Westinghouse Non-Proprietary Class 3

WCAP - 15074

Evaluation of the 1P3571 Weld Metal from the Surveillance Programs for Kewaunee and Maine Yankee

Westinghouse Energy Systems

Rec'd w/LTR 11/18/98
9811240248

ATTACHMENT 7

Letter from Mark L. Marchi (WPSC)

To

Document Control Desk (NRC)

Dated

November 18, 1998

Proposed Amendment 157

WCAP-15074
Evaluation of IP3571 Weld Metal
From the Surveillance Programs for Kewaunee and Maine Yankee

GBNUC1 N:\GROUP\NUCLEAR\WPFILES\LIC\NRC\PA157R1.XLS

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Evaluation of the 1P3571 Weld Metal from the Surveillance Programs for Kewaunee and Maine Yankee

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September 1998

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PREFACE

This report has been technically reviewed and verified by:

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FORWARD

This report along with four other companion documents have been prepared by Westinghouse Electric Corporation and ATI Consulting to assess and document the integrity of the Kewaunee Nuclear Power Plant (KNPP) reactor vessel relative to the requirements of 10 CFR 50.60, 10 CFR 50.61, Appendices G and H to 10 CFR Part 50, (which encompass pressurized thermal shock (PTS) and upper shelf energy (USE) evaluations), and any potential impact on low temperature overpressure (LTOP) limits or pressure-temperature limits. These reports: (1) summarize the KNPP weld metal (1P3571) surveillance capsule test results performed to date (WCAP-15074); (2) document supplemental surveillance capsule fracture toughness testing results for the KNPP weld metal both in the unirradiated and irradiated condition (WCAP-14279, Rev. 1); (3) introduce and apply a new methodology, based on the Master Curve Approach, for assessing the integrity of the KNPP reactor vessel (WCAP-15075); (4) include various PTS evaluations for KNPP conducted in accordance with the methodology given in 10CFR 50.61 and the Master Curve Approach (WCAP-14280, Rev. 1); and (5) present heatup and cooldown curves corresponding to end of plant life fluence (WCAP-14278, Rev. 1). The heatup and cooldown limit curves presented in WCAP-14278, Rev. 1 are derived using ASME Code Case N-588. These five documents support a new proposed amendment to modify the KNPP Technical Specification limits for heatup, cooldown, and low temperature overpressure protection. The current Technical Specification heatup and cooldown limit curves will expire at 20 EFPY which is scheduled to occur in spring of 1999. The engineering evaluations incorporate all known data pertinent to the analysis of structural integrity of the KNPP reactor vessel and therefore meet and exceed the intent of NRC regulation and expectations.

Background for much of this work is linked to ongoing efforts by the NRC staff to generically resolve concerns raised during their review of reactor vessel integrity for the Yankee Rowe Nuclear Power Station. As part of this effort, the NRC staff issued Generic Letter 92-01, Revision 1 and Generic Letter 92-01, Revision 1, Supplement 1. These generic communiqué seek to obtain certain information that will permit the NRC staff to independently assess and ensure that licensees are in compliance with requirements regarding reactor pressure vessel integrity.

During review of the responses to Generic Letter 92-01, Revision 1 and Generic Letter 92-01, Revision 1, Supplement 1 the NRC discovered inconsistencies within the industry concerning the methodology used to assess reactor pressure vessel integrity including:

1. Large variability in the reported chemistries, i.e., copper and nickel contents, for welds fabricated from the same heat of weld wire.

2. Different initial properties (RT_{NDT}) for welds fabricated from the same heat and weld wire.

3. Different transition temperature shifts for welds fabricated from the same heat and weld wire.

4. Operation with irradiation temperature less than 525°F.

5. Different approaches for determining fluence of the limiting material.

In response to this discovery, to provide assurance that all plants will maintain adequate protection against PTS events, the practice of the NRC staff has been to require that evaluations be performed using conservative inputs. This increase in conservatism seems to apply equally to all areas of assessment of reactor vessel integrity. When best estimate values have been used by utilities for the chemical composition of the reactor vessel, it appears that the NRC staff may require the use of increased margin terms to account for potential variability in chemistries. Furthermore, through the process of issuing RAIs, the NRC staff has requested that evaluations be performed using generic values for initial properties and a corresponding higher margin value from either 28°F to 56°F (if the initial RT_{NDT} is measured) or 44°F to 66°F (if the generic RT_{NDT} is used. Other recent changes include the mandatory use of the ratio procedure, if applicable; a 1°F penalty for each degree Fahrenheit when the irradiation temperature is less than 525°F; and other penalties on the projected fluence of the limiting reactor vessel beltline material at end of license. Collectively, this practice of requiring multiple conservative inputs in a layered fashion for assessment of reactor vessel integrity has the effect that a reactor vessel would be predicted to reach the PTS screening criteria at an earlier date than that given by the PTS assessment methodology given in 10 CFR 50.61. A situation of applying too much conservatism can create the illusion that a reactor vessel is unsafe to operate when in fact it may possess sufficient fracture toughness. If too much conservatism is applied the overall affect can be a decrease in safety because of unnecessary changes made to plant operations and design for the sole reason of addressing a conservative but erroneous PTS evaluation.

At about the same time Generic Letter 92-01, Revision 1, Supplement 1 was being issued, the NRC staff became aware of ABB-CE proprietary data that could affect the PTS assessment of the KNPP reactor vessel. Subsequently, ABB-CE provided KNPP a summary of the data for its evaluation in a letter dated April 6, 1995. The NRC staff met with the KNPP staff on April 13, 1995 to discuss the effect that the ABB-CE data and its plant specific surveillance data would have on their PTS assessment. Prior to this meeting, the NRC staff verbally expressed concern to KNPP management that the KNPP reactor vessel may reach the PTS screening criteria before the end of their license. The KNPP staff presented its plant specific surveillance program results and some new information related to the reactor vessel chemistry variability. Based upon using best estimate input parameters, the KNPP staff showed that the KNPP reactor vessel will not reach the PTS screening criteria before the end of their license. Recognizing that the NRC staff was still concerned about the possibility of the KNPP reactor vessel reaching the PTS screening criteria prior to end of license, the KNPP staff remained steadfast in their use of best estimate input parameters for assessment of reactor vessel integrity. At the same time KNPP committed resources to develop industry programs that would facilitate implementation of the applicable requirements specified in the 1992 Edition of Appendix G to 10 CFR 50 should it become necessary: supplemental fracture toughness tests of the beltline material after exposure to neutron irradiation; perform analysis that demonstrates the existence of equivalent margins of safety for continued operation, and thermal annealing. At the conclusion of the April 13, 1995 meeting, the KNPP staff described their future plans to ensure compliance with the requirements for reactor vessel integrity. These plans included participation with industry groups to create programs and a data base detailing the chemical composition of reactor vessel beltline materials; demonstration of the feasibility for annealing of a PWR reactor vessel of US design; and direct measurement of fracture toughness from irradiated surveillance capsule specimens.

In a NRC internal memorandum (dated May 6, 1995 from Jack R. Strosnider, Chief - Materials and Chemical Engineering Branch, Division of Engineering to Ashok C. Thadani, Associate Director for Technical Assessment, Office of Nuclear Reactor Regulation) released following the April 13, 1995 meeting, the NRC staff wrote that they had not completed their review of the new information on the KNPP reactor vessel. The NRC staff noted that the new chemistry data could significantly change the KNPP PTS evaluation. However, based on conservative evaluations, the NRC staff concluded that the KNPP reactor vessel will not reach the PTS screening criteria in the near future. During this same time period, WPSC submitted a proposed amendment to the NRC to modify KNPP Technical Specification limits relating to heatup, cooldown, and low temperature overpressure protection (LTOP). The NRC issued two requests for additional information regarding this proposed amendment, dealing with surveillance capsule fluence and material properties, and then requested that WPSC withdraw it from the docket pending resolution of Generic Letter 92-01, Revision 1, Supplement 1 activities.

While the NRC was performing a detailed review of licensee responses to Generic Letter 92-01, Revision 1, each of the PWR NSSS Owners Groups developed and implemented programs dealing with measurement of fracture toughness for reactor vessel materials. WPSC has funded both the WOG and ABB-CE/RVWG to measure the fracture toughness of two 1P3571 archive weld metals (utilizing different coils of weld wires) using the Master Curve Approach. The WOG and ABB-CE/RVWG have obtained unirradiated T_o values for weld metal 1P3571 in accordance with ASTM E1921-97. The WOG has also obtained the fracture toughness for 1P3571 weld metal from unirradiated 1/2T-CT specimens. Furthermore, the WOG has generated irradiated T_o values for the two of 1P3571 weldments reconstituted from surveillance capsule specimens from the KNPP and Maine Yankee reactor vessels that were irradiated to 3.36 x 10^{19} n/cm^2 and 6.11 x10^{19} n/cm^2, respectively. The ASME B&PVC is currently working under the direction of PVRC to develop recommendations and guidelines for the use of T_o values in lieu of RT_{NDT} values for assessment of reactor vessel integrity. The results of the supplemental fracture toughness testing for both the unirradiated and irradiated 1P3571 weld metal, along with application of the results, has been presented to the PVRC and ASME.

WPSC concluded that it is prudent to report the results of the recently completed fracture toughness testing of the EOL and beyond EOL irradiated 1P3571 weld metal along with the values derived for the various PTS evaluations given by the methodology described in 10 CFR 50.61. The results of the irradiated fracture toughness testing will serve as a means of assuring adequate conservatism is incorporated into the integrity assessment of the KNPP reactor vessel. Furthermore, since the fracture toughness transition shift is larger and more accurate than the Charpy transition shift, it is felt that continued use of the Charpy results could be inappropriate. The KNPP has volunteered to be a lead plant on behalf of the WOG for application of the Master Curve Approach. NRC feedback obtained on this application of the Master Curve Method will be considered, as appropriate, by the WOG. The fracture toughness results along with the methodology presented in WCAP-15075 indicate that the KNPP 1P3571 weld metal will continue to conservatively provide adequate fracture toughness up to and beyond extended end-of-life fluence.

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EXECUTIVE SUMMARY

The Kewaunee and Maine Yankee surveillance weldments have been evaluated relative to each other, incorporating other related industry information and utilizing traditional best-estimate transition temperature shift methods. Appropriately conservative margins using this traditional methodology have been applied, which have been separated into general uncertainty and material heat uncertainty components. The results indicate that the Kewaunee vessel at end of life has an ART (or RT_{PTS}) lower than the PTS screening criterion for a circumferential vessel weld. An analysis using the worst condition for all of the analytical parameters can result in a much higher value of ART above the screening criterion. However, a metallurgical inclusion analysis of the Kewaunee and Maine Yankee surveillance weldments supports that the worst condition for all of the analytical parameters should not be applied to the Kewaunee surveillance weld.

Additional work has been conducted using directly measured fracture toughness on the Kewaunee and Maine Yankee surveillance weldments to better understand the true toughness at end of life; these results are published in a companion report and indicate the degree of excess margin in the traditional transition temperature calculation approach.

1 INTRODUCTION

The Kewaunee nuclear reactor pressure vessel (RPV) was fabricated by Combustion Engineering (CE) using a Mil B-4 weld filler wire (1P3571 with Linde 1092 flux) in the circumferential welds in the beltline region. This weld wire is the most limiting material in the Kewaunee RPV beltline region with regard to neutron radiation embrittlement. Two other pressurized water reactor (PWR) vessels, Maine Yankee and D. C. Cook Unit 1, were fabricated using this same weld wire heat of material. At least one other vessel of boiling water reactor (BWR) design, LaSalle Unit 1, was fabricated using the 1P3571 weld wire heat. The surveillance program weldments for Kewaunee, Maine Yankee, and LaSalle Unit 1 were all fabricated using the 1P3571 weld wire heat; additionally, the surveillance weldment for the BWR vessel, Hatch Unit 1, also has been reported to be fabricated using 1P3571, but none of the actual vessel welds in Hatch Unit 1 were fabricated using 1P3571.

The effects of neutron radiation embrittlement are a loss in fracture toughness and an increase in the flow properties of the affected beltline materials (and in particular for the Kewaunee circumferential weld metal 1P3571). When the monitored fluence level increases to the point that the degree of embrittlement is significant, the toughness of the weld metal can be reduced to a level where specific steps must be taken. The traditional practice of monitoring embrittlement and accumulated fluence is through the vessel surveillance program. Safe operation is known to exist as long as the NRC screening criterion for pressurized thermal shock (PTS) of 300°F for the circumferential weld is met and conservative pressure–temperature heatup and cooldown curves are employed. Prior to exceeding the PTS screening criterion (as suggested by the NRC staff in a meeting on April 13, 1995), certain actions should be taken according to 10 CFR Part 50[1]: (1) implement flux reduction programs that are reasonably practicable to avoid exceeding the PTS screening criterion; (2) if flux reduction is not a practical solution, a safety analysis should be submitted to determine what, if any, modifications to equipment, systems, and operation are necessary to prevent potential failure of the reactor vessel as a result of postulated PTS events if continued operation beyond the screening criterion is allowed; (3) in the analysis, properties of the RPV materials using all available information including research results and plant surveillance data may be used coupled with probabilistic fracture mechanics techniques; (4) alternatively, the reactor vessel beltline may be given a thermal annealing treatment to recover the fracture toughness of the material.

It is not practicable to utilize flux reduction schemes for the Kewaunee vessel due to the number of years that the plant has already operated. Therefore, in a proactive manner, WPSC has moved forward with data collection and additional testing of the archive and surveillance program material of 1P3571. If ever needed this information could be used in a probabilistic fracture mechanics evaluation, but more importantly it provides the best current knowledge of the true toughness of the Kewaunee weld containing weld wire 1P3571. Additionally, WPSC has conducted a recent inservice inspection of the Kewaunee RPV using the latest inspection procedures and methods.

Traditional fracture mechanics evaluations require knowledge of the initial nil-ductility reference temperature (RT_{NDT}) for the weld material plus the estimate of the shift in RT_{NDT} as predicted or measured using the shift in the Charpy V-notch 30 ft-lb temperature (ΔT_{30}). For Kewaunee, the age of the vessel was such that a true measure of the initial RT_{NDT} was not originally required, and the initial RT_{NDT} was estimated using Charpy V-notch impact properties alone or using generic values for CE-type welds. After locating archive capsule material at Westinghouse, WPSC had supplemental drop weight nil-ductility transition temperature tests performed[2] in accordance with ASTM E208[3]. A properly measured value of initial RT_{NDT} is based upon the measured nil-ductility transition temperature (NDT) per ASTM E208 and Charpy V-notch properties at a temperature equal to or greater than NDT + 60°F. The measured initial RT_{NDT} for the Kewaunee surveillance weld is -50°F, but a measured value for the Maine Yankee surveillance weld is -30°F, where the RT_{NDT} is dictated by the measured NDT for both welds. This difference in NDT measurements between the two welds suggests a potential toughness difference in the materials prior to neutron exposure. However, the degree of scatter in measured NDT also can be within this 20°F difference, and the scatter in generic RT_{NDT} results for CE-fabricated welds (with a mean of –56°F) includes values as high as the –30°F. A coarse microstructural investigation of the two weldments was undertaken as described later to identify any differences in inclusion sizing or distribution which could account for these initial toughness differences.

Both the Kewaunee and the Maine Yankee RPVs have been monitored extensively for radiation embrittlement through plant-specific surveillance programs using tensile and Charpy V-notch specimens. The surveillance results between the two 1P3571 weldments are not in agreement for the same levels of fluence based upon the Charpy V-notch results. This difference is manifested also in the measured average copper contents for the two welds. These differences have led to the direct measurement of fracture toughness (using compact and precracked Charpy fracture toughness specimens) utilizing the new Master Curve methodology for both the unirradiated and irradiated conditions for the Kewaunee and Maine Yankee surveillance welds. The fracture toughness evaluation for these two surveillance materials is described in a companion report, "Master Curve Strategies for RPV Assessment (WCAP-15075)."[4] Note that irradiation results from LaSalle Unit 1 and Hatch Unit 1 are also available, but the irradiation environment for the BWRs is different enough from a PWR that the low fluence transition temperature shift measurement is not considered relevant for comparison with the PWR test results. The measurements of chemical composition for the LaSalle Unit 1 and Hatch Unit 1 surveillance welds are considered relevant and are used as discussed in this report.

The overall purpose of this report is to provide the framework and background data for assessment of the Kewaunee and Maine Yankee surveillance welds, but including any other pertinent data available in the industry. The emphasis is on the traditional RT_{NDT} and Charpy V-notch analyses to assess the effects of radiation embrittlement for the 1P3571 weld(s) in accordance with the methodologies in Regulatory Guide 1.99, Revision 2[5] and 10 CFR 50.61[6]. A companion report (WCAP-14279, Rev. 1)[7] documents the most recent measured fracture toughness of these welds in both the unirradiated and irradiated conditions to provide a direct comparison with the traditional transition temperature approach. This report presents different options for combining Kewaunee-specific and industry data on weld wire 1P3571. Recommendations, known to be acceptable to the NRC staff, based upon detailed evaluations using traditional transition temperature methodologies are presented. These recommendations are in direct response to the NRC staff requests made in April 1995.

This is the first report in a series of five that summarizes and documents recent integrity evaluations performed for the Kewaunee reactor vessel. The other reports describe the surveillance results (including the fracture toughness measurements, WCAP-14279, Rev. 1), the evaluation of the unirradiated and irradiated fracture toughness results, using the Master Curve methodology, WCAP-15075, the application of the results for assessing PTS, WCAP-14280, Rev. 1[8], and application of the results for new heatup and cooldown curves, WCAP-14278, Rev. 1[9].

2 BACKGROUND

Over 50% of the U.S. pressurized water reactor (PWR) vessels were fabricated by CE for either Westinghouse or CE nuclear steam supply system (NSSS) designs. Even more (a higher percentage of) boiling water reactor (BWR) vessels were fabricated by CE for General Electric (GE). Five Westinghouse NSSS-design vessels were initiated by Babcock & Wilcox (B&W), but the final welding was completed by CE. Most of these CE-fabricated vessels used SA533B-1 steel plate construction with three axial welds in each shell course; some of the B&W vessels completed by CE used SA508-2 ring forgings for each shell course. The CE production welds represent a population of vessel materials that have experienced an enhanced level of radiation embrittlement due to the presence of copper coating on the weld wire (and further exacerbated in some cases by relatively high levels of nickel alloying). Many vessels were fabricated during the same time period by CE at the Chattanooga, Tennessee facility, and a specific lot (heat) of weld wire often was used to fabricate more than one reactor pressure vessel (or alternatively a steam generator or pressurizer). One particular weld wire heat, 1P3571 (or sometimes denoted as 1P3571), was used to weld portions of the reactor beltline region for four commercial reactor pressure vessels. These four vessels and the associated operating utilities are:

- D. C. Cook Unit 1 (Cook-1) -- American Electric Power Service Corporation (AEP)
- Kewaunee -- Wisconsin Public Service Corporation (WPSC)
- LaSalle County Unit 1 (LaSalle-1) -- Commonwealth Edison Company (CECO)
- Maine Yankee (MY) -- Maine Yankee Atomic Corporation (MYAC)

One of the four, LaSalle-1, is the only BWR vessel, and the welds of concern are axial (longitudinal) in the middle beltline shell course (actually near the top of the active core region). The three PWR vessels have the subject weld wire heat in the circumferential welds in the beltline region (intermediate-to-lower shell welds). The surveillance program welds for Kewaunee, MY, and LaSalle-1 have weld wire heat 1P3571 as the surveillance weld; the surveillance weld at Cook-1 is a different beltline weld heat. Note that all of the 1P3571 welds listed here are reported to have been made using a 3/16-in. diameter wire rod with Linde 1092 flux lot number 3598. The Georgia Power Company Hatch Unit 1 (Hatch-1) surveillance weld was also fabricated using weld wire heat 1P3571, but none of the actual vessel welds correspond to this weldment.

As will be described later, the surveillance program Charpy V-notch results from MY and Kewaunee are not in good agreement, but this difference is not unexpected considering that the average bulk copper chemistry differs between these two welds. These differences could be consistent with the amount of copper in solid solution in the matrix microstructures for the two welds, but these measurements have not been made. Neither the Hatch-1 or the LaSalle-1 surveillance welds had any archive material available or baseline Charpy V-notch data; regardless, the shift in transition temperature is not expected to be large since the fluence level is low (being the first capsule pulled for these BWRs).

It has been common industry practice to provide and utilize, where appropriate, all known chemistry from related vessels fabricated using the same heat of material. The NRC initiated a request for utilities through Generic Letter 92-01 (and its supplements) to further identify and compare "sister" vessel information through the evaluation and interpretation of reported information. Both NRC and industry have developed databases that include the Generic Letter 92-01 information (NRC database RVID)[10] plus additional supporting information (industry database RPVDATA)[11]. The knowledge of "sister" vessels relative to 1P3571 was only partial until databases such as RPVDATA were utilized.

As indicated earlier, three of the vessels have weld wire heat 1P3571 as their surveillance weld. Results are available from four Kewaunee capsules and from four MY capsules (with two different lead factors). Also, there are test reactor data available for the MY surveillance weld. The testing of the first capsules for Hatch-1 (1985) and LaSalle-1 (early 1995) has been performed, but the importance of these very low fluence results (1-2 x 10^{17} n/cm^2 for E > 1 MeV) from a BWR environment is small for comparison with the PWR and test reactor-simulated-PWR data. However, measurements of copper and nickel chemistry for the surveillance weld specimens form Hatch-1 and LaSalle-1 have been made, and the measurements have been factored into the overall database for 1P3571 welds.

Archive material exists for the Kewaunee surveillance weld at WPSC, and also there is archive material for the MY weld at MYAC and at CE (now ABB-CE). There is no known archive 1P3571 weld metal for Cook-1, Hatch-1, or LaSalle-1.

The data available from weld wire heat 1P3571 have been compiled by WPSC and MYAC, and the results from the two sources do not agree in several ways (consistent with the fact that these two weldments represent various coils of the same heat of weld wire): the copper chemistry is lower on average for the Kewaunee weld, the measured shift in the 30 ft-lb Charpy transition temperature is lower for the Kewaunee weld, and the measured initial NDT temperature and subsequent reference transition temperature, RT_{NDT}, are lower for the Kewaunee weld. Each of these issues are addressed with the supporting information/data.

It is the goal of this report to determine the best estimate values of chemistry, initial pre-irradiated mechanical properties, and irradiated shift values for the 1P3571 weld based upon the overall, highly scattered population of data. Application to the Kewaunee vessel is emphasized as well as discussion of how limited data sets can produce different results.

Copper and Nickel Chemistry

There are about seventy documented chemistry measurements for weld wire heat 1P3571 including the most recent compilation by the CE Reactor Vessel Group results[12]. The results listed in Tables 2-1a through 2-1c were derived from the recent CE report with the data separated into distinct sets: Kewaunee surveillance (Table 2-1a), MY surveillance (Table 2-1b), and other measurements such as weld qualification, LaSalle-1, and Hatch-1 (Table 2-1c). The data have been re-evaluated here, but the overall results are not very different than those suggested by CE. The mean copper content for the Kewaunee surveillance weld is less than that for the MY surveillance weld, but the deviation is quite high allowing an overlap into the

MY average and spread. The weld qualification (WQ) results suggest higher levels of copper while the Hatch-1 and LaSalle-1 suggest intermediate levels. Note that the nickel distributions are essentially equivalent with small standard deviations.

The basis for the values listed in Tables 2-1a through 2-1c were derived from the CE evaluation of tabulated valid and indeterminate values[12] and the listed values from RPVDATA, Version 1.3[11]. Two sets of two reported measurements for the Maine Yankee weldment were adjusted since they were not independent measurements of different positions in the weldment; they were duplicate measurements of the same position and were simply averaged here to give two measurements (see the first four measurements listed in Table 2-1b). The last reported measurement for the MY weld in Table 2-1b may have been in a weld repair region where a lower copper E8018 electrode was used, but further investigation could not provide enough proof to delete from the evaluation. One of the weld qualification measurements included by CE was for a Linde 80 weldment made using 1P3571 weld wire; this measurement was excluded since it was not a Linde 1092 weldment. All of the indeterminate values listed by CE were included here in the new evaluation since there was not other external information available that could allow data exclusion. The Hatch Unit 1 results have been questioned as to independent measurements and validity as to being weld wire 1P3571, but no additional information could be found and all of the data were included in this evaluation. The CE estimate for the pertinent number of weld wire coils was used as listed in the tables.

The averaged values for the combined results are shown in Table 2-2. Different averaging methods were used to derive numbers that can then be assessed to give best estimate chemistry. It was judged that the most relevant copper value corresponds to the coil-weighted average (0.287 wt%), and the most relevant nickel value corresponds to the simple averaging method (0.756 wt%). These best estimate numbers for the Kewaunee vessel, as derived here, are termed the industry best estimate values; these values are only slightly higher than those determined by CE to be the best estimates: 0.283 wt% Cu using the coil-weighted average and 0.755 wt% Ni using a sample-weighted average[12].

The distributions for the copper measurements for the Kewaunee surveillance weld are shown as a bar graph in Figure 2-1; note the skewed behavior to higher copper values with a mean in the 0.219 wt% copper interval. Figure 2-2 shows a similar graph for the Maine Yankee surveillance weld; the graph is essentially Gaussian with a mean value of 0.351 wt%. Figure 2-3 shows the combination of the data from Figures 2-1 and 2-2 which clearly suggests bimodal response with only a slight overlap between the Kewaunee and Maine Yankee results. Bimodal response suggests that two distinct copper-coated coil types dominate the results. Figure 2-3 also shows the distribution of the other data from WQ, LaSalle-1, and Hatch-1. The overall chemistry results and corresponding chemistry factors per RG1.99R2, which will be used in the evaluations performed later, are summarized in Table 2-3.

These results for weld chemistry indicate the high degree of variability in the 1P3571 welds. The two surveillance weldments from Kewaunee and Maine Yankee are on the extremes of the bimodal copper chemistry behavior evident for this weld wire heat and should (and do) behave differently in terms of irradiation response. Also, the initial mechanical properties should be (and are) different between these surveillance weldments due to the sampling of different coils of weld wire 1P3571. As will be discussed later, the peculiar heat treatment for the MY surveillance weld appears to lead to poorer initial properties as compared to the Kewaunee surveillance weld. The study looking at metallurgical inclusions supports the differences seen in the initial mechanical properties (i.e., upper shelf Charpy energy and drop-weight NDT). In all likelihood, the Kewaunee and Maine Yankee vessel welds are similar to the Kewaunee surveillance weld. Since there is no direct proof of this, it is prudent to appropriately consider the MY surveillance weld, data when analyzing the Kewaunee vessel.

Charpy Shift Results and Surveillance Program Credibility

The surveillance program results from the Kewaunee and Maine Yankee reactor vessels are presented here to show the comparison between the two surveillance programs with reference to 10 CFR 50.61 and Regulatory Guide 1.99, Revision 2 (RG1.99R2) prediction and adjustment methodologies. Kewaunee has tested four capsules (V, R, P, and S)[13-16]. The results from Kewaunee were evaluated using CVGRAPH 4.1[17] as shown in Figure 2-4 for an averaged chemistry of 0.219 wt% copper and 0.724 wt% nickel (see Table 2-3). The chemistry factor based upon the average best-estimate copper and nickel is 187.2°F, and the chemistry factor derived using the surveillance results is 192.3°F, which is essentially equivalent. Table 2-4 shows the evaluation process used to obtain the surveillance data chemistry factor. Note the low degree of data scatter. These data meet all of the credibility requirements of RG1.99R2, as indicated in the appendix to the Capsule S companion report, WCAP-14279, Rev. 1. Note that the coolant inlet temperature for the Kewaunee RPV has been maintained at about 532°F, and all surveillance capsules are indicative of this temperature based on a time-weighted average.

The MY surveillance shift data from capsules MY263, MY253, MYA25, and MYA35[18-21] are shown in Figure 2-5 using an averaged best-estimate chemistry of 0.351 wt% copper and 0.771 wt% nickel from Table 2-3. Note that the surveillance capsules designated with the letter A indicate a much higher fluence rate for those capsule locations (i.e., accelerated irradiations). The chemistry-based chemistry factor is 237.2°F, and the chemistry factor using the surveillance results is 240.7°F. Table 2-5 provides the evaluation process used to derive the surveillance data chemistry factor. As in the case for the Kewaunee results, the data are not highly scattered, and the MY surveillance results meet the RG1.99R2 credibility criteria[22]. The coolant inlet temperature for the MY vessel is similar to that of the Kewaunee vessel, however, some of the surveillance capsules have a time-weighted average temperature above (MY253 at 542°F) and below (MYA25 at 522°F) that of Kewaunee.

The chemistry factor values for each data set are almost equivalent regardless of using the measured chemistry or using the fit through the associated Charpy surveillance results. But, the results are significantly different between the two surveillance weldments. These two sets of surveillance data produce surveillance-based chemistry factors that are consistent with two distinctly different levels of copper content as indicated previously in Table 2-3.

There also exist material test reactor (MTR) data for the MY weld[22]. These additional results are shown in Figure 2-6 along with MY surveillance results. These additional data from the MTR experiments are in excellent agreement with MY surveillance results. The chemistry factor for the MY surveillance weld when the MTR data are included is raised slightly to 242.6°F. See Table 2-6 for the evaluation to obtain the value of 242.6°F. This consistency validates very little, if any, fluence rate dependence of the test results.

All of the measured shift data (except for the MTR results) on weld wire heat 1P3571 are shown in Figure 2-7 (without adjusting the individual data values using the ratioing procedure), which results in an overall best-fit chemistry factor of 216.2°F. See Table 2-7 for the evaluation of the data to obtain this chemistry factor. This value is 24°F higher than the results from the Kewaunee surveillance program and about 25°F lower than MY surveillance result. However, note in Table 2-7 that the scatter of individual results exceeds 28°F which represents the approximate 1σ (one standard deviation) for the RG1.99R2 correlation for weld metal. Therefore, based upon current NRC assessment methods, this chemistry factor is non-credible.

All of the Kewaunee and MY data were adjusted using the RG1.99R2 so-called ratioing procedure using the chemistry results and subsequent chemistry factors as listed in Table 2-3. The ratioing procedure is an engineering adjustment process in which the individual capsule shift results are adjusted by the ratio of the chemistry factors derived from the RG1.99R2 tables (i.e., the industry best estimate chemistry factor divided by the surveillance weld-specific chemistry factor). The resultant evaluation is shown in Table 2-8, and the curve fit is shown in Figure 2-8. The derived chemistry factor is 218.5°F, and all of the individual data falls inside of the 1σ bound (28°F)on the fit, which meets the credible criterion.

If the Kewaunee data were analyzed alone using the ratioing method (which is the preferred approach of the NRC staff), the resultant chemistry factor would be 219.9°F, which is essentially the same as when all of the Kewaunee and Maine Yankee data are evaluated together using the ratioing method. These results are shown in Table 2-9 and Figure 2-9. Note that the assumed weld chemistry in Figures 2-8 and 2-9 is the industry average for weld wire 1P3571, and the results are very consistent with the chemistry factor derived using the ratioing approach.

Initial RT_{NDT}

Both WPSC and MYAC have measured values of the nil-ductility transition temperature (NDTT or NDT temperature) for their respective surveillance welds: for the MY surveillance weld[23], the measured value is -30°F, and the recently measured value for the Kewaunee surveillance weld[2,7] is -50°F. The type of starter weld used for each independent determination has been checked and verified as a single weld pass. Other aspects of the two NDT temperature determinations have been checked and match the ASTM E 208 Standards and industry practices used.

The Charpy V-notch energy results for each of the two surveillance welds[23-24] are shown in Figure 2-10 illustrating some degree of data scatter. Note that a higher transition temperature is evident for the MY weld as compared to the Kewaunee weld, which is consistent with the higher NDT temperature for the MY weld. Applying the ASME Code Section III rules for defining initial RT_{NDT}, both MY and Kewaunee data support an RT_{NDT} = NDT temperature.

These results mean that the RT_{NDT} is established using the measured NDT temperature consistent with most Linde 1092 welds.

The two measurements of NDT temperature are within the known scatter for non-Linde 80 welds as indicated in the PTS Rule, 10 CFR 50.61: a mean of –56°F with an estimated standard deviation of 17°F. Evaluations of Linde 1092 welds alone also support a mean of about –50°F and a 2σ scatter of about 35°F. Therefore, since the two weldments show a range of results consistent with known behavior, an appropriate value for integrity evaluation of the Kewaunee vessel is –50°F with no additional margin since the value has been measured directly. Alternatively a generic value of –56°F, with the inclusion of the potential uncertainty (1σ) of 17°F, could be applied.

As further support of the differences in the Kewaunee and MY weldments, a metallurgical inclusion study was performed as will be described in the next chapter. The Kewaunee surveillance weld is cleaner in terms of both number and size of Mn-S-Si inclusions, which is consistent with the measured lower transition temperatures and higher upper shelf energy for the Kewaunee weldment.

Tensile Test Results

Figure 2-11 shows the unirradiated and irradiated tensile yield strength results for the two surveillance weldments. The results are difficult to interpret since there are not one-to-one comparisons at the same test temperatures and fluence levels, but they are included here for completeness since they represent supporting results from the surveillance testing programs. There is a definite trend for the Maine Yankee weld to show more of an increase in strength as compared to the Kewaunee weld. These results are consistent with the greater degree of Charpy V-notch transition temperature shift for the Maine Yankee weldment.

Table 2-1a Chemistry Measurements for 1P3571 Weld Wire, Kewaunee Surveillance Weld

1P3571		Linde 1092 Type Flux			Included in	New Evaluation		
Cu	Ni	Flux Lot Number 3958			RPVDATA	Avg. Cu	Avg. Ni	# of
wt %	wt %	CE Pedigree	Weldment	Analysis	Version 1.3	wt %	wt %	Coils
		Kewaunee, Single Arc				0.219	0.724	4
0.17	0.51	Indeterminate Ni	K. HFJ-95-039		Y			
0.15	0.54	Indeterminate Ni	K. HFJ-95-040	MSE-MNA-229(95)	Y			
0.17	0.61	Valid	K. HFJ-95-041		Y			
0.17	0.64	Valid	K. HFJ-95-042		Y			
0.18	0.67	Valid	K. HFJ-95-043		Y			
0.19	0.67	Valid	K. HFJ-95-044		Y			
0.19	0.67	Valid	K. HFJ-95-045	MSE-MNA-229(95)	Y			
0.186	0.689	Valid	K. HFJ-95-046	MSE-MNA-229(95)	Y			
0.2	0.7	Valid	K. HFJ-95-047		Y			
0.19	0.71	Valid	K. HFJ-95-048	MSE-MNA-229(95)	Y			
0.172	0.717	Valid	K. HFJ-95-049		Y*			
0.34	0.72	Valid	K. HFJ-95-050		Y			
0.22	0.73	Valid	K. HFJ-95-051		Y			
0.191	0.734	Valid	K. HFJ-95-052	WCAP-14280	Y*			

Table 2-1a Chemistry Measurements for 1P3571 Weld Wire, Kewaunee Surveillance Weld (Cont.)					
1P3571		Linde 1092 Type Flux			Included in RPVDATA Version 1.3
Cu	Ni	Flux Lot Number 3958			
wt %	wt %	CE Pedigree	Weldment	Analysis	
0.066	0.736	Indeterminate Cu	K. HFJ-95-053		Y
0.24	0.74	Valid	K. HFJ-95-054		Y
0.182	0.742	Valid	K. HFJ-95-055		Y*
0.354	0.742	Valid	K. HFJ-95-056		Y*
0.207	0.769	Valid	K. HFJ-95-057		Y
0.2	0.77	Valid	K. HFJ-95-058		Y
0.43	0.78	Valid	K. HFJ-95-059		Y
0.23	0.79	Valid	K. HFJ-95-060		Y
0.209	0.795	Valid	K. HFJ-95-061	MSE-MNA-229(95)	Y
0.22	0.8	Valid	K. HFJ-95-062		Y
0.434	0.8	Valid	K. HFJ-95-063		Y
0.196	0.803	Valid	K. HFJ-95-064	MSE-MNA-229(95)	Y
0.214	0.816	Valid	K. HFJ-95-065		Y
0.223	0.871	Valid	K. HFJ-95-066	MSE-MNA-229(95)	Y

Y* indicates numbers not rounded in CE analysis

Table 2-1b Chemistry Measurements for 1P3571 Weld Wire, Maine Yankee Surveillance Weld								
1P3571		Linde 1092 Type Flux			Included in	New Evaluation		
Cu	Ni	Flux Lot Number 3958			RPVDATA	Avg. Cu	Avg. Ni	# of
wt %	wt %	CE Pedigree	Weldment	Analysis	Version 1.3	wt %	wt %	Coils
		Maine Yankee, Single Arc				0.351	0.771	4
0.25	0.66	Valid	MY. PR-EDB	BCL-585-21	Y	Averaged with value below:		
0.25	0.7	Valid	MY. PR-EDB	BCL-585-21	Y	(Cu = 0.25 Ni = 0.68)		
0.33	0.7	Valid	MY. PR-EDB	BCL-585-21	Y*	Averaged with value below:		
0.33	0.71	Valid	MY. PR-EDB	BCL-585-21	Y	(Cu = 0.33 Ni = 0.71)		
0.356	0.728	Valid	MY. PR-EDB	WCAP-12819	Y			
0.432	0.745	Valid	MY. PR-EDB	WCAP-12819	Y			
0.365	0.78	Valid	MY. PR-EDB	D9693	Y*			
NRV†	NRV†	Valid	MY. C.E.	D44439	Y			
NRV†	NRV†	Valid	MY. C.E.	D44447	Y			
0.34	0.73	Valid	MY. C.E.	D44441	Y			
0.3	0.76	Valid	MY. C.E.	D44449	Y			
0.35	0.76	Valid	MY. C.E.	D44440	Y			
0.33	0.77	Valid	MY. C.E.	D44443	Y			
0.31	0.78	Valid	MY. C.E.	D44445	Y			
0.32	0.78	Valid	MY. C.E.	D44446	Y			

Table 2-1b Chemistry Measurements for 1P3571 Weld Wire, Maine Yankee Surveillance Weld (Cont.)

1P3571		Linde 1092 Type Flux			Included in RPVDATA Version 1.3	
Cu	Ni	Flux Lot Number 3958				
wt %	wt %	CE Pedigree	Weldment	Analysis		
0.32	0.78	Valid	MY. C.E.	D44447	Y	
0.32	0.78	Valid	MY. C.E.	D44448	Y	
0.33	0.78	Valid	MY. C.E.	D44442	Y	
0.37	0.8	Valid	MY. C.E.	D44439	Y	
0.38	0.8	Valid	MY. C.E.	D44451	Y	
0.52	0.8	Valid	MY. C.E.	D44453	Y	
0.53	0.81	Valid	MY. C.E.	D44452	Y	
0.21	0.88	Valid	MY. C.E.	D44454	Y	**E8018 Repair?**

Y* indicates numbers not rounded in CE analysis

†NRV: No Reported Cu and Ni values

Table 2-1c Chemistry Measurements for 1P3571 Weld Wire, Other Measurements								
1P3571		Linde 1092 Type Flux			Included in RPVDATA Version 1.3	New Evaluation		
Cu	Ni	Flux Lot Number 3958				Avg. Cu	Avg. Ni	# of
wt %	wt %	CE Pedigree	Weldment	Analysis		wt %	wt %	Coils
		LaSalle-1, Tandem Arc				0.213	0.775	4
0.2	0.73	Valid	LS. HFJ-95-039		Y			
0.22	0.73	Valid	LS. HFJ-95-040		Y			
0.2	0.74	Valid	LS. HFJ-95-041		Y			
0.2	0.75	Valid	LS. HFJ-95-042		Y			
0.22	0.75	Valid	LS. HFJ-95-043		Y			
0.2	0.76	Valid	LS. HFJ-95-044		Y			
0.22	0.79	Valid	LS. HFJ-95-045		Y			
0.21	0.8	Valid	LS. HFJ-95-046		Y			
0.21	0.8	Valid	LS. HFJ-95-047		Y			
0.22	0.8	Valid	LS. HFJ-95-048		Y			
0.23	0.82	Valid	LS. HFJ-95-049		Y			
0.22	0.83	Valid	LS. HFJ-95-050		Y			
0.21	0.78	Valid	LS.	D11341	Y			

Table 2-1c Chemistry Measurements for 1P3571 Weld Wire, Other Measurements (Cont.)

1P3571		Linde 1092 Type Flux			Included in RPVDATA Version 1.3	New Evaluation		
Cu	Ni	Flux Lot Number 3958				Avg. Cu	Avg. Ni	# of
wt %	wt %	CE Pedigree	Weldment	Analysis		wt %	wt %	Coils
		Hatch-1, Tandem Arc				0.304	0.807	2
NRV†	0.76	Valid	H. PR-EDB	NEDC-30997	N			
0.28	0.76	Valid	H. PR-EDB	NEDC-30997	Y			
0.28	0.76	Valid	H. PR-EDB	NEDC-30997	Y			
0.32	0.82	Indeterminate	H. SNOC	NE-B1100691-01	N			
0.32	0.87	Indeterminate	H. SNOC	NE-B1100691-01	N			
0.32	0.87	Indeterminate	H. SNOC	NE-B1100691-01	N			
		Weld Qualification, Tandem Arc				0.370	0.750	2
0.37	0.75	Valid	C.E.	D8698	Y			
		Weld Qualification, Single Arc				Linde 80	Weld;	
0.22	0.67	Valid	C.E.	D19780	Y	Excluded		
		Weld Qualification, Single Arc				0.400	0.820	1
0.4	0.82	Valid	C.E.	D8669	Y			

Table 2-2 Best Estimate Chemistry Values Determined Using Different Averaging Methods					
Simple Average		Sample-Weighted Average		Coil-Weighted Average	
Cu (wt %)	Ni (wt %)	Cu (wt %)	Ni (wt %)	Cu (wt %)	Ni (wt %)
0.266	0.756	0.309	0.774	0.287	0.766

Table 2-3 Averaged Copper and Nickel Contents for 1P3571 Weldments

Weldment	Average Cu Content (wt%)	Average Ni Content (wt%)	Chemistry Factor from RG1.99R2 Table
Kewaunee Surveillance	0.219[a]	0.724[a]	187.2
Maine Yankee Surveillance	0.351[a]	0.771[a]	237.2
Industry Average for 1P3571	0.287[b]	0.756[c]	214.0

Notes:

[a] Simple average of results for the specific weldment

[b] Coil-weighted average from all of the pertinent industry data

[c] Simple average from all of the pertinent industry data

Table 2-4 Data and Analysis for Kewaunee Surveillance Weld (With No Ratio Adjustment)

	Cu (wt%)	Ni (wt%)	CF, Deg. F
1P3571 Kewaunee Only	0.219	0.724	187.16
Kewaunee Surveillance	0.219	0.724	187.16

Capsule	Measured Shift, Deg. F	Adjusted Shift, Deg. F	Fluence, 10^{19} n/cm^2 (E> MeV)	Fluence Factor (ff)	Adjusted Shift X ff	ff^2	Predicted Shift, Deg. F	Adj. Shift - Predicted Shift, Deg. F
V	175	175	0.597	0.855567	149.72424	0.732	164.5	10.5
R	235	235	1.81	1.162814	273.26124	1.35214	223.6	11.4
P	230	230	2.74	1.268842	291.8337	1.60996	244.0	-14.0
S	250	250	3.36	1.317261	329.31514	1.73518	253.3	-3.3
				Σ =	1044.1343	5.42927		

CF = 192.32 deg. F

Table 2-5 Data and Analysis for MY Surveillance Weld (With No Ratio Adjustment)			
	Cu (wt%)	Ni (wt%)	CF, Deg. F
1P3571 MY Only	0.351	0.771	237.20
Maine Yankee Surveillance	0.351	0.771	237.20

Capsule	Measured Shift, Deg. F	Adjusted Shift, Deg. F	Fluence, 10^{19} n/cm^2 (E> MeV)	Fluence Factor (ff)	Adjusted Shift X ff	ff^2	Predicted Shift, Deg. F	Adj. Shift - Predicted Shift, Deg. F
W-263	222	222	0.567	0.841262	186.7601	0.70772	202.5	19.5
W-253	260	260	1.25	1.062174	276.16523	1.12821	255.7	4.3
A-25	270	270	1.76	1.155356	311.94617	1.33485	278.1	-8.1
A-35	345	345	7.13	1.465848	505.71751	2.14871	352.9	-7.9
				Σ =	1280.589	5.31949		

CF = 240.74 deg. F

Table 2-6 Data and Analysis for MY Surveillance Weld Including Materials Test Reactor (MTR) Data

	Cu (wt%)	Ni (wt%)	CF, Deg. F
1P3571 MY Only	0.351	0.771	237.20
Maine Yankee Surveillance	0.351	0.771	237.20

Capsule	Measured Shift, Deg. F	Adjusted Shift, Deg. F	Fluence, 10^{19} n/cm^2 (E> MeV)	Fluence Factor (ff)	Adjusted Shift X ff	ff^2	Predicted Shift, Deg. F	Adj. Shift - Predicted Shift, Deg. F
W-263	222	222	0.567	0.841262	186.7601	0.70772	204.1	17.9
W-253	260	260	1.25	1.062174	276.16523	1.12821	257.7	2.3
A-25	270	270	1.76	1.155356	311.94617	1.33485	280.3	-10.3
A-35	345	345	7.13	1.465848	505.71751	2.14871	355.6	-10.6
B-7	315	315	3	1.290712	406.57441	1.66594	313.1	1.9
B-7	350	350	5.3	1.413643	494.77499	1.99839	343.0	7.0
B-8	55	55	0.12	0.454339	24.988646	0.20642	110.2	-55.2
B-8	240	240	0.66	0.883519	212.04455	0.78061	214.3	25.7
				Σ =	2418.9716	9.97085		

CF = 242.60 deg. F

Table 2-7 Data and Analysis for Kewaunee and MY Surveillance Welds (With No Ratio Adjustments)

	Cu (wt%)	Ni (wt%)	CF, Deg. F
1P3571 Industry Average	0.287	0.756	213.98
Kewaunee Surveillance	0.219	0.724	187.16
Maine Yankee Surveillance	0.351	0.771	237.20

Capsule	Measured Shift, Deg. F	Adjusted Shift, Deg. F	Fluence, 10^{19} n/cm^2 (E> MeV)	Fluence Factor (ff)	Adjusted Shift X ff	ff^2	Predicted Shift, Deg. F	Adj. Shift - Predicted Shift, Deg. F
V	175	175	0.597	0.855567	149.72424	0.731995	185.0	-10.0
R	235	235	1.81	1.162814	273.26124	1.352136	251.5	-16.5
P	230	230	2.74	1.268842	291.8337	1.60996	274.4	-44.4
S	250	250	3.36	1.317261	329.31514	1.735175	284.9	-34.9
W-263	222	222	0.567	0.841262	186.7601	0.707721	181.9	40.1
W-253	260	260	1.25	1.062174	276.16523	1.128214	229.7	30.3
A-25	270	270	1.76	1.155356	311.94617	1.334848	249.9	20.1
A-35	345	345	7.13	1.465848	505.71751	2.14871	317.0	28.0
				Σ =	2324.7233	10.74876		

CF = 216.28 deg. F

Table 2-8 Data and Analysis for Kewaunee and MY Surveillance Welds (With Ratio Adjustment)

	Cu (wt%)	Ni (wt%)	CF, Deg. F
1P3571 Industry Average	0.287	0.756	213.98
Kewaunee Surveillance	0.219	0.724	187.16
Maine Yankee Surveillance	0.351	0.771	237.20

Capsule	Measured Shift, Deg. F	Adjusted Shift, Deg. F	Fluence, 10^{19} n/cm^2 (E> MeV)	Fluence Factor (ff)	Adjusted Shift X ff	ff^2	Predicted Shift, Deg. F	Adj. Shift - Predicted Shift, Deg. F
V	175	200.0775	0.597	0.855567	171.1797	0.731995	187.0	13.1
R	235	268.6755	1.81	1.162814	312.41954	1.352136	254.1	14.6
P	230	262.959	2.74	1.268842	333.65342	1.60996	277.3	-14.3
S	250	285.825	3.36	1.317261	376.50595	1.735175	287.9	-2.0
W-263	222	200.2722	0.567	0.841262	168.48132	0.707721	183.8	16.4
W-253	260	234.553	1.25	1.062174	249.13609	1.128214	232.1	2.4
A-25	270	243.5743	1.76	1.155356	281.41505	1.334848	252.5	-8.9
A-35	345	311.2338	7.13	1.465848	456.22139	2.14871	320.3	-9.1
				Σ =	2349.0125	10.74876		

CF = 218.54 deg. F

Table 2-9 Data and Analysis for Kewaunee Surveillance Weld (With Ratio Adjustment)	Cu (wt%)	Ni (wt%)	CF, Deg. F
1P3571 Industry Average	0.287	0.756	213.98
Kewaunee Surveillance	0.219	0.724	187.16

Capsule	Measured Shift, Deg. F	Adjusted Shift, Deg. F	Fluence, 10^{19} n/cm^2 (E> MeV)	Fluence Factor (ff)	Adjusted Shift X ff	ff^2	Predicted Shift, Deg. F	Adj. Shift - Predicted Shift, Deg. F
V	175	200.0775	0.597	0.855567	171.1797	0.731995	188.1	12.0
R	235	268.6755	1.81	1.162814	312.41954	1.352136	255.7	13.0
P	230	262.959	2.74	1.268842	333.65342	1.60996	279.0	-16.0
S	250	285.825	3.36	1.317261	376.50595	1.735175	289.6	-3.8
				Σ =	1193.7586	5.429267		

CF = 219.87 deg. F

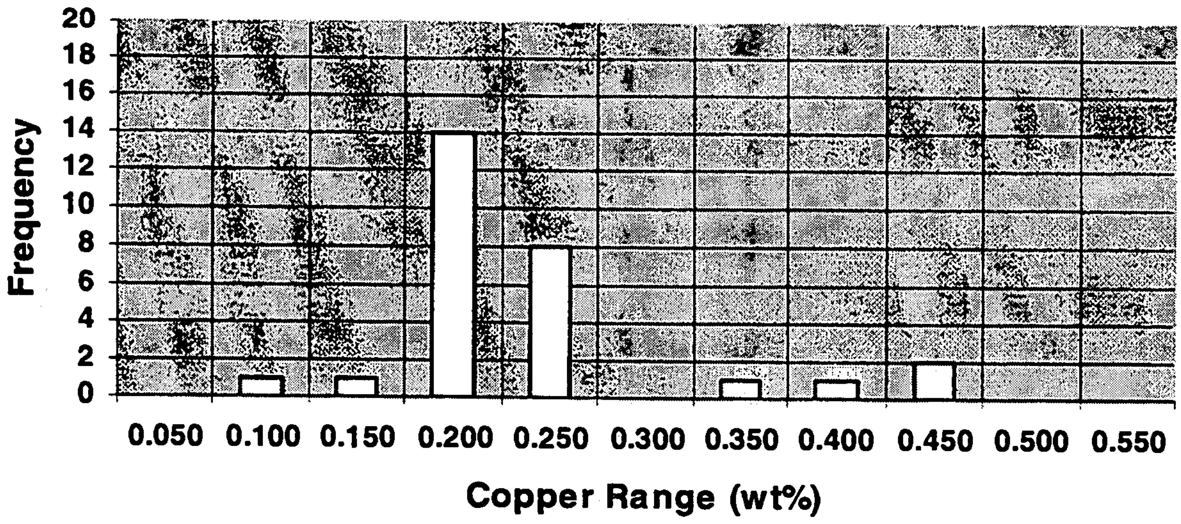


Figure 2-1 Kewaunee Weld Copper Chemistry Distribution

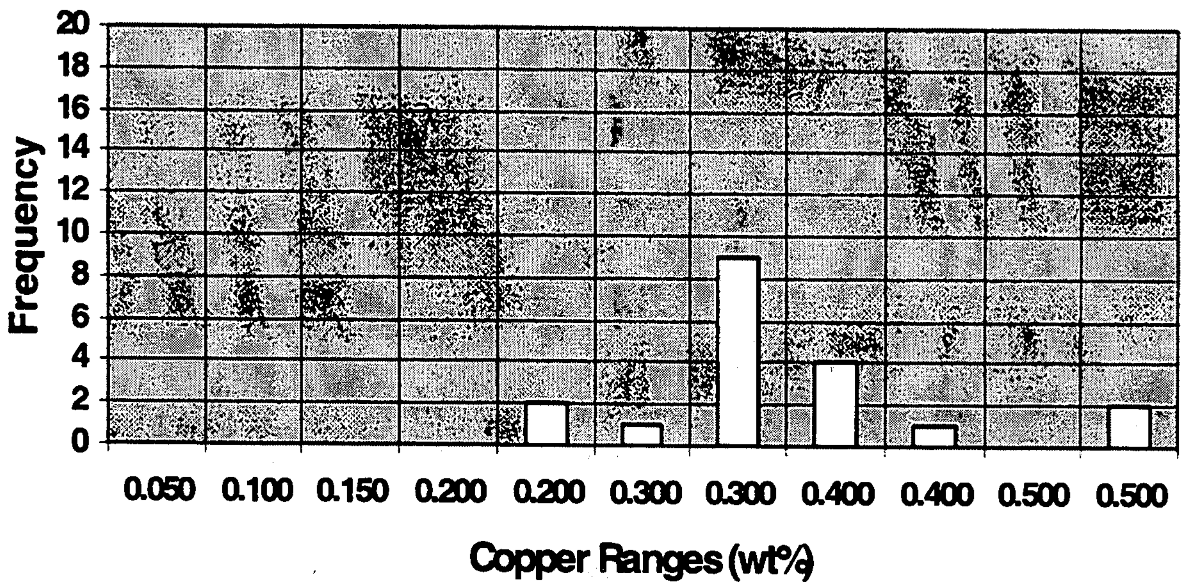


Figure 2-2 Maine Yankee Weld Chemistry Distribution

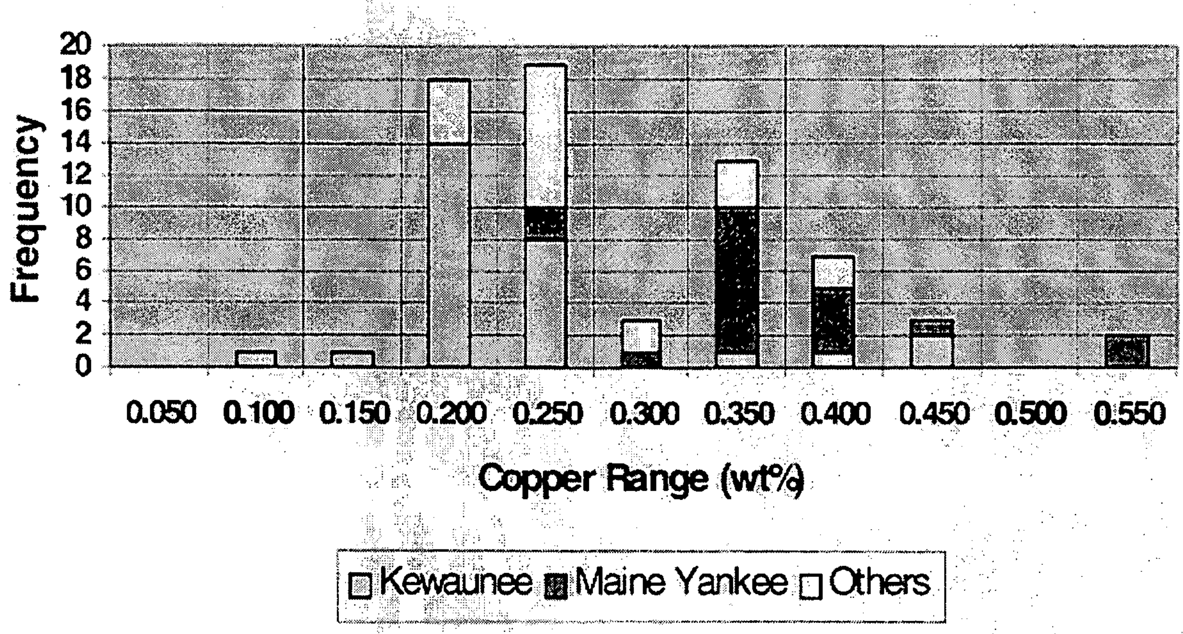


Figure 2-3 Total 1P3571 Weld Copper Chemistry Distribution

Chemical Content is as follows:

Copper = .219 wt%
Nickel = .724 wt%
Phosphorous = 0 wt%
Silicon = 0 wt%

The Chemistry Factor 187.16 F is found by the Reg. Guide 1.99 Revision 2 Method

The Chemistry Factor Fitted to the actual Input Data is 192.3159 F.

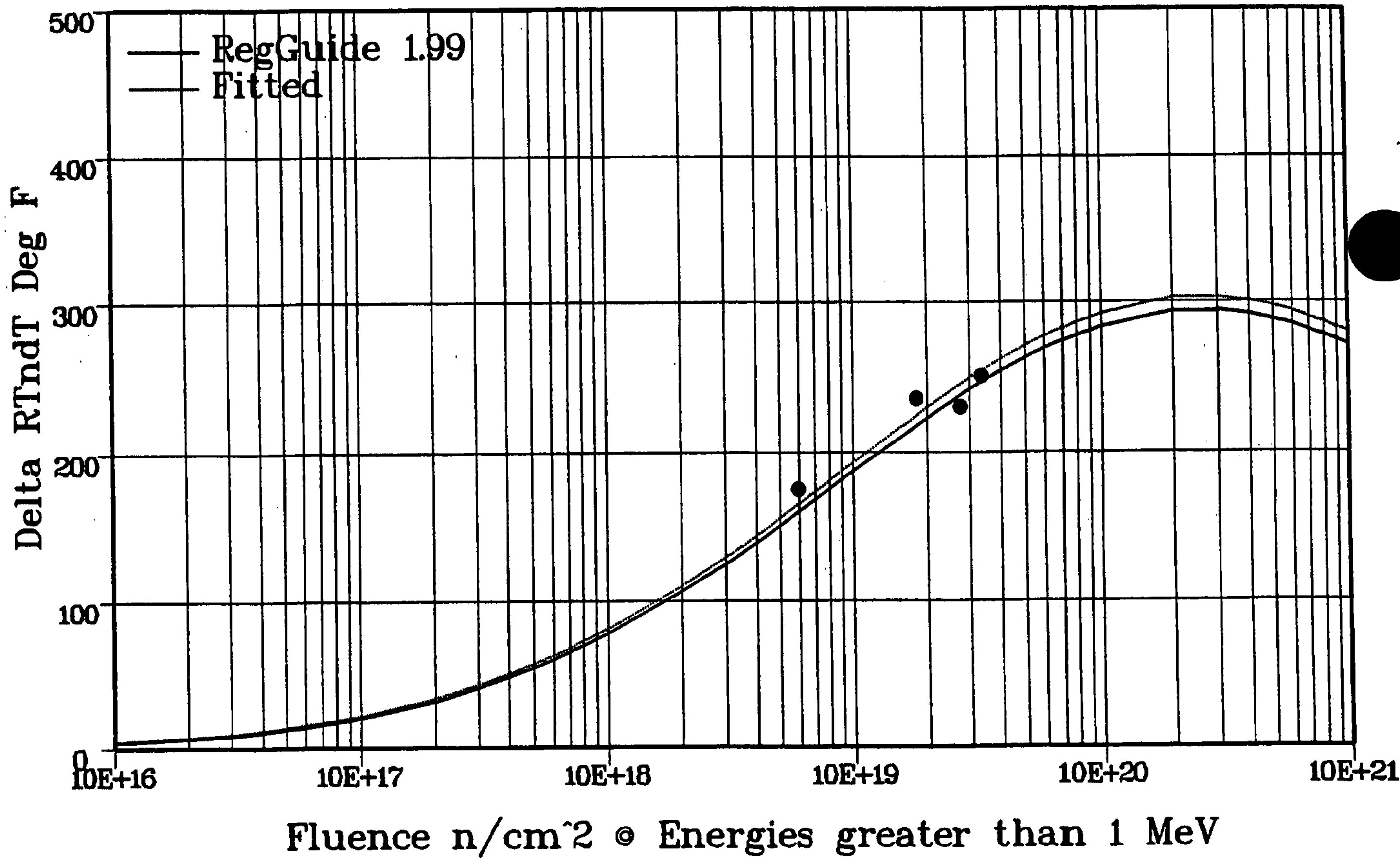


Figure 2-4 Kewaunee Surveillance Weld Data

Chemical Content is as follows:

Copper = .351 wt%

Nickel = .771 wt%

Phosphorous = 0 wt%

Silicon = 0 wt%

The Chemistry Factor 237.195 F is found by the Reg. Guide 1.99 Revision 2 Method

The Chemistry Factor Fitted to the actual Input Data is 240.7352 F.

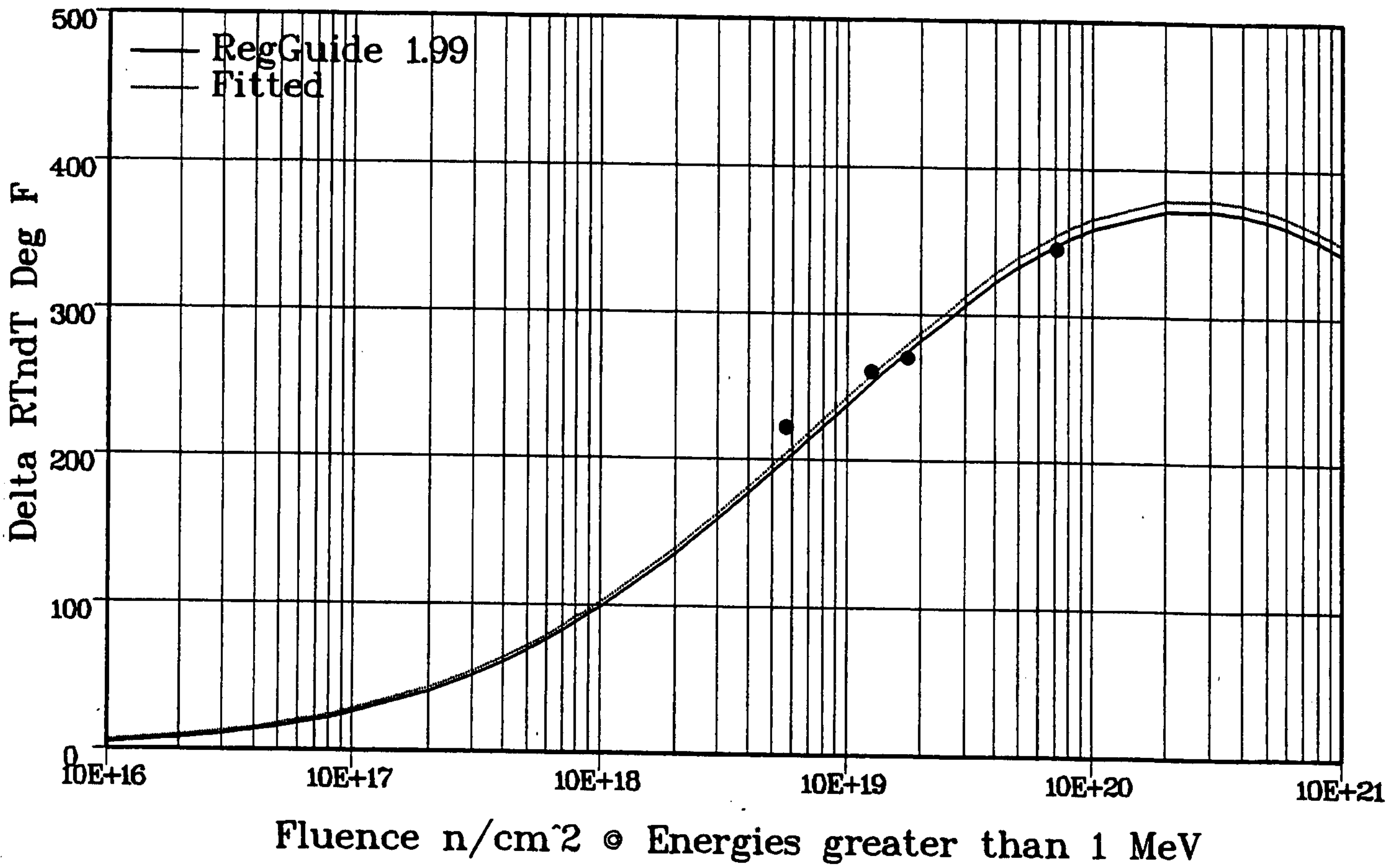


Figure 2-5 Maine Yankee Surveillance Weld Data

Chemical Content is as follows:

Copper = .351 wt%
Nickel = .771 wt%
Phosphorous = 0 wt%
Silicon = 0 wt%

The Chemistry Factor 237.195 F is found by the Reg. Guide 1.99 Revision 2 Method
The Chemistry Factor Fitted to the actual Input Data is 242.6044 F.

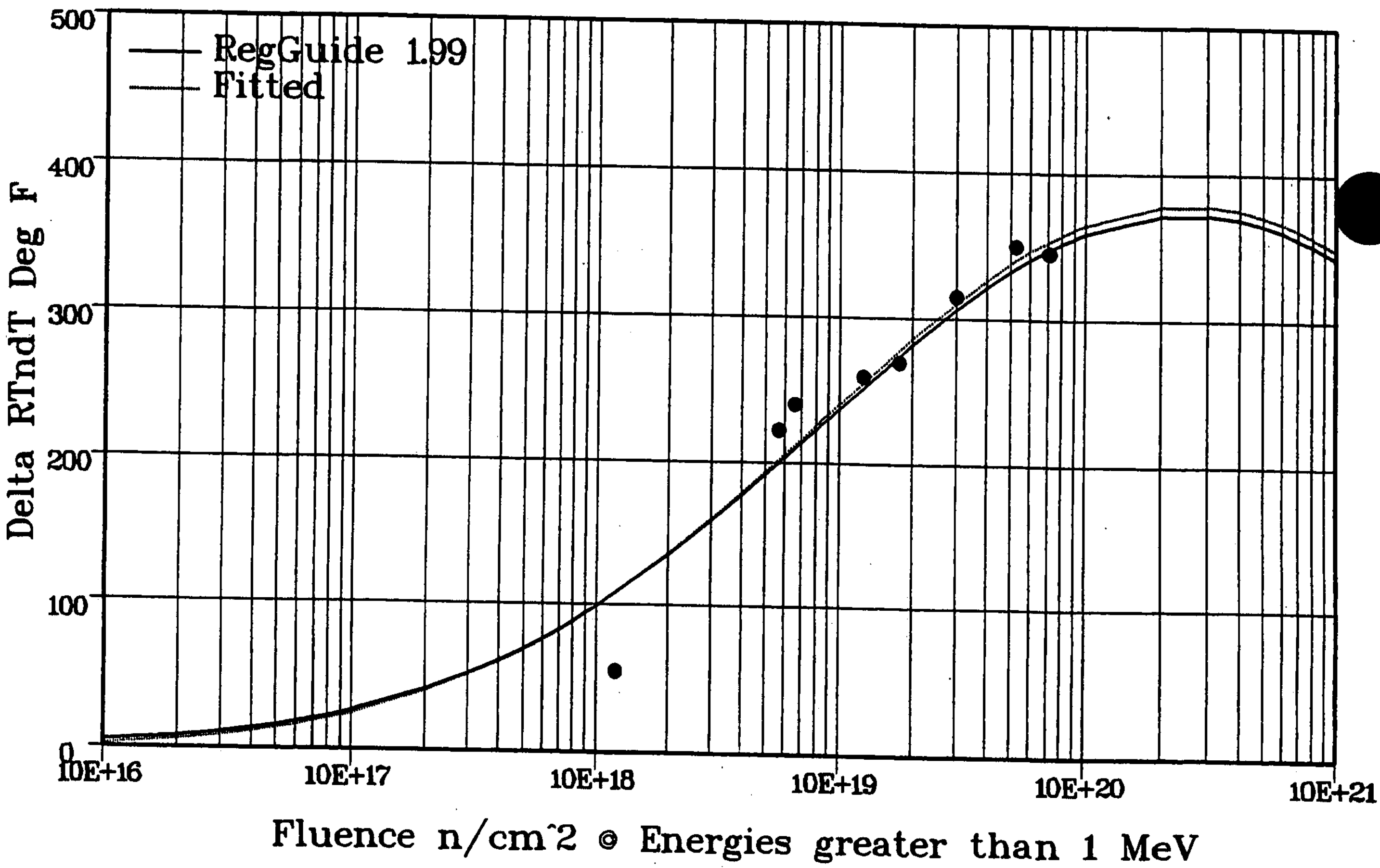


Figure 2-6 Maine Yankee Surveillance Plus MTR Weld Data

Chemical Content is as follows:

Copper = .287 wt%
Niekel = .756 wt%
Phosphorous = 0 wt%
Silicon = 0 wt%

Thc Chemistry Factor 213.98 F is found by the Reg. Guide 1.99 Revision 2 Mcthod
The Chemistry Factor Fitted to the actual Input Data is 216.2783 F.

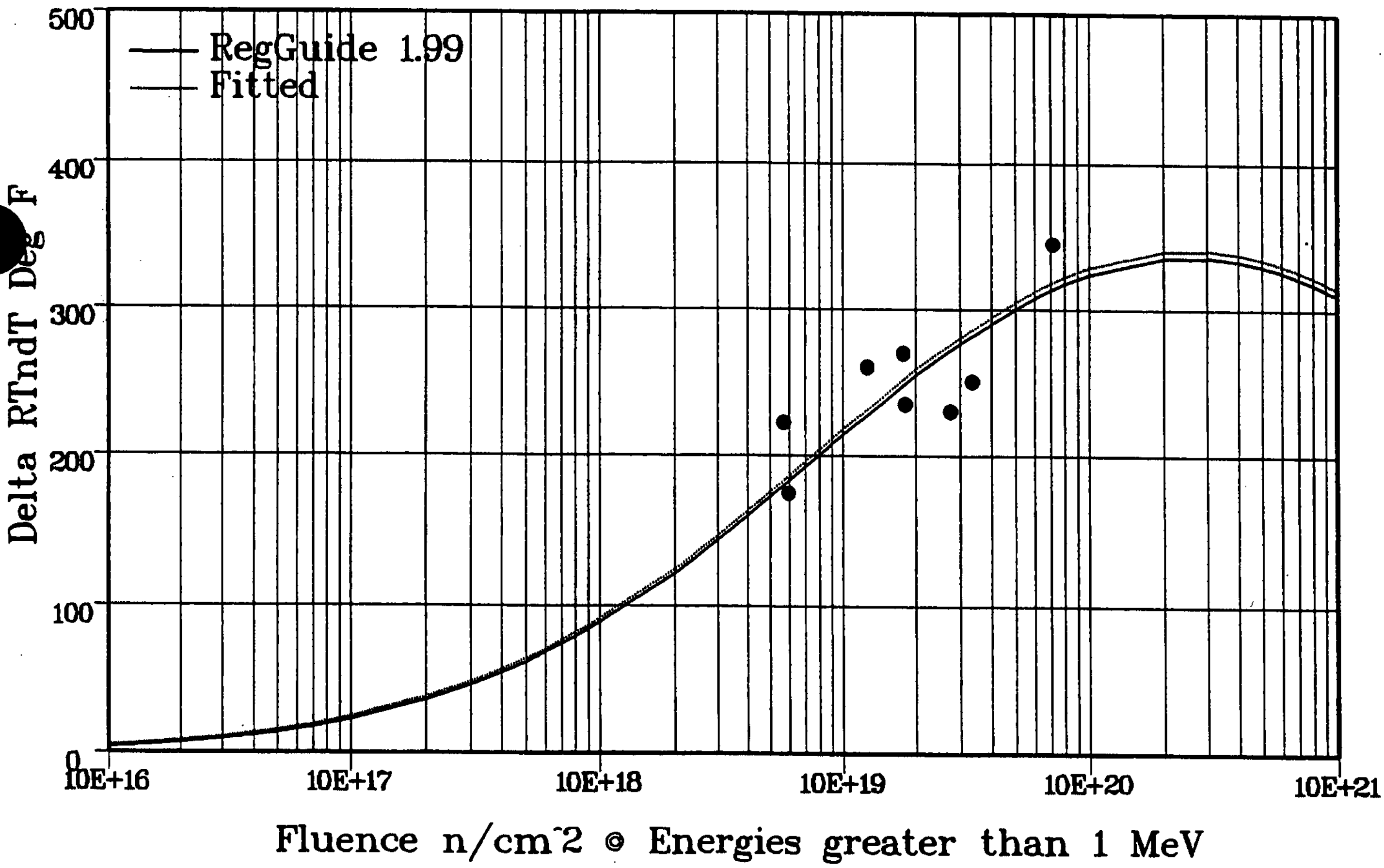


Figure 2-7 Kewaunee and Maine Yankee Surveillance Welds (No Ratioing)

Chemical Content is as follows

Copper = .287 wt%
Nickel = .756 wt%
Phosphorous = 0 wt%
Silicon = 0 wt%

The Chemistry Factor 213.98 F is found by the Reg. Guide 1.99 Revision 2 Method

The Chemistry Factor Fitted to the actual Input Data is 218.538 F.

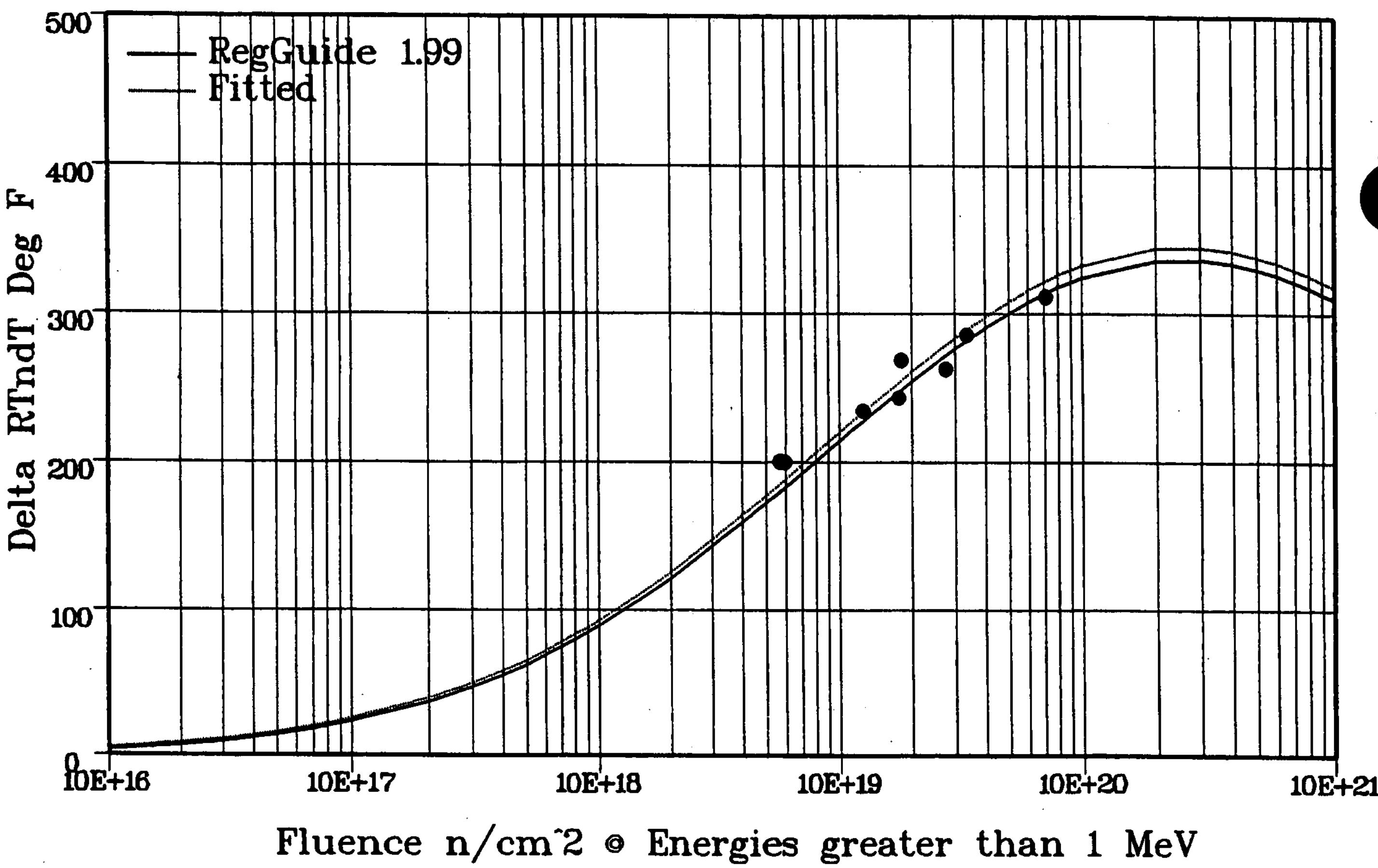


Figure 2-8 Kewaunee and Maine Yankee Surveillance Welds Using Ratioing

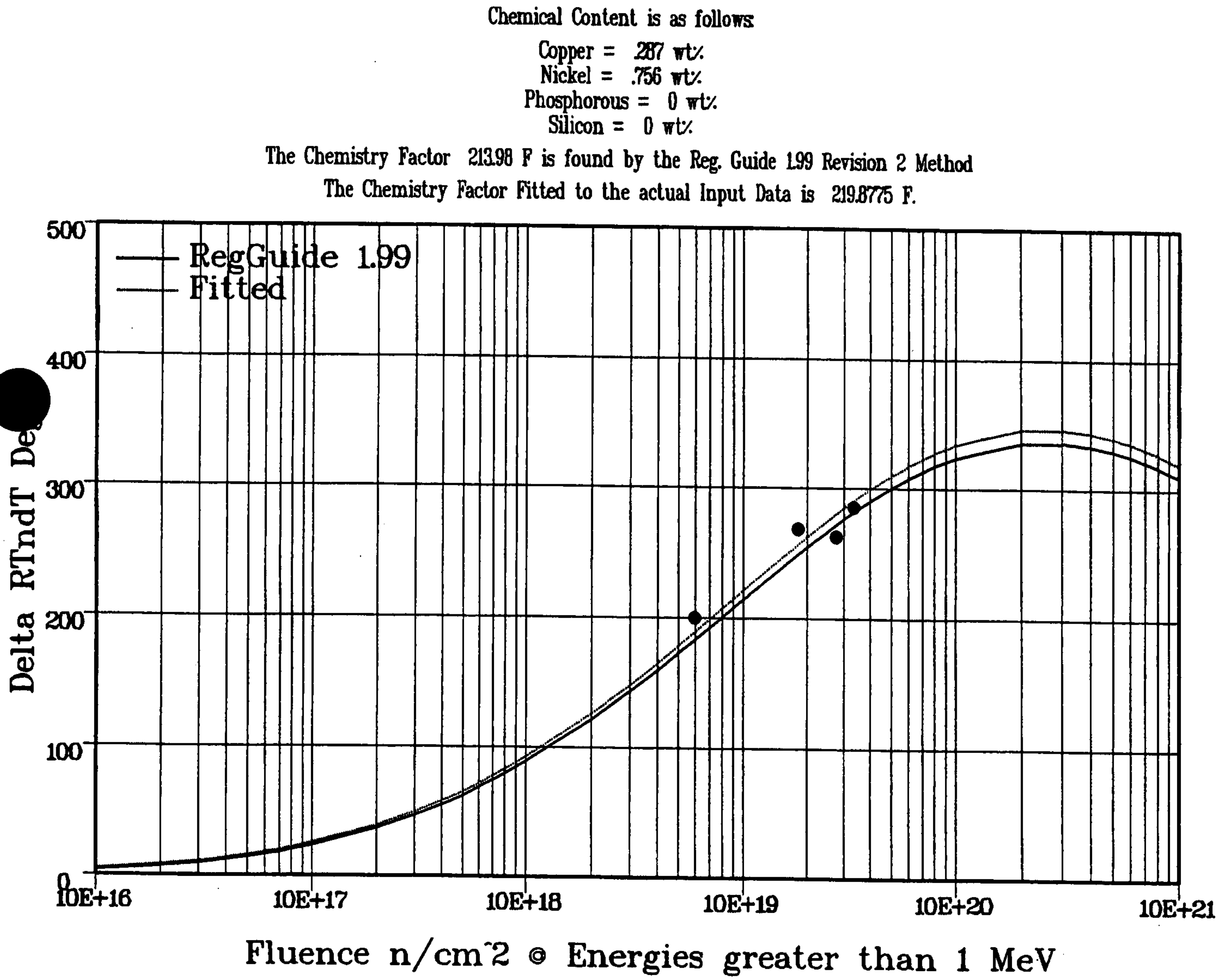


Figure 2-9 Kewaunee Surveillance Weld Data Using Ratioing

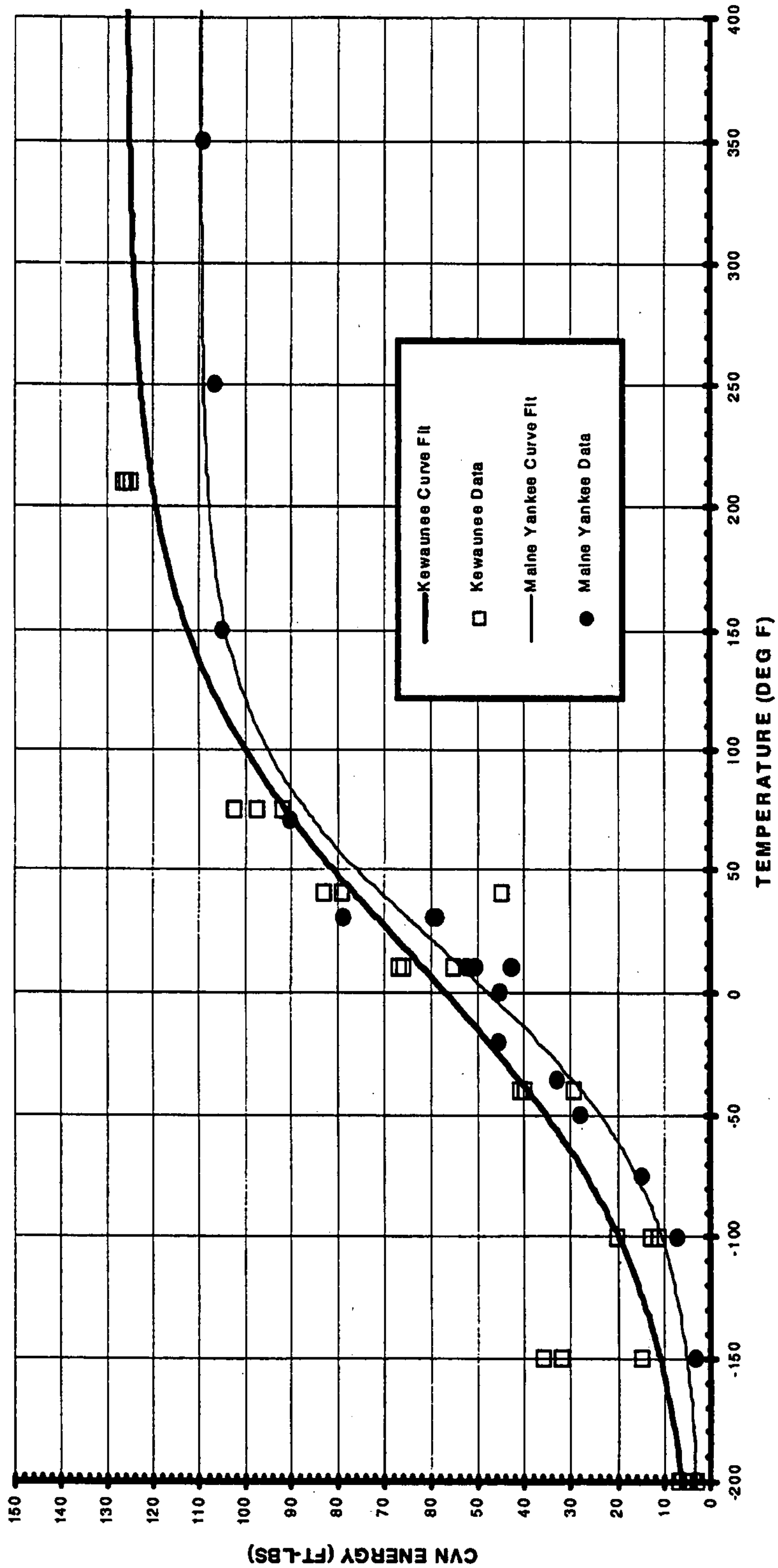


Figure 2-10 Unirradiated Baseline Charpy Energy Data

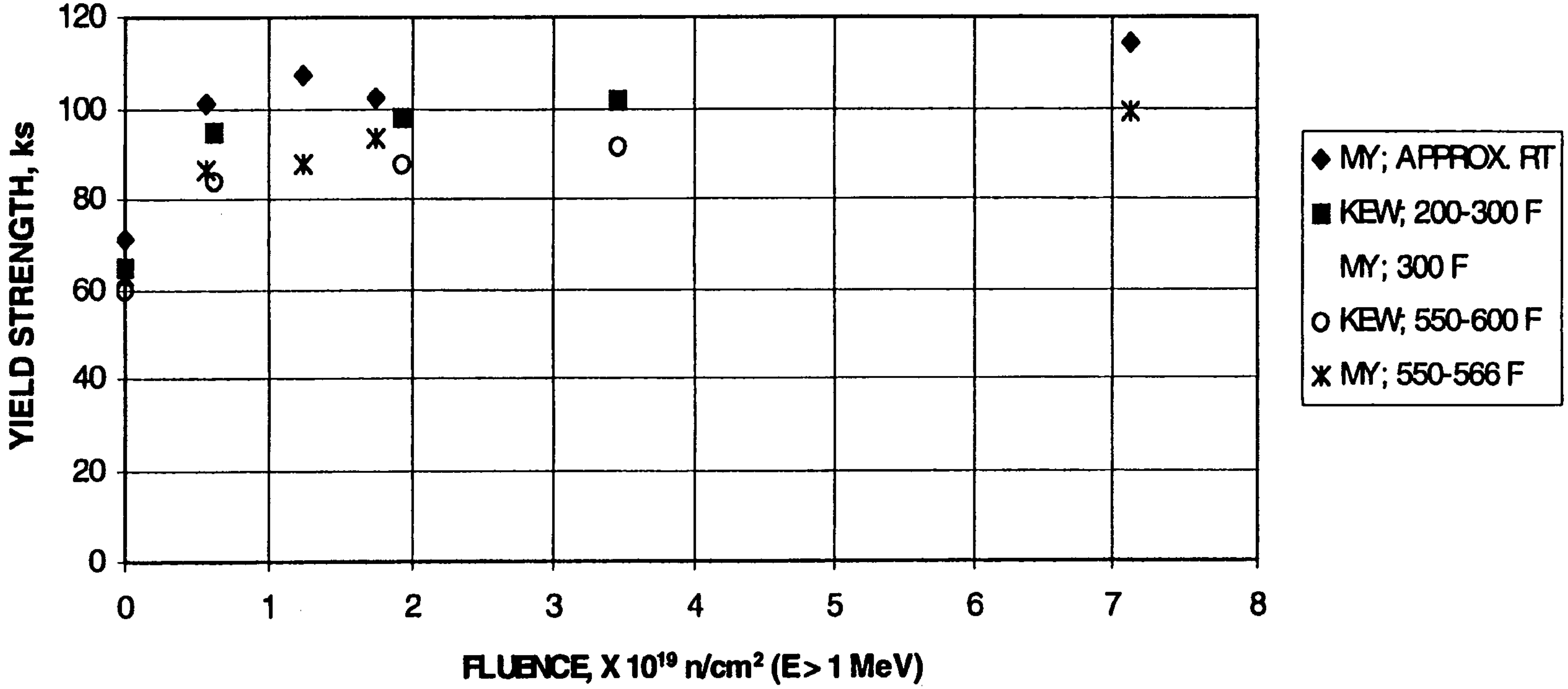


Figure 2-11 Tensile Yield Strength Results for Kewaunee and Maine Yankee Surveillance Welds

3 WELD MATERIALS HISTORY

FABRICATION SUMMARY

The Kewaunee surveillance weldment and the Maine Yankee surveillance weldment were fabricated using the same weld wire heat and the same lot of weld flux. However, there are some differences in the fabrication that would indicate that there may be some differences in mechanical properties, chemistry and irradiation response between the weldments. Table 3-1 lists some of the pertinent fabrication topics that could be important. One key item identified in Table 3-1 is the difference in final heat treatment for the MY surveillance weld. The extra time and multi-stage heat treatment of the MY surveillance weld should lead to differences in microstructure and initial mechanical properties.

The indications from Table 3-1 suggest that there may be some differences between the two surveillance welds, especially due to the longer post-weld heat treatment time and process for the MY surveillance weld. Differences were certainly obvious from the mechanical test results and chemical analyses for copper content reviewed in Section 2. The two surveillance welds are not good surrogates; indeed they behave as two distinct welds. To further validate and confirm these results, a separate study was conducted to compare the two welds through a detailed inclusion study examining the coarse microstructure.

MICROSTRUCTURE AND INCLUSION STUDY

The details of the coarse microstructure and inclusion study for the two surveillance welds are described in Appendix I. The results were conclusive that the two welds are very different in terms of the number, area, size, and distribution of Mn-S-Si inclusions. The MY surveillance weld metal (Figure 3-1a) showed a larger number, larger overall size, and a higher overall area distribution than the Kewaunee surveillance weld (Figure 3-1b). The Kewaunee surveillance weld was much cleaner. This information leads to the conclusion that the Kewaunee weldment should exhibit higher upper shelf energy (USE) and higher fracture toughness as compared to the MY weldment. The unirradiated mechanical property data (Charpy V-notch and drop-weight NDT temperature) are in agreement with these metallurgical observations. The longer and two-stage post-weld heat treatment for the MY surveillance weld appears to be the reason for the poorer unirradiated mechanical properties and the different coarse microstructure. Note that the final heat treatment for the Kewaunee vessel weld and the Kewaunee surveillance weld are essentially the same. Thus, the Kewaunee surveillance weld is the best surrogate for defining the initial (unirradiated) mechanical properties for the Kewaunee vessel weld.

Table 3-1 Comparison of Kewaunee / Maine Yankee RPV and Surveillance Welds

Topic	Kewaunee Weld	Maine Yankee Weld	Comments
Weld wire heat	1P3571	1P3571; RPV seam 9-203 also had some 33A277 as TSAA	Same
Flux type	Linde 1092	Linde 1092	Same
Flux lot/size	3958 (65 x 200)	3958 (65 x 200) except for TSAA on RPV weld	Same
Surveillance weld fabrication dates	October 9 – 16, 1970	September 19 – 23, 1970	Only a few weeks apart and after RPV welds
RPV fabrication dates	Seam 11-766, July 7 – 12, 1970	Seam 9-203, August 4 – 15, 1970	Approximately one month apart
RPV weld post-weld heat treatment	1150±25°F for 16.5 h	1125±25°F for 40 h	Longer PWHT for Maine Yankee
Surveillance weld post-weld heat treatment	1150±25°F for 19.25 h; closely matches RPV weld PWHT	1100-1175 for 40.5 h; PWHT had to be requalified – furnace malfunction caused block to be heated second time to reach total PWHT time	Effect of longer, two-stage heat treatment on MY surveillance weld could result in differences
Surveillance weld interpass temperatures	Pre-heat at 250°F; interpass at 300°F	Pre-heat at 250°F; interpass at 300°-400°F	Essentially the same
Surveillance weld repairs	None reported	3 repair areas that were extracted	Specimens are not taken from repaired regions
Specimen location in surveillance welds	All CVNs came from a 2.5-in. thickness of weld metal	All CVNs were taken from the full thickness of weld seam	MY weld CVNs sample more coils of wire than Kewaunee weld
Welding procedures	SAA-MA-500-0	SAA-MA-500-0	Same
Surveillance weld thickness	8.25-in. trimmed	8.125-in. trimmed	Similar
RPV weld thickness	6.5-in.	8.625-in. min. specified	Kewaunee vessel is thinner

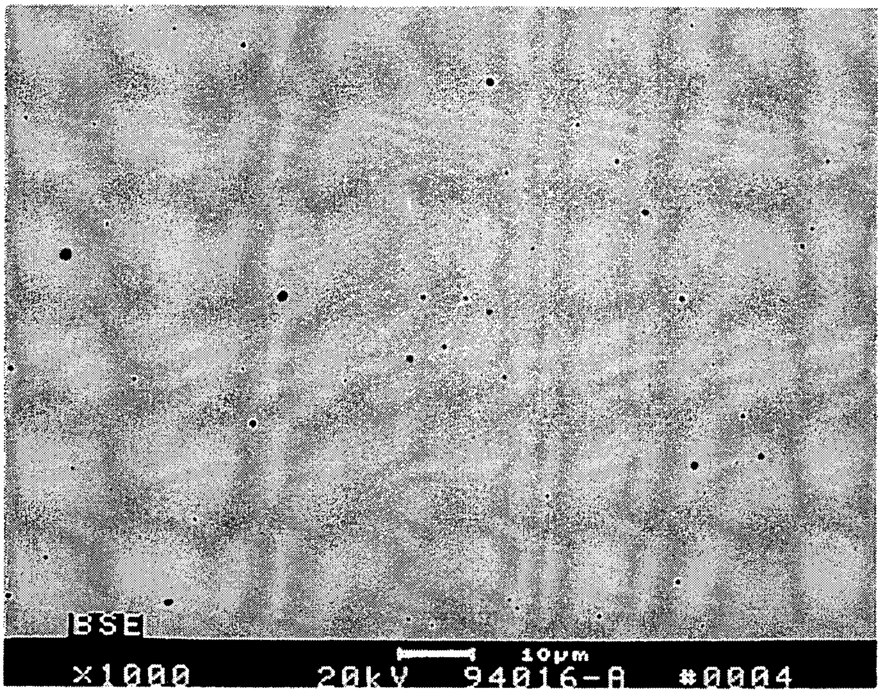


Figure 3-1a SEM Backscatter Micrograph of Maine Yankee Surveillance Weld

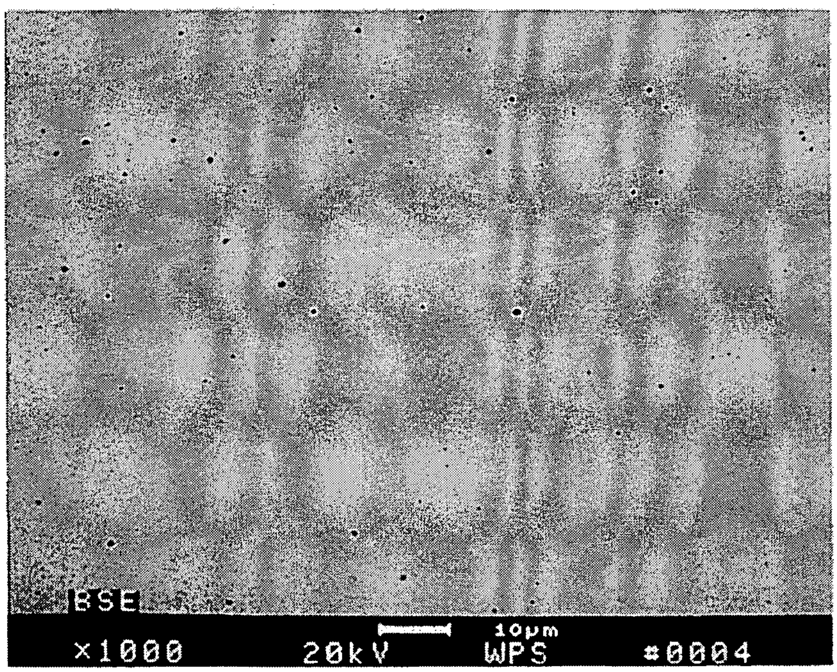


Figure 3-1b SEM Backscatter Micrograph of Kewaunee Surveillance Weld

4 EMBRITTLEMENT DATA ANALYSES

As indicated in Chapters 2 and 3 of this report, there are some distinct differences in the two surveillance weldments for Kewaunee and Maine Yankee. Emphasis has been placed on the known differences as evidenced by measured bulk copper chemistry, initial RT_{NDT}, inclusion size/distribution, heat treatment history, and Charpy shift (embrittlement) response. These differences are indeed real and are reflective of the potential scatter in the properties for the 1P3571 welds. The companion report on actual measured fracture toughness provides consistent results with regard to distinct differences between the Kewaunee and Maine Yankee surveillance weldments.

EVALUATION OF ADJUSTED RT_{NDT} AND ASSOCIATED MARGINS

The process of determining the adjusted RT_{NDT} (ART) for use in calculating pressure-temperature (P-T) curves for heatup and cooldown, or for evaluating pressurized thermal shock (PTS) through determination of RT_{PTS} (projected ART at end of operating life), is currently defined by the NRC using Regulatory Guide 1.99, Revision 2 (RG1.99R2) and the PTS Rule (10 CFR Part 50.61). Even though RG1.99R2 is strictly a Regulatory Guide for setting the input for P-T curves, its use essentially has evolved into a legal process; the determination of RT_{PTS} is directly a legal procedure from 10 CFR Part 50.61 and mirrors the process in RG1.99R2.

The discussion that follows provides the process of determining the ART including the required margins to account for uncertainties in the evaluation and material properties. The process for determining ART has several areas of uncertainty, and different evaluations may handle the best estimate values and uncertainties in slightly different ways. However, in all cases the NRC requires utilities to be conservative in the final determination of ART.

The calculation of ART is relatively simple in concept:

$$\text{Adjusted } RT_{NDT}\text{ (ART)} = \text{Initial } RT_{NDT} + \Delta RT_{NDT} + \text{Margin} \qquad (4\text{-}1)$$

The initial RT_{NDT} is the unirradiated value of RT_{NDT} sometimes designated here as IRT. This value can be a measured value following the process of NB-2330 of the ASME Code, Section III, or it can be estimated from a database or other accepted processes. Associated with the value of IRT is an uncertainty term that is treated as a standard deviation (σ). This uncertainty term is generally assessed as being zero when a measured value following the ASME Code has been determined for a specific material. If a database or some other estimation process is used, a finite value of σ_I is used to account for material and property uncertainty. In the case of Kewaunee, there are at least three scenarios for IRT: (1) the measured value of –50°F for the Kewaunee surveillance weld, this measured value is also consistent with the mean for Linde 1092 welds and is representative of the best surrogate for initial mechanical properties, (2) the accepted industry average value for non-Linde 80 welds of –56°F, or (3) the worst case measured value of –30°F from the Maine Yankee surveillance weld. The standard deviation for the measured cases can be assured to be zero, and the standard deviation for the industry average value of -56°F for non-Linde 80 welds is 17°F. Alternatively, there could be some other values used; e.g., the average of the Kewaunee and MY results (giving –40°F) with σ_I of zero or the mean of Linde 1092 welds alone (-50°F) with a similar standard deviation of 17°F. The most appropriate approach to represent the Kewaunee vessel weld is the measured value of –50°F (with $\sigma_I = 0$) from the Kewaunee surveillance weld since it is the best surrogate for initial mechanical properties.

The determination of the shift in transition temperature (ΔRT_{NDT}) is accomplished early in plant life using the measured best estimate copper and nickel chemistries and the Chemistry Factor (CF) tables in RG1.99R2 and 10 CFR Part 50.61, since adequate surveillance results are not yet available. The shift is determined as the product of CF and a fluence function (FF):

$$\Delta RT_{NDT} = CF \times FF = CF \times [f^{(0.28 - 0.1 \log (f))}] \tag{4-2}$$

where f is fluence reported for E > 1 MeV and units of 10^{19} n/cm^2.

The associated uncertainty term is based upon the statistical evaluation of the data used to derive the trend equations of RG1.99R2; for weld metal, the uncertainty value (σ_Δ) is 28°F, and for base metal, it is 17°F. The complicating issue for the 1P3571 weld metal is the large variability in the copper levels for the different weldments. Note that later evaluations will use shift values as calculated in Equation 4-2 using CF from the chemistry factor tables and from evaluation of the measured shift data for the surveillance capsule tests.

The normal process, as required by the NRC staff, is to assess the effects for the specific surveillance weld using the specific chemistry for that weld. However, some adjustments can be made using the NRC-defined ratio method when applying the results to the reactor vessel (which we define later as a heat uncertainty term). As indicated in Chapter 2, the Kewaunee surveillance weld has a lower copper content than the industry best estimate (which is selected here as being the most representative of the Kewaunee vessel).

The evaluation process gets more complicated once actual surveillance results are available, since an adjustment in CF is possible when "credible" surveillance data exist. The general process for determining the surveillance-based CF was shown in Chapter 2 of this report in Tables 2-4 and 2-5 and in Figures 2-4 and 2-5 (using CVGRAPH) for the Kewaunee and Maine Yankee surveillance results, respectively. Possible options in the assessment of credible surveillance results and how the specific adjustments are made in coming up with ΔRT_{NDT} and the overall Margin term are presented next.

The Margin term is handled as square root sum of the squares (SRSS) of the individual standard deviations of the terms (or the square root of the sum of the variances). It should be noted that these standard deviations are estimates of the uncertainties and are treated here as statistical standard deviations for simplicity. The overall margin is then considered to be 2σ:

$$\text{Margin} = 2\,(\sigma_I^2 + \sigma_\Delta^2)^{1/2} \tag{4-3}$$

When credible surveillance data exist for a minimum of two surveillance capsules and for relatively large shifts (greater than σ_Δ), the σ_Δ uncertainty can be reduced to one-half the value generally assumed. When credible surveillance data do not exist, the procedure is to use the predicted shift based upon the measured chemistry (not the adjusted CF using the surveillance data) and use the full shift uncertainty.

An additional uncertainty term can be defined to account for the variation in copper (and to a lesser extent nickel) chemical composition within the same weld wire heat. The source of this variation is due to the coil-to-coil variability in the copper coating that was used. The heat uncertainty (ΔRT_{HT}) is the difference between the calculated ART for the surveillance weld being analyzed and the ART value for the industry best estimate chemistry (or the ratio-adjusted surveillance results using the proper chemistry factor values). In this manner, the overall safety margin being applied for the vessel weld can be clearly seen.

CASE STUDIES

Figure 4-1 and Table 4-1 have been developed to illustrate the key input parameters (IRT, measured surveillance weld Cu and Ni chemistries, industry best estimate chemistries for Cu and Ni, surveillance capsule Charpy shift data, and neutron fluence), the associated uncertainties, and the overall margin. There are several ways to analyze the Kewaunee vessel weld due to the availability of weld-specific and generic industry data available on this weld wire heat (1P3571). Four cases have been analyzed that illustrate the range of traditional Charpy V-notch and chemistry-calculated possibilities for the Kewaunee vessel assessment. Note that the appropriate values for fluence, copper and nickel chemistry, predicted shift, and IRT are intended to be best estimate values. Margin is added to account for uncertainties and unknowns after using the best estimate values. The heat uncertainty term is determined after analyzing the Kewaunee surveillance weld first and then calculating the result for the industry best estimate values. The following cases provide the most realistic cases that should be potentially used for the Kewaunee vessel. Case 3 is the most representative since it utilizes the measured IRT for the Kewaunee surveillance weld and utilizes the NRC ratio adjustment (identified as the heat uncertainty term) to the Kewaunee credible surveillance results.

Case 1: Measured Kewaunee Initial RT_{NDT} and Assumed Non-Credible Surveillance Data; Calculated Using Mean and Industry Best-Estimate Chemistries

The first analysis in Table 4-1 utilizes the most appropriate value for IRT, initial RT_{NDT} (the measured Kewaunee surveillance weld result of –50°F), and utilizes an analysis in which the surveillance data are postulated to be non-credible. The IRT was measured as reported in Reference 2 to more accurately comply with RG1.99R2 and the PTS Rule. The measured value of -50°F for the Kewaunee surveillance weld reflects the best measurement for the 1P3571 weld wire heat and is consistent with the average for Linde 1092 welds. The heat-adjusted value in this case is calculated using the industry best estimate value for CF, based on chemistry (not surveillance Charpy results). As shown next, the best estimate shift results are based upon the Kewaunee surveillance weld (with CF_1) and the industry best estimate (CF_2). Chemistry values are used in this case.

Kewaunee Best Estimate Shift ($\Delta RT_{Kewaunee}$) = CF_1 x ff	Heat-adjusted shift ($\Delta RT_{Industry}$) = CF_2 x ff	$\Delta RT_{HT} = \Delta RT_{Industry} - \Delta RT_{Kewaunee}$
187.2°F x 1.316 = 246°F	214.0°F x 1.316 = 282°F	282°F – 246°F = 36°F

The numbers above and in Table 4-1 reflect the best estimate for Kewaunee at an end of life fluence of 3.34 x 10^{19} n/cm^2 (E>1 MeV); the fluence factor is 1.316.

The heat uncertainty was developed after applying an adjustment for chemistry alone (using the industry best estimate). Note that $\Delta RT_{HT} = ART_{Industry} - ART_{Kewaunee} = \Delta RT_{Industry} - \Delta RT_{Kewaunee}$. The overall heat-adjusted ART of 288°F from Table 4-1 is below the PTS screening limit of 300°F. The additional margin associated with heat uncertainty is separated at the end of Table 4-1 and Figure 4-1. This term is the result of including the Maine Yankee and other industry information on weld wire 1P3571 in the analysis. This separation is generally not done, but it provides insight into the total degree of margin applied in the evaluation process.

Case 2: Generic Initial RT_{NDT} and Assumed Non-Credible Surveillance Data; Calculated Using Mean and Industry Best-Estimate Chemistries

The second case in Table 4-1 is similar to Case 1, except using the generic IRT, initial RT_{NDT}, of -56°F. The ART result of 292°F, as indicated in Table 4-1, is 4°F higher than for Case 1 (288°F). The value of ΔRT_{HT} is the same, since only the IRT_{NDT} and the IRT-associated margin term are changed; i.e., ΔRT_{HT} = 282°F - 246°F = 36°F. The PTS screening criterion is not violated.

Case 3: Measured Kewaunee Initial RT_{NDT} and Credible Surveillance Data; Calculated Using the Ratio Procedure

Using the ratio procedure for chemistry and surveillance data together in the manner suggested by the NRC staff, leads to a calculation similar to Case 1 using the Kewaunee measured initial RT_{NDT}, but the surveillance data are now considered credible (which they are). The heat-adjusted ART of 267°F is less than for Cases 2 and 3. The calculation for ΔRT_{HT} is shown below:

Kewaunee Best Estimate Shift ($\Delta RT_{Kewaunee}$) = CF_1 x ff	Heat-adjusted shift ($\Delta RT_{Industry}$) = CF_2 x ff	$\Delta RT_{HT} = \Delta RT_{Industry} - \Delta RT_{Kewaunee}$
192.3°F x 1.316 = 253°F	219.9°F x 1.316 = 289°F	289°F – 253°F = 36°F

The ΔRT_{HT} is the same as in Cases 1 and 2, even though the methodology was quite different. The ratio adjustment is the ratio of the CF for the industry best estimate chemistry (187.2°F) and the CF for the Kewaunee surveillance weld (214.0°F) which is 1.143. The ratio methodology applied to the Kewaunee surveillance weld data is consistent with the results using the measured chemistries and the industry best estimate. This result is reflective of the fact that the ratio method applied to surveillance data and the chemistry methodology using just the RG1.99R2 tables closely match each other.

This case is the most applicable case for the Kewaunee vessel since it utilizes the Kewaunee surveillance weld measured initial RT_{NDT} of -50°F and the NRC-defined ratio method for credible surveillance data. The IRT of -50°F from the Kewaunee surveillance weld is the best surrogate measurement for the Kewaunee vessel weld and is equivalent to the average for Linde 1092 welds. The ART of 267°F is well below the PTS screening criterion, and this case will be used to generate the traditional heatup and cooldown curves – see WCAP14278, Rev. 1[9].

Case 4: Generic Initial RT_{NDT} and Credible Surveillance Data; Calculated Using the Ratio Procedure

This case is also plausible using the traditional transition temperature methodology. This case accounts for the measured and credible surveillance data from both Kewaunee and Maine Yankee programs (like Case 3 using the ratio adjustment procedure), but the generic initial RT_{NDT} is used to provide the best estimate for the Kewaunee vessel. The ART of 277°F is also well below the PTS screening criterion. The ΔRT_{HT} is the same as calculated for Case 3 since the same shift calculation is used.

SUMMARY OF RESULTS

Four cases that could be made for determining the ART for the Kewaunee vessel weld have been analyzed. The cases reflect two main differences: the value for IRT and whether the surveillance Charpy results from the Kewaunee program are treated as credible. Cases 1 and 2 compare the effect of IRT for the condition of no credible Charpy (CVN) data; the result is a 4°F higher value when the generic value of -56°F is used with its associated uncertainly (17°F) as compared to the measured value of -50°F with no IRT uncertainty term. Similarly, Cases 3 and 4 make this same comparison for the condition of credible surveillance data (and using the ratio method of adjustment). The result in comparing Cases 3 and 4 is a 10°F higher value when the generic IRT value is used.

A comparison of Cases 1 and 3 assesses the impact of using credible surveillance data (Case 3) versus non-credible data (Case 1) when the IRT was measured (-50°F). The clear advantage of credible data is evident in the 24°F lower value in ART for Case 3. A similar comparison of Cases 2 and 4 (when the IRT is the generic value is -56°F) yields a decrease in ART of 18°F when the surveillance weld data are credible.

The most applicable case for the Kewaunee vessel is Case 3. The initial RT_{NDT} from the Kewaunee surveillance weld has been directly measured as -50°F following the ASME Code method. This value is equivalent to the mean value for Linde 1092 welds and close to the mean value for non-Linde 80 welds. Additionally, the Kewaunee surveillance weld is the most applicable surrogate for defining initial mechanical properties for the Kewaunee vessel as discussed in Section 3 of this report. This was verified by examining the Kewaunee and Maine Yankee surveillance welds for microstructural differences. The Maine Yankee surveillance weld showed much larger and more inclusions than the Kewaunee surveillance weld, which is judged to be the result of the dual-stage, longer PWHT for the Maine Yankee surveillance weld. The ratio-adjusted method applied to the "credible" Kewaunee surveillance weld data is the most technically valid approach for analyzing the Kewaunee vessel using Charpy-based methods. The Kewaunee surveillance weld data meet all of the credibility requirements with and without the ratioing procedure.

The amount of conservation as evidenced by summing the total margin plus heat uncertainty (as listed in Table 4-1) can be as high as 102°F in Case 2. For Case 3, this value is the lowest for the four cases analyzed at 64°F, but this value is still high considering the other mandated margins associated with heatup and cooldown curves or in the development of the PTS screening criteria. Thus, the direct measurement of fracture toughness for the Kewaunee surveillance weld metal is a prudent approach to better define the embrittlement status of the Kewaunee reactor vessel.

Even more conservative assumptions could be made relative to the initial RT_{NDT} and the chemistry factor, even though these conservative assumptions are not realistic. For example, a worst case scenario using the Maine Yankee surveillance weld initial RT_{NDT} of -30°F, the Maine Yankee chemistry factor of 240.7 based upon the surveillance capsule Charpy data (see Table 2-5), and a total margin of 56°F (2 x σ_{Δ}), based on the data being assumed non-credible, culminates in the final ART (RT_{PTS}) at current EOL of 373°F. This value is significantly greater than the PTS screening criterion of 300°F for the Kewaunee vessel circumferential 1P3571 weld; such a high value is very unrealistic, but is reflective of the situation that the NRC staff was concerned about back in April 1995. The actions taken by WPSC, as discussed in this report and the companion reports on measured fracture toughness results, are in response to this worst case scenario. As shown in this report, the initial RT_{NDT} of -30°F for the MY surveillance weld is inappropriate as a surrogate value for the Kewaunee vessel weld due to the long, dual-stage PWHT. The MY surveillance weld chemistry factor of 240.7°F is inappropriate since most of the measured chemistry of other 1P3571 weldments show significantly lower effective chemistry factors; the industry best estimate CF value is 214.0°F (see Table 2-3) and the ratio-adjusted CF using the credible Kewaunee surveillance data is 219.9°F (see Figure 2-9 and Table 2-9). Case 3 utilizes the measured initial RT_{NDT} of -50°F and a CF of 219.9°F for estimating shift. Thus, our most applicable Case 3 value of final ART is 266°F, which is 107°F lower than this worst case scenario.

Table 4-1 ART Determination for the Kewaunee Vessel Weld

Method	Best Estimate of Initial RT_{NDT} Value (IRT), °F	Standard Deviation for IRT (σ_I),°F	Kewaunee Surveillance Estimate of Shift (ΔRT), °F	Standard Deviation for ΔRT (σ_Δ),°F	Best Estimate of Irradiated Value °F	Total Margin (M) °F	Adjusted Reference Temperature (ART_{HT}) °F	Additional Adjustment for Heat Uncertainty (ΔRT_{HT}) °F	Heat Adjusted Reference Temperature (ART_{HT}) °F
1.) Current Technology Measured IRT; No Credible CVN Data	Measured Value, -50	"Assumed" 0	RG1.99R2 CF Table 246	RG1.99R2 28	IRT+ΔRT 196	$2(\sigma_I^2+\sigma_\Delta^2)^{1/2}$ 56	IRT+ΔRT +M 252	Ind. Mean Chemistry 36	288
2.) Current Technology; Generic IRT; No Credible CVN Data	PTS Rule -56	PTS Rule 17	RG1.99R2 CF Table 246	RG1.99R2 28	IRT+ΔRT 190	$2(\sigma_I^2+\sigma_\Delta^2)^{1/2}$ 66	IRT+ΔRT+M 256	Ind. Mean Chemistry 36	292
3.) Current Technology; Measured IRT; Credible CVN Data	Measured Value, -50	"Assumed" 0	RG1.99R2 Data Fit 253	RG1.99R2 14	IRT+ΔRT 203	$2(\sigma_I^2+\sigma_\Delta^2)^{1/2}$ 28	IRT+ΔRT+M 231	Ratio Adj. 36	267
4.) Current Technology; Generic IRT; Credible CVN Data	PTS Rule -56	PTS Rule 17	RG1.99R2 Data Fit 253	RG1.99R2 14	IRT+ΔRT 197	$2(\sigma_I^2+\sigma_\Delta^2)^{1/2}$ 44	IRT+ΔRT+M 241	Ratio Adj. 36	277

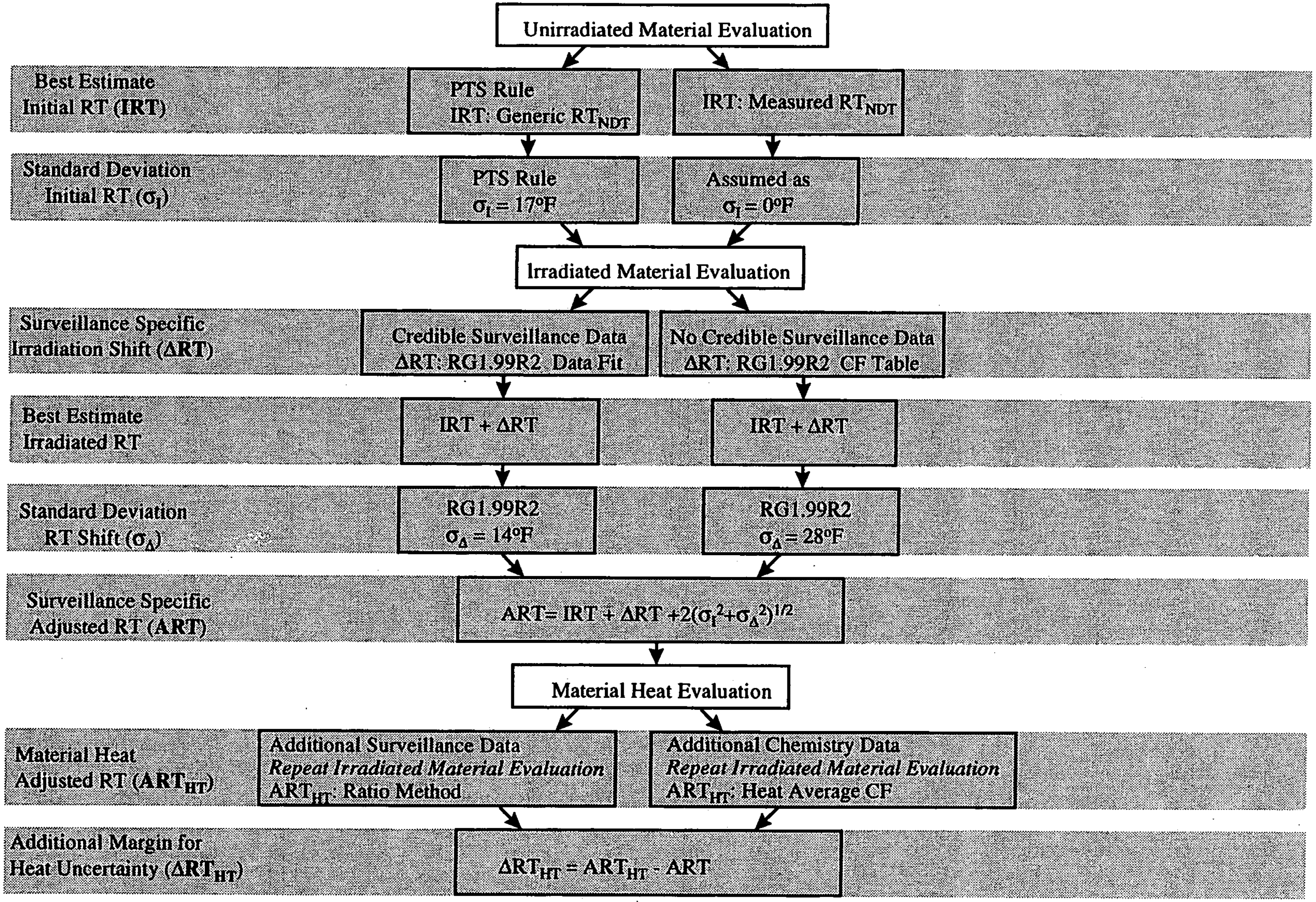


Figure 4-1 Current Technology for Fracture Toughness Reference Temperature

5 CONCLUSIONS

- The Kewaunee and Maine Yankee surveillance weld metals were fabricated by CE using the same weld wire heat, 1P3571, and weld flux, Linde 1092, but the two weldments exhibit very different behavior with respect to mechanical properties both before and after neutron radiation exposure.

- The best estimate chemistry for the Kewaunee vessel has been determined by evaluating all of the known Cu and Ni measurements for weld wire 1P3571: a coil-weighted average for Cu yields a value of 0.287 wt%, and a sample-weighted average for Ni yields 0.756 wt%. These values have been used to ratio the surveillance data and chemistry factors for each of the two surveillance welds.

- The Charpy transition temperature behavior of the two surveillance welds is in agreement with each other when the ratio adjustment procedure is applied.

- The initial RT_{NDT} determination for the two weldments are different, but are within the data scatter typical Linde 1092 welds. The applicable value for the Kewaunee vessel weld assessment is the measured value of -50°F, from the Kewaunee surveillance weld since it represents the best surrogate for initial mechanical/toughness properties. This assessment primarily is based on the close match in fabrication and heat treatment for the Kewaunee vessel and surveillance welds.

- Differences in the two weldments were investigated by microstructural and inclusion examination. The inclusion study revealed that the Maine Yankee surveillance weld has more and larger inclusions than the Kewaunee surveillance weld, which is consistent with the larger, dual-stage PWHT for the Maine Yankee surveillance weld. This information is consistent with the measured initial mechanical properties, especially the lower Charpy toughness (i.e., the initial RT_{NDT} of -30°F) for the Maine Yankee weld.

- The possible ART values for the Kewaunee vessel weld were evaluated by looking at four analytical cases. These cases involved varying assumptions for initial RT_{NDT}, chemistry factor, and overall margin. All four cases have ART values at current EOL less than the PTS screening limit of 300°F.

- A worst-case scenario can lead to an ART that is above the PTS screening limit of 300°F.

- The most applicable case for the Kewaunee vessel weld is felt to be an ART of 266°F, and this value has been used for generating traditional heatup and cooldown curves for EOL (33 EFPY). The initial RT_{NDT} as measured for the Kewaunee surveillance weld of -50°F was used, a chemistry factor of 219.9°F based on the ratio-adjusted Kewaunee surveillance weld results was applied, and a credible surveillance margin (28°F) was shown to be appropriate.

- The methodology developed for the traditional Charpy transition temperature approach has been evaluated in a slightly different manner in this study to generate a heat uncertainty term. This heat uncertainty term accounts for the fact that the Kewaunee vessel weld is most likely similar to the industry best estimate in terms of chemistry rather than exactly like the Kewaunee or Maine Yankee surveillance welds. This generalized approach has been used in a companion report (WCAP-15075) to evaluate the measured fracture toughness response for the two surveillance welds using the Master Curve methodology.

6 REFERENCES

1. 10CFR50, "Analysis of Potential Pressurized Thermal Shock Events," July 23, 1985.

2. WCAP-14042, Rev. 1, "Drop-Weight NDT for Kewaunee Weld," C. M. Pezze January, 1995.

3. ASTM E208, "Method for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels," American Society for Testing and Materials.

4. WCAP-15075, "Master Curve Strategies for RPV Assessment," August, 1998.

5. Regulatory Guide 1.99, Revision 2, "Radiation Embrittlement of Reactor Vessel Materials," U.S. Nuclear Regulatory Commission, May 1988.

6. 10CFR Part 50.61, "Fracture Toughness Requirements for Protection Against Pressurized Thermal Shock Events," Dec. 19, 1995 (PTS Rule).

7. WCAP-14279, Rev. 1, "Evaluation of Capsules from the Kewaunee and Capsule A-35 from the Maine Yankee Nuclear Plant Reactor Vessel Radiation Surveillance Programs," September, 1998.

8. WCAP-14280, Rev. 1, "Evaluation of Pressurized Thermal Shock for the Kewaunee Reactor Vessel," September, 1998.

9. WCAP-14278, Rev. 1, "Kewaunee Heatup and Cooldown Limit Curves for Normal Operation," September, 1998.

10. "RVID: Reactor Vessel Integrity Database Version 1.1," U.S. Nuclear Regulatory Commission, July 1995.

11. "RPVDATA: Reactor Vessel Materials Database Version 1.3," EPRI CM-106390, Electric Power Research Institute, January 1996.

12. "Best Estimate Copper and Nickel Values in CE Fabricated Reactor Vessel Welds," CEOG Report CE NPSD-1039, Revision 2, ABB Combustion Engineering, June 1997.

13. WCAP-8908, "Analysis of Capsule V from the WPSC Kewaunee Nuclear Plant Reactor Vessel Radiation Surveillance Program," S. E. Yanichko, et al., January 1977.

14. WCAP-9878, "Analysis of Capsule R from the WPSC Kewaunee Nuclear Plant Reactor Vessel Radiation Surveillance Program," S. E. Yanichko, et al., March 1981.

15. WCAP-12020, "Analysis of Capsule P from the Wisconsin Public Service Corporation Kawaunee Nuclear Plant Reactor Vessel Radiation Surveillance Program", S. E. Yanichko, et al., November 1988.

16. WCAP-14279, Rev. 0, "Analysis of Capsule S from the Kewaunee Nuclear Plant Reactor Vessel Radiation Surveillance Program," E. Terek, et al., March 1995.

17. "CVGRAPH Version 4.1, Charpy Graphics Program," ATI-96-C006, ATI Consulting, March 1996.

18. J. S. Perrin, et al., "Final Report on Maine Yankee Nuclear Plant Reactor Pressure Vessel Surveillance Program: Capsule 263," BCL-585-21, Battelle Columbus Laboratories, December 1980.

19. Terek, E., S. L. Anderson, and L. Albertin, "Analysis of the Maine Yankee Reactor Vessel Second Wall Capsule Located at 253°," WCAP-12819, Westinghouse Electric Corp., March 1991.

20. R. A. Wullaert and J. W. Sheckherd, "Evaluation of the First Maine Yankee Accelerated Surveillance Capsule," CR 75-317, Effects Technology, Inc., August 1975.

21. S. E. Yanichko, S. L. Anderson, R. P. Shogan, and R. G. Lott, "Analysis of the Maine Yankee Reactor Vessel Second Accelerated Surveillance Capsule," WCAP-9875, Westinghouse Electric Corp., March 1981.

22. Maine Yankee response to Generic Letter 92-01, Revision 1, Supplement 1, Reactor Vessel Structural Integrity - Final Report, MN-97-66 (MJM-97-004), May 13, 1997.

23. "Unirradiated Mechanical Properties of Maine Yankee Nuclear Pressure Vessel Materials," CR 75-269, Effects Technology, Inc., February 1975.

24. WCAP-8107, "WPSC Kewaunee Nuclear Power Plant Reactor Vessel Radiation Surveillance Program." S. E. Yanichko, et al., April 1973.

APPENDIX I
INCLUSION ANALYSIS OF KEWAUNEE AND MAINE YANKEE WELDS

1.0 INTRODUCTION

Non-metallic inclusions have long been known for their detrimental effects in reducing the ductility and fracture resistance of materials. Decades of work have shown the influence of size, shape, distribution, and coherency of inclusions on the mechanical properties of steels[1-18]. Increases in the volume fraction of inclusions and the clustering of the inclusions have deleterious effects on the fracture resistance of materials.

As with most low alloy steels, reactor pressure vessel steels generally have a large population of non-metallic inclusions in the microstructure. Although there has been considerable effort in establishing the mechanical properties of these pressure vessel steels, documentation of the non-metallic inclusions has never been performed systematically. Within recent years, the influence of these inclusions on the toughness response of pressure vessel steels has been recognized[1].

In this study, two similar reactor pressure vessel welds (Kewaunee and Maine Yankee) have been examined for inclusion content. This study was initiated due to the differences in the initial fracture toughness properties that were observed between the Kewaunee and Maine Yankee surveillance welds. Also, the effect of the longer, dual-stage heat treatment for the Maine Yankee surveillance weld was felt to possibly lead to a different inclusion morphology than for the Kewaunee surveillance weld. It was necessary to know if the different fracture toughness properties of the surveillance welds were from different characteristics of the inclusions in the material. The weld materials used for this study were obtained from the archive inventory by Westinghouse for Kewaunee and from the surveillance capsule baseline program for Maine Yankee. This study should allow a better understanding of the differences in mechanical properties between the two surveillance welds which have differing residual element chemistries and heat treatments.

2.0 PROGRAM OUTLINE

This study looked at the two surveillance welds described in the Section 1.0. These welds were examined for their inclusion contents. Detailed evaluations of the inclusion chemistries and size were performed on metallographic samples using backscattered electron imaging and simultaneous energy dispersive x-ray analysis in an Amray 1645 SEM equipped with a Link Backscattered Electron Detector and an LZ4 atmospheric thin window (ATW) energy dispersive x-ray spectrometer (EDS), eXL image analysis system and analyzer. All samples were analyzed at a magnification of 2000X and inclusions greater than 0.23 μm in length or .022 μm^2 in area were analyzed (limit of detection).

3.0 INCLUSION CHARACTERISTICS THAT INFLUENCE MECHANICAL PROPERTIES

There are a number of "inclusion" factors that effect the mechanical properties of the pressure vessel steel. These factors are as follows: (1) the number of inclusions in the material, (2) the total area (area percent) covered by inclusions, (3) the size of the inclusions, (4) the shape,

(5) the distribution, and (6) the inclusion type and characteristics. In this analysis, all of these factors have been examined. It is usually a combination of the above factors that effect the overall material response.

4.0 CHEMICAL CLASSIFICATION AND TYPE OF INCLUSIONS

In order to establish inclusion types, a classification system was developed based on the chemical weight percent of each element in an inclusion. This classification system was used consistently for this study. Table 1 lists all of these types and requirements for the inclusions. The inclusions were dominated by combinations of four elements: manganese (Mn), sulfur (S), silicon (Si), and aluminum (Al).

All steels contain non-metallic impurities. The predominant inclusions formed in the steel are manganese sulfides (MnS) and silicon or aluminum compounds. In addition, some combination of manganese, sulfur, aluminum, silicon, and oxygen is also usually present in the microstructure. There have been a number of papers written regarding the formation of these precipitates[2-9].

The shape of these MnS inclusions are controlled by the steel composition and the degree of deoxidation. Variation in trace constituents of the steel also can influence the morphology of the inclusions. Therefore, it may be possible to see occurrences of different shapes of inclusions in the microstructure as well[8-13]. Type I and III inclusions are precipitated in globular and idiomorphic forms which deform into ellipsoids if the steel is hot rolled. Type II inclusions are precipitated as extensive arrays of very fine rods in an interdendritic eutectic distribution[10-12]. Since this study is performed on weld metals, these different types are not applicable.

Table 1 Inclusion Classifications

Inclusion Type	Classification Limits
MnS	Mn + S > 90%, Al + Si = balance
MnSSi	Si > 10%, Al = 0%, Mn + S = balance
MnSAl	Al > 10%, Si = 0%, Mn + S = balance
MnSAlSi	Al + Si > 10%, Mn + S = balance
SSiAl	Mn = 0%, S < 90%, Si < 90%, Al < 90%
SSi	Mn + Al = 0%, S < 90%, Si < 90%
S	S > 90%
Si	Si > 90%
Al	Al > 90%

5.0 INCLUSION DETECTION METHOD

Inclusion detection was performed using the SEM at a magnification of 2000X. For all samples, thirty regions (fields), each with a cross-sectional area of 47.24 μm × 48.86 μm (2308.08 μm^2), were examined for inclusions. For each sample the total number of fields examined is denoted as one scan, and the overall coverage is felt to be representative of the two welds. Each field of a scan was analyzed for inclusions by using the software package called Link Analytical FEATURESCAN. This program uses energy dispersive spectrometry (EDS) to determine the chemical composition of each inclusion. In addition, the length and area of each inclusion are measured. Furthermore, the total number of inclusions from all of the fields is reported. Data reduction results in classification of each inclusion, average area, median area, maximum area, average length, median length, maximum length, and the area weighted chemistries for each element. In addition, the percent total area and average distance between inclusions can be calculated. The percent total area is defined as the ratio of the area of the specified inclusion(s) to the total area examined (scan area) times 100 percent.

There was no selection process used to identify the areas to be scanned. They were randomly selected in order to prevent bias in the data. After the feature scan was performed, light microscopy was performed and comments were made on the characteristics of the inclusions in the steel samples.

6.0 COMPARISON OF MEASURED DATA

6.1 NUMBER OF INCLUSIONS DETECTED

Table 2 shows the number of inclusions detected for both materials and the number of inclusions for each classification. It is easily seen that the Maine Yankee surveillance weld has the largest number of detected inclusions. In addition, the majority of these inclusions are specifically MnSSi. The Kewaunee surveillance weld also showed a large population of MnSSi type inclusions. In terms of percentages, the primary type of inclusions for both welds are this MnSSi type (see Table 3). Both samples show contributions from MnS with the Kewaunee surveillance weld showing 5 times the amount in terms of percentage of inclusions. It should be noted that the Maine Yankee surveillance weld has a large number (18.5%) of SSi inclusions. Both samples also showed contributions of Aluminum in the inclusions as well. The aluminum showed up in a combination of MnSSiAl type mixtures.

Table 2 Number of Inclusions Detected		
Inclusion Type	Number of Inclusions	
	Kewaunee	Maine Yankee
All Types	332	552
MnS	72	26
MnSSi	236	361
MnSAlSi	14	29
SSiAl	0	1
SSi	0	102
S	9	3
Si	1	0

Table 3 Percentage of Inclusions for Each Inclusion Type		
Inclusion Type	Percent of Inclusions	
	Kewaunee	Maine Yankee
All Types	100	100
MnS	21.7	4.7
MnSSi	71.1	65.4
MnSAlSi	4.2	5.3
SSiAl	0	.2
SSi	0	18.5
S	2.7	5.9
Si	0.3	0

6.2 AREA OF INCLUSIONS

The percent total area is calculated for all inclusions as well as for each inclusion type. This information is summarized in Tables 4, 5, and 6. Table 4 shows the sum of the inclusion area (area sum) for all thirty fields, and Table 5 shows the percentage of the area sum contributed by the inclusion types. Table 6 shows the percent of the total scan area for each material. Based on the total areas, it is seen that the Maine Yankee surveillance weld has the largest area of inclusions. As shown in Table 6, the largest percentage of the area sum which is contributed from MnSSi is associated with both materials. Both samples also have high contributions from MnSAlSi type inclusions (Figure 1).

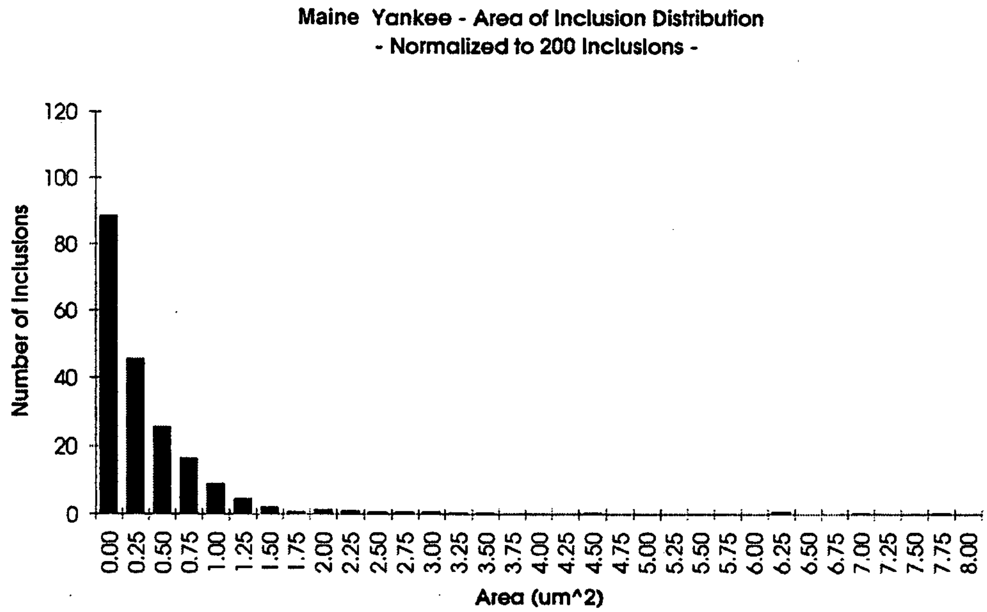
It should be recognized that the percent total area is a better measure of inclusion content, since it can be compared with other feature scans which have more or less fields in their analyses.

6.3 SIZE OF INCLUSIONS

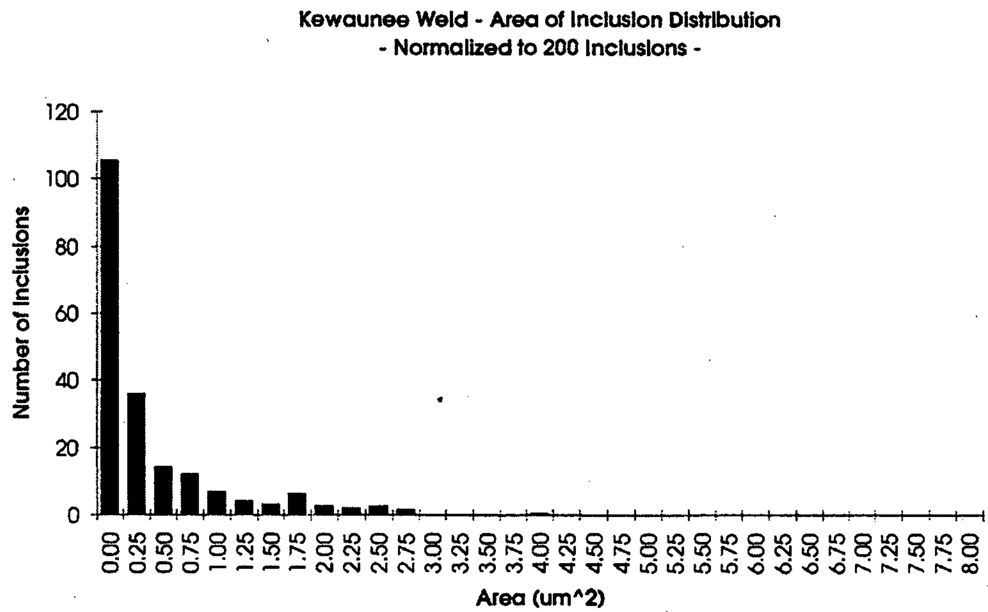
The individual size of an inclusion may also dictate the fracture response of a material. If the inclusion is large enough, it can act as the critical flaw or crack path in the material and fracture may easily propagate through or from this area. The individual areas as well as the individual lengths of all the inclusions and their types were analyzed in this program. Maximum lengths and areas are reported for each material as well as median and average lengths. They are summarized in Table 8. The average and median area of the Kewaunee surveillance weld is smaller than the Maine Yankee surveillance weld. Note, however, that the largest inclusion was found in the Kewaunee sample, however, it should be noted that the Maine Yankee sample on average has larger inclusions. Figure 1 shows the normalized area distributions for the Maine Yankee and Kewaunee surveillance welds, respectively.

In addition, the average length for the Kewaunee surveillance weld is higher than that for the Maine Yankee surveillance weld. Note the lower median value in the Kewaunee sample suggesting that the inclusions for the Maine Yankee surveillance weld tend to have more inclusions larger than the average. Figure 2 shows the normalized length distribution for the Maine Yankee and Kewaunee surveillance weld materials, respectively.

It should be noted that the inclusion length in this study was measured for each inclusion, and high degrees of clustering were not considered as individual inclusions. Previous work used high degrees of clustering as one inclusion[15]. While the approach taken here is certainly valid, it requires the technical judgment of the researcher. In the approach used in this study, the field with the highest degree of clustering is determined from measured as well as visual data. This measured data is used to calculate the minimum separation between inclusions, as presented later.

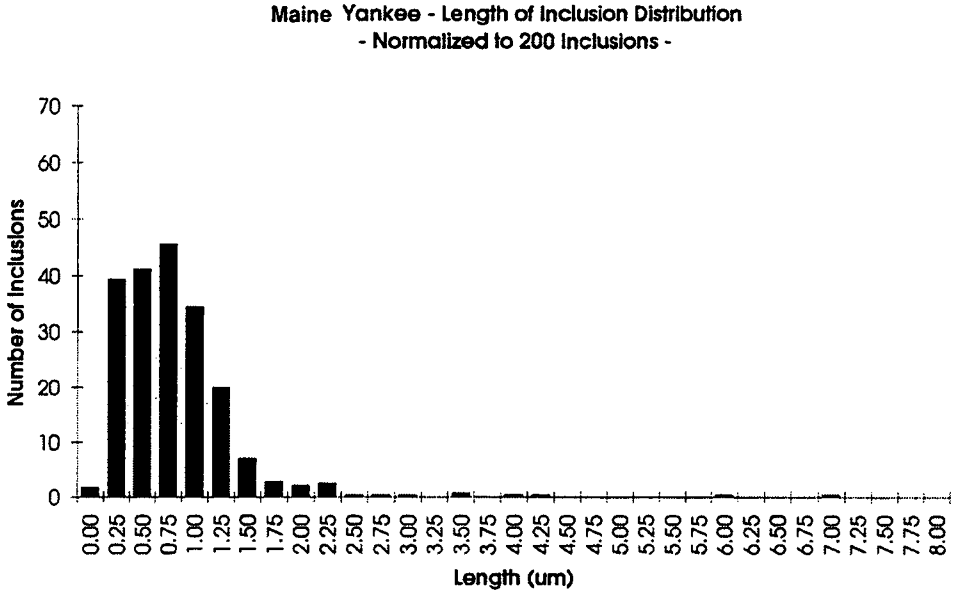


(a)

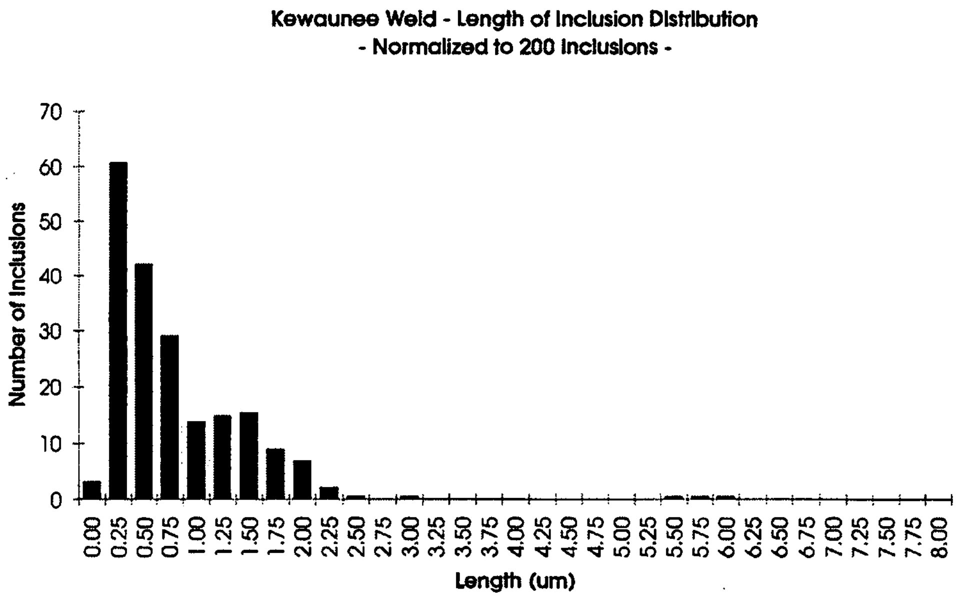


(b)

Figure 1 Normalized area distribution for (a) the Maine Yankee surveillance weld and (b) the Kewaunee surveillance weld materials, respectively.



(a)



(b)

Figure 2 Normalized length distribution for (a) the Maine Yankee surveillance weld and (b) the Kewaunee surveillance weld materials, respectively.

Table 4 Sum of the Inclusion Areas (Area Sum)		
Inclusion Type	Total Area (um^2)	
	Kewaunee	Maine Yankee
All Types	274.4	348.0
MnS	76.6	13.9
MnSSi	132.4	204.3
MnSAlSi	26.8	50.5
SSiAl	0	.02
SSi	0	59.0
S	25.2	20.3
Si	13.4	0

$$AreaSum = \sum_{i=1}^{n} [InclusionArea]_i$$ where n= number of inclusions

Table 5 Percentage of Area Sum Contributed by Each Inclusion Type		
Inclusion Type	Percent of Area Sum (%)	
	Kewaunee	Maine Yankee
All Types	100	100
MnS	27.9	4.0
MnSSi	48.2	58.7
MnSAlSi	9.8	14.5
SSiAl	0	<.006
SSi	0	17.0
S	9.2	5.8
Si	4.9	0

Table 6 Percent Total Area		
Inclusion Type	Percent of Area Sum (%)	
	Kewaunee	Maine Yankee
All Types	.396	.503
MnS	.110	.020
MnSSi	.191	.295
MnSAlSi	.039	.073
SSiAl	0	<.00003
SSi	0	.086
S	.036	029
Si	.019	0

Percent Total Area = [(100% × Area Sum)/(Total Scan Area)]

where: Total Scan Area = 1008051 μm^2

Table 7 Maximum Inclusion Area and Length		
Measurement	Material	
	Maine Yankee	Kewaunee
Avg. Length (μm)	.943	.952
Median Length (μm)	.869	.776
Max. Length (μm)	13.74	14.03
Avg. Area (μm^2)	.527	.488
Median Area (μm^2)	.322	.233
Max. Area (μm^2)	29.6	45.48

6.4 INCLUSION SHAPE CONSIDERATIONS

It has been long understood that the best transverse properties for plate steels come from inclusions which approach spheres. This shape can be reduced to a length over width (l/w) ratio. An l/w ratio of 1 is for spherical precipitates. This ratio was calculated for each inclusion. The aspect ratio was taken for both materials and is summarized in Table 9. Figure 3 shows the normalized aspect ratio distribution for the Maine Yankee and Kewaunee surveillance weld materials, respectively. The Kewaunee sample inclusions as a whole tend to be more round than for the Maine Yankee sample as shown by the aspect ratio.

Table 8 Aspect Ratio

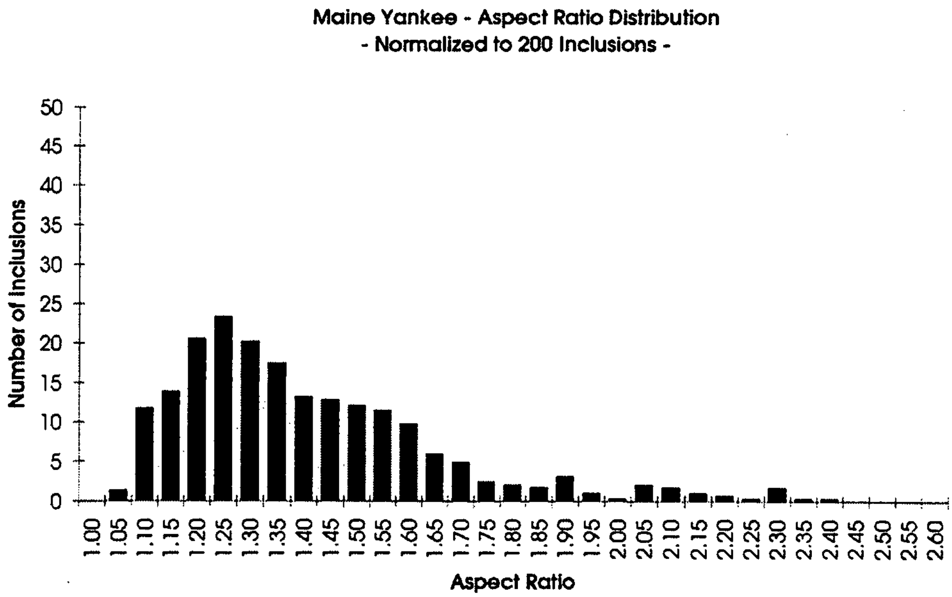
Measurement	Material	
	Maine Yankee	Kewaunee
Avg. Aspect Ratio	1.42	1.35
Median Aspect Ratio	1.36	1.26

6.5 INCLUSION DISTRIBUTION CONSIDERATIONS

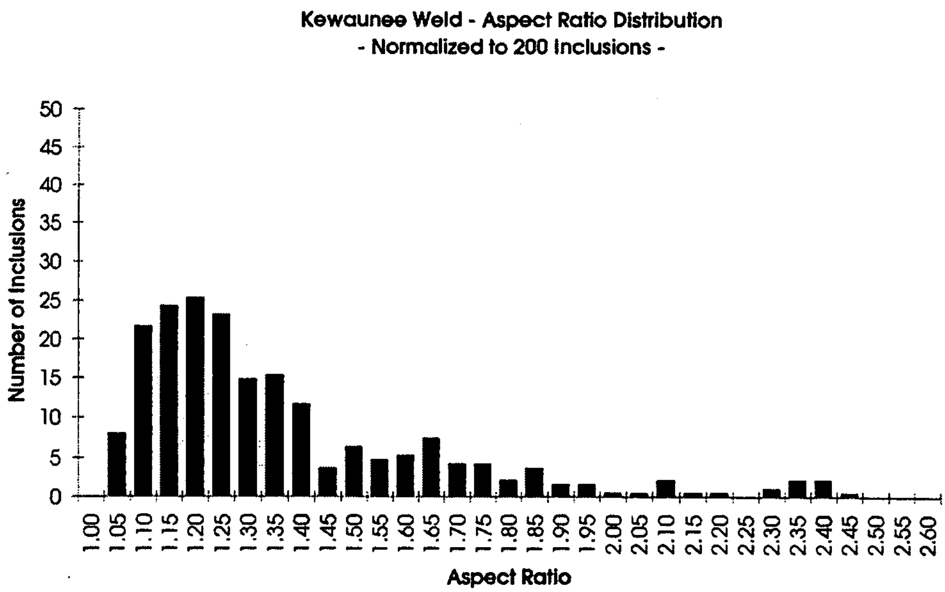
The inclusion spacing parameter is based on the largest number of inclusions in one field of each sample. Table 9 shows the smallest separation between inclusions in the most populated field as well as an average for the entire scan area. From this table, it is apparent that the Maine Yankee surveillance weld has the largest area of clustered inclusions. This observation was verified through visual observation of the samples. Other research has shown that closely spaced inclusions can act as one very long inclusion[15]. This effect results in a lower toughness. Therefore, when analyzing the data, it becomes increasingly important to analyze each field to determine if the spacing between inclusions is small.

Table 9 Average Inclusion Spacing

Material	Minimum Field Spacing (μm)	Average Scan Spacing (μm)
Maine Yankee	6.9	11.9
Kewaunee	8.1	13.5



(a)



(b)

Figure 3 Normalized aspect ratio distribution for (a) the Maine Yankee surveillance weld and (b) the Kewaunee surveillance weld materials, respectively.

7.0 DISCUSSION OF RESULTS

Based on the observations in this study, the Maine Yankee surveillance weld (Figure 4a) has more inclusions as a whole which are larger on average than the Kewaunee surveillance weld sample (Figure 4b). In addition, the inclusions in the Kewaunee surveillance weld sample on average tend to be more round which also would help to maximize the properties. The distribution of the inclusions based on the average spacing and minimum field spacing also show that the inclusions are closer together in the Maine Yankee surveillance material.

8.0 CONCLUSIONS

Decades of work have been performed on non-metallic inclusions in steels. Unfortunately, nuclear pressure vessel steels have little documentation on their non-metallic inclusions. It is shown based on previous research and this study that inclusion analysis can be used to explain variations in the toughness response of the pressure vessel steels[1, 8, 10, 12, 15-18]. The analysis can be used to explain the deleterious effects of inclusions on the initial mechanical properties for two surveillance welds (Kewaunee and Maine Yankee) that experienced different heat treatment conditions.

The work performed in this study has been used to collaborate observed trends in the mechanical properties of the Kewaunee and Maine Yankee (1P3571) surveillance welds. Based on the results of this inclusion analysis, it is concluded that the Kewaunee 1P3571 surveillance weld metal should have higher fracture toughness than the Maine Yankee surveillance weld. The different heat treatments between these two welds may account for the differences on the inclusion size, shape, and distribution seen in this examination.

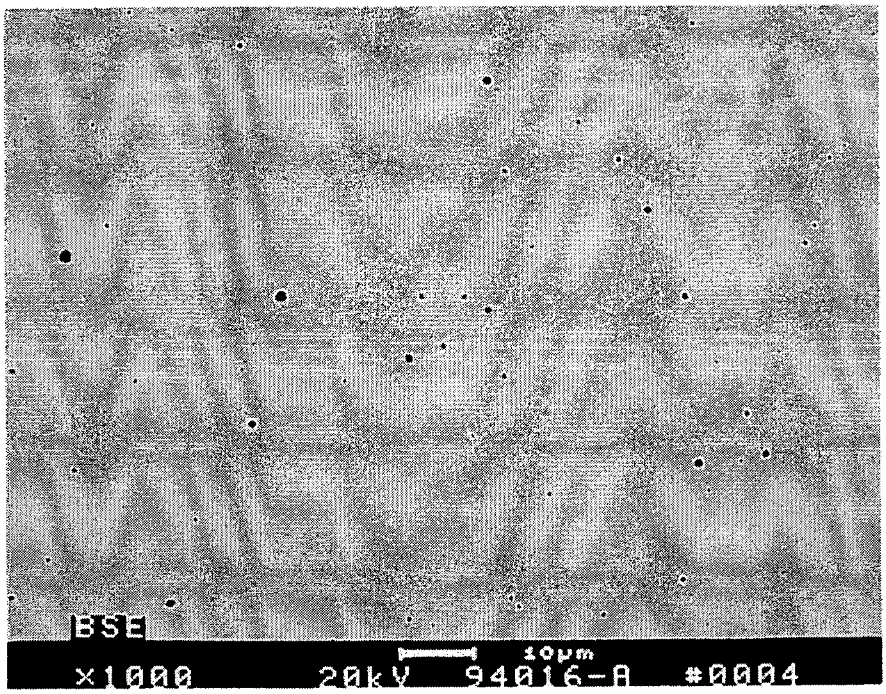


Figure 4a SEM Backscatter Micrograph of Maine Yankee Surveillance Weld

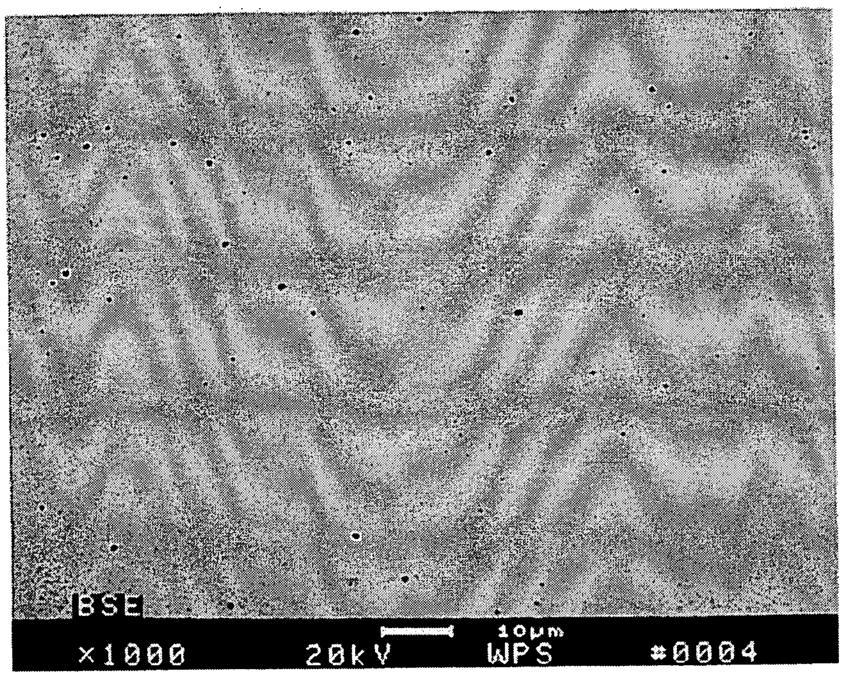


Figure 4b SEM Backscatter Micrograph of Kewaunee Surveillance Weld

REFERENCES

[1] Begley, J. A., "Effects of Section Size and Cleanliness on the Upper Shelf and Transition Range Toughness of Three Nuclear Pressure Vessel Steels," Packer Engineering and Westinghouse Electric Corporation Nuclear and Advanced Technology Division, August, 1992.

[2] Sims, Clarence E., "The Nonmetallic Constituents of Steel," Transactions of the Metallurgical Society of AIME, Volume 215, June 1959, pp 367-393.

[3] Baeyertz, M., Nonmetallic Inclusions in Steel, The American Society for Metals, 1947.

[4] Gschneidner, Jr., K. A., "Thermodynamic Stability and Physical Properties of Metallic Sulfide and Oxysulfides," Sulfide Inclusions in Steel, Proceedings of an International Symposium, November 7-8, 1974, American Society of Metals, 1975. pp 159-177.

[5] Kiessling, B. and Lange, N., Non-metallic Inclusions in Steel, Section K. Sulfide Inclusions, The Iron and Steel Institute, 1966.

[6] Yeo, R. B. G., "The Effects of Oxygen in Resulfurized Steels - Part 1," Journal of Metals, June 1967, pp 29-32.

[7] Skrabec, Q. R., "Deoxidation and Sulfide Control," Casting Engineering/Foundry World, Winter 1980-1981, pp 57-61.

[8] Bernard G., Grumbach M., Moliexe F., "Inclusions in Steel Plates and Mechanical Anisotropy," Metals Technology, November 1975, pp 512-521.

[9] Farrar, J. C. M. and Dolby, R. E., "Lamellar Tearing in Welded Steel Fabrication," The Welding Institute, England, 1975, pp 252-269.

[10] Baker, T. J., Gove, K. B., and Charles, J. A., "Inclusion Deformation and Toughness Anisotropy in Hot-rolled Steels," Metals Technology, April 1976, pp 183-193.

[11] Baker, T. J. and Charles, J. A., "Morphology of Manganese Sulfide in Steel," Journal of the Iron and Steel Institute, September 1972, pp 702-706.

[12] Baker, T. J. and Charles, J. A., "Type II Manganese Sulfides: Their Deformation and Effect on Steel Fracture," Journal of the Iron and Steel Institute, March 1973, pp 187-192.

[13] Baker, T. J. and Charles, J. A., "Deformation of MnS Inclusions in Steel," Journal of the Iron and Steel Institute, September 1972, pp 680-690.

[14] Leach, J. C. C., "Clean Steel" pp 11-19.

[15] DeArdo, Jr., A. J., and Hamburg, E. G., "Influence of Elongated Inclusions on the Mechanical Properties of High Strength Steel Plate," Sulfide Inclusions in Steel, Proceedings of an International Symposium, November 7-8, 1974, American Society of Metals, 1975. pp 309-337.

[16] Seraphin, L. G. and Tricot, Roland H., "Effect of Sulfide Inclusions on Mechanical Properties of Ultra-High Strength Steels," Sulfide Inclusions in Steel, Proceedings of an International Symposium, November 7-8, 1974, American Society of Metals, 1975. pp 338-360.

[17] Baker, T. J., "Use of Scanning Electron Microscopy in Studying Sulfide Morphology on Fracture on Fracture Surfaces," Sulfide Inclusions in Steel, Proceedings of an International Symposium, November 7-8, 1974, American Society of Metals, 1975. pp 135-158.

[18] Yukawa, S., "Non-metallic Inclusions and Fracture Behavior of Steels," Journal of Basic Engineering, June 1960, pp 411-416.