GE Nuclear Energy

**Engineering & Technology**
*General Electric Company*
*175 Curtner Avenue, San Jose, CA 95125*

GE-NE-B1302026-00-01
April 1999

# Surveillance Specimen Program Evaluation for Tennessee Valley Authority Browns Ferry Unit 3

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## ACKNOWLEDGMENT

The author would like to thank Sam Ranganath for valuable technical input to this document.

## 1. ABSTRACT

Browns Ferry Unit 3 (BFN-3) has maintained a vessel surveillance program to meet the intent of 10CFR50, Appendix H [1]. The current Browns Ferry Unit 3 surveillance program schedule requires that the first surveillance capsule be removed at eight (8) Effective Full Power Years (EFPY) for BFN-3. The original licensed schedule required removal of the first capsule at six (6) EFPY, however this was subsequently changed to eight EFPY by a revision to the BFN-3 Technical Specification [2].

The current Browns Ferry Unit 3 schedule was developed in accordance with the intent of 10CFR50, Appendix H, and did not incorporate BFN-3 specific conditions listed below:

- Plate and weld chemistry (copper content from 0.09% - 0.24%)[3,4];
- Low RPV 1/4T 32 EFPY beltline fluence (<< $5 \times 10^{18}$ n/cm$^2$ fluence) [5];
- Resulting low predicted shift in the capsule material reference nil-ductility temperature ($RT_{NDT}$), < 30°F at 32 EFPY.

If the current schedule is executed, the measured data for the first capsule material may not be useful, as the expected shift in $RT_{NDT}$ ($\Delta RT_{NDT}$) is low. In addition, the data provided by the first capsule can be replaced by information from other sources. Therefore, the surveillance program's withdrawal schedule can be extended.

The extended schedule can be justified because:

- Actual industry BWR data shows predicted BFN-3 $\Delta RT_{NDT}$ + margin values based on Regulatory Guide 1.99 Revision 2 (Rev 2) [6] are expected to bound the measured $\Delta RT_{NDT}$ values;
- There is inherent conservatism present in the pressure-temperature (P-T) curves for BWRs;

- The derived fracture toughness values are lower bound values and are based on crack arrest ($K_{Ia}$) rather than the higher crack initiation ($K_{Ic}$) toughness;
- Data from other plants can be used to predict the behavior of the material early in plant life.

Based on the evaluation presented in this report, the recommended withdrawal schedule for the first surveillance capsule for Browns Ferry Unit 3 is 24 EFPY. This new schedule meets the intent of ASTM E185-82 [5], as the first capsule would be removed with the capsule fluence being less than $5 \times 10^{18}$ n/cm$^2$ and the value of $\Delta RT_{NDT}$ would be less than 50°F.

## 2. INTRODUCTION

Vessel fracture toughness is a major consideration for nuclear vessels; irradiation is known to decrease the fracture toughness of vessel materials. Therefore, measurement of the long term effects of vessel irradiation is a key component of surveillance programs. Tennessee Valley Authority (TVA) maintains a vessel surveillance program at Browns Ferry Unit 3 (BFN-3) meeting the intent of 10CFR50, Appendix H to monitor for changes in fracture toughness of vessel beltline materials as required by the NRC.

The BFN-3 surveillance program meets the intent of 10CFR50, Appendix H and ASTM E185-73 (for design) for the following reasons:

- The selected base and weld metals are representative of the vessel beltline materials;
- The capsule materials have a similar fabrication history to the vessel;
- The number, type, and design of capsule specimens are equivalent to ASTM E185-73.

The surveillance program implemented at BFN-3 consists of three specimen holders installed in the reactor during vessel construction. The number of holders was determined per ASTM E185-66.

The three specimen holders were designed, built, and analyzed to ASME Section III, 1965 Edition, with Addenda through Summer 1966. The selection of holder location was established to duplicate as closely as possible the temperature history, neutron flux spectrum, and maximum accumulated RPV beltline fluence, considering:

- interference/accessibility with other reactor hardware (e.g., jet pumps);
- peak fluence as a function of height;
- peak fluence as a function of radial position.

Using these criteria, the capsules were located at the vessel inner diameter at core mid-height at the 30°, 120° and 300° vessel azimuths (available areas considering jet pumps).

In 1989, when the withdrawal schedule of 8 EFPY for the first capsule was approved by the NRC [4], ASTM E185-82 was in effect. Withdrawal schedule requirements per 10CFR50, Appendix H and ASTM E185-82, state that the first specimen holder be removed at 6 EFPY (or when the accumulated fluence of the capsule exceeds $5 \times 10^{18}$ n/cm$^2$ or when the highest predicted $\Delta RT_{NDT}$ of the capsule materials is approximately 50°F, whichever comes first) and the second be removed at 15 EFPY. All testing and reporting (regardless of withdrawal schedule) is to be performed in accordance with ASTM E185-82.

This capsule withdrawal schedule was recommended for two reasons:

1. Data would be provided for future pressure-temperature (P-T) curve calculations. The data would be used to remove conservatism present in the (P-T) calculations. The P-T curves would be recalculated after the first capsule had been removed, using the capsule flux wire measurements instead of the conservative calculated fluence.

2. The data obtained from the first capsule would be used to identify any anomalous conditions, i.e. a greater than expected shift in $RT_{NDT}$.

However, withdrawal at eight (8) EFPY of the Browns Ferry Unit 3 capsule is not essential for continued safe operation for the following four reasons:

1. The BFN-3 fluence [7] used for shift predictions in accordance with Rev 2 is based upon a conservative calculation, and will bound the actual fluence.

2. Predicted shifts bound the measured results based on review of predicted $RT_{NDT}$ shifts and measured $RT_{NDT}$ shifts from other BWR surveillance capsules. Figure 2-1 is a plot of actual shift measurements versus predicted shifts (calculated per Rev 2) for base material. This figure shows that the predicted shift plus margin conservatively bounds the actual shifts measured from BWR surveillance specimen data. The same plot for weld material (Figure 2-2) again shows the predicted shift plus margin term bounds the measured shift.

3. Based on actual ART calculations performed in accordance with Rev 2 (see Appendix A), the shift ($\Delta RT_{NDT}$ + margin) for the Browns Ferry Unit 3 surveillance weld is calculated to be 60°F at 32 EFPY. If the first capsule is removed at 8 EFPY, the actual shift (predicted to be 13°F) may not be large enough to be differentiated from the data scatter, since the predicted fluence of the capsule at 8 EFPY ($1.85 \times 10^{17}$ n/cm$^2$) is low, and the chemistry of the BFN-3 capsule weld material is good (0.11% copper). Thus, the data obtained may not be useful for predicting the material behavior, as it may be indistinguishable from the unirradiated data.

4. Supplemental Surveillance Program (SSP) specimens will provide early test data for a weld similar to the BFN-3 surveillance weld; the weld is the material of concern, as the vessel weld material is limiting throughout plant life. This program supplements the BFN-3 surveillance program by providing timely detection of anomalous $RT_{NDT}$ shifts, should any occur. The fluences on the

SSP capsules are comparable to the fluence for the BFN-3 vessel wall in the time frame of interest.

This report supports the extension of the surveillance capsule testing schedule for BFN-3 for the following reasons:

- The fluence experienced by the BFN-3 vessel wall is low;
- The BFN-3 capsule plate and weld material has good alloy chemistry (i.e., low copper in the range of 0.10% - 0.11%)[3,4];
- The actual shift in the BFN-3 weld material may not be distinguishable from the data scatter with early testing.

The justification for extending the schedule is based on the following reasons:

- Predicted shifts bound the actual BWR industry surveillance results, and are expected to bound the BFN-3 shifts as well;
- The P-T curve calculations are inherently conservative;
- The supplemental surveillance program will supplement the BFN-3 surveillance program by providing for the timely detection of anomalous $RT_{NDT}$ shifts.

Extension of the surveillance program schedule will ensure that useful data is obtained and continued safe operation of Browns Ferry Unit 3 is ensured by using the SSP data and maintaining the BFN-3 P-T curves in accordance with Rev 2.

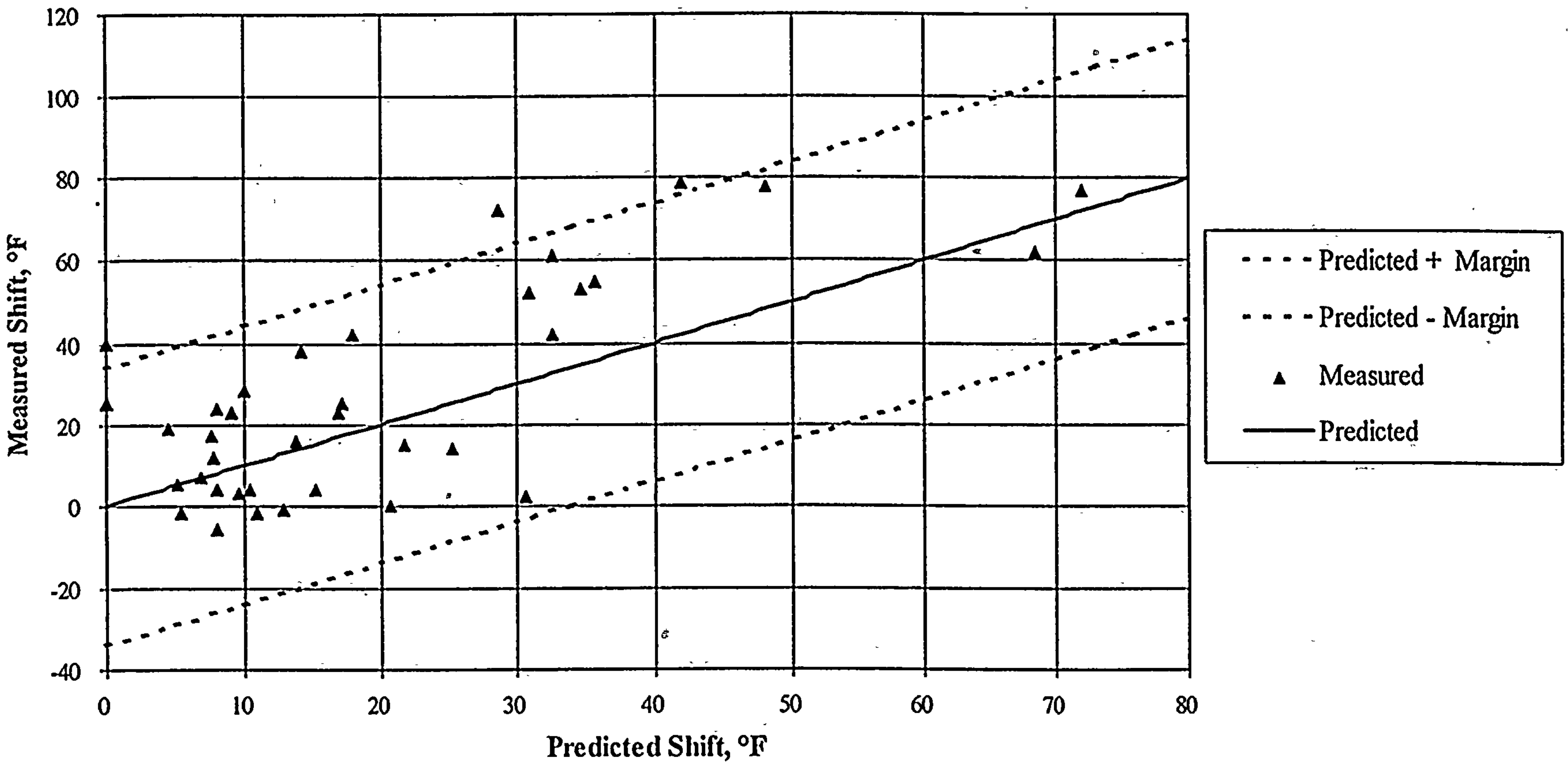


Figure 2-1 Measured Shift vs. Predicted Shift for Base Metal

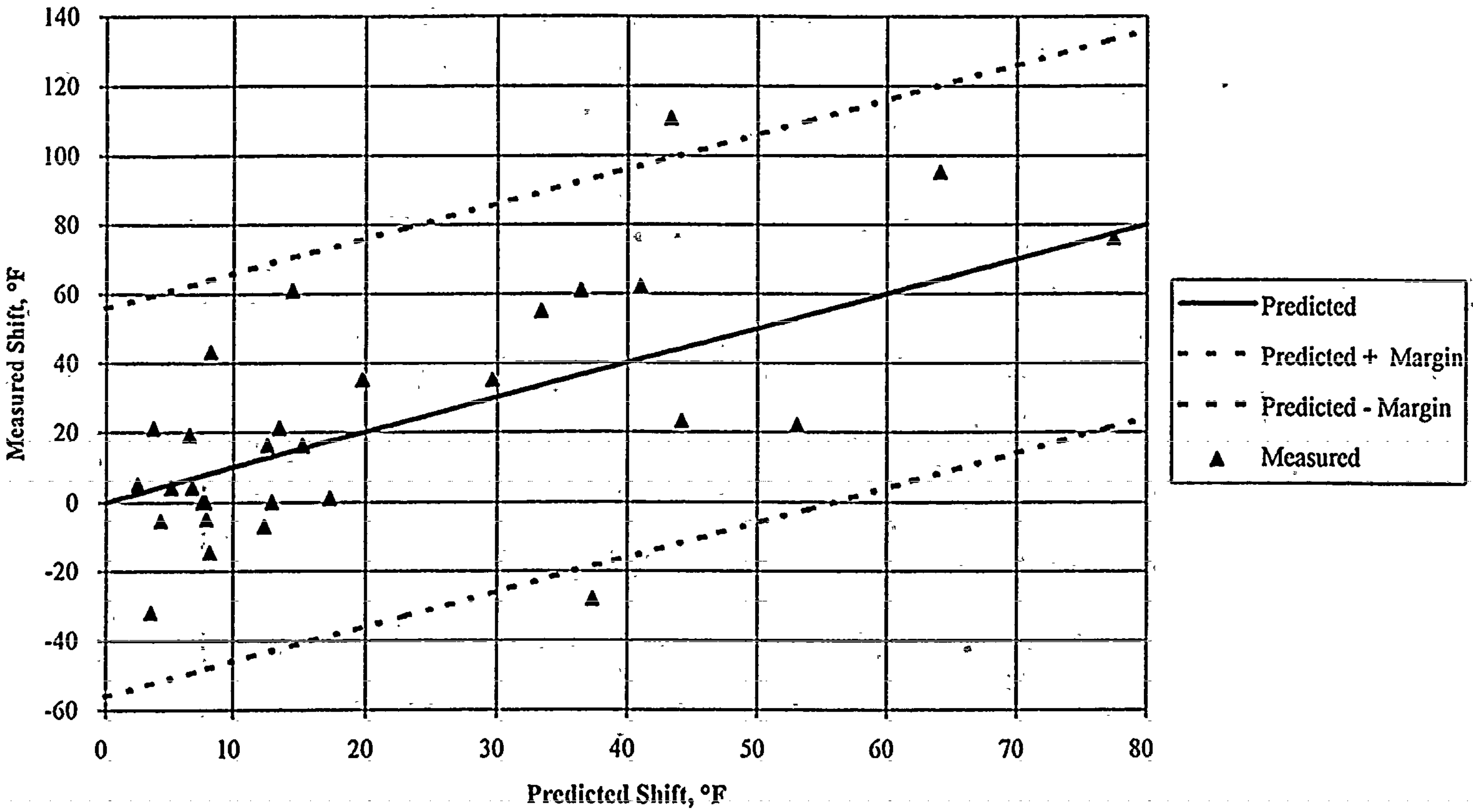


Figure 2-2 Measured Shift vs. Predicted Shift for Weld Metal

## 3. COMPARISON WITH OTHER SURVEILLANCE DATA

The evaluation of the shift in the $RT_{NDT}$ for Browns Ferry Unit 3 (see Appendix A) was performed using the techniques of Rev 2 for vessel material and the predicted fluence (i.e., no additional surveillance data). These predicted values of $RT_{NDT}$ shift indicate that the BFN-3 vessel will not experience a large shift over vessel life. To confirm the conservative predicted shift plus margin values (used to modify the surveillance program schedule), a comparison has been made between calculated shift and fluence values, and actual measured surveillance data from other BWRs.

A significant number of surveillance capsules from BWRs have been tested. Table 3-1 is a tabulation of the base metal results from these surveillance programs. The most significant feature, for a range of material chemistries and fluences, is that the expected shift is bounded by the calculated Rev 2 shift plus margin. For example, the measured BWR/4, 251" vessel (similar to Browns Ferry Unit 3) shifts are less than the predicted Rev 2 shift plus margin values by an average of 28°F (based upon the five complete data sets). For BWR/4-251 capsules, the average first capsule shift observed was 17°F, while the average predicted shift plus margin was 45°F. This data indicates that the BFN-3 capsule shift (predicted to be 13°F at 8 EFPY) will be small and may not be distinguishable from data scatter.

Similarly, Table 3-2 lists surveillance capsule data for weld material. The measured shifts are bounded by the predicted shift plus margin values. BWR/4-251 weld data (for the six complete data sets) shows the predicted shift plus margin to exceed the measured values by an average of 47°F. The average shift observed was 20°F, while the predicted shift plus margin was 67°F.

The predicted shift values are plotted against the measured shifts in Figures 3-1 and 3-2 for all BWR data available; the data is from Tables 3-1 and 3-2, respectively. These graphs show that the measured shifts are bounded by the predicted shift ± the margin term [5]. Based on these data, the measured shift for BFN-3 would be conservatively bounded by the Rev 2 prediction.

Since fluence has a significant effect on the Rev 2 calculation, use of an appropriate fluence value is essential for accurate shift prediction. The shift + margin predictions in Tables 3-1 and 3-2 utilize fluence values determined from flux wires removed early in plant life. In the case of BFN-3, however, a conservative estimate of the fluence [7] is used which will bound the actual fluence. Therefore, the fluence used for the ART calculations (as described in Appendix A) for BFN-3 is considered conservative.

Other than fluence, the most significant effect on the ART is the chemistry factor (CF). The CF is determined from the copper and nickel levels, copper having the more significant effect.

A study has been performed [8] on the copper levels present in BWR beltline materials, in response to NRC letter 92-01, Supplement 1. The intent was to identify the plants with significant variation in the reported copper levels. For the electroslag weld material, recently available information in an NRC SER for Commonwealth Edison (which is a best estimate chemistry)[9] has been used in determining CF and ART values for BFN-3 [10].

Based on the evaluation of previous surveillance data of actual shifts and fluences, the expected measured fluence for BFN-3 and the chemistry of the BFN-3 vessel material, the actual shift for BFN-3 is expected to be conservatively bounded by the calculated value of shift + margin.

| | | | | | | | | >1 MeV | | 1.99,REV2 | REV2 | 30 FT-LB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | RPV | Capsule | | | | | FLUENCE | @EFPY | DELTA | DELTA+ | TEST |
| PLANT | BWR | ID | I.D. | Cu | Ni | P | CF | (x10^17) | | RTNDT | MARGIN | SHIFT |
| | | (in) | (deg) | | | | | (n/cm^2) | | | | |
| BWR/2 | | | | | | | | | | | | |
| AC | 2 | 213 | 30 | 0.24 | 0.50 | 0.041 | 146.7 | 3.60 | 5.80 | 35.8 | 69.8 | 55 |
| | | | 300 | 0.24 | 0.50 | 0.041 | 146.7 | 4.78 | 7.98 | 41.9 | 75.9 | 79 |
| AS | 2 | 213 | 210 | 0.17 | 0.11 | 0.011 | 79.5 | 7.46 | 8.15 | 28.7 | 62.7 | 72 |
| BWR/3 | | | | | | | | | | | | |
| H | 3 | 251 | 215 | 0.20 | 0.45 | 0.030 | 131.0 | 0.52 | 6.23 | 9.0 | 43.0 | 23 |
| AR | 3 | 251 | 95 | 0.13 | 0.54 | 0.008 | 89.5 | 0.40 | 2.65 | 5.1 | 39.1 | 5 |
| | | | 215 | 0.13 | 0.54 | 0.008 | 89.5 | 0.71 | 5.98 | 7.7 | 41.7 | 12 |
| AL | 3 | 224 | 210 | 0.21 | 0.49 | 0.010 | 140.7 | 3.30 | 8.96 | 32.7 | 66.7 | 61 |
| | | | 300 | | | | 140.7 | 6.60 | 14.80 | 48.0 | 82.0 | 78 |
| A | 3 | 205 | 30 | 0.17 | 0.66 | | 128.3 | 2.90 | 7.63 | 27.6 | 61.6 | N/A |
| AJ | 3 | 188 | 10 | 0.08 | 0.72 | 0.012 | 66.0 | 5.70 | 6.90 | 20.7 | 54.7 | 0 |
| | | | 190 | | | | 66.0 | 12.60 | 15.85 | 30.7 | 64.7 | 2 |
| AG | 3 | 224 | 30 | 0.13 | 0.63 | 0.015 | 91.8 | 2.30 | 4.17 | 17.2 | 51.2 | 25 |
| W | 3 | 251 | 215 | 0.20 | 0.55 | 0.010 | 143.0 | 0.55 | 6.64 | 10.3 | 44.3 | 4 |
| AB | 3 | 251 | 215 | 0.09 | 0.52 | 0.008 | 65.0 | 0.66 | 5.63 | 5.3 | 39.3 | -2 |
| BWR/4 | | | | | | | | | | | | |
| Y | 4 | 251 | 30 | 0.14 | 0.55 | 0.007 | 98.0 | 1.52 | 9.05 | 14.2 | 48.2 | 38 |
| V | 4 | 201 | 30 | 0.17 | 0.53 | 0.016 | | 1.30 | 7.06 | 0.0 | 34.0 | 25 |
| G | 4 | 201 | 30 | 0.11 | 0.53 | 0.011 | | 1.30 | 7.43 | 0.0 | 34.0 | 40 |
| Q | 4 | 218 | 30 | 0.21 | 0.76 | 0.009 | 164.6 | 2.30 | 6.80 | 30.9 | 64.9 | 52 |
| | | | 300 | | | | 164.6 | 2.80 | 11.20 | 34.7 | 68.7 | 53 |
| N | 4 | 183 | 288 | 0.15 | 0.70 | 0.006 | 112.5 | 4.90 | 5.90 | 32.6 | 66.6 | 42 |
| | | | 36 | 0.15 | 0.61 | 0.011 | 165.0 | 11.00 | 14.70 | 72.0 | 106.0 | 77 |
| C | 4 | 218 | 30 | 0.12 | 0.63 | 0.011 | 83.5 | 2.60 | 5.98 | 16.9 | 50.9 | 23 |
| | | | 120 | | | | 74.0 | 5.00 | 13.40 | 21.7 | 55.7 | 15 |
| K | 4 | 218 | 30 | 0.11 | 0.63 | 0.010 | 93.5 | 2.40 | 5.75 | 18.0 | 52.0 | 42 |
| | | | 120 | 0.13 | 0.70 | 0.010 | 245.0 | 4.60 | 14.30 | 68.5 | 102.5 | 62 |
| F | 4 | 218 | 30 | 0.08 | 0.63 | 0.010 | 51.0 | 2.30 | 6.58 | 9.6 | 43.6 | 3 |
| AY | 4 | 251 | 30 | 0.09 | 0.64 | 0.012 | 58.0 | 1.42 | 6.01 | 8.0 | 42.0 | 4 |
| P | 4 | 251 | 120 | 0.10 | 0.54 | | 65.0 | 1.80 | 7.53 | 10.5 | 44.5 | N/A |
| J | 4 | 251 | 30 | 0.13 | 0.63 | 0.011 | 91.8 | 1.60 | 7.58 | 13.7 | 47.7 | 16 |
| AW | 4 | 251 | 30 | 0.09 | 0.61 | 0.009 | 58.0 | 1.40 | 6.68 | 8.0 | 42.0 | 24 |
| AT | 4 | 251 | 30 | 0.12 | 0.63 | 0.010 | 83.0 | 1.30 | 6.20 | 10.8 | 44.8 | -2 |
| O | 4 | 205 | 30 | 0.10 | 0.68 | 0.014 | 74.9 | 0.43 | 7.54 | 4.5 | 38.5 | 19 |
| BWR/5 | | | | | | | | | | | | |
| AX | 5 | 251 | 300 | 0.14 | 0.54 | 0.014 | 97.0 | 0.90 | 6.50 | 9.9 | 43.9 | 28 |
| AZ | 5 | 251 | 300 | 0.10 | 0.48 | 0.010 | 65.0 | 1.15 | 6.98 | 7.8 | 41.8 | N/A |
| AK | 5 | 251 | 300 | 0.14 | 0.50 | 0.017 | 88.0 | 1.55 | 7.20 | 12.9 | 46.9 | -1 |
| BWR/6 | | | | | | | | | | | | |
| R | 6 | 218 | 3 | 0.029 | 0.6 | 0.005 | 20 | 8.4 | 5.67 | 7.7 | 41.7 | 17 |
| AE | 6 | 218 | 177 | 0.06 | 0.6 | 0.008 | 37 | 9.6 | 6.85 | 15.1 | 49.1 | 4 |
| AF | 6 | 218 | 3 | 0.09 | 0.58 | 0.008 | 58 | 11.0 | 6.99 | 25.3 | 59.3 | 14 |
| D | 6 | 239 | 345 | 0.06 | 0.63 | | 37 | 2.2 | 9.28 | 6.8 | 40.8 | 7.2 |
| AU | 6 | 238 | 3 | 0.06 | 0.61 | 0.010 | 33 | 3.5 | 5.50 | 8.0 | 42.0 | -6 |

Table 3-1 BWR Surveillance Program Results for Base Metal

| PLANT | BWR | RPV ID (in) | Capsule I.D. (deg) | Cu (%) | Ni (%) | P (%) | CF | >1 MeV FLUENCE (x10^17) (n/cm^2) | @EFPY | 1.99,REV2 DELTA RTNDT | REV2 DELTA+ MARGIN | 30 FT-LB TEST SHIFT |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BWR/2 | | | | | | | | | | | | |
| AC | 2 | 213 | 30 | 0.17 | 0.07 | | 81 | 3.6 | 5.80 | 19.8 | 75.8 | N/A |
| | | | 300 | 0.17 | 0.07 | | 81 | 4.78 | 7.98 | 23.1 | 79.1 | N/A |
| AS | 2 | 213 | 210 | 0.29 | 0.05 | 0.022 | 131.5 | 7.5 | 8.15 | 47.6 | 103.6 | N/A |
| BWR/3 | | | | | | | | | | | | |
| H | 3 | 251 | 215 | | | | | | | | | |
| AR | 3 | 251 | 95 | 0.21 | 0.35 | 0.009 | 119 | 0.4 | 2.65 | 6.7 | 62.7 | 4 |
| | | | 215 | 0.21 | 0.35 | 0.009 | 119 | 0.28 | 5.98 | 5.1 | 61.1 | 4 |
| AL | 3 | 224 | 210 | 0.20 | 1.05 | 0.019 | 228.5 | 3.3 | 8.96 | 53.0 | 109.0 | 22 |
| | | | 300 | | | | | 6.6 | 14.80 | 77.4 | 133.4 | 76 |
| A | 3 | 205 | 30 | 0.05 | 0.92 | | 68 | 2.9 | 7.63 | 14.6 | 70.6 | N/A |
| AI | 3 | 188 | 10 | 0.30 | 0.09 | 0.016 | 138 | 5.7 | 6.90 | 43.3 | 99.3 | 110.5 |
| | | | 190 | | | | | 12.6 | 15.85 | 64.1 | 120.1 | 95 |
| AG | 3 | 224 | 30 | 0.16 | 0.79 | 0.014 | 178 | 2.3 | 4.17 | 33.4 | 89.4 | 55 |
| W | 3 | 251 | 215 | 0.19 | 0.32 | 0.012 | 105.5 | 0.55 | 6.64 | 7.6 | 63.6 | 0 |
| AB | 3 | 251 | 215 | 0.16 | 0.34 | 0.009 | 100.1 | 0.66 | 5.63 | 8.2 | 64.2 | 43 |
| BWR/4 | | | | | | | | | | | | |
| Y | 4 | 251 | 30 | 0.20 | 0.33 | 0.010 | 120 | 1.52 | 9.05 | 17.4 | 73.4 | 1 |
| V | 4 | 201 | 30 | 0.14 | 0.68 | 0.011 | | 1.3 | 7.06 | 0.0 | 56.0 | N/A |
| G | 4 | 201 | 30 | 0.12 | 0.66 | 0.012 | | 1.3 | 7.43 | 0.0 | 56.0 | N/A |
| Q | 4 | 218 | 30 | 0.23 | 0.75 | 0.014 | 194.5 | 2.3 | 6.80 | 36.5 | 92.5 | 61 |
| | | | 300 | | | | | 2.8 | 11.20 | 41.0 | 97.0 | 62 |
| N | 4 | 183 | 288 | 0.02 | 0.95 | 0.011 | 27 | 4.9 | 5.90 | 7.8 | 63.8 | 0 |
| | | | | | | | 29 | 11 | 14.70 | 12.7 | 68.7 | 16 |
| C | 4 | 218 | 30 | 0.31 | 0.72 | 0.015 | 216 | 2.6 | 5.98 | 43.6 | 99.6 | N/A |
| | | | 120 | | | | 208 | 5 | 13.40 | 60.9 | 116.9 | N/A |
| K | 4 | 218 | 30 | 0.28 | 0.76 | 0.013 | 212 | 2.4 | 5.75 | 40.8 | 96.8 | N/A |
| | | | | | | | | 4.6 | 14.30 | 0.0 | 56.0 | N/A |
| F | 4 | 218 | 30 | 0.13 | 0.10 | 0.014 | 68.8 | 2.3 | 6.58 | 12.9 | 68.9 | 0 |
| AY | 4 | 251 | 30 | 0.08 | 0.59 | 0.014 | 105 | 1.42 | 6.01 | 14.5 | 70.5 | 61 |
| P | 4 | 251 | 120 | 0.10 | 0.32 | | 84.2 | 1.8 | 7.53 | 13.6 | 69.6 | 21 |
| J | 4 | 251 | 30 | 0.11 | 0.41 | 0.009 | 102.5 | 1.6 | 7.58 | 15.3 | 71.3 | 16 |
| AW | 4 | 251 | 30 | 0.02 | 0.95 | 0.012 | 27 | 1.4 | 6.68 | 3.7 | 59.7 | 21 |
| AT | 4 | 251 | 30 | 0.02 | 0.95 | 0.014 | 27 | 1.3 | 6.20 | 3.5 | 59.5 | -32 |
| O | 4 | 205 | 30 | 0.03 | 0.95 | 0.013 | 41 | 0.43 | 7.54 | 2.5 | 58.5 | 5 |
| BWR/5 | | | | | | | | | | | | |
| AX | 5 | 251 | 300 | 0.21 | 0.78 | 0.016 | 194 | 0.9 | 6.50 | 19.8 | 75.8 | 35 |
| AZ | 5 | 251 | 300 | 0.04 | 0.89 | 0.010 | 54 | 1.15 | 6.98 | 6.5 | 62.5 | 19 |
| AK | 5 | 251 | 300 | 0.03 | 0.90 | 0.011 | 34 | 1.55 | 7.20 | 7.9 | 63.9 | -5 |
| BWR/6 | | | | | | | | | | | | |
| R | 6 | 218 | 3 | 0.07 | 0.76 | 0.013 | 97.5 | 8.4 | 5.67 | 37.3 | 93.3 | -28 |
| AE | 6 | 218 | 177 | 0.08 | 0.88 | 0.009 | 108 | 9.6 | 6.85 | 44.1 | 100.1 | 23 |
| AF | 6 | 218 | 3 | 0.05 | 0.87 | 0.010 | 68 | 11.0 | 6.99 | 29.7 | 85.7 | 35 |
| D | 6 | 239 | 345 | 0.05 | 0.7 | | 68 | 2.2 | 9.28 | 12.4 | 68.4 | -7.2 |
| D | 6 | 239 | 9 | 0.01 | 0.04 | | 20 | 2.9 | 9.28 | 4.3 | 60.3 | -5.4 |
| AU | 6 | 238 | 3 | 0.02 | 0.82 | 0.013 | 34 | 3.5 | 5.50 | 8.2 | 64.2 | -14.7 |

Table 3-2 BWR Surveillance Program Results for Weld Metal

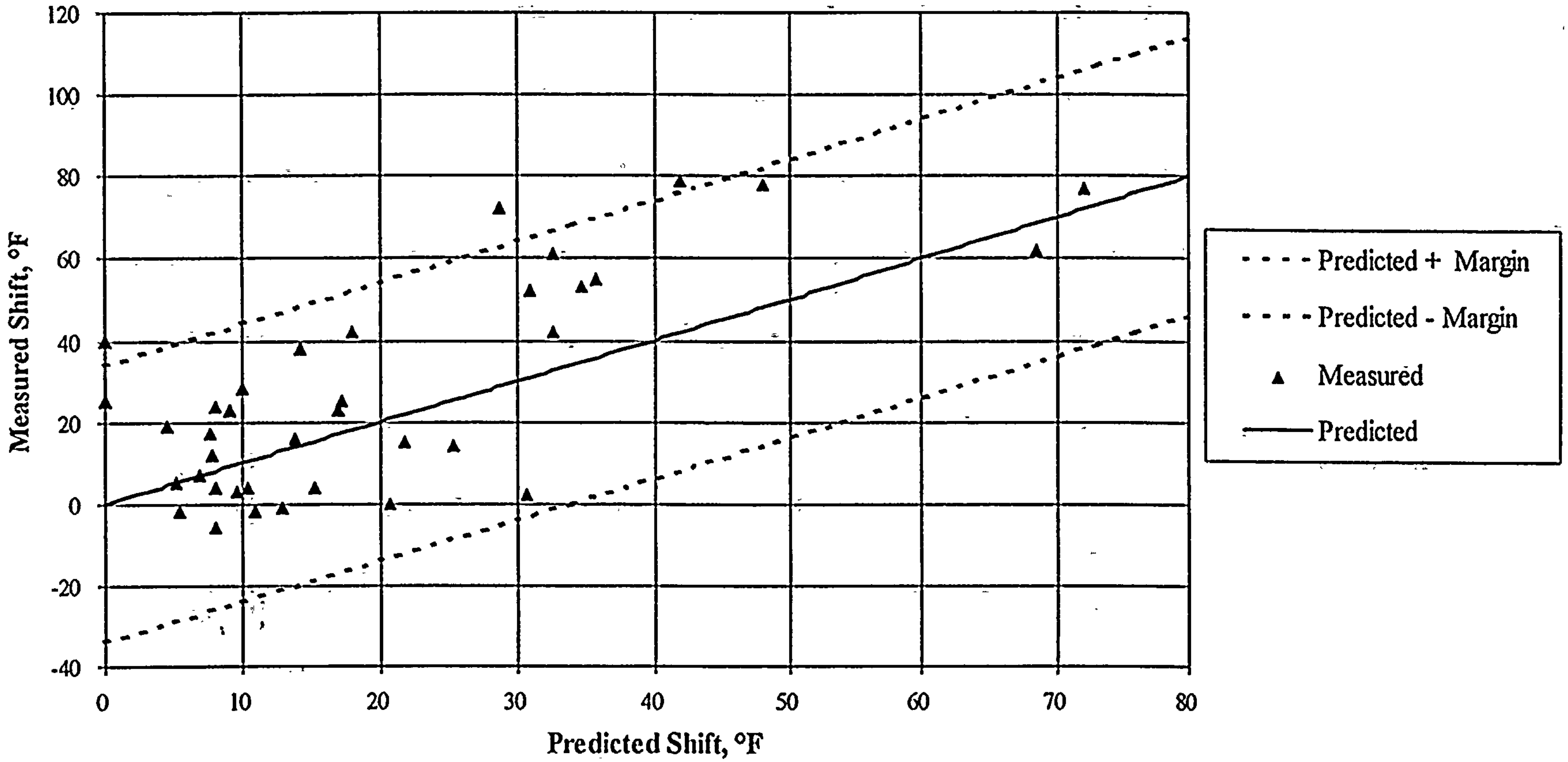


Figure 3-1 Measured Shift vs. Predicted Shift for Base Metal

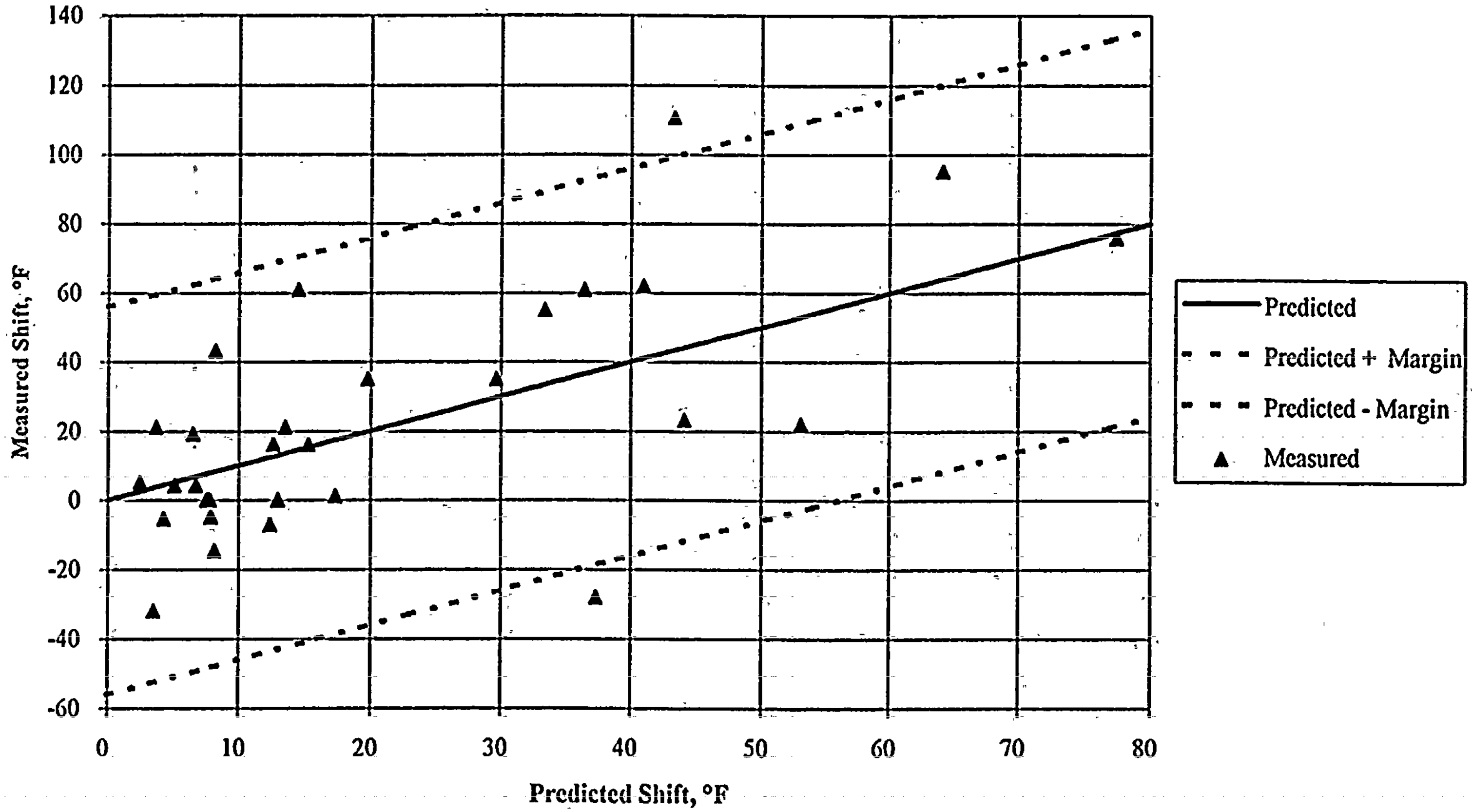


Figure 3-2 Measured Shift vs. Predicted Shift for Weld Metal

## 4. PRESSURE-TEMPERATURE (P-T) CURVES

The shift in $RT_{NDT}$ obtained from surveillance testing is used to evaluate the long term effects of irradiation on the fracture toughness of the vessel. The reference fracture toughness ($K_{IR}$) is determined using the shift in $RT_{NDT}$; $K_{IR}$ is part of the calculations of the P-T curves performed in accordance with ASME Section XI, Appendix G. The current Browns Ferry Unit 3 P-T curves were calculated with the shift in $RT_{NDT}$ corresponding to 20 EFPY.

The $K_{IR}$ correlation was developed from several sets of material data on pressure vessel steel [11]. The $K_{IR}$ curve was drawn to bound the available data. Thus the correlation has inherent conservatism.

In addition, operation of BFN-3 follows the steam saturation curve, therefore, the operating temperatures are expected to be well in excess of the minimum required temperature. During normal and accident conditions, the BFN-3 vessel maintains more than adequate margins. The operational issues of Pressurized Thermal Shock (PTS) and Low Temperature Over Pressurization (LTOP) are not applicable to BFN-3. The limiting case for BFN-3 is the pressure test.

The P-T curve associated with the pressure test is calculated using the crack arrest fracture toughness, $K_{IR}$ ($K_{Ia}$). The static crack initiation fracture toughness, $K_{Ic}$ is significantly higher than $K_{IR}$ in the temperature range of interest [12]. Therefore, use of $K_{IR}$ conservatively bounds the fracture toughness of the vessel.

Figure 4-1 is a plot of $K_{Ia}$ and $K_{Ic}$ as a function of T-$RT_{NDT}$ [13]. The $K_{Ia}$ curve is shown to be lower than the $K_{Ic}$ curve, conservatively bounding the fracture toughness. For example, at a pressure test temperature of 221°F and a vessel ART of 112°F (corresponding to 20 EFPY for BFN-3), the fracture toughness for initiation and arrest are estimated to be:

$K_{Ic} = 200.0$ ksi$\sqrt{in}$

$K_{IR} = 87.2$ ksi$\sqrt{in}$

Thus the $K_{Ic}$ value is approximately 2.3 times the $K_{Ia}$ value, clearly showing $K_{Ia}$ to conservatively bound the calculations.

The combination of lower bound fracture toughness, the Browns Ferry Unit 3 operating characteristics and the conservative fracture toughness values indicate that the BFN-3 vessel fracture toughness is not a significant concern over the life of the plant.

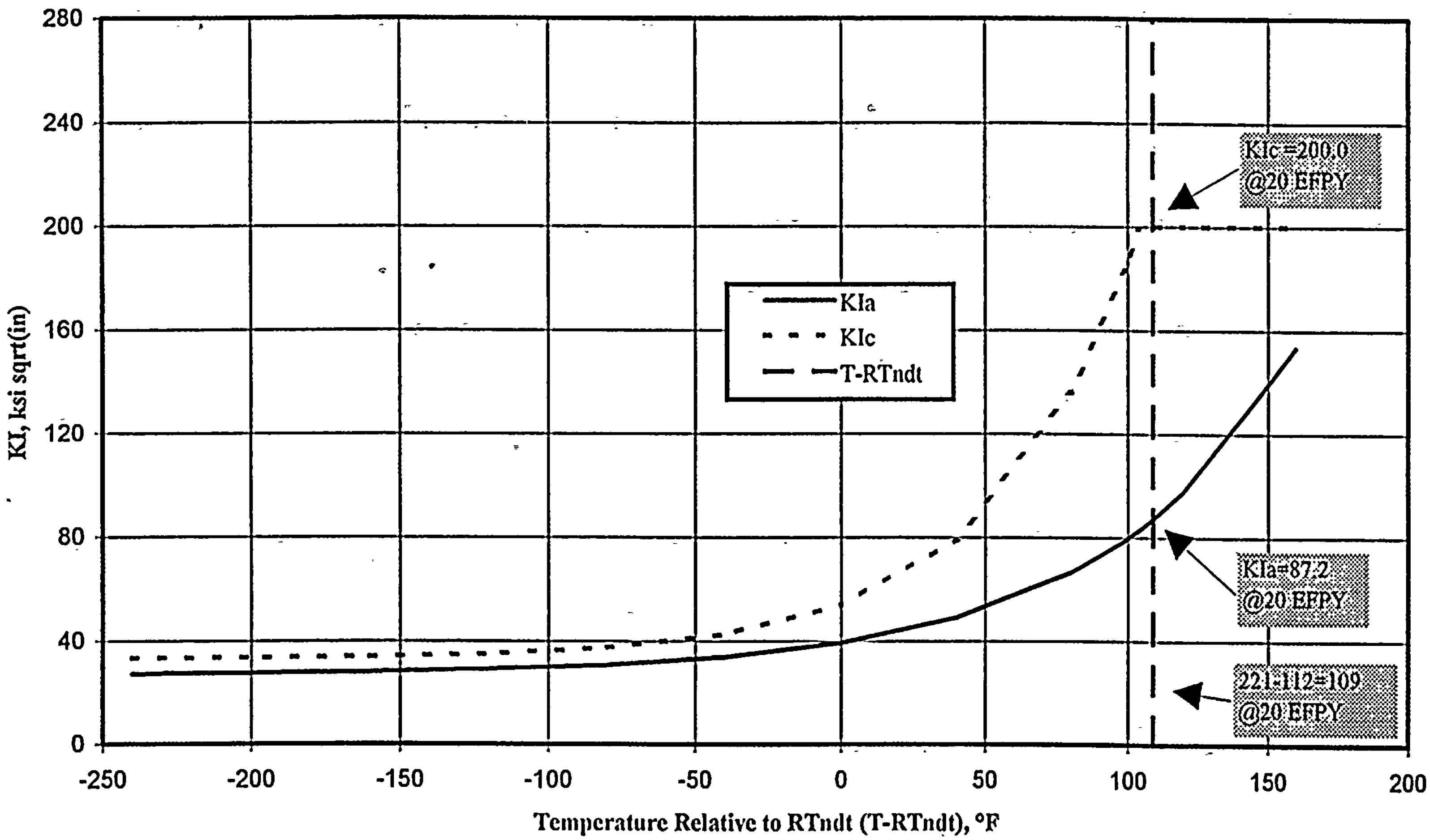


Figure 4-1 Comparison of $K_{Ia}$ and $K_{Ic}$

## 5. SUPPLEMENTAL SURVEILLANCE PROGRAM

The BWRVIP is in the midst of executing a supplemental test program being administrated by EPRI (and originated by the BWR Owner's Group [BWROG]) that is designed to significantly increase the amount of BWR surveillance data in a systematic manner which should permit the development of a BWR-specific equivalent to Rev 2.

### Description

The Supplemental Surveillance Program (SSP) was begun in the late 1980s when the BWROG concluded from their review of BWR surveillance data the following:

- Due to the smaller number of capsules per plant and the relatively fewer number of BWRs than PWRs, there is limited BWR surveillance data at higher fluences available to analyze;
- The ARTs associated with Rev 2 imposed some hardships on pressure testing for BWRs, some of which might be relieved if better predictive models of the BWR embrittlement phenomenon were obtained.

In light of these issues, the BWROG prepared supplemental capsules which were installed in Cooper and Oyster Creek. One capsule from Oyster Creek was withdrawn in 1996, with additional withdrawals planned for 2000 and 2002.

The results of the SSP will be the equivalent of 84 additional surveillance capsules, compared to about 35 which have been tested to date. These capsules were designed to systematically evaluate embrittlement trends in BWRs. For example:

- The capsules are positioned so that flux differs by a factor of 2. Also, irradiation times differ by a factor of 2. In this way, some capsules have matching flux but with different fluence, while some have matching fluence and a differing flux level;
- The materials used were selected to bound the range of chemistries in BWR beltline materials, and in most cases *are* BWR beltline materials;
- Irradiations are being done in BWRs to correctly simulate conditions like temperature, neutron spectrum and transient operation.

**Relationship to Browns Ferry Unit 3**

The SSP does not contain BFN-3 specific material among the materials in the capsules. However, the SSP contains material similar to the BFN-3 limiting weld (for BFN-3 the weld material is the limiting material throughout plant life, so the plate is not a significant concern). The SSP Quad Cities 2 Electroslag Weld material contained in the program has a composition similar to the BFN-3 surveillance program material, and was made by the same manufacturer (B&W) in the same time period (Quad Cities 2, 1970; BFN-3, 1971). The copper content of the Quad Cities 2 weld material is higher than the BFN-3 surveillance weld (0.18% vs. 0.11%), and the Quad Cities 2 nickel content is lower (0.18% vs. 0.28%). The resultant chemistry factors (CF) (per Rev 2) are 93 and 81 for Quad Cities 2 and BFN-3, respectively. In addition, the BFN-3 surveillance plate is represented by materials with similar chemistry in each of the SSP capsules. The SSP results will be applicable to BFN-3 for two reasons:

- Generically, the SSP results will be from representative environmental conditions on materials representative of all BWRs, including BFN-3;

- Specifically, results will be developed which will provide information on a material which is expected to respond to irradiation similar to the weld in the Browns Ferry Unit 3 surveillance program.

The SSP capsules, when tested, will have collected between $5 \times 10^{17}$ n/cm$^2$ (20.5 EFPY for BFN-3 at 1/4T) and $2 \times 10^{18}$ n/cm$^2$ (82.1 EFPY for BFN-3 at 1/4T) fluence. Thus, the results of the SSP are complementary to the BFN-3 surveillance program such that postponement of the capsule withdrawal will have minimal impact on the understanding of irradiation effects on the BFN-3 vessel.

## 6. REVISED SURVEILLANCE SCHEDULE

The surveillance program is intended to characterize the vessel properties as a function of irradiation over the life of Browns Ferry Unit 3. The Charpy impact energy obtained from the prescribed testing is used to evaluate the reference fracture toughness of the BFN-3 vessel ($K_{IR}$) in accordance with ASME Section III, Appendix G. The schedule for the surveillance program testing should be designed to obtain the best data, while maintaining safe operation.

The expected change in fracture toughness of the BFN-3 weld material (the limiting beltline material) as a function of EFPY is plotted in Figure 6-1. Since the pressure test is the limiting case, the calculated $K_{IR}$ is for a 1140 psig pressure test. The pressure test temperature was modified at selected intervals for illustration purposes. This figure demonstrates that the $K_{IR}$ used to calculate the P-T curves is expected to conservatively bound the required vessel fracture toughness.

Since the $K_{IR}$ is considered a conservative prediction, and the SSP will identify a greater than expected shift relative to BFN-3, the first surveillance capsule testing should be at the time at which a majority of the shift in the vessel $RT_{NDT}$ has been achieved, consistent with the intent of ASTM E185-82. Early testing of the surveillance weld specimens may result in the measured shift being less than the data scatter (sometimes resulting in negative shifts in $RT_{NDT}$). Correct selection of the removal time will ensure useful data from all specimens. If the shift is greater than expected, then the margin present in the P-T calculations together with the limiting fracture toughness represent an added margin of safety.

Since the SSP can be used to identify anomalous shifts, the first surveillance capsule testing schedule should be developed to measure a significant portion of the fracture toughness change, as measured by $\Delta RT_{NDT}$. Since the limiting weld material for the vessel has a low expected $\Delta RT_{NDT}$ of 52°F (at 1/4T) over the life of the plant, the recommended schedule should be designed to measure a majority of $\Delta RT_{NDT}$ of the plate material. Given the low expected shift, a criteria of 75% of the expected shift in $RT_{NDT}$ of the vessel weld material was selected to determine the revised schedule. For BFN-3, 75% of the expected 52°F shift is 39°F.

Figure 6-2 is a plot of the capsule shift in $RT_{NDT}$ as a function of EFPY. The surveillance capsule material will experience a shift of 30°F in $\Delta RT_{NDT}$ over the life of the plant. Using a criteria of 75% of the expected shift of the limiting vessel material (39°F), the capsule will experience this shift for the weld material at approximately 59 EFPY. The removal schedule may be set to 24 EFPY in order to provide a reasonable schedule where a significant shift will have occurred in the capsule material. In support of this schedule, at 24 EFPY an expected 25°F shift will have occurred in the surveillance capsule limiting material, which will provide sufficient data to determine the required vessel material properties. In addition, upon evaluation of the SSP materials, the BFN-3 schedule can be further evaluated.

The fluence data, as determined from the surveillance capsule flux wires at 24 EFPY, will provide an accurate indication of neutron fluence. As noted in Section 3, the current predicted fluence is conservative. The flux wires in the capsule withdrawn at 24 EFPY will be used to modify the predicted fluence, meeting the requirements of the BFN-3 Technical Specifications. The use of the flux wires at 24 EFPY will meet the requirements of 10CFR50 Appendix H and ASTM E185.

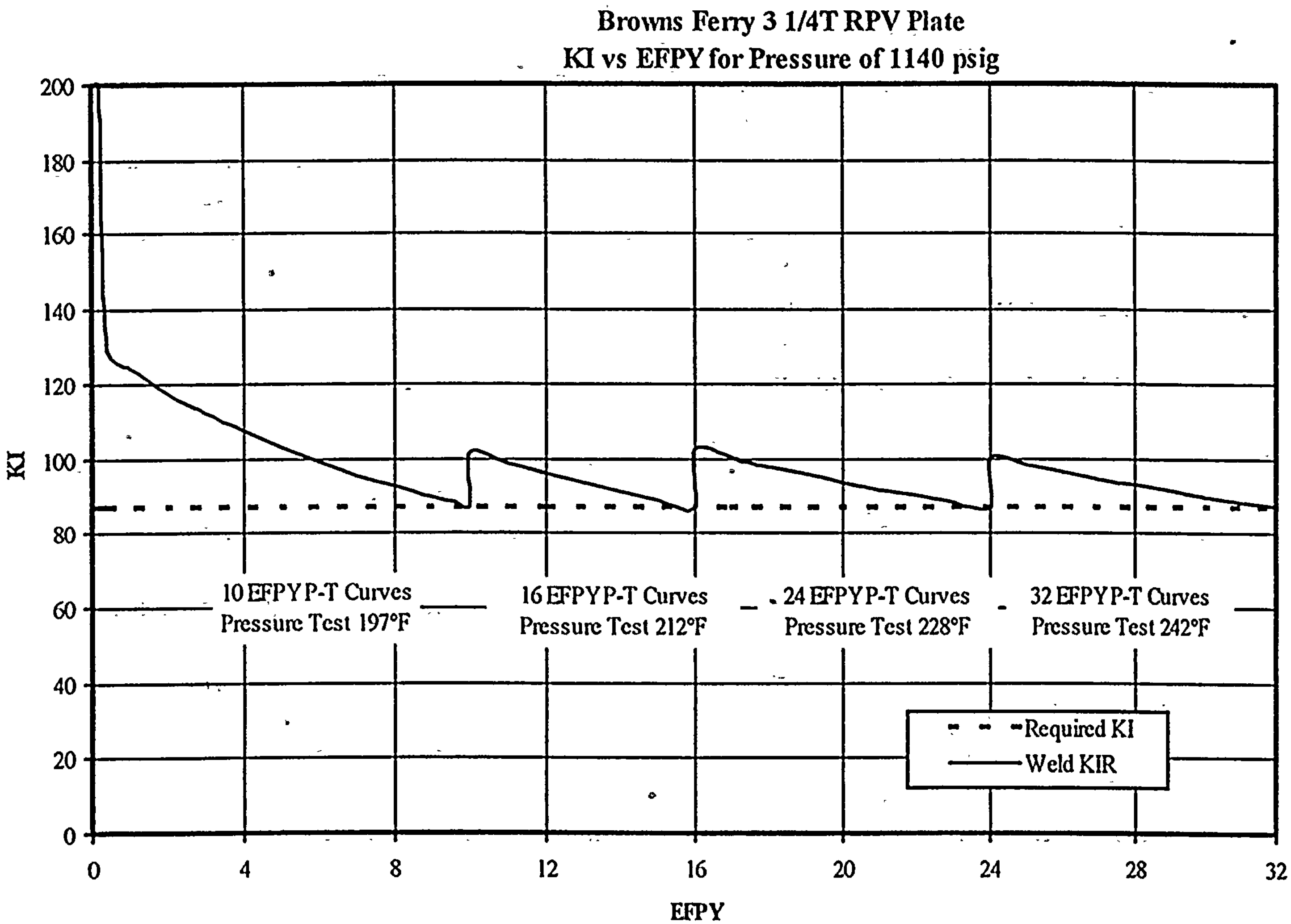


Figure 6-1 $K_{IR}$ vs. EFPY for Browns Ferry Unit 3 Weld Material

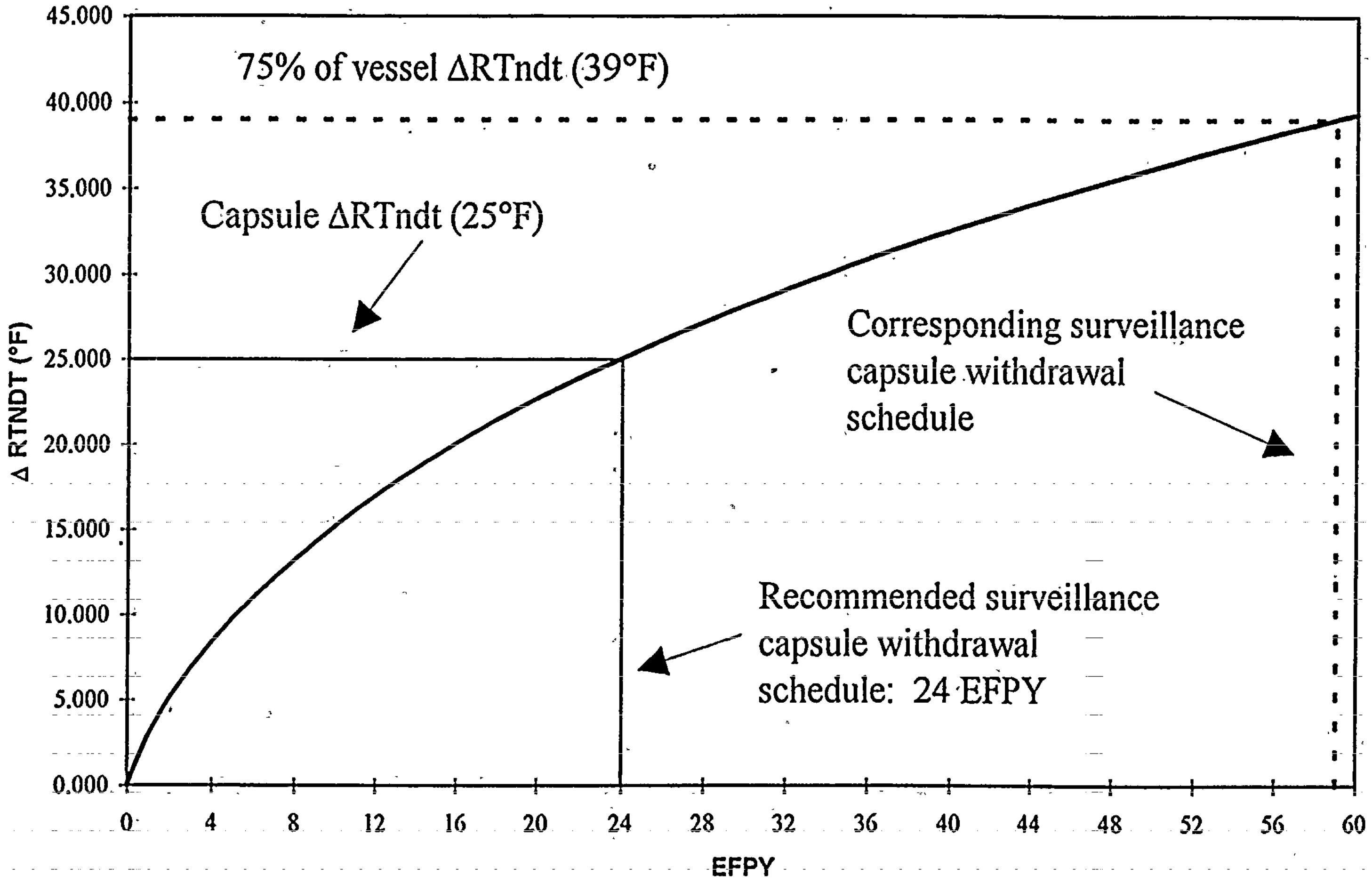


Figure 6-2 Predicted Shift vs. EFPY, Browns Ferry Unit 3 Surveillance Capsule Weld

## 7. CONCLUSIONS

The purpose of the vessel surveillance program is to characterize the vessel properties as a function of irradiation. The current schedule for Browns Ferry Unit 3 is a withdrawal schedule of eight (8) EFPY for the first surveillance capsule.

Schedules developed according to 10CFR50, Appendix H, however, are general guidelines for all reactor pressure vessels. The schedules do not take into account some specific characteristics of BFN-3 such as low fluence and good alloy chemistry for the capsule materials (0.10% - 0.11% copper), which results in a low shift in $RT_{NDT}$. If the first capsule is removed and tested according to the current schedule (8 EFPY), the data obtained for the plate specimens may be heavily affected by the scatter in Charpy results.

Since early information on a material similar to the limiting BFN-3 weld material can be obtained from the SSP to identify anomalous shifts, the BFN-3 surveillance schedule should be extended. The schedule can be extended for the following reasons:

1. Evaluation of similar data obtained from actual surveillance programs has shown that the measured fluence, shift and chemistry are bounded by expected values. In particular, the BWR/4 data has shown small $RT_{NDT}$ shifts for capsules removed from vessels similar to Browns Ferry Unit 3. Therefore, the surveillance capsule withdrawal schedule should be extended based on the conservatism in the calculated shift of $RT_{NDT}$.

2. In addition, the P-T curves contain inherent conservatism, as noted in Section 4. The fracture toughness values used for these calculations are considered to be lower bound values and are significantly less than the crack initiation fracture toughness in the temperature range of interest. At operating temperatures, BFN-3 maintains more than adequate margins; the limiting condition is the pressure test. This conservatism

provides an added margin of safety; therefore, the capsule withdrawal schedule can be modified.

3. In addition, the SSP data will complement the available data on surveillance specimens and also identify any anomalous information in the predicted values. This characterization will enhance the understanding of vessel embrittlement issues and provide data for BFN-3 using a weld similar to the limiting weld material. Hence the change in schedule for the BFN-3 surveillance specimens will not have a significant effect on the understanding of vessel irradiation issues.

These reasons justify extending the withdrawal schedule while maintaining reactor safety margins, and provide for more accurate measured data near EOL. Therefore, the BFN-3 surveillance schedule can be extended.

The material property of most concern is the fracture toughness of the vessel; the surveillance schedule should be based on evaluation of this property. Since the fracture toughness ($K_{IR}$) is dependent on the shift in $RT_{NDT}$, the optimum EFPY for removal of the capsule ensures useful data (measuring significant shift), while identifying any anomalous conditions. If such an anomalous shift were to occur (which is unlikely), the margin between $K_{Im}$ (primary membrane fracture toughness) and $K_{IR}$, as well as the inherent conservatism of the calculations, can provide a sufficient safety margin for extending the surveillance schedule. In addition, operation of BFN-3 follows the steam saturation curve; the operating temperatures are expected to be well in excess of the minimum required temperature.

As shown in Section 6, the appropriate $\Delta RT_{NDT}$ value selected was 75% of the predicted beltline material 32 EFPY change in $\Delta RT_{NDT}$. Using this value to determine the appropriate shift in the capsule (hence the appropriate EFPY), the recommended withdrawal schedule for the first Browns Ferry Unit 3 surveillance capsule is 24 EFPY. This proposed schedule meets the intent of ASTM E185-82, as the first capsule would be removed with the fluence being less than 5 x $10^{18}$ n/cm$^2$ and the value of $\Delta RT_{NDT}$ would be less than 50°F. Removal of the capsule at the appropriate EFPY will provide more meaningful data for fracture toughness predictions.

# 8. REFERENCES


[1] "Reactor Vessel Material Surveillance Program Requirements," Appendix H to Part 50 of Title 10 of the Code of Federal Regulations, December 1995.

[2] USNRC Docket Nos. 50-259, 50-260, and 50-296, "Revision to Technical Specifications Pertaining to Surveillance Requirement 4.6.A.3 and Bases Section 3.6/4.6 - (TAC 73141, 73142, 73143) (TS 270) - Browns Ferry Nuclear Plants, Units 1, 2, and 3", 8/3/89

[3] Letter, P. Salas (TVA) to USNRC, "Browns Ferry Nuclear Plant (BFN) - Units 1, 2, and 3 - Generic Letter (GL) 92-01, Reactor Vessel Structural Integrity - Update to the Initial Reference Nil Ductility Temperature ($RT_{NDT}$) Chemical Composition and Fluence Values", 3/27/95

[4] Letter, T. Abney (TVA) to USNRC, "Browns Ferry Nuclear Plant (BFN) - Units 1, 2, and 3 - Generic Letter (GL) 92-01, Revision 1, Supplement 1, Reactor Vessel Structural Integrity - Response to NRC Request for Additional Information", 9/3/98

[5] ASTM E185-82.

[6] "Radiation Embrittlement of Reactor Vessel Materials," U.S. NRC Regulatory Guide 1.99, Revision 2, May 1988.

[7] Letter #RGC-9803, Ray Carey (GE) to HL Williams (TVA), "New Bounding EFPY for Previously Generated P-T Curves Considering Power Uprate for Browns Ferry Units 2 & 3 Using Calculated Fluence and Estimated ESW Information" (DRF B13-02002-00), 12/11/98

[8] "Bounding Assessment of BWR/2-6 Reactor Pressure Vessel Integrity Issues," BWR VIP-08NP, November 1995.

[9] Letter, USNRC to I. Johnson (Commonwealth Edison Company), "Issuance of Amendments", 2/28/97

[10] Letter #R92 981209 917, RD Ryan (TVA) to L. Eichenberger (TVA), "Browns Ferry Nuclear Plant (BFN) - Work Impact - Scope of Response to NRC Request for Additional Information (RAI) Regarding Pressure-Temperature (P-T) Curve Update for BFN Units 2 and 3", 12/9/98

[11] S.T. Rolfe and J.M. Barsom, Fracture and Fatigue Control in Structures, Prentice-Hall, Inc., New Jersey, 1977, p. 447.

[12] Ibid., p. 455.

[13] ASME Section XI, Appendix A, 1992 Edition through Summer 1993 Addenda.

[14] Letter, RH Shell (TVA) to USNRC, "Browns Ferry Nuclear Plant (BFN), Sequoyah Nuclear Plant (SQN), and Watts Bar Nuclear Plant (WBN) - Response to Generic Letter 92-01 (Reactor Vessel Structural Integrity", Docket Nos. 50-259, 50-260, 50-296, 50-327, 50-328, 50-390, 50-391, 7/7/92

# APPENDIX A

## ADJUSTED REFERENCE TEMPERATURE (ART) CALCULATION

The ART is, according to Rev 2, a function of the initial $RT_{NDT}$, the shift, and a margin term. The shift in $RT_{NDT}$ is dependent on the chemistry (specifically copper and nickel) and fluence. The methods of Rev 2 are used to determine the ART; the procedure used depends on whether or not surveillance specimen data is available.

In order to re-evaluate the surveillance specimen program schedule, the ART for both the vessel itself and the specimens must be calculated. For Browns Ferry Unit 3, surveillance specimens have not been tested, which requires the procedure of evaluating ART without surveillance specimens, as described below.

The ART for each beltline material is given by the following equation:

$$ART = Initial\ RT_{NDT} + \Delta RT_{NDT} + Margin \tag{1}$$

Initial $RT_{NDT}$ is the reference temperature determined according to ASME Section III, Paragraph NB-2331 for the unirradiated material.

The shift in the reference temperature, $\Delta RT_{NDT}$, is determined by a combination of the chemistry and fluence as shown by Equation (2):

$$\Delta RT_{NDT} = CF * f^{(0.28-0.10\log f)} \tag{2}$$

The CF is the chemistry factor (dependent on the copper and nickel content) and is determined from the tables for weld and base material in Rev 2. The fluence, f, at any depth in the vessel wall, is determined by Equation (3),

$$f = f_{surf} * (e^{-0.24x}) \tag{3}$$

where $f_{surf}$ is the calculated neutron fluence at the vessel ID and x is the depth into the vessel measured from the inner (wetted) surface. For these calculations, the value of f (at 1/4T) used was 7.8 x $10^{17}$ n/$cm^2$, obtained from [7].

The Margin term is included to obtain the upper bound values of the ART. Since the Margin term provides upper bound values of the ART (which is a function of CF and fluence), it is unnecessary to add extra conservatism by using the upper bound fluence. Any uncertainty in the fluence is captured by the Margin term. The Margin term is given by Equation (4):

$$Margin = 2\sqrt{\sigma_I^2 + \sigma_\Delta^2} \tag{4}$$

where

$\sigma_I$ = standard deviation of the initial $RT_{NDT}$

$\sigma_\Delta$ = standard deviation for $\Delta RT_{NDT}$

The standard deviation for $\Delta RT_{NDT}$, $\sigma_\Delta$, is assumed to be 28°F for welds and 17°F for base metal, except that $\sigma_\Delta$ need not exceed 0.50 times the mean $\Delta RT_{NDT}$ [5]. The conservative nature of the initial $RT_{NDT}$ determination generally results in $\sigma_I$ being equal to zero.

Using Equations (1) through (4), the ART can be calculated for plants with no surveillance data, including Browns Ferry Unit 3.

*EXAMPLE CALCULATION*

To better illustrate the ART methodology, the following calculation was performed for the limiting BFN-3 vessel weld material (Electroslag Weld); this material's chemistry and initial $RT_{NDT}$ bound that for the weld material in the surveillance capsule. (The %Cu is 0.24 compared to the capsule material 0.11%; the %Ni is 0.37 compared to the capsule material 0.28%, and the initial $RT_{NDT}$ is 23.1°F compared to the capsule 10°F.) The data was obtained from [7] and [14]:

| | |
|---|---|
| Initial $RT_{NDT}$: | 23.1°F |
| Nickel: | 0.37% |
| Copper: | 0.24% |
| Peak Fluence: | $7.8 \times 10^{17}$ n/cm$^2$ (32 EFPY at 1/4T) |
| Wall Thickness: | 6.13 inches |

From Table 2 of Rev 2, the chemistry factor for this heat of material is 141. The fluence at the 1/4T depth, $7.8 \times 10^{17}$ n/cm$^2$, was used. The change in reference temperature, $\Delta RT_{NDT}$, is calculated according to Equation (2):

$$\Delta RT_{NDT} = 141 * 0.19^{(0.28-0.10 \log 0.19)}$$

$$\Delta RT_{NDT} = 141 * 0.166 = 51.8°F \approx 52°F$$

For the margin term, the standard deviation of the initial $RT_{NDT}$, $\sigma_I$, is 13°F as provided by [10]. The standard deviation for $\Delta RT_{NDT}$, $\sigma_\Delta$, is 28°F, as it is weld metal.

Therefore, using equation (1), the ART at 32 EFPY for the Electroslag Weld is:

$$ART = 23 + 52 + 58 = \underline{133°F}$$

This calculation was repeated for all of the vessel beltline materials. The results of the calculations for all the beltline materials and the surveillance capsule materials are shown in Table A-1. Figure A-1 is a plot of the ART against EFPY for the expected plant lifetime for the limiting (at EOL) vessel plate and weld materials.

| | | | |
|---|---|---|---|
| Low-Int Shell | | Low-Int Shell: | |
| Thickness = | 6.13 inches | 32 EFPY Peak I.D. fluence = | 1.1E+18 n/cm$^2$ |
| | | 32 EFPY Peak 1/4 T fluence = | 7.8E+17 n/cm$^2$ |
| Lower Shell | | Lower Shell: | |
| Thickness = | 6.13 inches | 32 EFPY Peak I.D. fluence = | 1.1E+18 n/cm$^2$ |
| | | 32 EFPY Peak 1/4 T fluence = | 7.8E+17 n/cm$^2$ |

| COMPONENT | I.D. | HEAT | %Cu | %Ni | CF | INITIAL RTndt | 32 EFPY Δ RTndt | σI | σΔ | MARGIN | 32 EFPY SHIFT | 32 EFPY ART |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PLATES: | | | | | | | | | | | | |
| Lower Shell | 6-145-4 | C3222-2 | 0.15 | 0.52 | 106 | 10 | 39.1 | 0 | 17.0 | 34.0 | 73.1 | 83.1 |
| Lower Shell | 6-145-7 | C3213-1 | 0.13 | 0.58 | 90 | -20 | 33.2 | 0 | 16.6 | 33.2 | 66.3 | 46.3 |
| Lower Shell | 6-145-12 | C3217-2 | 0.14 | 0.66 | 101.5 | -4 | 37.4 | 0 | 17.0 | 34.0 | 71.4 | 67.4 |
| Low-Int Shell | 6-145-1 | C3201-2 | 0.13 | 0.60 | 91 | -20 | 33.5 | 0 | 16.8 | 33.5 | 67.1 | 47.1 |
| Low-Int Shell | 6-145-2 | C3188-2 | 0.10 | 0.48 | 65 | -20 | 24.0 | 0 | 12.0 | 24.0 | 47.9 | 27.9 |
| Surveillance | | C3188-2 | 0.10 | 0.51 | 65 | -30 | 24.0 | 0 | 12.0 | 24.0 | 47.9 | 17.9 |
| Low-Int Shell | 6-145-6 | B7267-1 | 0.13 | 0.51 | 88 | -20 | 32.4 | 0 | 16.2 | 32.4 | 64.9 | 44.9 |
| WELDS: | | | | | | | | | | | | |
| Longitudinal | ESW* | | 0.24 | 0.37 | 141 | 23.1 | 51.8 | 13 | 25.9 | 58.0 | 109.8 | 132.9 |
| Surveillance | ESW** | | 0.11 | 0.28 | 81 | 10 | 29.8 | 0 | 14.9 | 29.8 | 59.7 | 69.7 |
| Circumference | D55733 | | 0.09 | 0.66 | 117 | -40 | 43.1 | 0 | 21.6 | 43.1 | 86.2 | 46.2 |

* ESW chemistry based on NRC SER that was issued in February 1997 for Commonwealth Edison Co.

* Specific weld heat chemistries are not available.

** Chemistry based upon NRC Letter 92-01

Table A-1 Browns Ferry Unit 3 RPV Beltline Material Data

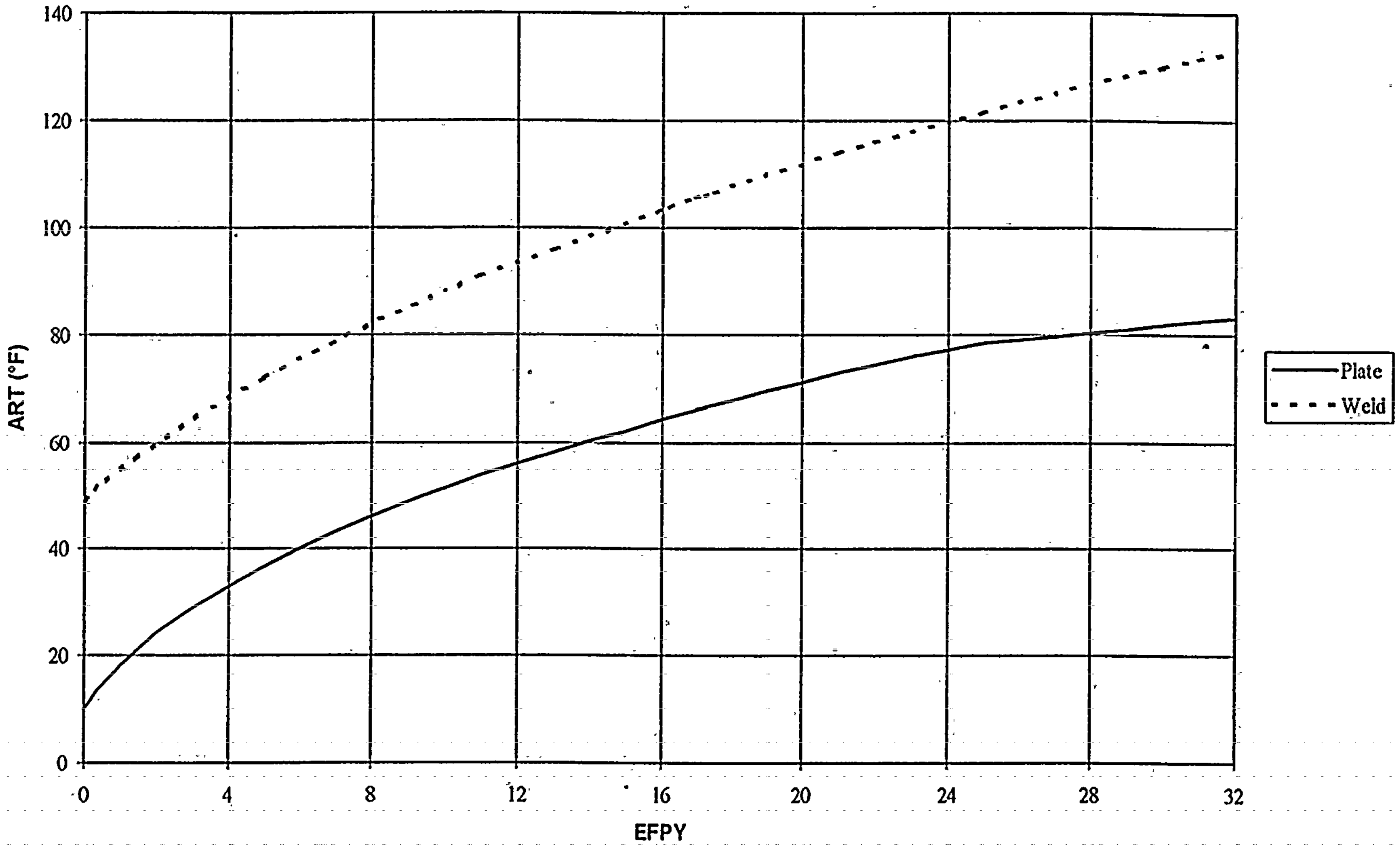


Figure A-1 ART vs. EFPY

ENCLOSURE 2
TENNESSEE VALLEY AUTHORITY
BROWNS FERRY NUCLEAR PLANT (BFN)
UNIT 3

PROPOSED REVISION TO THE UNIT 3 REACTOR PRESSURE
VESSEL MATERIAL SURVEILLANCE PROGRAM

COMMITMENT

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Material testing results from the SSP and/or the first Unit 3 capsule will be used to develop an appropriate schedule for the second surveillance capsule.