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FUEL ELEMENT TENSION TEST RESULTS AT ROOM TEMPERATURE

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1.0 INTRODUCTION

The purpose of the fuel element tension tests described in this report is to provide data on the axial strain required to produce fracture under bundling conditions. Previous analysis shows that element fractures may result due to the combined effects of: bundling pressure, temperature differences between adjacent elements, differences in the coefficient of expansion between an element and its adjacent members, the coefficient of friction, and the extent of corrosion. The tests reported were developed employing friction lockup at room temperature to study the strain required to produce fracture. With this strain data and other information it is possible to analyze reactor conditions to predict the probability of fuel element mechanical failure.

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2.0 TEST RESULTS

The test arrangement used for friction lockup tests is described in detail in the Appendix. In brief, it consists of a cluster of seven 10-inch graphite elements, hydraulically bundled in a metal fixture. The six outer elements of the cluster are unfueled single-hole elements instrumented with strain gages. The fueled test specimen, taken from a fueled nineteen-hole element, is placed in the center of the cluster. The test procedure consists of: (1) axially loading the outer elements in compression, (2) bundling the cluster under lateral pressure, (3) incrementally releasing the axial load on the outer elements, and (4) recording the strain data. The reduction in strain on the outer elements is equal to the buildup of tensile strain in the test specimen or central element due to the friction lockup.

Twenty-one 10-inch long test specimens were used in these tests. The specimens were taken from nine fueled elements, six manufactured by Oak Ridge and three by WANL. Five of the Oak Ridge elements and two of the WANL elements were previously corrosion tested in the WANL Corrosion Test in accordance with Process Specification 294613, Revision 8. In this corrosion test, the elements reach a temperature of $1975 \pm 50^{\circ}\text{C}$ at Station 37 under a flow of 500 scfm of hydrogen.

Two of the Oak Ridge elements were subjected to 40-minute corrosion tests and three to 20-minute corrosion tests. Two WANL elements were subjected to a 20-minute corrosion test. To provide comparisons between corroded and uncorroded elements, one Oak Ridge and one WANL element were not subjected to the corrosion tests. The element serial numbers, corrosion test durations, weight losses, and fracture test results are shown in Table 1.

The high, low, and average fracture strains for five Oak Ridge test specimens, removed from three elements corrosion tested for 20-minutes were 2330, 2000, and 2217 $\times 10^{-6}$ in./in. as compared to 2420, 1665, and 2020 $\times 10^{-6}$ in./in. for six specimens from two WANL elements subjected to identical corrosion tests.

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TABLE 1

SUMMARY OF FRICTION LOCKUP TESTS ON CORRODED AND NON-CORRODED FUEL ELEMENTS

Fuel Element (Serial Number)	Specimen Removed Between Stations (in.)	Manufacturer	Corrosion Time (min)	Total Weight Loss (grams)	Specimen wt./in. (grams)	Fracture Strain ($\times 10^{-6}$ in./in.)	Modulus of Elasticity* ($\times 10^6$ psi)	Ultimate Strength ⁺	
								(lb)	(psi)
99-73753	0-10	Oak Ridge	40	19.5	13.18	2000		----	----
	10-20				13.03	1960-2050**		----	----
	20-30				13.22	2010-2200**		----	----
	30-40				13.73	----	1.8	----	----
	40-50				13.64	----	1.6	----	----
99-74785	0-10	Oak Ridge	20	6.2	13.36	2255		1415	4060
	10-20				13.71	2290		1440	4120
	30-40				13.90	2000	1.8	1255	3600
99-98314	10-20	Oak Ridge	0	0	13.25	2260	2.2	1735	4970
	20-30				13.62	2360		1810	5190
99-25928	0-10	WANL	20	5.9	13.04	2340		1635	4680
	20-30				13.53	1840**		1250	3680
	30-40				13.52	1665-2305**	2.0	1160-1610	3330-4610
99-29677	0-10	WANL	20	8.0	12.92	1740		1155	3310
	10-20				13.01	2120	1.9	1405	4030
	30-40				13.20	2420		1600	4590
99-23796	30-40	WANL	0	0	12.65	2080	2.0	1455	4170
	40-50				12.66	2560		1790	5120
99-74513	15-25	Oak Ridge	40	23.0	13.24	1830-2060**	----	----	----
99-73094	15-25	Oak Ridge	20	6.1	13.38	2210	----	----	----
99-73841	15-25	Oak Ridge	20	5.6	13.79	2330	----	----	----

* Modulus of elasticity measured under axial and flexural loads (original cross section assumed).

** Specimens fractured in two places at different time intervals and strain levels.

⁺ Ultimate strength based on dimensions of elements before corrosion testing.

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Tests were performed on two specimens removed from each manufacturer's non-corroded elements. The fracture strain results obtained for the Oak Ridge and WANL specimens were 2260, 2360, 2080, and 2560×10^{-6} in./in., respectively. Specimens from the more severely corroded elements, where either pinholes or highly localized corrosion was present, showed generally lower fracture strains. Fracture strain results for the specimens from the 20-minute corroded elements were similar to those obtained for the specimens from the non-corroded elements and appeared to be independent of location.

One of the Oak Ridge test specimens, removed from element S/N 99-74513 shown in Figure 1, had a pinhole at Station 21-3/8 inch (1-3/8 inches from the center of the specimen). The first fracture occurred through the pinhole at a tensile strain of 1830×10^{-6} in./in. A second failure occurred in the same specimen at a strain of 2060×10^{-6} in./in. through a second defect which was about to develop into a pinhole. Figure 2 shows this specimen fractured in two different locations approximately 2-3/4 inches apart. When multiple failures within a test specimen occurred during these tests, it was always at a different time and in most cases at a different load. With surface defects such as pinholes, a much lower fracture strain was anticipated because of the sensitivity of brittle materials to notches. A square or flat type of fracture, shown in Figures 3 and 4, was typical for all friction lockup failures as contrasted with irregular or lip-type fractures which occur in bending tests.

For comparison, friction lockup specimens from an Oak Ridge element (S/N 99-73753) corroded for 40 minutes had fracture strains that varied from 1960 to 2200×10^{-6} in./in. Two of the specimens from this test fractured in two places. If only the initial fractures are considered, the fracture strain range is reduced to 1960 to 2010×10^{-6} in./in., indicating little change in fracture strain for the two cases. The fracture strains obtained in the friction lockup apparatus are in the range of values obtained for direct tension tests as reported by ORNL 65-4-71 (Graphite Mechanics Program Progress Report No. 3).

Table 1 shows values of the modulus of elasticity that were obtained under axial compressive and flexural loads of up to about one-half of the fracture strain value. Each

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Figure 1. Test Specimen Removed from an Oak Ridge Element
Subjected to a 40-Minute Corrosion Test

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Figure 2. Photograph of Specimen Shown in Figure 1 after Fracture Test

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Figure 3. View of Ends and Fractured Faces of Specimens
Shown in Figures 1 and 2

Figure 4. View of Opposite Ends and Fractured Faces of
Specimens Shown in Figures 1 and 2

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fueled specimen was instrumented with strain gages, and the results acquired by axial loading were in good agreement with those obtained by flexural loading. In these determinations the original cross sections were assumed. After the modulus determinations, the strain gages mounted on the outer surfaces of the fueled specimens were removed and the specimens were subjected to friction lockup tests. In these cases, an ultimate load and stress were obtained by multiplying the modulus of elasticity by the fracture strain. For the corroded samples it was assumed that the cross-sectional area as well as the mechanical properties were not affected by corrosion tests and that the modulus of elasticity was a constant over the range of strains to the fracture strain value. It was apparent that the holes at the fracture interfaces were enlarged in elements subjected to a 40-minute corrosion test. In one such Oak Ridge specimen which failed near Station 19, one hole was enlarged to 0.127 inch ID (nominal hole diameter = 0.097). The greatest weight loss recorded in the WANL corrosion tests occurred between Stations 15 and 25. Three of the Oak Ridge specimens were sectioned at these points to determine the fracture strain in the area of greatest weight loss. The results were comparable to those for prior specimens except for the specimen with the pinhole. Little or no corrosion, as evidenced by an increase in hole diameters, was apparent at the flat fracture interfaces for Oak Ridge and WANL samples which were removed from elements subjected to a 20-minute corrosion test.

To investigate the effect of discontinuities within a specimen, such as pinholes or loss of material around the bores, on the strain distribution along its length, some test specimens were modified and subjected to lockup tests similar to those run on the other specimens. The modification consisted of increasing the bore from 0.365 to 0.500 inch from one end to the center. Thus, these test specimens had two different bores, 0.365 and 0.500 inch diameter, each five inches long, as illustrated in Figure 5. Pairs of resistance strain gages were applied on the ID of these specimens at four different locations; it was established that the average measured strains equidistant from the discontinuity were almost equal. The results appear in Table 2 and Figure 5. Failure occurred in the discontinuity at an average strain of 1255×10^{-6} in./in., as based on the two pairs of gages on either side of the fracture.

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Figure 5. Strain Distribution Along the Length of an Unfueled Single-Hole Specimen with Different Cross Sections

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TABLE 2

EFFECTS OF REDUCTION OF AXIAL LOAD ON PERIPHERAL ELEMENTS UNDER
VARIOUS BUNDLING PRESSURES ON STRAIN DISTRIBUTION IN A
CENTRAL ELEMENT CONTAINING TWO DIFFERENT HOLE DIAMETERS

Bundling Pressure (psi)	Reduction of Axial Load on Peripheral Elements (lb)	Average Strain ($\times 10^{-6}$ in./in.) Strain Gages				Bundling Pressure (psi)	Reduction of Axial Load on Peripheral Elements (lb)	Average Strain ($\times 10^{-6}$ in./in.) Strain Gages			
		1 & 2	3 & 4	5 & 6	7 & 8			1 & 2	3 & 4	5 & 6	7 & 8
200	500	55	55	58	65	700	1000	133	130	143	143
200	1000	130	130	125	135	700	2000	303	295	308	310
200	1500	218	210	180	200	700	3000	503	495	468	485
200	2000	298	290	203	218	700	3500	588	570	530	553
						700	4000	688	665	580	608
300	500	65	65	73	63	800	1000	128	120	140	140
300	1000	138	140	143	133	800	2000	295	280	303	305
300	1500	220	215	208	215	800	3000	470	455	458	463
300	2000	310	300	255	263	800	3500	583	555	545	553
300	2500	400	385	295	295	800	4000	665	635	600	615
300	3000	478	465	305	308	800	4500	763	725	650	660
						800	5000	860	820	693	698
400	1000	145	140	153	155	900	1000	118	120	130	138
400	2000	323	300	290	303	900	2000	290	285	303	315
400	3000	490	465	384	368	900	3000	488	465	488	490
500	1000	150	145	158	158	900	4000	655	630	618	648
500	2000	320	320	320	325	900	5000	838	805	728	750
500	2500	423	405	385	390	900	6000	1040	1005	815	813
500	3000	508	490	423	442	900	7000	1213	1175	865	840

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Specimen failed at mid-length at discontinuity at an average strain of 1255×10^{-6} in./in. (900 psi bundling pressure).

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The reduction in fracture strain may be attributed to the stress concentration and notch effect due to the discontinuity as in the case of the pinhole in the corroded element.

It is also apparent from Figure 5 that under a bundling pressure of 950 psi, required for adequate friction lockup, the strain distribution was fairly uniform along the length of the modified specimen at strains up to about 600×10^{-6} in./in. However, at higher strain values slip began to occur at the gages located 2-7/8 inches on either side of the center of the test specimen. The results over the central section remained quite uniform until failure occurred. When failure occurred in the center of the modified specimen at an axial load reduction of 7300 pounds on the peripheral elements, the gages located 2-7/8 inches on either side of the fracture were only slightly affected, indicating that friction lockup was still maintained at these locations. Even after failure occurred, a strain of approximately 600×10^{-6} in./in. was retained in the sample only 7/8 inch away from the fracture.

These tests show that there is no apparent correlation between weight and fracture strain. This is illustrated in the plot of fracture strain versus weight per inch of the various specimens tested (Figure 6). In this plot the weight per inch of the specimen is directly related to the weight loss due to corrosion testing. Note that there is little difference between fracture strains for corroded and uncorroded specimens. This supports the conclusion that fracture strain is independent of cross-sectional area and is a material constant for the given test conditions.

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Figure 6. Plot of Fracture Strain versus Weight per Inch

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3.0 CONCLUSIONS

The major conclusions obtained as a result of the room temperature friction lockup tests are as follows:

- 1) There is no apparent correlation of weight per inch of sample with that of fracture strain. (Refer to Figure 6.)
- 2) The tests show that multiple fractures occurred only in the corroded elements. Five of the multiple fractures occurred 1-1/2 to 3-3/8 inches from the center of the specimens. The distance between multiple fractures in a given test specimen varied between 2-3/4 and 3-7/8 inches.
- 3) When fracture within an element occurs, the strain in the element under friction lockup, approximately 2 inches on either side of the fracture, is only slightly altered by the fracture. The strain, however, is altered markedly in regions up to 2 inches from the fracture. This was true for the friction lockup test where bundling pressures on the order of 950 psi were required to produce fracture.
- 4) To produce fracture in 10-inch fuel element specimens at room temperature by friction lockup, it was necessary that the bundling pressures approach 950 psi and the strains in the adjacent elements approach 2500×10^{-6} in./in.
- 5) The range of fracture strains for Oak Ridge specimens was more uniform than for WANL specimens exposed to similar environments.

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4.0 APPENDIX

DESCRIPTION OF FRICTION LOCKUP TEST APPARATUS AND TEST METHODS

The frame of the friction lockup apparatus was a steel tube (10 in. x 6 in. OD x 5 in. ID). The apparatus was constructed to accommodate a seven-element cluster approximately 10 inches long. Three vertical rows of bolts threaded into the frame 30 degrees apart were employed to accurately center the cluster within the frame and to provide rigidity to ensure axial alignment. Hydraulic cylinders in three rows of four cylinders each were threaded into the steel tube 180 degrees opposite the centering bolts. The assembly shown in Figure 7 provided the bundling pressure or lateral load capability necessary to produce friction lockup under various load conditions.

The six outer or peripheral single-hole elements (unfueled) of the test cluster were precisely machined to length (0.250 inches), and the ends were made flat and parallel to provide a uniform distribution of load among the elements and uniform strain in subsequent axial loading. Approximately 0.0035 inch was removed from each of the mating faces of the outer elements to prevent bridging. The 10 inch long, nineteen-hole, fueled elements or test specimens were placed in the center of the cluster.

Single-hole graphite elements were selected for placement around the test specimen because much higher bundling loads could be applied without producing failures and instrumentation could be more easily installed.

To calibrate the test apparatus, a single-hole element was used at the center of the test cluster. This element was also instrumented with resistance strain gages. Ten strain gages, 1/4 inch in length, were attached to each of the outer elements, five on each of the two exposed faces. The gages were located at 1-1/8, 3-1/8, 5-1/8, 7-1/8, and 9-1/8 inch stations along the length of each element. The 10-inch central calibration element, unlike the outer elements, was instrumented on the ID with ten 1/4-inch gages, two at each of the 1, 3, 5, 7, and 9 inch stations.

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Figure 7. Friction Lockup Test Apparatus

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Each of the seven elements was then calibrated in a Wiedemann test machine under compressive loads to 900 pounds to evaluate the performance of the strain gages and to establish uniformity of load and strain distribution with the elements. The results of these calibration tests indicated that uniform distribution of load and strain was obtained for each of the elements.

An assembly of a typical test cluster appears in Figure 8. Steel shims (0.007 x 0.5 x 9.0 in.) were inserted in the interfacial gaps between the outer elements. To provide uniformly distributed lateral loads to the elements, ground steel bars (1/2 x 1 x 10 in.) were placed between the elements, the centering bolts, and the hydraulic cylinders. Two layers of 0.005-inch thick pyrolytic graphite foil with lubricated interfaces were inserted between the backup bars and the outer elements to minimize the friction and the influence of the backup bars and frame on the distribution of load and strain. A thin layer of grease applied to the steel bars proved adequate to hold the two layers of foil in place during the assembly. Considerable care was exercised to prevent contact of any type of lubricant with the element. Prior to assembly the test specimen as well as the peripheral elements were cleansed with acetone and methyl-ethyl ketone to remove any traces of moisture which would tend to lower the coefficient of friction and thus lower the degree of friction lockup in the cluster.

The lightly bundled (with rubber bands) elements with the steel backup bars, pyrofoil, and shims were then carefully centered in the tubular frame. The test specimens were centered longitudinally in the cluster with a 1/8-inch gap at each end. The lateral load was then hydraulically increased to about 10 psi, and the entire assembly was positioned in the test machine. An axial load of several hundred pounds was applied and the shims between the peripheral element interfaces were removed. Zero conditions were assumed at a bundling pressure of 10 psi and an axial load of 250 lb. Figures 7 and 8 show a typical assembly before and after placement in the test fixture. Figure 9 shows the test assembly located between the platen and movable crosshead of the test machine.

The compressive load was incrementally increased on the peripheral elements to approximately 12,000 pounds under a bundling pressure of 10 psi. Strain readings were initially recorded for all gages to establish the uniformity of strain distribution. The bundling

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Figure 8. Test Cluster with Interfacial Shims Placed within Bundling Fixture

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Figure 9. Test Apparatus with a Seven-Element Cluster Located Between Platen and Crosshead of Test Machine

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pressure was then increased to 950 psi and the strain gages were read again; this reading with a bundling pressure of 950 psi and axial load of 12,000 pounds was the new zero. The axial load was then incrementally reduced under a bundling pressure of 950 psi, and the differences in the strain gage readings provided a measure of decrease in strain on the outer elements and an increase of tension strain on the center test specimen.

The average of the strains as measured at each station on the peripheral elements was in good agreement with the average increase in strain at each station on the test element (single hole). As the axial load on peripheral elements was further reduced, slipping became evident near the ends by the divergence of the average strain gage readings at each station as illustrated in Figure 10. This divergence characterizes slip which begins at the ends and gradually approaches the central portion as the axial load is further reduced. Figure 11 shows a curve of maximum strain buildup at the center of the test specimen for various bundling pressures. The occurrence of slip or fracture is also illustrated in Figure 12 by the abrupt divergence of the strain buildup curve in the center of the test element from the average reduction in strain in the peripheral elements.

Because of the good agreement of the reduction in strain in the peripheral elements with the buildup in strain in the single-hole test element, it was assumed that the fracture strain in the test specimens (nineteen-hole) was equal to the average measured strain (reduced) in the peripheral elements at the axial position corresponding to the fracture location on the test specimen. At strain levels of approximately 2500×10^{-6} in./in., the length of the uniformly strained sections is reduced to about 2 inches, 1 inch on either side of center.

Occasional noise was heard during testing; this was concluded to be the result of slip-stick occurrence. The location of the slip could be determined by the degree of discontinuity of strain versus axial load as measured in the peripheral elements. When this occurred, only the strain gages within about an inch were affected. When fracture occurred, a sharp report was heard; again the location was established by observing the calibration data of strain versus load for each station. A longer discontinuity in the curves occurred under fracture and a zone extending to approximately 2 inches on either side of the fracture was affected.

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Figure 10. Strain Distribution Along Length of Test Specimen versus Reduction in Axial Load of Peripheral Elements

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Figure 11. Maximum Strain Buildup at the Center of the Test Specimen for Various Bundling Pressures

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Figure 12. Comparison of Average Strain Reduction in the Peripheral Elements with Tensile Strain Buildup in Single-Hole Test Specimen

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In the course of testing the elements, multiple fractures (two) were obtained in five of the nineteen tests. In all cases of multiple fracture two distinct fractures were heard at either of two different loads or different time intervals. Initial fracture could again be determined by viewing the curves of strain versus load for each station.

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