LMFBR Fuel Pin Cladding Transient Performance Capabilities: An Analysis of FCTT Data

**Prepared for
The U.S. Nuclear Regulatory Commission Under
Related Services Contract TDO 699 to the Prime
Contract E(45-1): 1830 with the Energy Research
and Development Administration**

**by
John W. Wald
Ira S. Levy**

March 1976

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ABSTRACT

Fuel Cladding Transient Tester (FCTT) data, from experiments being performed at Westinghouse Hanford Company - Hanford Engineering Development Laboratories (HEDL), has been evaluated to establish a basis for assessing the margin of safety provided by the fuel pin transient performance design criteria for Transient Overpower events (TOP).

These criteria, as presented in the Clinch River Breeder Reactor Plant Preliminary Safety Analysis Report, describe cladding temperature limits from PPS trip settings, residual strength values utilized in CDF rod integrity analyses, and incremental cladding strain limits for transients.

The FCTT data analyses indicate that:

- Most failures occur below the cladding temperature limits for upset (1450°F) and emergency (1600°F) events.
- Residual strength values less than those used in the CDF analysis (0.736 to 0.864 of unirradiated values) were observed (and for fluences less than one-third of goal exposures).
- Failures with incremental strain values below the design limit (0.1%) were observed and the scatter in these strain data is large.

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1.0 INTRODUCTION

This report is the result of work performed under Subtask B, Cladding Design Bases Evaluation, of Task 2: LMFBF Fuel and Control Rod Behavior, of the Fuel Rod Integrity Project. The work was performed under the joint sponsorship of the Divisions of Systems Safety and Project Management, Office of Nuclear Reactor Regulation, U.S. Nuclear Regulatory Commission.

The purpose of this report is to analyze recently available fuel pin transient performance data to satisfy two requirements:

- A) Provide NRC with a basis for assessing the margin of safety provided by the fuel pin transient performance design criteria for Transient Overpower (TOP) events presented in the Clinch River Breeder Reactor Plant Preliminary Safety Analysis Report (CRBRP PSAR)¹.
- B) Provide input to fuel rod failure criteria and failure location analyses being performed in other facets of this NRC project (Subtask D).

The fuel pin transient performance data to be analyzed are from Fuel Cladding Transient Tester (FCTT) experiments being performed at the Westinghouse Hanford Company - Hanford Engineering Development Laboratory (HEDL).^{2,3}

2.0 FCTT EXPERIMENTAL PROCEDURE AND DATA

2.1 Experimental Procedure

The FCTT system at HEuL was specifically designed to perform transient tests on reactor cladding. In this apparatus, controlled rapid specimen heating was provided by appropriately designed induction heating coils. Pressurization was accomplished with a low-volume argon gas system. The small gas volume in the specimen and FCTT system is intended to make the failure event more prototypic of a fuel-column cladding failure than would be found in a conventional burst test.³

The experimental concept used in these FCTT tests was to apply a predetermined stress to the fuel pin, heat it under controlled heating rates to failure, and then experimentally determine the failure temperature and incremental failure strain. Heating rates of 10°F/sec and 200°F/sec were selected as representative of the range of interest of transient overpower conditions for the Fast Flux Test Facility (FFTF). The two heating rates produce different amounts of thermal recovery and annealing, as well as impose different cladding strain rates, as anticipated in the various reactor transients.

The experimental procedure for the FCTT tests were as follows:

- A) The specimen was pressurized to approximately 80% of desired initial pressure while the specimen was at room temperature.
- B) The specimen was heated to the initial temperature of 700°F and the pressure was adjusted to the exact level desired.
- C) After the initial temperature and pressure were obtained, the specimen was heated at 10°F/sec or 200°F/sec until it failed.

The specimens used in the FCTT studies were standard 20% cold-worked 316 stainless steel, 0.230 inch O.D. X 0.015 inch wall X 2.45 inch nominal length. Specimens were taken from unirradiated lots as well as from fuel pins irradiated in EBR-II.

2.2 Data Base

The data base available to date from FCTT on irradiated² and unirradiated³ specimens are presented in Tables I and II, respectively. Since the CRBRP fuel pin performance criteria and accident scenarios relate to pin failure in the core (fueled) region of the fuel pin, data from the fueled and plenum (unfueled) regions of the irradiated pins are presented separately in this report in Tables IA and IB, respectively.

Fuel column height in EBR-II runs was 13.5 inches; therefore, all sections taken above this distance from the bottom of the fuel, as well as those sections taken below the fuel bottom, are considered plenum. All samples were taken from either NUMEC-F, PNL-10, or PNL-11 pins.

Specimen wastage is noted in Tables IA and IB; these are due to sodium corrosion on the O.D., fuel attack on the I.D., and wear marks on the O.D. from the wire wrap. These data will be denoted by an asterisk but will be given full weight when they are graphically presented later in this report since there is no reason to consider them as representing anything other than prototypic of fuel rod performance to be expected in CRBRP and commercial reactors.

3.0 DATA ANALYSIS RELATIVE TO CRPRP DESIGN CRITERIA

The CRBRP PSAR presents three criteria relative to fuel pin TOP performance: strength, temperature, and cladding strain. The analyses here will deal with the FCTT data relative to these criteria.

3.1 Temperature

3.1.1 PSAR Presentations

The temperatures of 1450°F and 1600°F are utilized in the PSAR to describe the maximum cladding temperature for upset and emergency events, respectively, for any extended period of time, allowed by Plant Protection System trip subsystems and their settings.^{4,5}

3.1.2 FCTT Data Analysis

Figures 1 and 2 illustrate the relationship between plenum and fueled data for net sectional hoop stress versus failure temperature. The solid line in each figure represents the unirradiated data appearing in Table II. As indicated by the banded regions in these figures, the performance of specimens from fueled and plenum regions differ. While the plenum region's behavior tended to be quite similar to that of the unirradiated material, the fueled region material indicated, overall, a decrease in failure temperature over the unirradiated for given values of failure stress. This trend tended to be most apparent in the 10°F/sec rate (Figure 1), where reductions in failure temperature approached 450°F at higher temperatures and lower stresses. For 200°F/sec (Figure 2), a lesser reduction in failure temperature for a given failure stress occurs; the maximum differential here is about 100°F.

For both ramp rates, failure temperatures of the fueled specimens occur well below 1600°F, with failures observed at temperatures as low as 1005°F. At 10°F/sec, 100% of the fueled specimen failed below 1450°F; at 200°F/sec, 67% failed below 1600°F and 53% failed below 1450°F.

3.2 Strength

3.2.1 PSAR Presentation

The Cumulative Mechanical Damage Function (CDF)⁶ monitors clad integrity through steady-state and transient operation. CDF includes a function, R_0 , describing the relative residual strength of the unirradiated cladding subjected to prior strain that is utilized in the PSAR fuel rod integrity analysis.⁷ Relative residual strengths for unirradiated cladding of from 0.736 to 0.864 were used to evaluate CDF. The PSAR states that a preliminary analysis indicates that the fuel rod design life can be achieved with a 74 day margin in life.⁸

3.2.2 FCTT Data Analysis

Utilizing data in Tables IA and II, irradiated fuel rod cladding transient strength has been examined in terms of percent of unirradiated load bearing capability. This quantity, which is defined as the ratio of irradiated failure stress to unirradiated failure stress, taken at similar failure temperatures, is equivalent in concept to the "relative residual strength" used in the PSAR. Since hoop stress is an experimental input variable in FCTT, failure temperature will become the dependent variable; and, for a given failure temperature, the ratio of stress at failure of irradiated specimens to that for unirradiated specimens will reflect the fraction of unirradiated load bearing capability remaining in the irradiated specimens.

Figures 3 and 4 present data for percent of unirradiated load bearing capability versus steady-state midwall irradiation temperature. These data indicate decreased load-bearing capability as a result of irradiation and temperature ramp-rate. The low temperature-ramp (10°F/sec) reduces irradiated specimen load-bearing capability to values as low as 40% of unirradiated values, with the best straight line ranging from 50-70% of unirradiated values. The higher temperature-ramp (200°F/sec) resulted in a lesser reduction in irradiated specimen load bearing capability than that seen for the 10°F/sec temperature-ramp. While reductions to values as low as 45% were also observed, the best straight line ranged from 95-110% of unirradiated values.

3.3 Ductility

3.3.1 PSAR Presentation

The allowed incremental strain during all operational (upset) and worst minor incident (emergency) events at a 2-to-1 stress biaxiality is a maximum of 0.1%. (The total allowed strain for steady-state and transient operations is less than 0.3%,⁹ while that allowed for steady-state operation only is less than 0.2%.¹⁰)

3.3.2 FCTT Analysis

Data in Tables IA and IB were analyzed in terms of the steady-state midwall irradiation temperature to assess the incremental failure strain during transients relative to axial rod position; these data are presented in Figures 5 and 6. The lower failure strains of the fueled regions of the rod is evident at both ramp-rates for all midwall irradiation temperatures.

Least squares linear fit of the fueled data are presented for the two ramp rates in Figures 7 and 8. At 10°F/sec (Figure 7), a number of data points can be seen to fall below the 0.1% additional strain allowed during transient. Moreover, the lower limit established by the deviation of the data about the line indicates that failures will occur below 0.1% additional strain at steady-state irradiation temperatures as high as 1000°F at these fluence levels.

At the 200°F/sec heating rate (Figure 8), the least squares fit indicates that higher strain values are experienced for all midwall irradiation temperatures; however, the data scatter is larger as well. A 95% confidence limit analysis indicates that failure could be expected to occur below the 0.1% additional strain limit up through an 1100°F steady-state irradiation temperature at these fluence levels (zero added strain is within the lower limit).

4.0 DISCUSSION AND CONCLUSIONS

4.1 FCTT Data Analysis Relative to CRBRP Design Criteria

The FCTT data indicate reason to question with the CRBRP fuel rod design performance criteria. These criteria have been compared with experimentally-determined cladding properties and variances have been noted.

4.1.1 Temperature

The majority of specimens failed at temperatures below those described in the PSAR as the maximum expected to be allowed for upset and emergency events (1450°F and 1600°F respectively). The basis for the protection system setpoints should be examined.

4.1.2 Strength

Percent of unirradiated load bearing capability of fuel rods after irradiation to only 1/3 goal CRBRP exposure,* is significantly less than the "residual strength" values used to verify CDF, and upon which a fuel rod design life was predicted to be achieved with a 74-day margin in life. Moreover, since continued residence time of fuel pins in-reactor towards relevant cladding fluences would be expected to cause further degradation to the cladding by irradiation and sodium- and fuel-attack, further reductions in load-bearing capabilities would be expected. This would increase the disparity between experimental results and those values used in the CDF analysis of fuel rod design life. The basis for these residual strength values should be examined.

4.1.3 Ductility

At 10°F/sec, failures occur at less than the specified transient strain limit (0.1% additional strain) for steady-state rod temperatures up to 900°F and the lower 95% confidence limit indicates failures can be expected at less than 0.1% strain up through the 1000°F irradiation temperature. At 200°F/sec, the lower 95% confidence limit indicates failures can be expected below 0.1% strain for steady-state rod temperatures up through 1000°F. These data are for low cladding exposures ($\leq$ 1/3 goal CRBRP burnups*). The basis for the $\leq$ 0.1% transient strain limit should be examined.

*Goal CRPRP burnup is 80,000 MWD/T.

4.2 FCTT Analysis Relative to Fuel Rod Failure Criteria and Failure Location Studies

The analysis provides an independent data base for a "strain-to-failure" fuel rod failure criteria through Figures 7 and 8. Best straight lines and limit bands are provided. Failure strain varies with axial location at the 10°F/sec heating ramp rate but not at 200°F/sec; the magnitude of the failure strains are larger at the 200°F/sec ramp rate.

REFERENCES

1. Clinch River Breeder Reactor Plant - Preliminary Safety Analysis Report, issued by Project Management Company, April 1975.
2. C. W. Hunter, G. D. Johnson and R. L. Fish, "Mechanical Properties During Simulated Overpower Transients of Fast Reactor Cladding Irradiated from 700-1100°F," HEDL-TME 75-28, September 1975.
3. C. W. Hunter, R. L. Fish and J. J. Holmes, "Mechanical Properties of Unirradiated Fast Reactor Cladding During Simulated Overpower Transients," HEDL-SA 770, October 1974.
4. CRBRP - PSAR, p. 15.1-74.
5. ibid, p. 4.2-42.
6. ibid. p. 15.1-50.
7. ibid, p. 15.1-54 through 15.1-62
8. ibid, p. 4.2-45
9. ibid, p. 4.2-6
10. ibid, p. 4.2-5

TABLE I-A. Irradiated Cladding Burst Test Results from
NUMEC and PNL Pins - Fueled Region Data

Specimen I.D. Number	Distance Above Fuel Bottom, in.	Midwall Temperature °F	Fluence [$>1\text{MeV}$] $\text{ft} \times 10^{22} \text{ n/cm}^2$	Gas Pressure, PSI	Transient Heating Rate, °F/sec	Nominal Hoop Stress, KSI	Maximum Cladding Wastage, mils	Net Section Hoop Stress, KSI	Diametral Failure Strain, %	Failure Temperature, °F
NUMEC-F										
N-005: D	4.5 - 7.0	825 - 870 (848)	3.1 - 3.2 (3.05)	4,000	10	28.8	0	28.8	0.15	1325
N-035: B	(-0.5) - 2.0	700 - 785 (743)	2.0 - 2.7 (2.35)	6,000	10	43.2	0.8	45.6	0.06	1005
N-027: D	2.0 - 4.5	785 - 840 (813)	2.6 - 3.0 (2.80)	6,000	10	43.2	0.4	44.4	0.15	1180
N-035: C	2.0 - 4.5	785 - 850 (818)	2.7 - 3.1 (2.90)	6,000	10	43.2	0	43.2	0.16	1170
N-035: D	4.5 - 7.0	850 - 910 (880)	3.1 - 3.2 (3.05)	6,000	10	43.2	0	43.2	0.08	1125
N-035: F	9.5 - 12.0	960 - 1000 (980)	2.9 - 2.4 (2.65)	6,000	10	43.2	0.5	44.7	0.13	1175
N-159: D	2.0 - 4.5	785 - 845 (815)	2.5 - 3.0 (2.75)	10,000	10	72.0	0.1	72.5	0.13	1020
N-027: F	7.0 - 9.5	900 - 955 (928)	3.1 - 2.8 (2.95)	10,000	10	72.0	0.2	73.0	0.35	1175
N-005: B	(-0.5) - 2.0	700 - 775 (738)	2.0 - 2.7 (2.35)	13,500	10	97.2	0	97.2	0.25	1040
PNL-10, PNL-11										
10-63: G	2.0 - 4.5	770 - 855 (813)	3.6 - 4.1 (3.85)	4,000	10	28.8	0(1)	28.8	0.04	1395
10-23: I	4.0 - 6.5	825 - 885 (855)	3.8 - 4.0 (3.90)	4,000	10	43.2	0(1)	43.2	0.05	1095
10-63: M	8.94 - 11.44	890 - 925 (908)	4.1 - 3.4 (3.75)	4,000	10	43.2	2.7(2)	43.2	0.21	1105
11-20R: L	8.75 - 11.25	925 - 965 (945)	2.4 - 2.0 (2.20)	6,000	10	43.2	0	43.2	0.17	1165
11-12: G	3.0 - 5.5	797 - 840 (819)	2.3 - 2.5 (2.40)	10,000	10	72.0	0	72.0	0.12	1070
NUMEC-F										
N-005: E	7.0 - 9.5	870 - 910 (890)	3.2 - 2.9 (3.05)	2,500	200	18.0	0	18.0	0.80	1940
N-005: C	2.0 - 4.5	775 - 825 (800)	2.7 - 3.1 (2.90)	4,000	200	28.6	0	28.8	0.40	1670
N-035: E	7.0 - 9.5	910 - 960 (935)	3.2 - 2.9 (3.05)	4,000	200	28.8	0	28.8	0.25	1625
N-159: C	(-0.5) - 2.0	700 - 785 (743)	1.8 - 2.5 (2.15)	6,000	200	43.2	0.2	43.8	0.30	1520
N-035: H	12.5 - 15.0	945 - 920 (935)	2.2 - 1.6 (1.90)	6,000	200	43.2	0	43.2	0.18	1490
N-070: D	0.5 - 3.2	750 - 812 (781)	2.1 - 2.7 (2.40)	10,000	200	72.0	0	72.0	0.20	1210
N-027: E	4.5 - 7.0	840 - 900 (870)	3.0 - 3.1 (3.05)	10,000	200	72.0	0	72.0	0.40	1310
N-027: H	12.0 - 14.5	990 - 975 (983)	2.3 - 1.6 (1.95)	10,000	200	72.0	2.2	84.4	0.70	1205
N-070: N	12.0 - 14.5	1000 - 990 (995)	2.2 - 1.6 (1.90)	10,000	200	72.0	3.9	97.3	0.29	1070
N-035: H	12.5 - 15.0	1000 - 990 (995)	2.2 - 1.6 (1.90)	10,000	200	72.0	0.8	76.1	0.22	1140
N-027: C	(-0.5) - 2.0	700 - 785 (743)	1.9 - 2.6 (1.25)	13,500	200	97.2	0	97.2	0.40	1120
PNL-10, PNL-11										
10-63: O	12.44 - 14.94	940 - 920 (930)	3.1 - 2.5 (2.80)	2,500	200	18.0	0	18.0	0.96	1980
10-23: H	1.5 - 4.0	770 - 825 (798)	3.2 - 3.8 (3.50)	4,000	200	28.8	0	28.8	0.65	1770
10-23: M	8.5 - 11.0	925 - 980 (953)	3.9 - 3.4 (3.65)	4,000	200	28.8	2.5(1,2)	28.8	0.20	1400
11-12: K	7.5 - 10.0	870 - 905 (888)	2.5 - 2.2 (2.35)	10,000	200	72.0	0	72.0	0.17	1230

NOTES:

- (1) Sample Sectioned but did not find failure site.
(2) Did not fail at wear mark.

TABLE I-B. Irradiated Cladding Burst Test Results from
NUMEC and PNL Pins - Plenum Region Data

Specimen I.D. Number	Distance Above Fuel Bottom, in	Midwall Temperature °F	Fluence [E>1MeV] φt x 10 ²² n/cm ²	Gas Pressure, PSI	Transient Heating Rate, °F/sec	Nominal Hoop Stress, KSI	Maximum Cladding Wastage, mils	Net Section Hoop Stress, KSI	Diametral Failure Strain, %	Failure Temperature, °F
NUMEC-F										
N-035: I	15.0 - 17.5	990	1.6 - 1.2 (1.40)	4,000	10	28.8	0	28.8	0.40	1630
N-005: N	33.6 - 36.1	920	0.1 (0.10)	6,000	10	43.2	5.5	68.2	0.23	1420
N-035: K	20.0 - 22.5	990	0.8 - 0.5 (0.65)	6,000	10	43.2	0	43.2	0.70	1505
N-035: J	17.5 - 20.0	900	1.2 - 0.8 (1.00)	6,000	10	43.2	0	43.2	1.00	1540
PNL-10, PNL-11										
10-63: B	(-7.0) - (-4.5)	700	1.0 - 1.5 (1.25)	6,000	10	43.2	0	43.2	0.65	1540 ⁽¹⁾
10-63: D	(-2.0) - 0.5	700	2.1 - 3.1 (2.60)	6,000	10	43.2	0.7 ⁽²⁾	45.3	0.30	1330
10-63: Q	17.44 - 19.94	920	1.7 - 1.2 (1.45)	6,000	10	43.2	2.1	50.2	0.30	1485
10-23: C	(-5.5) - (-3.0)	700	1.3 - 1.8 (1.55)	10,000	10	72.0	0	72.0	0.54	1340
11-20R: P	13.74 - 16.25	960	1.5 - 1.1 (1.30)	10,000	10	72.0	0	72.0	0.65	1325
NUMEC-F										
N-027: I	14.5 - 17.0	975	1.7 - 1.2 (1.45)	2,500	200	18.0	0	18.0	0.90	1920
N-005: K	20.0 - 22.5	920	0.8 - 0.6 (0.70)	4,000	200	28.8	5.2	44.1	0.80	1705
N-005: J	17.5 - 20.0	920	1.2 - 0.8 (1.00)	4,000	200	28.8	4.8	38.6	0.60	1710
N-035: N	33.6 - 36.1	990	0.1 (0.10)	4,000	200	28.8	0	28.8	0.70	1820
N-035: M	31.1 - 33.6	990	0.2 - 0.1 (0.15)	6,000	200	43.2	0	43.2	0.60	1600
N-159: M-2	15.0 - 17.2	990	1.5 - 1.1 (1.30)	6,000	200	43.2	0	43.2	0.70	1680
PNL-10, PNL-11										
10-63: C	(-4.5) - (-2.0)	700	1.5 - 2.1 (1.80)	4,000	200	28.8	0	28.8	0.56	1890
10-23: S	13.94 - 16.44	995	2.4 - 1.8 (2.10)	6,000	200	43.2	4.4	55.9	0.35	1550
10-63: P	14.94 - 17.44	919	2.5 - 1.7 (2.10)	10,000	200	72.0	1.9	82.5	0.26	1270
10-23: B	(-8.0) - (-5.5)	700	0.8 - 1.3 (1.05)	13,500	200	97.2	0	97.2	0.69	1230
10-23: O	(-3.0) - (-0.5)	700	1.8 - 2.6 (2.20)	13,500	200	97.2	0	97.2	0.54	1320

NOTES:

(1) Estimated.

(2) Sample failed adjacent to Swagelok; many inner surface cracks 0.7 mils deep which were not wastage.

Table II Unirradiated Cladding Burst Test Results

Speciman Identification	Gas Pressure psi	Hoop Stress ksi	Transient Heating Rate °F/sec	Diametral Strain %	Termination or Failure Temp., °F
28	180	1.30	10	0.7*	2385*
30	450	3.24	10	2.4*	2300*
67	1,000	7.20	10	6.3*	2090*
52	1,000	7.20	10	6.7	2045
	1,000	7.20	10	8.2*	2055*
53	1,000	7.20	10	4.3	2030
	1,000	7.20	10	7.4*	2050*
68	2,500	18.0	10	7.4*	1870*
48	2,500	18.0	10	4.2	1835
	2,500	18.0	10	8.2*	1860*
50	2,500	18.0	10	2.6	1820
51	2,500	18.0	10	1.3	1800
49	2,500	18.0	10	0.60	1760
59	4,000	28.0	10	6.6*	1720*
69	4,000	28.8	10	5.2*	1720*
80	4,000	28.8	10	5.0*	1710*
47	6,000	43.2	10	4.0*	1570*
43	10,000	72.0	10	1.5*	1340*
46	10,000	72.0	10	0.75	1310
44	10,000	72.0	10	0.40	1290
45	10,000	72.0	10	0.20	1250
81	12,500	89.9	10	0.61*	1130*
42	13,500	97.2	10	0.9*	1030*
76	14,300	103.0	10	0.65*	830*
75	15,350	110.5	10	0.39*	490*
74	15,800	113.8	10	0.43*	490*
37	180	1.30	200	0.22	2500
	180	1.30	200	0.4*	2510*
73	1,000	7.20	200	4.3*	2260*
38	1,000	7.20	200	0.5	2115
	1,000	7.20	200	3.3*	2150*
39	1,000	7.20	200	0.2	1910
70	2,500	18.0	200	4.3*	1960*
65	2,500	18.0	200	4.3*	1930*
35	2,500	18.0	200	2.2	1870
	2,500	18.0	200	3.8*	1935*
71	4,000	28.8	200	3.7*	1850*
61	4,000	28.8	200	3.4*	1835*
78	4,100	29.5	200	2.7*	1790*
36	6,000	43.2	200	1.0	1660
	6,000	43.2	200	1.9*	1680*
72	6,000	43.2	200	2.3*	1635*
55	10,000	72.0	200	0.3	1390
	10,000	72.0	200	0.9*	1420*
57	10,000	72.0	200	0.2	1300
79	12,100	87.1	200	0.43*	1200*
40	13,500	97.2	200	0.25	1070
	13,500	97.2	200	0.7*	1115*
77	14,200	102.5	200	0.48*	830*

*Indicates failure ductility and temperature for specimen which failed.

FIGURE 1. FCTT: Net Hoop Stress versus Failure Temperature
(Heating Rate - 10°F/sec)

FIGURE 2. FCTT: Net Hoop Stress versus Failure Temperature
(Heating Rate = 200°F/sec)

FIGURE 3. Percent of Unirradiated Load Bearing Capability versus Average Midwall Irradiation Temperature (Heating Rate = 10°F/sec)

FIGURE 4. Percent of Unirradiated Load Bearing Capability versus Average Midwall Irradiation Temperature (Heating Rate = 200°F/sec)

FIGURE 6. FCTT: Failure Strain versus Average Midwall
 Irradiation Temperature (Heating Rate = 200°F/sec)

FIGURE 7. Data Statistics Relative to Design Criteria Failure Strain versus Average Midwall Irradiation Temperature (Heating Rate = 10°F/sec)

FIGURE 8. Data Statistics Relative to Design Criteria Failure Strain versus Average Midwall Irradiation Temperature (Heating Rate = 20°F/sec)

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