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FUEL ROD-GRID INTERACTION WEAR: IN-REACTOR TESTS

(LWBR Development Program)

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**BETTIS ATOMIC POWER LABORATORY
WEST MIFFLIN, PENNSYLVANIA**

**Operated for the U. S. Department of Energy by
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FUEL ROD-GRID INTERACTION
WEAR: IN-REACTOR TESTS

(LWBR Development Program)

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FOREWORD

The Shippingport Atomic Power Station located in Shippingport, Pennsylvania was the first large-scale, central-station nuclear power plant in the United States and the first plant of such size in the world operated solely to produce electric power. This program was started in 1953 to confirm the practical application of nuclear power for large-scale electric power generation. It has provided much of the technology being used for design and operation of the commercial, central-station nuclear power plants now in use.

Subsequent to development and successful operation of the Pressurized Water Reactor in the DOE-owned reactor plant at the Shippingport Atomic Power Station, the Atomic Energy Commission in 1965 undertook a research and development program to design and build a Light Water Breeder Reactor core for operation in the Shippingport Station.

The objective of the Light Water Breeder Reactor (LWBR) program has been to develop a technology that would significantly improve the utilization of the nation's nuclear fuel resources employing the well-established water reactor technology. To achieve this objective, work has been directed toward analysis, design, component tests, and fabrication of a water-cooled, thorium oxide fuel cycle breeder reactor for installation and operation at the Shippingport Station. The LWBR core started operation in the Shippingport Station in the Fall of 1977 and is expected to be operated for about 3 to 4 years. At the end of this period, the core will be removed and the spent fuel shipped to the Naval Reactors Expended Core Facility for a detailed examination to verify core performance including an evaluation of breeding characteristics.

In 1976, with fabrication of the Shippingport LWBR core nearing completion, the Energy Research and Development Administration established the Advanced Water Breeder Applications (AWBA) program to develop and disseminate technical information which would assist U.S. industry in evaluating the LWBR concept for commercial-scale applications. The program will explore some of the problems that would be faced by industry in adapting technology confirmed in the LWBR program. Information to be developed includes concepts for commercial-scale prebreeder cores which would produce uranium-233 for light water breeder cores while producing electric power, improvements for breeder cores based on the technology developed to fabricate and operate the Shippingport LWBR core, and other information and technology to aid in evaluating commercial-scale application of the LWBR concept.

All three development programs (Pressurized Water Reactor, Light Water Breeder Reactor, and Advanced Water Breeder Applications) have been administered by the Division of Naval Reactors with the goal of developing practical improvements in the utilization of nuclear fuel resources for generation of electrical energy using water-cooled nuclear reactors.

Technical information developed under the Shippingport, LWBR, and AWBA programs has been and will continue to be published in technical memoranda, one of which is this present report.

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Wear of the Zircaloy cladding of LWBR irradiation test fuel rods, resulting from relative motion between rod and rod support contacts, is reported. Measured wear depths were small, 0.0 to 2.7 mils, but are important in fuel element behavior assessment because of the local loss of cladding thickness, as well as the effect on grid spring forces that laterally restrain the rods. An empirical wear analysis model, based on out-of-pile tests, is presented. The model was used to calculate the wear on the irradiation test fuel rods attributed to a combination of up-and-down motions resulting from power and pressure/temperature cycling of the test reactor, flow-induced vibrations, and assembly handling scratches. The calculated depths are generally deeper than the measured depths.

FUEL ROD-GRIP INTERACTION WEAR: IN-REACTOR TESTS

(LWBR Development Program)

Edited by R.M. Stackhouse

I. INTRODUCTION

The LWBR core employs ordered arrays of long (10 feet), small diameter (0.3 to 0.8 inch), Zircaloy clad, cylindrical fuel elements. The fuel rods are supported axially by threaded end connectors on the rods attached to either the top or bottom baseplate of a module assembly. Each rod is thus fixed at one end and free at the other end. Lateral support for the rods is provided by a series of supports, called grids, at several axial locations along the length of the rods. Each grid contains, for each rod, a hexagonally-shaped cell with a spring and opposing fixed reaction dimples set at 120 degrees circumferentially from the spring (see Figures A-1 and A-2). The spring applies lateral force on the fuel rod in the cell to hold it firmly against the dimples, while allowing relative axial movement between the rod and grid support points during reactor operation. Interaction between the fuel rod and the supporting springs and dimples caused by fuel rod length changes and vibration can result in wear on the Zircaloy cladding of the fuel rods. Wear of the AM-350 stainless steel grid contact points has been found by test experience to be negligible relative to the fuel rod cladding wear.

Local metal removal from the cladding can be caused by the combined effects of three types of interaction between fuel rods and support grids: (1) handling scratches, often along the full rod length, that occur when fuel rods are initially pulled into the grid supports; (2) axial motion of the rod relative to the grid supports due to fuel rod axial expansion and contraction during reactor power cycles and pressure/temperature cycles; and (3) flow-induced vibratory wear.

Loss of cladding thickness resulting from wear is of concern because the thinning of the cladding increases stresses in the thinned section with a consequent reduction in margin-to-failure stress limits, and because of its contribution to a reduction in the grid spring fuel rod support force with potential for reduced rod-to-rod and rod-to-structure clearances. In addition, a complete loss of grid contact force can result in excessive fuel rod vibration, creating a potential wear/fretting condition, as demonstrated in out-of-pile wear tests.

This report presents fuel rod cladding wear data obtained from in-reactor rod bundles tested in the LWBR fuel element development program and compares these data to wear estimates predicted using a model developed from out-of-pile wear tests. The in-pile test results are presented and discussed in Section II. Section III describes the analytical model which was developed empirically from out-of-pile data. A comparison of wear calculated using this model with the in-pile test data is given in Section IV. Conclusions are presented in Section V.

II. IN-PILE TEST RESULTS

A. General

The fuel rods irradiated as part of the LWBR fuel element development program were composed of high density $\text{ThO}_2\text{-UO}_2$ and ThO_2 fuel pellets contained within Zircaloy-4 tubes having outside diameters of approximately 0.30 or 0.57 inch, and lengths of approximately eight feet. The rods were precorrosion filmed before insertion into the grid supports prior to irradiation.

Wear measurements were obtained on 34 fuel rods. These rods were supported laterally by AM-350 stainless steel grids having cell geometry similar to the design presented in Reference (1). This support system makes use of hexagonally-shaped grid cells which contain a spring and two dimples, or two pairs of dimples, set at 120 degrees circumferentially from each other. Figures A-1 and A-2 of Appendix A illustrate grid cells with two dimples, and two pairs of dimples, opposing the spring. The fuel rods, their support systems, and the coolant conditions are described in detail in Appendix A.

B. Summary of Wear Depth Measurements

Altogether 1298 support contact points are represented by the 34 fuel rods examined. (The number of support contact points for each rod was determined by multiplying the number of spring and dimple reaction points at each grid level by the number of grid levels supporting the rod. The multiple sets of wear marks on several rods, as indicated in Table A-II of Appendix A, also are included in the total.) Only 176 contact points were directly measured. The remaining 1122 support contact points that were not measured because they were undetectable or obviously shallow are assumed to have wear depths of 0.0 to 0.5 mils. The wear depth measurements are summarized in the histogram of Figure 1. Ninety-five percent of the wear spot depths are 1.0 mil or less, 4 percent are 1.1 to 2.0 mils, and 1 percent are 2.1 to 2.7 mils deep.

C. Method of Examination

During examination of the irradiated fuel rods, wear depths were measured at the free end grid levels, located as shown in Figure 2, and also at other levels where visual examination indicated that significant cladding wear had occurred. Other cladding wear spots that appeared to be smaller than 0.5 mil in depth were usually not measured. For all but six of the 34 rods included in this report, maximum rod wear occurred at the free-end grid support location. The occurrence of maximum wear at the rod free ends is attributed to the fact that this location is where the longest rod axial

FIGURE I
HISTOGRAM OF IRRADIATED FUEL ROD WEAR
DEPTH MEASUREMENTS

FIGURE 2
SCHEMATIC REPRESENTATION OF GRID
LOCATION AND ROD ORIENTATION IN A
TYPICAL LWBR IRRADIATION TEST

movement relative to grids occurs during power and pressure/temperature cycling, with resulting higher reciprocating wear. Flow-induced vibrational wear also is expected to be a maximum at the free end of top mounted rods because of rod excitation by coolant flow impingement on the ends of the rods.

Wear mark depth was measured nondestructively with a profilometry instrument considered to have an accuracy of ± 0.2 mil. Figure 3 shows circumferential profilometry traces obtained at a typical wear mark. In addition, destructive examination of wear depth was performed metallographically on some rods by polishing transverse rod sections through the wear mark in successive planes approximately 20 to 30 mils apart. Photomicrographs taken at each plane were measured to obtain wear depth. The depth of the wear spot shown in the photomicrograph of rod 79-524 in Figure 4 is 2.4 mils. The profilometry measurement of 2.7 mils agreed well with the metallographic measurement.

All wear measurements, and their location with respect to individual grids and to grid springs and dimple reaction points, are presented in Appendix A. Table I includes the maximum measured free-end wear depth for each of the 34 rods. It is primarily these wear data that are discussed in this report. Also included in Table I are test reactor exposure times, numbers of actual power and pressure/temperature cycles, stroke lengths, and measured overall rod length increases.

D. Rod Wear Depth versus Test Life

Two parameters that indicate the length of irradiation test life are the number of EFPH (effective full power hours) and the total number of actual power and pressure/temperature reactor cycles experienced by the fuel rods. Maximum wear depths measured on the irradiated fuel rods are plotted in Figures 5 and 6 in order to show the relationships of wear to these parameters. Figures 5 and 6 indicate that wear depth does not increase significantly with increasing EFPH or reactor cycles, but remains relatively constant. This observed quasi-equilibrium state of nearly constant wear depth with increasing test life is a result of continuing rod axial growth during reactor operation, and is consistent with the analysis model described in Section III.

FIGURE 3. PROFILOMETER TRACES ACROSS THE SPRING WEAR SPOT AT THE FREE-END GRID ON ROD 79-524

FIGURE 4. PLANE OF MAXIMUM WEAR AT FREE-END GRID ON ROD 79-524 (100X)

TABLE I
MAXIMUM MEASURED FREE-END WEAR DEPTH ON IRRADIATED FUEL RODS

Rod No.	EFPH(1)	Number of Cycles			Stroke Length(5) (mils)		Maximum Measured Free-End Wear Depth	Overall Rod Length Increase, ΔL
		Power(2)	P/T(3)	Total	Power	P/T(3)	(mils)	(mils)
79-613	5900	65	9	74	40	150	0.3	61
79-614D	5900	65	9	74	40	150	0.2	35
79-617	5900	65	9	74	40	150	0.4	112
79-622	5900	65	9	74	40	150	2.1	115
79-623	5900	65	9	74	40	150	2.5	119
79-619	19970	123	68	191	68	208	0.5	266
79-621	19970	123	68	191	68	208	0.4	346
79-624	19970	123	68	191	68	208	1.0 ⁽⁶⁾	468
79-630	19970	123	68	191	68	208	0.3 ⁽⁶⁾	273
79-610	3340	55	4	59	40	150	0.2	76
79-631	3340	55	4	59	40	150	0.2	60
79-632	3340	55	4	59	40	150	0.2	49
79-439	3690	42	14	56	40	150	1.5	138
79-440	8540	78	16	94	40	150	1.7	177
79-441D	4850	36	2	38	40	150	2.1	129
79-442 ⁽⁴⁾	3690	42	14	56	40	150	0.6	60
79-442 ⁽⁴⁾	4850	36	2	38	40	150	0.5	75
79-443D	3690	42	14	56	40	150	1.0	132
79-444 ⁽⁴⁾	3690	42	14	56	40	150	0.3	99
79-444 ⁽⁴⁾	4850	36	2	38	40	150	0.4	60
79-445 ⁽⁴⁾	3690	42	14	56	40	150	1.2	147
79-445 ⁽⁴⁾	4850	36	2	38	40	150	1.6	45
79-449	8540	78	16	94	40	150	1.8	213
79-450	4850	36	2	38	40	150	1.4	110
79-455	3690	42	14	56	40	150	0.0 ⁽⁶⁾	108
79-459	4850	36	2	38	40	150	0.4 ⁽⁶⁾	90

NOTE: See following page for footnotes.

TABLE I (continued)

Rod No.	EFPH ⁽¹⁾	Number of Cycles			Stroke Length ⁽⁵⁾ (mils)		Maximum Measured Free-End Wear Depth	Overall Rod Length Increase, ΔL
		Power ⁽²⁾	P/T ⁽³⁾	Total	Power	P/T ⁽³⁾	(mils)	(mils)
79-502	12080	122	37	159	40	150	0.8	125
79-504D	12080	122	37	159	40	150	1.2 ⁽⁶⁾	74
79-509	12080	122	37	159	40	150	1.6 ⁽⁶⁾	186
79-513	12080	122	37	159	40	150	1.4	166
79-514	12080	122	37	159	40	150	1.8	151
79-516	12080	122	37	159	40	150	2.2	146
79-517	12080	122	37	159	40	150	2.2	194
79-522	12080	122	37	159	40	150	1.8	222
79-524	12080	122	37	159	40	150	2.7	168
79-572	14360	145	41	186	40	150	1.5	245
79-586 ⁽⁴⁾	4051	43	12	55	40	150	1.0	102
79-586 ⁽⁴⁾	3381	26	11	37	40	150	1.5	77
79-586 ⁽⁴⁾	6928	76	18	94	40	150	2.5	73

(1) EFPH = Effective full power hours.

(2) A reactor power cycle is a change in power from 20% to 100% power and then back to 20% power, with no depressurization.

(3) P/T = Pressure/temperature cycle. A pressure/temperature cycle is the establishment of system pressure followed by a period of operation at pressure and power, and finally withdrawal of power and system pressure to ambient conditions.

(4) Rods had more than one set of wear marks as a result of removal and reassembly during irradiation testing.

(5) Stroke length is the length that a fuel rod axially expands and subsequently contracts during reactor power and pressure/temperature cycling. Here, it is the length of rod relative expansion or contraction at the free-end grid.

(6) These six rods show deepest wear at a grid location other than the free end, as indicated in Table II.

FIGURE 5. ROD MAXIMUM WEAR DEPTH VERSUS OPERATING TIME

FIGURE 6 . MAXIMUM WEAR DEPTH VERSUS NUMBER OF POWER AND PRESSURE/TEMPERATURE CYCLES

E. Other Observations

1. Axial Location of Deepest Wear

The deepest wear mark on 28 of the 34 rods was located at the free end. The six rods containing a deeper wear mark at a grid level other than the free end are listed in Table II, which includes the depth and location of the free-end wear mark for each of the six rods, as well as the maximum wear depth and location for comparison. Differences in wear mark depth between the maximum and the free end vary from 0.1 to 1.0 mil. The differences between the spring forces at the grids of maximum wear and at the free ends are small for all six rods, and therefore the greater wear cannot be attributed to excessive spring forces. It was noted, however, that maximum wear on one of the six rods, 79-624, occurred at the location of maximum rod bowing. Furthermore, maximum wear on rod 79-509 occurred, as indicated in Table A-II, where the rod contacted an auxiliary support point formed in the grid cell wall. These two observations indicate that the occurrence of maximum wear away from the free-end grids of these six rods may be related to bowing and other off-nominal conditions.

2. Effects of Rod Mounting, Rod Diameter, and Overhang Length on Rod Wear

The free-end maximum wear depths for the 34 irradiation tested fuel rods are summarized in Table III. The data are arranged to permit a comparison of wear as a function of top or bottom mounting, rod diameter, and overhang length.

a. Top versus Bottom Mounting

The average of the maximum free-end wear depths for top mounted rods is 1.4 mils, compared with 0.9 mil for the bottom mounted rods. This condition is attributed to greater vibratory wear experienced by the top mounted rods due to the impingement of the coolant flow on the bottom free ends of these rods. Flow velocity of the coolant ranged from 12 to 18 feet per second, as indicated in Appendix A.

TABLE II
AXIAL DISTRIBUTION OF DEEPEST WEAR MARKS⁽¹⁾

Rod No.	Mounted End	Maximum Depth Wear Marks		Free End Wear Marks	
		Depth (mils)	Grid Level ⁽²⁾	Depth (mils)	Grid Level ⁽²⁾
79-624	Top	1.6	3	1.0	1
79-630	Bottom	1.0	4	0.3	12
79-455	Bottom	1.0	2	0.0	7
79-459	Bottom	0.5	2	0.4	7
79-504D	Top	1.4	2	1.2	1
79-509	Bottom	1.9	5	1.6	8

(1) All other 28 rods studied exhibited the maximum depth wear marks at the free-end grid.

(2) Grid levels are numbered upward from the bottom support plate, as shown in Figure 2. The total number of grid levels for each test is given in Table A-I.

TABLE III
ROD FREE-END MAXIMUM WEAR COMPARISON

Rod Diameter (in.)	Top Mounted Rods			Bottom Mounted Rods		
	Rod Number	Max. Wear Depth at Free End (mils)	Overhang Length (in.) ⁽¹⁾	Rod Number	Max. Wear Depth at Free End (mils)	Overhang Length (in.) ⁽¹⁾
0.25/0.30 ⁽²⁾	79-622	2.1	1.9	79-613	0.3	1.9
	79-623	2.5	1.9	79-614D	0.2	1.9
				79-617	0.4	1.9
	79-621	0.4	1.9	79-619	0.5	1.9
	79-624	1.0	1.9	79-630	0.3	1.9
	79-631	0.2	1.9	79-610	0.2	1.9
	79-632	0.2	1.9			
	79-439	1.5	2.65	79-442	0.6	2.65
	79-440	1.5	2.65	79-443D	1.0	2.65
	79-441D	2.1	2.65	79-455	0.0	2.65
	79-444	0.4	2.65	79-459	0.4	2.65
	79-445	1.6	2.65			
	79-449	1.8	2.65			
	79-450	1.4	2.65			
0.52/0.57 ⁽²⁾	79-502	0.8	1.25	79-509	1.6	1.25
	79-504D	1.2	1.25	79-513	1.4	1.25
	79-514	1.8	1.25	79-516	2.2	1.25
	79-524	2.7	1.25	79-517	2.2	1.25
				79-522	1.8	1.25
	79-586	2.5	3.15	79-572	1.5	2.15
	Avg. = 1.4 mils			Avg. = 0.9 mil		

(1) Overhang Length is the distance from the axial centerline of the free-end grid to the end of the rod, as shown in Figure 2.

(2) The outside diameter of each rod is reported in Table A-I.

b. Rod Diameter

Twenty-three of the fuel rods had a diameter of 0.25/0.30 inch, and 11 had a diameter of 0.52/0.57 inch. The average of the maximum wear depths on the free ends of the smaller diameter rods is 0.9 mil compared with the average of 1.8 mils measured on the larger diameter rods. The greater wear on the larger diameter rods may be attributed to increased reciprocating wear resulting from the larger spring forces, shown in Table IV, used to support the larger diameter rods. The average of the spring forces on the 11 large diameter rods was 10.8 pounds; that on the 23 small diameter rods was 2.9 pounds. In addition, the larger diameter rods may have experienced more vibrational wear because they were supported by only two dimples per grid cell instead of four for the smaller rods, as shown in Figures A-1 and A-2.

c. Rod Free-End Overhang Length

Rod free-end overhang would be expected to have a significant effect on rod free-end vibratory wear if overhang were excessive. No correlation of free-end rod wear with free-end overhang length, however, is apparent for the 1.9 to 3.15 inches of free-end overhang present on these rods.

F. Wear Mark Geometry

Photomicrographs of wear marks on four fuel rods are presented in Figures 7 to 10. Figures 7 and 8 illustrate the wear marks at the free-ends of rods 79-502 and 79-524. The wear mark depths on rod 79-502 were 0.6 to 0.8 mil, and those on rod 79-524 were 2.6 to 2.7 mils. Both of these two rods have clearly defined reciprocating wear marks, similar to that illustrated in Figure 12. Rod 79-524, with the greater measured wear depth, also has greater wear mark width, which is to be expected. In addition to a difference in size, the wear marks on these two rods have a difference in appearance. The reciprocating wear marks of rod 79-524 appear to be overlaid with deeper

TABLE IV
MEASURED VERSUS CALCULATED WEAR DEPTH

Rod Number	Wear Model Parameters			Measured Maximum Wear Depth On Free End of Rod (mils)	Calculated Wear Depth ⁽²⁾	
	Avg. Spring Force, L (1b)(1)	Mean Stroke Length, S (in.)(2)	Effective Reciprocating Cycles, N _R (2)		Reciprocating (mils)	Total ⁽⁴⁾ (mils)
79-613	2.8	0.059	52	0.3	0.9	1.6
79-614D	1.8	0.053	74	0.2	1.1	1.6
79-617	2.2	0.071	32	0.4	<0.5	1.4
79-622	2.5	0.072	31	2.1	<0.5	1.5(2.1)
79-623	2.5	0.072	31	2.5	<0.5	1.5(2.1)
79-619	3.3	0.156	84	0.5	2.2	2.6
79-621	3.3	0.156	65	0.4	1.8	2.4
79-624	2.8	0.156	48	1.0	1.2	2.2
79-630	3.1	0.156	83	0.3	2.1	2.6
79-610	3.4	0.053	33	0.2	<0.5	1.5
79-631	2.5	0.051	41	0.2	0.6	1.5
79-632	2.7	0.049	49	0.2	0.8	1.5
79-439	3.3	0.099	26	1.5	<0.5	1.6
79-440	2.6	0.088	32	1.7	<0.5	1.6(2.2)
79-441D	2.1	0.057	13	2.1	<0.5	1.2(2.0)
79-442(3)	4.6	0.077	42	0.6	0.8	1.8
79-442(3)	3.9	0.050	21	0.5	<0.5	1.3
79-443D	3.1	0.097	27	1.0	<0.5	1.6
79-444(3)	3.6	0.090	31	0.3	<0.5	1.6
79-444(3)	2.5	0.048	26	0.4	<0.5	1.3
79-445(3)	3.2	0.102	25	1.2	<0.5	1.6
79-445(3)	2.2	0.046	34	1.6	<0.5	1.4(2.2)
79-449	2.7	0.087	26	1.8	<0.5	1.5(2.1)
79-450	2.3	0.055	15	1.4	<0.5	1.2(2.0)
79-455	3.2	0.091	30	0.0	<0.5	1.6
79-459	2.7	0.052	18	0.4	<0.5	1.2
79-502	11.2	0.094	76	0.8	1.7	2.3
79-504D	14.0	0.080	103	1.2	2.1	2.4
79-509	12.8	0.099	56	1.6	1.3	2.1
79-513	12.0	0.099	62	1.4	2.0	2.2
79-514	15.2	0.099	69	1.8	1.7	2.4
79-516	10.7	0.099	71	2.2	1.6	2.2
79-517	10.4	0.099	54	2.2	1.2	2.0(2.5)
79-522	11.2	0.099	47	1.8	1.1	2.0
79-524	18.0	0.099	62	2.7	1.6	2.4(2.7)

TABLE IV (continued)

Rod Number	Wear Model Parameters			Measured Maximum Wear Depth On Free End of Rod (mils)	Calculated Wear Depth ⁽²⁾	
	Avg. Spring Force, L (1b)(1)	Mean Stroke Length, S (in.)(2)	Effective Reciprocating Cycles, N_R (2)		Reciprocating (mils)	Total ⁽⁴⁾ (mils)
79-572	4.6	0.096	49	1.5	0.9	1.7
79-586(3)	8.1	0.095	29	1.0	<0.5	1.5
79-586(3)	7.0	0.106	25	1.5	<0.5	1.5
79-586(3)	5.4	0.090	60	2.5	1.1	1.8(2.3)

- (1) Average spring force is defined here as the average of the spring forces measured before and after irradiation testing at the free-end grid cell supporting each rod. The maximum difference between the before-and after-testing spring forces was 3.6 pounds.
- (2) See Appendix C for sample calculations of mean stroke length, number of effective reciprocating cycles, and wear depth.
- (3) Rods had more than one set of wear marks as a result of removal and reassembly during irradiation testing.
- (4) The total calculated wear depth is the sum of the reciprocating wear, plus an allowance equivalent to one or two mils (the values in parentheses represent the two mil allowance) of wear due to vibration and to scratches incurred during handling and assembly, as discussed in Section III.C. The procedure for including the one or two mils allowance for vibration and scratching in total calculated wear depth is described in Appendix C.

Reaction
Points

6.67

0.6 mil Depth

6.67

0.6 mil Depth

Wear Mark Length

Rod
Diameter

Wear Mark
Width

Spring

6.67

0.8 mil Depth

FIGURE 7

PHOTOGRAPHS OF WEAR MARKS ON FUEL ROD 79-502 AT GRID NO. 1 (FREE END)

6.67X

2.6 mil Depth

6.67X

2.6 mil Depth

Reaction
Points

Wear Mark Length

Rod
Diameter

6.67X

2.7 mil Depth

Wear Mark
Width

Spring

FIGURE 8

PHOTOGRAPHS OF WEAR MARKS ON FUEL ROD 79-524 AT GRID NO. 1 (FREE END)

markings not present on rod 79-502. These additional markings on rod 79-524 are attributed to vibratory wear. Photographs of the wear marks at the free-ends of test rods 79-444 and 79-441D are shown in Figures 9 and 10. These rods also show reciprocating wear marks, but not as clearly as rods 79-502 and 79-524. Unlike rods 79-502 and 79-524, rods 79-444 and 79-441D were removed and reinstalled in the test bundle, and were therefore subject to more handling scratches. The multiple sets of wear marks, in addition, indicate that the rods were probably reassembled at different orientations after each examination. The reciprocating wear marks on rod 79-441D have greater size and depth (2.1 mils) than those on rod 79-444 (0.4 mil) and appear to be overlaid with additional markings not so much in evidence on rod 79-444. These additional markings also are interpreted as evidence of vibrational wear.

In summary, the visual appearance of the wear marks on four test rods confirms that rods with deeper measured wear depth also have wider wear marks. This observation is in agreement with the wear model assumption (discussed in Section III) that the cross-sectional area of a wear spot is a segment of a circle. The larger wear markings also show indications of what is believed to be vibratory wear.

III. ANALYTICAL MODEL

A. Reciprocating Wear Model

The reciprocating wear model used in this report is based upon results obtained from out-of-pile reciprocating wear tests designated REM 124 and REM 128. The REM 124 testing was performed in static water at 500 and 600°F; the REM 128 tests were performed dry at room temperature. These tests and their results are described in Appendix B.

Upper
Reaction
Point

6.67X

0.4 mil Depth (max)

Wear Mark Length

Rod
Diameter

Spring

6.67X

0.4 mil Depth (max)

Wear
Mark
Width

Lower
Reaction
Point

6.67X

0.3 mil Depth (max)

FIGURE 9

PHOTOGRAPHS OF WEAR MARKS ON FUEL ROD 79-444 AT GRID NO. 1 (FREE END)

11X

1.5 mils Depth (max)

Upper
Reaction
Points

11X

1.6 mils Depth (max)

Wear Mark
Length

↑
Rod
Diameter
↓

11X

1.2 mils Depth (max)

Spring

↑
Wear Mark
Width
↓

11X

1.5 mils Depth (max)

Lower
Reaction
Points

11X

2.1 mils Depth (max)

FIGURE 10

PHOTOGRAPHS OF WEAR MARKS ON FUEL ROD 79-441D AT GRID NO. 1 (FREE END)

The relationship between wear depth and number of cycles for 0.304 inch diameter rods is shown in Figure 11. The curves in Figure 11 show that wear depth per cycle decreases as the number of cycles increases, and also that for a given number of reciprocating wear cycles, greater wear occurs with longer stroke lengths.

The REM 128 tests, which covered a greater range of spring load than did the REM 124 tests, indicated that cladding thickness loss was approximately proportional to the cube root of the spring load. The REM 124 test data tended to confirm this relationship, although the small spring load range and the data scatter in REM 124 results do not present a strong correlation of the effect of spring load.

Because rods of differing diameters were studied in the REM 124 and REM 128 tests, an improved correlation is obtained if the data are arranged on the basis of wear spot cross-sectional area rather than depth. The basic assumption is that the wear mark is in the form of a flat, elongated-oval spot on the cladding cylindrical surface, as shown in Figure 12. The cross-sectional area of the material removed during formation of the wear mark is considered to be a segment of a circle as shown in the transverse view of the wear mark in Figure 12. This approach has the advantage of producing a model that may be applied to any diameter rod. When the effect of stroke length, number of cycles, and spring load are combined, the resulting equation is of the form

$$A = L^{1/3} (aS + b) (c \log N_R + d) \quad (1)$$

where: L = spring load, pounds

S = stroke length, the length of rod movement relative to a given support point, inches

N_R = number of effective reciprocating wear cycles (defined by Equation (3) in the following section)

A = wear spot cross-sectional area considered as a segment of a circle, square inches

a,b,c,d = constants determined by fitting the data

FIGURE II. OUT-OF-PILE ROD WEAR DEPTH VERSUS
NUMBER OF WEAR CYCLES.

FIGURE 12
SCHEMATIC REPRESENTATION OF A
RECIPROCATING WEAR MARK PRODUCED
BY A CYLINDRICAL CONTACT POINT

This relationship applies specifically to wear on Zircaloy rods supported by AM-350 springs and dimples that have cylindrically-shaped contact points; nearly all of the REM 124 and REM 128 tests were performed using these materials and support configurations. It is to be noted that the axes of the cylindrical grid contact surfaces are transverse to the rod axis, as shown in Figures A-1 and A-2 of Appendix A.

Figure 13 includes the REM-124 and REM 128 test data plotted in the form of Equation(1). Values for A in the ordinate of Figure 13 were obtained by converting the measured wear depths to cross-sectional areas by means of Figure 14. The straight line curve that bounds all the data points for N greater than 30 cycles is defined by

$$A = L^{1/3} (22.7 S + 1.6) (2.13 \log N_R - 3.13) (10^{-5}) \quad (2)$$

Equation (2) may be used to conservatively predict reciprocating wear spot cross-sectional area for any combination of stroke length, number of cycles greater than 30, and spring load within the range of test data. Depth of wear spots then may be obtained from the geometrical relationship of cross-sectional area to depth for any rod diameter. The validity of this relationship is illustrated by the photomicrograph of the cladding wear mark in Figure 4, and by the schematically depicted reciprocating wear mark in Figure 12. This relationship is shown graphically in Figure 14 by curves for rods having diameters of 0.300 and 0.570 inches. Curves for rods of other diameters may be readily derived using the relationship included in Figure 14. Equation (2) is not valid when N_R is less than 30. (See Figure 13) In this circumstance, an arbitrary wear depth of 0.0005 inch could be assigned to the wear spot.

B. Discussion of Cladding Wear on an Operating Fuel Rod

Early in the life of a fuel rod there may be very little interaction between the fuel pellets and the cladding, provided that a large enough annular clearance (fuel-cladding gap) is present between the fuel and cladding, so that rod axial elongation and contraction during a reactor power

FIGURE 13. OUT-OF-PILE RECIPROCATING WEAR DATA.

FIGURE 14. WEAR SPOT CROSS-SECTIONAL AREA VERSUS DEPTH ON 0.300-INCH AND 0.570-INCH-DIAMETER FUEL RODS.

cycle is due only to thermal expansion of the cladding. The portion of the rod supported by the free-end grid (Figure 2) will exhibit the greatest relative axial motion, while those portions of the rod closer to the fixed end will show less movement corresponding to lesser distance from the fixed end. Later in life, after the fuel pellets and cladding have come into contact as a result of fuel volume swelling and creep shrinkage of the cladding under pressure of the coolant, the extent of rod movement during reactor cycling will be influenced by the extent of the interaction between the fuel and cladding. With full interaction, rod movement is proportional to the thermal expansion of the fuel pellets, and maximum rod elongation occurs. Permanent length increase in rods with little or no fuel-cladding interaction results almost solely from irradiation induced growth of the cladding. In fuel rods with considerable interaction, axial growth is approximately twice that in rods with little interaction. This permanent and progressive rod growth relative to the contacting grid distributes reciprocating and vibrational rod wear over a length of the rod and, therefore, limits the depth of wear at any given support point. The number of effective wear cycles experienced by any support point on a rod can be expressed by

$$N_R = \frac{SN_A}{\Delta L} \quad (3)$$

where: N_R =number of effective reciprocating wear cycles on the rod. If N_R exceeds N_A because S is greater than ΔL , N_A should be used in the wear area calculation, Equation (2).

S = stroke length, the length of rod relative movement at a given support point, inches

N_A = actual number of reciprocating cycles accumulated by the fuel rod

ΔL = permanent length increase exhibited by the irradiated rod at a given support point, inches

Equation (3) demonstrates that the number of effective cycles occurring at a support point decreases as the permanent overall length of the rod increases. Equation (3) also shows that, because N_R is directly proportional to stroke length S , maximum reciprocating wear is to be expected on the free end of rods in accordance with the mathematical wear model, Equation (2).

C. Combined Wear

Vibratory wear was not accounted for in Equation (2), the expression for predicting reciprocating wear spot cross-sectional area. The combined effects of flow-induced vibration, assembly scratching, and handling are provided for by making an allowance for these mechanisms. The depth allowance is incorporated into the wear area equation by considering it as wear on an unworn rod; it is not simply added to a pre-existing reciprocating wear spot. This is because the wear rate decreases as wear depth increases, due to the increasing width of the wear spot on the cylindrical rod surface. The effect of the vibratory wear, therefore, is considered to be an addition to the number of wear cycles that a given rod location experiences. The total wear spot cross-sectional area due to all mechanisms may then be calculated using the increased number of cycles, as shown in the relationship

$$A = L^{1/3} (22.7 S + 1.6) (2.13 \log N - 3.13) (10^{-5}) \quad (4)$$

where: A = wear spot cross-sectional area, square inches. Depth of wear spot can be obtained from A by means of Figure 14.

L = spring load, pounds

S = stroke length, the length of rod movement at a given support point, inches

N = total number of effective wear cycles = $N_R + N_V$. N_R is the number of effective reciprocating wear cycles. N_V is the number of reciprocating wear cycles required to produce a wear spot of a specified depth on an unworn rod of the type being analyzed, under identical conditions of spring load and axial motion.

Appendix C describes how stroke length was determined for the irradiation tested fuel rods, shows how the effective number of reciprocating wear cycles and mean stroke lengths were obtained, and illustrates the method of calculating combined wear for test rod 79-522.

IV. COMPARISON OF MAXIMUM MEASURED WEAR DEPTHS WITH MODEL PREDICTIONS

In order to evaluate the predictive capability of the wear models, wear depths at the free end of the 34 fuel rods studied were calculated. Values of one and two mils allowance for vibratory wear depth were investigated. The vibratory wear was taken into account, as shown in the sample calculation in Appendix C, by calculating the number of effective cycles required to produce either a one mil or two mil deep wear mark on the unworn surface of each rod. Table IV presents a comparison of maximum measured cladding wear depths at free-end grids with those calculated by means of the wear depth models, Equations (2) and (4). One set of values in Table IV represents wear depths calculated on the basis of reciprocating wear only (i.e., Equation 2). The second set includes the wear due to reciprocating rod motion combined with wear due to the equivalent of one or two mils of wear due to vibration and scratching. The calculated reciprocating wear depths are approximately 0.5 to 1.5 mils lower than the calculated combined wear depths.

Approximately three quarters of the calculated values of combined wear depth equal or exceed the maximum measured free-end values. For 10 of the rods, however, the calculated wear depths that include only a one mil allowance for vibration and scratching are less than the maximum measured values by 0.1 to 1.0 mil. Figure 15 presents the comparisons graphically. The 10 points that lie under the dashed line represent the rods for which the calculated combined wear depths are less than the maximum depths measured at the free end grids. The combined wear for these 10 rods was recalculated, using an allowance of two mils for vibratory wear. These values, also included in Table IV, leave only four rods (79-623, 79-441D, 79-517, and 79-586) underpredicted by 0.1 to 0.4 mils. It should be noted that nine of the ten underpredicted rods were top mounted and, as discussed in Section II.E., top mounted rods showed an average of 55 percent greater wear than bottom mounted rods. This fact appears to explain why a greater allowance for vibratory wear is required for these rods.

FIGURE 15. CALCULATED VERSUS MAXIMUM FREE-END MEASURED WEAR DEPTH ON IRRADIATED FUEL RODS

V. CONCLUSIONS

1. Maximum measured wear depth on the irradiation tested fuel rods supported in grids having geometry similar to the LWBR design was 2.7 mils, and was located at the free-end grid support of a top-mounted fuel rod.
2. Fuel rod wear was deepest at the rod free-end grid support on 28 of 34 rods.
3. Top mounted rods showed greater wear depth at the free-end grid support than bottom mounted rods. This condition is attributed to greater vibratory wear experienced by the top mounted rods due to impingement of the coolant flow on the bottom free-ends of these rods.
4. Wear depth on fuel rods that accumulated a high number of effective full power hours or power and pressure/temperature cycles was not significantly greater than that on rods with shorter test lives. This behavior is in accordance with the basis for the wear analysis model and is a result of rod axial growth during reactor operation.
5. The maximum measured wear depths were generally less than the total amount of wear predicted by a wear analysis model developed from out-of-pile reciprocating wear tests. The predicted values included reciprocating wear, plus an allowance for vibratory wear and assembly and handling scratches.
6. A high proportion, approximately 95%, of the rod-grid contact points examined showed low wear of less than one mil depth.
7. High wear is sometimes found at contact points associated with off-nominal conditions such as high rod bowing or contacts between the rod and grid at other than the spring and dimples.

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APPENDIX A

DESCRIPTION OF FUEL RODS

Table A-I describes the 34 fuel rods included in this study. These rods were supported in grids having cell geometry similar to the LWBR design. The support system associated with these rods made use of hexagonally-shaped cells which contained a spring and two reaction dimples for large (0.57 inch) diameter rods, or a spring and two pairs of upper and lower reaction dimples for small (0.30 inch) diameter rods, set at 120 degrees circumferentially from each other. Figures A-1 and A-2 illustrate cells having two dimples or two pairs of dimples opposing the grid cell spring.

Table A-II presents the in-pile test fuel rod wear data.

TABLE A-I
DESCRIPTION OF FJEL RODS AND SUPPORT SYSTEMS

<u>Rod No.</u>	<u>Rod Outside Diameter (inches)</u>	<u>Rod Length (inches)</u>	<u>Type of Support System</u>	<u>Mounted End (1)</u>	<u>Grid Material⁽³⁾</u>	<u>Number of Grids</u>	<u>Coolant Velocity⁽⁴⁾ (ft/sec.)</u>
79-613	0.301	93	(2)	B	AM-350	7	18
79-614D	0.301	93	(2)	B	AM-350	7	18
79-617	0.301	93	(2)	B	AM-350	7	18
79-622	0.301	93	(2)	T	AM-350	7	18
79-623	0.301	93	(2)	T	AM-350	7	18
79-619	0.301	93	(2)	B	AM-350	12	18
79-621	0.301	93	(2)	T	AM-350	12	18
79-624	0.301	93	(2)	T	AM-350	12	18
79-630	0.301	93	(2)	B	AM-350	12	18
79-610	0.301	93	(2)	B	AM-350	7	18
79-631	0.301	93	(2)	T	AM-350	7	18
79-632	0.301	93	(2)	T	AM-350	7	18
79-439	0.252	94/95	(2)	T	AM-350	7	18
79-440	0.252	94/95	(2)	T	AM-350	7	18
79-441D	0.256	94/95	(2)	T	AM-350	7	18
79-442	0.255	94/95	(2)	B	AM-350	7	18
79-443D	0.256	94/95	(2)	T	AM-350	7	18
79-444	0.256	94/95	(2)	T	AM-350	7	18
79-445	0.252	94/95	(2)	T	AM-350	7	18
79-449	0.255	94/95	(2)	T	AM-350	7	18
79-450	0.256	94/95	(2)	T	AM-350	7	18
79-455	0.256	94/95	(2)	B	AM-350	7	18
79-459	0.256	94/95	(2)	B	AM-350	7	18

TABLE A-I (continued)

Rod No.	Rod Outside Diameter (inches)	Rod Length (inches)	Type of Support System	Mounted End (1)	Grid Material (3)	Number of Grids	Coolant Velocity (ft/sec.) (4)
79-502	0.527	91	(2)	T	AM-350	8	12
79-504D	0.523	91	(2)	T	AM-350	8	12
79-509	0.523	91	(2)	B	AM-350	8	12
79-513	0.568	91	(2)	B	AM-350	8	12
79-514	0.569	91	(2)	T	AM-350	8	12
79-516	0.571	91	(2)	B	AM-350	8	12
79-517	0.568	91	(2)	B	AM-350	8	12
79-522	0.522	91	(2)	B	AM-350	8	12
79-524	0.567	91	(2)	T	AM-350	8	12
79-572	0.568	93	(2)	B	AM-350	6	13
79-586	0.568	96	(2)	T	AM-350	6	13

(1) B = Bottom; T = Top

(2) These rods were supported laterally in hexagonally-shaped grid cells which contained a spring and two dimples for large diameter rods, or a spring and two pairs of dimples for small diameter rods, set at 120 degrees circumferentially from each other, as shown in Figures A-1 and A-2.

(3) AM-350 stainless steel. Nominal composition (weight percent): 16.5 Cr, 4.5 Ni, 2.5 Mo, 0.02-0.06 C, 0.01-0.08 N, balance Fe.

(4) Coolant temperature and pressure were approximately 530 to 600°F and 2000 to 2100 psi.

TABLE A-II
IN-PILE TEST FUEL ROD WEAR DATA

Rod No.	Exposure Time (EFPD)	Grid No. & Location (1)	Rod Wear Depth (mils)	Grid Element (2)
79-613	5900	7, Free End	0.3	S
79-614D	5900	7, Free End	0.2	(3)
79-617	5900	7, Free End	0.4	(3)
79-622	5900	1, Free End	0.5	S
			1.1, 2, 1	R
79-623	5900	1, Free End	2.5 (4)	L-R
		1, Free End	2.5 (5)	L-R
79-619	19970	12, Free End	0.3	S
			0.6	U-R
			0.5	L-R
79-621	19970	1, Free End	0.4	S
			0.4	U-R
			0.4	L-R
79-624	19970	1, Free End	0.8	S
			1.0	U-R
			0.9	L-R
79-624	19970	2, 13.5 in. from Free End Grid	0.8	S
			0.8	U-R
			0.9	L-R
79-624	19970	3, 27.5 in. from Free End Grid	0.9	S
			0.8	U-R
			1.6	L-R
			0.7 (5)	S
79-624	19970	4, 41.5 in. from Free End Grid	0.5	S
			0.6	U-R
			0.4	L-R
79-624	19970	5, 55.5 in. from Free End Grid	0.3	S
			0.4	U-R
			0.4	L-R

TABLE A-II (continued)

Rod No.	Exposure Time (EFPH)	Grid No. & Location (1)	Rod Wear Depth (mils)	Grid Element (2)
79-630	19970	12, Free End	0.3	S
			0.3	U-R
			0.3	L-R
79-630	19970	5, 55.5 in. from Fixed End Grid	0.3	S
			0.3	U-R
			0.4	L-R
79-630	19970	4, 41.5 in. from Fixed End Grid	0.7	S
			0.6	U-R
			1.0	L-R
79-630	19970	3, 27.5 in. from Fixed End Grid	0.6	S
			0.6	U-R
			0.4	L-R
79-630	19970	2, 13.5 in. from Fixed End Grid	0.4	S
			0.5	U-R
			0.5	L-R
79-630	19970	1, Fixed End	0.2	S
			0.2	U-R
			0.9	L-R
79-610	3340	7, Free End	0.2	(3)
79-631	3340	1, Free End	0.2	(3)
			0.2(5)	U-R
79-632	3340	1, Free End	0.2	(3)
79-439	3690	1, Free End	0.9	S
			1.1, 1.5	U-R
			1.5, 1.5	L-R
79-439	3690	2, 16 in. from Free End Grid	0.5	S
			0.2, 0.6	U-R
			0.6, 0.7	L-R
79-440	8540	1, Free End	0.7	S
			1.6, 1.7	U-R
			1.0, 1.7	L-R

TABLE A-II (continued)

<u>Rod No.</u>	<u>Exposure Time (EFPH)</u>	<u>Grid No. & Location (1)</u>	<u>Rod Wear Depth (mils)</u>	<u>Grid Element (2)</u>
79-441D	4850	1, Free End	1.2	S
			1.5, 1.6	U-R
79-442 ⁽⁶⁾	3690	7, Free End	1.5, 2.1	L-R
			0.4	S
			0.0, 0.3	U-R
			0.0, 0.2	L-R
			0.3 ⁽⁵⁾	S
79-442 ⁽⁶⁾	4850	7, Free End	0.2, 0.6 ⁽⁵⁾	U-R
			0.3	S
			0.2, 0.2	U-R
			0.2, 0.2	L-R
			0.3 ⁽⁵⁾	S
			0.2, 0.5 ⁽⁵⁾	U-R
79-443D	3690	1, Free End	1.0	S
79-444 ⁽⁶⁾	3690	1, Free End	0.5, 1.0	R
			0.1	S
			0.3, 0.3	U-R
79-444 ⁽⁵⁾	4850	1, Free End	0.3, 0.3	L-R
			0.4	S
			0.4, 0.4	U-R
79-445 ⁽⁵⁾	3690	1, Free End	0.2, 0.3	L-R
			0.2	S
			1.2, 1.0	U-R
			0.9, 1.0	L-R
79-449	8540	1, Free End	0.9	S
			1.6, 1.8	U-R
			0.4, 1.4	L-R
79-450	4850	1, Free End	0.9	S
			1.0, 1.2	U-R
			1.3, 1.4	L-R

TABLE A-II (continued)

<u>Rod No.</u>	<u>Exposure Time (EFPH)</u>	<u>Grid No. & Location (1)</u>	<u>Rod Wear Depth (mils)</u>	<u>Grid Element (2)</u>
79-455	3690	1, Fixed End	0.0	S
			0.0	R
79-455	3690	2, 16 in. from Fixed End Grid	1.0	S
			0.3, 0.5	U-R
			0.5, 0.8	L-R
79-459	4850	7, Free End	0.4	S
			0.3, 0.1	U-R
			0.2, 0.2	L-R
79-459	4850	2, 71 in. from Fixed End Grid	0.5	S
			0.5, 0.4	U-R
			0.4, 0.5	L-R
79-502	12080	1, Free End	0.8	S
			0.6, 0.6	R
79-504D	12080	1, Free End	0.6	S
			0.8, 1.2	R
79-504D	12080	2, 9 in. from Free End Grid	0.7	S
			1.0, 1.4	R
79-509	12080	8, Free End	1.2	S
			1.4, 1.6	R
79-509	12080	7, 15 in. from Free End Grid	1.3	S
			1.1, 1.4	R
79-509	12080	6, 25.5 in. from Free End Grid	0.7	S
			1.1, 1.3	R
79-509	12080	5, 36.5 in. from Free End Grid	1.2	S
			0.8	R
			1.8, 1.9	Aux. R (7)
79-513	12080	8, Free End	1.4	S
			1.2, 1.4	R
79-514	12080	1, Free End	1.2	S
			1.7, 1.8	R

TABLE A-II (continued)

<u>Rod No.</u>	<u>Exposure Time (EFPH)</u>	<u>Grid No. & Location (1)</u>	<u>Rod Wear Depth (mils)</u>	<u>Grid Element (2)</u>
79-516	12080	8, Free End	1.4	S
			2.2, 1.6	R
79-517	12080	8, Free End	1.9	S
			1.4, 2.2	R
79-522	12080	8, Free End	1.6	S
			1.6, 1.8	R
79-524	12080	1, Free End	2.7	S
			2.6, 2.6	R
			2.4 (5)	S
			1.8, 1.9 (5)	R
79-572	14360	6, Free End	1.5	(3)
79-586 (6)	4051	1, Free End	0.8	S
			0.9, 1.0	R
79-586 (6)	3381	1, Free End	1.3	S
			1.3, 1.5	R
79-586 (6)	6928	1, Free End	1.6	S
			1.5, 2.5	R

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- (1) Grid levels are numbered upward from the bottom support plate, as shown in Figure 2.
(2) S = spring; U = upper; L = lower; R = reaction point dimple.
(3) The identity of the specific grid element is unknown.
(4) The deep wear is attributed to the off-vertical alignment of rod 79-623 in grid number 1.
(5) Values obtained by metallographic examination; all others by non-destructive profilometry.
(6) Rods had more than one set of wear marks as a result of removal and reassembly during irradiation testing.
(7) Auxiliary spherical dimples were formed in the cell wall opposite the spring in order to insure separation between rod 79-509 and this wall. The rod contacted these dimples, in grid number 5, to form wear marks.

FIGURE A-1. HEXAGONALLY-SHAPED GRID CELLS EMPLOYING A SET OF TWO DIMPLES OPPOSING THE SPRING

TYPICAL LWBR SUPPORT GRID
FOR 0.30 IN. DIAMETER ROD

FIGURE 2. HEXAGONALLY-SHAPED GRID CELLS EMPLOYING
A SET OF TWO PAIRS OF DIMPLES OPPOSING THE SPRING

APPENDIX B
OUT-OF-PILE WEAR TESTS

I. Description of Tests

The out-of-pile wear tests upon which the reciprocating wear model is based are REM 124 and REM 128. Table B-I summarizes the major variables in these two series of tests.

TABLE B-I
OUT-OF-PILE WEAR TESTS

Variable	REM 124	REM 128
(a) Number of Tests	7	4
(b) Grids	Hexagonally-shaped grid cells of Inconel or AM-350 were held stationary; the rod specimens were moved back and forth.	None (Rods held stationary; the weighted AM-350 dimple was moved back and forth along the rods.)
(c) Quantity of Wear Cycles	60 to 1100 ⁽¹⁾	10 to 1000
(d) Stroke Length per Half Cycle (in.)	0.015-0.165	0.060
(e) Spring Load (lb)	1.3-7.8	5 and 15
(f) Temperature (°F)	500 and 600 (in autoclave; wet)	Room (dry)
(g) Rod Diameter (in.)	0.304 and 0.570	0.53 and 0.57
(h) Rod Composition	Zircaloy-4	Zircaloy-4

II. Test Data

Table B-II contains the wear depth data obtained in the REM 124 tests. Figure 11 in this report presents graphically the wear data from the 0.304 inch diameter rod specimens. The wear depth data obtained in the REM 128 tests are shown in Table B-III, and depicted graphically in Figure B-1.

(1) Nine minute dwell after each half cycle.

TABLE B-II
OUT-OF-PILE WEAR TEST DATA
REM 124

<u>Zircaloy-4 Rod Number</u>	<u>Spring Load(lb)</u>	<u>Number of Cycles</u>	<u>Stroke Length(mils)</u>	<u>Maximum Wear Depth(mils)</u>	<u>Wear Spot -- Reaction Point(R) Or Spring (S)</u>
2 (RW 46) (1)	4.5	1100	90	5.7	R
3 (RW 44) (1)	7.8	1100	150	4.2	R
5 (RW 44) (1)	1.3	1100	150	4.0	R
8 (RW 45)	2.8	1100	150	4.1	S
9 (RW 45)	4.2	1100	150	4.5	R
11 (RW 45)	3.6	1100	150	5.0	S
1 (RW 47) (1)	6.0	1100	150	3.7	S
4 (RW 47) (1)	4.5	1100	150	4.0	S
6 (RW 48)	4.8	60	165	1.7	S
	4.5	140	165	3.0	S
	4.4	900	165	4.2	R
10 (RW 48)	4.3	200	165	3.1	S
	3.9	900	165	3.5	S
7 (RW 48)	4.3	1100	165	5.1	S
7 (RW 50)	4.8	250	42	2.0	S
		293	42	1.0	S
		557	42	2.2	S
10 (RW 50)	4.4	543	42	1.8	S
		557	42	2.1	S
11 (RW 50)	4.5	1100	42	2.3	S
7 (RW 49)	4.8	550	15	1.9	S
		1100	15	2.0	S
10 (RW 49)	4.4	550	15	1.2	S
		1100	15	1.0	S
11 (RW 49)	4.6	550	15	1.7	S
		1100	15	1.8	S

(1) Diameters of these five rods were 0.570 inch; grid material was Inconel 718.
All other rods were 0.304 inch in diameter; grid material was AM-350.

TABLE B-III
OUT-OF-PILE WEAR TEST DATA
REM 128

<u>Zircaloy-4 Rod Number</u>	<u>Dimple Load(lb)</u>	<u>Number of Cycles</u>	<u>Stroke Length(mils)</u>	<u>Maximum Wear Depth(mils)</u>	<u>Wear Spot -- Reaction Point(R) Or Spring (S)</u>
0.55 in. diameter with corrosion film; 0.05 in. radius cylindrical reaction point of AM-350	15 15 15 15 15 15 15 15 15	10 20 40 70 100 200 300 400 500 600	60 60 60 60 60 60 60 60 60 60	.4 .5 .7 1.1 1.3 2.0 1.9 2.5 2.5 2.4	(1)
0.53 in. diameter, with no corrosion film; 0.05 in. radius cylin- drical reaction point of AM-350	5 5 5 5 5 5 5 5 5 5 5 5	10 20 40 70 100 200 300 400 500 600 700 900 1000	60 60 60 60 60 60 60 60 60 60 60 60 60	.3 .5 .6 .8 1.1 1.5 1.5 1.5 1.9 1.8 1.8 1.9 2.2	(1)
0.55 in. diameter with corrosion film; flat reaction point of AM-350	5 15 15	500 100 200	60 60 60	.1 .2 1.0	(1) (1)

(1) A single AM-350 reaction point was traversed back and forth along the rod under the indicated load.

FIGURE B-I. REM 128 TEST ROD WEAR DEPTH VS NUMBER OF WEAR CYCLES

APPENDIX C
SAMPLE CALCULATION OF COMBINED ROD WEAR
(Rod 79-522)

I. STROKE LENGTH

The length of rod axial motion that occurs during a reactor power⁽¹⁾ or pressure/temperature⁽²⁾ cycle is the stroke length. The amplitude is dependent upon the degree of fuel pellet and cladding interaction, which varies nonuniformly during rod test life, and is not usually measurable in-pile. Therefore, stroke length values for the irradiation tested fuel rods were calculated using the CYGRO-4 fuel rod analysis computer program⁽³⁾ (Reference C-1). Table I in the main body of this report includes the power and pressure/temperature stroke lengths that were derived from the CYGRO-4 computer program for the 34 fuel rods analyzed.

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- (1) A reactor power cycle is a change in power from 20% to 100% power and then back to 20% power, with no depressurization.
- (2) A pressure/temperature cycle is the establishment of system pressure followed by a period of operation at pressure and power, and finally return of power and system pressure to ambient conditions.
- (3) CYGRO-4 is designed for the analysis of axisymmetric deformation of fuel pellets and cladding at cross-sections of oxide fueled rod-type fuel elements.

II. EFFECTIVE NUMBER OF RECIPROCATING CYCLES

The effective number of reciprocating cycles is calculated by

$$N = \frac{SN_A}{\Delta L} \quad (\text{Equation (3), Section III.B})$$

Table I in the main body of this report indicates that rod 79-522 experienced 122 power cycles and 37 pressure/temperature cycles, and that the overall rod length increase was 222 mils. Table I also indicates a power stroke length of 40 mils, and a pressure/temperature stroke length of 150 mils. Therefore,

$$(a) \text{ Power Cycles: } N_{E_P} = \frac{S_P}{\Delta L} (N_{A_P}) = \frac{.040(122)}{.222} = 22$$

$$(b) \text{ Press./Temp.Cycles: } N_{E_{P/T}} = \frac{S_{P/T}}{\Delta L} (N_{A_{P/T}}) = \frac{.150(37)}{.222} = 25$$

for a total of 47 effective reciprocating cycles. (NOTE: When ΔL is less than S, N is taken as equal to N_A).

III. MEAN STROKE LENGTH

$$\text{Mean Stroke Length} = \frac{(N_{E_P} \times S_P) + (N_{E_{P/T}} \times S_{P/T})}{(N_{E_P} + N_{E_{P/T}})}$$

For rod 79-522

$$\begin{aligned} \text{Mean Stroke Length} &= \frac{(22 \times .040) + (25 \times .150)}{47} \\ &= 99 \text{ mils} \end{aligned}$$

IV. COMBINED ROD WEAR

The maximum amount of combined wear expected on a fuel rod is that due to

- a. Reciprocating wear
- b. Wear from vibration, assembly scratching, and handling (one mil in this example).

In order to calculate combined rod wear

1. Calculate number of effective reciprocating cycles required to cause 0.001 inch vibratory wear depth on a nonworn surface of rod 79-522

$$\frac{A}{L^{1/3} (22.7 S - 1.6)} = (2.13 \log N_V - 3.13) (10^{-5})$$

where: $A = 3.18 \times 10^{-5} \text{ in}^2$ = cross sectional area of a 0.001 inch deep wear spot on a 0.570 inch diameter fuel rod (from Figure 14 of this report)

$S = 0.099 \text{ mils}$ = mean stroke length

$L = 11.2 \text{ pounds}$ = spring load (from Table IV of this report)

Therefore,

$$\frac{3.18 \times 10^{-5}}{(11.2)^{1/3} [22.7(0.099) + 1.6]} = 0.369 (10^{-5})$$

$$0.369(10^{-5}) = (2.13 \log N_V - 3.13) (10^{-5})$$

$$\log N_V = \frac{0.369 + 3.13}{2.13} = 1.643$$

$$N_V = 44 \text{ cycles}$$

$$N = N_R + N_V = 47 + 44 = 91 \text{ cycles}$$

C3

2. Calculate total wear spot cross-sectional area

$$A = L^{1/3} (22.7 S + 1.6) (2.13 \log N - 3.13) (10^{-5}) \quad (\text{Equation (4), Section III.C})$$

$$\begin{aligned} &= (11.2)^{1/3} [(22.7(0.099) + 1.6) (2.13 \log 91 - 3.13) (10^{-5})] \\ &= 8.98 \times 10^{-5} \text{ in}^2 \end{aligned}$$

3. Calculated wear depth (from Figure 14 in this report) for a cross-sectional area of $8.98 \times 10^{-5} \text{ in}^2$

d - 2.0 mils (1.8 mils measured) for rod 79-522.

REFERENCES TO APPENDIX C

- C-1 J.B. Newman, J.F. Giovengo, L.P. Comden, "The CYGRO-4 Fuel Rod Analysis Computer Program", WAPD-TM-1300, July 1977.