saturated fracture toughness below 255 kJ/m^2.

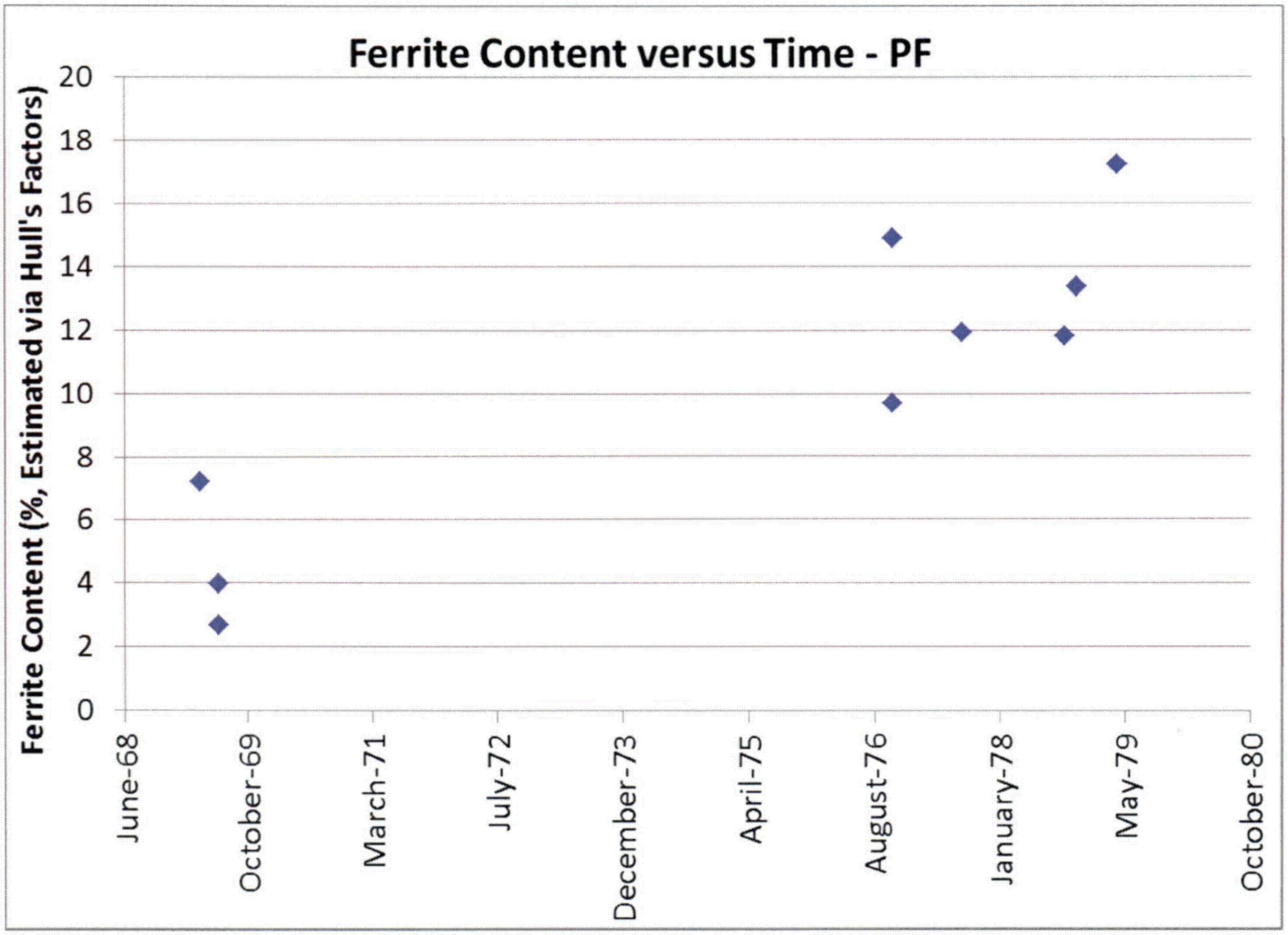

Figure A-26. Ferrite Content over Time - PF

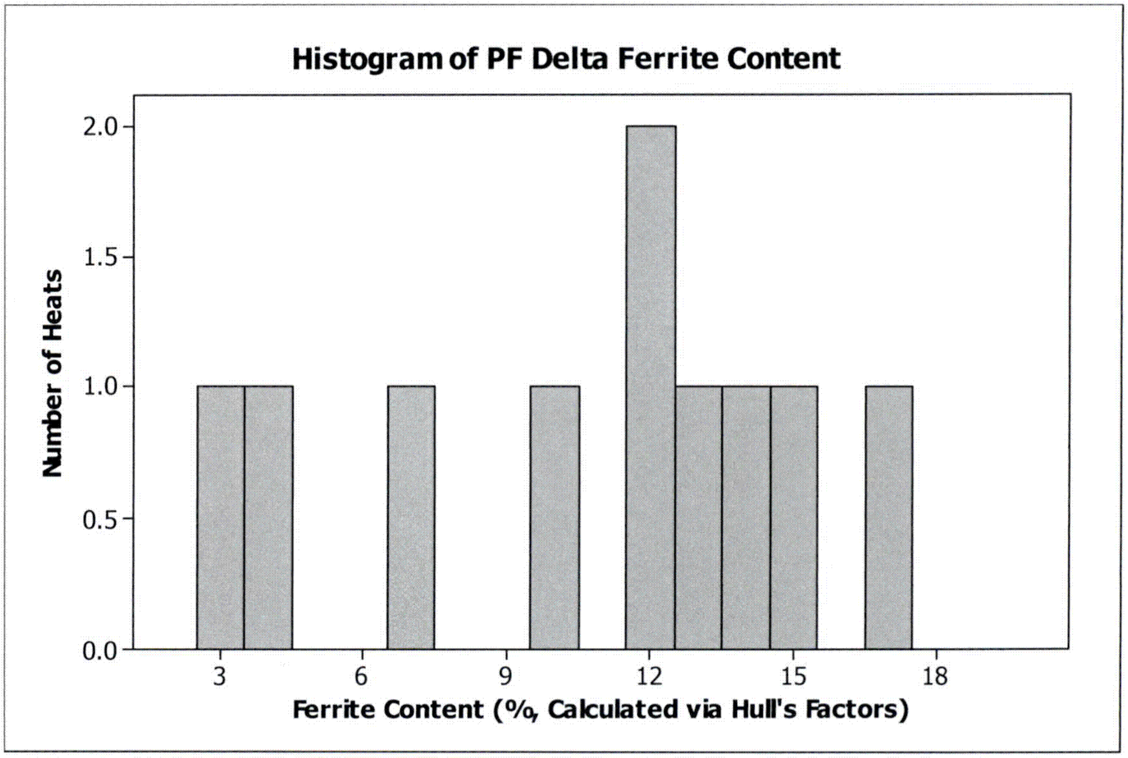

Figure A-27. Histogram of PF Delta Ferrite Content

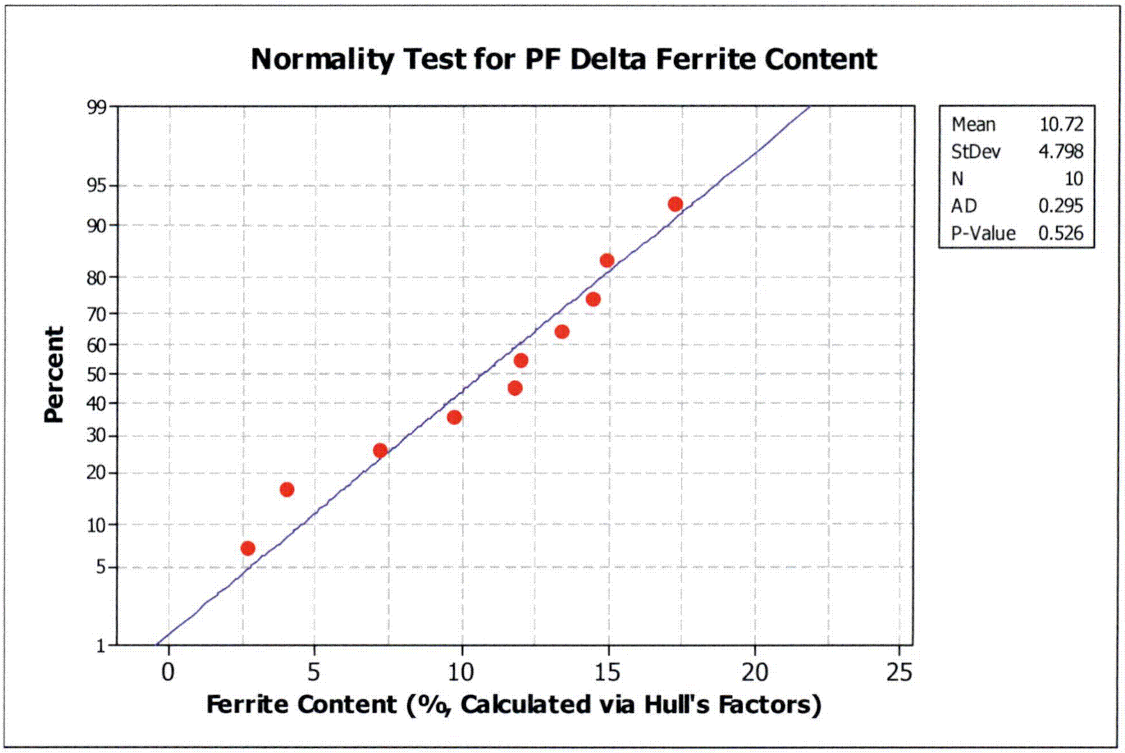

Figure A-28. Normality Test for PF Delta Ferrite Content

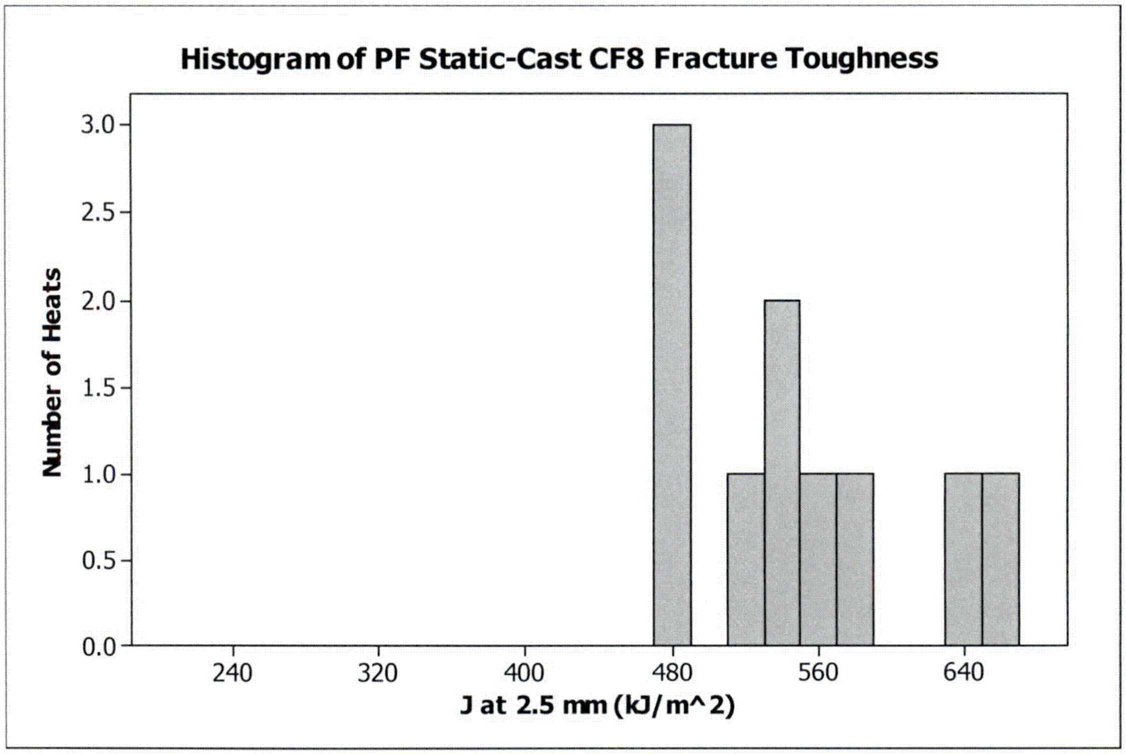

Figure A-29. Histogram of PF Fracture Toughness

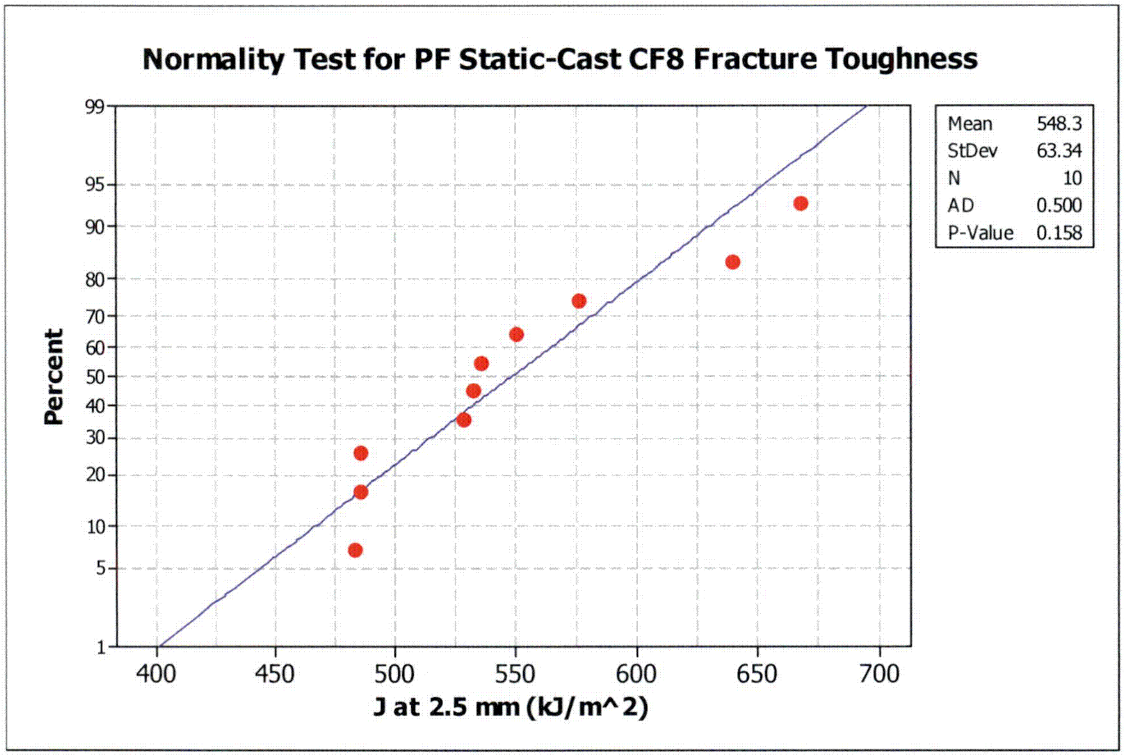

Figure A-30. Normality Test for PF Fracture Toughness

A.9 QACC

Quaker Alloy Casting Company (QACC) provided CASS RV internals components for B&W plants. CMTR data were available for 24 individual heats of material supplied by QACC. The QACC-supplied CASS RV internals were all fabricated from low-molybdenum Grade CF8 material. QACC provided CASS RV internals components from 1965 to 1970; however there was not enough readily available information on the dates of manufacture to generate a meaningful distribution of ferrite content over time.

The distribution of ferrite content for components fabricated by QACC is shown in Figure A-31, with the accompanying normality test in Figure A-32. A normal distribution was used to model the QACC ferrite content distribution. The calculated p value (0.866) associated with applying the normal distribution passes the acceptance criterion. Figure A-31 shows that there are no heats of material produced by QACC that exceed 20 percent and there are two heats that exceed 15 percent ferrite content, as estimated via Hull's factors. The average ferrite content for QACC materials is 9.4 percent, and the standard deviation is 4.0 percent. The 95/95 limit for ferrite content for QACC is 18.7 percent.

Figure A-33 shows the fracture toughness distribution for material heats made by QACC, and Figure A-34 is the normality test associated with that distribution. A normal distribution was used to model the QACC saturated fracture toughness distribution. The calculated p value (0.097) associated with applying the normal distribution passes the acceptance criterion. The average saturated fracture toughness for QACC-supplied materials is 545 kJ/m^2 and the standard deviation is 72.5 kJ/m^2. The 95/95 bound for fracture toughness for QACC is 378 kJ/m^2. Thus, it can be stated with a high degree of confidence that no components fabricated by QACC will have a saturated fracture toughness below 255 kJ/m^2.

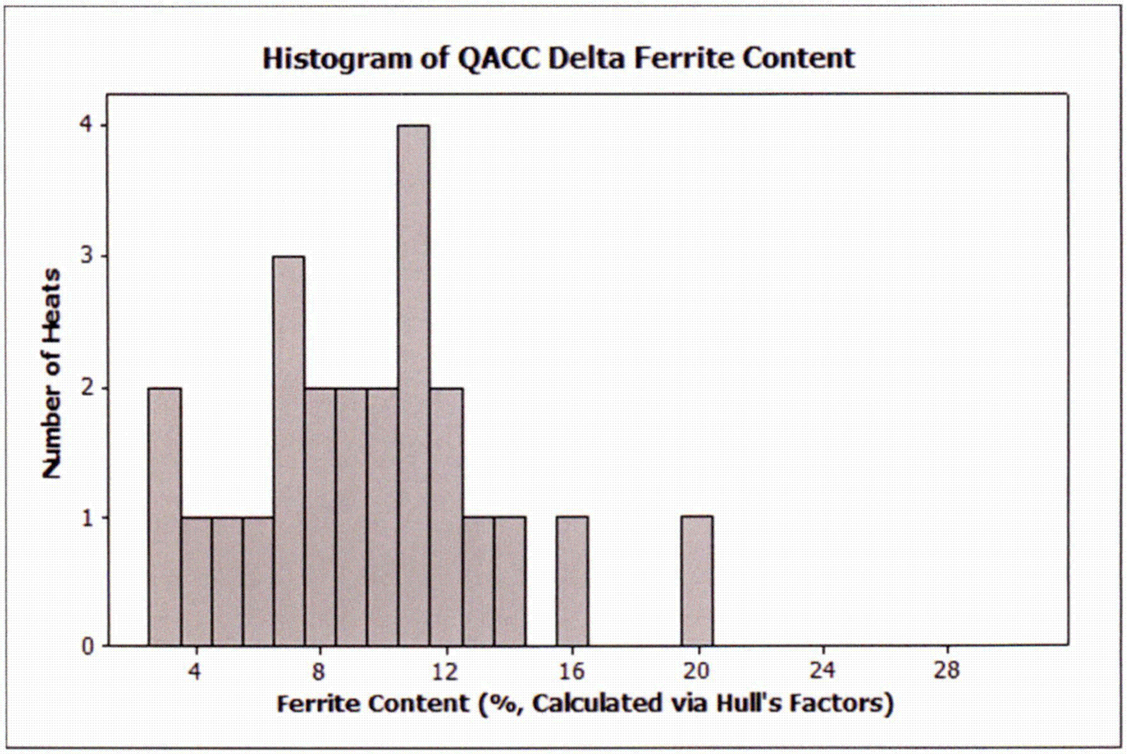

Figure A-31. Histogram of QACC Delta Ferrite Content

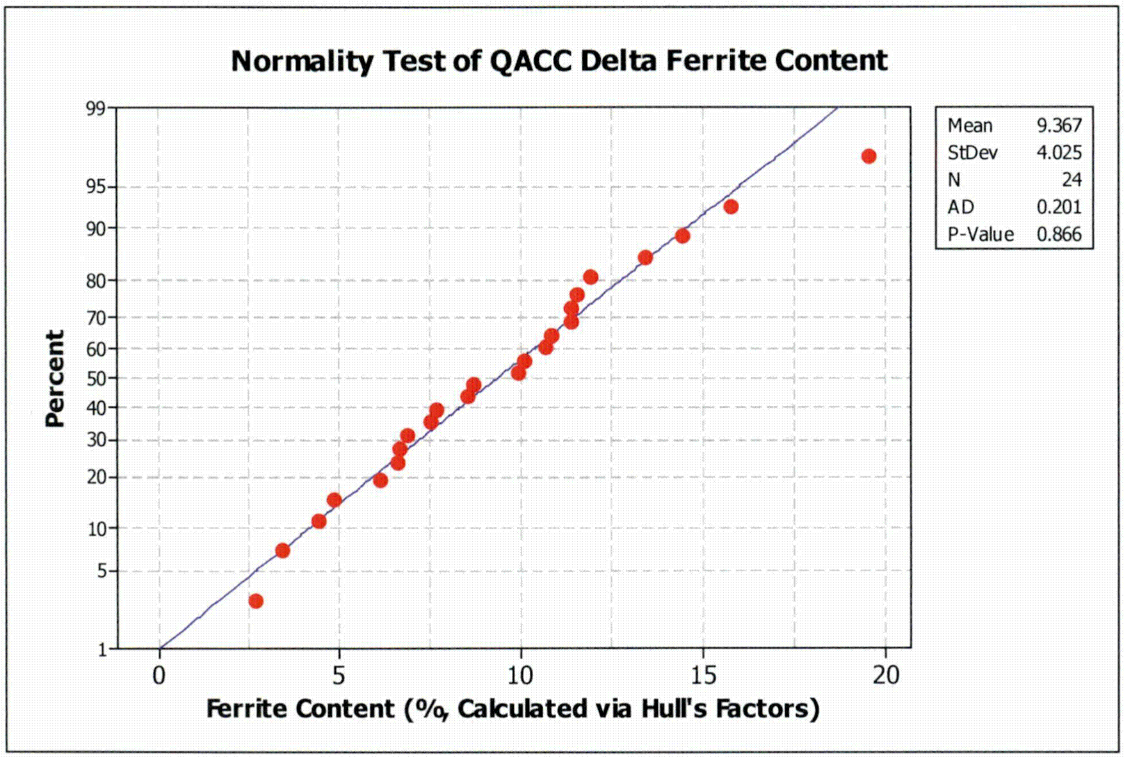

Figure A-32. Normality Test for QACC Delta Ferrite Content

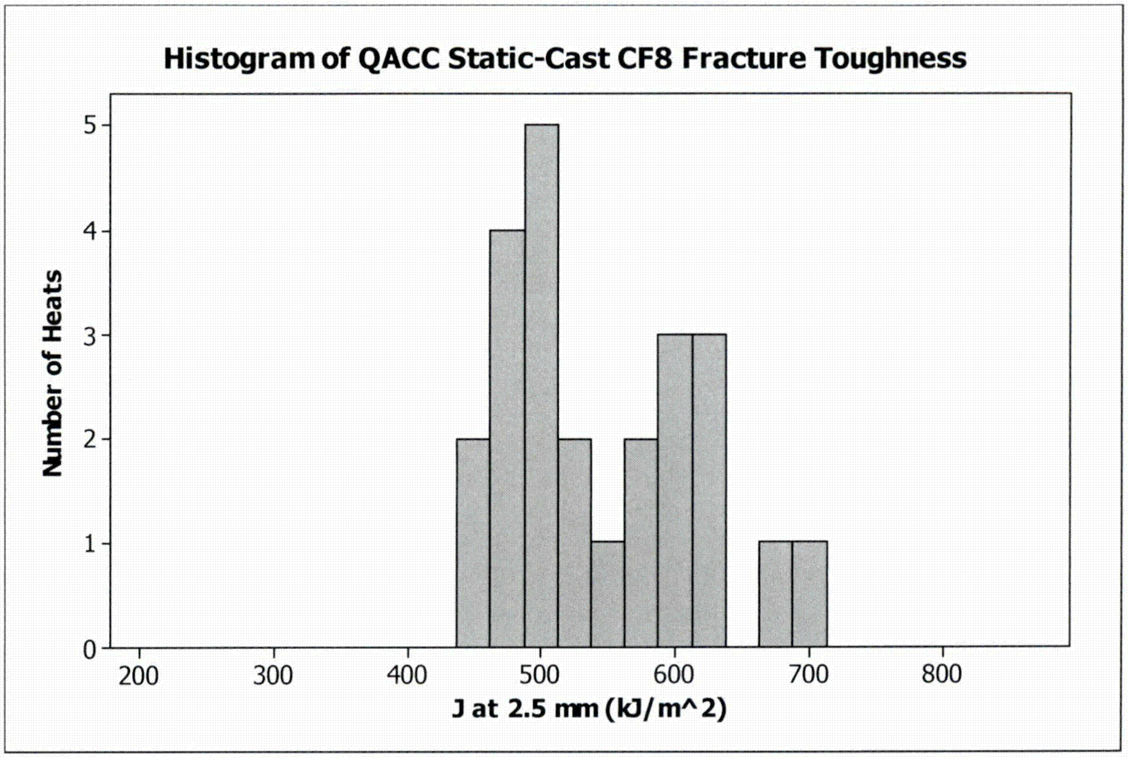

Figure A-33. Histogram of QACC Fracture Toughness

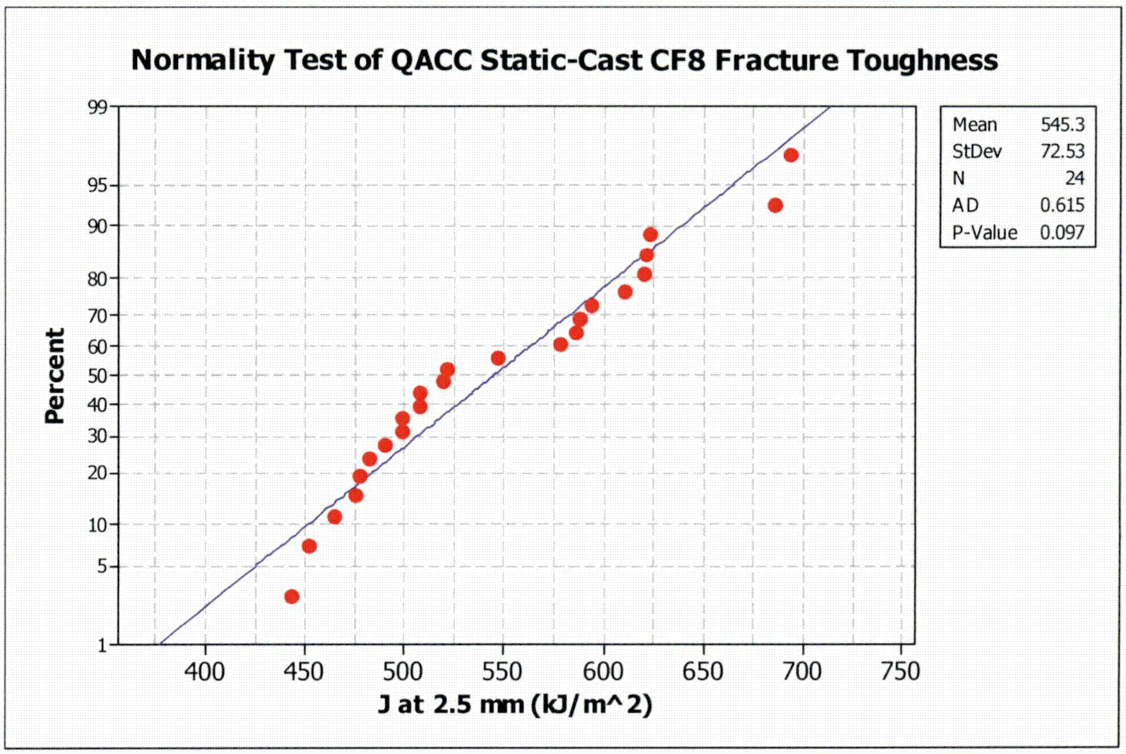

Figure A-34. Normality Test for QACC Fracture Toughness

A.10 VALCAST

The Valcast Corporation (Valcast) provided CASS mixing devices, column bases, and conduit supports for Westinghouse-designed plants. CMTR data were available for 16 individual heats of material supplied by Valcast. Valcast was unique among manufacturers examined in this study, as the typical number of parts produced per heat was much greater, with batch sizes in the dozens or hundreds rather than five or less. The Valcast-supplied CASS RV internals were all fabricated from static-cast, low-molybdenum Grade CF8 material. Valcast provided CASS RV internals components from 1969 to 1972, as shown in Figure A-35.

The distribution of ferrite content for components fabricated by Valcast is shown in Figure A-36, with the accompanying normality test in Figure A-37. A lognormal distribution was used to model the Valcast ferrite content distribution. The calculated p value (0.687) associated with applying the lognormal distribution passes the acceptance criterion. Figure A-36 shows that there are no heats of material produced by Valcast that exceed 15 percent ferrite content, as estimated via Hull's factors. The average ferrite content for Valcast materials is 5.6 percent, and the standard deviation is 2.0 percent. The 95/95 limit for ferrite content for Valcast is 13.4 percent.

Figure A-38 shows the fracture toughness distribution for material heats made by Valcast, and Figure A-39 is the normality test associated with that distribution. A normal distribution was used to model the Valcast saturated fracture toughness distribution. The calculated p value (0.655) associated with applying the normal distribution passes the acceptance criterion. The average saturated fracture toughness for Valcast-supplied materials is 593 kJ/m^2 and the standard deviation is 38.1 kJ/m^2. The 95/95 bound for fracture toughness for Valcast is 496 kJ/m^2. Thus, it can be stated with a high degree of confidence that no components fabricated by Valcast will have a saturated fracture toughness below 255 kJ/m^2.

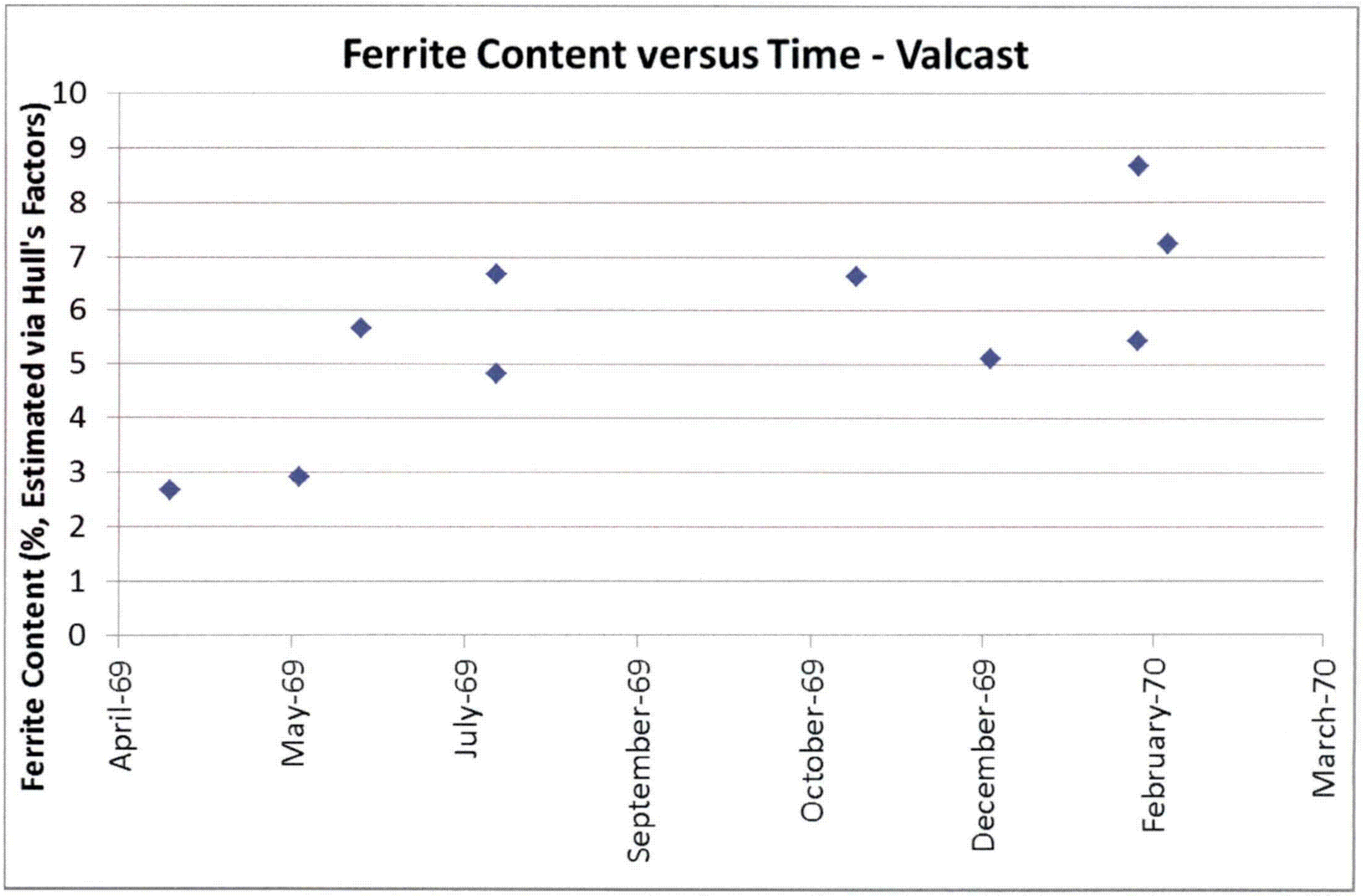

Figure A-35. Ferrite Content over Time - Valcast

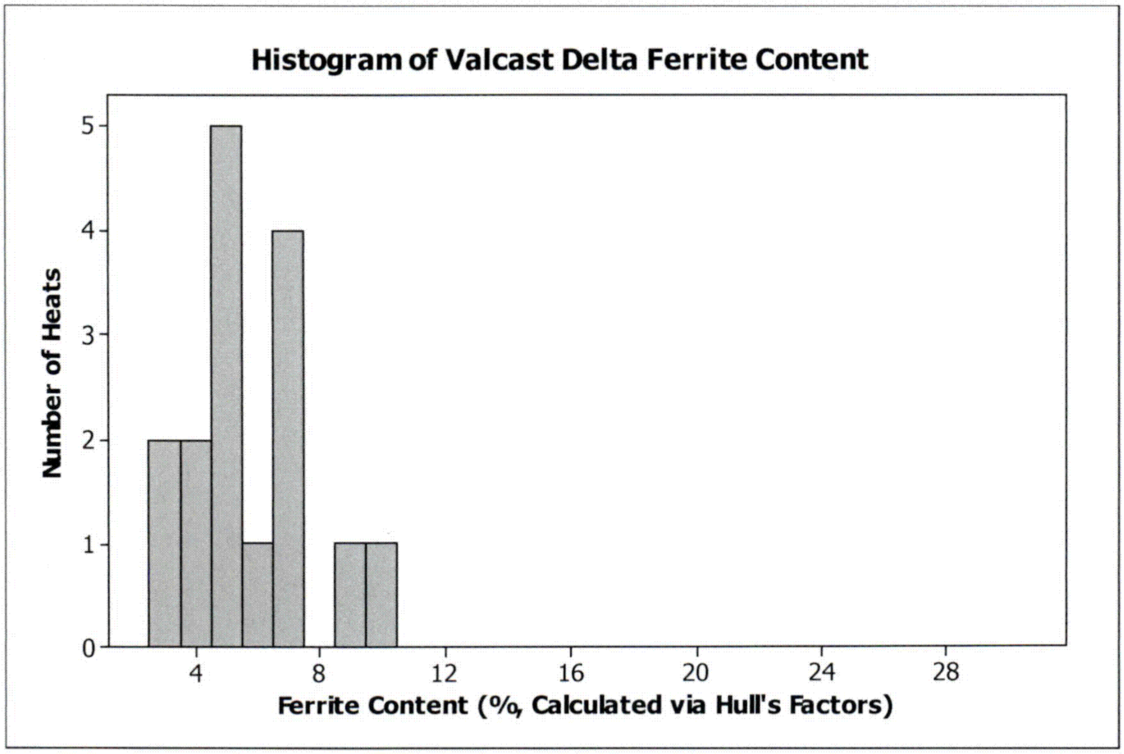

Figure A-36. Histogram of Valcast Delta Ferrite Content

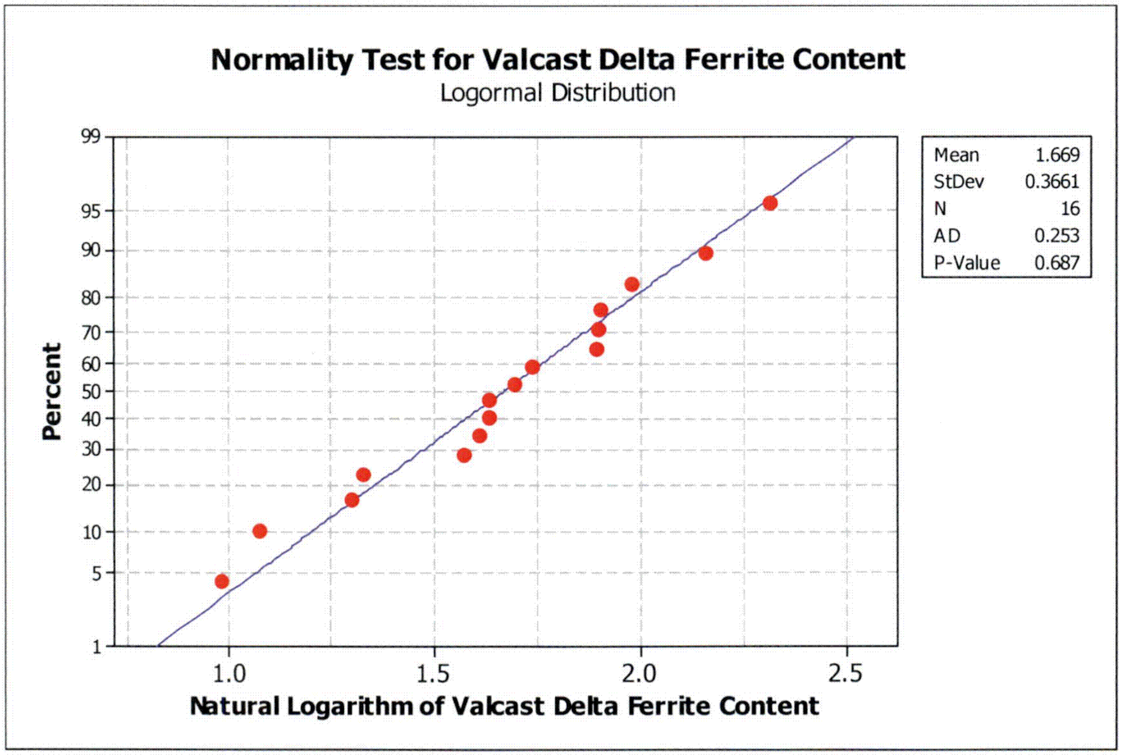

Figure A-37. Normality Test for Valcast Delta Ferrite Content

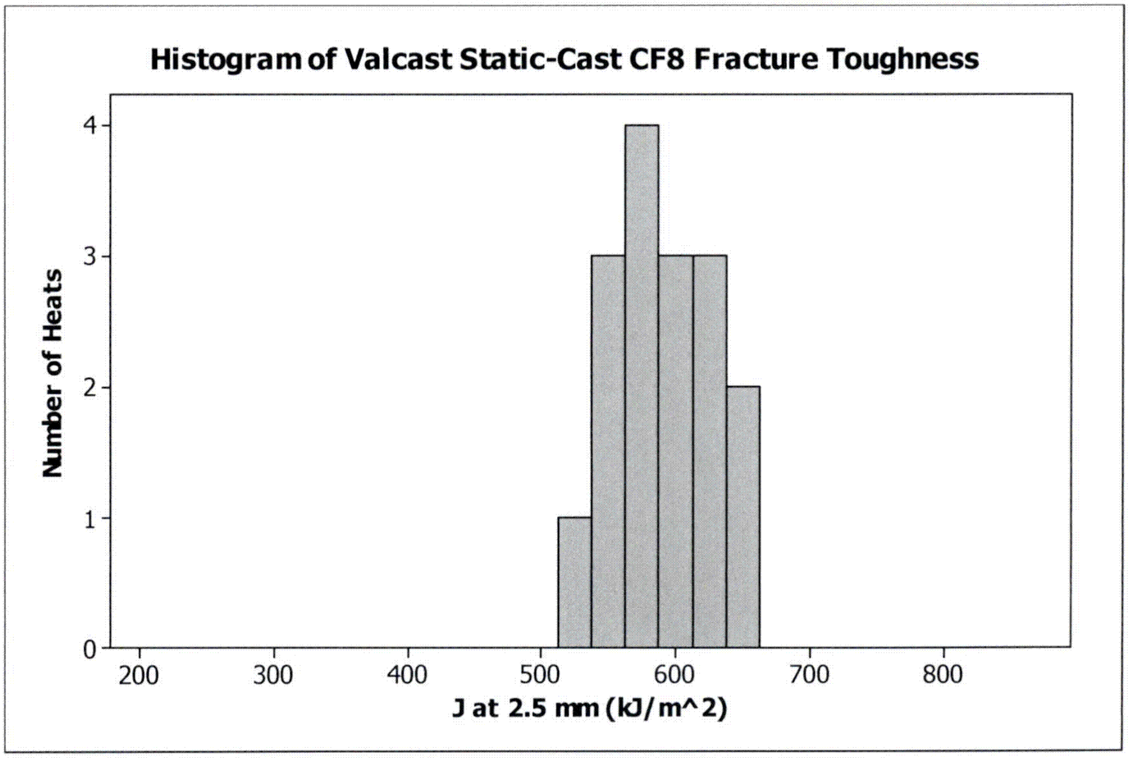

Figure A-38. Histogram of Valcast Fracture Toughness

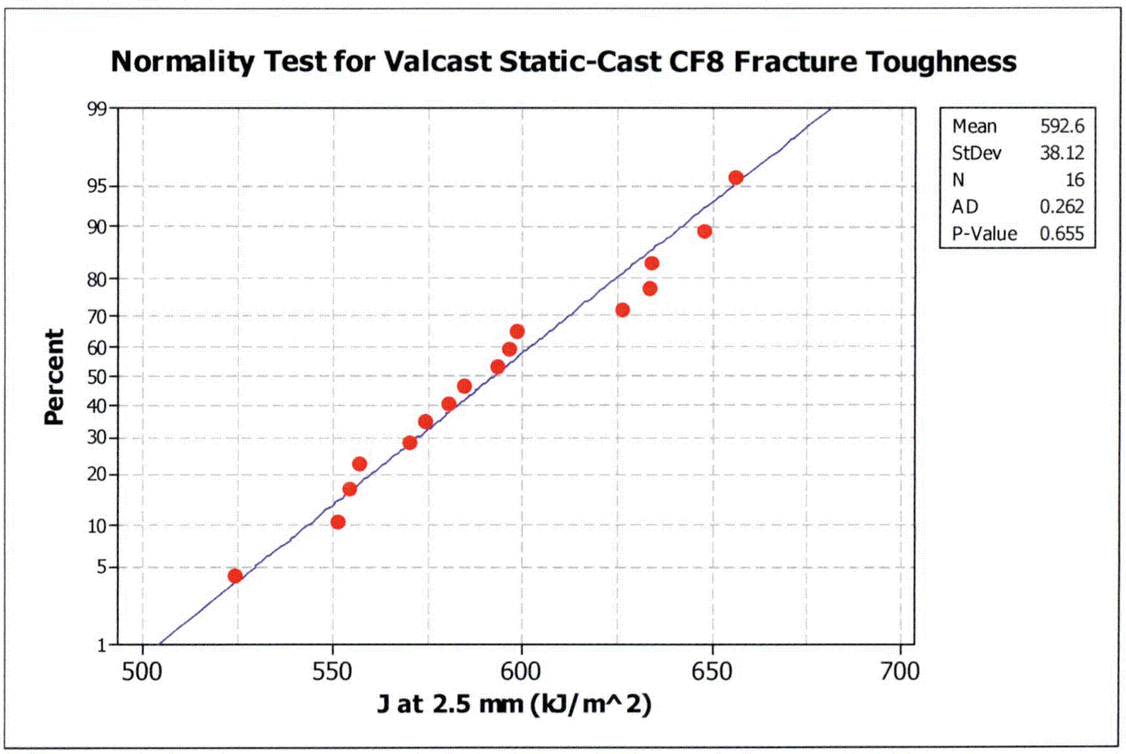

Figure A-39. Normality Test for Valcast Fracture Toughness

A.11 WAUKESHA

Waukesha supplied numerous CASS RV internals components for Westinghouse-designed plants, as illustrated in Figure A-41. CMTR data were available for 263 individual heats of material supplied by Waukesha. The Waukesha-supplied CASS RV internals were all fabricated from static-cast, low-molybdenum Grade CF8 material. Data for this manufacturer includes heats made from 1968 to 1979. The ferrite content of material supplied by Waukesha over time is shown in Figure A-40.

The distribution of ferrite content for components fabricated by Waukesha is shown in Figure A-42, with the accompanying normality test in Figure A-43. A normal distribution was used to model the Waukesha ferrite content distribution. The calculated p value (<0.005) associated with applying the normal distribution does not pass the acceptance criterion, however it provides a reasonable and conservative fit to the data. Figure A-42 shows that there are a few heats of material produced by Waukesha that exceed 20 percent ferrite content, as estimated via Hull's factors, and a small but not insignificant fraction of heats that exceed 15 percent ferrite content. The average ferrite content for Waukesha materials is 13.3 percent, and the standard deviation is 3.0 percent. The 95/95 limit for ferrite content for Waukesha is 18.7 percent. Ferrite content distributions for each individual type of component are shown in Figure A-44. Figure A-44 shows that there is no significant difference in the estimated ferrite component between components made by Waukesha.

Figure A-45 shows the fracture toughness distribution for material heats made by Waukesha, and Figure A-46 is the normality test associated with that distribution. A normal distribution was used to model the Waukesha ferrite content distribution. The calculated p value (<0.005) associated with applying the lognormal distribution does not pass the acceptance criterion, however it provides a reasonable and conservative fit to the data. The average saturated fracture toughness for Waukesha-supplied materials is 462 kJ/m^2 and the standard deviation is 35.4 kJ/m^2. The 95/95 bound for fracture toughness for Waukesha is 398 kJ/m^2. Thus, it can be stated with a high degree of confidence that no components fabricated by Waukesha will have a fracture toughness below 255 kJ/m^2.

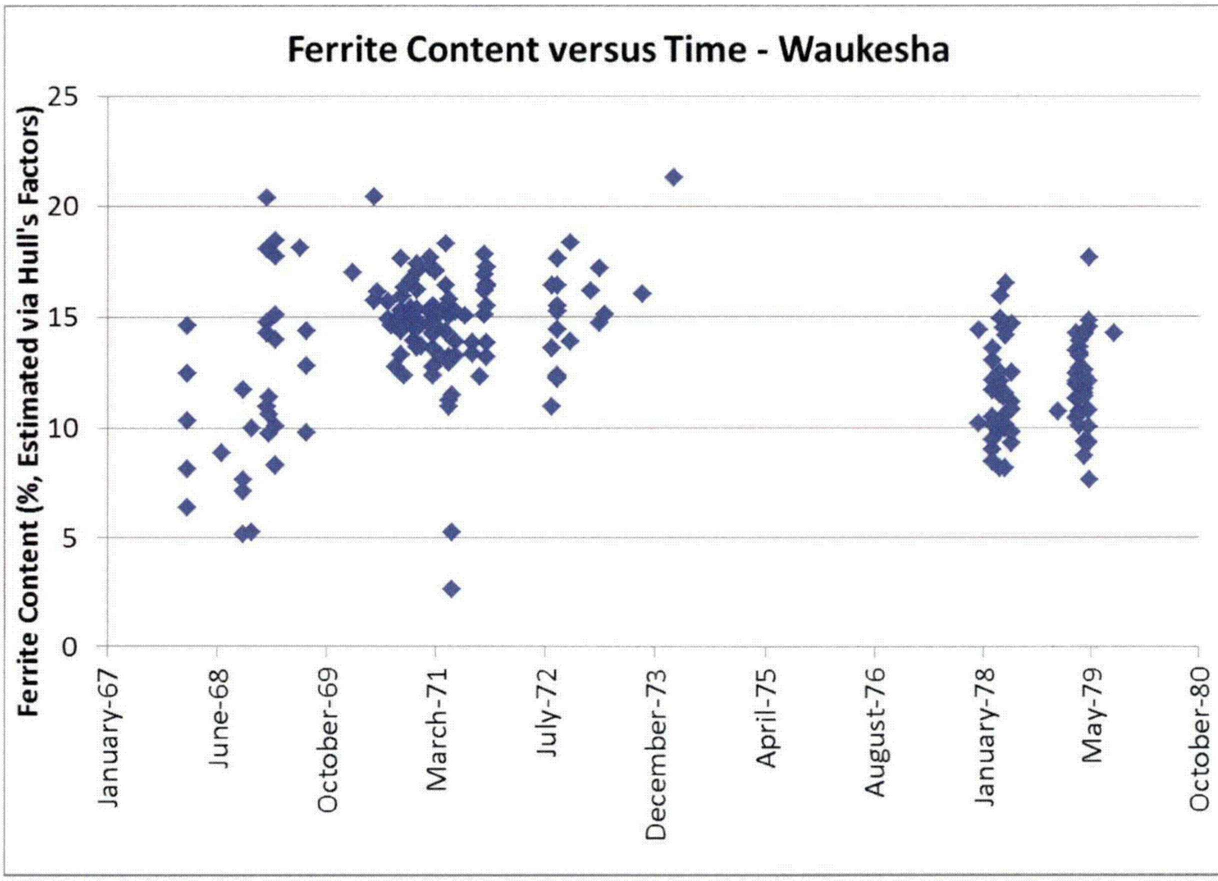

Figure A-40. Ferrite Content of Material Supplied by Waukesha over Time

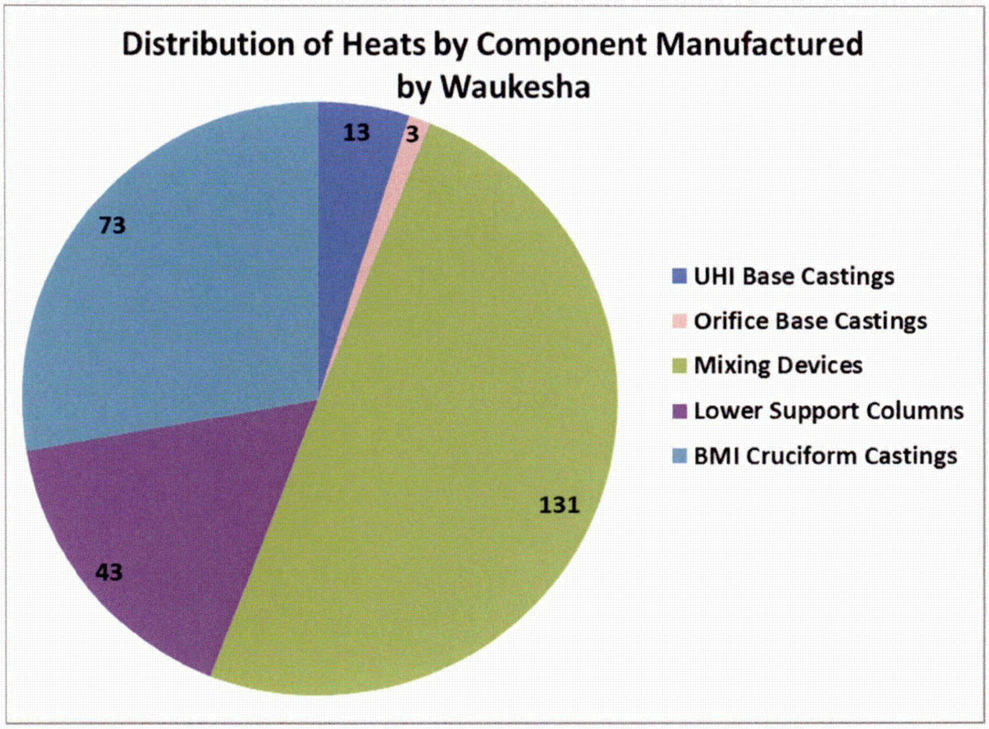

Figure A-41. Distribution of Heats by Component Manufactured by Waukesha

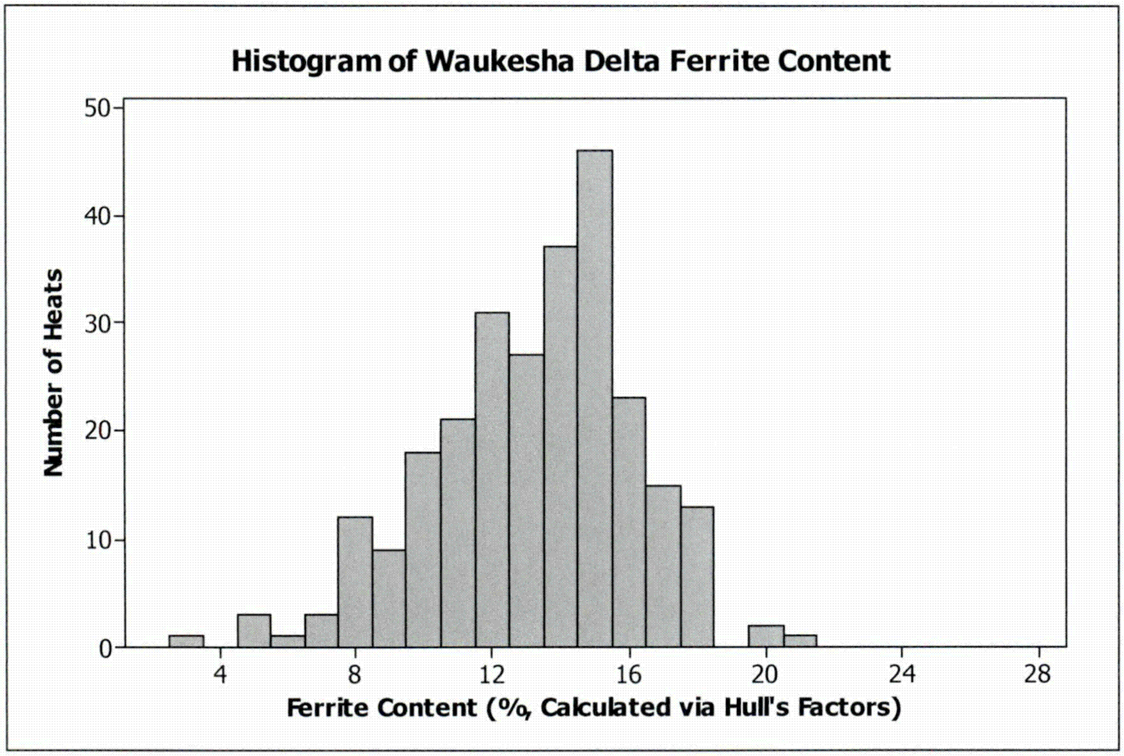

Figure A-42. Histogram of Ferrite Content for Waukesha

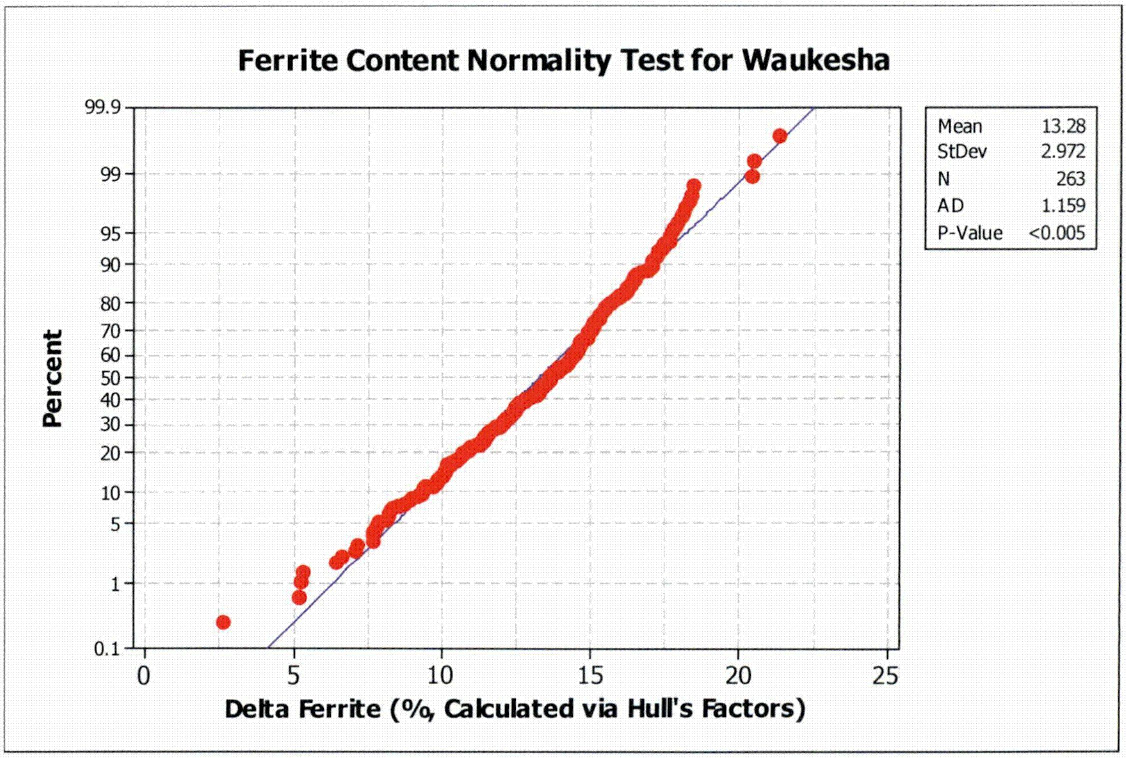

Figure A-43. Ferrite Content Normality Test for Waukesha

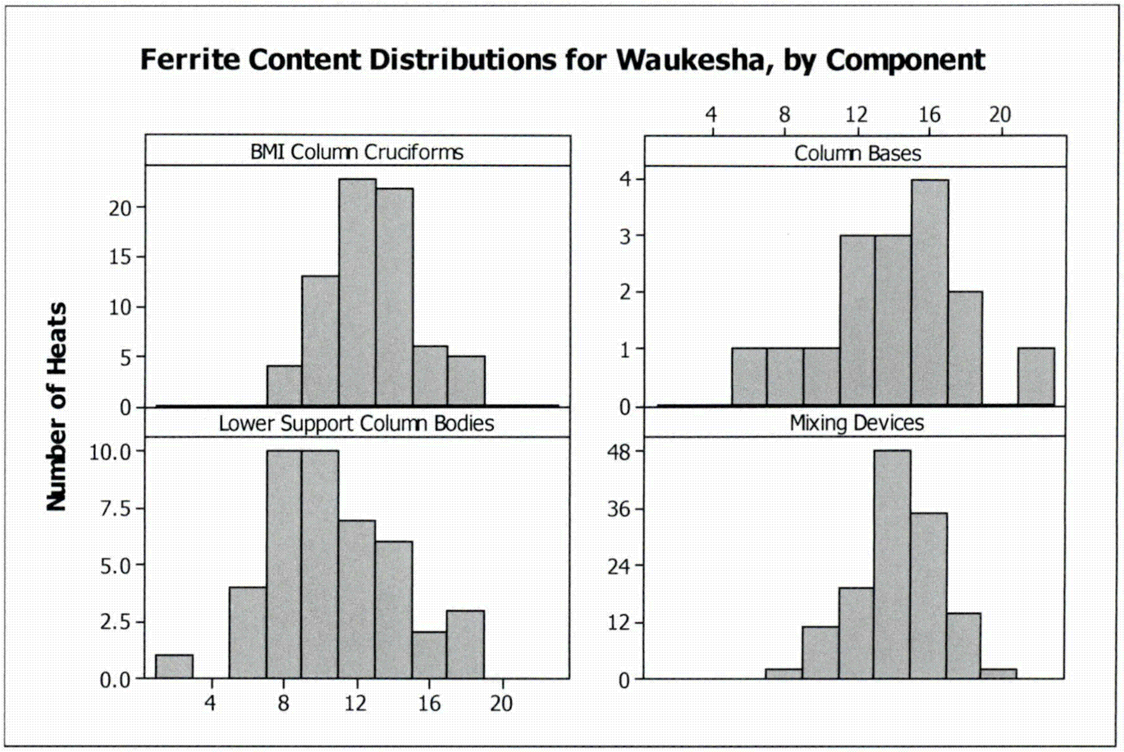

Figure A-44. Ferrite Content Distributions by Component Manufactured by Waukesha

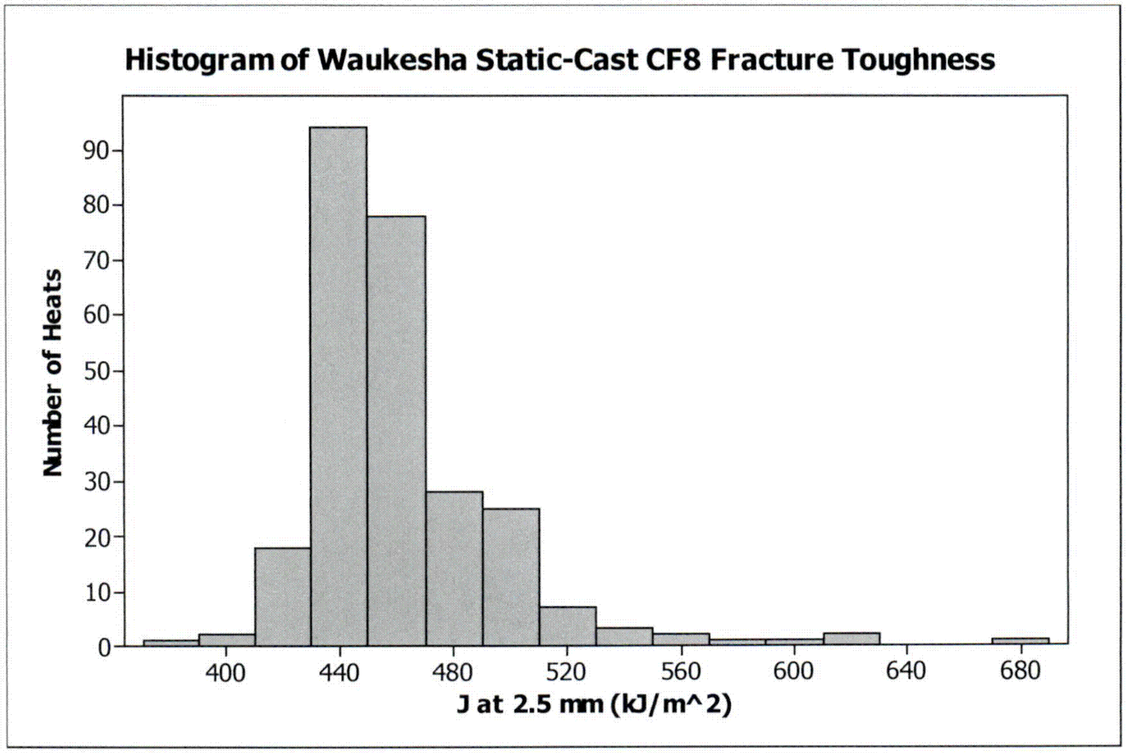

Figure A-45. Histogram of Fracture Toughness for Waukesha

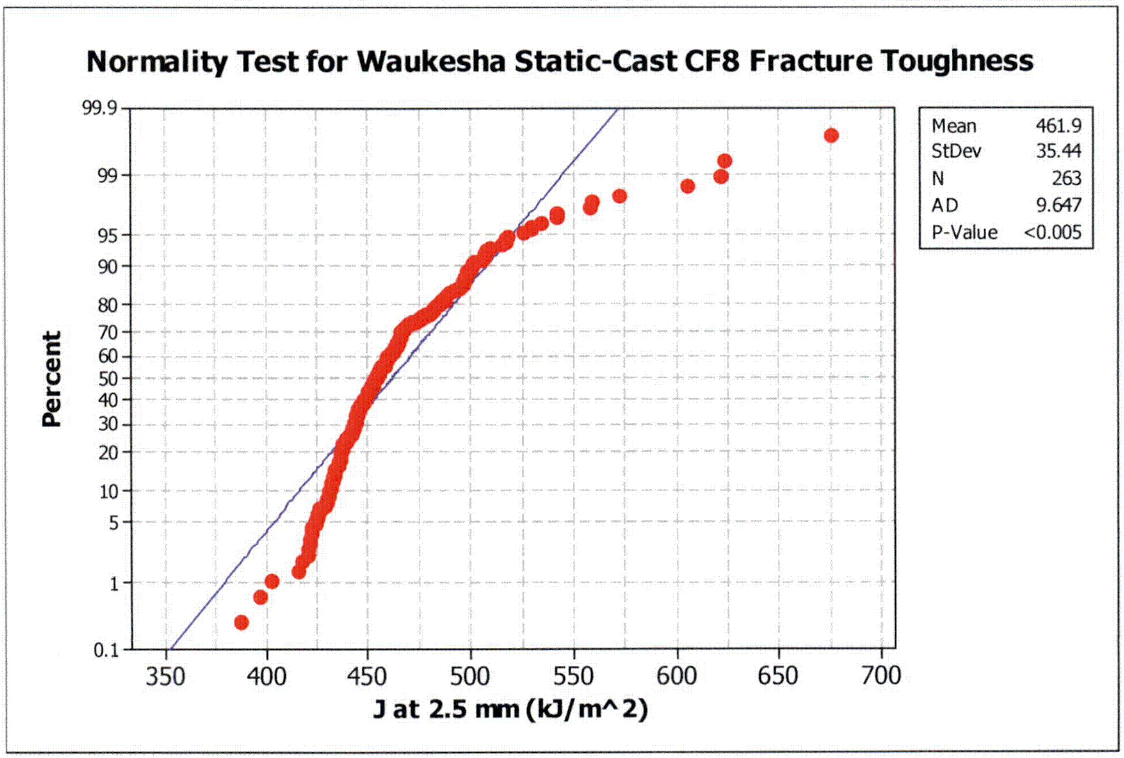

Figure A-46. Fracture Toughness Normality Test for Waukesha

A.12 WISCONSIN CENTRIFUGAL

Wisconsin Centrifugal (WC) primarily provided CEA shroud tubes for CE-designed plants that were produced using a centrifugal casting method. WC also produced two heats worth of flow bypass inserts for CE-designed plants using a static-cast method. CMTR data were available for 183 individual heats of centrifugally-cast material and 2 heats of static-cast material supplied by WC. The CMTRs from WC include both product and ladle analyses of chemical composition, and so both are used to separately calculate ferrite and fracture toughness values. No information on the dates of manufacture was available for WC.

The distribution of ferrite content for the product analysis of the centrifugally-cast components fabricated by WC is shown in Figure A-47, with the accompanying normality test in Figure A-48. A normal distribution was used to model the WC product analysis ferrite content distribution. The calculated p value (0.283) associated with applying the normal distribution passes the acceptance criterion.

The distribution of ferrite content for the ladle analysis of the centrifugally-cast components fabricated by WC is shown in Figure A-49, with the accompanying normality test in Figure A-50. A normal distribution was used to model the WC ladle analysis ferrite content distribution. The calculated p value (0.428) associated with applying the normal distribution passes the acceptance criterion. The centrifugally-cast components provided by WC were all CEA shroud tubes.

Only two CMTRs were available from WC for static-cast components, and so it is difficult to determine any meaningful statistical parameters from this data alone. The available manufacturing information for the WC static-cast components is summarized in Table A-4. Both heats have low delta ferrite and correspondingly high fracture toughness.

Table A-4 WC Static-Cast Component Manufacturing Information

	Product Analysis		Ladle Analysis	
	Delta Ferrite (%)	Fracture Toughness J at 2.5 mm (kJ/m^2)	Delta Ferrite (%)	Fracture Toughness J at 2.5 mm (kJ/m^2)
Heat 1	10.9	575	11.7	597
Heat 2	11.3	569	11.5	567
Average	11.1	572	11.6	582
Standard Deviation	0.3	3.9	0.2	20.8

The average ferrite contents for WC centrifugally-cast materials are 16.2 percent for the ladle analysis and 14.2 percent for the product analysis. The standard deviations are 3.5 percent for the ladle analysis and 3.6 percent for the product analysis. The 95/95 limits for ferrite content for centrifugally-cast WC materials are 22.7 percent for the ladle analysis and 20.8 percent for the product analysis.

Figure A-51 and Figure A-53 show the fracture toughness distributions for centrifugally-cast material heats made by WC, and Figure A-52 and Figure A-54 are the normality tests associated with those distributions. A normal distribution was used to model the WC saturated fracture toughness distributions. The calculated p values (<0.005) associated with applying the normal distribution do not pass the acceptance criterion, however it provides a reasonable and conservative fit to the data. The average saturated fracture toughnesses for WC centrifugally-cast materials are 581 for the ladle analysis and 590 for the product analysis. The standard deviations are 50.7 for the ladle analysis and 55.3 for the product analysis.

The fracture toughnesses for the static-cast components are nearly equivalent to the mean values determined for the centrifugally-cast components. It is very possible, and logical from the standpoint of manufacturing economics, that the same or similar raw material would be used to make the static and centrifugal components, as the chemical composition requirements are identical. This was observed for another manufacturer which provided both static- and centrifugally-cast components (Kearsarge, Appendix A.6). Therefore, for this manufacturer, it is reasonable to assess the static-and centrifugally-cast material together to develop a meaningful 95/95 limit for fracture toughness covering all WC materials.

The 95/95 criteria for fracture toughness for WC material are 487 kJ/m^2 for the ladle analysis and 488 kJ/m^2 for the product analysis. The slightly lower result for the ladle analysis will be considered as the final result for this manufacturer. Thus, it can be stated with a high degree of confidence that no components fabricated by WC will have a saturated fracture toughness below 255 kJ/m^2.

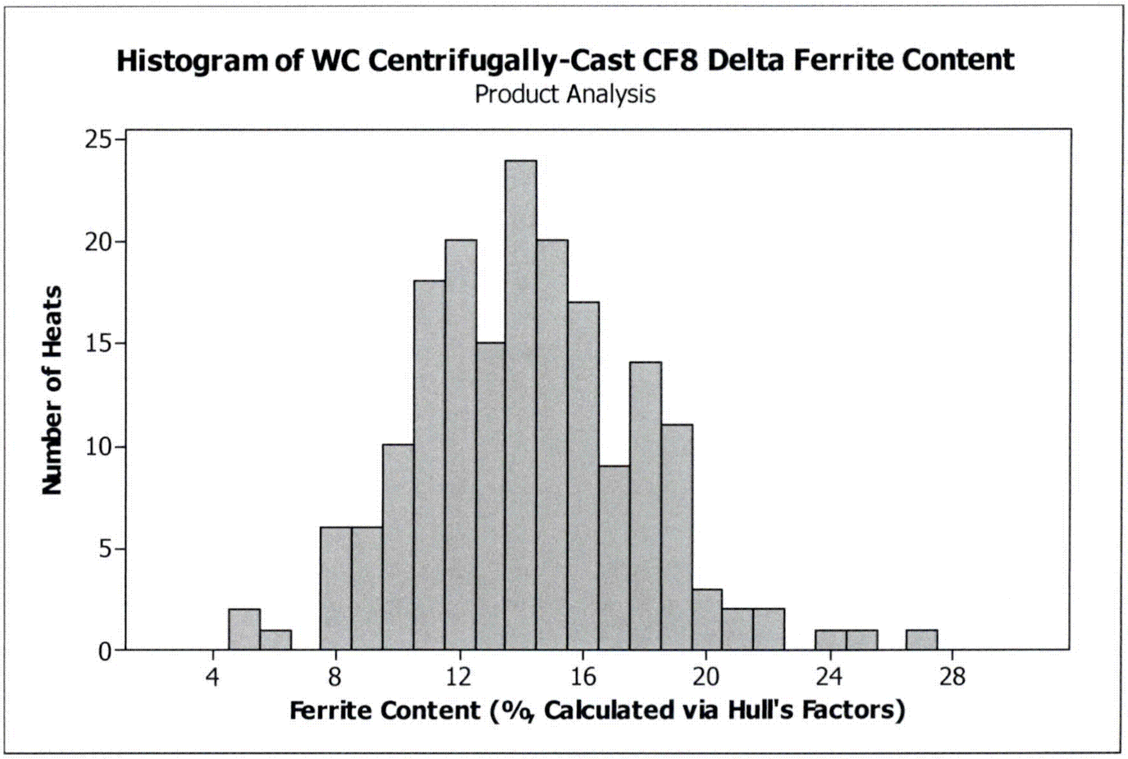

Figure A-47. Histogram of WC Delta Ferrite Content

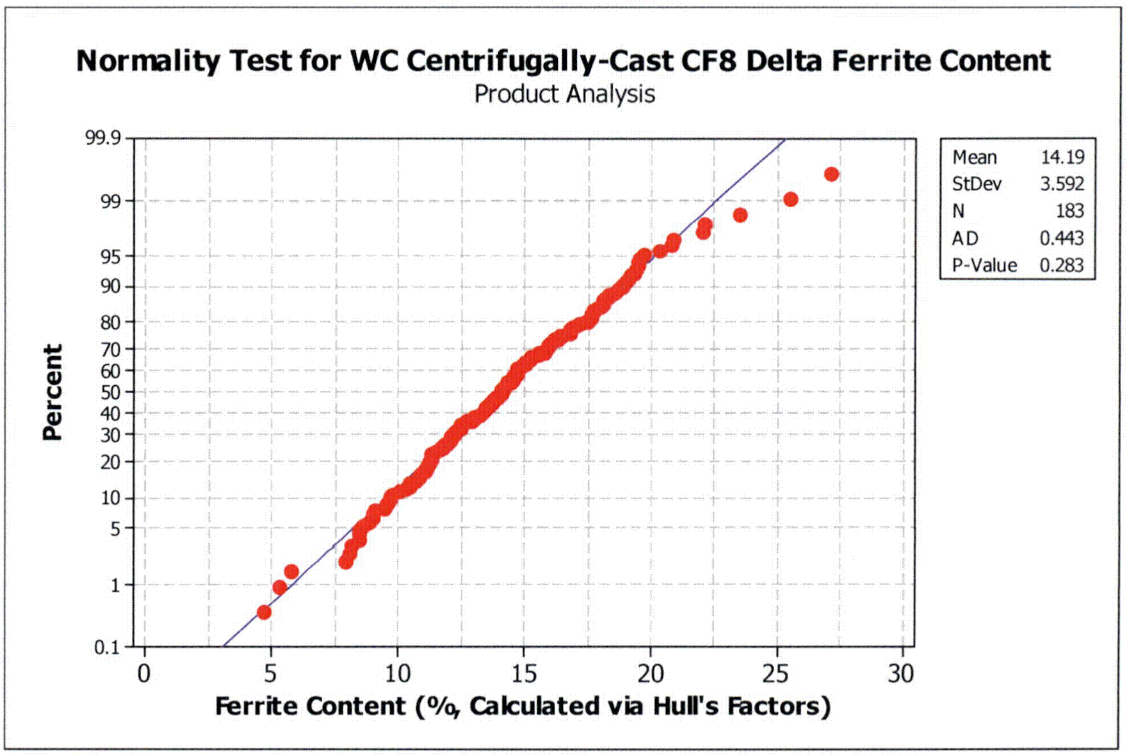

Figure A-48. Normality Test for WC Delta Ferrite Content (Product Analysis)

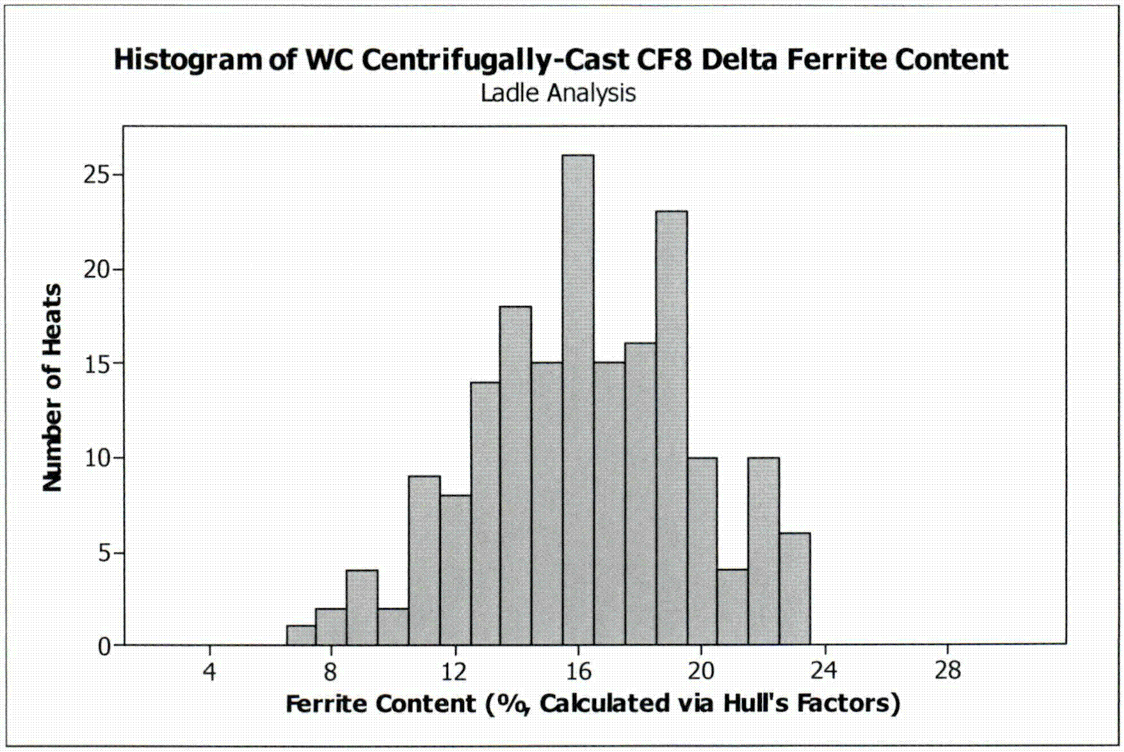

Figure A-49. Histogram of WC Delta Ferrite Content

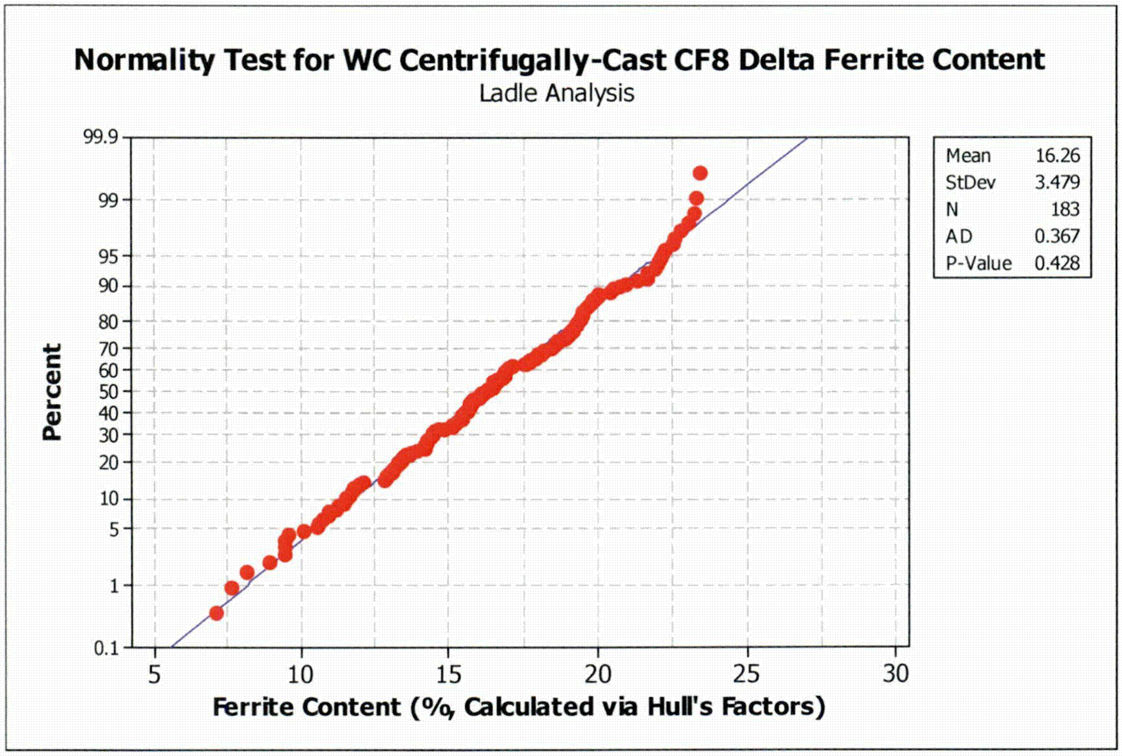

Figure A-50. Normality Test for WC Delta Ferrite Content (Ladle Analysis)

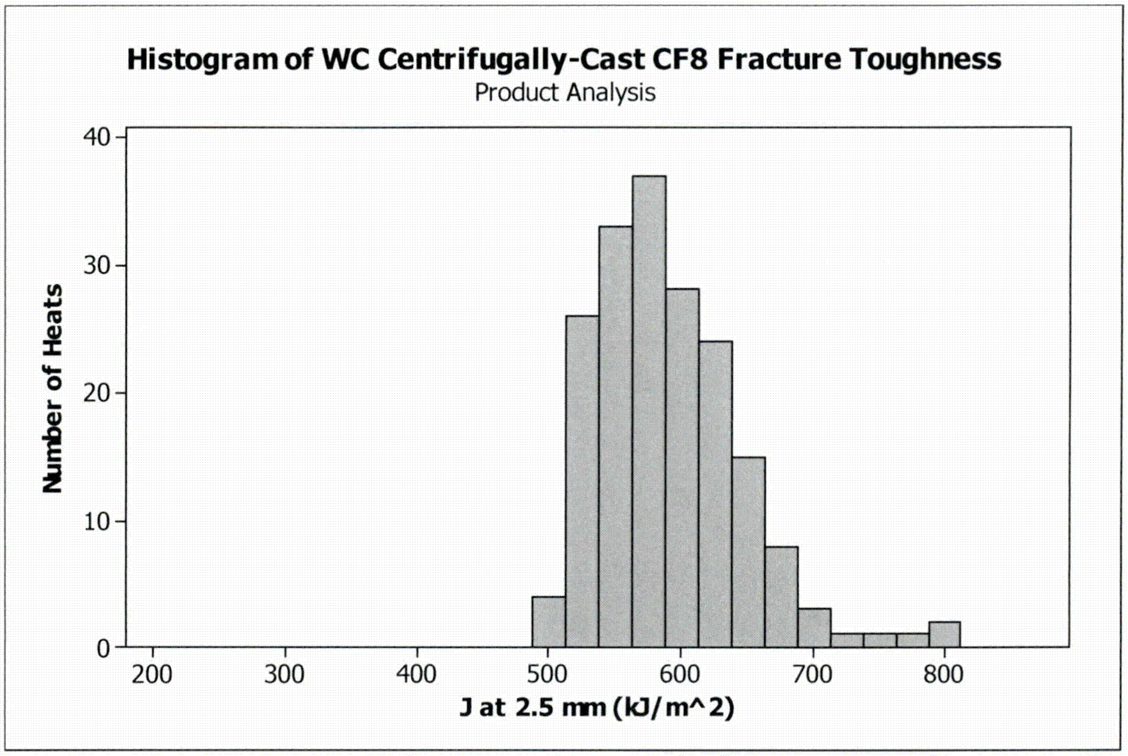

Figure A-51. Histogram of WC Fracture Toughness

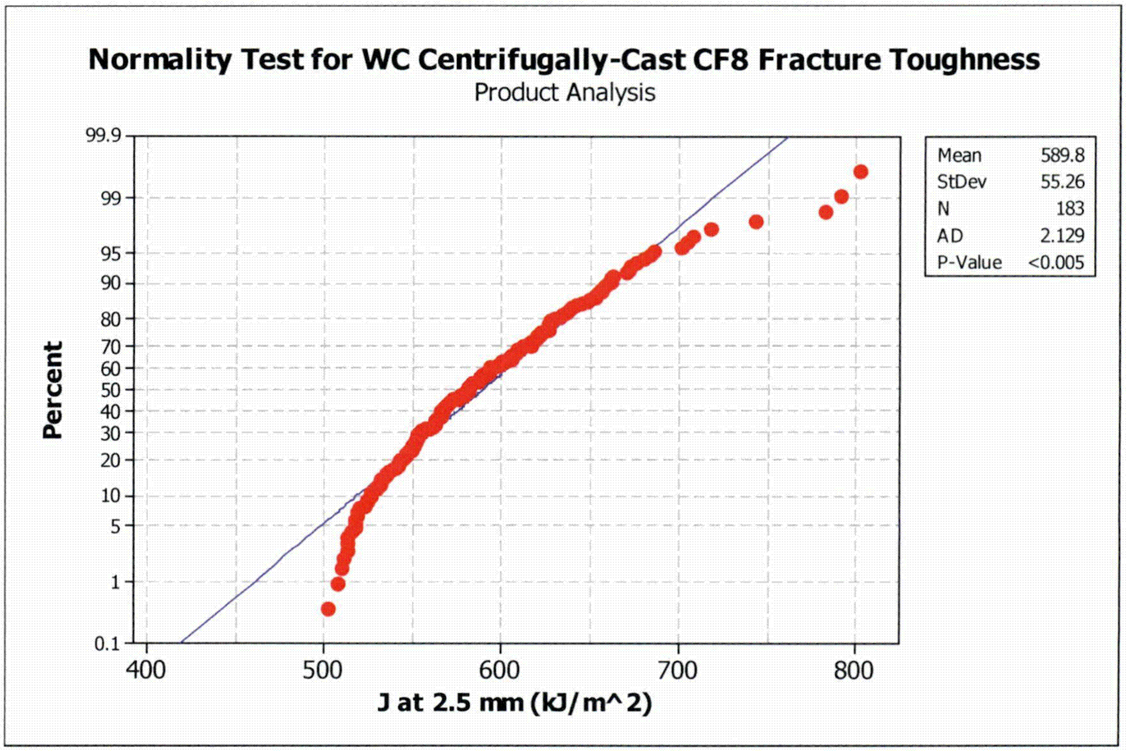

Figure A-52. Normality Test for WC Fracture Toughness (Product Analysis)

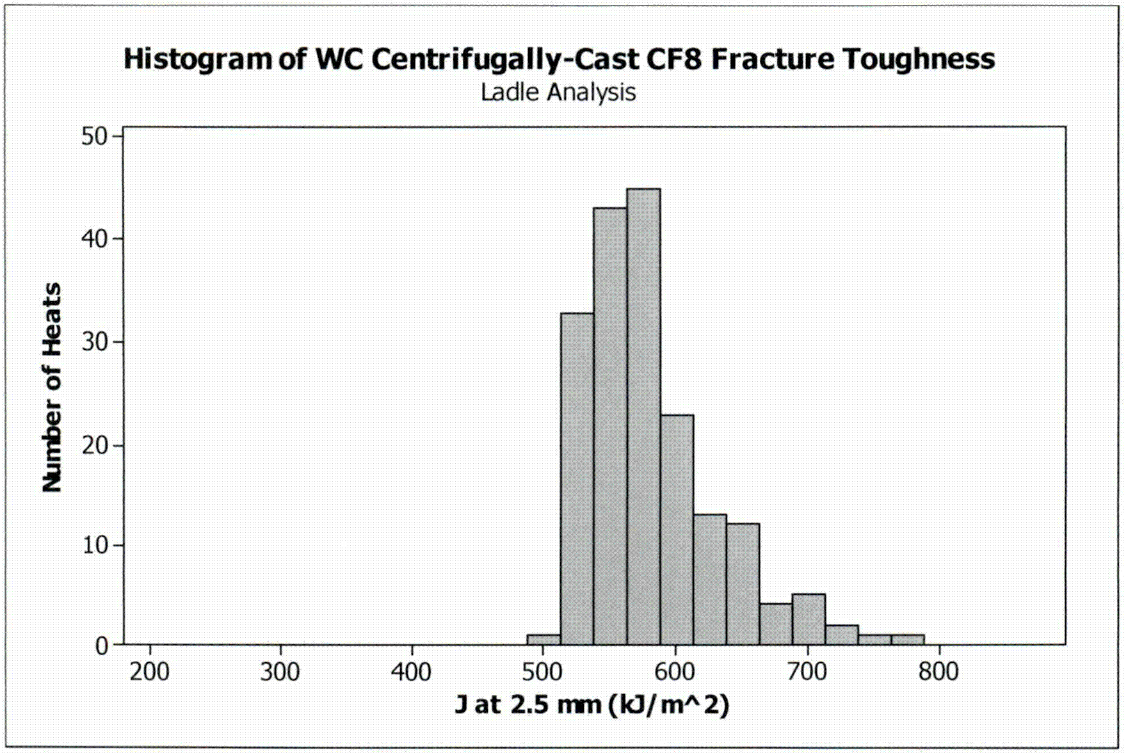

Figure A-53. Histogram of WC Fracture Toughness

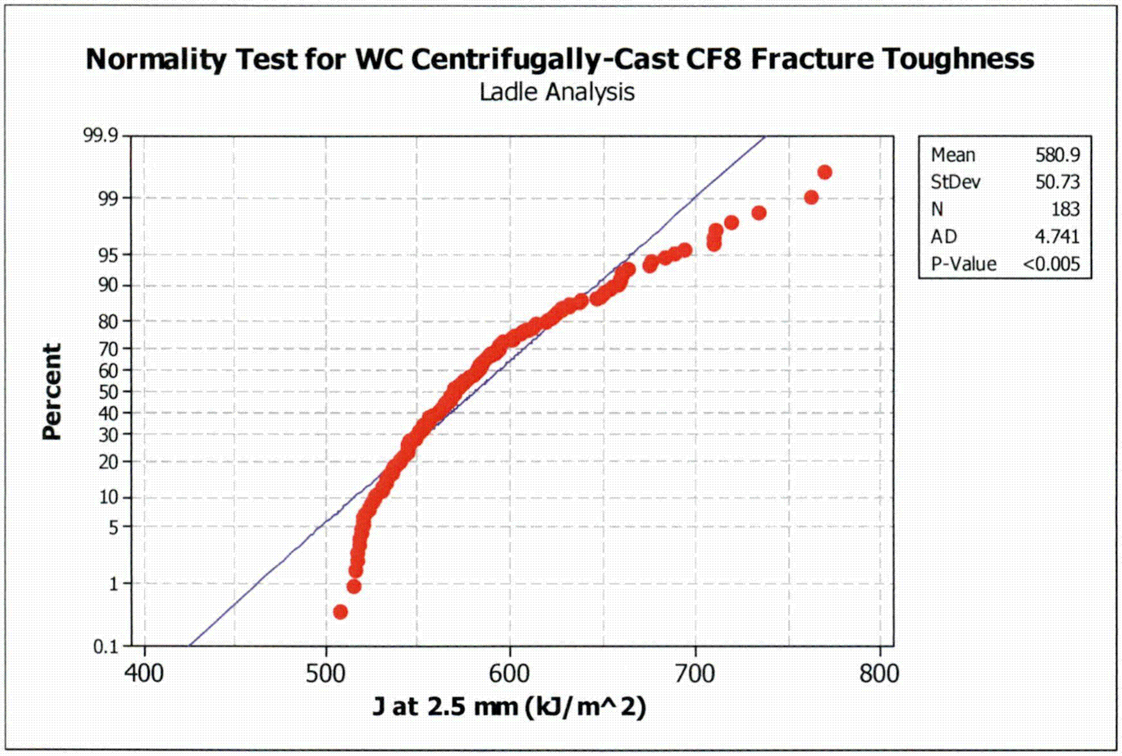

Figure A-54. Normality Test for WC Fracture Toughness (Ladle Analysis)

A.13 WOLLASTON ALLOYS

Wollaston Alloys (Wollaston) provided RV internals components for B&W plants. The Wollaston-supplied CASS RV internals were fabricated from static-cast, low-molybdenum Grade CF8 material or static-cast, high-molybdenum Grade CF3M. The Grade CF3M material was used exclusively in the CRGT spacer castings, which are an MRP-227-A primary component [1]. CMTR data were available for 39 individual heats of static-cast Grade CF8 material and 227 heats of static-cast Grade CF3M material supplied by Wollaston. Wollaston provided CASS RV internals components from 1965 to 1970; however there was not enough readily available information on the dates of manufacture to generate a meaningful distribution of ferrite content over time.

The distribution of ferrite content for Grade CF8 components fabricated by Wollaston is shown in Figure A-55, with the accompanying normality test in Figure A-56. A lognormal distribution was used to model the Wollaston Grade CF8 ferrite content distribution. The calculated p value (0.898) associated with applying the lognormal distribution passes the acceptance criterion. The average ferrite content for Grade CF8 Wollaston materials is 12 percent, and the standard deviation is 4.5 percent. The 95/95 limit for ferrite content for Grade CF8 Wollaston materials is 24.5 percent.

Figure A-57 shows the fracture toughness distribution for Grade CF8 material heats made by Wollaston, and Figure A-58 is the normality test associated with that distribution. A normal distribution was used to model the Wollaston Grade CF8 saturated fracture toughness distribution. The calculated p value (0.519) associated with applying the lognormal distribution passes the acceptance criterion. The average saturated fracture toughness for Grade CF8 Wollaston-supplied materials is 544 kJ/m^2 and the standard deviation is 45.1 kJ/m^2.

The 95/95 bound for fracture toughness for Grade CF8 Wollaston material is 448 kJ/m^2. Thus, it can be stated with a high degree of confidence that no Grade CF8 components fabricated by Wollaston will have a saturated fracture toughness below 255 kJ/m^2.

The distribution of ferrite content for Grade CF3M components fabricated by Wollaston is shown in Figure A-59, with the accompanying normality test in Figure A-60. A normal distribution was used to model the Wollaston Grade CF3M ferrite content distribution. The calculated p value (0.441) associated with applying the normal distribution passes the acceptance criterion.

Figure A-61 shows the fracture toughness distribution for Grade CF3M material heats made by Wollaston, and Figure A-62 is the normality test associated with that distribution. A normal distribution was used to model the Wollaston saturated fracture toughness distribution. The calculated p value (0.028) associated with applying the normal distribution does not pass the acceptance criterion, however it provides a reasonable and conservative fit to the data. The average saturated fracture toughness for Grade CF3M Wollaston-supplied materials is 327 kJ/m^2 and the standard deviation is 101.67 kJ/m^2.

The 95/95 bound for fracture toughness for Grade CF3M Wollaston material is 141 kJ/m^2. This is below the established screening criterion of 255 kJ/m^2. In the development of MRP-189 Rev.

1 [25], it was recognized that this material had the potential to lose enough fracture toughness that aging management would be required. This resulted in the spacer castings fabricated from the Grade CF3M material being categorized as an MRP-227-A [1] primary component, with inspection requirements appropriate to manage the potential loss of fracture toughness. This is a demonstration of the effectiveness of the MRP process in developing recommendations for aging management of RV internals components in the period of extended operation.

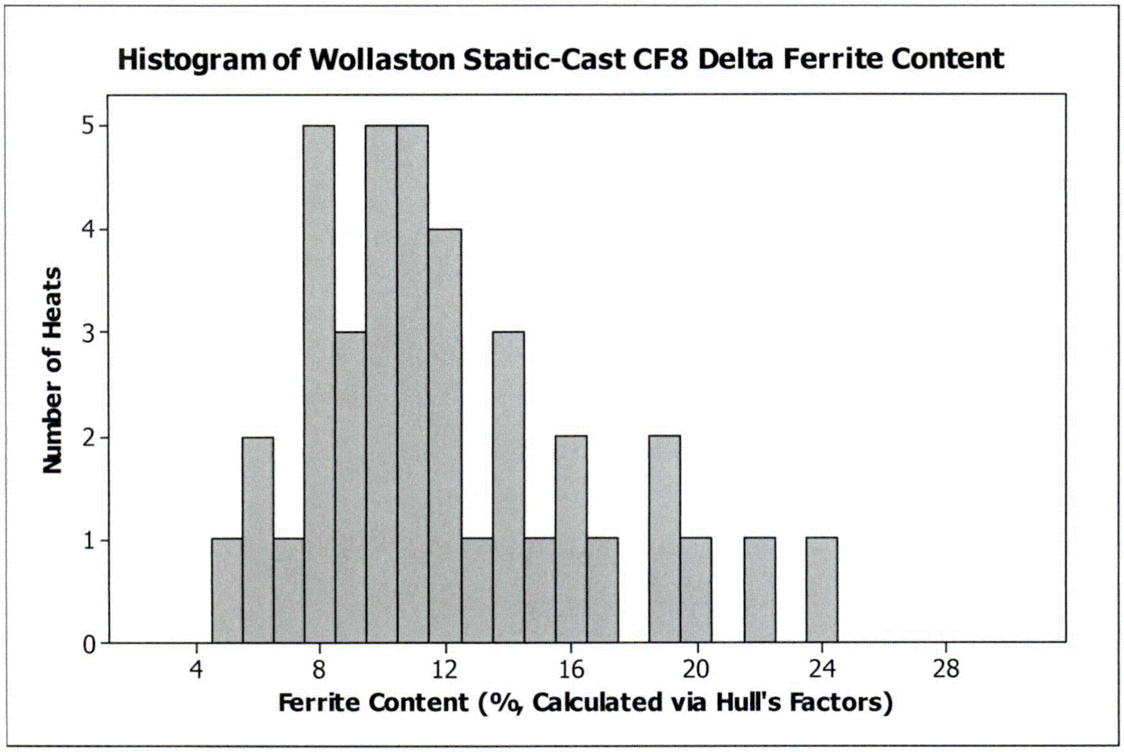

Figure A-55. Histogram of Wollaston Delta Ferrite Content

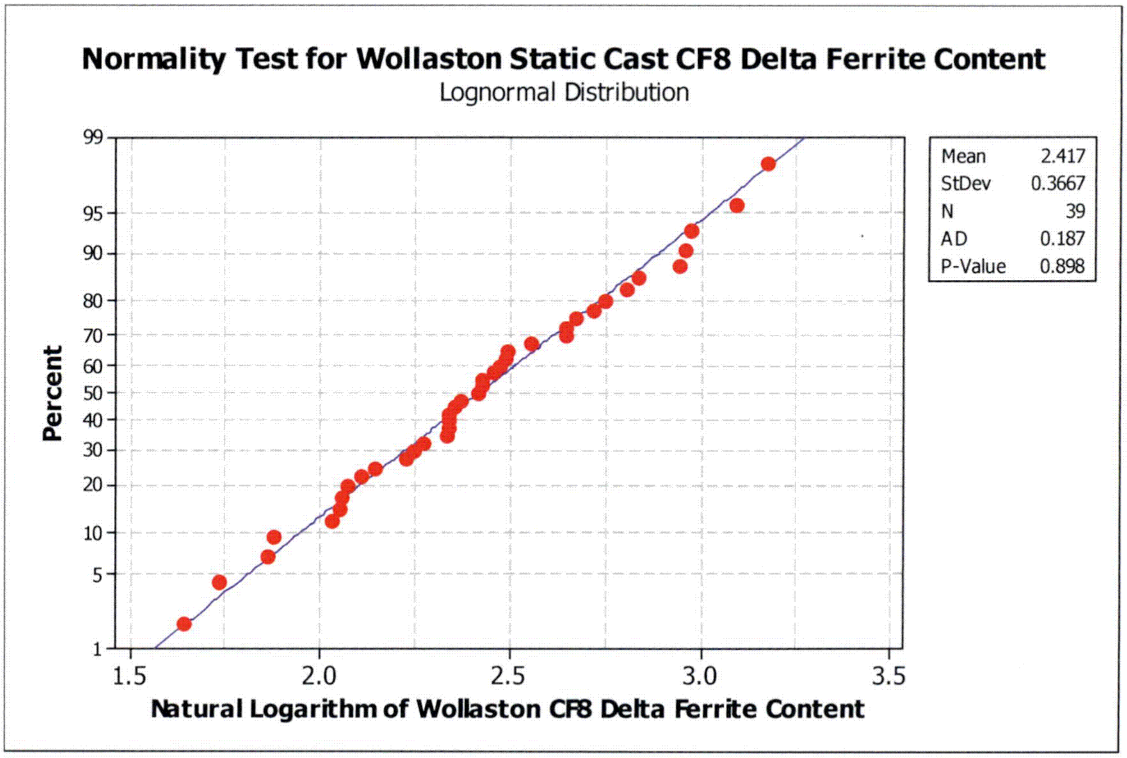

Figure A-56. Normality Test for Wollaston Delta Ferrite Content (CF8)

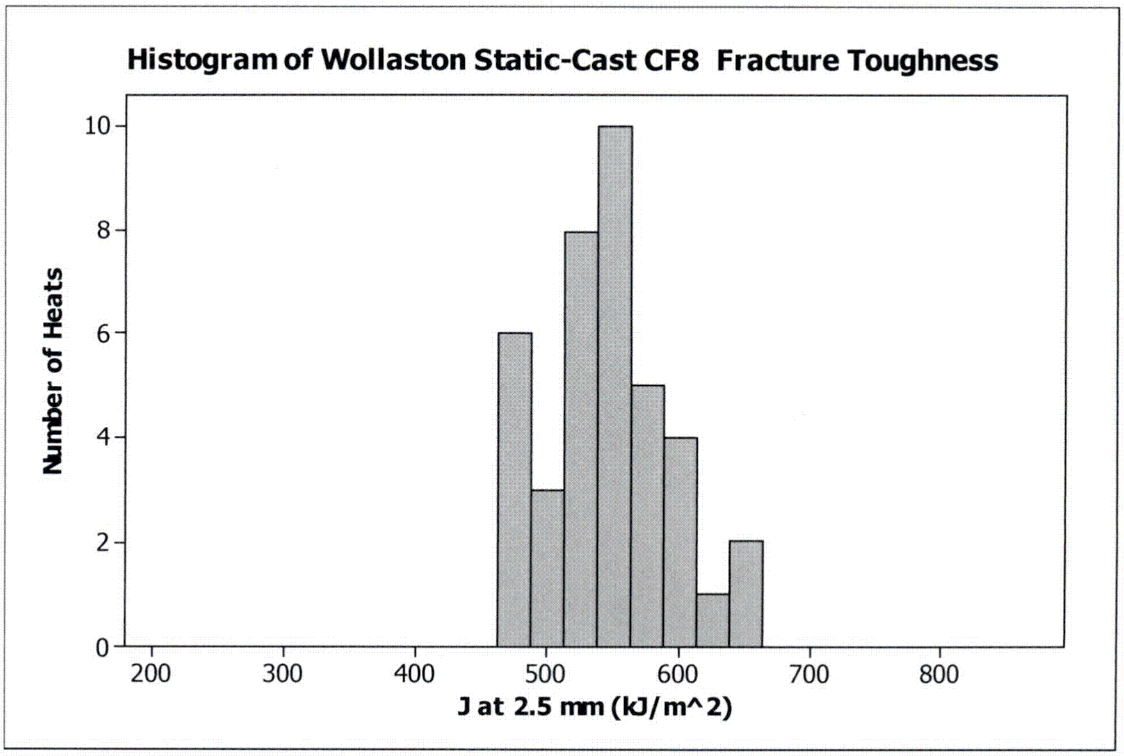

Figure A-57. Histogram of Wollaston Fracture Toughness

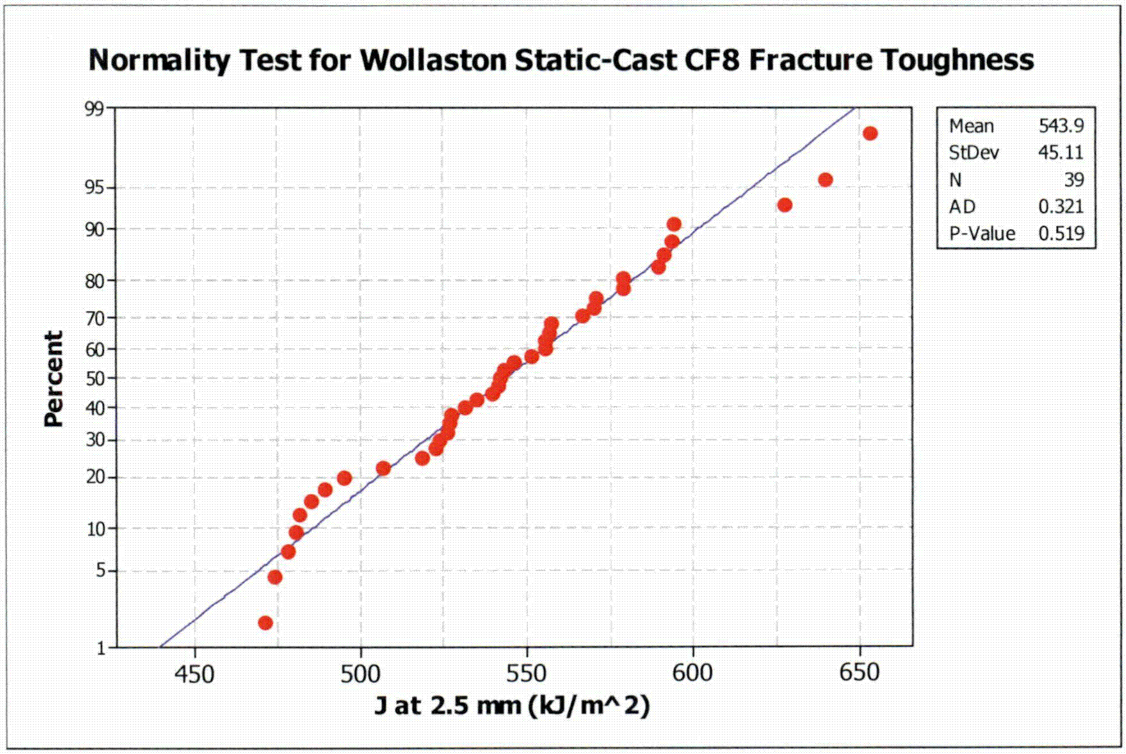

Figure A-58. Normality Test for Wollaston Fracture Toughness (CF8)

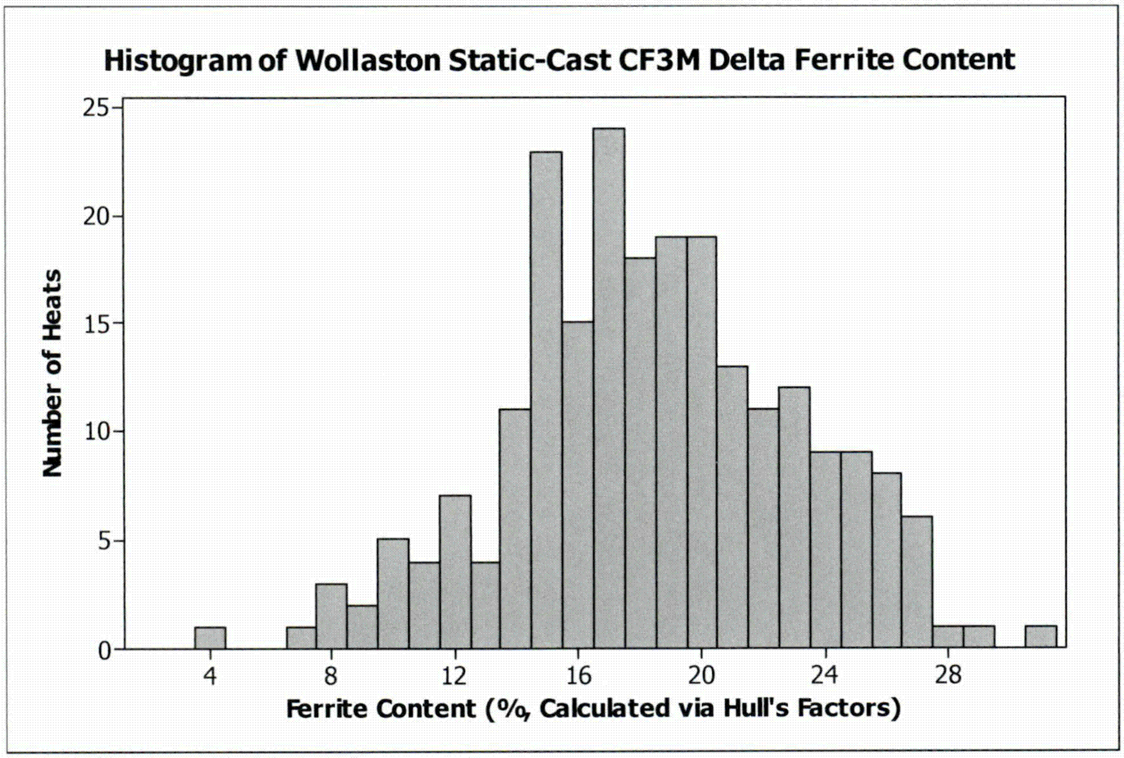

Figure A-59. Histogram of Wollaston Ferrite Content (Grade CF3M)

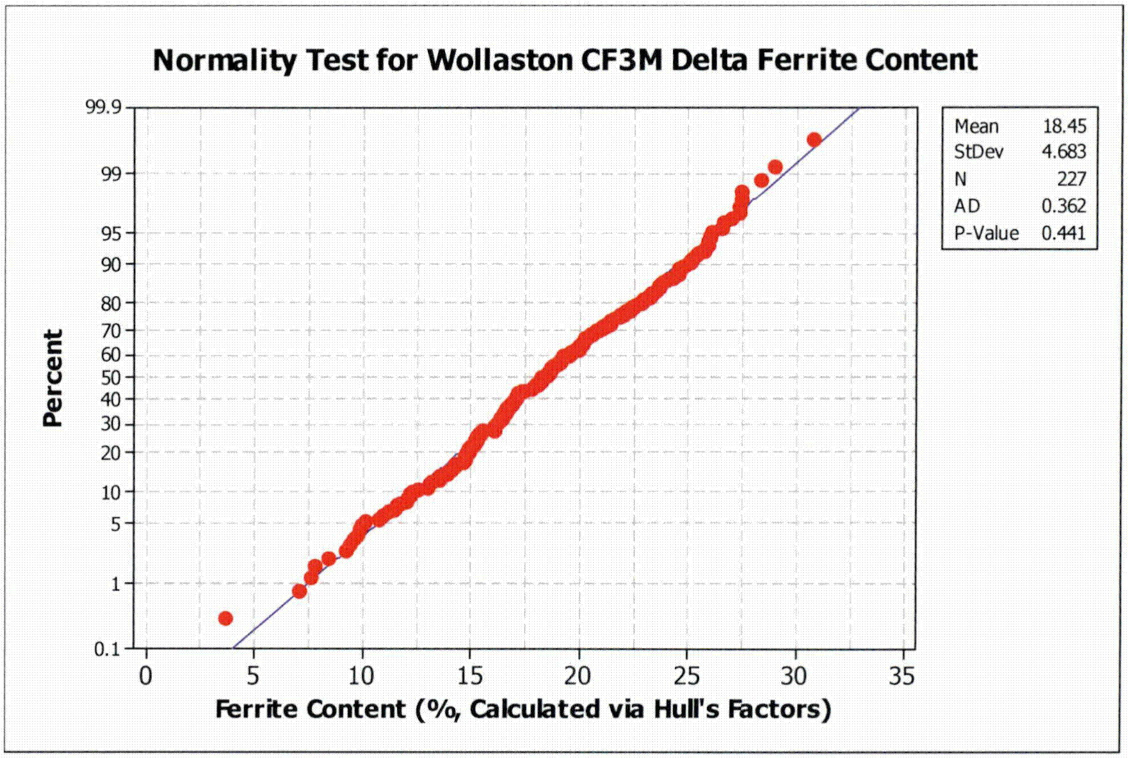

Figure A-60. Normality Test for Wollaston Delta Ferrite Content (Grade CF3M)

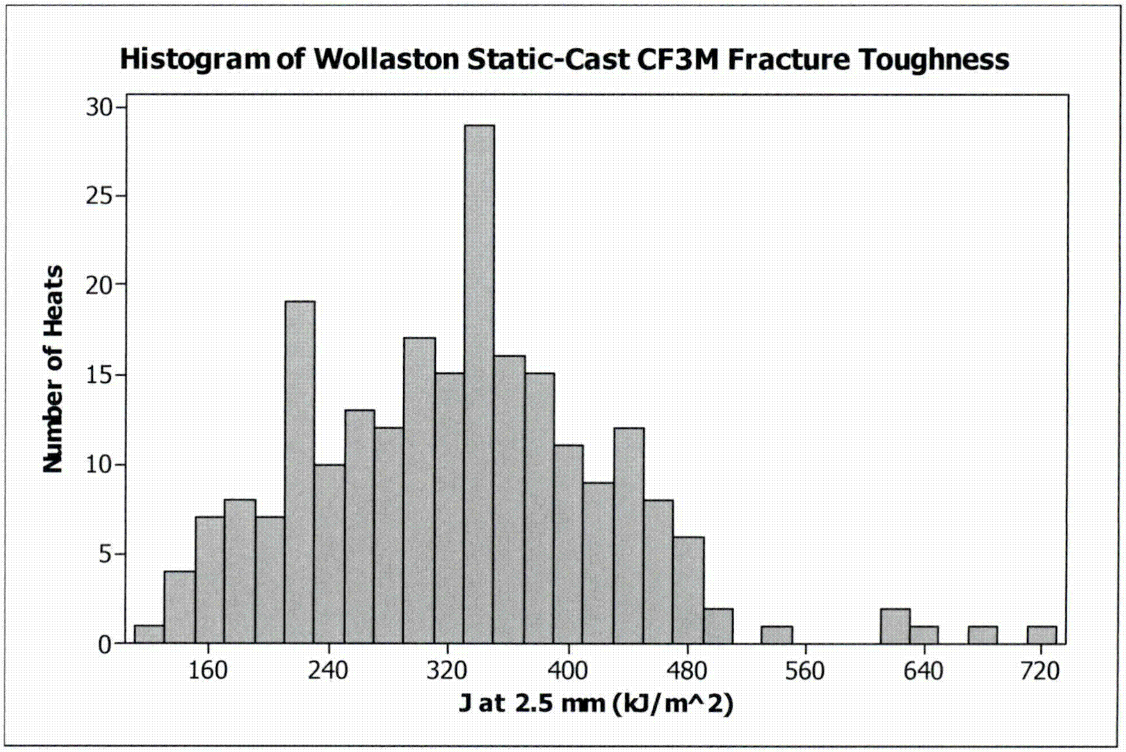

Figure A-61. Histogram of Wollaston Fracture Toughness (Grade CF3M)

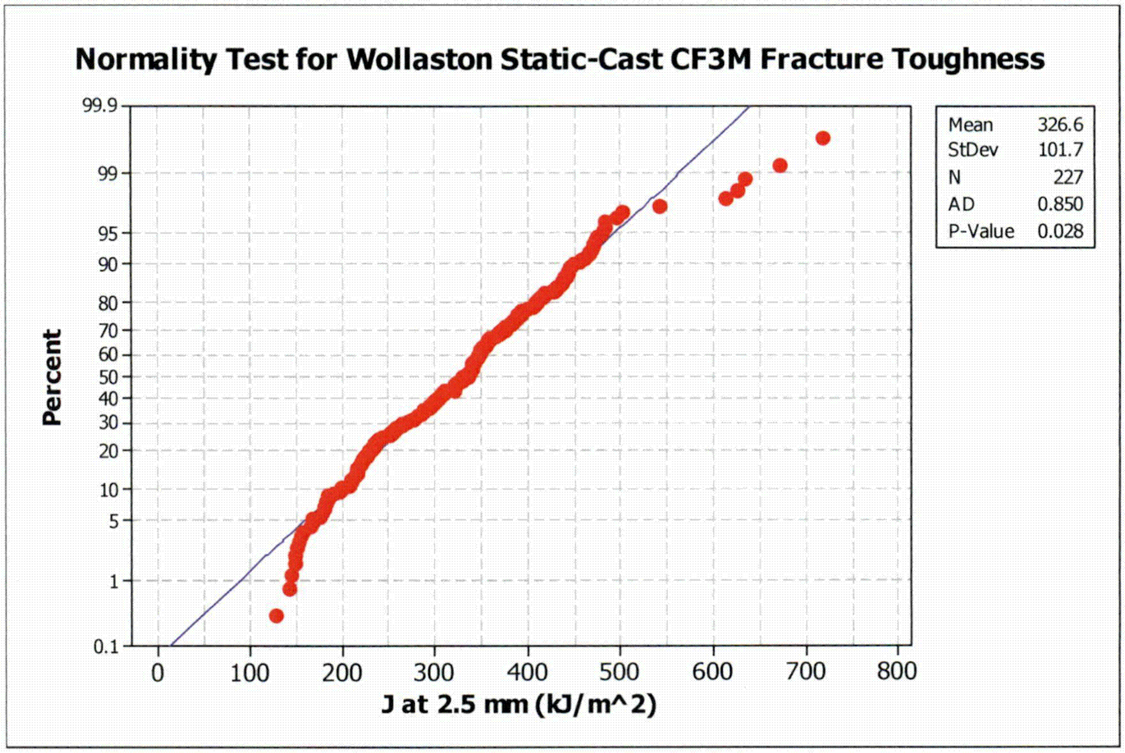

Figure A-62. Normality Test for Wollaston Fracture Toughness (Grade CF3M)