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INITIAL RT_{NDT} OF LINDE 80 WELD MATERIALS

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Prepared for

B&W Owners Group
Reactor Vessel Working Group

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Executive Summary

This report was prepared by the B&W Owners Group (B&WOG) Reactor Vessel Working Group (RVWG) to justify alternative initial reference temperatures (IRT_{NDT}) for the Linde 80 beltline welds in the B&W fabricated reactor vessels. The alternative IRT_{NDT} was determined based on brittle-to-ductile transition range fracture toughness test data of these weld metals obtained in accordance the ASTM Standard E1921 and using ASME Boiler and Pressure Vessel Code Case N-629. This report is submitted to the U. S. NRC for review and acceptance as a B&W Owners Group topical for application to the pressurized thermal shock (PTS) rule (10CFR50.61) and 10CFR50, Appendix G, pressure-temperature limits.

The fracture toughness curves used to determine plant operating pressure-temperature limits and PTS analyses are referenced to the material's unirradiated IRT_{NDT}. The original method for determining the initial RT_{NDT} was incorporated into Section III of the ASME Boiler and Pressure Vessel Code in 1972. At that time, there were insufficient data to judge whether the Section III method for determining IRT_{NDT} was appropriate for the low upper-shelf toughness weld metals used in reactor vessel fabrication. According to NB-2331 of Section III of ASME Code, two types of tests are needed for determining IRT_{NDT}: drop weight tests used to obtain T_{NDT} and Charpy impact energy tests used to determine the 50 ft-lb transition temperature (TT_{50}). The higher of T_{NDT} or TT_{50} minus 60°F becomes the RT_{NDT} of the material. In all cases, the TT_{50} minus 60°F value is the controlling parameter for the Linde 80 welds. The RT_{NDT} values are consistently higher for Linde 80 welds than for other weld materials *not* controlled by the Charpy transition temperature. Therefore, the "code method" is not particularly appropriate for the low upper-shelf toughness Linde 80 class of materials.

In BAW-2202, the B&WOG RVWG demonstrated that the drop-weight test data for determining an upper-bound IRT_{NDT} value is appropriate for Linde 80 weld material WF-70. The Master Curve approach, which is based directly on fracture toughness test data generated in the transition range, was used to show that the drop-weight data is more appropriate then Charpy data for establishing the IRT_{NDT}. Topical report BAW-2202 was submitted to and approved by the NRC in 1994 granting an exemption from Subarticle NB-2300 in Section III of the ASME Code (Federal Register, Vol. 59, No. 40, March 1, 1994, pages 9782~9785).

In this report, alternative IRT_{NDT} values of the Linde 80 weld heats were determined using the Master Curve approach and ASME Code Case N-629 with an appropriate initial margin. The alternative IRT_{NDT} values were determined from an extensive database of over 300 transition-temperature fracture toughness tests in which the majority of the beltline limiting weld heats are represented. The initial margin was determined using a Monte Carlo analysis to assess material and test variability coupled with an uncertainty term related to the sample size. The alternative IRT_{NDT} values are intended to be used with the shift prediction specified in Regulatory Guide 1.99. The Regulatory Guide 1.99 shift prediction is demonstrated to be conservative for the Linde 80 class of welds using over 100 irradiated fracture toughness tests.

Table of Contents

List of Tables

List of Tables (Continued)

Table **Page**

List of Figures

Figure **Page**

1. INTRODUCTION

This report was prepared by the B&W Owners Group Reactor (B&WOG) Vessel Working Group (RVWG) (See Table 1-1) to justify more realistic initial RT_{NDT} (IRT_{NDT}) values for the Linde 80 class of welds. The IRT_{NDT}, for the Linde 80* class of welds, was determined by the 50 ft-lb Charpy impact energy according to NB-2331 of Section III of the ASME B&PV Code, which gave overly conservative IRT_{NDT} values. In contrast, for most ferritic pressure vessel steel welds the IRT_{NDT} is determined by the drop weight nil-ductility temperature (T_{NDT}). A more realistic IRT_{NDT} is proposed which uses the fracture toughness based Master Curve reference temperature method and ASME B&PV Code Case N-629 [1].

1.1 Background of Linde 80 Welds

The reactor vessels of interest were fabricated by Babcock & Wilcox using the automatic submerged-arc welding process with Mn-Mo-Ni low alloy steel weld filler wire and Linde 80 flux. There were 15 beltline weld filler wire heats used in the fabrication of the B&W built reactor pressure vessels of concern to the RVWG (see Table 1-2). The weld wire was copper plated, introducing variable amounts of copper into the weld bead. The Linde 80 flux is a neutral flux, that is, it does not significantly influence the composition of elements known to contribute to irradiation induced changes in fracture toughness properties, e.g. copper, nickel. Each particular wire heat / flux lot combination was uniquely identified by a designation with either an "SA" or "WF" prefix followed by a number and was subjected to weld qualification testing.

According to NB-2331 of Section III of ASME Code, two types of tests are needed for determining RT_{NDT}: drop weight tests used to obtain T_{NDT} and Charpy impact energy tests used to determine the 50 ft-lb transition temperature (TT_{50}). The higher of T_{NDT} or TT_{50} minus 60°F becomes the IRT_{NDT} of the material. The IRT_{NDT} of all Linde 80 welds is controlled exclusively by the TT_{50} parameter determined through Charpy impact energy tests. It is a characteristic of these welds that the IRT_{NDT} values are consistently higher (i. e. –7 and -5°F) than other weld material *not* controlled by the Charpy transition temperature (typically around –50°F). The exact relationship between the IRT_{NDT} determining method to any specific attribute has not been established. However, since a related common characteristic of all the Linde 80 welds is low upper-shelf toughness, this is likely related to IRT_{NDT} determination method.

* Linde 80 is a proprietary designation of the Linde Division of the Union Carbide Corporation.

Table 1-1 B&W Owners Group Reactor Vessel Working Group

Utility	Plants	NSSS Vendor
Entergy Operations, Inc.	ANO 1	B&W
FirstEntergy Nuclear Operations, Inc.	Davis Besse	B&W
Duke Energy Company	Oconee 1,2,3	B&W
Exelon Corporation	TMI-1	B&W
Florida Power Corporation	Crystal River-3	B&W
Florida Power & Light Company	Turkey Point 1, 2	W
Dominion	Surry 1, 2	W
Nuclear Management Company	Point Beach 1, 2	W

1.2 B&W Owners Group Objective

The objective of this report is to establish alternative IRT_{NDT} (RT_{To} and associated σ_I) for the unirradiated Linde 80 welds for the B&W Owners Group member utilities in their licensing calculations. This alternative IRT_{NDT} is obtained by using the B&W Owners Group Master Curve reference temperature database and ASME Code Case N-629. Fracture mechanics based Master Curve reference temperature (T_0) data are available for most of the limiting heats in the subject vessels. For these heats, heat specific values of an alternative IRT_{NDT} are presented. However, there are a few heats for which there are no T_0 data due to the lack of available materials for testing. For these heats a generic alternative IRT_{NDT} is presented. An appropriate σ_I based on ASTM E1921 and the NRC Master Curve based methodology used for the Kewanee reactor vessel integrity assessment Safety Evaluation [2] is presented for both cases. It is proposed that the shift in RT_{NDT} , ΔRT_{NDT}, be calculated using currently accepted practices (i.e. Regulatory guide 1.99 rev. 2 [3] and 10CFR50.61 [4]). It is demonstrated that the current Regulatory Guide 1.99, Rev. 2 predicted shift in RT_{NDT} is conservative compared with the shift in T_0.

1.3 Requested Regulatory Actions

If this topical report is deemed acceptable by the staff, it is anticipated that following regulatory actions may be needed:

1. <u>Exemption from Subarticle NB-2331, Section III, ASME Code</u>
   Since the proposed alternative IRT_{NDT} only affects the RT_{NDT} of unirradiated Linde 80 material, this exemption suffices for use of the proposed alternative approach (narrow interpretation).

2. <u>10CFR50</u>
   In a broader interpretation, the above action relates to Appendix G of 10CFR50.60 and 10CFR50.61.

a. Appendix G to Part 50 Fracture Toughness Requirements

Since Appendix G states that "For the pre-service or unirradiated condition, RT_{NDT} is evaluated according to the procedures in the ASME Code, Paragraph NB-2331," an exemption to 10CFR50 Appendix G is required to use the alternative IRT_{NDT} described in this submittal using ASME Code Case N-629 for calculating adjusted reference temperature and pressure-temperature limit curves.

b. 10CFR50.61 Fracture Toughness Requirements for Protection Against Pressurized Thermal Shock Events.

The proposed alternative RT_{NDT} replaces $RT_{NDT(U)}$ in 50.61. Since this submittal requests the use of an alternative $RT_{NDT(U)}$, using ASME Code Case N-629, approval of the Director, Office of Nuclear Reactor Regulation is required.

Table 1-2. B&WOG RVWG Reactor Vessel Beltline Welds

Filler Wire Heat	Weld No.	Flux Lot No.	Reactor Vessel	Cu Content (%)	Remarks
1P0661	SA-775	8304	Point Beach-1	0.17	Outside weld
1P0815	SA-812	8350	Point Beach-1	0.17	
1P0962	SA-1073	8445	Oconee-1	0.21	
8T1554	SA-1494 WF-169-1	8579 8754	Surry-1; Three Mile Island-1 Crystal River-3	0.16	Outside weld or low fluence location
8T1762	SA-1426 SA-1430 SA-1493 SA-1580 WF-4 WF-8 WF-18	8553 8553 8578 8596 8597 8632 8650	Oconee-1; Point Beach-1 Oconee-1 Oconee-1 Crystal River-3 Surry-2; Zion-1 Crystal River-3; Surry-2; TMI-1 Zion-1; ANO-1; Crystal River-3	0.19	
8T3914	WF-232	8790	Davis-Besse	0.18	Low fluence
299L44	SA-1526 WF-25	8596 8650	Surry-1; TMI-1 Oconee-1; Oconee-2; TMI-1	0.34	63W, 64W ORNL
406L44	WF-112 WF-154 (WF-193)	8688 8720	ANO-1 Oconee-2; Zion-1	0.27	
821T44	WF-182-1 WF-200	8754 8773	ANO-1; Davis-Besse Oconee-3; Zion-2	0.24	
61782	SA-847 SA-1135	8350 8457	Point Beach-1 Oconee-1	0.23	
71249	SA-1101 SA-1229 SA-1769	8445 8492 8738	PB-1; Turkey Point-3; TP-4 Oconee-1 Crystal River-3; Zion-2	0.23	
72105	WF-70	8669	Crystal River-3; Oconee-3; TMI-1; Turkey Point-4; Zion-1; Zion-2	0.32	
72442	SA-1484 WF-67	8579 8669	Point Beach-2; Turkey Point-3 Oconee-3; Turkey Point-4	0.26	
72445	SA-1585 SA-1650	8597 8632	Oconee-1; Surry-1; Surry-2 Surry-1	0.22	65W ORNL
T29744	WF-233	8790	Davis-Besse	0.21	Low fluence

2. FRACTURE TOUGHNESS TESTING

2.1 Master Curve Method

The ASTM Committee on Fatigue and Fracture developed a standard entitled "*Test method for the determination of a reference temperature T_0 for ferritic steels in the transition range*," ASTM E1921-97 [6]. This test method defines the procedure for obtaining a reference temperature, T_0. The T_0 defines a "Master Curve" which characterizes the fracture toughness of a ferritic steel in the brittle-to-ductile transition temperature range.

ASTM E1921-97 was based on a single test temperature procedure. Recently a multi-temperature version of the test method was developed and added to the updated version of E1921, which is to be released as ASTM E1921-02 [7]. A description of these standards are provided in Appendix A of this report.

The new standard, ASTM E1921-02, allows a plane strain conversion equation between J and K_{Jc}, but the old plane stress equation in ASTM E1921-97 was used in this analysis. This is slightly more conservative yielding lower K_{Jc} values.

2.2 B&W Owners Group Test Procedures

Details of B&W Owners Group test procedures conducted at Lynchburg Technology Center and the Alliance Research Center are described in Appendix B.

3. FRACTURE TOUGHNESS OF LINDE 80 WELD MATERIALS

3.1 Mechanical Properties

Tensile test data indicate that both yield and ultimate strength have relatively narrow scatter band resulting in a small standard deviation of yield strength data of all the Linde 80 welds. This supports the claim that these welds belong in the same family. Figure 3-1 shows room temperature tensile strength values for 14 wire/flux combinations covering 8 of the 15 wire heats in the Linde 80 class of welds. Figure 3-2 shows the ultimate strength values. (These values are for surveillance material, and since the same material was used for more than one plant, there is more than one entry for some wire/flux combinations.) These test values were obtained over a long period of time, with testing at more than one laboratory using both hydraulic and screw driven testing machines. Inspection of the values shows them to be sufficiently close (standard deviation is 4.7 ksi for yield and 4.3 ksi for ultimate stress [8]. This supports the premise that Linde 80 welds constitute a single weld class.

In Figure 3-3 ultimate strengths are shown against yield strengths of Linde 80 weld materials. Kirk [9] has shown that there is a universal linear relationship between these two strengths for all ferritic steels. When the Linde 80 weld data are plotted a very good agreement was observed with the universal strength curve shown by Kirk.

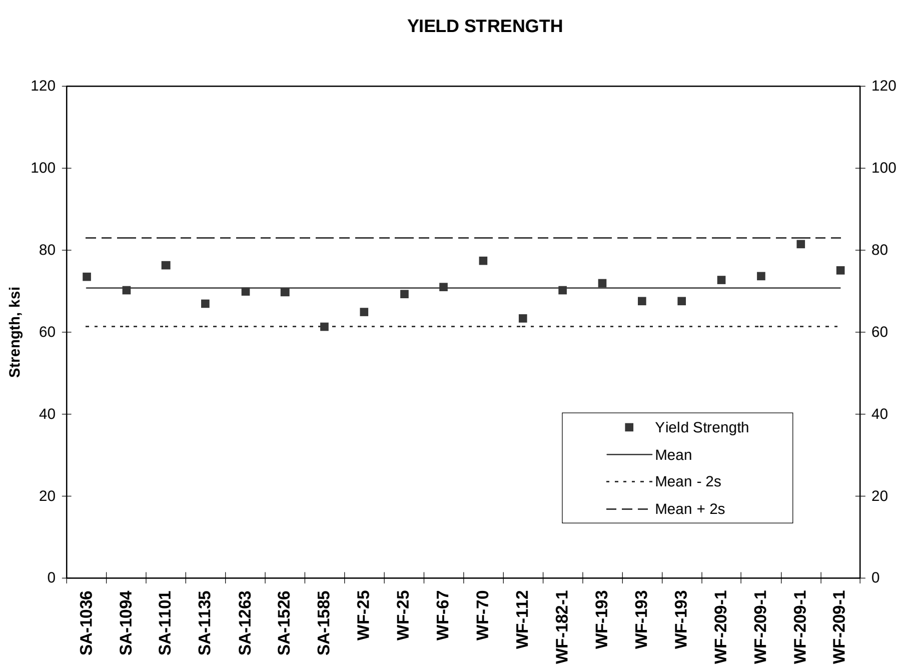

Figure 3-1 Yield Strengths of Linde 80 Welds – Room Temperature

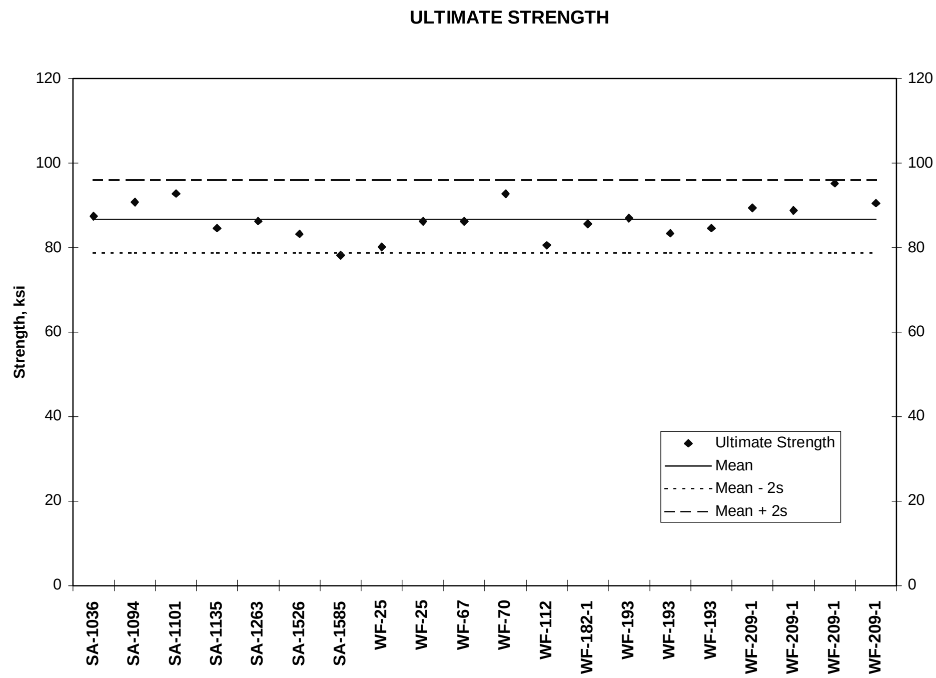

Figure 3-2 Ultimate Strengths of Linde 80 Welds – Room Temperature

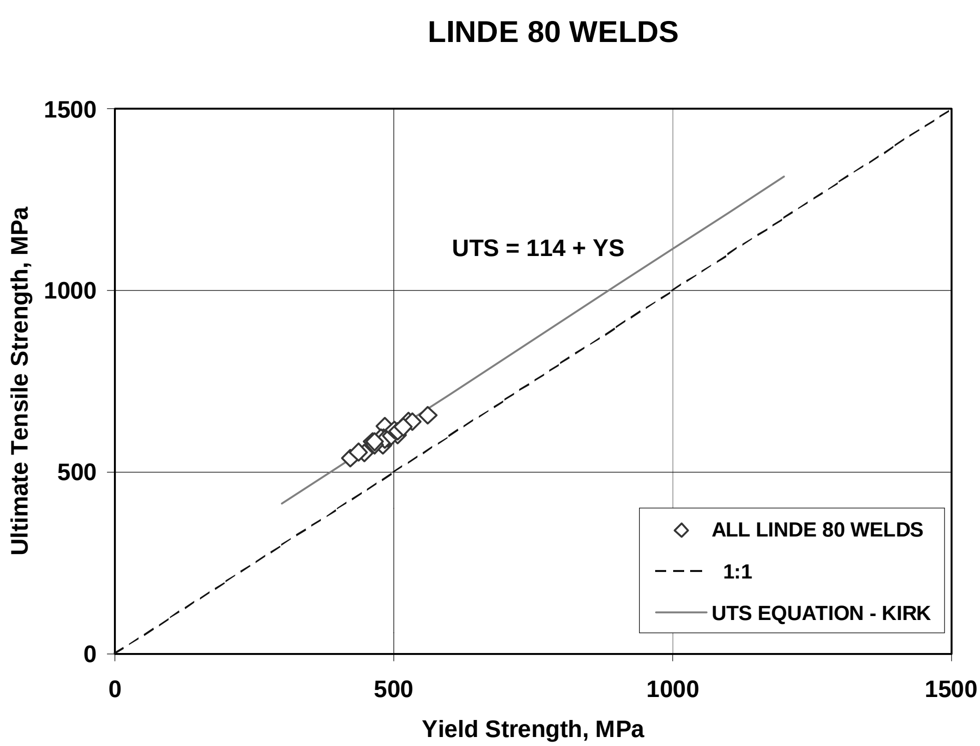

Figure 3-3 Yield versus Ultimate Tensile Strengths

3.2 Current RT_{NDT} of Unirradiated Linde 80 Welds

According to NB-2331 of Section III of ASME Code, two types of tests are needed for determining IRT_{NDT}; drop weight tests to obtain T_{NDT} and Charpy impact energy tests to determine the 50 ft-lb transition temperature (TT_{50}). The higher of T_{NDT} or TT_{50} minus 60°F becomes the IRT_{NDT} of the material.

A characteristic feature of Linde 80 welds is that all IRT_{NDT} values are determined by Charpy transition temperature minus 60°F, not by drop-weight test based T_{NDT} . Due to this characteristic, the IRT_{NDT} values of the Linde 80 welds are consistently higher than non-Linde 80 welds, whose IRT_{NDT} values are typically around -50°F as established by T_{NDT}. The exact relationship between IRT_{NDT} determining method to any specific attribute has not been established. Since another common characteristic of all the Linde 80 welds is low upper-shelf toughness, this is likely related to IRT_{NDT} determination method.

In BAW-2202 [5], the B&WOG RVWG demonstrated that the drop-weight test data for determining an upper-bound IRT_{NDT} value is appropriate for Linde 80 weld material WF-70. The Master Curve approach, which is based directly on fracture toughness test data generated in the transition range, was used to show that the drop-weight data is more appropriate then Charpy data for establishing the IRT_{NDT}. BAW-2202 was submitted to and approved by the NRC in a topical report in 1994. The B&WOG justified an IRT_{NDT} value of -56°F with a standard deviation of 14.8°F.

The current licensing basis IRT_{NDT} values for all Linde 80 welds are listed in Table 3-1. Individual weld specific IRT_{NDT} and T_{NDT} values are shown in Table 3-2, which were used to establish the generic IRT_{NDT} and σ_I.

Table 3-1 Licensing Basis IRT_{NDT}

Weld Id	**Initial RT_{NDT} (°F)**	**σ_I (°F)**	**Source**
WF-25 and SA-1526	-7	20.6	NRC letter to GPU 8/16/1993 [10]
WF-70	-26	0.0	BAW-2202 [5]
Linde 80 -Generic	-5	19.7	BAW-2325 Rev. 1 [11]

In Figure 3-4, the IRT_{NDT} values from Charpy impact energy tests of the Midland WF-70 weld are plotted [12]. This plot shows a very large scatter in IRT_{NDT} values at various locations in the vessel. This plot illustrates a shortcoming of the IRT_{NDT} determination method based on Charpy impact energy since the IRT_{NDT} values shown here are supposed to represent the same material.

The B&W Owners Group IRT_{NDT} Linde 80 weld data (determined by Charpy transition temperature) are plotted against T_0 values in Figure 3-5 where IRT_{NDT} shows a decreasing trend while the T_0 value is increasing. This is contrary to the expectation if IRT_{NDT} is truly a measure of fracture toughness. Therefore, for Linde 80 welds, the Charpy transition temperature based IRT_{NDT} appears to be inappropriate as a measure of fracture toughness. On the other hand, T_{NDT} shows an increasing trend with increasing T_0 as shown in Figure 3-6. T_{NDT} seems to be a better indicator of fracture toughness (T_0).

Table 3-2 Data Used for Determination of Generic Initial RT_{NDT} for Linde 80 Welds

Weld ID	Heat No.	T_{NDT} (°F)	CVN Properties Temp. (°F)	Energy (ft-lbs)	Lat. Exp. (mils)	RT_{NDT} (°F)
WF-25(9)	299L44	-40	---	---	---	+7
WF-25(6)	299L44	-10	---	---	---	+33
WF-25(5)	299L44	-20	---	---	---	-13
SA-1526	299L44	-40	---	---	---	-20
WF-112	406L44	-50	---	---	---	+19
WF-193	406L44	-100	---	---	---	+20
SA-1101	71249	-90	---	---	---	-50
WF-67	72442	-20	---	---	---	-3
SA-1585	72445	-50	---	---	---	-7
WF-182-1(6)	821T44	-30	---	---	---	+15
WF-182-1(14)	821T44	-20	---	---	---	-15
SA-1036	61782	-70	---	---	---	-1
PQ 3170	---	-40	70	52,52,60	38,39,47	+10
PQ 2923	---	-20	80	50,50,53	42,49,46	+20
PQ 3443	---	-20	70	50,51,57	44,43,55	+10
PQ 3116	---	-30	70	51,54,61	56,48,45	+10
PQ 3117	---	-30	50	53,59,65	44,45,59	-10
PQ 3299	---	-20	40	65,68,68	35,36,40	-20
WF-291	82912	-40	20	54,56,57	53,55,53	+40
WF-275	T49544	-40	80	50,51,54	51,47,51	+20
WF-292	82915	-30	50	53,54,56	48,52,54	-10
WF-282	T29744	-40	70	52,53,55	51,52,58	+10
WF-308	20506	-40	30	50,54,63	36,39,44	-30
WF-314	T49544	-30	40	50,53,53	50,50,51	-20
WF-351	442001	-40	60	52,55,59	44,44,48	0
WF-635	41404	-40	70	50,55,55	40,40,41	+10
WF-307	82919	-40	40	52,54,67	45,49,54	-20
WF-324	1P5412	-30	30	53,55,57	40,40,43	-30
WF-696	1084-18	-50	40	50,53,59	40,41,43	-20
WF-336	442002	-30	30	51,67,71	44,49,53	-30
SA-2050	41402	+10	70	51,52,65	41,44,53	+10
WF-353	72105	+10	70	50,52,65	41,44,53	+10
WF-645	H4498	-50	40	54,62,72	43,52,58	-20
WF-610	H4498	-60	50	50	39	-10

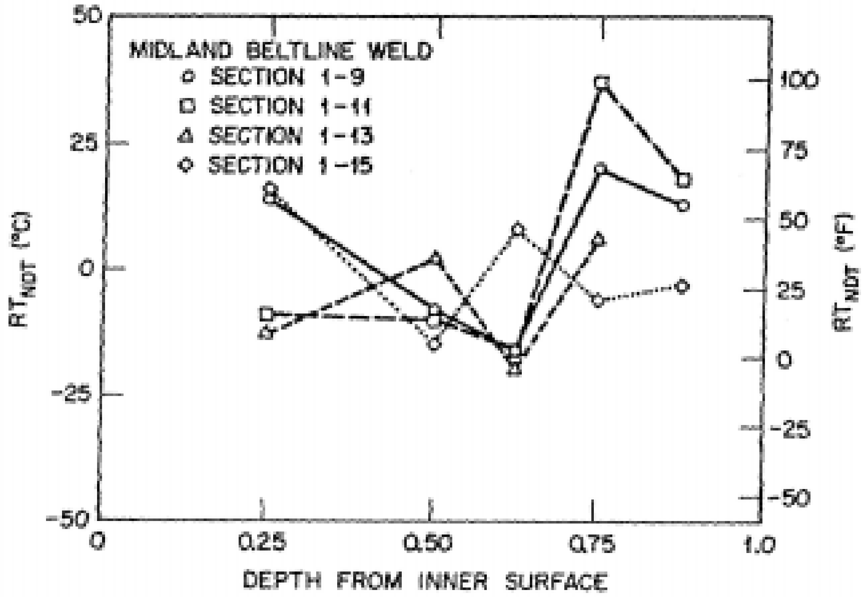

Figure 3-4 ORNL Charpy Impact Energy Data for Midland WF-70 Weld

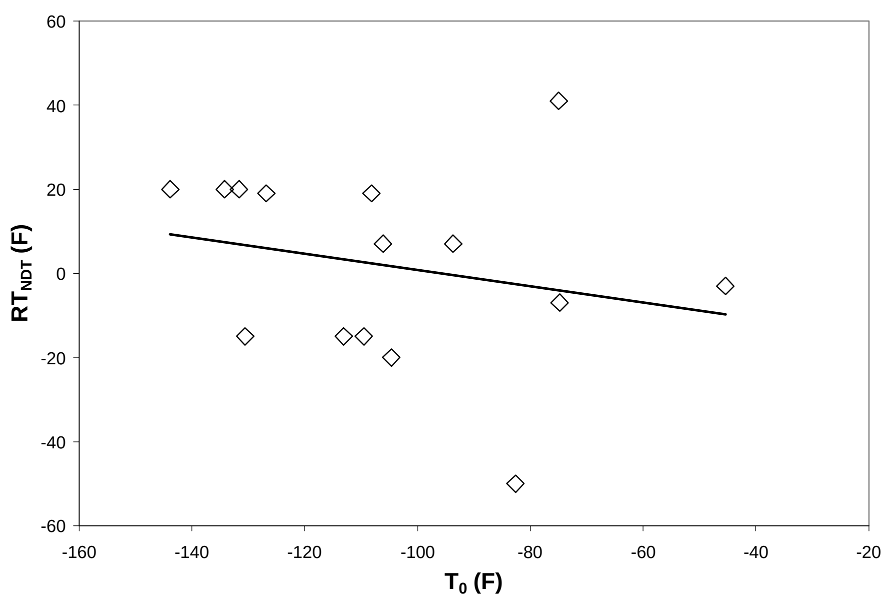

Figure 3-5 RT_{NDT} (TT_{50} based) versus T_0 for Linde 80 Welds – Unirradiated

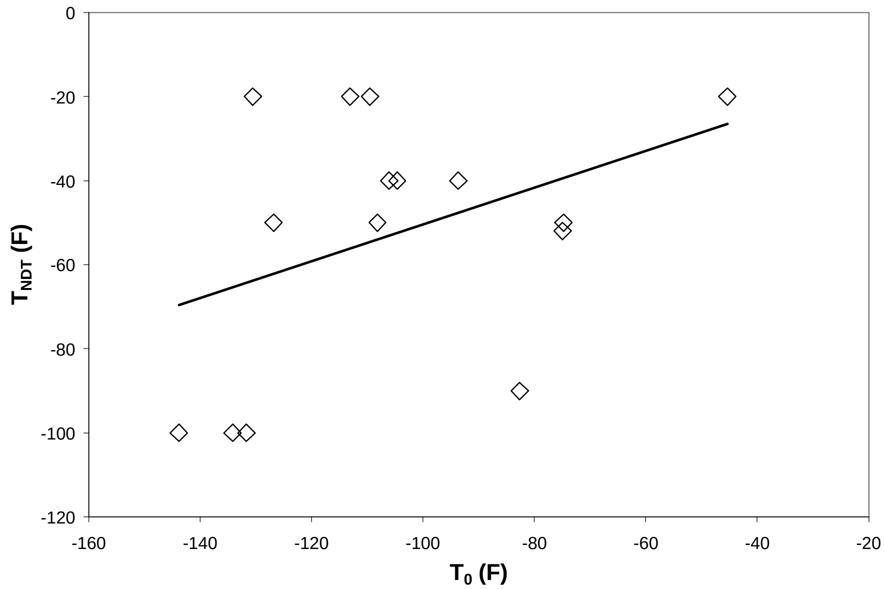

Figure 3-6 T_{NDT} (drop-weight test based) versus T_0 for Linde 80 Welds – Unirradiated

All available archive Linde 80 welds were tested to determine T_0 (See Section 4). This testing generated T_0 values for seven of the Linde 80 heats comprising nearly all of the beltline limiting welds. There are some Linde 80 heats, which have no T_0 data available, due to a lack of archival materials. However, there are T_{NDT} data available for a greater number of the Linde 80 heats. The T_{NDT} data was split into two groups: one group of heats for which T_0 data are available and another group of heats for which T_0 data are unavailable.

This grouping was done to determine whether the group for which T_0 data are available can adequately represent the entire Linde 80 class of welds. The mean and standard deviation for T_{NDT} are shown in Table 3-3. The mean and standard deviation of T_{NDT} are not significantly different from each other or the entire Linde 80 class of welds as demonstrated using a student T test. From this table, the seven heats of Linde 80 welds that have T_0 may be considered to be representative of the entire Linde 80 class of welds.

Table 3-3 T_{NDT} Population

Group	Mean (°F)	Standard Deviation (°F)
Seven heats for which T_0 data is available	-42.7	29
Remaining heats for which T_0 data are unavailable	-33.5	18

4. T_0 FOR UNIRRADIATED LINDE 80 WELDS

The B&W Owners Group conducted fracture toughness tests in the brittle-to-ductile transition temperature range in accordance with ASTM Standard E1921-97 for all available Linde 80 weld materials. All K_{Jc} values from the tests are listed in Appendix C. The resulting K_{Jc} data are used to calculate reference temperatures, T_0, which are listed in Table 4-1. The ASTM E1921-97 method was used to calculate T_0 with one noted exception.

In addition to the substantial B&W Owners Group database, there are other Linde 80 weld fracture toughness data available in the industry. The available industry data consist predominantly of test results from the WF-70 weld removed from the Midland Unit 1 reactor vessel. The Oak Ridge National Laboratory (ORNL) and the Westinghouse Owners Group tested a large number of specimens fabricated from the Midland weld. Table 4-1 includes the ORNL T_0 data. The ORNL program also tested weld materials designated 72W and 73W. The 72W and 73W are simulated welds to represent low upper-shelf toughness materials like the Linde 80 welds. These two weld materials yielded T_0 values very close to the T_0 values of WF-70 tested by ORNL. The Westinghouse Owners Group tests resulted in similar T_0 values to the ORNL data for the Midland WF-70 weld material. ORNL also tested other Linde 80 weld materials (63W, 64W, and 65W) in the transition range and the resulting data were analyzed for their Master Curves [13]. These specimens were originally fabricated by B&W and were donated to the ORNL HSST program for testing. The 63W and 64W welds are both the WF-25 weld. Weld 65W is the SA-1585 weld. The reference temperatures calculated from these data are included in Table 4-1.

Table 4-1 Linde 80 Weld T_0 Data

Wire Heat	Weld Metal	Source	Specimen Type	Test Temp (°F)	T_0 (°F)	No. Valid Spec.	Comments
299L44	SA-1526	CR3 ND	0.5TCT	-70	-96	6	
	WF-25	OC3 ND	PCCS	-145	-126	7	
			0.5TCT	-70	-99	6	
406L44	WF-112	OC1 RVSP	PCCS	-160	-141	8	
			0.5TCT	-70	-119	8	
	WF-193	RS1 RVSP	PCCS	-180	-176	10	
			0.5TCT	-150	-146	9	
			0.5TCT	-70	-126	8	
71249	SA-1094	TP4 RVSP	PCCS	-140	-115	11	
72105	WF-70(B)	MD Beltline	PCCS	-120	-108	7	
			2TCT	-13	-72	6	ORNL[12]
			1TCT	-13	-78	7	ORNL[12]
			0.5TCT	-13	-74	8	ORNL[12]
			2TCT	-58	-72	6	ORNL[12]
			1TCT	-58	-53	6	ORNL[12]
			0.5TCT	-58	-72	6	ORNL[12]
			1TCT	-103	-47	6	ORNL[12]
			1TCT	-148	-42	6	ORNL[12]
	WF-70(N)	MD ND	1TCT	-13	-22	8	ORNL[12]
			1TCT	-58	-2	6	ORNL[12]
			0.5TCT	-58	-36	7	ORNL[12]
			1TCT	-148	-31	6	ORNL[12]
72442	SA-1484	CR3 ND	PCCS	-100	-91	7	
	WF-67	MD ND 11 hr SR	PCCS	-120	-101	7	
		MD ND 50 hr SR	Various CTs	-51 to -74	-60	7	Multi-temp.
72445	SA-1585	ANO1 ND	PCCS	-150	-107	10	
821T44	WF-182-1	DB1 RVSP	PCCS	-180	-163	6	
			0.5TCT	-70	-105	6	
			0.5TCT	-140	-124	12	

RVSP = Reactor Vessel Surveillance Program Weld
ND = Nozzle Drop-Out
PCCS = Pre-Cracked Charpy Size Specimen
TCT = Compact Fracture Toughness Specimen
SR = Stress Relief

4.1 Variations in T_0

Table 4-1 shows variation in the T_0 values within the same weld wire heat. The sources of variation can be grouped into two categories:

- Recognized sources of variation, which can be compensated for

  1) specimen loading rate,
  2) PCCS bias, and
  3) stress relief time/material source

- Other sources of variation, which can only be compensated for through the initial margin term

  1) testing laboratory,
  2) test procedure,
  3) material,
  4) sample size (number of specimens), and
  5) other.

  A Monte Carlo analysis and sample size uncertainty evaluations were performed to determine the appropriate initial margin due to the above sources and the results are presented in Section 4.3.

4.2 Recognized Sources of Variation

4.2.1 Specimen Loading Rate

Based on a large database of static and dynamic fracture toughness data of ferritic steels that B&W Owners Group collected (Pressure Vessel Research Council, B&WOG, and literature), a linear relationship between T_0 and logarithm of loading rate has been established in the following equation form [14,15]:

$$T_0 = A + B\ \ell n(dK_I/dt) \qquad (4\text{-}1)$$

where the constants A and B can be determined from the experimental data such as shown in Figure 4-1. Most of the data in Figure 4-1 were obtained from tests conducted under quasi-static and high rate loading conditions. However, the JRQ material (A-533B1 plate) [15] were tested under two quasi-static loading conditions and one much higher rate. The rate effect seen in the JRQ material within the quasi-static loading regime is also seen in SA-515 steel [15] as shown in the same figure.

There are some variations in the slope, B, for the materials plotted in Figure 4-1. Some of these variations are undoubtedly due to the differences in the material response to the various ferritic pressure vessel materials. But it also could be attributed to the different dynamic responses due to varying amount of data used, differing ways in which testing rate is calculated, and various test techniques used to conduct dynamic tests. There was not a statistically significant difference in rate effect between plate and weld materials, so all the ferritic steels were lumped together to determine the effect of loading rate. Likewise, Linde 80 welds showed some differences in slope B. The slope of this linear fit varies from 2.2 to 5.5. The values of these slopes are listed in Table 4-2.

A weighted averaging method was used to calculate the slope B. The calculated weighted average is 4.75 with a standard deviation of 0.86 as shown in Table 4-2. The published value of 5.33 was used in adjusting the Linde 80 data in this report [14].

Based on equation 4-1, the loading rate correction to T_0 can be made by the following equation for any two different loading rates:

$$T_0\big|_{R2} = T_0\big|_{R1} + 5.33\, \ell n(R2/R1) \qquad (4\text{-}2)$$

where R1 and R2 are loading rates in units of MPa√m/sec.

From Figure 4-1, it is evident that a loading rate adjustment is needed for quasi-static testing even though ASTM E1921 does not address this issue. When examining the T_0 shift between static and dynamic fracture toughness data it should be noted that the current ASTM E1921-97 does not require the reporting of the loading rate for a quasi-static test. The loading rates for quasi-static test data range from 0.2 to 2 MPa√m/sec indicating the loading rate variation of ten fold for the B&WOG data. The T_0 variation from the loading rate alone can be as high as 12°C (22°F) according to Equation 4-2. Using equation 4-2, all the T_0 values listed in Table 4-3 were adjusted to a common loading rate of 1 MPa√m/sec. The loading rate for each test is listed in Appendix C.

Table 4-2 Determination of Slope B for Linear Fit Equation

Material ID	**Number of T_0s N**	**Slope B**	**Product N x B**
JSEW	50	5.06	253.05
HSST Pl 02	8	2.16	17.28
HSST Pl 14	4	3.56	14.24
JSW	19	4.51	85.69
JRQ	3	4.68	14.04
L-80 heat 72105	5	3.57	17.85
L-80 non-72105 heat	17	5.52	93.84
Joyce SA-515	12	5.34	64.08
	Total	Average	Weighted Average
	118	4.30	4.75

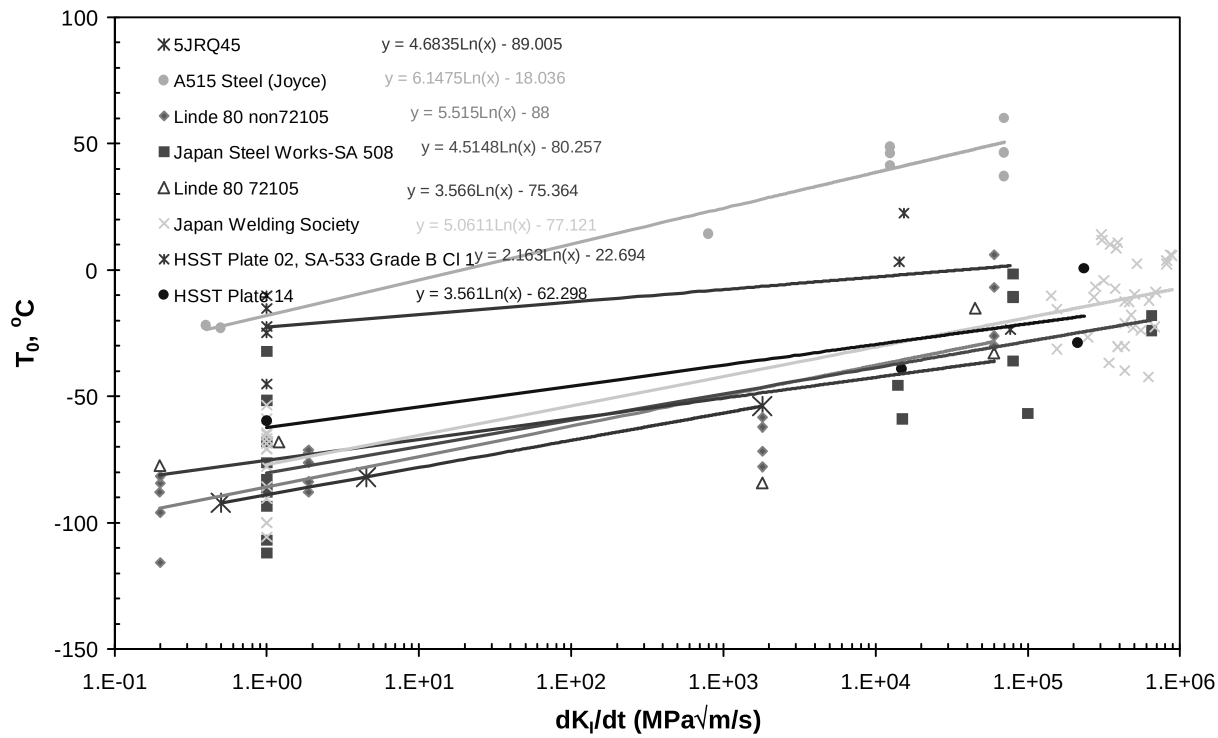

Figure 4-1 Loading Rate Effect on T_0

4.2.2 PCCS Specimen Bias

There are some differences in T_0 when tested using compact specimen versus three point bend specimens of the same size. The Japanese K_{IR} database [16] includes data where both specimen types from the same material were tested. The results are inconclusive at this time since some show marked difference and some do not. The ASTM E08 Committee will pursue this issue in the future.

Tregoning and Joyce suggested a systematic bias toward the Pre-Cracked Charpy Size bend (PCCS) specimen of about 18°F (10°C) [17]. The B&WOG data showed a varying PCCS bias averaging 18°F (10°C). The NRC used a 8.5°F (4.7°C) bias term for the Kewaunee reactor vessel [2]. The B&WOG used a bias of 18°F value to adjust all the Linde 80 weld PCCS data in Table 4-3, which is conservative relative to the NRC bias used for the Kewaunee safety evaluation. This eliminates large variations in T_0 for most of the tested welds.

4.2.3 Stress Relief Time/Material Source

Actual measurements of the weld in the vessel are unavailable so typically a surrogate weld is used to produce the initial properties. The surrogate weld is typically the reactor vessel surveillance program (RVSP) block, which was fabricated at the same time as the vessel weld using the same procedures and wire heat. The B&W fabricated RVSP blocks were also given the same stress relief time as the represented weld in the vessel. For the B&W fabricated vessels, this SR time ranged from 10 to 31 hours. The B&WOG has 3 weld wire heats of RVSP block material (406L44, 71249, and 821T44) for which unirradiated ASTM E1921 reference temperature data are available, and one heat (72105) for which actual vessel material removed from Midland unit 1 is available.

In addition, testing has been conducted on three additional heats (299L44, 72442, and 72445), which are actual vessel weld cutouts (dropouts) removed from the nozzle belt region of the vessel during fabrication. The nozzle dropouts (ND) were removed for subsequent attachment of the nozzles. The nozzle dropout welds consist of a thicker section (12" versus 8") than the beltline and RVSP block welds. In addition, the nozzle dropouts received 50 to 53 hours of stress relief. This was to ensure that any initial toughness data gathered from them would be conservative relative to the same wire heats used for the beltline welds. Logston demonstrated that long stress relief times reduce fracture toughness for ASME SA508 Class 2a and SA533 Grade B Class 2 [18]. This can also be seen in the Linde 80 welds (Figure 4-2).

Since it was demonstrated in Section 3.2 that T_{NDT} has some correlation with T_0, the same trend should be seen with stress relief time and T_{NDT}. In fact, T_{NDT} does increase as the stress relief time increases as shown in Figure 4-3. In addition, the effect of stress relief time is presented for two specific welds as shown in Figure 4-4 for heats 72442 and 72105. T_{NDT} and T_0 show consistent trends with respect to increase in transition temperature relative to stress relief time [19].

The difference in stress relief time may not be the only difference between the beltline/RVSP welds and the nozzle belt welds. The difference in weld thickness may also have an effect on transition toughness. The Linde 80 weld wire heat 72105 was used in both the beltline [WF-70(B)] and nozzle belt [WF-70(N)] of Midland Unit 1 reactor vessel with similar stress relief times (22.5 and 25.5 hours respectively). Both of these welds were tested by the ORNL [13]. The reference temperature for WF-70(N) is 40°F higher than WF-70(B).

For the above reasons, it is concluded the ND data conservatively represents the Linde 80 beltline welds in calculating the initial T_0.

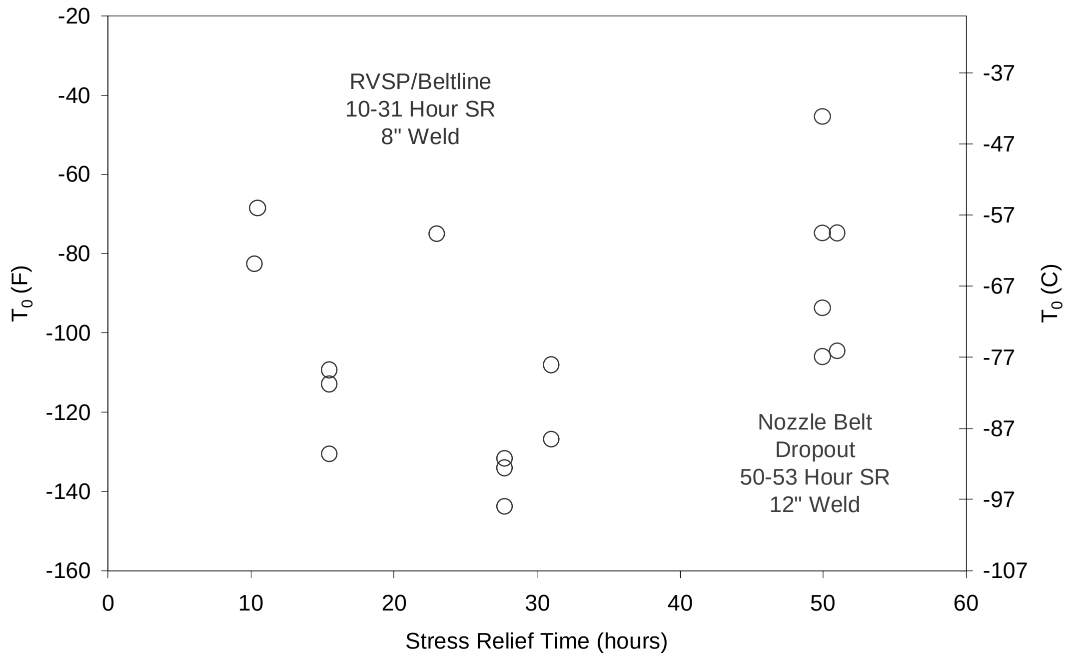

Figure 4-2 Stress Relief Time Effect on T_0 – B&WOG Data

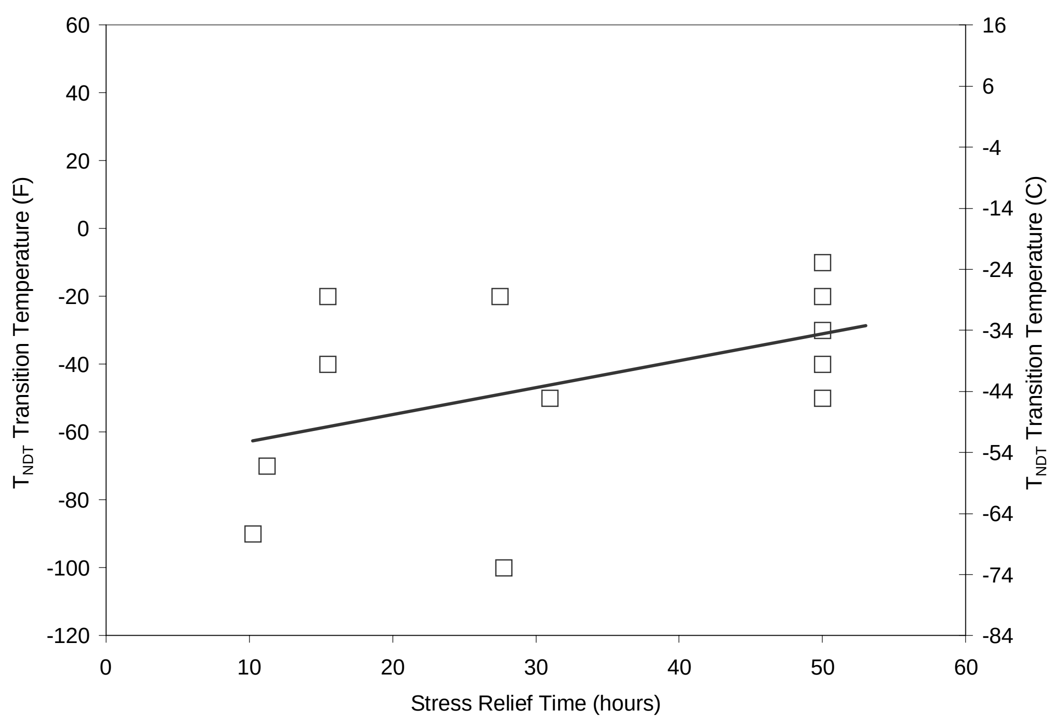

Figure 4-3 T_{NDT} as a Function of SR Time

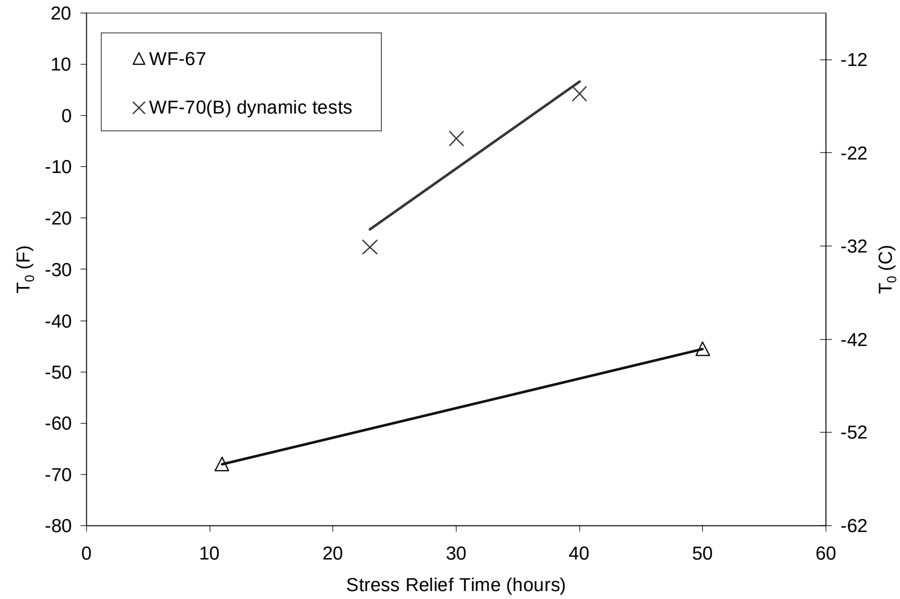

Figure 4-4 T_0 Increases as a Function of SR Time for Two Linde 80 Weld Heats

4.2.4 Heat Specific T_0 with Adjustments

Table 4-3 contains the T_0 values adjusted for the loading rate effect and PCCS bias as described in 4.2.1 and 4.2.2. The individual values of T_0 were averaged for each heat and are also listed in Table 4-3.

In addition, all available data for each heat was combined and the multi-temperature T_0 calculation described in Appendix A was performed. The number of available data points for this calculation was larger than that for the ASTM E1921-97 calculation since there is no single test temperature restriction. The data from the multi-temperature T_0 calculations were also adjusted for loading rate effect and PCCS bias as described in 4.2.1 and 4.2.2. The new standard, E1921-02, allows a plane strain conversion equation, but the old plane stress equation in E1921-97 was used in this analysis. This is conservative yielding slightly lower K_{Jc} values. The results are presented in Table 4-4 with the number of specimens used for computation.

Table 4-3 Linde 80 Weld Adjusted T_0 Data

Wire Heat	Weld Metal	Source	Specimen Type	Test Temp (°F)	T_0 (°F)	Rate Adj. T_0 (°F)	PCCS + Rate Adj. T_0 (°F)	No. Valid Spec.	Average Adjusted T_0 (°F)	Comments
299L44	SA-1526	CR3 ND	0.5TCT	-70	-96	-105	-105	6	-102	
	WF-25	OC3 ND	PCCS	-145	-126	-112	-94	7		
			0.5TCT	-70	-99	-106	-106	6		
406L44	WF-112	OC1 RVSP	PCCS	-160	-141	-126	-108	8	-129	
			0.5TCT	-70	-119	-127	-127	8		
	WF-193	RS1 RVSP	PCCS	-180	-176	-162	-144	10		
			0.5TCT	-150	-146	-132	-132	9		
			0.5TCT	-70	-126	-134	-134	8		
71249	SA-1094	TP4 RVSP	PCCS	-140	-115	-101	-83	11	-83	
72105	WF-70(B)	MD Beltline	PCCS	-120	-108	-93	-75	7	-72	
			2TCT	-13	-72	-78	-78	6		ORNL
			1TCT	-13	-78	-86	-86	7		ORNL
			0.5TCT	-13	-74	-82	-82	8		ORNL
			2TCT	-58	-72	-80	-80	6		ORNL
			1TCT	-58	-53	-61	-61	6		ORNL
			0.5TCT	-58	-72	-80	-80	6		ORNL
			1TCT	-103	-47	-55	-55	6		ORNL
			1TCT	-148	-42	-50	-50	6		ORNL
	WF-70(N)	MD ND	1TCT	-13	-22	-30	-30	8	-30	ORNL
			1TCT	-58	-2	-10	-10	6		ORNL
			0.5TCT	-58	-36	-42	-42	7		ORNL
			1TCT	-148	-31	-39	-39	6		ORNL
72442	SA-1484	CR3 ND	PCCS	-100	-91	-93	-75	7	-63	
	WF-67	MD ND 11 hr SR	PCCS	-120	-101	-86	-68	7		
		MD ND 50 hr SR	Various CTs	-51 to -74	-60	-45	-45	7		Multi-temp.
72445	SA-1585	ANO1 ND	PCCS	-150	-107	-93	-75	10	-75	
821T44	WF-182-1	DB1 RVSP	PCCS	-180	-163	-149	-131	6	-118	
			0.5TCT	-70	-105	-113	-113	6		
			0.5TCT	-140	-124	-110	-110	12		

RVSP = Reactor Vessel Surveillance Program Weld
ND = Nozzle Drop-Out
PCCS = Pre-Cracked Charpy Size Specimen
TCT = Compact Fracture Toughness Specimen
SR = Stress Relief

Table 4-4 Multi-Temperature T_0 Calculation Results

Heat	Source	T_0 (°C)	T_0 (°F)	Number of Specimens
406L44	RVSP	-89.9	-129.9	43
71249	RVSP	-63.6	-82.4	11
72105[a]	MD-1	-58.6	-73.4	107
821T44	RVSP	-81.8	-115.2	24
299L44	ND	-82.7	-116.8	42
72442	ND	-53.9	-65.0	24
72445	ND	-77.5	-107.5	22
All 7 Linde 80 Heats[b]	**ALL**	**-74.8**	**-102.6**	**314**

a WF70(B) from the Midland Unit 1 vessel.

b Includes WF70(N); all data was combined for single multi-temperature calculation for information only and is not used in subsequent analysis.

4.3 Uncertainty Evaluation

A Monte Carlo analysis was performed to evaluate the uncertainty in T_0 relative to material and test laboratory variations. In addition, the uncertainty in T_0 due to the sample size was calculated. These were combined to form the basis of the initial uncertainty margin, σ_I.

4.3.1 Monte Carlo Analysis

There are other possible sources of variation in reference temperature including 1) testing laboratory, 2) test procedure, and 3) material. These uncertainties can be addressed through an uncertainty term, in this case, called the initial margin, σ_I.

To determine variations of T_0 within a Linde 80 heat, a Monte Carlo analysis was performed treating all available fracture toughness data in each heat as a single population. Each heat has a K_{Jc} population size varying between 11 and 107. The same database used for the multi-temperature calculation in Section 4.2.4 was used for the Monte Carlo simulations. The database was adjusted for the loading rate effect and PCCS bias as described in Sections 4.2.1 and 4.2.2, prior to the simulations. A total of 1000 simulations were made for each heat. Each simulation consisted of randomly selecting eight K_{Jc} data points and calculating T_0 with the selected K_{Jc} values. The multi-temperature method described in Appendix A was used for the T_0 calculation. The average T_0 and σ for each heat determined from the Monte Carlo analysis is presented in Table 4-5. A Monte Carlo analysis was performed for all the available Linde 80 data combined into a single population. Due to the larger amount of data, 5000 simulations were performed. The result is also shown in Table 4-5. The result is a larger σ, as expected, due to the combination of the data from the seven Linde 80 heats.

This σ accounts for any variation between the measured toughness of the source material (RVSP block, ND, or MD-1 beltline weld) and the actual vessel weld.

The test data in the B&W Owners Group database came from three different laboratories over a time span of nearly 10 years. The sources of the test materials are from various origins: the RVSP welds, the Midland vessel beltline weld, and other plant nozzle dropouts. Because the data are from various test laboratories, times, and sources, all reasonable variation within a Linde 80 heat are represented.

Table 4-5 Summary of Monte Carlo Analysis Results for Linde 80 Weld Data

Heat	Source	Ave. T_0 (°C)	Std Dev (°C)	Ave. T_0 (°F)	Std Dev (°F)	Number of Specimens
406L44	RVSP	-88.5	5.4	-127.3	9.7	43
71249	RVSP	-61.8	4.0	-79.2	7.2	11
72105B[a]	MD-1	-55.7	6.3	-68.3	11.3	107
821T44	RVSP	-81.4	3.6	-114.5	6.5	24
299L44	ND	-76.1	5.2	-104.9	9.3	42
72442	ND	-51.7	5.2	-61.0	9.3	24
72445	ND	-65.7	4.2	-86.2	7.5	22
all heats[b]	all	-70.3	9.5	-94.6	17.1	314

a WF70(B) from the Midland Unit 1 vessel.
b Includes WF70(B) and WF70(N) from the Midland Unit 1 vessel.

4.3.2 Sample Size Uncertainty

ASTM E1921 recommends a shift in T_0 due to the T_0 uncertainty related to the size of the measured sample (number of valid specimens used to calculate T_0). The following equation calculates the standard deviation accounting for uncertainty in T_0 due to sample size and $K_{Jc(med)}$:

$$\sigma = \beta/\sqrt{n}$$

where:

β is a function of $K_{Jc(med)}$:

1T equivalent $K_{Jc(med)}$ (MPa√m)	β
> 84	18
83 to 66	18.8
65 to 58	20.1

and n is the sample size (number of valid specimens tested).

σ can then be multiplied by a normal deviate, Z, to obtain a specific confidence limit. No multiplier (i.e. Z=1, which corresponds to a standard single-tail confidence limit of 84%) was used here, since σ_I is defined in Regulatory Guide 1.99 and 10CFR50.61 as the standard deviation for the IRT_{NDT} or an estimate of the precision of the test method.

Table 4-6 Sample Size Uncertainty for Linde 80 Weld Data

Heat	Source	Number of Uncensored Specimens	1T $K_{Jc(med)}$ (MPa√m)	β	σ (°F)
406L44	RVSP	39	103	18	5.2
71249	RVSP	10	71	18.8	10.7
72105[a]	MD-1	86	114	18	3.5
821T44	RVSP	24	102	18	6.6
299L44	ND	22	107	18	6.9
72442	ND	21	82	18.8	7.4
72445	ND	12	77	18.8	9.8
all heats[b]	all	249	95	18	2.1

a WF70(B) from the Midland Unit 1 vessel.
b Includes WF70(B) and WF70(N) from the Midland Unit 1 vessel.

4.3.3 Initial Margin

The standard deviation from the Monte Carlo analysis, which accounts for material and laboratory variations and the ASTM E1921 sample size standard deviation are combined. These two uncertainty terms are unrelated: therefore, they can be combined using the square root of the sum of the squares method. The heat specific Monte Carlo analysis standard deviation is combined with each heat ASTM E1921 sample size standard deviation as shown in Table 4-7.

Table 4-7 Linde 80 Weld Heat Specific σ_I

Heat	Source	Material/Test (Monte Carlo) σ (°F)	ASTM E1921 σ (°F)	σ_I (°F)
406L44	RVSP	9.7	5.2	11.0
71249	RVSP	7.2	10.7	12.9
72105[a]	MD-1	11.3	3.5	11.8
821T44	RVSP	6.5	6.6	9.3
299L44	ND	9.3	6.9	11.6
72442	ND	9.3	7.4	11.9
72445	ND	7.5	9.8	12.3
all heats[b]	All	17.1	2.1	17.2

a WF70(B) from the Midland Unit 1 vessel.
b Includes WF70(B) and WF70(N) from the Midland Unit 1 vessel.

4.4 Summary of T_0 Data

Table 4-8 shows three different columns of average T_0 values calculated from 1) single-temperature method, 2) multi-temperature method, and 3) Monte Carlo simulations. The E1921-97 average T_0 values for heats 299L44 and 72445 are significantly different from the multi-temperature calculation since the ORNL data acquired from Reference 13 did not contain enough valid data below the upper limit to calculate valid single temperature T_0s. The multi-temperature calculation of T_0 will be used for subsequent calculation of initial RT_{To}, since this calculation used the most test data.

Table 4-8 Summary of Reference Temperature Calculations

Heat	Source	E1921-97 Average T_0 (°F)	Multi-Temperature T_0 (°F)	Monte Carlo average T_0 (°F)	Number of Specimens[b]
406L44	RVSP	-129	-129.9	-127.3	43
71249	RVSP	-83	-82.4	-79.2	11
72105[a]	MD-1	-72	-73.4	-68.3	107
821T44	RVSP	-118	-115.2	-114.5	24
299L44	ND	-102	-116.8	-104.9	42
72442	ND	-63	-65.0	-61.0	24
72445	ND	-75	-107.5	-86.2	22
All 7 Linde 80 Heats[c]	**ALL**	**-92**	**-98.6**	**-91.6**	**273**

a WF70(B) from the Midland Unit 1 vessel.
b Number of Specimens does not apply to E1921-97 Average T_0.
c Average of all seven heat specific T_0s.

5. IRRADIATION INDUCED SHIFT IN FRACTURE TOUGHNESS

Since an alternative IRT_{NDT} of the Linde 80 welds is proposed using the Code Case N-629 approach, a key question is whether combining this alternative initial RT_{T0}, based on T_0, with the shift prediction, ΔRT_{NDT}, from Regulatory Guide 1.99 Rev. 2 is appropriate. The regulatory guide has the following equation for adjusted RT_{NDT} ;

$$\text{Adjusted } RT_{NDT} = IRT_{NDT} + \Delta RT_{NDT} + M$$

where M is the margin term.

The current approach combines an IRT_{NDT} determined from either T_{NDT} or Charpy TT_{50} with a shift based on TT_{30}. These are different measures of transition temperature. Substituting a different appropriate measure of transition temperature (Code Case N-629) for IRT_{NDT} does not affect the shift term. Both the IRT_{NDT} and the ΔRT_{NDT} have there own independent measures of uncertainty as captured in the margin term:

$$M = 2\sqrt{\sigma_I^{\ 2} + \sigma_\Delta^{\ 2}}$$

where σ_I is the standard deviation of the initial RT_{NDT} which consists of the measurement uncertainty, σ_{To} and $\sigma_{\text{Monte Carlo}}$.

$$\sigma_I^2 = \sigma_{T0}^{\ 2} + \sigma_{\text{Monte Carlo}}^{\ 2}$$

σ_Δ is the standard deviation of the shift, ΔRT_{NDT}. Since ΔRT_{NDT} is unchanged with the resetting of the IRT_{NDT}, the current σ_Δ is appropriate. Adequacy of σ_Δ is further examined using the B&W Owners Group irradiated specimen test data.

The measured T_0 values for all the Linde 80 weld heats irradiated in surveillance capsules, which were tested for T_0 are listed in Table 5-1. ΔT_0 can be compared to the measured Charpy 41-Joule (30ft-lb) shift (ΔTT_{30}).

Kirk [9] showed the industry irradiation induced T_0 shift (ΔT_0) data plotted against the measured ΔTT_{30} in Figure 5-1. The weld fit slope is 0.99 indicating that there is approximately one-to-one correlation between the 41-Joule Charpy energy shift and ΔT_0.

A similar plot using the B&WOG data is shown in Figure 5-2. The best-fit slope is 0.94. The use of the ΔTT_{30} is conservative relative to T_0 shift for Linde 80 welds. Therefore, using a T_0-based initial RT_{To} with the Regulatory Guide 1.99 Rev. 2 predicted RT_{NDT} shift is conservative and acceptable.

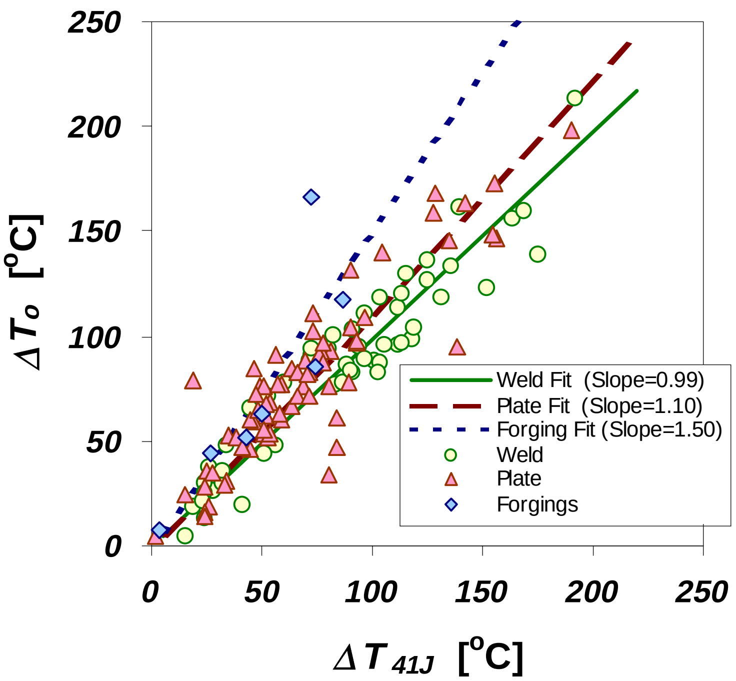

Figure 5-1 ΔT_0 versus ΔTT_{30} [9]

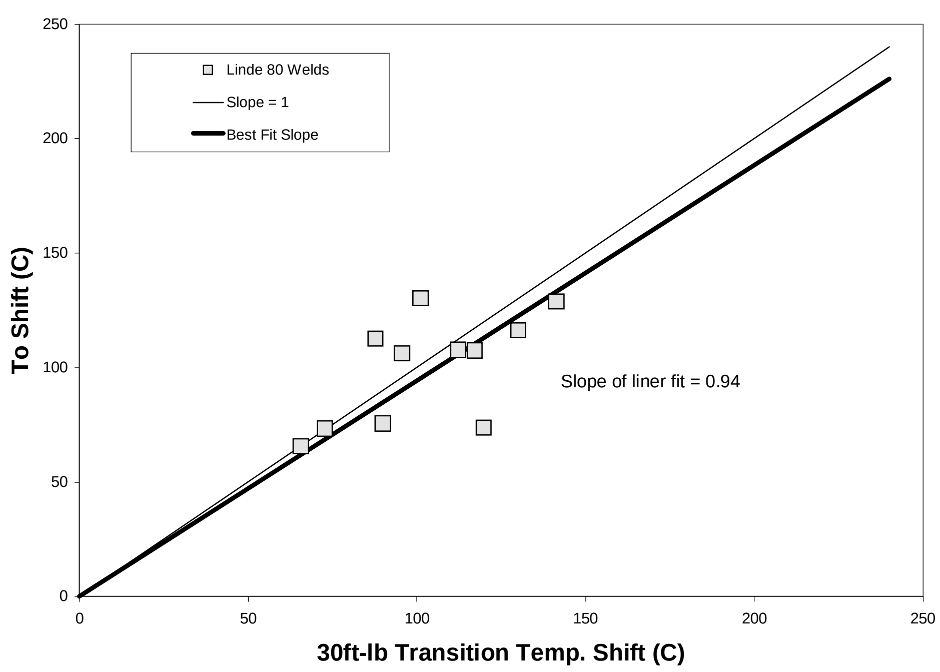

Figure 5-2 ΔT_0 versus ΔTT_{30} for Linde 80 Weld Metals

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The next step is to further assure that the generic σ_Δ value of 28°F is adequate for this combination of unirradiated RT_{NDT} based on T_0 with the Regulatory Guide 1.99 Rev. 2 RT_{NDT} shift. First all available Linde 80 RT_{NDT} Charpy shift data are plotted against fluence as shown in Fig. 5-3. These data are normalized to a single value of chemistry factor of 167.

When a best-fit equation is derived from the Linde 80 data set, the resulting curve is similar to the Regulatory Guide 1.99 Rev. 2 curve except that this curve gets flatter at higher fluence. The standard deviation of the best-fit equation to the data 29.8°F compared with the generic value of 28°F. All data points lie within the mean ±2σ curves. When the RG1.99 curve with $\pm 2\sigma_\Delta$ curves are superposed, these curves also bound almost all the data points. This is a clear indication that the Regulatory Guide 1.99 Rev. 2 generic σ_Δ value is applicable to this data set.

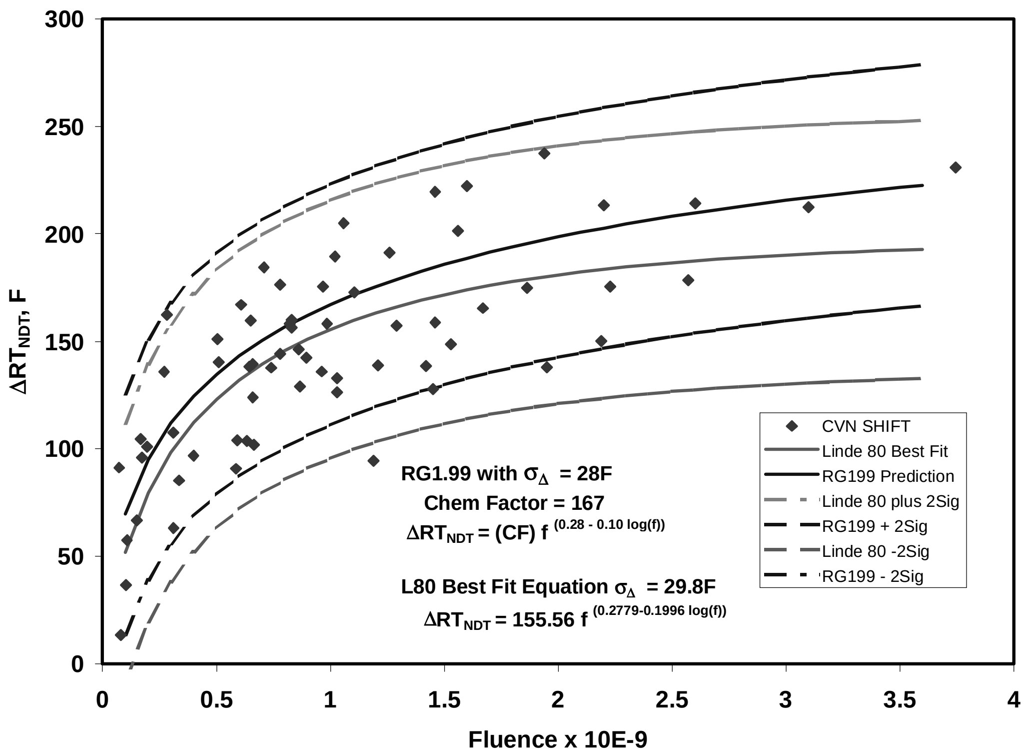

Figure 5-3 ΔTT_{30} versus Fluence for Linde 80 Welds

Secondly, all the available T_0 shift data are plotted with the Regulatory Guide 1.99 Rev. 2 mean $\pm 2\sigma_\Delta$ curves in Figure 5-4. The T_0 data was not normalized to a common chemistry factor. This figure reaffirms adequacy of the premise that the Regulatory Guide 1.99 Rev. 2 shift curve with the generic weld σ_Δ value can be used with the proposed alternative set of unirradiated RT_{NDT}.

Table 5-2 lists the measured values of ΔT_0 and the Regulatory Guide 1.99 Rev. 2 prediction for each material that was tested. On average, the Regulatory Guide 1.99 Rev. 2 over-predicts the ΔT_0 by 9°F with a standard deviation of about 28°F. (This excludes WF-70(N) at 1.59E+19 n/cm^2 and SA-1585 which had insufficient data for a valid reference temperature and were greatly over predicted by Regulatory Guide 1.99 Rev. 2.)

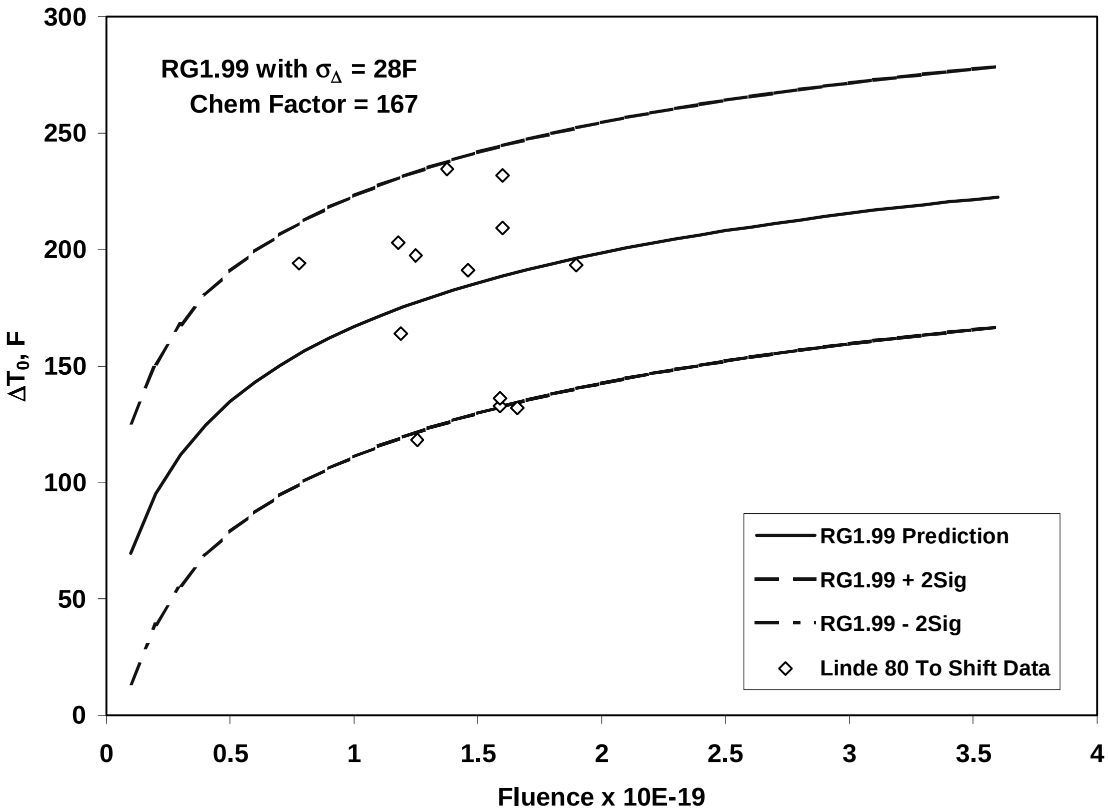

Figure 5-4 ΔT_0 Data Plot with RG1.99 Rev. 2 Shift Model

The approach taken in this report (alternative IRT_{NDT} plus Regulatory Guide 1.99 Rev. 2 ΔRT_{NDT}) is compared to the RT_{T0} obtained from T_0 values of irradiated Linde 80 data in Table 5-3. There are four with alternative IRT_{NDT} plus Regulatory Guide 1.99 Rev. 2 shift that exceeded the irradiated RT_{To}. The four that exceeded the irradiated RT_{To} were all within the expected uncertainty, which is covered by the margin term (well within 2σ range). Excluding WF-70(N) at 1.59E+19 n/cm^2 and SA-1585 which had insufficient data for a valid reference temperature, the irradiated RT_{To} averaged 6°F higher than the approach taken in this report.

For the reasons described above, it is appropriate and conservative to combine the alternative IRT_{NDT}, based on Code Case N-629, with the Regulatory Guide 1.99 Rev. 2 shift prediction.

Table 5-1 Measured Irradiated T_0

Heat	**Weld**	**Source**	**Fluence (n/cm^2, E > 1 MeV)**	**Specimen Type**	**Test Temp (°F)**	**T_0 (°F)**	**Rate Adj. T_0 (°F)**	**PCCS + Rate Adj. T_0 (°F)**	**Number of Valid Tests**
406L44	**WF-193**	ANO1 RVSP	1.46E+19	RPCCS	10	22	37	55	8
71249	**SA-1094**	TP4 RVSP	1.60E+19	PCCS	20	117	131	149	7*
	SA-1101	TP3 RVSP	1.38E+19	PCCS	20	119	134	152	7*
72105	**WF-70(N)**	MD1 ND	1.19E+19	RPCCS	40	60	74	92	6
	WF-70(N)	MD1 ND	1.59E+19	1/2TCT	0	88	103	103	4*
	WF-209-1	Z1 RVSP	1.90E+19	PCCS	45	89	103	121	7
821T44	**WF-182-1**	DB1 RVSP	1.18E+19	PCCS&DCT	20 to 110	82	78	85	8
299L44	**WF-25**	OC3 ND	7.79E+18	RPCCS	40	62	76	94	8
	SA-1526	S1 RVSP	1.60E+19	RPCCS	60	72	87	105	8
72442	**SA-1484**	CR3 ND	1.25E+19	PCCS&DCT	10 to 120	113	110	123	17
	WF-67	MD1 ND	1.26E+19	PCCS&DCT	-30 to 30	38	51	62	13
	WF-67	MD1 ND	1.66E+19	Var. CTs	0 to 90	61	76	76	8
72445	**SA-1585**	ANO1 ND	1.59E+19	1/2TCT	0	47	62	62	3*

RVSP = Reactor Vessel Surveillance Program Weld
ND = Nozzle Drop-Out
PCCS = Pre-Cracked Charpy Size Specimen
TCT = Compact Fracture Toughness Specimen
DCT = 0.936” Thick Disk Shaped Compact Specimen
*Insufficient data for a valid reference temperature.

Table 5-2 Measured Shift in T_0 Compared to Regulatory Guide 1.99 Rev. 2 Prediction

Heat	**Weld**	**Fluence (n/cm^2, E > 1 MeV)**	**Measured T_0 Shift (°F)**	**Reg. Guide 1.99 R.2 Prediction (°F)**	**Number of Valid Tests**
406L44	**WF-193**	1.46E+19	191	200	8
71249	**SA-1094**	1.60E+19	232	216	7*
	SA-1101	1.38E+19	235	219	7*
72105	**WF-70(N)**	1.19E+19	164	183	6
	WF-70(N)	1.59E+19	133	254	4*
	WF-209-1	1.90E+19	193	197	7
821T44	**WF-182-1**	1.18E+19	203	180	8
299L44	**WF-25**	7.79E+18	194	214	8
	SA-1526	1.60E+19	209	199	8
72442	**SA-1484**	1.25E+19	198	191	17
	WF-67	1.26E+19	118	178	13
	WF-67	1.66E+19	132	190	8
72445	**SA-1585**	1.59E+19	136	187	3*

*Insufficient data for a valid reference temperature.

Table 5-3 Irradiated T_0 Compared to Alternative IRT_{NDT} plus Regulatory Guide 1.99 Rev. 2 Shift

Heat	**Weld**	**Fluence (n/cm^2, E > 1 MeV)**	**Alternative IRT_{NDT} + Reg. Guide 1.99 R.2 Shift (°F)**	**Measured Irradiated T_0 +35°F (°F)**	**Difference (°F)**
406L44	**WF-193**	1.46E+19	105	90	15
71249	**SA-1094**	1.60E+19	169	184	-15
	SA-1101	1.38E+19	172	187	-15
72105	**WF-70(N)**	1.19E+19	145	127	18
	WF-70(N)	1.59E+19	216	138	78
	WF-209-1	1.90E+19	159	156	3
821T44	**WF-182-1**	1.18E+19	100	120	-20
299L44	**WF-25**	7.79E+18	132	129	3
	SA-1526	1.60E+19	117	140	-23
72442	**SA-1484**	1.25E+19	161	158	3
	WF-67	1.26E+19	148	97	51
	WF-67	1.66E+19	160	111	49
72445	**SA-1585**	1.59E+19	114	97	17

6. ALTERNATIVE INITIAL RT_{NDT} OF LINDE 80 WELDS

Code Case N-629 of ASME Boiler and Pressure Vessel Code allows an alternative IRT_{NDT} based on T_0 designated as RT_{To} which is:

$$RT_{To} = T_0 + 35, °F$$

From the B&W Owners Group fracture toughness database, T_0 data are available for seven heats of Linde 80 welds. These weld wire heats represent most of the limiting welds of the 13 B&W fabricated reactor vessels. For the welds, which belong to these seven heats, it is proposed that the heat specific value of IRT_{To} be used with the appropriate initial margin.

For the other welds that do not belong to these seven heats, a generic Linde 80 alternative IRT_{To} is proposed with a larger appropriate initial margin. Only about two limiting Linde 80 welds and a number of non-limiting welds would require the use of the generic RT_{To} and corresponding initial margin.

6.1 Heat Specific Initial RT_{To}

The proposed seven heat specific RT_{To} values are listed in Table 6-1.

Table 6-1 Heat Specific Initial RT_{To}

Heat	Multi-Temperature T_0 (°F)	RT_{To} (°F)	Initial Margin σ_I (°F)
406L44	-129.9	-94.9	11.0
71249	-82.4	-47.4	12.9
72105	-73.4	-38.4	11.8
821T44	-115.2	-80.2	9.3
299L44	-116.8	-81.8	11.6
72442	-65.0	-30.0	11.9
72445	-107.5	-72.5	12.3

Figure 6-1 shows all the data included in the above analysis relative to the Master Curve, 5%/95% tolerance bounds and the ASME K_{Ic} curve offset by 35°F plus the smallest $2\sigma_I$ (i.e. 53.6°F). It is noted that all the data are bounded by the offset K_{Ic} curve.

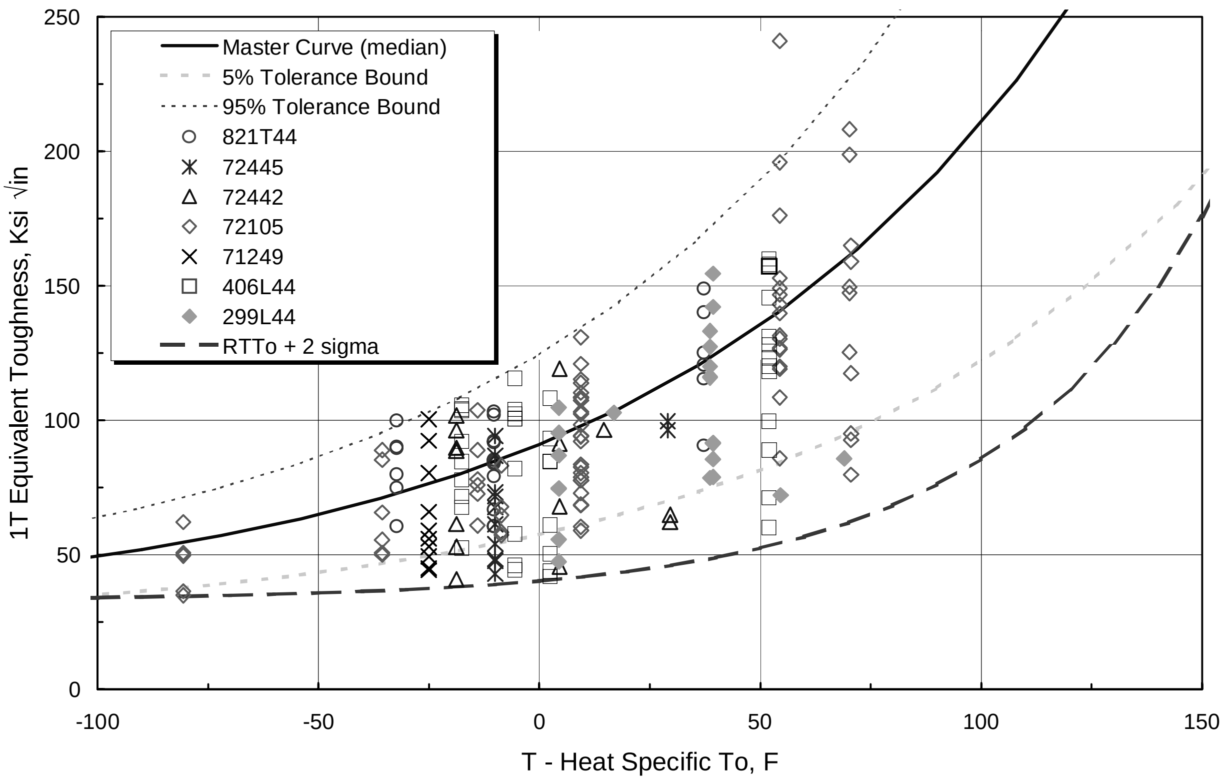

Figure 6-1 K_{Ic} with RT_{To} versus Linde 80 Data with Heat Specific T_0

6.2 Generic Initial RT_{To} for Heats Without T_0 Data

The current licensing base allows for the B&W Owners Group to use a generic IRT_{NDT} values (-5 and -7°F). This generic approach was derived from a statistical evaluation performed on the available data listed in Table 3-1. B&W Owners Group's current proposal to assign a generic IRT_{NDT} value for the Linde 80 class of welds is not new but based on a better fracture toughness indexing parameter T_0.

T_0 values are available for seven of the 15 heats of high copper Linde 80 welds that currently exist in the beltline of operating B&W fabricated reactor vessels. In addition, the 7 heats of Linde 80 welds represent all but two of the 11 limiting or near limiting heats in the belt-line regions of the participating plants.

The multi-temperature T_0 for each heat is listed in Table 6-1. The mean of the Linde 80 class of materials is calculated from the heat multi-temperature T_0 resulting in a value of –98.6°F. Since the data measurements comprise a significant portion of the Linde 80 welds and are similar to the unrepresented heats (Table 3-3), it is concluded that the measurements are representative of the entire Linde 80 class of welds.

Using Code Case N-629, RT_{To} is taken to be the mean T_0 plus 35°F (The NRC Kewaunee Safety Evaluation RT_{To} was T_0 plus 33°F [2]), therefore the initial RT_{To} is

$$RT_{To} = –98.6°F + 35°F = -63.6°F.$$

It is apparent from the data (see Table 6-1) that there are significant differences in heat specific T_0 values within the Linde 80 class of welds. A measure of the uncertainty of generically representing all the Linde 80 heats from the representative 7 heats tested is warranted. This uncertainty is accounted for by performing a Monte Carlo analysis on all the Linde 80 data in a similar manner to what was done for the heat specific case. Of the 13 B&W fabricated plants represented, 11 of these plants have a limiting weld from one of the 7 representative heats tested. Five plants have a limiting weld in which the conservative nozzle belt dropout was tested for that heat. The other two plants have a limiting weld in which there are no materials available for testing. These two plants could make use of the generic alternative IRT_{To}. Neither of the heats are currently close to the PTS screening criteria.

Monte Carlo analysis produced a standard deviation of 17.1°F for the generic alternative Linde 80 weld IRT_{To}. The standard deviation from the Monte Carlo analysis, which accounts for material and laboratory variations and the ASTM E1921 sample size standard deviation (Table 4-6) are combined. These two uncertainty terms are unrelated therefore, they can be combined using the square root of the sum of the squares method.

The σ_I for generic alternative IRT_{To} for the Linde 80 class of welds is:

$$\sigma_I = \sqrt{17.1^2 + 2.1^2} = 17.2°F$$

This is the proposed σ_I to be used with the generic alternative Linde 80 weld IRT_{NDT} of –63.6°F. The approach taken conservatively accounts for uncertainties due to testing and material variation for the generic Linde 80 weld class.

Figure 6-2 shows all the data included in the above analysis relative to the Master Curve, 5%/95% bounds and the K_{Ic} curve offset by 35°F plus $2\sigma_I$ (i.e. 69.4°F). Essentially all the data are bounded by the offset K_{Ic} curve.

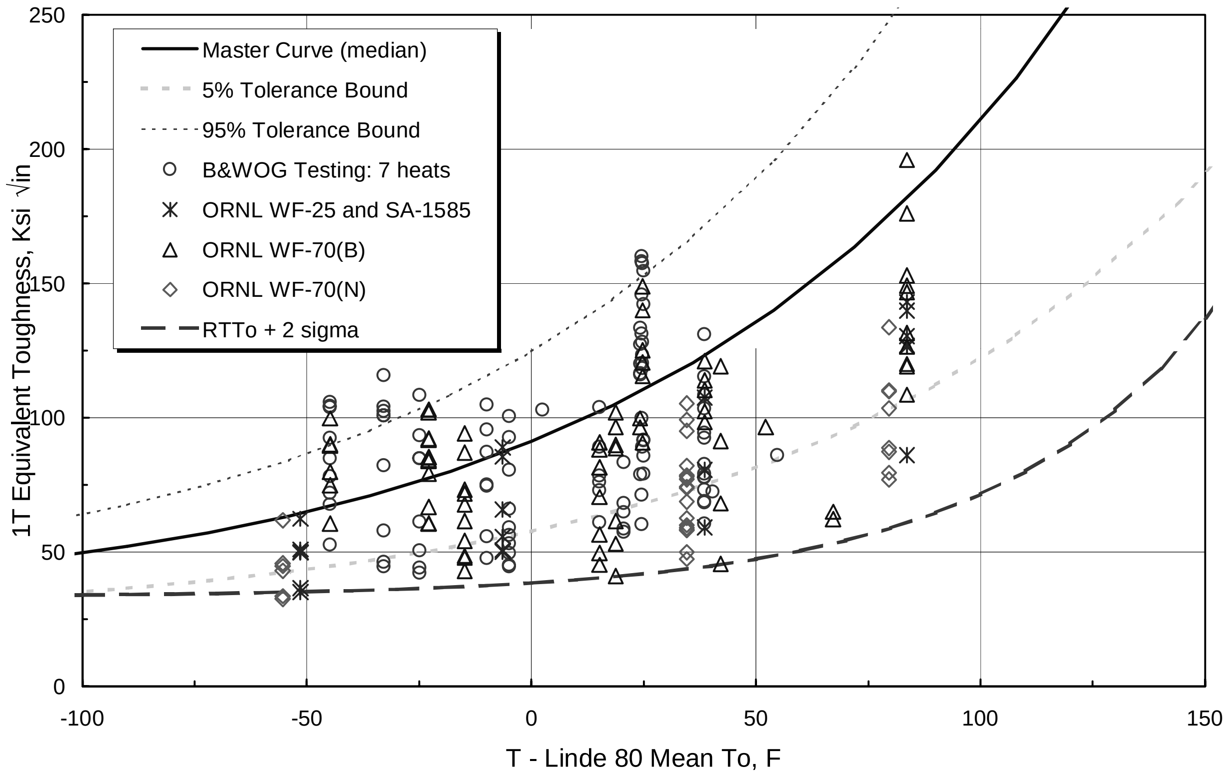

Figure 6-2 K_{Ic} with RT_{To} versus Linde 80 Data with Generic T_0

7. SUMMARY AND CONCLUSIONS

This report was prepared by the B&W Owners Group Reactor Vessel Working Group to justify more realistic initial RT_{NDT} values for the Linde 80 class of welds. All reactor pressure vessels of the member utilities have the Linde 80 welds. Previously, the IRT_{NDT} for the Linde 80 class of welds was determined by the 50 ft-lb Charpy impact energy according to NB-2331 of Section III of the ASME B&PV Code, which gave overly conservative IRT_{NDT} values. For most pressure vessel steels the IRT_{NDT} is determined by the drop weight nil-ductility temperature (T_{NDT}). The proposed more realistic IRT_{NDT} is determined using the fracture toughness based Master Curve reference temperature method and ASME B&PV Code Case N-629.

The B&W Owners Group conducted a test program to obtain fracture toughness data for all available Linde 80 welds in their member plant reactor vessels. Additional Linde 80 weld materials from the HSST programs and other sources were included comprising a database of over 300 unirradiated fracture toughness tests.

Code Case N-629 of ASME Boiler and Pressure Vessel Code allows an alternative IRT_{NDT} based on T_0 designated as RT_{To} which is:

$$RT_{To} = T_0 + 35, °F$$

Most of the limiting welds of the 13 B&W fabricated reactor vessels, consist of a Linde 80 weld heat for which T_0 data are available. For the welds that have T_0 data available, it is proposed that the heat specific value of IRT_{To} be used with the appropriate initial margin. However, there are two limiting welds and other non-limiting welds for which there is no T_0 data available. For the heats that have no data, a generic Linde 80 weld alternative IRT_{To} is proposed with a larger appropriate initial margin. The heat specific and generic alternative IRT_{To}s are listed in Table 7-1 with associated σ_I.

Table 7-1 Heat Specific and Generic Initial RT_{To} with Associated Initial Margin

Linde 80 Heat	**RT_{To} (°F)**	**Initial Margin σ_I (°F)**
406L44	-94.9	11.0
71249	-47.4	12.9
72105	-38.4	11.8
821T44	-80.2	9.3
299L44	-81.8	11.6
72442	-30.0	11.9
72445	-72.5	12.3
Other heats	-63.6	17.2

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9. CERTIFICATION

This report is an accurate and true description of the fracture toughness characterization of Linde 80 weld materials and the results are accurately reported. The conclusions described are based on the data analysis presented.

7/26/02
K. K. Yoon Date
Materials and Structural Analysis

This report was reviewed and was found to be an accurate description of the work reported.

7-26-02
J. B. Hall Date
Materials and Structural Analysis

Verification of independent review.

7-29-02
A. D. McKim, Manager Date
Materials and Structural Analysis Unit

This report has been approved for release.

7/31/02
D. L. Howell, Program Manager Date
B&W Owners Group - RV Integrity Program

APPENDIX A

MASTER CURVE METHOD

The ASTM Committee on Fatigue and Fracture developed a standard entitled "*Test method for the determination of a reference temperature T_0 for ferritic steels in the transition range*" ASTM E1921-97 [6]. This method defines the procedure for obtaining a reference temperature, T_0, and a "Master Curve" which characterizes the fracture toughness of a ferritic material in the brittle-to-ductile transition temperature range.

The ASME Code fracture toughness curves, K_{Ic} and K_{IR}, are lower bound curves which were drawn through the lowest data that existed at the time and was not based on probability assessment. K. Wallin [20] has shown that by treating cleavage fracture as a statistical phenomenon it is possible to model the cleavage fracture as a three-parameter Weibull distribution. Consequently, a probability-based estimate of lower bound for a given data population can be made. In addition, the probability-based estimates of median fracture toughness of ferritic steels form transition curves of the same shape and only differ in the location on the temperature scale. This is the origin of the term "Master Curve". Under the Master Curve method, a fracture toughness curve is determined by a single parameter called the reference temperature, which is the temperature where the median fracture toughness of that material is at 100 MPa√m. Fracture toughness data for any carbon and low alloy steel in the transition range, can be uniquely determined by the reference temperature. The reference temperature is the single parameter that completely characterizes the fracture toughness in the transition range for ferritic steels.

The cumulative probability of failure for $K_I > K_{Ic}$ in cleavage fracture is

$$P_f = 1 - \exp[-(K_I - K_{min})/(K_o - K_{min})]^m$$

K_0 is a specimen thickness and temperature-dependent scale parameter. It was determined by Wallin, that among the three parameters, the Weibull slope is equal to 4 and the location parameter, K_{min}, can adequately be set at 20 MPa√m. Once two parameters are fixed, only scale factor K_0 remains to be determined and fortunately, this is the one parameter that requires the least data replication to obtain an accurate estimate of the true value. Wallin (1997) further showed that the value of K_{min} is rather insensitive to the outcome of the K_0 value, which in turn determines the reference temperature, T_0.

The key steps of Master Curve data analysis are presented below:

Toughness Measurement

The reference temperature, T_0, is determined from fracture toughness test data converted to an equivalent 1T-specimen size. The elastic-plastic equivalent toughness K_{Jc} is calculated from toughness reported as a J_c value at the initiation of cleavage by the following equation in the ASTM E1921-97 Standard:

$$K_{Jc} = \sqrt{J_c E}$$

The ASTM E1921-02 Standard uses the following plane strain equation reflecting that the deformation state is closer to plane strain than plane stress:

$$K_{Jc} = \sqrt{\frac{J_c E}{1-\nu^2}}$$

The plane stress conversion from J_c to K_{Jc} (ASTM E1921-97) was used for the calculation of all T_0 values in this report. This conversion is conservative relative to the plane strain conversion (ASTM E1921-02) [7].

The K_{Jc} value of each test is evaluated to determine whether it exceeded the $K_{Jc(limit)}$ or the amount of ductile tearing exceeded more than 5% of the initial ligament. If the K_{Jc} limit or the ductile tearing limit is exceeded the data is censored in the calculation of T_0. If the $K_{Jc(limit)}$ was exceeded, the $K_{Jc(limit)}$ value is used as the censored value, whereas, if ductile tearing exceeded 5% of the initial ligament, the highest valid K_{Jc} from the data set was used.

$$K_{Jc(limit)} = \sqrt{\frac{E b_o \sigma_{ys}}{30}}$$

where E = elastic modulus
b_0 = initial remaining ligament
σ_{ys} = yield strength.

The following equation is used to normalize the specimen fracture toughness to the 1T specimen size:

$$K_{Jc(1T)} = K_{min} + \left[K_{Jc(B1)} - K_{min}\right]\left(\frac{B1}{B2}\right)^{1/4}$$

where:

K_{min} = 20 MPa√m
B2 = 1 inch, the thickness of the 1T specimen
B1 = the thickness of the test specimen, inches.

T_0 Determination

The reference temperature, T_0, is calculated from a set of test data obtained from a single test temperature in accordance with the ASTM E1921-97 standard. The new ASTM E1921-02 standard may be used for data sets from more than one test temperature.

ASTM E1921-97 Single Test Temperature Method

Through the use of the Weibull statistics it has been determined that ferritic steels within a specified yield strength range have a fracture toughness cumulative probability distribution of the same shape, independent of specimen shape and size. The Weibull scale parameter, K_0, can be calculated as follows for a group of valid K_{Jc} tests:

$$K_o = \left[\sum_{I=1}^{n} \frac{(K_{Jc(I)} - 20)^4}{N - 0.3068} \right]^{1/4} + 20, \ \text{MPa}\sqrt{\text{m}}$$

where n is the number of tests and is equal to or greater than the required minimum listed below.

Required Minimum Number of Valid K_{Jc} Data Points

1T equivalent $K_{Jc(med)}$ (MPa√m)	Number of valid K_{Jc} values
100 to 84	6
83 to 66	7
65 to 58	8
57 to 53	9
52 to 50	10

The estimated median value of the population can be obtained from K_0 using the following equation:

$$K_{Jc(med)} = (K_o - 20)(0.9124) + 20 \ , \text{MPa}\sqrt{\text{m}}$$

The Master Curve reference temperature is calculated as follows:

$$T_o = T - \frac{1}{0.019} \ln\left[\frac{K_{Jc(med)} - 30}{70} \right], \ ^\circ\text{C}$$

where T is test temperature in ºC.

ASTM E1921-02 Multiple Test Temperature Method

Wallin developed a more general approach for determining T_0 based on test data conducted at more than one test temperature. This method was incorporated into E1921-02. The maximum likelihood estimate, for randomly censored data sets, for estimating T_0 and $K_0 = a + b \exp[c\,(T_I - T_0)]$ is determined from

$$\sum_{i=1}^{n} \frac{\delta_i \cdot e^{0.019(T_i - T_o)}}{11 + 77 \cdot e^{0.019(T_i - T_o)}} = \sum_{i=1}^{n} \frac{(K_{Jc(1T)i} - 20)^4 \cdot e^{0.019(T_i - T_o)}}{[11 + 77 \cdot e^{0.019(T_i - T_o)}]^5}$$

where T_I = specimen test temperature
T_0 = reference temperature
n = number of specimens
$K_{Jc(1T)i}$ = 1T equivalent valid or dummy K_{Jc}
δ_I = 1 or 0, 1 for uncensored data point, 0 for censored (dummy) data point

Master Curves

The median fracture toughness, $K_{Jc(med)}$, for 1T specimens is described by

$$K_{Jc(med)} = 30 + 70e^{0.019(T - T_o)}, \text{ MPa}\sqrt{\text{m}}$$

The 5% tolerance bound curve is expressed using the following equation:

$$K_{5\%(1T)} = 25.4 + 37.8e^{0.019(T - T_o)}, \text{ MPa}\sqrt{\text{m}}$$

The 95% tolerance bound curve is expressed using the following equation:

$$K_{95\%(1T)} = 34.6 + 102.2e^{0.019(T - T_o)}, \text{ MPa}\sqrt{\text{m}}$$

APPENDIX B

FRACTURE TOUGHNESS TEST PROCEDURES

The ASTM Standard E 1921-97 (ASTM 1998) was closely adhered to during the testing of the transition range fracture toughness. Some of the test and analyses were performed prior to the issuance of the standard, therefore, all test data analyses were redone to comply with the final standard.

Some of the detailed aspects of the testing is provided below.

Specimen Preparation

Most of the weld metal specimens selected were originally fabricated as Type A Charpy V-notch impact specimens therefore modification of the existing notch was required. The modified notch was machined to a 0.165-inch depth and 0.012 inch width using an Electro Discharge Milling (EDM) machine for each selected weld metal specimen. Some specimens had knife-edges integrally machined, otherwise a knife edge was spot-welded on each side of the notch for mounting the clip gage. No modification was necessary for the specimens of the compact toughness specimen geometry.

Specimen Reconstitution

Due to insufficient material, some specimens were reconstituted from broken Charpy specimens. Reconstitution was conducted in accordance with ASTM E1253-88 "*Standard Guide for Reconstitution of Irradiated Charpy Specimens*" [21]. The Charpy halves were first swabbed with 5% Nital to reveal the extent of weld metal. Specimens with at least 18 mm of weld metal were chosen for reconstitution.

Arc stud welding was selected for this work based on its characteristics of compactness, adaptability to irradiated specimens, and capability of welding square cross sections with very localized heating. The welding equipment consists of a stud gun and an associated alignment fixture, a motor generator, a controller, and a DC power supply for the electromagnetic coil.

A milling machine and a surface grinder were used to machine the weld studs to full size Charpy specimens with an Electric Discharge Milling (EDM) machined notch in the center of the specimen. The new notch was located on the same face as the original notch.

Precracking

Precracking of the specimens was controlled by a computer and was conducted on an MTS Servo-hydraulic machine in compliance with the proposed ASTM E1921-97. The crack length was determined from the compliance method (CMOD versus force). Based on the crack length measurement, the force (thus the applied stress intensity factor) that was applied to the specimen decreased gradually during the precracking process. Typical stress intensity factors applied were 20 MPa√m at the beginning and decreased to less than 15.4 MPa√m at the end. The specimens were subject to cyclic loadings (R=0.05) to grow the crack length from 4 mm to 5.02 mm which was slightly larger than 50% of specimen width (10 mm).

Machine/Fixture Compliance for PCCS Specimens

Charpy bars manufactured from a reactor vessel weld metal were loaded to the calculated limit load at room temperature, -100ºF, and -200ºF to determine the machine/fixture compliance. Note that some interpolation was needed for the actual test temperatures. These values were then used in correcting load-line displacements during actual testing as specified in ASTM E813-89 Annex A1.4.

Material Properties

Actual yield strength from the weld heat and test temperature was used when available. Otherwise, yield strength at another test temperature was adjusted to the fracture toughness test temperature using the equation in ASTM E399-90 Appendix A7.

$$\sigma_{Y(FT)} = \sigma_{Y(TT)} + \frac{174000}{12(FT - TT + 529)} - 27.2\ ksi$$

where: $\sigma_{Y(TT)}$ = yield strength at tensile test temperature (ksi)
$\sigma_{Y(FT)}$ = yield strength at fracture toughness test temperature (ksi)
FT = fracture toughness test temperature (F)
TT = tensile test temperature (F).

Note that the yield strength is only used in determining the $K_{Jc(limit)}$ and rarely affects the reference temperature, since only a few data sets had censored data.

Young's modulus used in this work was obtained using the following equation based on ASME Code data:

Modulus = 29480 - 5.055 x T (ºF) (from ASME Code Section II part D)

Testing Procedure

Tests were performed in displacement control mode on a servo-hydraulic test machine. A double cantilever beam clip gage was mounted onto the knife-edges for monitoring the CMOD. The CMOD measurements were used to determine the crack length during the test. Force and load-line displacement were monitored continuously through loading and unloading cycles with a load cell and a LVDT interfaced to a personal computer. Crack lengths were calculated based on material compliance relationships using CMOD and force data collected during the unloading portion of each cycle in conjunction with specimen geometry information. All tests were performed in an ATS split type furnace designed to handle both elevated temperature and sub-zero temperature testing. Temperature was determined by placing a Type K thermocouple wire onto the specimen surface near the crack tip. A soak time of at least 20 minutes, after reaching test temperature, was used to assure uniform temperature distribution in the specimen. Temperature control for maintaining sub-zero temperatures was provided by automated control of a solenoid valve, which regulated the flow rate of liquid nitrogen into the furnace. Test temperatures were controlled to within ± 2ºF.

Initially, upon program execution, the specimen was loaded to approximately 20% of the limit load to determine the initial crack length using the compliance method. The measured crack length was used to check against the known precrack final crack length, which should be consistent. This process was then repeated several times. If the measurements were consistent, the crack length checking process was considered complete. If results were not consistent, the test system was checked and the clip gage was examined for proper seating. This process was continued until reproducible results were obtained. Since the force applied to the specimen was significantly lower than material yield strength and lower than the forces used in the precracking process, no impact to the test results was expected.

Following the initial crack length measurement cycling, the actual test began. The specimen was loaded and unloaded in accordance with the parameters entered prior to the test. Compliance data (force versus CMOD) during each unloading was used for a crack length calculation. Because the extreme high and low ends of the unload process are relatively noisy, only the middle portion of the unload process is used to calculate the crack length to achieve higher accuracy. The percent unloading parameter specifies the amount of unload for each unloading cycle during the test. An unloading value of 20% from the current load was specified for each specimen.

J Computation

Since all specimens were tested in the transition temperature region, very limited crack growth if any was expected. Using the load versus load line displacement (LLD) data, the J value was calculated using the following equations:

$$J_c = J_e + J_p$$

where:

J_e = the elastic component
J_p = the plastic component

The following was (as an example) used to calculate the J value for a Charpy size specimen. The other equations in ASTM E1921-97 were used as appropriate for the other specimen geometries. The elastic component is:

$$J_e = \frac{K^2}{E}$$

$$K = [\frac{PS}{(BB_N)^{1/2} W^{3/2}}] f(\frac{a}{w})$$

where p = load
B = specimen thickness
S = span
B_N = net thickness
W = width

$$f(\frac{a}{w}) = \frac{3(a/w)^{1/2}[1.99 - (a/w)(1 - a/W)(2.15 - 3.93(a/w) + 2.7(a/w)^2]}{2(1 + 2a/W)(1 - a/w)^{3/2}}$$

and a = crack depth

The plastic component for the ith loading step is calculated as follows:

$$J_{p(i)} = [J_{p(i-1)} + \frac{\eta_i}{b_i}(\frac{A_{p(i)} - A_{p(i-1)}}{B_N})]$$

where $\eta_i = 1.9$
$b_i = W - a_i$

and

$$A_{p(i)} = A_{p(i-1)} + \frac{[P_{(i)} + P_{(i-1)}][\Delta_{p(i)} - \Delta_{p(i-1)}]}{2}$$

where: A_p = the plastic portion of the area under the load versus displacement (LLD) curve.

and Δ_p = the plastic portion of the LLD
($\Delta_{p(I)} = \Delta_{total(I)} - P_iC_i$)

$\Delta_{total(I)}$ = total LLD after the ith step

P_i = ith step end load

C_i = ith step compliance

Crack Length Measurement

After the test, the specimens were heat-tinted in a furnace between 500 ºF and 550ºF for 10 to 15 minutes. The specimens were then removed from the furnace and placed back onto the test fixture and loaded to failure at or below -50 ºF. The precrack final crack length and test final crack length were measured using a video micrometer system. The cracks were measured at nine locations across the crack front spanning the specimen thickness. These nine measurements were used to determine an average initial and final crack length as follows:

$$a_{AVG} = \frac{1}{8}\left[\frac{(a_1 + a_9)}{2} + a_2 + a_3 + a_4 + a_5 + a_6 + a_7 + a_8\right]$$

where

a_{AVG} is the average crack length from nine measurements
a_n is nine point measured crack length

These values were later used as references to verify the accuracy of the crack length determined by the compliance method.

APPENDIX C

LINDE 80 WELD
UNIRRADIATED
FRACTURE TOUGHNESS DATA

Table C-1 Transition Temperature Fracture Toughness Data for Linde 80 Heat 299L44

Weld Identification	Test Temp. (^{0}F)	K_{Jc} (ksi√in)	Specimen Type	Loading Rate (ksi√in/sec)
WF-25	-70	180.3	0.5TCT	2
WF-25	-70	165.6	0.5TCT	2
WF-25	-70	90.4	0.5TCT	2
WF-25	-70	105.5	0.5TCT	2
WF-25	-70	105.2	0.5TCT	2
WF-25	-70	98.3	0.5TCT	2
SA-1526	-70	134.8	0.5TCT	2.14
SA-1526	-70	147.9	0.5TCT	2.14
SA-1526	-70	154.9	0.5TCT	2.14
SA-1526	-70	90.1	0.5TCT	2.14
SA-1526	-70	139.3	0.5TCT	2.14
SA-1526	-70	134.3	0.5TCT	2.14
WF-25	-145	65.5	PCCS	0.2
WF-25	-145	89.6	PCCS	0.2
WF-25	-145	105.0	PCCS	0.2
WF-25	-145	115.6	PCCS	0.2
WF-25	-145	127.4	PCCS	0.2
WF-25	-145	55.2	PCCS	0.2
WF-25	-145	89.3	PCCS	0.2
63W WF-25	-112	125.0	PCCS	1.7
63W WF-25	-112	132.7	PCCS	1.7
63W WF-25	-112	138.9	PCCS	1.7
63W WF-25	-112	149.2	PCCS	1.7
63W WF-25	-112	165.6	PCCS	1.7
63W WF-25	-74	86.4	PCCS	1.7
63W WF-25	-74	134.0	PCCS	1.7
63W WF-25	-74	151.1	PCCS	1.7
63W WF-25	-74	154.3	PCCS	1.7
63W WF-25	-74	170.1	PCCS	1.7
63W WF-25	-74	223.2	PCCS	1.7
64W WF-25	-60	103.5	PCCS	1.7
64W WF-25	-60	146.7	PCCS	1.7
64W WF-25	-60	150.2	PCCS	1.7
64W WF-25	-60	155.1	PCCS	1.7
64W WF-25	-60	157.0	PCCS	1.7
64W WF-25	-60	194.4	PCCS	1.7
64W WF-25	3	147.9	PCCS	1.7
64W WF-25	3	152.7	PCCS	1.7
64W WF-25	3	187.8	PCCS	1.7
64W WF-25	3	198.5	PCCS	1.7
64W WF-25	3	205.6	PCCS	1.7
	3	224.3	PCCS	1.7

Table C-2 Transition Temperature Fracture Toughness Data for Linde 80 Heat 406L44

Weld Identification	Test Temp. (^{0}F)	K_{Jc} (ksi√in)	Specimen Type	Loading Rate (ksi√in/sec)
WF-193	-70	183.6	0.5TCT	2.05
WF-193	-70	102.3	0.5TCT	2.05
WF-193	-70	143.2	0.5TCT	2.05
WF-193	-70	148.9	0.5TCT	2.05
WF-193	-70	139.4	0.5TCT	2.05
WF-193	-70	205.8	0.5TCT	2.05
WF-193	-70	229.9	0.5TCT	2.05
WF-193	-70	137.2	0.5TCT	2.05
WF-193	-150	65.3	0.5TCT	0.2
WF-193	-150	118.3	0.5TCT	0.2
WF-193	-150	116.3	0.5TCT	0.2
WF-193	-150	94.1	0.5TCT	0.2
WF-193	-150	51.4	0.5TCT	0.2
WF-193	-150	134.0	0.5TCT	0.2
WF-193	-150	120.3	0.5TCT	0.2
WF-193	-150	116.1	0.5TCT	0.2
WF-193	-150	49.4	0.5TCT	0.2
WF-112	-70	152.4	0.5TCT	2.08
WF-112	-70	184.4	0.5TCT	2.08
WF-112	-70	213.6	0.5TCT	2.08
WF-112	-70	115.0	0.5TCT	2.08
WF-112	-70	169.8	0.5TCT	2.08
WF-112	-70	186.8	0.5TCT	2.08
WF-112	-70	81.2	0.5TCT	2.08
WF-112	-70	68.0	0.5TCT	2.08
WF-193	-180	111.6	PCCS	0.2
WF-193	-180	126.8	PCCS	0.2
WF-193	-180	128.6	PCCS	0.2
WF-193	-180	153.9	PCCS	0.2
WF-193	-180	61.6	PCCS	0.2
WF-193	-180	85.8	PCCS	0.2
WF-193	-180	102.1	PCCS	0.2
WF-193	-180	93.6	PCCS	0.2
WF-193	-180	126.2	PCCS	0.2
WF-193	-180	80.6	PCCS	0.2
WF-112	-160	58.8	PCCS	0.2
WF-112	-160	102.1	PCCS	0.2
WF-112	-160	102.2	PCCS	0.2
WF-112	-160	131.9	PCCS	0.2
WF-112	-160	50.7	PCCS	0.2
WF-112	-160	112.9	PCCS	0.2
WF-112	-160	72.4	PCCS	0.2
WF-112	-160	48.2	PCCS	0.2

Table C-3 Transition Temperature Fracture Toughness Data for Linde 80 Heat 71249

Weld Identification	**Test Temp. (^{0}F)**	**K_{Jc} (ksi√in)**	**Specimen Type**	**Loading Rate (ksi√in/sec)**
SA-1094	-140	111.9	PCCS	0.2
SA-1094	-140	78.5	PCCS	0.2
SA-1094	-140	65.9	PCCS	0.2
SA-1094	-140	62.2	PCCS	0.2
SA-1094	-140	51.2	PCCS	0.2
SA-1094	-140	52.1	PCCS	0.2
SA-1094	-140	57.6	PCCS	0.2
SA-1094	-140	96.7	PCCS	0.2
SA-1094	-140	166.4	PCCS	0.2
SA-1094	-140	69.7	PCCS	0.2
SA-1094	-140	122.0	PCCS	0.2

Table C-4 Transition Temperature Fracture Toughness Data for Linde 80 Heat 72105

Weld Identification	Test Temp. (^{0}F)	K_{Jc} (ksi√in)	Specimen Type	Loading Rate (ksi√in/sec)
WF-70(B)	1	117.4	1TCT	1.36
WF-70(B)	1	79.8	1TCT	1.36
WF-70(B)	1	92.8	1TCT	1.36
WF-70(B)	1	95.1	1TCT	1.36
WF-70(B)	1	164.9	1TCT	1.36
WF-70(B)	1	158.9	1TCT	1.36
WF-70(B)	0	125.4	1TCT	1.27
WF-70(B)	0	147.3	1TCT	1.27
WF-70(B)	0	149.6	1TCT	1.27
WF-70(B)	0	208.2	1TCT	1.27
WF-70(B)	0	258.1	1TCT	1.27
WF-70(B)	0	198.8	1TCT	1.27
WF-70(B)	-120	72.1	PCCS	0.2
WF-70(B)	-120	87.1	PCCS	0.2
WF-70(B)	-120	91.1	PCCS	0.2
WF-70(B)	-120	93.9	PCCS	0.2
WF-70(B)	-120	107.5	PCCS	0.2
WF-70(B)	-120	126.2	PCCS	0.2
WF-70(B)	-120	128.6	PCCS	0.2
WF70(B)	-94	67.6	PCCS	1.7
WF70(B)	-94	69.0	PCCS	1.7
WF70(B)	-94	77.0	PCCS	1.7
WF70(B)	-94	81.0	PCCS	1.7
WF70(B)	-94	100.3	PCCS	1.7
WF70(B)	-76	217.9	PCCS	1.7
WF70(B)	-76	202.7	PCCS	1.7
WF70(B)	-76	71.5	PCCS	1.7
WF70(B)	-76	128.4	PCCS	1.7
WF70(B)	-76	94.9	PCCS	1.7
WF70(B)	-76	93.2	PCCS	1.7
WF70(B)	-76	81.9	PCCS	1.7
WF70(B)	-76	81.4	PCCS	1.7
WF70(B)	-76	238.5	PCCS	1.7
WF70(B)	-76	93.3	PCCS	1.7
WF70(B)	-76	111.7	PCCS	1.7
WF70(B)	-76	131.9	PCCS	1.7
WF70(B)	-76	140.0	PCCS	1.7
WF70(B)	-76	99.5	PCCS	1.7
WF70(B)	-58	152.2	0.5TCT	1.7

Table C-4 Transition Temperature Fracture Toughness Data for Linde 80 Heat 72105 (Continued)

Weld Identification	Test Temp. (^{0}F)	K_{Jc} (ksi√in)	Specimen Type	Loading Rate (ksi√in/sec)
WF70(B)	-58	83.4	0.5TCT	1.7
WF70(B)	-58	133.6	0.5TCT	1.7
WF70(B)	-58	108.6	0.5TCT	1.7
WF70(B)	-58	125.3	0.5TCT	1.7
WF70(B)	-58	119.3	0.5TCT	1.7
WF70(B)	-13	200.2	0.5TCT	1.7
WF70(B)	-13	195.6	0.5TCT	1.7
WF70(B)	-13	193.5	0.5TCT	1.7
WF70(B)	-13	166.7	0.5TCT	1.7
WF70(B)	-13	98.7	0.5TCT	1.7
WF70(B)	-13	279.9	0.5TCT	1.7
WF70(B)	32	298.5	0.5TCT	1.7
WF70(B)	32	256.6	0.5TCT	1.7
WF70(B)	-148	62.2	1TCT	1.7
WF70(B)	-148	50.0	1TCT	1.7
WF70(B)	-148	34.9	1TCT	1.7
WF70(B)	-148	36.5	1TCT	1.7
WF70(B)	-148	49.7	1TCT	1.7
WF70(B)	-148	50.8	1TCT	1.7
WF70(B)	-103	55.6	1TCT	1.7
WF70(B)	-103	50.7	1TCT	1.7
WF70(B)	-103	50.1	1TCT	1.7
WF70(B)	-103	65.7	1TCT	1.7
WF70(B)	-103	88.9	1TCT	1.7
WF70(B)	-103	85.4	1TCT	1.7
WF70(B)	-58	80.4	1TCT	1.7
WF70(B)	-58	59.1	1TCT	1.7
WF70(B)	-58	107.5	1TCT	1.7
WF70(B)	-13	126.4	1TCT	1.7
WF70(B)	-13	126.9	1TCT	1.7
WF70(B)	-13	130.3	1TCT	1.7
WF70(B)	-13	139.8	1TCT	1.7
WF70(B)	32	288.2	1TCT	1.7
WF70(B)	32	232.6	1TCT	1.7
WF70(B)	32	127.4	1TCT	1.7
WF70(B)	32	304.9	1TCT	1.7
WF70(B)	32	311.6	1TCT	1.7

Table C-4 Transition Temperature Fracture Toughness Data for Linde 80 Heat 72105 (Continued)

Weld Identification	**Test Temp. (^{0}F)**	**K_{Jc} (ksi√in)**	**Specimen Type**	**Loading Rate (ksi√in/sec)**
WF70(B)	32	293.6	1TCT	1.7
WF70(B)	70	306.7	1TCT	1.7
WF70(B)	70	289.8	1TCT	1.7
WF70(B)	-58	108.5	1TCT	1.7
WF70(B)	-58	83.6	1TCT	1.7
WF70(B)	-58	94.0	1TCT	1.7
WF70(B)	-13	241.1	1TCT	1.7
WF70(B)	-13	119.9	1TCT	1.7
WF70(B)	-13	108.5	1TCT	1.7
WF70(B)	-13	176.1	1TCT	1.7
WF70(B)	32	248.8	1TCT	1.7
WF70(B)	32	172.0	1TCT	1.7
WF70(B)	32	297.9	1TCT	1.7
WF70(B)	70	273.0	1TCT	1.7
WF70(B)	70	232.1	1TCT	1.7
WF70(B)	-58	88.9	2TCT	1.7
WF70(B)	-58	98.6	2TCT	1.7
WF70(B)	-58	95.6	2TCT	1.7
WF70(B)	-58	104.7	2TCT	1.7
WF70(B)	-58	85.5	2TCT	1.7
WF70(B)	-13	109.2	2TCT	1.7
WF70(B)	-13	167.6	2TCT	1.7
WF70(B)	-13	113.5	2TCT	1.7
WF70(B)	-13	128.3	2TCT	1.7
WF70(B)	-13	131.4	2TCT	1.7
WF70(B)	32	295.0	2TCT	1.7
WF70(B)	32	325.8	2TCT	1.7
WF70(B)	32	164.0	2TCT	1.7
WF70(B)	32	347.3	2TCT	1.7
WF70(B)	-13	89.5	4TCT	1.7
WF70(B)	-13	109.0	4TCT	1.7

Table C-5 Transition Temperature Fracture Toughness Data for Linde 80 Heat 72442

Weld Identification	Test Temp. (^{0}F)	K_{Jc} (ksi√in)	Specimen Type	Loading Rate (ksi√in/sec)
WF-67 11hr SR	-120	45.2	PCCS	0.2
WF-67 11hr SR	-120	57.8	PCCS	0.2
WF-67 11hr SR	-120	66.5	PCCS	0.2
WF-67 11hr SR	-120	84.1	PCCS	0.2
WF-67 11hr SR	-120	98.1	PCCS	0.2
WF-67 11hr SR	-120	106.4	PCCS	0.2
WF-67 11hr SR	-120	109.7	PCCS	0.2
WF-67 11hr SR	-120	130.8	PCCS	0.2
WF-67 50hr SR	-50	62.9	0.936TDCT	0.2
WF-67 50hr SR	-50	65.7	0.936TDCT	0.2
WF-67 50hr SR	-75	110.4	0.394TCT	0.2
WF-67 50hr SR	-75	52.7	0.394TCT	0.2
WF-67 50hr SR	-75	145.7	0.394TCT	0.2
WF-67 50hr SR	-75	81.0	0.394TCT	0.2
WF-67 50hr SR	-65	111.2	0.5TCT	0.2
SA-1484	-100	72.9	PCCS	1.1
SA-1484	-100	40.9	PCCS	1.1
SA-1484	-100	123.8	PCCS	1.1
SA-1484	-100	107.0	PCCS	1.1
SA-1484	-100	116.9	PCCS	1.1
SA-1484	-100	62.2	PCCS	1.1
SA-1484	-100	132.0	PCCS	1.1
SA-1484	-100	108.6	PCCS	1.1
SA-1484	-75	146.3	PCCS	1.1

Table C-6 Transition Temperature Fracture Toughness Data for Linde 80 Heat 72445

Weld Identification	Test Temp. (^{0}F)	K_{Jc} (ksi√in)	Specimen Type	Loading Rate (ksi√in/sec)
65W SA-1585	-90	116.8	PCCS	1.7
65W SA-1585	-90	121.0	PCCS	1.7
65W SA-1585	-90	129.4	PCCS	1.7
65W SA-1585	-90	142.6	PCCS	1.7
65W SA-1585	-90	156.8	PCCS	1.7
65W SA-1585	-90	185.8	PCCS	1.7
65W SA-1585	-36	137.3	PCCS	1.7
65W SA-1585	-36	163.7	PCCS	1.7
65W SA-1585	-36	178.2	PCCS	1.7
65W SA-1585	-36	214.6	PCCS	1.7
65W SA-1585	-36	235.3	PCCS	1.7
65W SA-1585	-36	240.4	PCCS	1.7
SA-1585	-150	63.4	PCCS	0.2
SA-1585	-150	72.7	PCCS	0.2
SA-1585	-150	80.6	PCCS	0.2
SA-1585	-150	87.6	PCCS	0.2
SA-1585	-150	56.3	PCCS	0.2
SA-1585	-150	49.4	PCCS	0.2
SA-1585	-150	104.9	PCCS	0.2
SA-1585	-150	85.7	PCCS	0.2
SA-1585	-150	114.0	PCCS	0.2
SA-1585	-150	55.5	PCCS	0.2

Table C-7 Transition Temperature Fracture Toughness Data for Linde 80 Heat 821T44

Weld Identification	Test Temp. (^{0}F)	K_{Jc} (ksi√in)	Specimen Type	Loading Rate (ksi√in/sec)
WF-182	-70	173.6	0.5TCT	2.06
WF-182	-70	104.4	0.5TCT	2.06
WF-182	-70	133.8	0.5TCT	2.06
WF-182	-70	145.3	0.5TCT	2.06
WF-182	-70	162.9	0.5TCT	2.06
WF-182	-70	140.0	0.5TCT	2.06
WF-182	-140	97.8	0.5TCT	0.2
WF-182	-140	68.6	0.5TCT	0.2
WF-182	-140	98.0	0.5TCT	0.2
WF-182	-140	96.7	0.5TCT	0.2
WF-182	-140	90.6	0.5TCT	0.2
WF-182	-140	117.7	0.5TCT	0.2
WF-182	-140	96.3	0.5TCT	0.2
WF-182	-140	106.3	0.5TCT	0.2
WF-182	-140	119.1	0.5TCT	0.2
WF-182	-140	68.4	0.5TCT	0.2
WF-182	-140	105.5	0.5TCT	0.2
WF-182	-140	75.9	0.5TCT	0.2
WF-182	-180	71.7	PCCS	0.2
WF-182	-180	89.6	PCCS	0.2
WF-182	-180	96.0	PCCS	0.2
WF-182	-180	108.3	PCCS	0.2
WF-182	-180	108.9	PCCS	0.2
WF-182	-180	121.0	PCCS	0.2

APPENDIX D

LINDE 80 WELD
IRRADIATED
FRACTURE TOUGHNESS DATA

Table D-1 Transition Temperature Fracture Toughness Data for Irradiated Linde 80 Heat 299L44

Weld Identification	Test Temp. (^{0}F)	K_{Jc} (ksi√in)	Specimen Type	Loading Rate (ksi√in/sec)	Fluence (x10^{19} n/cm^2, E>1MeV)	Irradiation Temp. (^{0}F)
WF-25 OC3 ND	40	77.1	RPCCS	0.2	0.779	556
WF-25 OC3 ND	40	62.2	RPCCS	0.2	0.779	556
WF-25 OC3 ND	40	102.7	RPCCS	0.2	0.779	556
WF-25 OC3 ND	40	191.3	RPCCS	0.2	0.779	556
WF-25 OC3 ND	40	59.8	RPCCS	0.2	0.779	556
WF-25 OC3 ND	40	98.9	RPCCS	0.2	0.779	556
WF-25 OC3 ND	40	94.7	RPCCS	0.2	0.779	556
WF-25 OC3 ND	40	81.7	RPCCS	0.2	0.779	556
WF-25 OC3 ND	40	104.4	RPCCS	0.2	0.779	556
SA-1525 S1 RVSP	60	101.5	RPCCS	0.2	0.779	556
SA-1525 S1 RVSP	60	104.7	RPCCS	0.2	1.599	538
SA-1525 S1 RVSP	60	77.3	RPCCS	0.2	1.599	538
SA-1525 S1 RVSP	60	58.9	RPCCS	0.2	1.599	538
SA-1525 S1 RVSP	60	86.1	RPCCS	0.2	1.599	538
SA-1525 S1 RVSP	60	122.8	RPCCS	0.2	1.599	538
SA-1525 S1 RVSP	60	101.5	RPCCS	0.2	1.599	538
SA-1525 S1 RVSP	60	146.9	RPCCS	0.2	1.599	538
SA-1525 S1 RVSP	60	78.5	RPCCS	0.2	1.599	538

Table D-2 Transition Temperature Fracture Toughness Data for Irradiated Linde 80 Heat 406L44

Weld Identification	Test Temp. (^{0}F)	K_{Jc} (ksi√in)	Specimen Type	Loading Rate (ksi√in/sec)	Fluence (x10^{19} n/cm^2, E>1MeV)	Irradiation Temp. (^{0}F)
WF-193 ANO1 RVSP	10	92.5	RPCCS	0.2	1.46	556
WF-193 ANO1 RVSP	10	124.2	RPCCS	0.2	1.46	556
WF-193 ANO1 RVSP	10	73.8	RPCCS	0.2	1.46	556
WF-193 ANO1 RVSP	10	128.5	RPCCS	0.2	1.46	556
WF-193 ANO1 RVSP	10	117.2	RPCCS	0.2	1.46	556
WF-193 ANO1 RVSP	10	116.5	RPCCS	0.2	1.46	556
WF-193 ANO1 RVSP	10	63.7	RPCCS	0.2	1.46	556
WF-193 ANO1 RVSP	10	66.2	RPCCS	0.2	1.46	556
WF-193 ANO1 RVSP	10	75.6	RPCCS	0.2	1.46	556
WF-193 ANO1 RVSP	10	101.1	RPCCS	0.2	1.46	556

Table D-3 Transition Temperature Fracture Toughness Data for Irradiated Linde 80 Heat 71249

Weld Identification	Test Temp. (°F)	K_{Jc} (ksi√in)	Specimen Type	Loading Rate (ksi√in/sec)	Fluence ($x10^{19}$ n/cm^2, E>1MeV)	Average Irradiation Temp. (°F)
SA-1094 TP4 RVSP	20	46.9	PCCS	0.2	1.602	550[1]
SA-1094 TP4 RVSP	20	50.6	PCCS	0.2	1.602	550[1]
SA-1094 TP4 RVSP	20	51.4	PCCS	0.2	1.602	550[1]
SA-1094 TP4 RVSP	20	56.8	PCCS	0.2	1.602	550[1]
SA-1094 TP4 RVSP	20	59.6	PCCS	0.2	1.602	550[1]
SA-1094 TP4 RVSP	20	70.5	PCCS	0.2	1.602	550[1]
SA-1094 TP4 RVSP	20	75.1	PCCS	0.2	1.602	550[1]
SA-1101 TP3 RVSP	20	54.5	PCCS	0.2	1.376	551[2]
SA-1101 TP3 RVSP	20	54.7	PCCS	0.2	1.376	551[2]
SA-1101 TP3 RVSP	20	58.6	PCCS	0.2	1.376	551[2]
SA-1101 TP3 RVSP	20	61.6	PCCS	0.2	1.376	551[2]
SA-1101 TP3 RVSP	20	62.7	PCCS	0.2	1.376	551[2]
SA-1101 TP3 RVSP	20	65.7	PCCS	0.2	1.376	551[2]
SA-1101 TP3 RVSP	20	66.6	PCCS	0.2	1.376	551[2]

1. Irradiated at 546°F through 0.708 x 10^{19} n/cm^2 then irradiated at 556°F through withdrawal.
2. Irradiated at 546°F through 0.74 x 10^{19} n/cm^2 then irradiated at 556°F through withdrawal.

Table D-4 Transition Temperature Fracture Toughness Data for Irradiated Linde 80 Heat 72105

Weld Identification	Test Temp. (^{0}F)	K_{Jc} (ksi√in)	Specimen Type	Loading Rate (ksi√in/sec)	Fluence (x10^{19} n/cm^2, E>1MeV)	Irradiation Temp. (^{0}F)
WF-70 MD1 ND	40	93.6	RPCCS	0.2	1.19	556
WF-70 MD1 ND	40	79.7	RPCCS	0.2	1.19	556
WF-70 MD1 ND	40	109.2	RPCCS	0.2	1.19	556
WF-70 MD1 ND	40	90.7	RPCCS	0.2	1.19	556
WF-70 MD1 ND	40	127.6	RPCCS	0.2	1.19	556
WF-70 MD1 ND	40	80.1	RPCCS	0.2	1.19	556
WF-70 MD1 ND	0	42.4	0.5TCT	0.2	1.59	556
WF-70 MD1 ND	0	45.0	0.5TCT	0.2	1.59	556
WF-70 MD1 ND	0	57.6	0.5TCT	0.2	1.59	556
WF-70 MD1 ND	0	76.2	0.5TCT	0.2	1.59	556
WF-209-1 ZN1 RVSP	45	61.9	PCCS	0.2	1.897	547[1]
WF-209-1 ZN1 RVSP	45	70.5	PCCS	0.2	1.897	547[1]
WF-209-1 ZN1 RVSP	45	74.2	PCCS	0.2	1.897	547[1]
WF-209-1 ZN1 RVSP	45	77.8	PCCS	0.2	1.897	547[1]
WF-209-1 ZN1 RVSP	45	89.2	PCCS	0.2	1.897	547[1]
WF-209-1 ZN1 RVSP	45	89.5	PCCS	0.2	1.897	547[1]
WF-209-1 ZN1 RVSP	45	106.1	PCCS	0.2	1.897	547[1]

1. Irradiated at 529^{0}F through 1.26 x 10^{19} n/cm^2 then irradiated at 556^{0}F through withdrawal.

Table D-5 Transition Temperature Fracture Toughness Data for Irradiated Linde 80 Heat 72442

Weld Identification	Test Temp. (^{0}F)	K_{Jc} (ksi√in)	Specimen Type	Loading Rate (ksi√in/sec)	Fluence (x10^{19} n/cm^2, E>1MeV)	Irradiation Temp. (^{0}F)
WF-67 MD1 ND	-30	45.6	PCCS	0.25	1.169	556
WF-67 MD1 ND	5	121.7	PCCS	0.25	1.169	556
WF-67 MD1 ND	0	43.7	PCCS	0.25	1.169	556
WF-67 MD1 ND	0	46.6	PCCS	0.25	1.169	556
WF-67 MD1 ND	0	59.7	PCCS	0.25	1.169	556
WF-67 MD1 ND	0	75.4	PCCS	0.25	1.169	556
WF-67 MD1 ND	0	76.2	PCCS	0.25	1.169	556
WF-67 MD1 ND	0	89.2	PCCS	0.25	1.169	556
WF-67 MD1 ND	30	44.0	0.936TDC(T)	0.25	1.392	556
WF-67 MD1 ND	30	96.1	0.936TDC(T)	0.25	1.392	556
WF-67 MD1 ND	30	98.1	0.936TDC(T)	0.25	1.392	556
WF-67 MD1 ND	30	106.7	0.936TDC(T)	0.25	1.392	556
WF-67 MD1 ND	30	115.6	0.936TDC(T)	0.25	1.392	556
WF-67 MD1 ND	0	48.9	0.5TC(T)	0.2	1.59	556
WF-67 MD1 ND	0	50.6	0.5TC(T)	0.2	1.59	556
WF-67 MD1 ND	0	72.5	0.5TC(T)	0.2	1.59	556
WF-67 MD1 ND	0	86.6	0.5TC(T)	0.2	1.59	556
WF-67 MD1 ND	35	70.2	0.394TC(T)	0.2	1.28	556
WF-67 MD1 ND	35	116.0	0.394TC(T)	0.2	1.93	556
WF-67 MD1 ND	90	139.8	0.936TDC(T)	0.2	1.86	556
WF-67 MD1 ND	90	102.1	0.936TDC(T)	0.2	1.86	556
SA-1484 CR3 ND	10	51.0	PCCS	1.2	1.246	556
SA-1484 CR3 ND	10	78.4	PCCS	1.2	1.246	556
SA-1484 CR3 ND	10	82.3	PCCS	1.2	1.246	556
SA-1484 CR3 ND	40	47.4	PCCS	1.2	1.246	556
SA-1484 CR3 ND	40	66.0	PCCS	1.2	1.246	556
SA-1484 CR3 ND	40	75.9	PCCS	1.2	1.246	556
SA-1484 CR3 ND	80	43.8	PCCS	1.2	1.246	556
SA-1484 CR3 ND	80	44.8	PCCS	1.2	1.246	556
SA-1484 CR3 ND	80	91.7	PCCS	1.2	1.246	556
SA-1484 CR3 ND	100	74.4	PCCS	1.2	1.246	556
SA-1484 CR3 ND	100	79.8	PCCS	1.2	1.246	556
SA-1484 CR3 ND	100	139.4	PCCS	1.2	1.246	556
SA-1484 CR3 ND	120	92.6	0.936TDC(T)	1.2	1.261	556
SA-1484 CR3 ND	120	100.5	0.936TDC(T)	1.2	1.261	556
SA-1484 CR3 ND	120	111.7	0.936TDC(T)	1.2	1.261	556
SA-1484 CR3 ND	120	123.5	0.936TDC(T)	1.2	1.261	556
SA-1484 CR3 ND	120	128.5	0.936TDC(T)	1.2	1.261	556

Table D-6 Transition Temperature Fracture Toughness Data for Irradiated Linde 80 Heat 72445

Weld Identification	Test Temp. (^{0}F)	K_{Jc} (ksi√in)	Specimen Type	Loading Rate (ksi√in/sec)	Fluence (x10^{19} n/cm^2, E>1MeV)	Irradiation Temp. (^{0}F)
SA-1585 ANO1 ND	0	74.3	0.5TC(T)	0.2	1.59	556
SA-1585 ANO1 ND	0	76.2	0.5TC(T)	0.2	1.59	556
SA-1585 ANO1 ND	0	84.7	0.5TC(T)	0.2	1.59	556

Table D-7 Transition Temperature Fracture Toughness Data for Irradiated Linde 80 Heat 821T44

Weld Identification	Test Temp. (^{0}F)	K_{Jc} (ksi√in)	Specimen Type	Loading Rate (ksi√in/sec)	Fluence (x10^{19} n/cm^2, E>1MeV)	Irradiation Temp. (^{0}F)
WF-182-1 DB RVSP	20	89.1	PCCS	1.3	1.052	556
WF-182-1 DB RVSP	60	103.9	PCCS	1.3	1.052	556
WF-182-1 DB RVSP	60	120.5	PCCS	1.3	1.052	556
WF-182-1 DB RVSP	110	100.5	0.936TDC(T)	1.3	1.261	556
WF-182-1 DB RVSP	110	102.5	0.936TDC(T)	1.3	1.261	556
WF-182-1 DB RVSP	110	103.0	0.936TDC(T)	1.3	1.261	556
WF-182-1 DB RVSP	110	113.5	0.936TDC(T)	1.3	1.261	556
WF-182-1 DB RVSP	110	114.7	0.936TDC(T)	1.3	1.261	556