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FAILURE ANALYSES AND PROPERTIES OF SAFETY ROD GUIDE TUBES FROM THE HWCTR

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FAILURE ANALYSES AND PROPERTIES OF SAFETY ROD GUIDE TUBES FROM THE HWCTR

by

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ABSTRACT

Four of the six safety rod guide tubes in the Heavy Water Components Test Reactor at the Savannah River Plant failed after operating ~6000 hours at 200°C; two tubes contained 2- to 3-inch longitudinal cracks, one contained a 30-inch crack, and one contained short cracks, a long crack, and a complete transverse fracture. During service, the six tubes each had experienced between 222 and 327 test drops of the safety rods at 22 to 260°C.

The failures were caused by stress pulses generated in the tubes during hydraulic deceleration of the falling safety rods. The cracks were initiated by low-cycle fatigue, due to repeated drops at elevated temperatures, and were propagated by drops at low temperatures. Residual stresses and high hydrogen contents, both from fabrication and from high in-pile corrosion rates, were significant contributing factors. In-pile corrosion rates were three to ten times the rates that would be expected in autoclave tests at the same temperature.

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FAILURE ANALYSES AND PROPERTIES OF SAFETY ROD GUIDE TUBES FROM THE HWCTR

INTRODUCTION

The safety rods of the Heavy Water Components Test Reactor (HWCTR) were boron-stainless-steel rods, which in combination with their extensions weighed about 60 pounds each. The rods were positioned above the core during nuclear operation, and on a "scram" signal fell by gravity through 9-1/2 feet of D_2O to the bottom of the core. The six rods operated inside Zircaloy guide tubes that had a reduced diameter for the bottom 42 inches, forming a dashpot section that decelerated the rods near the end of their fall[1] (Figure 1 on page 8).

During tests of the safety rod system in April 1964, one rod dropped completely into the core without any deceleration near the bottom of its fall. An examination of the safety rod system in the reactor revealed that the Zircaloy guide tube had broken transversely at the beginning of the dashpot section. The six guide tubes were discharged and underwater examination showed that a total of four of the six tubes had cracked. All six tubes were replaced.

This report describes the tests on the six guide tubes to investigate in detail the causes of failure and to determine the effects of irradiation on Zircaloy properties.

SUMMARY

- The safety rod guide tubes failed because of the repeated stress pulses generated in the tubes during deceleration of the falling safety rods.

- Residual stresses, the reduction at the beginning of the dashpot section of the guide tube, and high hydrogen contents were major contributing factors.

- Fabrication process, hydride orientation, crystalline texture, and neutron hardening of mechanical properties were not significant factors.

- In-pile corrosion rates were three to ten times corresponding rates in autoclave tests at the service temperature. The increased corrosion was partly due to the neutron flux. Hydrogen pickup was normal for the HWCTR coolant conditions.

Based on these results, several changes were recommended for new, spare guide tubes:

- Increase the diameter transition zone from 1/4-3/8 inch to about 2 inches in length, to reduce the magnitude and concentration of the induced stress pulse.

- Use Zircaloy-4 or low-nickel Zircaloy-2, to reduce hydrogen pickup in the high-pD water used in the HWCTR.

- Anneal tubes after the final fabrication process, to eliminate residual stresses.

DISCUSSION

OPERATING HISTORY

The HWCTR protective measures required that the safety rods be inserted 90 percent of the distance into the core within 1.25 sec of receipt of the scram signal. The drop time for each safety rod was measured weekly during low-power physics tests and before each reactor startup thereafter, but at least once monthly during the first six months of power generation. In addition, the drop time of a rod was measured whenever any part of its drive train was physically disturbed.

The six safety rod guide tubes were irradiated for ~6000 hours in the HWCTR beginning in March 1962 and were discharged in April 1964. Metal temperatures during the exposure was 200°C ±10°C. The maximum neutron flux and exposure are given below.

Neutron Energy	Neutron Flux	Neutron Exposure
>1.0 Mev	3×10^{12} n/(cm^2)(sec)	7×10^{19} n/cm^2
Thermal	8×10^{13} n/(cm^2)(sec)	2×10^{21} n/cm^2

Throughout the irradiation in the HWCTR the six safety rods experienced from 222 to 327 individual drops at 22 to 260°C. The complete history for each guide tube is given in Table I.

Table I shows that the history, and thus the stress exposure, of the six guide tubes was very similar, and therefore, the failures in Guide Tubes 2, 4, 5, and 6 were not the result of a different operational history from Guide Tubes 1 and 3.

TABLE I

History of Safety Rod Drop Tests

Coolant Temperature, °C	Tube →	5	6	4	2	3	1
		Number of Drops					
22-102		143	125	213	144	203	228
103-149		3	3	3	3	3	3
150-200		26	26	30	24	32	30
201-239		7	6	7	7	7	7
240-260		61	62	59	59	62	59
	Total	240	222	312	237	307	327
Failure behavior (cracks)		longest	long	short	short	none	none

The operating temperature had a significant effect on the drop speed of the safety rods. As the temperature increased, the density of the water decreased, and the speed of rod insertion increased. For example, the average time required for 90 percent insertion was 1.16 sec at 25° and 1.08 sec at 240°C.[1] Thus, a rod drop at 250°C generated a substantially greater shock wave in the coolant and higher stress pulse in the guide tube than a rod drop at 25°C. Table I shows that 70 percent of the rod drops were at temperatures below 100°C, but a substantial number, 20 percent, were at 240-260°C.

During drop tests in April 1964, one safety rod dropped too rapidly because it was not hydraulically decelerated near the bottom of its fall. An examination of the safety rod system in the reactor revealed that the Zircaloy Guide Tube 5 had broken transversely at the beginning of the reduced diameter section (Figure 1). Examination revealed that the bottom of the tube was also split longitudinally from the diameter reduction almost to the bottom end fitting (Figure 2). During later examinations a longitudinal split of similar length, about 30 inches, was found in another guide tube and shorter cracks were found in two more guide tubes. The other two guide tubes appeared undamaged.

The safety and control rod guide tubes for the HWCTR were fabricated of Zircaloy-2 seamless tubing in two lots by two different processes, as shown in Table II.

There is no record of how the bottom 42 inches of the tubes were reduced in diameter to produce the hydraulic dashpot section, and it is not known whether the tubes were annealed afterward.

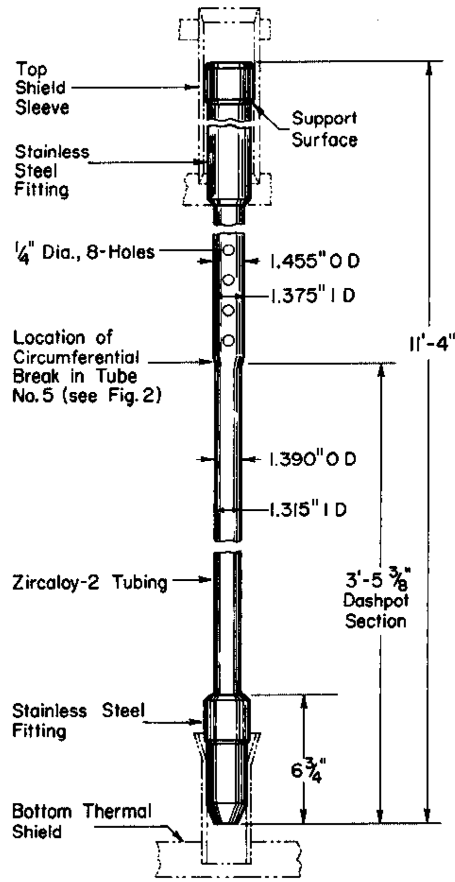


FIG. 1 HWCTR SAFETY ROD GUIDE TUBE

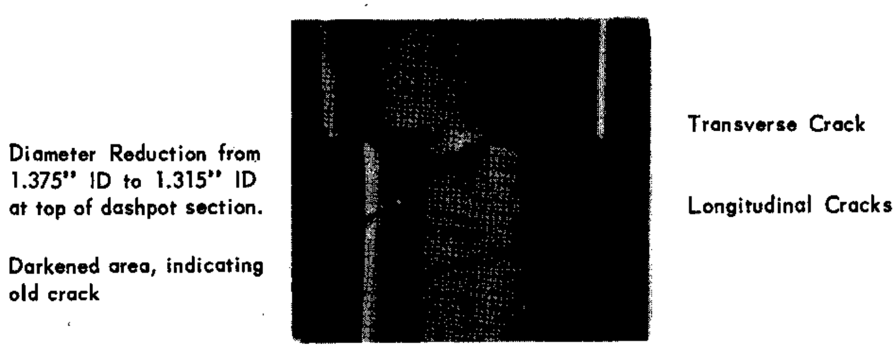


FIG. 2 FRACTURES IN GUIDE TUBE 5 (Note darkened area at top of major longitudinal crack, indicating that the initial crack was arrested for some time, until final propagation caused total failure of the tube.)

TABLE II

Fabrication Sequence for HWCTR Guide Tubes

Lot No. 1 (tube reduced)	Lot No. 2 (drawn)
Extruded at 1550°F	Extruded at 1350°F
Tube reduced 50%[a] Annealed[b]	Drawn 28%[a] Annealed[b]
Drawn 11% Annealed	Drawn 34% Annealed
Drawn 13% Annealed	Drawn 33% Annealed
	Drawn 28% Annealed

(a) Percent reductions in area.
(b) 1400-1450°F

The manufacturer had difficulty etching and rinsing the tubes. After the tubes failed the specified autoclave corrosion test, etching and rinsing were successfully performed by another firm. The several autoclaving cycles given the tubes led to initial hydrogen contents of up to 50 ppm.

Unfortunately, identification of the manufacturer's tube number with the HWCTR position was lost during fitting and installation. Thus, the only way of identifying the tube lot and pre-irradiation history and properties of each irradiated tube was through its grain size. Properties are summarized in Table III.

TABLE III

Properties of Guide Tubes Before Irradiation

(Vendor's report)

Property	Lot No. 1 (tube reduced)	Lot No. 2 (drawn)
Yield strength at 600°F, psi	18,100	17,600
Ultimate strength at 600°F, psi	33,600	31,300
Elongation at 600°F, %	26	25
Rockwell "B" hardness	84-86	86-89
Grain size, mm	0.03	0.02

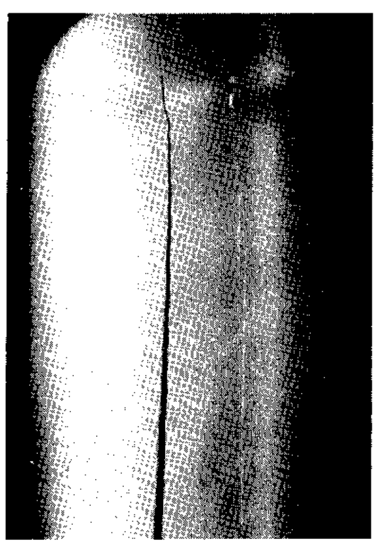
RESULTS OF METALLURGICAL EXAMINATIONS

Appearance of Guide Tubes

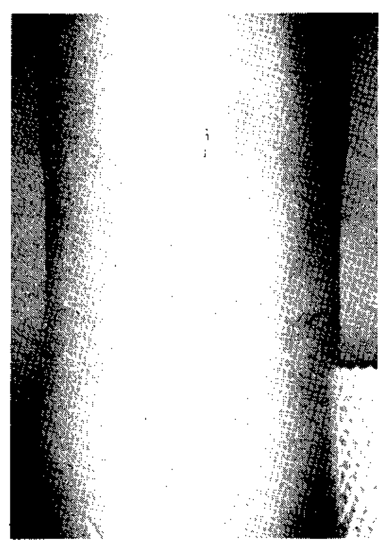
Visual examination of Guide Tube 5, the most severely damaged of the six, revealed that the initial failure was a longitudinal crack. This was shown by the greater age of the longitudinal cracks and the irregular path of the transverse crack (Figure 2). Approximately 1/2 inch of both the main longitudinal crack and the shorter longitudinal cracks on each side of the transverse crack had bright blue surfaces, which indicated that the cracks had been exposed to high-temperature coolant. The remaining surfaces of the longitudinal cracks and the entire surface of the transverse crack were a bright metallic grey and were obviously fresh.

The inner surface of the tube contained many score marks ~0.001 inch deep, but no indentations from possible impact of the safety rod against the diameter transition.

The crack surfaces in Guide Tubes 2, 4, and 6 (Figure 3) had the same appearance and coloration as in Guide Tube 5. No cracks were found in Guide Tubes 1 and 3. The inner and outer surfaces of these five tubes appeared similar to Guide Tube 5.



Guide Tube 6



Guide Tube 2

FIG. 3 CRACKS IN GUIDE TUBES 6 AND 2 (Note that these cracks are similar in nature, but at an earlier stage of development than the cracks shown in Figure 2.)

Corrosion Behavior

The zirconium oxide film thickness was measured metallographically on samples from the top, middle, and bottom of each tube after solvent cleaning in an ultrasonic bath. The thickest films were found in the middle of the tubes, apparently as a result of the neutron flux profile. The maximum film thickness was 0.2 mil on Guide Tubes 1, 2, and 3 and 0.3 mil on Guide Tubes 4, 5, and 6.

Sample data for Guide Tube 6 are shown in Table IV.

TABLE IV

Corrosion Data for Guide Tube 6

Position in Tube	Relative Neutron Flux	ZrO_2 Thickness,[a] mil: Inner Surface	ZrO_2 Thickness,[a] mil: Outer Surface	Hydrogen Content[a]: H_2,[b] ppm	Hydrogen Content[a]: D_2,[b] ppm	Hydrogen Content[a]: Pickup, % of hydrogen generated
Top	0.1	-	0.14	50	115	30
Near diameter reduction	0.9	0.26	0.27	63	328	42
Bottom	0.2	0.16	0.19	40	260	34
Approximate effect of autoclave treatment in D_2O for same time-temp. history	0	0.03		-	60	50

(a) Averages of measurements on 2 specimens for ZrO_2 thickness and 2-4 specimens for hydrogen content at each location.
(b) The H_2 resulted from autoclave tests during fabrication and the D_2 from the HWCTR irradiation.
The D_2 content in ppm is twice the same atom pickup of H_2.

The maximum thickness of the ZrO_2 film on Guide Tube 6 was 0.3 mil, which corresponds to a weight gain of 110 mg/dm^2; the D_2 content was 328 ppm at this point. On the basis of ex-reactor corrosion data on Zircaloy-2, the expected corrosion during the lifetime of the guide tube (~6000 hours at 200°C) would be a weight gain of 10 mg/dm^2, a film thickness of 0.03 mil, and a deuterium pickup of 60 ppm. By comparison, the data on the guide tubes showed a three- to tenfold increase in corrosion primarily because of the neutron flux, possibly enhanced by the fact that the corrosion process had been established during the autoclave tests at 750°F. The "hydrogen pickup" of 25 to 50% was expected for the HWCTR coolant conditions of 0.01 std cc O_2 and 15 std cc D_2 per kg D_2O and a pD adjusted to 10.5 to 11 with LiOH.

The D_2 content of each tube varied with ZrO_2 film thickness; i.e., higher in the middle and usually lower at each end (Table V). Vacuum fusion analyses of sections from two tubes showed that the D_2 content was about 40% higher just below the diameter reduction than just above it. The H_2 content from preirradiation autoclaving was fairly uniform throughout each tube and varied from 28 to 48 ppm.

TABLE V

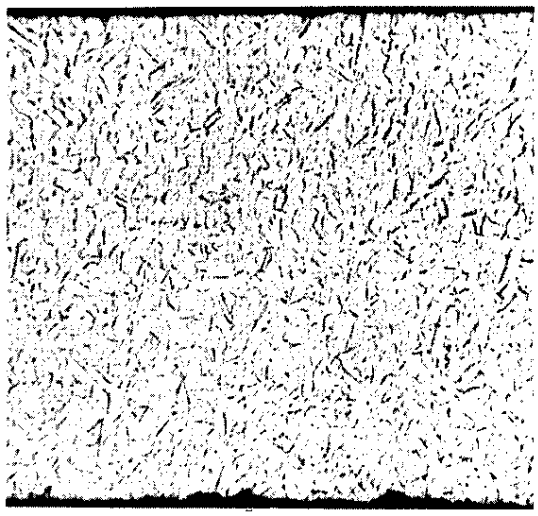
Comparison of Hydrogen Content and Failure Experience

Tube	Sample Position	Cracks	Hydrogen[a] H_2, ppm	D_2, ppm	Total Hydrogen (H_2 + 1/2 D_2), ppm
1	Top		31	46	54
	Middle	None	36	92	82
	Bottom		38	70	73
3	Top		25	39	45
	Middle	None	29	128	93
	Bottom		30	110	85
2	Top				
	Middle	1 short	37	29	52
	Bottom		40	192	136
4	Top		45	93	91
	Middle	1 short	45	280	185
	Bottom		45	137	113
6	Top		50	115	107
	Middle	1 long	63	328	227
	Bottom		40	260	170
5	Top	1 long +	-	-	-
	Middle	Many short +	40	290	185
	Bottom	Transverse	59	67	93

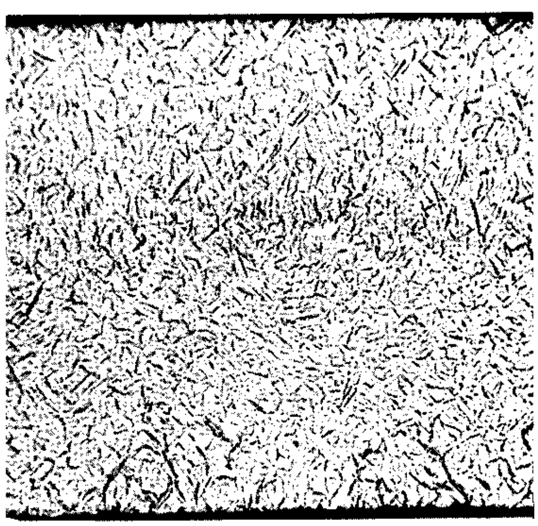
(a) Averages of two to four analyses at each position, except Tube 5 for which only one analysis was available at each position.

The D_2 content from the HWCTR irradiation varied widely from tube to tube and was apparently related to performance (Table V). Guide Tubes 1 and 3, which did not crack, had maximum hydrogen contents of 82 and 93 ppm (in H_2 equivalents). Similarly, Guide Tubes 2 and 4 with short cracks had 136 and 185 ppm total hydrogen, and Guide Tubes 5 and 6 with very long cracks had 185 and 227 ppm total hydrogen.

In all tubes, the hydride platelets were oriented predominantly 45° to the circumferential direction above the diameter transition with little variation across the wall (Figure 4a). Below the diameter reduction, however, the platelets were preferentially oriented 45 to 90° to the circumferential direction at the outer surface and 0 to 45° to the circumferential direction at the inner surface (Figure 4b). These orientations resulted mainly from stress orientation of the hydrides[2] because of the 13 to 28 kpsi residual stresses in the bottom of the tubes.



a. Above diameter transition



b. In dashpot section below diameter transition

FIG. 4 HYDRIDE ORIENTATION IN GUIDE TUBE 5
(Transverse sections as-polished 60X)

Residual Stresses

When some unirradiated tube ends were cut from the bottom of the guide tubes and sectioned longitudinally for examination, the saw cut widened, which indicated that the tubes contained a substantial amount of residual stress. Strain-gage measurements on additional sections of the tubes indicated residual stresses of 13 to 28 kpsi hoop tension in the outer surface, and comparable compressive stresses in the inner surface. There were too few samples to determine if the average residual stresses were different for the two types of tubing. Since the stresses were almost certainly the result of no annealing after the smaller diameter sections had been formed at the bottom of the tubes, similar residual stress levels would be expected for all tubes. These stresses were, in fact, confirmed by the hydride orientations observed in all irradiated tubes.

Grain Size and Texture

The grain size of each tube was measured to identify the fabrication history of each guide tube and thus assist in relating failure experience and preirradiation properties, such as texture. The mean grain diameters were measured by counting the grain boundary intercepts on circles scribed on micrographs of the grain structure of samples from the top, middle, and bottom of each tube. Use of circles instead of straight lines eliminated any bias in grain size determination because of an oriented grain shape in the tube. For comparison, grain sizes were measured on identified tube ends from both some of the irradiated tubes and the replacement set of "tube-reduced" guide tubes. These data are shown in Table VI. The grain size data indicate that Guide Tubes 5 and 6 with the longest cracks were from the tube-reduced lot of tubes, whereas the other four guide tubes were drawn tubes.

The crystalline texture of the two lots of tubes were determined by X-ray diffraction measurements[3] on two end samples from the original set of guide tubes. The tube-reduced tubing contained a uniaxial texture with the basal poles in the circumferential tubing direction. In contrast, the drawn tubing contained a biaxial or planar texture with the basal poles oriented in the transverse tubing plane (i.e., high in radial and circumferential directions), as shown in Table VII.

TABLE VI

Grain Size of Guide Tubes

	Mean Planar Grain Diameter, mm
Unirradiated Tube Ends	
Drawn tube	0.016 - 0.018
Tube-reduced tube	0.022 - 0.025
Tube-reduced replacement tubes	0.022 - 0.029
Irradiated Guide Tubes	
1	0.016
3	0.018
2	0.018
4	0.017
5	0.022
6	0.022

TABLE VII

Textures of Two Lots of Guide Tubes

	Texture Coefficient, relative number of (hkxl) poles in indicated tubing direction	
Tubing Direction	Tube-Reduced Tubing	Drawn Tubing
Circumferential		
(0001)	4.04	3.69
$(10\bar{1}0)$	0.21	0.97
Radial		
(0001)	0.81	2.84
$(10\bar{1}0)$	0.81	1.01
Longitudinal		
(0001)	0.14	0.04
$(10\bar{1}0)$	4.93	2.89

Strength and Ductility

The mechanical properties of the guide tubes were determined by hydraulic burst tests of sections from the top, middle, and bottom of Guide Tubes 1, 2, 3, and 4. The tube sections were fitted with molded plastic end seals and pressurized to failure with oil. The ultimate hoop strength was calculated from the oil pressure at burst; the yield strength was not measured. Ductility was measured by the average increase in diameter throughout the burst test section and the maximum increase in diameter at the bulge.

The combined effects of irradiation, hydrogen content, and hydride orientation on burst strength are shown in Figure 5. At a fast neutron exposure of 7×10^{18} nvt (top tube sections), irradiation hardening had caused little increase in strength before higher hydrogen contents apparently began to limit strength. With increased neutron exposure, 2×10^{19} nvt (bottom tube sections), some irradiation-induced increase in strength occurred before higher hydrogen contents again limited the strength. At

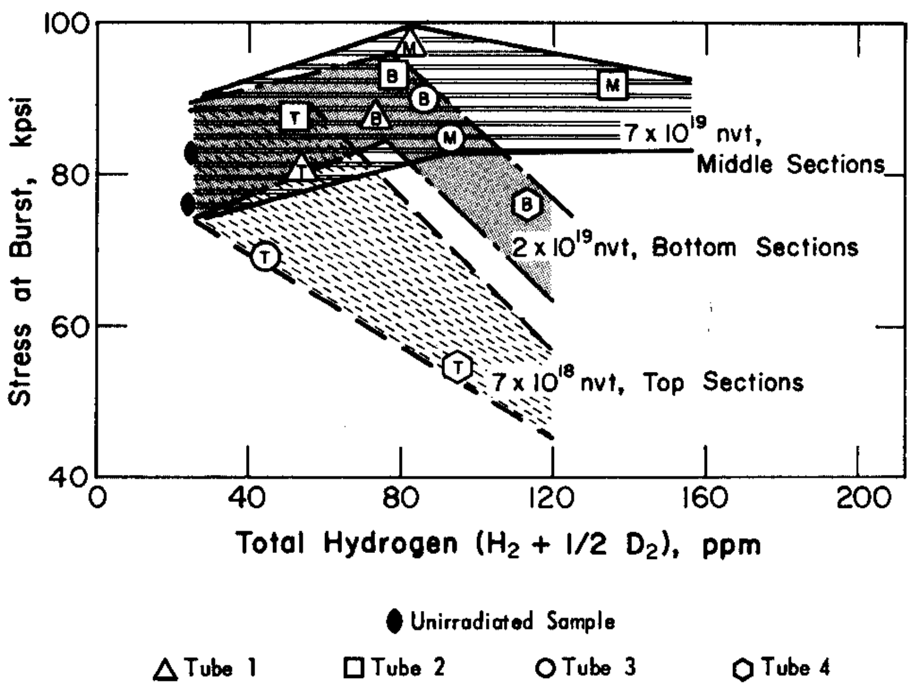


FIG. 5 BURST STRENGTH OF IRRADIATED SECTIONS

the highest neutron exposure, 7 x 10^{19} nvt (middle tube sections), an increase in strength due to irradiation was observed, but hydrogen up to 136 ppm had no effect. These data indicate that hydride orientation had no significant effect on burst strength because the top and bottom sections had much different hydride orientations but exhibited about the same effects of irradiation and total hydrogen.

As shown in Figure 6, ductility was lowered by the combination of increased neutron exposure and higher hydrogen contents, and it was not possible to separate the two effects. Hydride orientation had no significant effect on ductility possibly because the radially oriented hydrides were contained in only the outer layer of the tubing.

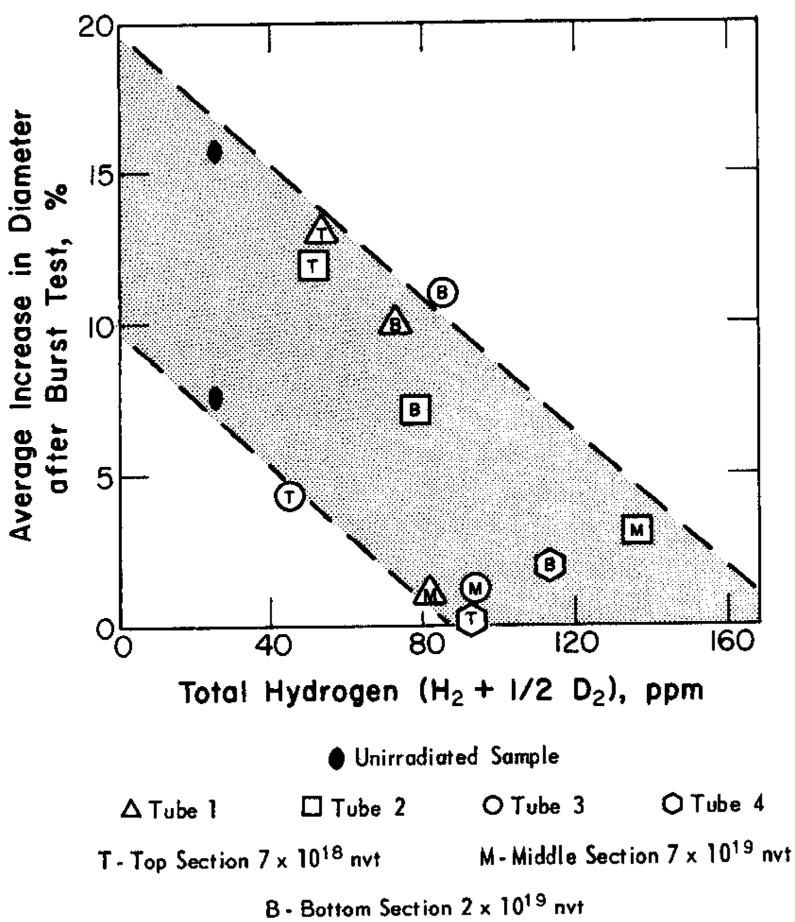


FIG. 6 DUCTILITY OF IRRADIATED SECTIONS DURING BURST TEST

FAILURE ANALYSIS

Properties of the Tubing

The results described above have shown that most of the properties of the two lots of tubes and the HWCTR history of the six guide tubes were very similar. While preirradiation strength, residual stress, neutron exposure, rod drop history, and hydride orientation may have been factors in causing the failures, these variables were generally uniform from tube to tube and, therefore, were not specific in causing a particular tube to fail.

Two factors, hydrogen content and crystallographic texture, do appear to have influenced the specific failures and the magnitude of the failures. The total hydrogen content correlated very well with tube failure (Table V); the failed tubes contained over 125 ppm total hydrogen at the diameter reduction; the unfailed tubes contained less than 100 ppm. In addition, Guide Tubes 5 and 6 (with 30-inch cracks) contained ~300 ppm of hydrogen, which indicated that crack propagation was also favored by the higher hydrogen contents. The variable hydrogen contents of the individual tubes was probably a result of variable etching and autoclaving history during fabrication.

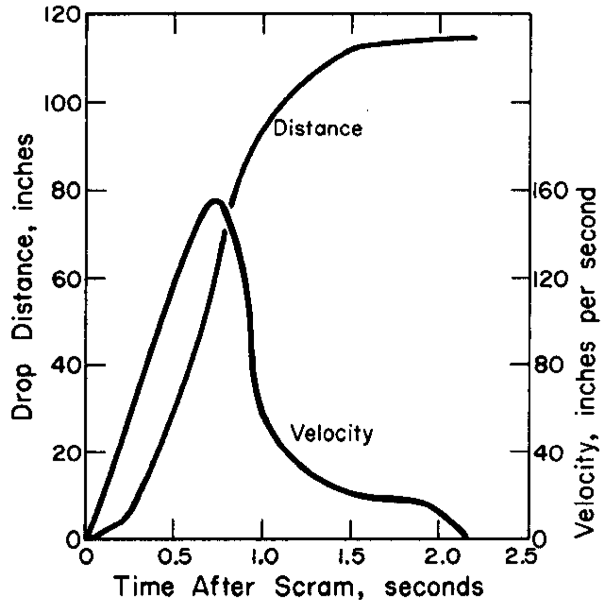
The texture of Guide Tubes 5 and 6 may also have contributed to these failures. Work at the Savannah River Laboratory[4] has shown that these tubes, with the basal poles oriented predominantly in the circumferential tubing direction, would have been more severely embrittled by a given hydrogen content than the drawn tubes with a biaxial texture.

Service Conditions

These examinations show that failures were primarily caused by the stress pulse generated in the tubes while the tubes decelerated the rapidly falling safety rods. The failures may be described, therefore, as low-cycle fatigue failures.

The precise value of stress pulse in the guide tubes during the safety rod drop tests is unknown; calculations indicate a range of 10,000 to 75,000 psi, depending on the deceleration rate, compressibility of coolant, etc. The maximum stress pulse must contain a large circumferential tensile component from the transient increase in pressure of the coolant, but also must include a large amount of stress concentration and some biaxiality because of the sharpness of the diameter transition at the top of the dashpot section. The distance-time-velocity graphs (Figure 7) show that the stress pulse was very rapid. True mechanical impact

FIG 7 DISTANCE - VELOCITY CHARACTERISTICS OF A SAFETY ROD SCRAM (30°C moderator temp.)



loading was discounted as a cause of the initial cracks because no dents were seen on the inner surfaces and because the impact of the rod with the tube should have generated longitudinal, not circumferential stresses.

Tube 5 failed in three stages. First, short, longitudinal cracks were nucleated at the diameter transition. Secondly, the cracks propagated rapidly to the bottom end fitting, probably in one step. Finally, the transverse fracture was produced by the impact of the safety rod on the bottom end fitting. The last two stages, rapid crack propagation and transverse cracking, undoubtedly occurred at low temperatures, but the properties of irradiated Zircaloy show that the initial failures occurred at elevated temperatures, as discussed in the following paragraphs.

The importance of elevated temperature strain cycling in crack initiation is based primarily on the stress pulses necessary to cause various types of failure. Calculated stress pulses required to cause tensile and strain fatigue failures are shown in Table VIII.

These data indicate that the stress pulse needed for tensile failure or for low-cycle fatigue failure is smaller at 250°C than at <100°C. We also know that the maximum velocity of the falling safety rod was greater at 250°C than at <100°C.[1] Therefore, any given rod drop is more likely to cause a tube failure at 250°C than at <100°C. For example, the stress pulse necessary to cause failure in 61 cycles (Table I) at 250°C, approximately 50,000 psi, would have had little effect below 100°C. Conversely,

TABLE VIII

Calculated Hoop Stresses for Failure of Zircaloy-2

Item	At 100°C [b]	At 250°C [c]
Yield strength [a] of irradiated Zircaloy, psi	85,000	50,000
Ultimate strength [a] of irradiated Zircaloy, psi	90,000	55,000
Stress pulse required for tensile failures, psi	90,000	55,000
Stress pulse required for low-cycle fatigue, psi	~85,000	~50,000

(a) Strength data for 7-10 x 10^{19} nvt (>1 Mev).
(b) From this report.
(c) From Reference 5.

any stress pulse large enough to cause failure in 143 cycles at 100°C would have caused failure in the first few cycles at 250°C.

This conclusion is based on the plastic strain concept for low-cycle fatigue, where the number of cycles to failure is primarily a function of the plastic strain per cycle.[6] The two temperatures considered here, 100°C and 250°C, are close enough (and both are below the important structural temperatures such as the recovery temperature) for the "plastic strain per cycle" parameter to be the controlling parameter. Fatigue data that are available on Zircaloy fit the "plastic strain" relationship in this temperature range.[7,8] Thus, stress pulses of ~50,000 psi would have caused measurable plastic strains per cycle at 250°C, but very little, if any, plastic strain per cycle at <100°C.

Finally, the arrest of the crack (indicated by color of the fracture surface, Figure 2) before final, rapid propagation indicates that crack initiation must have occurred at higher temperatures, because at low temperatures the crack would have progressed immediately to a complete failure. For Zircaloy containing large amounts of hydride, crack arrest at low temperature has not been reported.

ACKNOWLEDGMENT

The authors wish to thank Dr. E. F. Sturcken and his group for their X-ray diffraction measurements of Zircaloy texture.

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