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POSTIRRADIATION EVALUATION OF ZIRCALOY-2

PRTR PRESSURE TUBES - PART III

JANUARY 1965

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POSTIRRADIATION EVALUATION OF ZIRCALOY-2 PRTR PRESSURE TUBES - PART III

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POSTIRRADIATION EVALUATION OF ZIRCALOY-2 PRTR PRESSURE TUBES - PART III

INTRODUCTION

An additional three Zircaloy-2 pressure tubes have been discharged from the Plutonium Recycle Test Reactor (PRTR), and specimens from two of these tubes and from other tubes have been burst tested since the last status report (1) was written. Also, irradiated and unirradiated specimens of PRTR Zircaloy-2 pressure tubes have been used for room temperature crack propagation tests. The results of vacuum fusion analyses for hydrogen content of specimens taken from all of the discharged PRTR Zircaloy-2 pressure tubes have been received.

The collected data of this and the previous two reports (1, 2) are sufficient, technically, to support a new criteria for PRTR Zircaloy-2 pressure tube selection for destructive examination. The new criteria scope will include neutron exposure (as do the present criteria), (3) crack propagation, notch sensitivity, and hydrogen concentration information.

The testing is described and discussed in this report. The objective of the report is to present the technical basis for new criteria of tube selection for destructive examination.

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(1) M. C. Fraser. Postirradiation Evaluation of Zircaloy-2 PRTR Pressure Tubes - Part II, HW-83164. September 1964.

(2) L. J. Defferding. Postirradiation Evaluation of Zircaloy-2 PRTR Pressure Tubes - Part I, HW-73698 REV. November 1962.

(3) R. W. Porter, Chairman. Highlights - Twelfth Meeting - Technological Hazards Council September 11-13, 1963.

SUMMARY

PRTR Surveillance Program work performed and information obtained since the last status report is reported. In addition to more burst test strength and circumferential elongation data, zirconium hydride concentration values from all tubes examined and crack propagation data for irradiated specimens are presented.

The burst test strength data show that strength increases with neutron exposure, and they indicate that this trend will not be substantially changed by doubling the neutron exposure.

The burst test circumferential elongation data show decreasing elongation values with increasing neutron exposure. The curves indicate that a factor of two increase in neutron exposure will produce a small additional ductility decrement.

Zirconium hydride concentration data indicate generally low levels but at flaws high concentrations (300 to 500 ppm maximum) have been found.

Crack propagation data indicate that neutron irradiation of 5 x 10^{20} nvt has no effect on critical crack lengths. The indicated PRTR operational critical crack length is about 10 in.

The above conclusions are bases of criteria for selection of PRTR Zircaloy-2 pressure tubes for destructive examination.

REPORT

PRTR Tube 6079 was discharged from Channel 1354 on March 3, 1964, having an average exposure of 326.5 MWd which is, because of the types of fuel elements which resided in this tube, 9.47 x 10^{20} fast (E > 1 MeV) nvt. Selection of Tube 6079 to be the twelfth destructively examined was based upon the number of fret marks observed during in-reactor monitoring on the inside surface of the tube, and the tube's exposure. Of the fret marks observed, three had depths of 10 to 15 mils. They had been formed by fretting corrosion at the fuel element supports.

Two 20 in. long pieces of this tube were pressurized to failure at room temperature. The fret marks mentioned above were on these pieces. The hoop strengths at maximum pressures sustained were 108, 600 and 124, 000 psi. The piece with the lower strength had annealed microstructure and it displayed 12% circumferential elongation and 9 to 18% reduction in wall thickness. The other piece had cold worked microstructure and it displayed 7% circumferential elongation and 3 to 14% reduction in wall thickness.

Vacuum fusion analysis of samples from both burst specimens indicated that the metal in the region of the burst origin had 70 to 80 ppm hydride; whereas, at the ends of the specimens the hydride concentration was 25 to 40 ppm.

The above evidence indicates that the combination of fret marks and hydride concentration determined the burst origins of these two specimens. Their burst strength values indicate that reduction in strength due to fret marks and the hydride was negligible. The circumferential elongation and the reduction in wall thickness values indicate ductility.

Tube 5526 was discharged from Channel 1558 on October 10, 1964, because of the presence of a large unclassified flaw on the inside surface. The flaw was discovered by in-reactor monitoring at 7 ft 11 in. from the flange. The examination of this flaw and its results have been reported.(4) The findings were:

- The flaw had been formed in the tube prior to its insertion into the PRTR reactor.
- Metallography indicated that hydride concentration in the metal surrounding the flaw was normal—less than 50 ppm.
- The flaw was 0.36 in. long, 0.053 in. wide, and 0.045 in. thick. The thickness was approximately equally distributed above and below the inside surface of the tube.

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(4) M. C. Fraser. Examination of Flaws in PRTR Zircaloy-2 Pressure Tubes, HW-84440. October 14, 1964.

- The flaw was football shaped.
- The flaw was partially filled with a white nonmetallic substance which chemical analysis indicated to be zirconium dioxide.

Tube 6084 was discharged from Channel 1253 on August 25, 1964. It had an average exposure of 479.4 MWd (1.4×10^{21} fast ($E > 1$ MeV) nvt. A piece of this tube, taken from the region having received the greatest neutron exposure, was burst tested at room temperature. The piece sustained a maximum pressure of 12,490 psig and the calculated Lamé hoop stress for this pressure was 142,600 psi. The specimens displayed about 6% hoop elongation. Postburst test examination of this specimen is not completed.

Figure 1 shows curves relating burst test hoop strength to fast ($E > 1$ MeV) neutron exposure of irradiated specimens of Zircaloy-2 pressure tubes. The curves show that the total PRTR reactor environment is increasing the burst test hoop strength. The most recently obtained values are shown. They indicate that the trend of strength increase with increased neutron exposure is continuing. The strength data indicate that the hoop strength of burst test specimens has become indistinguishable at exposures of the order of 10^{21} nvt with respect to microstructure.

The burst test hoop elongation curves of Figure 2 show a gradual value decrease with increasing exposure. At room temperature the values for annealed material are indicated to be decreasing more rapidly than the values for cold-worked material. The most recently obtained values are shown. The room temperature values indicate no change in the trend, but the elevated temperature value indicates significant decrease.

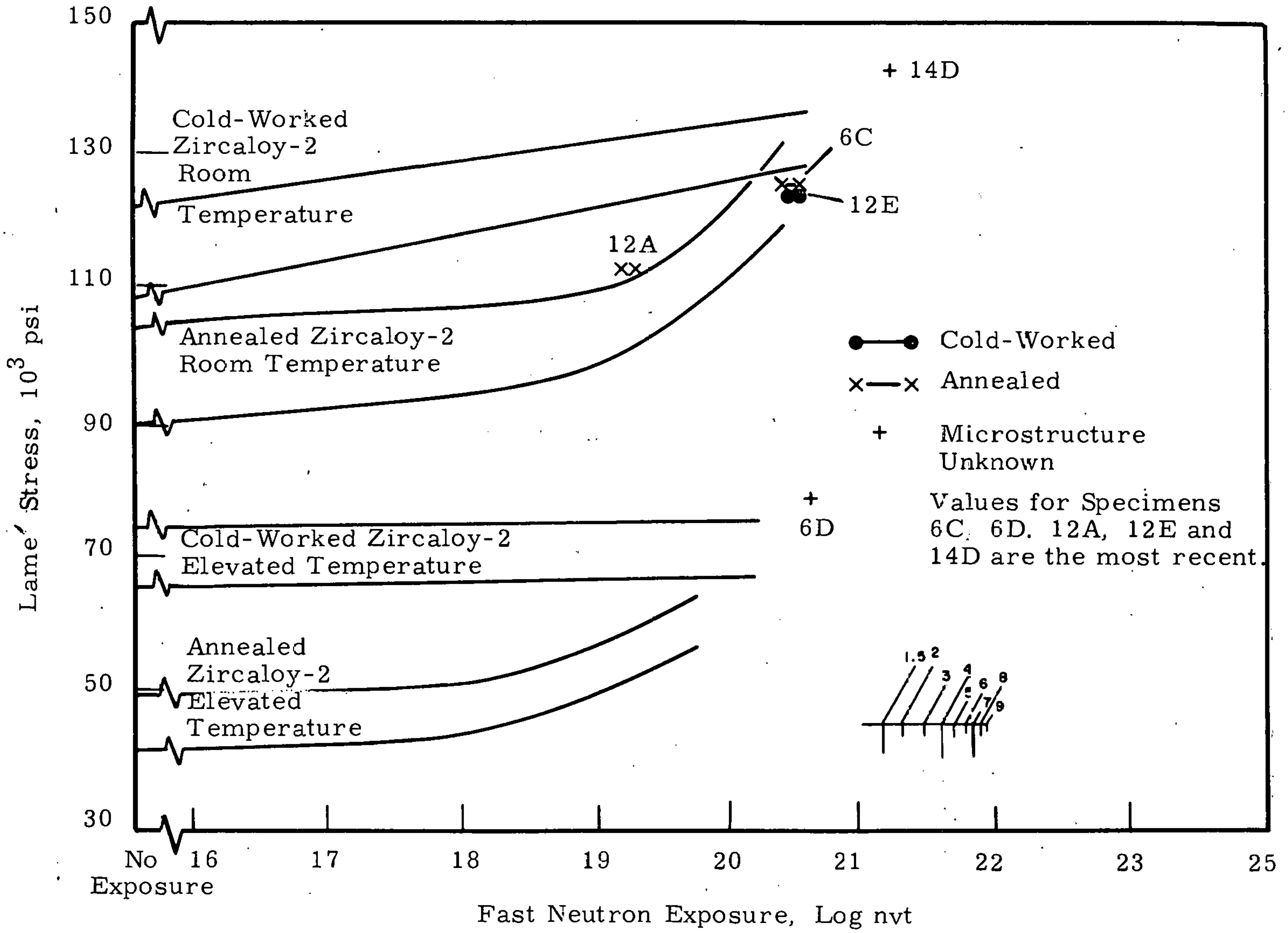

FIGURE 1

Hoop Strength and Fast Neutron Exposure of PRTR Zircaloy-2 Pressure Tubes

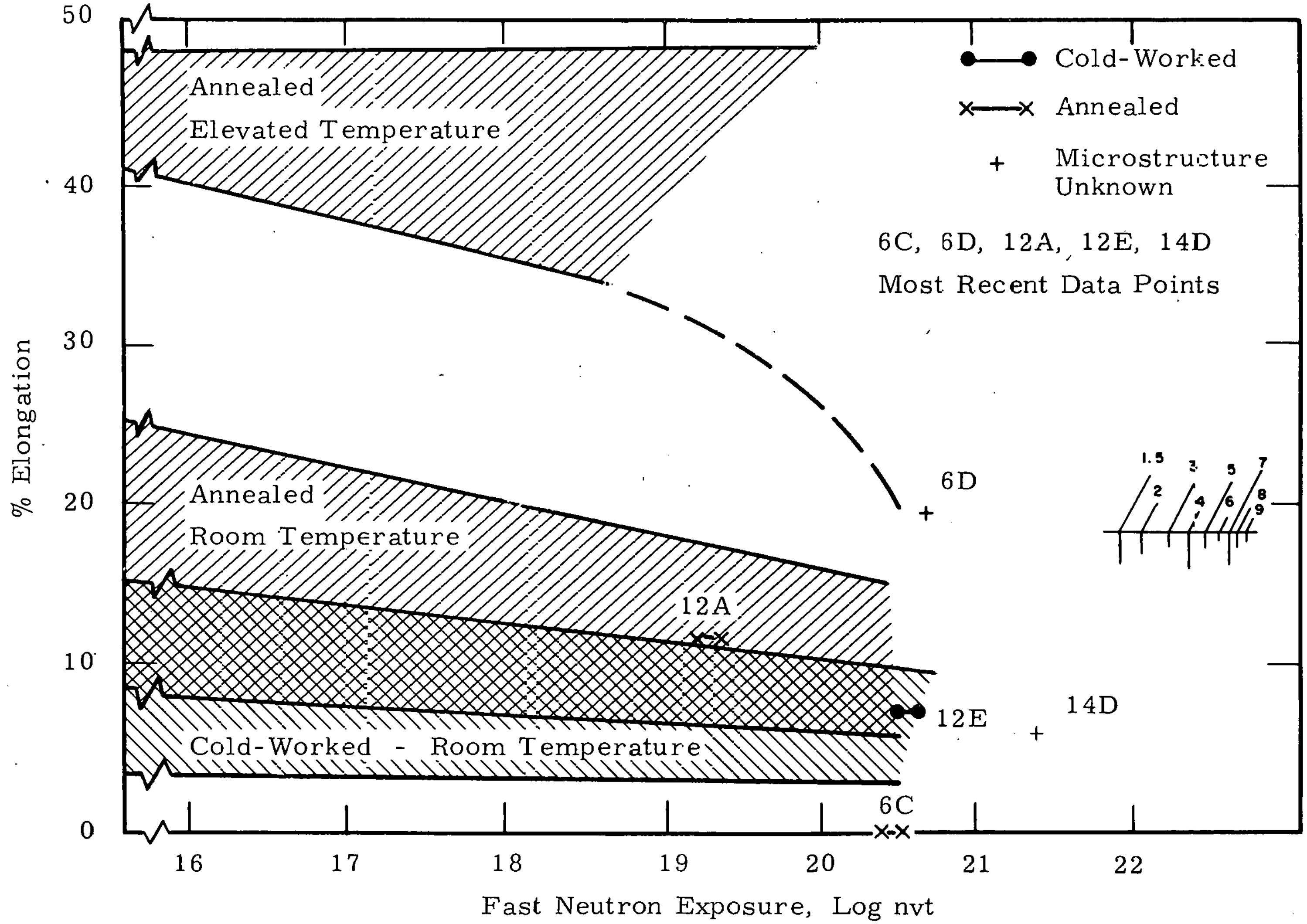

FIGURE 2

Hoop Elongation and Fast Neutron Exposure of PRTR Zircaloy-2 Pressure Tubes

A method for measuring crack propagation characteristics of Zircaloy-2 tubes has been developed.(5) The method involves milling of a slot in the wall of a burst test specimen. The slot dimensions are usually 1/16 in. wide by 80% of the wall thickness deep, and the slot length is dictated by the desired crack length. The crack is produced by pressurizing the burst test specimen to failure of the thin area at the base of the slot. A compressible rubber gasket assembly is then placed inside the burst test specimen and compressed until the crack is sealed. Upon pressurization of the specimen, the crack is caused to propagate. Pressure equalization on either side of the gasket assembly is achieved by a hole through the compressing bolt.

By this method, 11 specimens of PRTR Zircaloy-2 pressure tubes have been tested. Four of these had cold-worked microstructure and seven had annealed microstructure. Three cold-worked specimens had been irradiated to exposures of 4.5, 5.5, and 6×10^{20} nvt. Three annealed specimens had been irradiated also to exposures of about 2×10^{20} nvt. The five unirradiated specimens consisted of four annealed and one cold-worked. The range of crack lengths used for these tests was 0.3 to 3.0 in. All tests were done at room temperature. The results of the tests indicate that the crack propagation characteristics of these tube specimens can be described by:

$$\text{Stress (Crack Length)}^{N} = \text{Constant}$$

where N has a value between 0.6 and 0.66, and the constant has a value of about 43,500.

Figure 3 is a log-log plot of the data obtained. Mid-wall stress values were calculated assuming the absence of the "slot-crack." Figure 3 also shows some to the data obtained by R. C. Aungst using KER Zircaloy-2 pressure tube specimens.

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(5) R. C. Aungst and L. J. Defferding. Crack Propagation Tests on Zircaloy-2 Reactor Pressure Tubing in Both Normal and Hydrided Conditions, HW-80567. April 23, 1964.

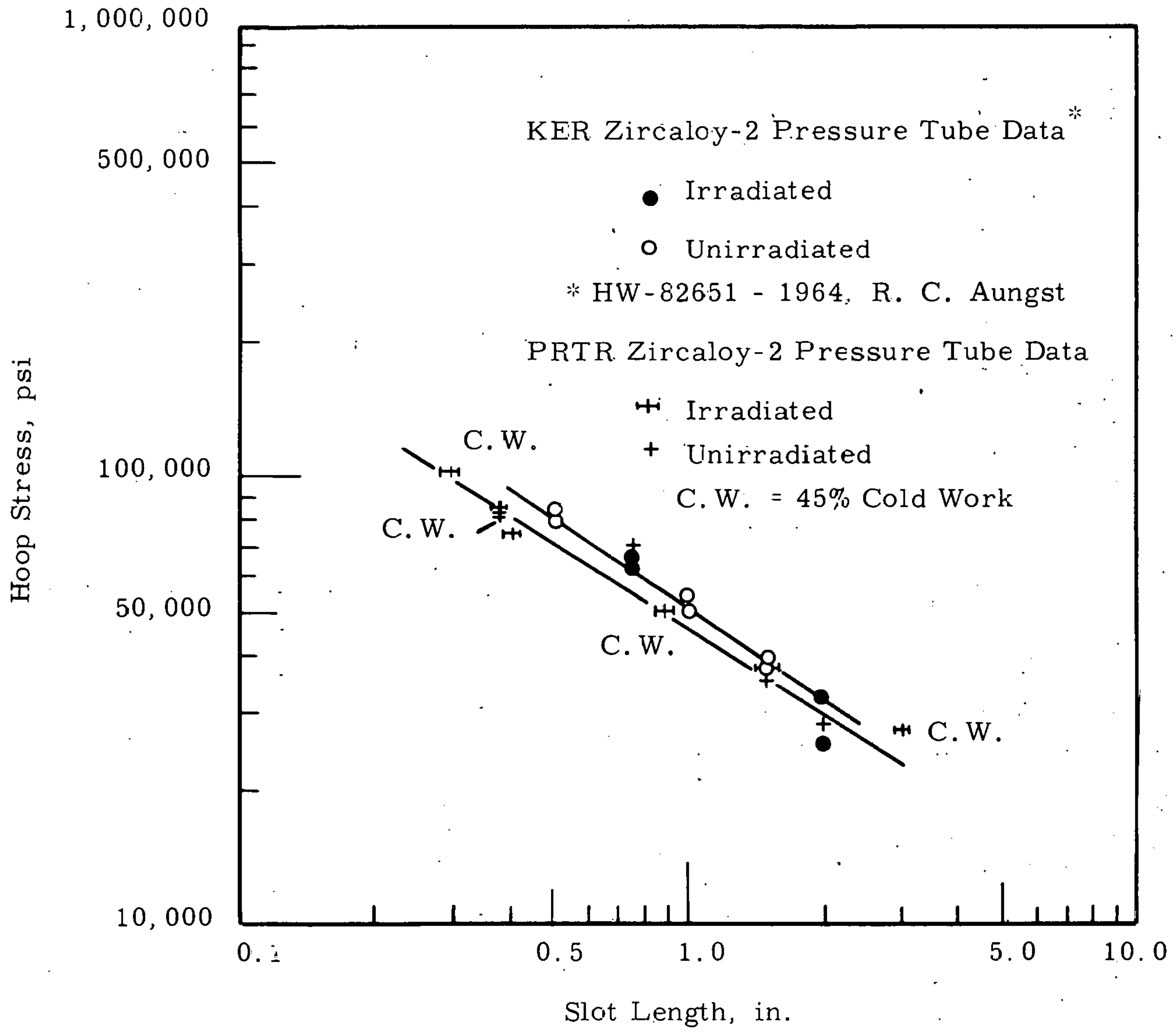

FIGURE 3

Crack Propagation Characteristics of PRTR Zircaloy-2 Pressure Tubes

Hydride analyses of specimens taken from burst test specimens have been performed. These data are arranged in Table I. The average value of all analyses listed in Table I, excluding high localized concentrations which are explained in the table foot notes, is 46 ppm, and the concentration range is 4 ppm to 112 ppm. The tubes most recently discharged are indicated by these data to have hydride concentrations comparable to unirradiated tubes.

TABLE I

ZIRCONIUM HYDRIDE CONCENTRATIONS

Tube	Hydride Concentration, ppm	Sample Location on Tube, Feet From Inlet
6100	ZrH_2 at BW Mark (a, b)	8
	ZrH_2 at UFES Mark (b)	13
	58	12-15 (e)
	24	15
	27	17
6061	ZrH_2 at UFES Mark (b)	13
	24-122 (c)	12-15 (e)
5529	ZrH_2 at LFES Mark (b)	5
	50	1 1/2
	56	11 3/4
5679	202	3 1/2
	27	5 1/2
	93	6 1/2
	200-300 by Metallography	6 1/2
	78	7 3/4
	74 and 86	9 1/2
	84	11 1/2
	112	13 1/2

TABLE I (Contd.)

Tube	Hydride Concentration, ppm	Sample Location on Tube, Feet From Inlet
5702	52	8 1/4
	89	10 1/4
	30-40 (c)	12 1/4-14 1/2 (e)
5540	43	6 1/2
	26 and 39	9
	205 (d)	10 1/2-13 1/2 (e)
5537	-	-
0720	55	3-5 (e)
	6	5-7 1/2 (e)
	27	7 1/2
	35	9 1/3
	10-17 (c)	9 1/3-10 (e)
	40	10
	50-75 by Metallography	9 1/3-10 (e)
	69	11 3/4
	46	11 3/4-14 (e)
5683	15	3 3/4
	24 and 34	6 1/2-6 3/4 (e)
	38 and 69	7-7 1/4 (e)
	25 and 59	9
	38 and 42	10
	15 and 75	11 1/2
	15 and 51	13-13 1/4
	30	15
5682	4	6
	23 and 50	7 3/4
	69	9 1/3
	24 and 53	11
	21	12 1/2

Tube	Hydride Concentration, ppm	Sample Location on Tube, Feet From Inlet
6115	300-500 by Metallography	6
	74	8 2/3
	41 and 45	10 1/2
	38	12 1/4
	41	14
	32	15 3/4
6079	36	6
	35 and 50	7 3/4
	38	9 1/2
5526	60	9 1/2
6084	44	7 2/3
	35 and 61	9 1/4
	33	11

(a) ZrH_2 is of the order of 21, 000 ppm Hydrogen

(b) BW Mark - Fuel Element Bundle Wire Fret Mark
UFES Mark - Fuel Element Upper Support Fret Mark
LFES Mark - Fuel Element Lower Support Fret Mark

(c) Several specimens analyses were within this range.

(d) High value may have been due to metallography mounting substance

(e) Sample location uncertain but is within indicated limits

There were three instances discussed in Reference (1) of service produced flaws which during burst testing caused strength reductions of 24%, 23%, and 11%. The more recent tubes tested had service flaws of lesser strength reduction influence. The tabulated burst test data are presented in Table II.

TABLE II

BURST TEST DATA

Tube	Specimen	Microstructure	Test Temperature, F	Fast Neutron Exposure at Burst, nvt	Hoop Strength, psi	Hoop Elongation, %	Remarks
6100	1 B	Annealed	70	$1.6 - 3.3 \times 10^{16}$	86,200	9	No apparent cause for low strength.
	1 C	Annealed	70	$1.25 - 1.35 \times 10^{19}$	86,700	0	Burst started by 0.002 in. deep crack in 0.002 in deep hydride layer over a fret mark.
6061	2 C	Annealed	70	$5.2 \times 10^{17} - 1.1 \times 10^{18}$	106,200	20	-
	2 D	Annealed	575	$4.7 - 5.4 \times 10^{19}$	58,200	Not Measured	-
5529	3 2	Annealed	70	$6.8 \times 10^{17} - 1.35 \times 10^{18}$	97,000	17	-
	3 3	Annealed	70	$3.6 - 6.3 \times 10^{19}$	111,000	15	-
5679	4 B	Annealed	550	$1.3 - 2.4 \times 10^{18}$	47,200	36	-
	4 C	Annealed	540	$3.8 - 7 \times 10^{19}$	61,200	48	-
	4 F	Cold Worked	565	$6.2 \times 10^{19} - 1.2 \times 10^{20}$	70,500	Not Measured	-
5702	5 B	Annealed	70	$3.3 - 6.2 \times 10^{18}$	107,000	Not Measured	0.009 - 0.011 in. deep fret marks had no apparent effect on burst.
	5 C	Annealed	205	$1.35 - 1.8 \times 10^{20}$	111,000	Not Measured	-
	5 E	Cold Worked	70	$2.1 - 2.25 \times 10^{20}$	130,000	3.3	Burst started by 0.017 in. deep fret mark.
	5 G	Cold Worked	555	$6.8 \times 10^{18} - 1.7 \times 10^{19}$	74,000	Not Measured	-
5540	6 B	Annealed	560	$1.4 - 2.8 \times 10^{19}$	56,900	Not Measured	Test was stopped before burst.
	6 C	Annealed	430	$2.9 - 3.2 \times 10^{20}$	78,100	16	"Pinhole" failure.
	6 E	Cold Worked	70	$1.3 - 2.2 \times 10^{20}$	120,000	0	Burst started at 0.014 in. deep fret mark.
	6 C	Second Test	70	$2.9 - 3.2 \times 10^{20}$	125,800	0	Elongation of zero probably due to first burst test.
	6 D	Undetermined	550	4.2×10^{20}	78,400	20	"Pinhole" failure.
0720	8 B	Annealed	207	1×10^{16}	75,000	Not Measured	-
	8 C	Annealed	410	$3.2 - 6.2 \times 10^{17}$	58,000	Not Measured	-
	8 F	Cold Worked	410	$1.2 - 1.7 \times 10^{18}$	84,500	Not Measured	-
5683	9 B	Annealed	70	$3.5 - 6.5 \times 10^{18}$	104,800	7.5	-
	9 H	Cold Worked	70	$1.6 - 2.6 \times 10^{20}$	134,200	7	-
5682	10 C	Annealed	70	$2.7 - 3.5 \times 10^{20}$	129,000	15	-
	10 G	Cold Worked	70	$3.2 - 4.1 \times 10^{20}$	134,800	9	-
6115	11 C	Annealed	70	$1.45 - 2.0 \times 10^{20}$	97,500*	Less than 0.2%	*Based on average ID and wall; no allowance for stress concentration. Burst started by 0.016 - 0.020 in. deep mark at the onset of uniform plastic strain.
6079	12 A	Annealed	70	1.9×10^{19}	112,800	12	
	12 E	Cold Worked	70	3.3×10^{20}	123,700	7	
6084	14 D	Undetermined	70	1.8×10^{21}	142,650	6	

DISCUSSION

Static burst strength data of Figure 1 indicate Zircaloy-2 pressure tube bursting strengths are 140,000 psi at room temperature and 77,500 psi at elevated temperature for exposures between 450 and 500 Mwd ($\sim 10^{21}$ nvt, $E > 1$ MeV). Compared with values from unirradiated material these bursting strengths are 0 to 55% greater at room temperature and are 25% to 50% greater at elevated temperature depending upon microstructure. Furthermore, these data indicate that at this exposure the strength difference between annealed and cold-worked Zircaloy-2 pressure tube material is not significant.

The most recent static burst strength data (specimen 6D burst at 550 F and 78,400 psi had an exposure of 4.2×10^{20} nvt) indicate strength values will show further increases with increasing neutron exposure. If burst strengths do not change abruptly at a critical exposure, the shape of the curves indicates that at twice the neutron exposure the margin of safety from tube failure by overloading will be about seven. The factor of safety now is between six and seven.

The circumferential elongation values plotted in Figure 2 indicate that Zircaloy-2 pressure tube material having exposure values of 450 to 500 MWd will display about 6% circumferential elongation when pressurized to failure at room temperature and at least 20% circumferential elongation when pressurized to failure at elevated temperature. The shape of the room-temperature elongation versus neutron exposure curve suggests a continued gradual loss of circumferential elongation with increasing neutron exposure. At twice the current exposure the indicated elongation is about 3% or more.

The crack propagation data of Figure 3 indicate that fast neutron irradiation of 2×10^{20} to 6×10^{20} nvt has not changed crack propagation characteristics of Zircaloy-2 pressure tube material. They also indicate the necessary crack length for propagation at PRTR operating pressure and room temperature is about 10 in. Catastrophic PRTR Zircaloy-2 pressure tube failure is therefore indicated to be not probable. The envisioned events in the life of a developing crack in a PRTR tube are:

- The crack grows radially from a source until the tube wall is penetrated.
- The crack length increases.
- Water flows into the gas annulus
- The water pressure drop along the tube changes...
- The water leak is detected by helium moisture analysis or by pressure losses before the crack reaches critical size.

The data of Table I show there were several cases of hydriding at service produced flaws. Some of these flaws were burst test fracture origins. The worst flaw-hydriding combination tested (300 to 500 ppm hydride and theoretical notch factor of 4.5 in specimen 11C of Tube 6115) caused an effective strength reduction of 25%.

The data of Table I indicate that Tube 5679 had an average hydride concentration greater than 50 ppm. The other tubes are indicated to have had average hydride concentrations of less than 50 ppm.

Service produced flaws with theoretical stress concentration factors of two to three and one-half have demonstrated effective stress concentration factors of less than one and one-half. An effective stress concentration factor of about four to six is necessary for a service produced flaw to cause in-service tube failure.

CONCLUSIONS

The data provide a technical basis for selection of PRTR Zircaloy-2 pressure tubes for discharge and examination under the PRTR surveillance program. The technical basis is:

- Burst test hoop strength and elongation data show that tubes having fast neutron exposure of 10^{21} or less have high strength with ductility;

furthermore, the curves indicate that increasing exposure by a factor of two will not substantially change these conditions.

- Crack propagation data for tubes having fast neutron exposure of 5×10^{20} nvt or less show that resistance to crack propagation is unaffected by the neutron exposure, and that the crack length necessary for propagation at PRTR operating pressures is about 10 in.
- Hydride concentration data indicate general levels of hydride concentration are low, but high hydride concentrations have been found at flaws. The worst combined effect of flaw plus hydride produced a strength reduction of 25%.

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1	UNION CARBIDE CORPORATION, CLEVELAND
2	UNION CARBIDE CORPORATION (ORGDP)
5	UNION CARBIDE CORPORATION (ORNL)
1	UNION CARBIDE CORPORATION (PADUCAH PLANT)
2	UNITED NUCLEAR CORPORATION (NDA)
1	U. S. GEOLOGICAL SURVEY, DENVER
1	U. S. GEOLOGICAL SURVEY, MENLO PARK
1	U. S. GEOLOGICAL SURVEY, WASHINGTON
1	U. S. PATENT OFFICE
2	UNIVERSITY OF CALIFORNIA, BERKELEY
2	UNIVERSITY OF CALIFORNIA, LIVERMORE
1	UNIVERSITY OF PUERTO RICO
1	WESTERN RESERVE UNIVERSITY (MAJOR)
4	WESTINGHOUSE BETTIS ATOMIC POWER LABORATORY
1	WESTINGHOUSE ELECTRIC CORPORATION
1	WESTINGHOUSE ELECTRIC CORPORATION (NASA)
325	DIVISION OF TECHNICAL INFORMATION EXTENSION
75	CLEARINGHOUSE FOR FEDERAL SCIENTIFIC AND TECHNICAL INFORMATION

*New listing or change in old listing.