GEAP-4020

EROSION FLOW TESTING OF PURPOSELY DEFECTED STAINLESS STEEL CLAD COMPACTED UO_2 POWDER FUEL

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February 1962

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GEAP 4020
METALS, CERAMICS, AND MATERIALS

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ATOMIC POWER EQUIPMENT DEPARTMENT

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ABSTRACT

Compacted UO_2 powder specimens with purposely defected stainless steel cladding were erosion flow tested under simulated boiling water reactor operating conditions, excluding neutron flux. The type of clad defects were 0.020-inch wide slits, completely through the clad, varying in length from 1/4-inch to 1-inch. Maximum erosion flow test exposure was 6000 hours in 7 ft/sec, 536 F flowing water. The results of post test examination indicated that defected stainless clad swaged fuel with UO_2 densities greater than 90 per cent T.D. is comparable to pellet type fuel with respect to erosion resistance. Within the tests parameters, the stresses and imperfections introduced into the stainless clad as a result of swaging did not adversely affect the corrosion characteristics of stainless steel in a boiling water reactor coolant environment. As a result of the test data, two swaged fuel rods containing 1/2-inch long slits were inserted into the VBWR reactor. The defected rods are performing satisfactorily after accumulating 1000 MWD/T exposure, with activity due to fission gas release below 20 μc/sec.

SECTION I

INTRODUCTION AND SUMMARY

1.1 Introduction

The development of compacted UO_2 powder type fuel is being vigorously pursued throughout the country because of the fabrication cost incentives inherent in the compacted powder processes. Swaging, tandem rolling, and vibratory compaction are examples of these processes that have been investigated by the General Electric Company under the AEC-sponsored High Power Density Development Project. Progress on these compacted powder fuel fabricating processes has been the subject of previous topical and progress reports.(1-6)

Several possible performance limitations have been suggested for compacted powder fuel should a defect occur in the fuel rod clad during reactor operation. One is the problem of waterlogging(also applicable to pellet type fuel); another is the washing away of UO_2 particles by the erosion action of the coolant stream. Millhollen, et al, have reported two apparent cases of water-logging type failures in purposely defected fuel rods tested in the MTR.(7) In one case the bulk density of the fuel rod was 81 per cent of theoretical density, and in the second case, 85 per cent TD. The same investigators also report on an unpremeditated clad failure of a swaged rod (88 per cent TD) during irradiation testing in the MTR.(8) In this case, no water-logging or appreciable loss of UO_2 occurred. Out-of-reactor erosion experiments of compacted powder fuel under dynamic steam flow have been reported by Spalaris, et al.(9) They observed no apparent consequences that would preclude the use of compacted powder fuel for nuclear superheat application.

The performance of compacted powder fuel with a fuel clad defect in a boiling water reactor environment is a matter of speculation

based on the above information. In order to better adjudge possible performance limitations on compacted powder fuel, long term out-of-reactor and short term in-reactor erosion flow test of purposely defected fuel were conducted. The results of these tests is the subject of this report.

1.2 Summary

Twenty-three three-inch long compacted UO_2 powder fuel specimens and one pellet fuel specimen, all with purposely defected stainless steel cladding were erosion flow tested under simulated boiling water reactor operating conditions, excluding neutron flux. The cladding defect consisted of a 0.020-inch wide slit, varying in length from 1/4-inch to 1-inch long, and deep enough to just break through the clad. Twelve specimens were tested in 7 ft/sec, 536 F flowing water, and twelve were tested in 11 ft/sec, 546 F steam-water. Water chemistry was controlled to maintain a pH of 7.0 ± 0.5, a resistivity of 3.5×10^6 ohm-cm, and a chloride content of <0.1 ppm. Sixteen specimens were tested 1000 hours, four specimens were tested 2000 hours, and four specimens were tested 6000 hours.

The erosion test specimens were fabricated utilizing the following compacted powder processes: cold swaging, hot swaging, tandem rolling, and vibratory compaction. Within the cold swaged and tandem rolled specimen groups were samples that were annealed at 1000 C to stress relieve the clad and possibly promote sintering of the UO_2 particles.

Evaluation of the erosion performance of the specimens was based on data from diameter and weight measurements before and after testing and metallographic examination of samples sectioned through the defected area. The data obtained from the evaluation showed:

1. No significant loss of UO_2 (<50 mg) from cold swaged (92 per cent TD) or hot swaged (95 per cent TD) specimens.

2. Variable loss of UO_2 ($<$ 50 mg to 1-1/2 grams) from tandem rolled (88 per cent TD) and vibratory compacted samples (65 per cent TD and 92 per cent TD)

3. No significant change ($>$ 0.002-inch) in specimen diameter measurements after testing, with two exceptions, as noted in 4 below.

4. A significant change (~0.006-inch) in specimen diameter occurred with two samples that contained a CaO addition to the UO_2. Hydrolysis of the CaO is believed responsible for the swelling.

5. No unusual erosion or corrosion reactions between the coolant environment and the clad, between the coolant and the UO_2, or between the clad and the UO_2 were observed by metallographic examination for all compacted powder specimens. The one pellet fuel specimen contained a narrow region at the surface of the UO_2 pellet where intergranular attack of the pellet had occurred.

The data obtained by this test provided substantial evidence that indicates the resistance of 90-95 per cent dense compacted powder type fuel to UO_2 removal by the coolant in the event of a narrow slit or crack type cladding failure should be adequate. However, irradiation testing of purposely defected compacted powder fuel is required to substantiate this conclusion. In view of the need for in-reactor tests, two stainless clad, swaged fuel rods with a slit type clad defect are currently being irradiated in the VBWR. The results of the test after 1000 MWD/T exposure at a heat flux of 350,000 BTU/hr-ft^2 indicate no loss of UO_2 by erosion, no swelling or propagation of the clad defect, and low fission gas activity ($>$ 20 μc/sec). Figure 16 is a photograph of the defects after 1000 MWD/T exposure.

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SECTION II

EROSION FLOW TEST EXPERIMENTAL DETAILS

2.1 Goals and Objectives

The primary objective of the erosion test was to determine the relative resistance of fused UO_2 to removal by flowing water and steam-water utilizing purposely defected specimens fabricated by various compacted powder processes. A secondary objective was the characterization of the stainless steel cladding corrosion performance with respect to the various fabrication and annealing treatments used in preparing the specimens. Meeting the objectives would provide background data to substantiate irradiation testing of purposely defected fuel rods in the Vallecitos Boiling Water Reactor.

2.2 Test Specimen Preparation

Twenty-three compacted UO_2 powder test specimens were prepared for erosion flow testing according to Figure 1. One pellet specimen was prepared to act as a control. Ceramic grade natural UO_2 was used to fabricate the pellets. The remaining specimens, with the exception of vibratory compacted specimens, were removed from the center section of 3-foot long fuel rods fabricated by either cold swaging, hot swaging, or tandem rolling. Vibratory compaction specimens were fabricated to size. The cladding was 0.025 or 0.016-inch thick 304 stainless steel. The fused UO_2 was natural enrichment, -20 mesh, fused UO_2 furnished by Spencer Chemical Company, Table I. Six cold swaged specimens and two tandem rolled specimens were hydrogen annealed at 1000 C for one hour. Two of the swaged sepcimens had 1/2 per cent CaO added to the UO_2, another two had 1/2 per cent TiO_2 added to the UO_2, and the final two specimens had no additives. The two tandem rolled specimens had 1/2 per cent TiO_2 added to the UO_2. The purpose for the CaO and TiO_2 additives and the annealing treatment

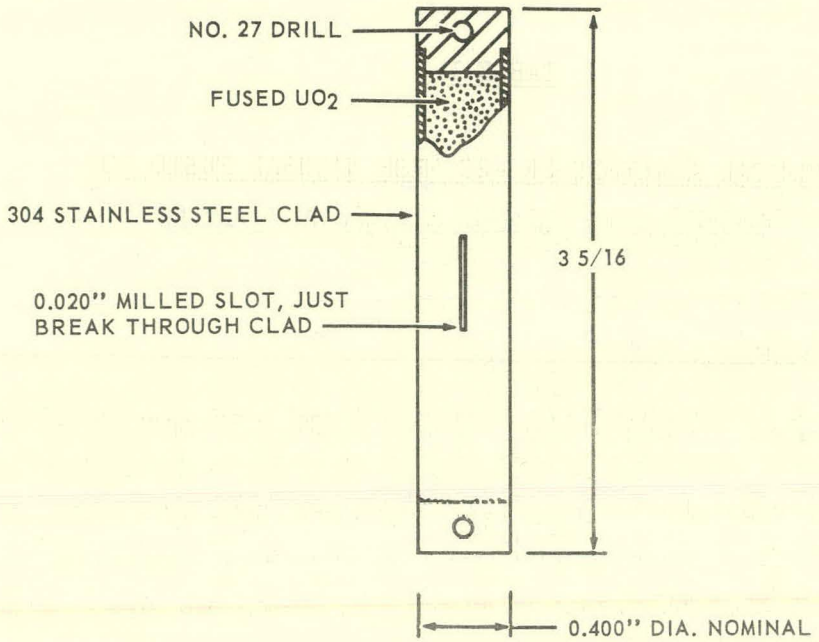


FIGURE 1 EROSION TEST SAMPLE

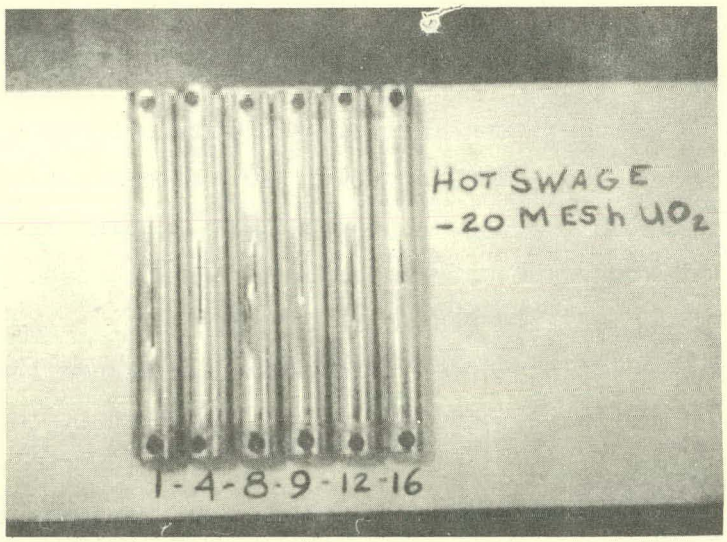


FIGURE 2 TYPICAL DEFECTED SPECIMENS (3/4 MAGNIFICATION)

TABLE 1

CHEMICAL ANALYSIS OF -20 MESH NATURAL FUSED UO_2

USED IN EROSION SPECIMENS

Al	200 ppm	Si	30 ppm
Bi	1	Ag	1
B	0.2	Na	35
C	125	Sn	2
cd	1	V	15
Ca	10	Zn	10
Cr	8	Ni	2
Co	2	Sb	1
Cu	10	Ti	100
Fe	150	W	10
Pb	5	Ta	10
Mg	5	N_2	250
Mn	1	O/U	2.009
Mo	3		

was to evaluate the UO_2 erosion resistance resulting from possible surface sentering of the UO_2.

Each specimen was defected by milling a 0.20-inch wide slit in the clad just deep enough to break through the clad and expose the UO_2. Length of the slot varied from specimen to specimen, being either 1/4-inch, 1/2-inch or 1 inch. Extreme care was exercised at all times in preparing and handling the defected specimen. After milling, the slot was examined under 20X magnification. Any burrs, wire edges, loose metal, or incompletely removed metal in the defect were removed using jeweler's tools. Loose surface particles were carefully removed prior to weighing of the samples on a Metler balance.

A tabulation of the specimens fabrication history, the length of the defect in each sample, and the position of the sample in the flow loop is presented in Table 2. Typical defected specimens are shown in Figure 2.

2.3 Flow Test Conditions

The specimens were tested under simulated reactor operating conditions (exoluding neutron flux) in the CL-4 loop, Figure 3. The specimens were exposed to either 7 ft/sec, 536 F (280 C) recirculating water or 11 ft/sec, 546 F (285 C) steam water. Water chemistry of the loop was controlled to maintain a pH of 7.0 ± 0.5, a resistivity of 3.5×10^6 ohm-cm, and a chloride content of <0.1 ppm. Details of the loop operating conditions are presented in Table 3. Positioning of the specimens within the loop was done utilizing a specimen holder design shown in Figure 4. The twenty-four specimens were tested 1000 hours; 12 in the water and 12 in the steam water positions in the loop. Eight of the 24 were selected for an additional 1000 hours testing; 4 in the water and 4 in the steam-water positions. Finally, the four specimens that were in water section of the loop were tested an additional 4000 hours. The resultant total test time on the four specimens exposed to flowing water amounted to 6000 hours.

TABLE 2
EROSION SAMPLE FABRICATION HISTORY

Sample No.	Fabrication Method	Length of Defect Slit	Position in Loop
1	Hot Swaged[1]	1"	Water
2	Cold Swaged-Annealed[2]	1/2"	Water
3	Cold Swaged[3]	1/2"	Water
4	Hot Swaged	1/2"	Water
5	Cold Swaged-Annealed (CaO)[4]	1/2"	Water
6	Cold Swaged	1/4"	Water
7	Cold Swaged-Annealed (TiO_2)[5]	1/4"	Water
8	Hot Swaged	1/4"	Water
1-2	Pellets[6]	1/2"	Water
11-2	Tandem Rolled[7]	1/2"	Water
13-2	Rolled-Annealed (TiO_2)[8][9]	1/2"	Water
15-2	Vibratory Compacted	1/2"	Water
9	Hot Swaged	1"	Steam-Water
10	Cold Swaged-Annealed	1/2"	Steam-Water
11	Cold Swaged	1/2"	Steam-Water
12	Hot Swaged	1/2"	Steam-Water
13	Cold Swaged-Annealed (CaO)	1/2"	Steam-Water
14	Cold Swaged	1/4"	Steam-Water
15	Cold Swaged-Annealed (TiO_2)	1/4"	Steam-Water
16	Hot Swaged	1/4"	Steam-Water
10-2	Vibratory Compacted[10]	1/2"	Steam-Water
12-2	Tandem Rolled	1/2"	Steam-Water
14-2	Rolled-Annealed (TiO_2)[9]	1/2"	Steam-Water
16-2	Vibratory Compacted	1/2"	Steam-Water

NOTES:

(1) Cold swaged to 88 per cent density, then hot swaged at 1000 C to 95 per cent density.
(2) Cold Swaged to 92 per cent density, then annealed 1 hour at 1000 C in hydrogen atmosphere.
(3) Cold swaged to 92 per cent density.
(4) Cold Swaged to 92 per cent density (with 1/2 per cent CaO added to UO_2 as a sintering aid), then annealed 1 hour at 1000 C in hydrogen atmosphere.
(5) Cold swaged to 92 per cent density (with 1/2 per cent TiO_2 added to UO_2 as a sintering aid), then annealed 1 hour at 1000 C in hydrogen atmosphere.

TABLE 2 (Continued)

(6) Sintered UO_2 pellets, 95 per cent density.
(7) Tandem rolled to 88 per cent density.
(8) Tandem rolled, then annealed at 1000 C for 1 hour - 1/2 per cent TiO_2 added to UO_2.
(9) Vibration compacted to 92 per cent density.
(10) Vibration compacted to 65 per cent density.

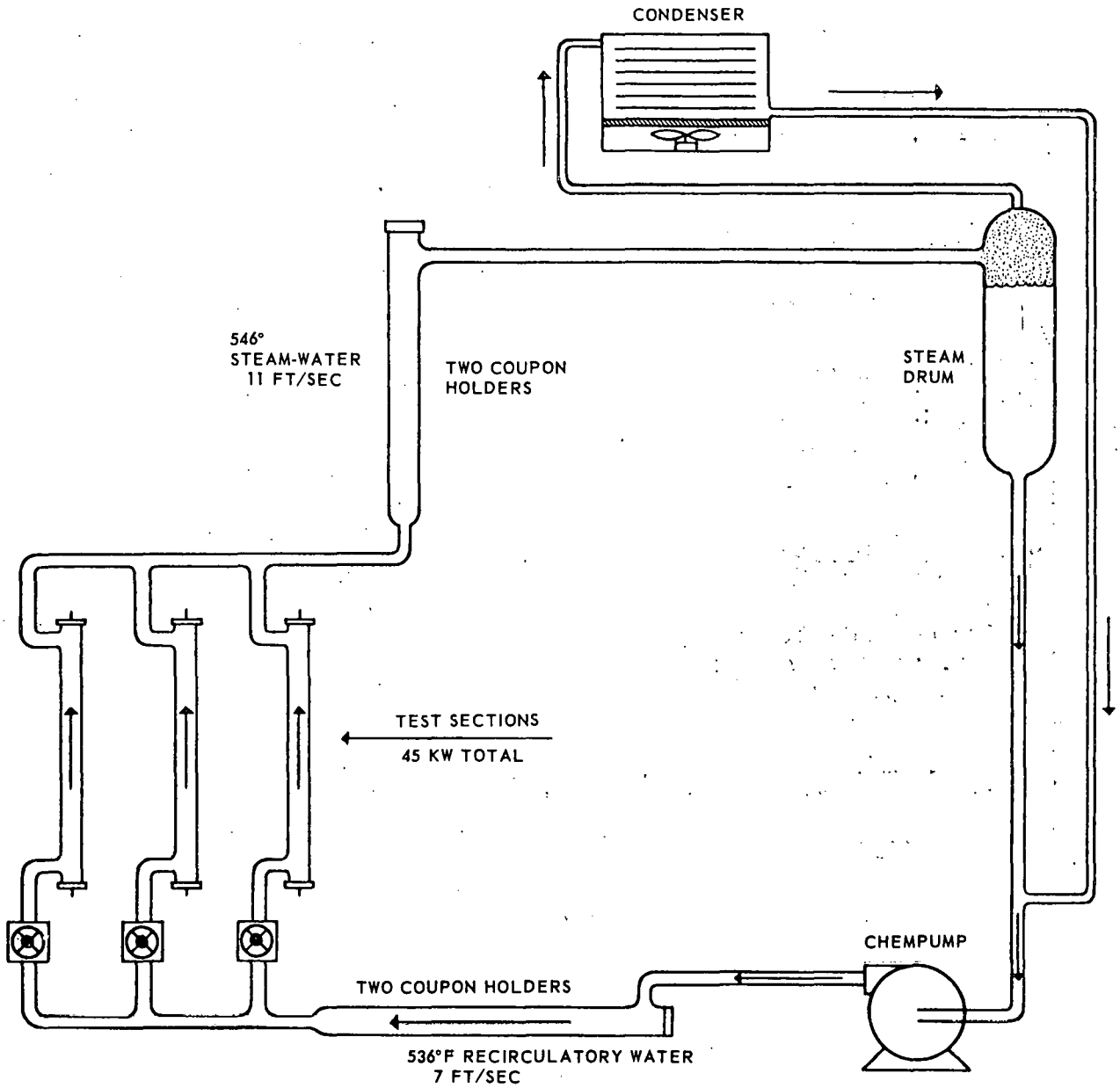
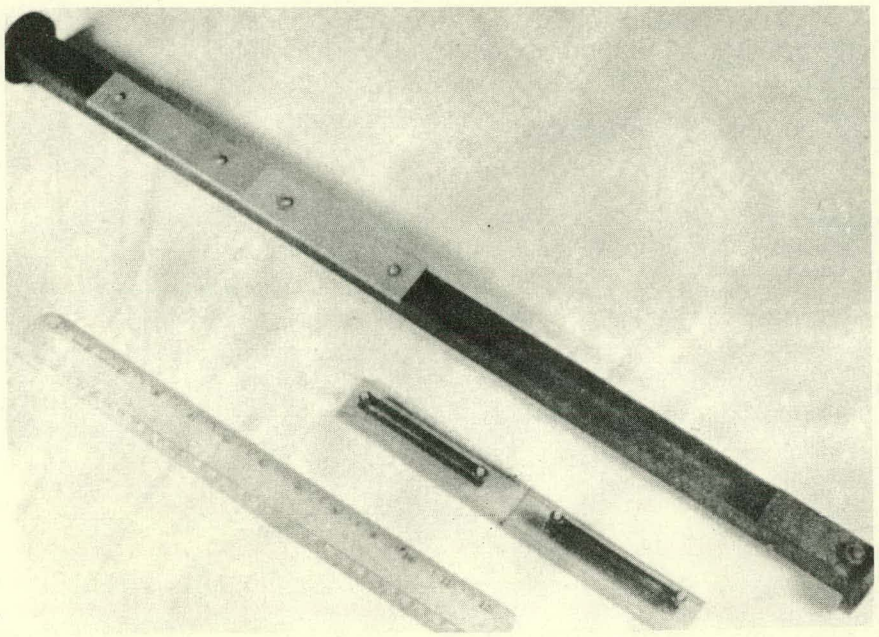


FIGURE 3 CL-4 CORROSION LOOP BOILING OPERATION FLOW DIAGRAM - 1000 PSI

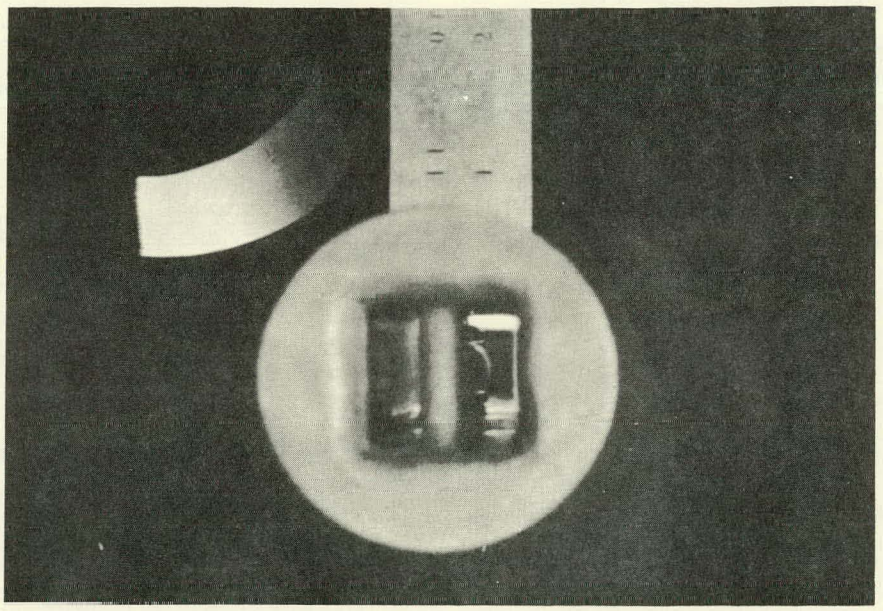
TABLE 3

FLOW LOOP OPERATING CONDITIONS

Run Duration, Hours	1009	998	4164
Water Chemistry			
Chloride, ppm	< 0.1	< 0.1	< 0.1
pH	7.0 ± 0.5	7.5 ± 0.1	7.0 ± 0.5
Resistivity, ohm-cm	3.5×10^6	4.8×10^6	3.0×10^6
Recirculating Water Coupon Section			
Temperature, °F	536	536	536
Oxygen Content, ppm	0.2	0.2	0.2
Velocity, ft/sec	7	7	7
Steam-Water Section			
Temperature, °F	546	546	
Steam Quality, w/o	3.1	3.3	
Oxygen Content, ppm	6	5	
Hydrogen Content, ppm	0.8	0.9	
Velocity, ft/sec	11	11	
Activity Results			
Average, d/m/ml	3×10^{-2}	9×10^{-2}	$s \times 10^{-2}$



OBLIQUE VIEW OF HOLDER AND SPECIMENS



END VIEW OF HOLDER WITH SPECIMENS IN PLACE

FIGURE 4 SPECIMEN HOLDER USED IN CL-4 LOOP EROSION FLOW TEST PROGRAM

2.4 Test Results

The specimens were removed from the loop for examination and measurements after 1000, 2000, 4000 and 6000 hours exposure to flow test conditions. Prior to examination and measurements, the specimens were dried at 95 C for 24 hours. After drying, the specimens were photographed at 4X magnification. Photographs of the specimens after 1000 and 4000 hours are included in the Appendix. Photographs of the specimens after 6000 hours are included in metallography examination as discussed later in this report.

2.4.1 Diameter Measurements

Specimen diameter measurements taken at the center and ends of the clad split are tabulated in Tables 4-7. With two exceptions, as discussed below, the measurable change in specimen diameter due to exposure to flow test conditions was of the order of 0.001 to 0.002 inches. The two exceptions were swaged and annealed specimens Nos. 5 and 13, which had 1/2 per cent CaO added to the UO_2. Diameter increases of up to 0.006 inches over pre-test diameter measurements were observed. It is believed the slight swelling of these two samples was due to the hydrolysis of the CaO. Of particular significance is the diameter stability exhibited by the four specimens tested 6000 hours. The data in Table 7 reveals that specimen diameter variation is only of the order of 0.001-inch.

2.4.2 Weight Measurements

Weight measurement data and weight changes for individual specimens following each test run are presented in Table 8. A graphical presentation of the weight change vs exposure time for individual specimens is shown in Figure 5. The data shows that the weights of a majority of specimens were not significantly affected by the test, indicating no loss of UO_2. Only four specimens had a slight loss after 2000 hours testing greater than 50 miligrams. These were:

a. tandem rolled #12-2, 339 mg
b. tandem rolled-annealed #13-2, 234 mg
c. vibratory compacted #10-2, 171 mg
d. vibratory compacted #16-2, 1412 mg

TABLE 4

DIAMETER MEASUREMENTS OF SAMPLES BEFORE AND AFTER 1000 HOURS OF EROSION FLOW TESTING

Sample No.	Before Test			After Test			Diameter Difference		
	End	Middle	End	End	Middle	End	End	Middle	End
1	(a) .4372	.4380	.4401	.4380	.4389	.4398	.0008	.0009	- .0003
	(b) .4376	.4363	.4365	.4379	.4370	.4365	.0003	.0007	.0000
5	4433	4420	4470	4500	4463	4471	.0067	.0043	.0001
	4416	4417	4395	4422	4438	4430	.0006	.0021	.0035
6	4372	4355	4355	4373	4369	4362	.0001	.0014	.0007
	4359	4365	4360	4365	3467	4368	.0006	.0002	.0008
7	4470	4466	4454	4489	4478	4456	.0019	.0012	.0002
	4442	4424	4420	4450	4430	4428	.0008	.0006	.0004
13	4393	4405	4397	4419	4437	4423	.0026	.0032	.0026
	4320	4366	4384	4382	4380	4400	.0062	- .0004	.0016
14	4422	4414	4412	4433	4428	4423	.0011	.0014	.0012
	4395	4395	4386	4400	4405	4399	.0005	.0010	.0013
15	4455	4463	4460	4461	4465	4473	.0006	.0002	- .0013
	4436	4426	4418	4442	4432	4420	.0006	.0006	.0002
16	4388	4398	4401	4381	4391	4395	- .0007	- .0007	- .0006
	4377	4372	4369	4385	4382	4374	.0008	.0010	.0005

Diameter measurements taken at end, middle, and end of milled slot, two measurements, 90° apart.
(a) Measurement taken on milled slot - All measurements in inches.
(b) Measurement taken 90° from milled slot

TABLE 5

DIAMETER MEASUREMENTS OF SAMPLES BEFORE AND AFTER 2000 HOURS OF EROSION FLOW TESTING

Sample No.	Before Test			After Test			Diameter Difference		
	End	Middle	End	End	Middle	End	End	Middle	End
1-2	(a) .4465	.4490	.4480	.4485	.4490	.4478	+.0020	.0000	-.0002
	(b) .4402	.4400	.4400	.4402	.4403	.4408	.0000	+.0003	+.0008
2	.4425	.4421	.4430	.4423	.4435	.4430	-.0002	+.0014	.0000
	.4399	.4399	.4390	.4398	.4400	.4401	-.0001	+.0001	+.0011
3	4408	4432	4414	4420	4439	4462	+.0012	+.0007	+.0048
	4388	4406	4407	4390	4412	4420	+.0002	+.0006	+.0013
4	4390	4391	4412	4402	4395	4392	+.0012	+.0004	-.0020
	4370	4378	4380	4388	4382	4376	+.0018	+.0004	-.0004
11-2	4065	4085	4052	4080	4085	4078	+.0015	.0000	+.0026
	4025	4032	4032	4029	4041	4030	+.0004	+.0009	-.0002
13-2	4055	4075	4085	4090	4062	4077	+.0035	-.0013	-.0008
	4030	4035	4030	4028	4039	4030	-.0002	+.0004	.0000
15-2	4432	4455	4470	4471	4446	4433	+.0039	-.0009	-.0037
	4401	4420	4430	4434	4425	4407	+.0033	+.0005	-.0028
8	4374	4390	4391	4376	4390	4390	+.0003	.0000	-.0001
	4377	4378	4376	4387	4382	4382	+.0010	+.0004	+.0006
9	4388	4371	4376	4365	4372	4373	-.0023	+.0001	-.0003
	4368	4364	4367	4380	4379	4375	+.0012	+.0015	+.0008
10	4400	4430	4445	.4406	4412	4438	+.0006	-.0018	-.0007
	4381	4392	4382	4399	4398	4396	+.0018	+.0006	+.0014

All measurements in inches.

TABLE 5 (Continued)

Sample No.	End	Middle	End	End	Middle	End	End	Middle	End
11	4422	4418	4397	4418	4435	4428	-.0004	+.0017	+.0031
	4400	4390	4408	4413	4398	4403	+.0013	+.0008	-.0005
12	4386	4376	4375	4372	4379	4380	-.0014	-.0004	+.0005
	4368	4367	4367	4378	4378	4372	+.0010	+.0011	+.0005
10-2	4412	4375	4412	4418	4372	4415	+.0006	-.0003	+.0003
	4412	4412	4415	4415	4410	4413	+.0003	-.0002	-.0002
12-2	4060	4060	4060	4061	4059	4092	+.0001	-.0001	+.0032
	4015	4020	4015	4026	4031	4021	+.0011	+.0011	+.0006
14-2	4070	4130	4090	4125	4129	4110	+.0055	-.0001	+.0020
	4020	4025	4022	4026	4030	4025	+.0006	+.0005	+.0003
16-2	4469	4444	4413	4410	4448	4479	-.0059	+.0004	+.0066
	4405	4390	4400	4400	4398	4399	-.0005	+.0008	-.0001

All measurements in inches.

TABLE 6

DIAMETER MEASUREMENTS OF SAMPLES BEFORE AND AFTER 4000 HOURS OF EROSION FLOW TESTING

Sample No.	Before Test			After Test			Diameter Differences		
	End	Middle	End	End	Middle	End	End	Middle	End
2	(a) .4425	.4421	.4430	.4425	.4435	.4430	.0000	+.0014	.0000
	(b) .4399	.4399	.4390	.4399	.4398	.4402	.0000	-.0001	+.0012
3	4408	4432	4414	4421	4439	4462	+.0013	+.0007	+.0048
	4388	4406	4407	4388	4410	4417	.0000	+.0004	+.0010
8	4374	4390	4391	4375	4390	4390	+.0001	.0000	-.0001
	4377	4378	4376	4387	4382	4382	+.0010	+.0004	+.0006
11-2	4065	4085	4052	4079	4089	4078	+.0014	+.0004	+.0026
	4025	4037	4032	4031	4039	4027	+.0006	+.0002	-.0005

All measurements in inches

TABLE 7

DIAMETER MEASUREMENT OF SAMPLES BEFORE AND AFTER 6000 HOURS OF EROSION FLOW TESTING

Sample No.	Before Test			After Test			Diameter Differences		
	End	Middle	End	End	Middle	End	End	Middle	End
2	(a) .4425	.4421	.4430	.4429	.4431	.4430	+.0004	+.0009	.0000
	(b) .4399	.4399	.4390	.4398	.4404	.4390	-.0001	+.0005	.0000
3	4408	4432	4414	4419	4430	4461	+.0011	-.0002	+.0047
	4388	4406	4407	4398	4413	4400	+.0010	+.0007	-.0007
8	4374	4390	4391	4385	4391	.4380	+.0011	+.0001	-.0011
	4377	4378	4376	4382	4386	.4390	+.0005	+.0008	+.0014
11-2	4065	4085	4052	4082	4083	4076	+.0017	-.0002	+.0024
	4025	4037	4032	4037	4039	4034	+.0012	+.0002	+.0002

(a) Measurement taken on milled slot - All measurements in inches
(b) Measurement taken 90° from milled slot

TABLE 8

WEIGHT DATA OF EROSION SAMPLE BEFORE AND AFTER FLOW TESTING

Sample No.	Fabrication Method	Slit Length	Start	End 1000 Hrs	End 2000 Hrs	End 4000 Hrs	End 6000 Hrs	Sample Weight Change, Mgs* After 1000 Hrs	After 2000 Hrs	After 4000 Hrs	After 6000 Hrs
1	Hot Swaged	1"	71.3457g	71.3672 g				+12.5			
2	Cold Swaged-Annealed	1/2"	70.7694	70.7849	70.7870 g	70.7855 g	70.7807 g	+6.5	+7.6	+7.1	-0.7
3	Cold Swaged	1/2"	70.4037	70.4053	70.4114	70.4032	70.3973	-7.4	-2.3	-11.5	-18.4
4	Hot Swaged	1/2"	74.0060	73.9712				-43.8			
5	Cold Swaged-Annealed	1/2"	69.5936	Not Taken							
6	Cold Swaged	1/4"	69.3725	69.3787				-3.2			
7	Cold Swaged-Annealed	1/4"	71.4725	41.4942				+12.7			
8	Hot Swaged	1/4"	71.7506	71.7616	71.7659	71.7668	71.7711	+2.0	+5.3	+5.2	+8.5
1-2	Pellets	1/2"	70.9357	70.9199				-25.0			
11-2	Rolled	1/2"	57.7757	57.7440	57.7356	57.7205	57.5027	-40.7	-50.1	-66.2	-85.0
13-2	Rolled-Annealed	1/2"	58.6141	58.3839				-239.2			
15-2	Vibratory Compacted	1/2"	70.7627	70.6853				+3.4			
9	Hot Swaged	1"	70.1721	70.1370	70.1473			-47.1	-37.8		
10	Cold Swaged-Annealed	1/2"	69.4257	69.4442	69.4558			+6.5	+17.1		
11	Cold Swaged	1/2"	69.6920	69.6914	69.7014			-12.6	-3.6		
12	Hot Swaged	1/2"	72.3085	72.3259	72.3360			+5.4	+14.5		
13	Cold Swaged-Annealed	1/2"	68.5305	68.5863				+43.8			
14	Cold Swaged	1/4"	70.1852	70.1952				-2.0			
15	Cold Swaged-Annealed	1/4"	70.9217	70.9556				+21.9			
16	Hot Swaged	1/4"	72.0037	72.0259				+10.2			
10-2	Vibratory Compacted	1/2"	57.3335	47.1712				-171.3			
12-2	Rolled	1/2"	57.9263	56.5965				-338.8			
14-2	Rolled-Annealed	1/2"	58.1706	58.1528				-26.8			
15-2	Vibratory Compacted	1/2"	69.7688	68.3653				-1412.5			

* Values normalized to account for weight gain due to stainless steel film formation.

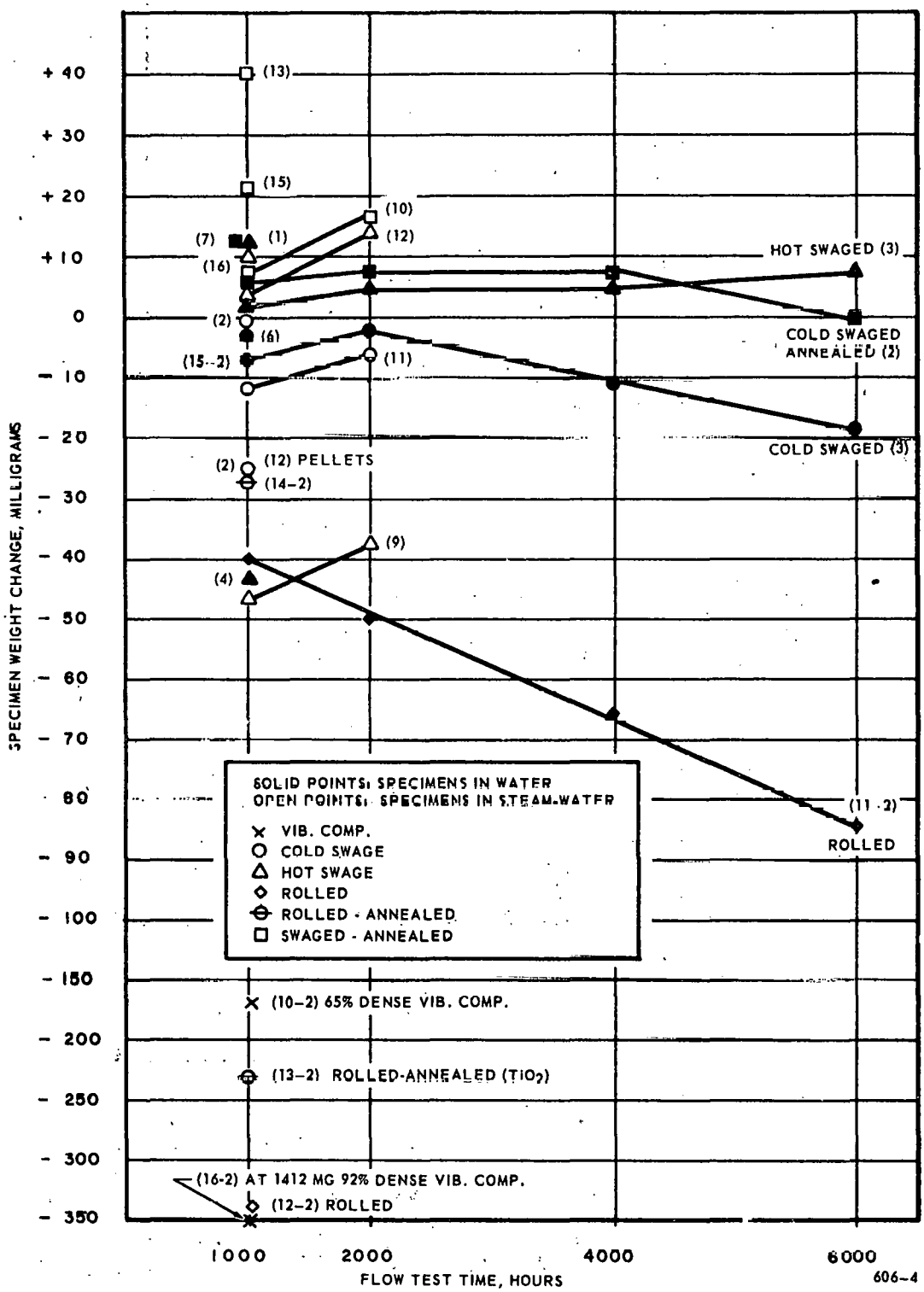


FIGURE 5 SPECIMEN WEIGHT CHANGE VS. FLOW TEST TIME

With the exception of specimen #16-2, these specimens had UO_2 densities less than 90 per cent TD. About 50 per cent of the specimens had a positive weight change (or weight gain) which may be indicative of systematic errors in weighing or oxidation of the UO_2 to a higher oxide state, i.e., U_4O_9 or U_3O_8. Spalaris, et al[9] discovered U_4O_9 and U_3O_8 in erosion specimens tested under dynamic steam flow conditions.

2.4.3 Metallographic Examination

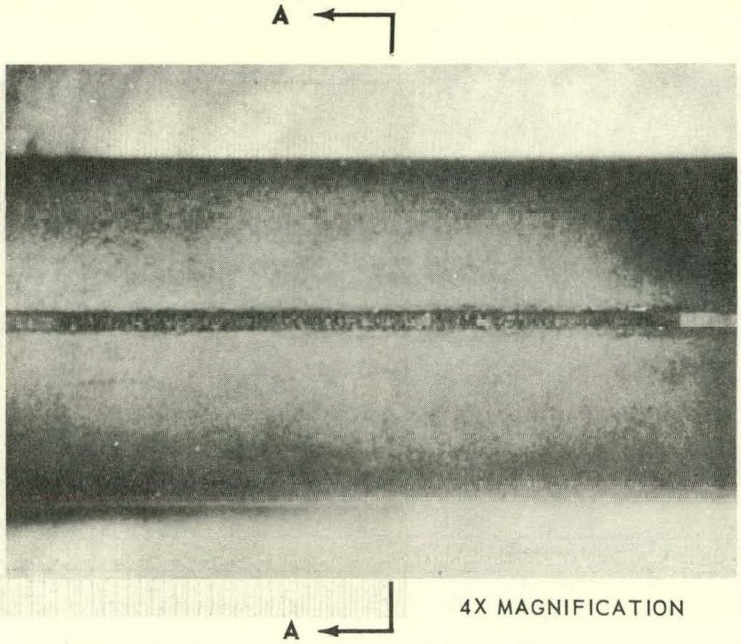
The specimens tested 6000 hours were transversely sectioned through the clad slit for metallographic examination. Photographs of the specimens before and after sectioning are shown in Figures 6-9. These photographs clearly show the amount of UO_2 removed below the clad defect. The depth of removal was limited to 0.020 inch for the three swaged samples and 0.040 inch for the rolled sample. Photographs of the pellet fuel specimen is presented in Figure 10. Note the narrow band below and on either side of the slit. This band was caused by UO_2 grains being removed during metallographic polishing. Apparently an intergranular attack was in progress between the coolant and the grain boundries of the sintered pellet.

The cladding of the four specimens tested 6000 hours was examined for evidences of corrosion attack after exposure to flowing 536 F water. The clad conditions represented by the four specimens were: cold swaged and cold rolled (~ 1/2 hard condition), hot swaged (~1/8 hard condition), and fully annealed. Typical clad surfaces are shown in Figures 11-14. None of the clad surfaces showed evidences of corrosion attack or unusual film formation. Of particular interest is Figure 13, showing a fold in the clad produced during hot swaging. Note that no corrosion attack is evident within the crevice.

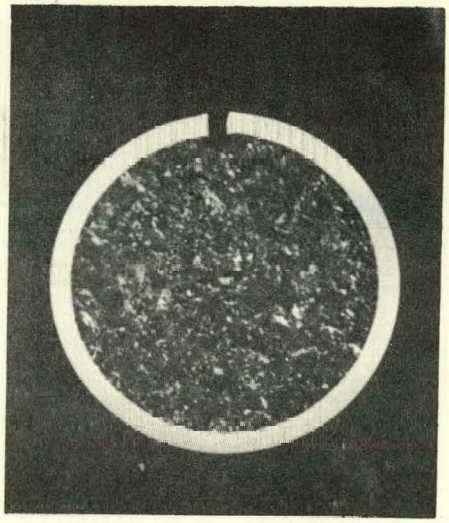
No reaction with the clad and UO_2 was apparent in any of the specimens.

2.5 Discussion of Test Results

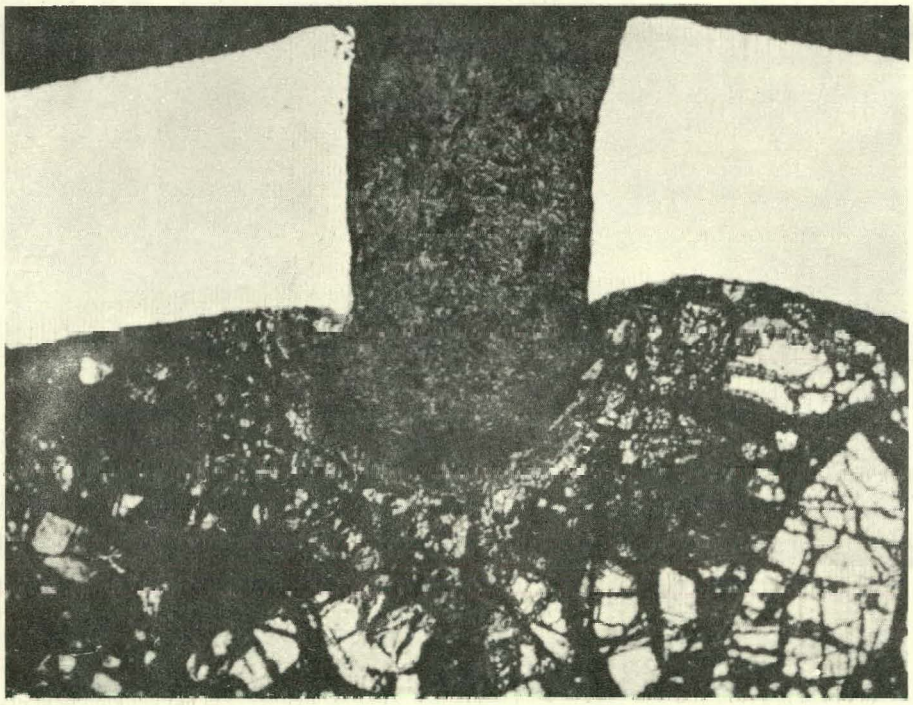
The primary objective of the erosion test was to determine the relative erosion resistance of compacted UO_2 powder fabricated by



4X MAGNIFICATION



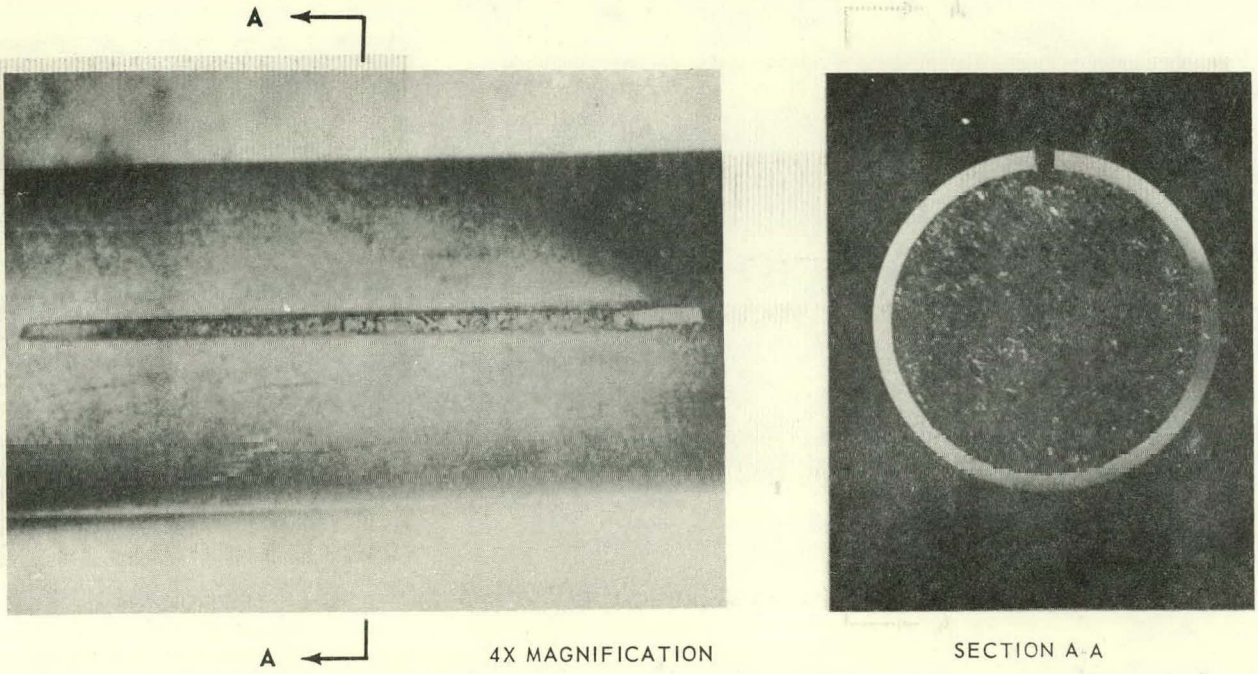
SECTION A-A

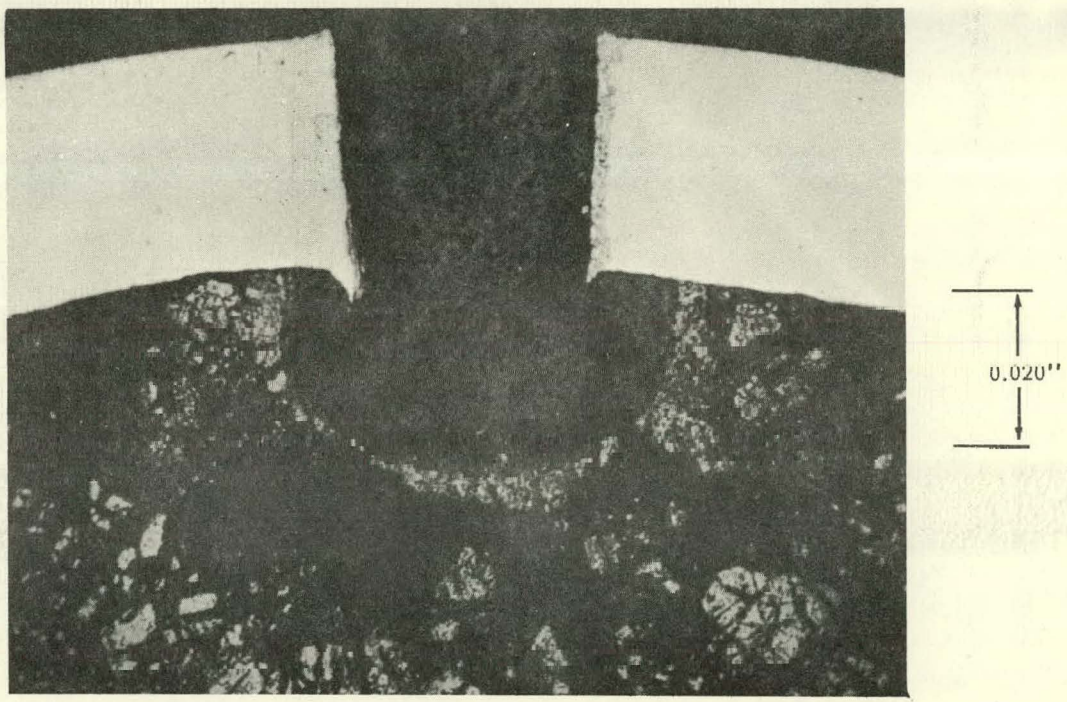


SECTION A-A 50X MAGNIFICATION

606–5

FIGURE 6 COLD SWAGED-ANNEALED SAMPLE NO. 2 AFTER 6000 HOURS FLOW TESTING IN 536°F, 7 FPS WATER

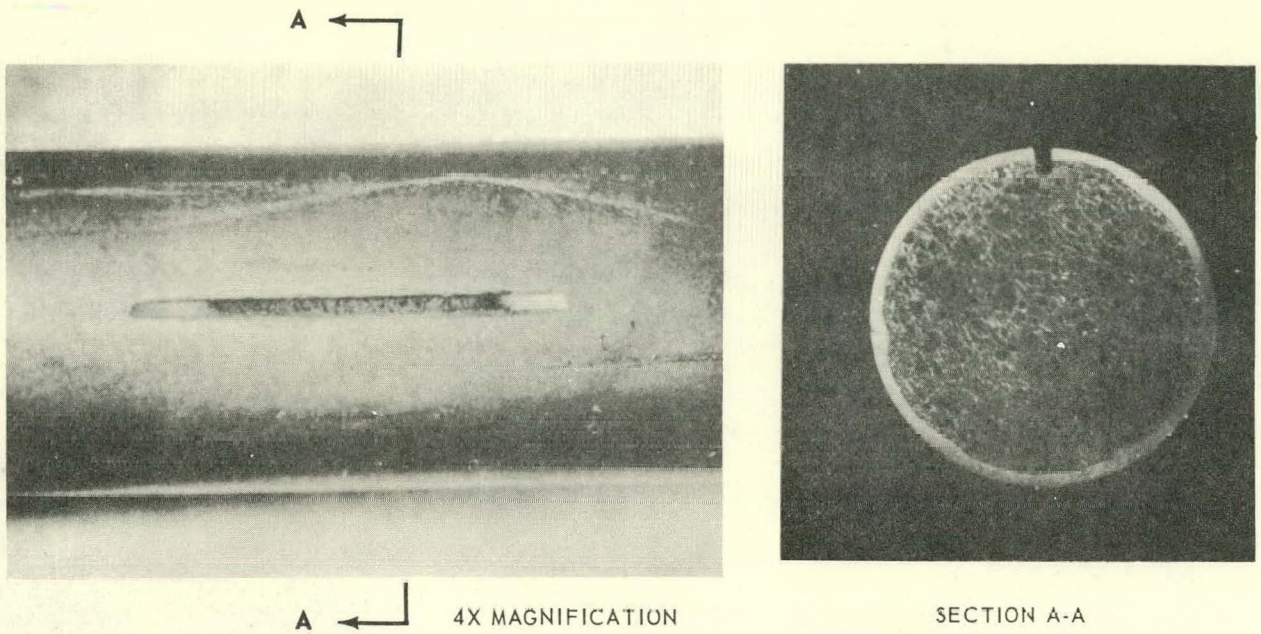


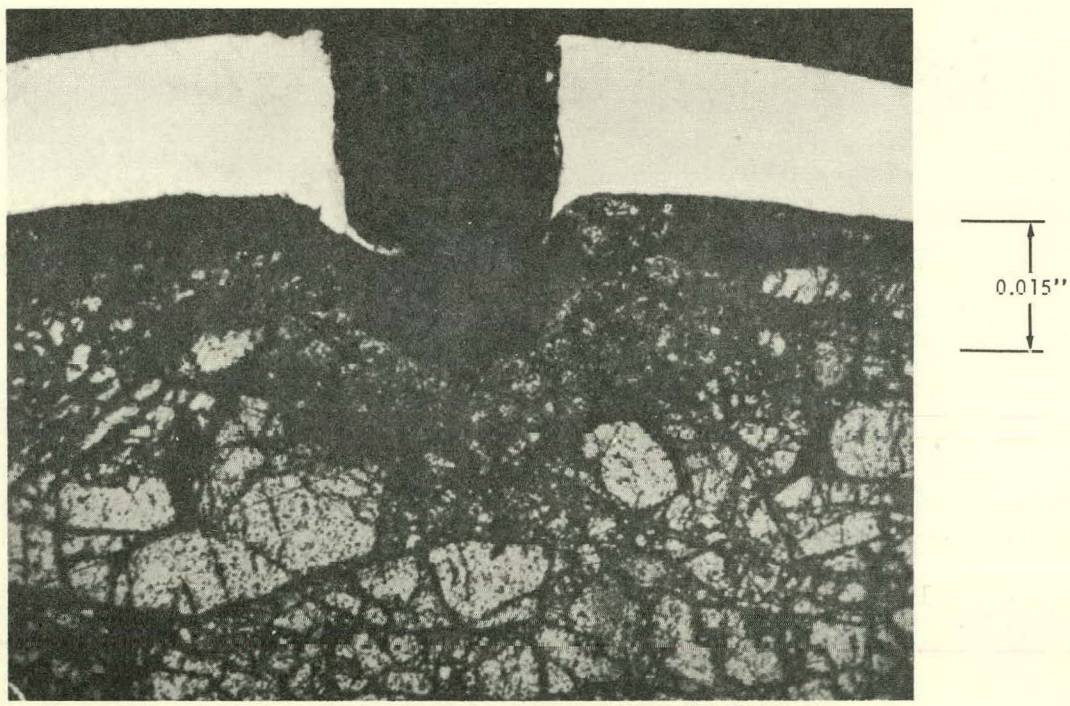


SECTION A-A 50X MAGNIFICATION

606-6

FIGURE 7 COLD SWAGED SAMPLE NO. 3 AFTER 6000 HOURS FLOW TESTING IN 536°F, 7 FPS WATER.

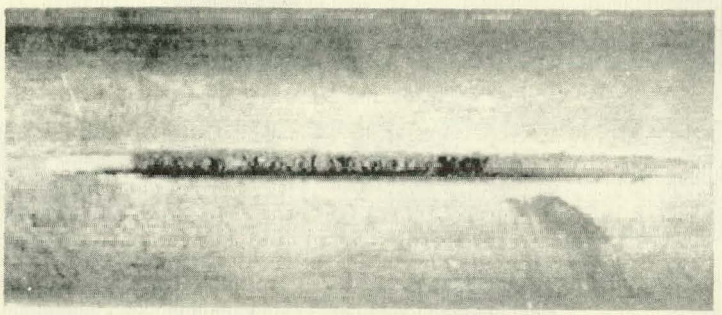




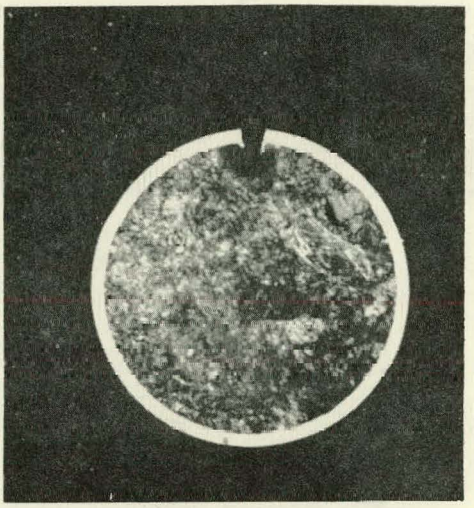
SECTION A-A 50X MAGNIFICATION

606–7

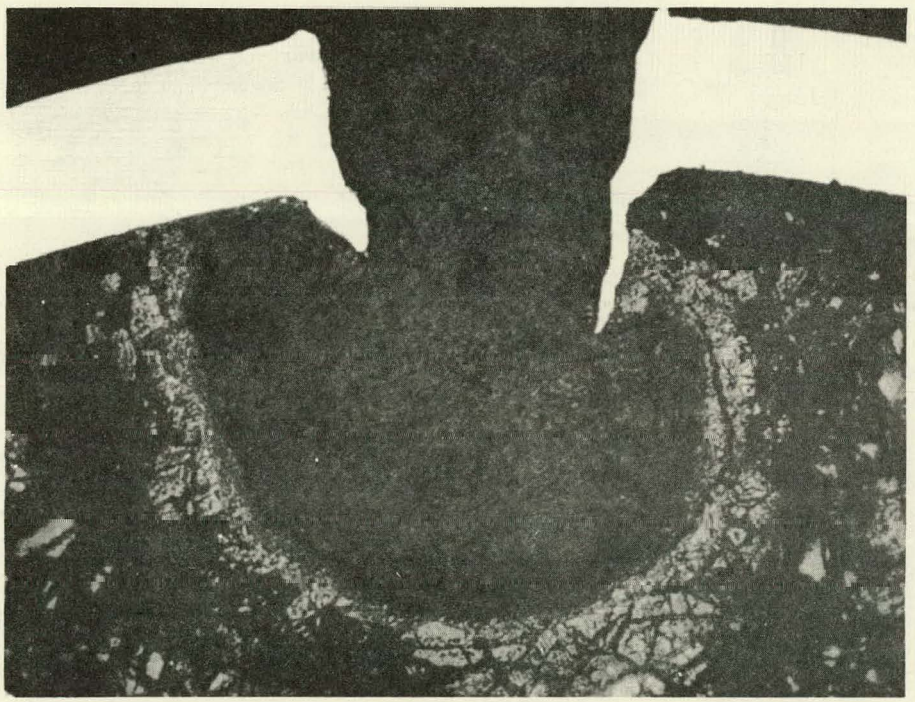
FIGURE 8 HOT SWAGED SAMPLE NO. 8 AFTER 6000 HOURS FLOW TESTING IN 536°F, 7FPS WATER



4X MAGNIFICATION



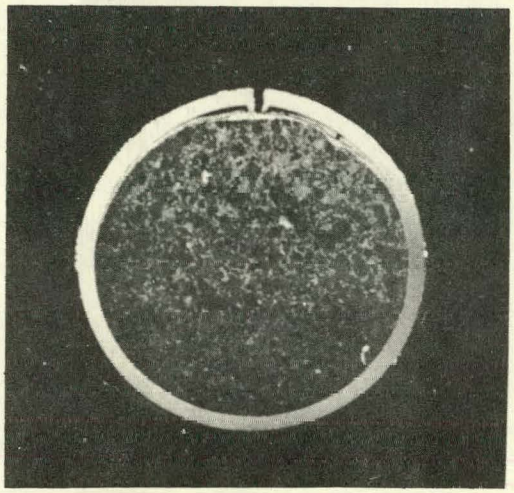
SECTION A-A



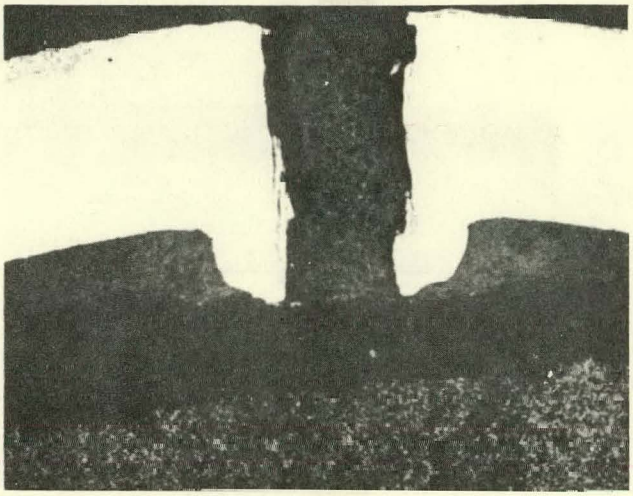
SECTION A-A 50X MAGNIFICATION

606-8

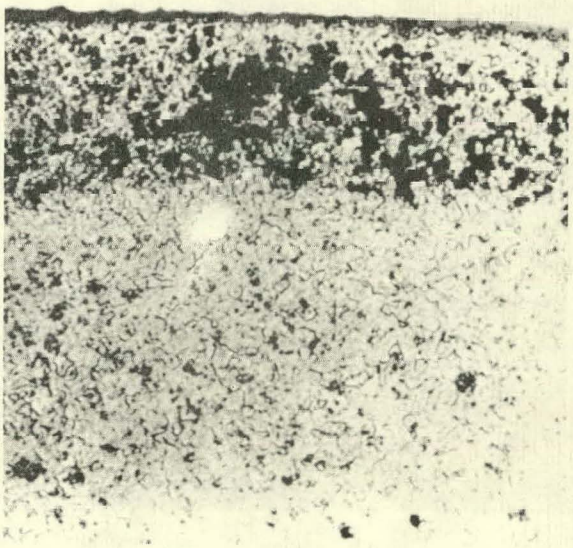
FIGURE 9 TANDEM ROLLED SAMPLE NO. 11-2 AFTER 6000 HOURS FLOW TESTING IN 536°F, 7 FPS WATER



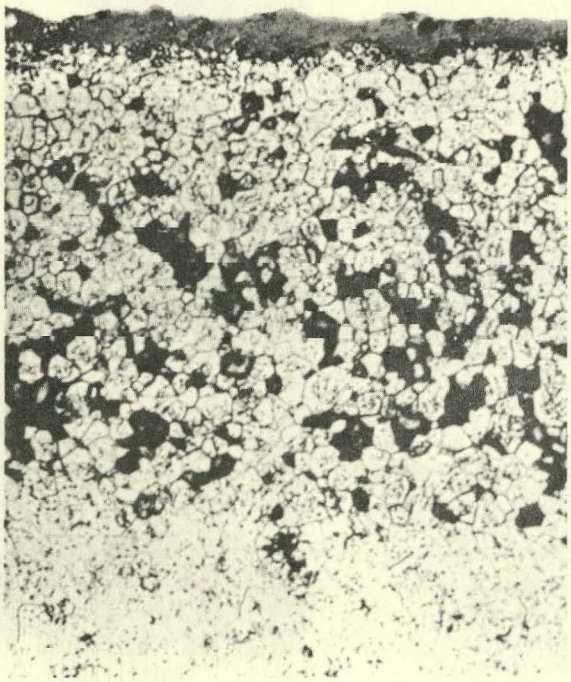
4X



75X



100X MAG.

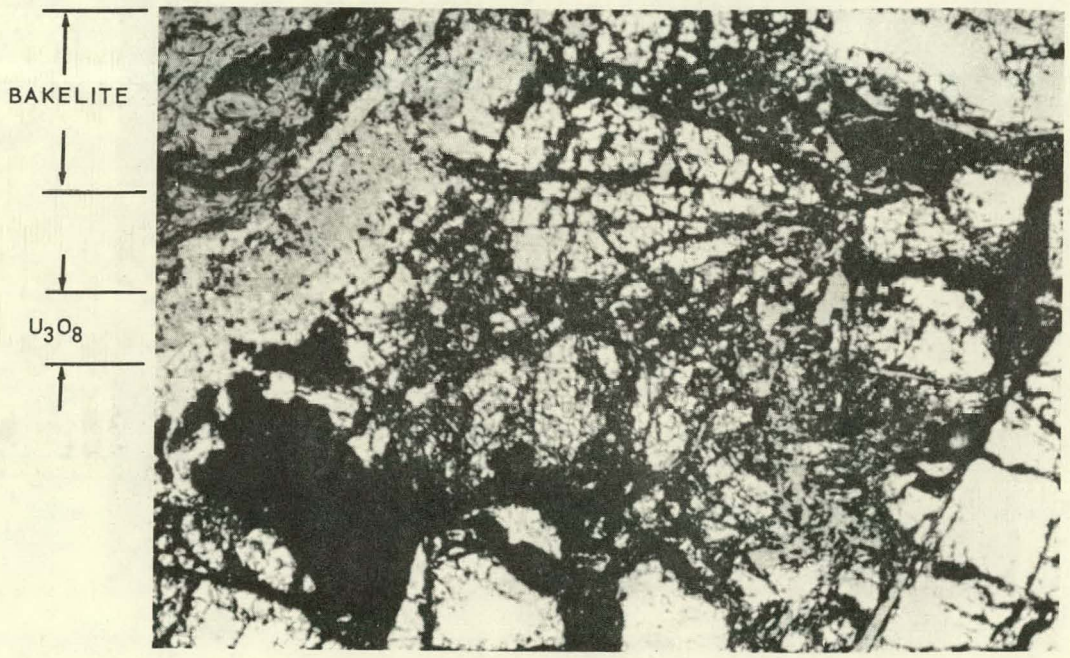


500X MAG.

606-9

FIGURE 10 TRANSVERSE SECTION OF PELLET SAMPLE NO. 1-2

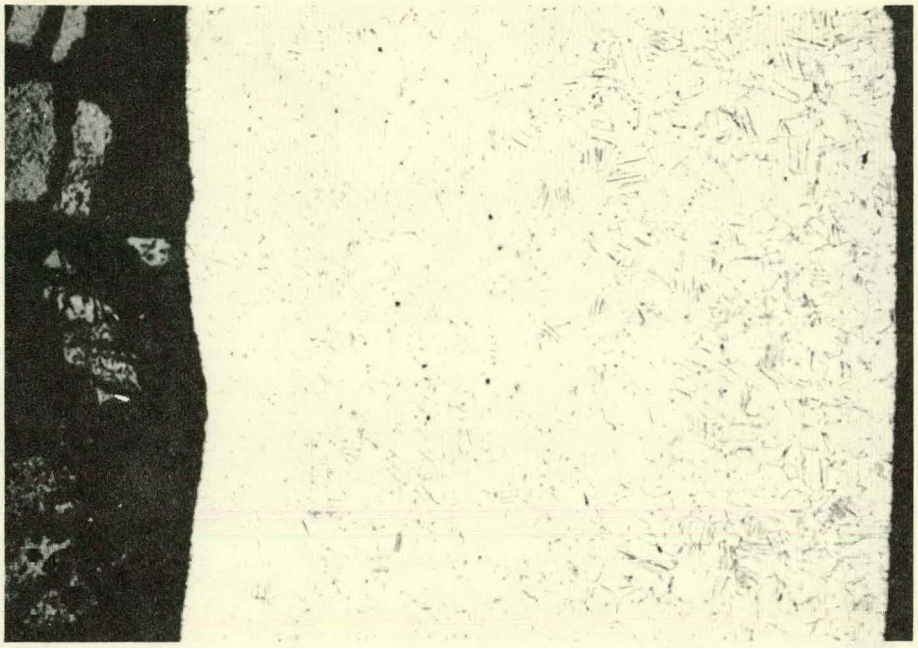
ID CLADDING OD



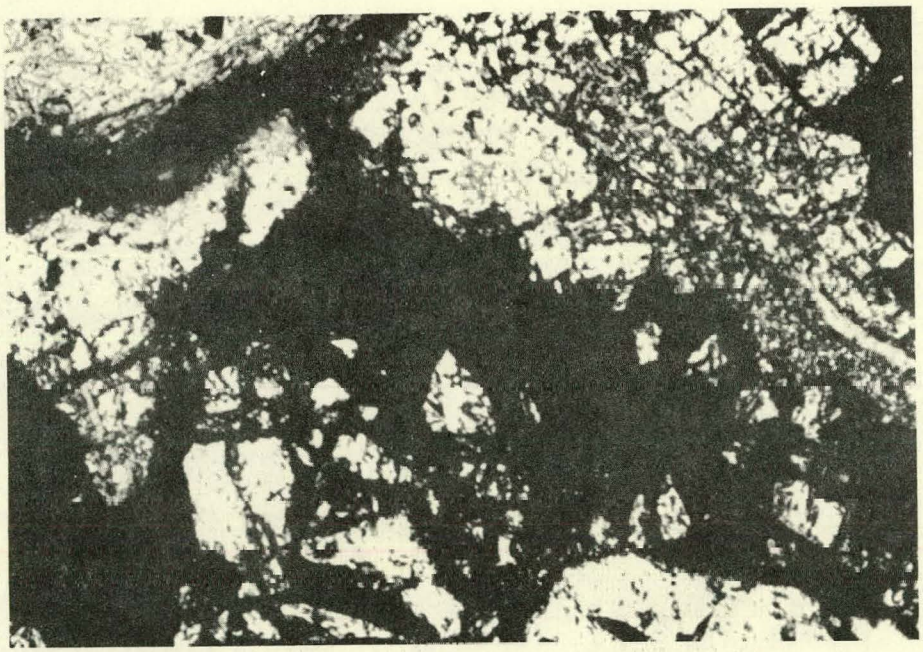
UO_2 AT BASE OF SLIT

606-10

FIGURE 11 PHOTOMICROGRAPHS (150X) OF CLAD AND UO_2 FROM COLD SWAGE-ANNEALED SAMPLE



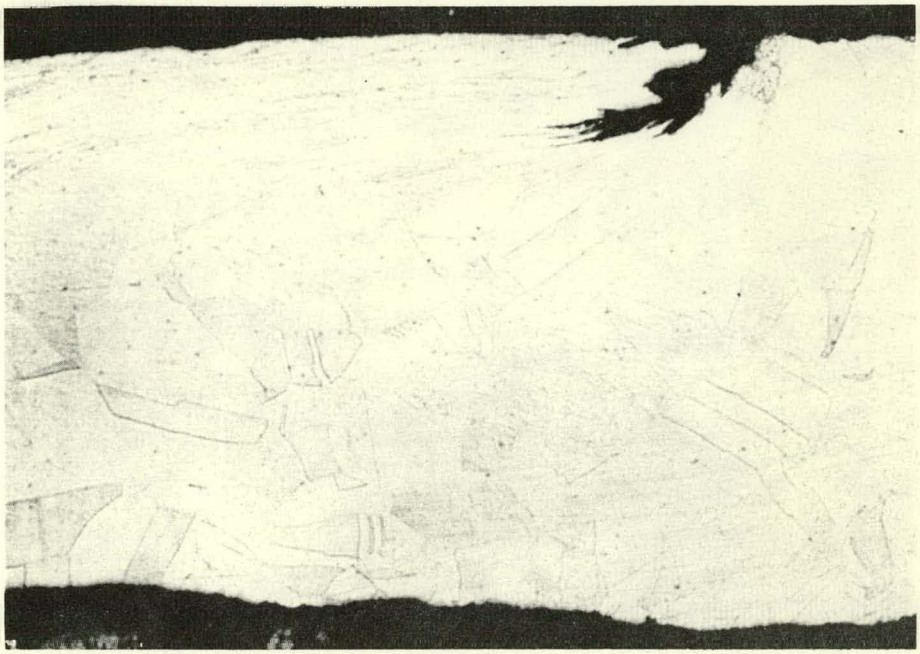
ID CLADDING OD



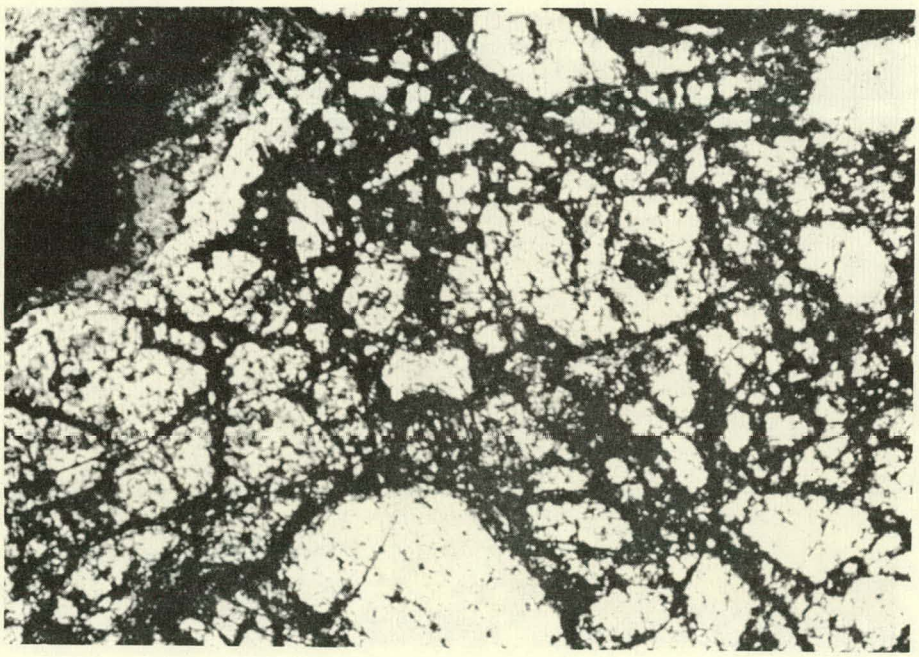
UO_2 AT BASE OF SLIT

606-11

FIGURE 12 (150X) PHOTOMICROGRAPHS, OF CLAD AND UO_2 FROM COLD SWAGED SAMPLE NO. 3



CLAD DEFECT PRODUCED BY HOT SWAGING
(NOTE ABSENCE OF CORROSION ATTACK IN DEFECT)

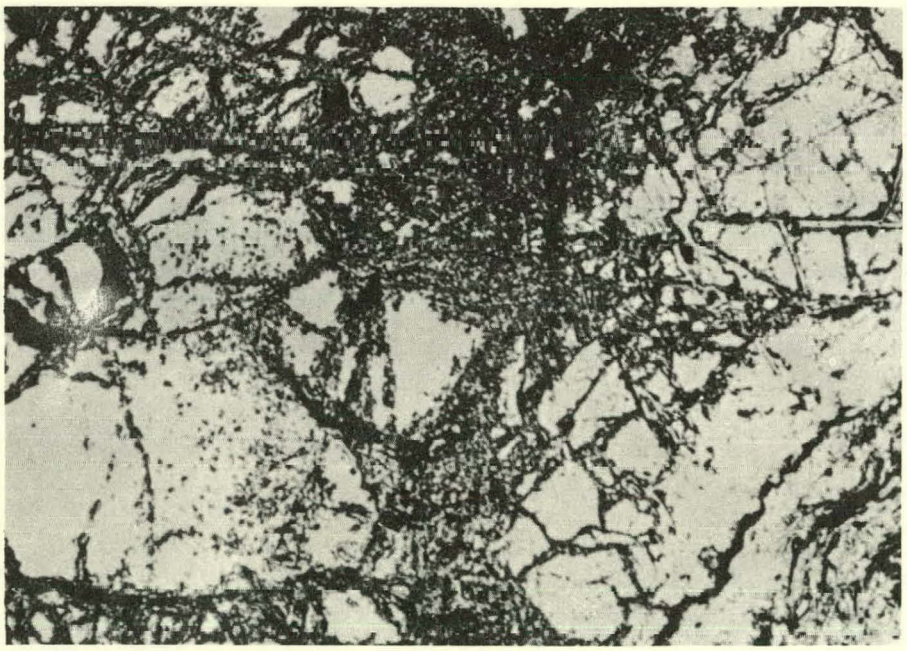


UO_2 AT BASE OF SLIT

606–12

FIGURE 13 PHOTO MICROGRAPHS (150X) OF CLAD AND UO_2 FROM HOT SWAGED SAMPLE NO. 8

CLADDING (TOP)



UO_2 AT BASE OF SLIT

606-13

FIGURE 14 PHOTO MICROGRAPHS (150X) OF CLAD AND UO_2 FROM TANDEM ROLLED SAMPLE 11-2

various techniques. Relative erosion resistance was established among the samples tested with swaged samples showing the best performance. A discussion of the erosion resistance related to test variables is presented below.

2.5.1 Effect of Defect Length and Loop Position on Specimen Weight Change

The majority of the specimens were tested with a 1/2-inch long slit. Two hot swaged specimens were each tested with 1 inch, 1/2-inch and 1/4-inch long slits. Two cold swaged specimens were each tested with 1/2-inch and 1/4-inch slits. Examination of the weight change data in Table 8 reveals that no appreciable difference exists between 1-inch and 1/2-inch slits. Some difference does exist between 1/2-inch and 1-4 inch slits, but the difference is slight; i.e., 6 mg for cold swaged specimens, and 25 mg for hot swaged specimens. The specimens with 1/4-inch slits showed a lower weight loss than those with 1/2-inch slits. No effect of loop position on the specimen weight changes was observed. Within each fabrication group of specimens comparable weight changes occurred in both the water and the steam water sections of the loop.

Examining the data in Table 8 reveals therefore that neither the length of slot nor the position of the specimen in the loop had a major influence on the weight changes experienced by the specimens. The major influencing factors were the fabrication process and the UO_2 density of the specimen. These factors are discussed in the following sections.

2.5.2 Erosion Resistance vs Specimen UO_2 Density

The test specimens covered a UO_2 density range from 65 per cent to 95 per cent TD. The specimen UO_2 density was dependent upon the fabrication process. It will be shown later that specimens with similar density but different fabrication history vary in erosion performance. At present, we shall be concerned only with density, per se. A plot of specimen UO_2 density vs specimen weight change is presented in Figure 15. The plot clearly shows that for specimens with UO_2 density values greater than 90 per cent TD, no appreciable weight changes were experienced. However, for density values less than

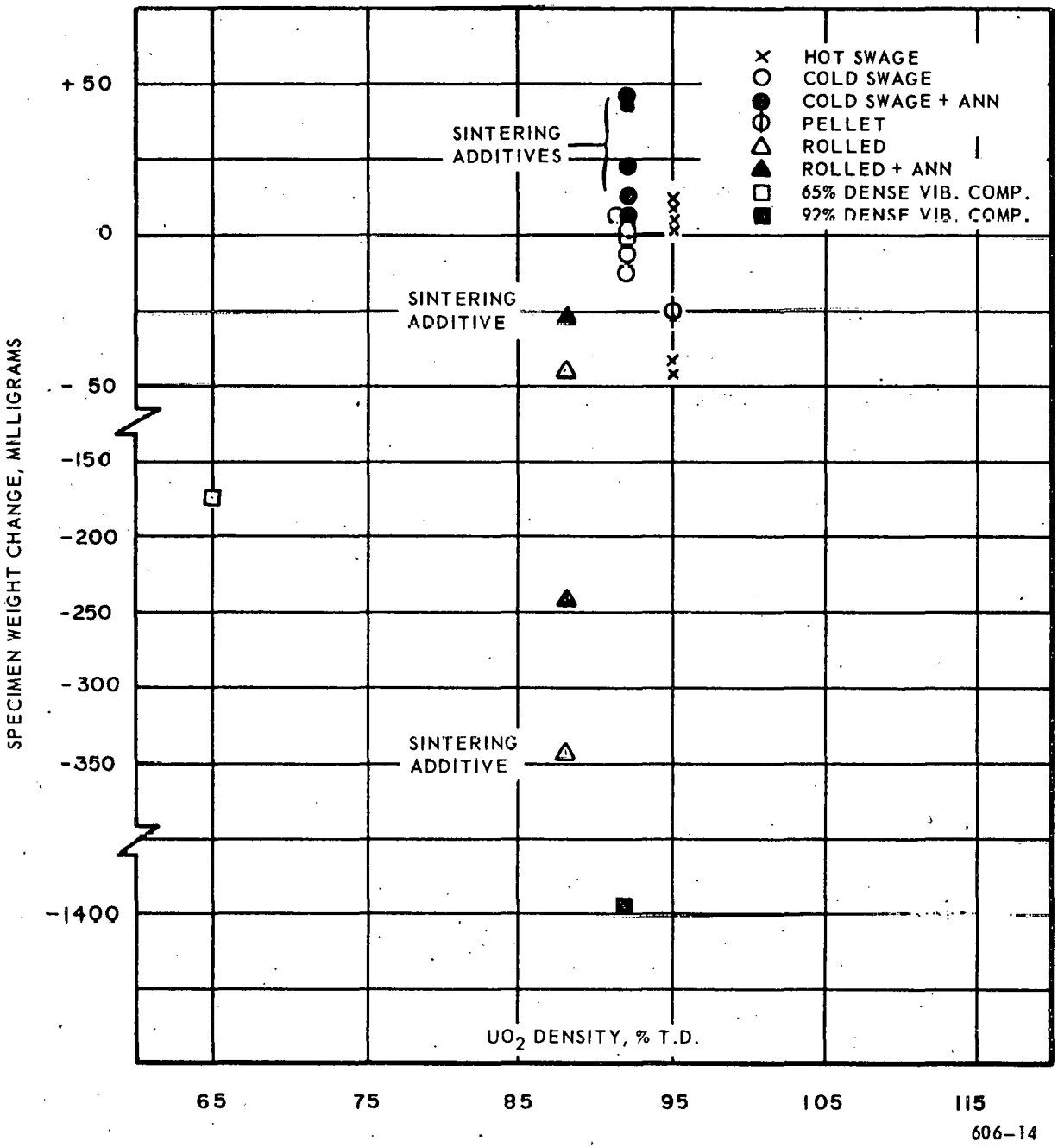


FIGURE 15 RELATIONSHIP BETWEEN SPECIMEN UO_2 DENSITY AND FABRICATION HISTORY VS. SPECIMEN WEIGHT CHANGE

90 per cent TD, considerable data variation and relatively greater weight changes were experienced. There was no significant difference in the weight change data between the 92 per cent and 95 per cent density groupings. (The one 90 per cent point falling at -1412 mg weight change is excluded for reasons discussed below).

2.5.3 Erosion Resistance vs Specimen Fabrication History

The processes used to fabricate the compacted powder test specimens were cold swaging, hot swaging, tandem rolling and vibratory compaction. The swaging and rolling processes mechanically reduce the diameter of the fuel rod to achieve final UO_2 density. The vibratory compaction process achieves final UO_2 density by vibration techniques alone. A portion of the particle size distribution used in vibratory compaction must necessarily be of a fine fraction (<200-mesh). This fine fraction, which may be as high as 30 per cent of the total UO_2 weight, is susceptible to being lost from a fuel rod through a clad defect. Eight vibratory compaction samples were prepared for erosion testing; however, only three were tested because of the above problem. Upon defecting, five of the vibratory compacted samples lost UO_2 through the defect slit. This loss of the fine particle fraction in vibratory compacted specimens is believed to account for the loss of 1412 mg in sample 16-2. It should be noted here that the loss of fines from an irradiated vibratory compacted fuel rod is not suggested. Under irradiation, the major portion of the UO_2 would become sintered, leaving only a small annulus adjacent to the inner clad surface with discrete UO_2 particles.

The relationship between specimen weight change and specimen fabrication process is also shown in Figure 15. The cold swaged specimens show the best relative erosion performance. Following the cold swaged group are the cold swaged specimens that were annealed. However, the annealed specimens containing sintering additives (CaO and TiO_2) did not perform as well as the two specimens without additives. The CaO additive in fact caused swelling of the specimen by hydrolysis of the CaO. No benefit was apparent using TiO_2 as an additive. The hot swaged group is close to being as good as the cold swaged group. Two

of the hot swaged specimens showed a relatively high weight loss (-45 mg); the largest experienced for the swaged group as a whole. The average weight loss for the two swaged groups however closely coincides. The two swaged groups also had less UO_2 loss than experienced by the single pellet specimen.

The erosion resistnace of the tandem rolled samples was erratic. In one sample (#14-2), the TiO_2 additive improved the erosion resistance, whereas in the second sample (#13-2), it appeared to have the opposite effect. The performance of the tandem rolled group is inferior to the swaged groups. However, the UO_2 losses experienced with the tandem rolled samples on an absolute value basis are not considered excessive.

The performance merits of any new fuel is usually compared to that of the standard pellet type fuel. One would intuitively believe that pellet type fuel would be more resistant to the erosion action of flowing coolant than compacted powder type fuel. However, from the intergranular attack observed in pellet specimen (Figure 10) there may be a more serious area of concern for pellet type fuel. Pellets must necessarily contain grains (and grain boundries) by the method of manufactuer. Fused UO_2, on the other hand, is essentially made up of single crystals. In compacte UO_2 powder fuel, intergranular modes of attack are not likely to occur.

2.5.4 Specimen Dimensional Stability

The dimensional stability of the test specimens were, with two exceptions, excellent; within 0.002-inch of original dimensions. The two exceptions were specimens containing CaO added to the UO_2 as a sintering aid. The CaO hydrolyzed causing swelling of the clad around the defect area. The excellent dimensional stability of the specimens would indicate that no significant reactions occurred (except the above noted case) with the UO_2 and the coolant.

2.5.5 Corrosion Performance of the Specimen Clad

A secondary objective of the erosion test was to evaluate possible clad corrosion effects resulting from the long term testing of the specimens under a boiling water reactor coolant environment. The data

presented in Section 2.4.3 showed that no corrosion attack or unusual film formation was evident on clad surfaces of the four specimens tested 6000 hours. The stress conditions represented by these specimens were 1/2 hard, 1/8 hard and annealed. The excellent condition of the cladding, in particular the 1/2 hard condition, should mitigate concern over stress corrosion attack on cold swaged fuel rods. The test also illustrated by way of the hot swaged specimen that even severely abused 304 stainless clad performs admirably in a boiling water reactor coolant environment.

2.5.6 Test Results as Applied to Reactor Fuel Performance

From the data and discussions presented three salient observations can be drawn with respect to irradiation performance of compacted powder fuel in boiling water reactors.

1. Stainless clad swaged fuel with UO_2 densities greater than 90 per cent TD is comparable to pellet type fuel, and should withstand erosion tendencies of the coolant to wash out UO_2 in the event of a clad split.

2. The stresses and imperfections introduced into the stainless clad as a result of swaging does not appear to adversely effect the corrosion characteristics of stainless steel in a boiling water reactor coolant environment.

3. Stainless clad, compacted powder fuel fabricated by rolling or vibratory compaction techniques with UO_2 densities less than 90 per cent TD appear to have sufficient erosion resistance to prevent substantial losses of UO_2 in the event of a clad failure.

The above observations must, of course, be substantiated by in-reactor testing of purposely defected compacted powder fuel rods.

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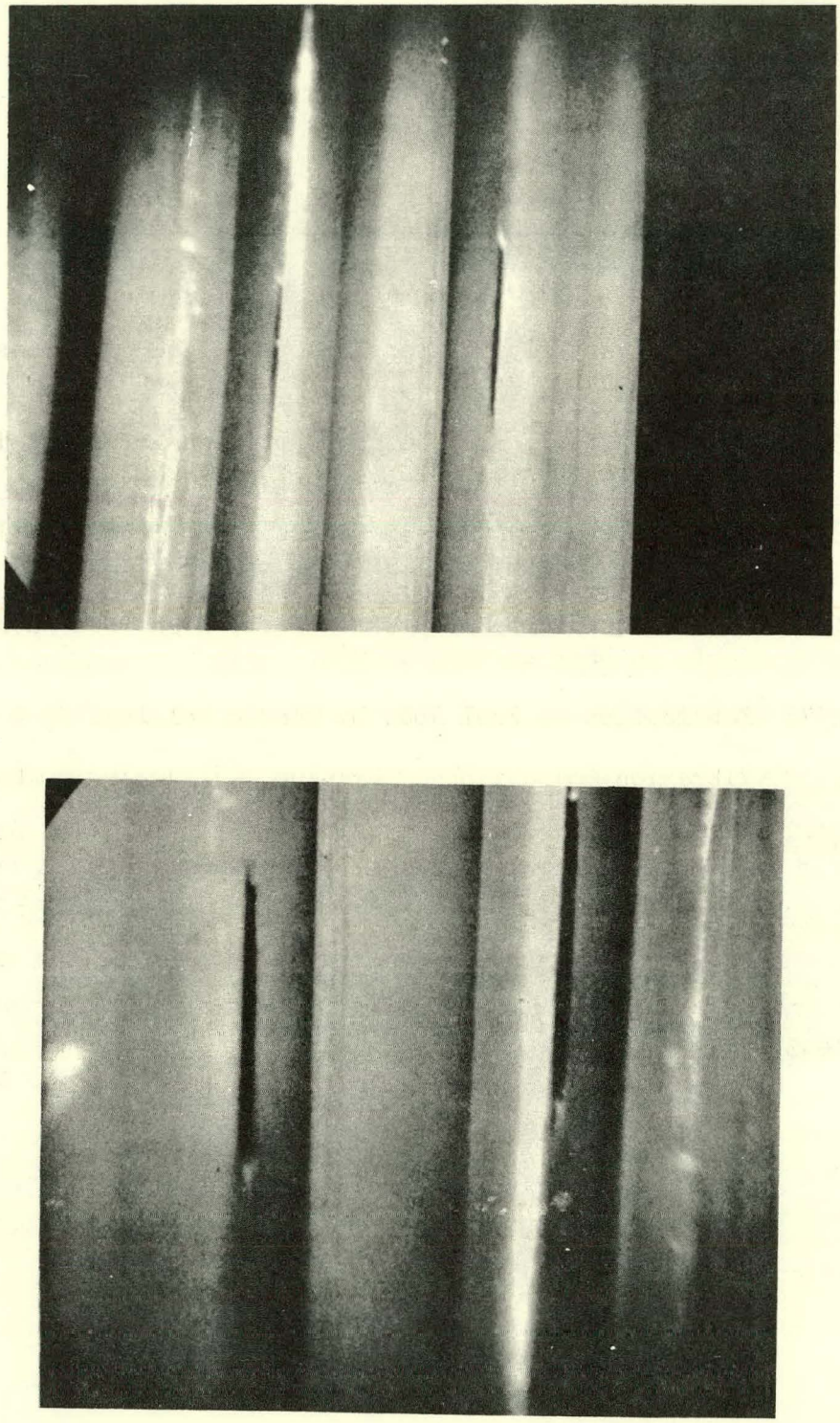
SECTION III

IRRADIATION TESTING OF DEFECTED FUEL RODS

Based on the data presented in Section 2.4, two fuel rods were prepared for irradiation testing with 1/2-inch long slits. The rods were 0.015-inch stainless clad x 0.400-inch diameter x 38 inches long. One rod was 90 per cent dense cold swaged and the other was 95 per cent dense hot swaged. The defect was made identical in nature to those of the erosion specimen: 1/2-inch long x 0.020-inch wide, and just deep enough to break through the clad. The defect was located eleven inches from the bottom of the fuel rod such as to place it in the maximum heat flux zone (~350,000 BTU/hr-ft^2).

The two defected rods were inserted into HPD assembly 1S in December, 1961. The defected rods started testing December 17, 1961. The rods have accumulated 1000 MWD/T exposure to date. Photographs of the defected rods after 1000 MWD/T UO_2 exposure is shown in Figure 16. The activity release from these two defects has been approximately 20 μc/sec. No swelling of the fuel rods or loss of UO_2 from the defects has been observed.



606-15

FIGURE 16 PHOTOGRAPHS AT TWO DIFFERENT MAGNIFICATIONS OF SLIT TYPE DEFECTS IN SWAGED FUEL RODS. IRRADIATION EXPOSURE OF 1000 MWD/T.

SECTION IV

BIBLIOGRAPHY

1. GEAP 3717 Fourth Quarterly Progress Report, High Power Density Project, January-March, 1961.

2. GEAP 3830 Fifth Quarterly Progress Report, High Power Density Project, April-June, 1961.

3. GEAP 3884 Sixth Quarterly Progress Report, High Power Density Project, July-September, 1961.

4. GEAP 4001 Seventh Quarterly Progress Report, High Power Density Project, October-December, 1961.

5. GEAP 3775 Fabrication of Fuel Rods by Tandem Rolling, J. W. Lingafelter

6. GEAP 4032 Vibration Compaction of Uranium Dioxide, W. R. DeHollander

7. HW 65465 Hydriding In Purposely Defected, Zircaloy-Clad Fuel Rods, M. K. Millhollen, G. R. Horin, J. L. Bates.

8. HW 70315 Erosion Resistance of Swaged UO_2 Following An In-Reactor Fuel Rod Cladding Failure, M. K. Millhollen, G. R. Horn, J. L. Bates.

9. GEAP 3698 Erosion Experiments of Powder Compacted UO_2 under Dynamic Steam Flow, C. N. Spalaris, F. A. Comprelli, M. Siegler.

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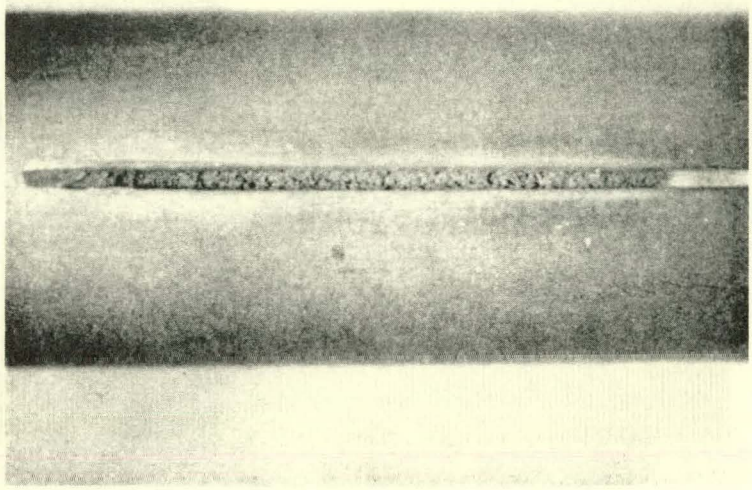
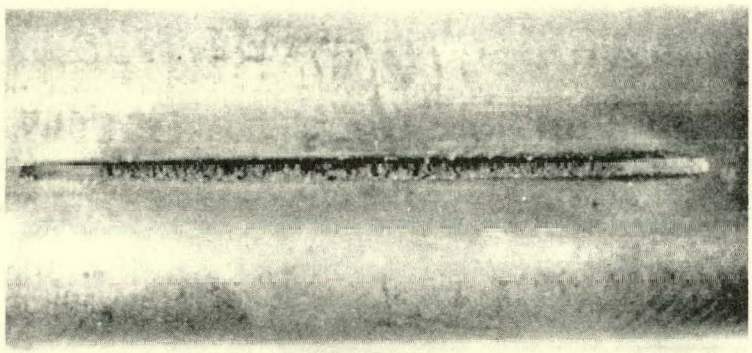
APPENDIX

Photographs of Erosion Specimens after

1000 and 4000 hours of Flow Testing



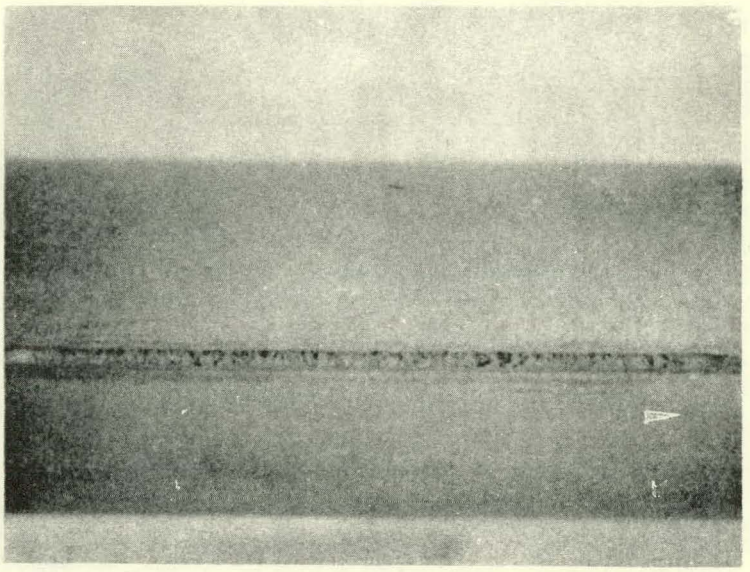
SAMPLE NO. 3 536°F WATER
WEIGHT CHANGE: -7 mg



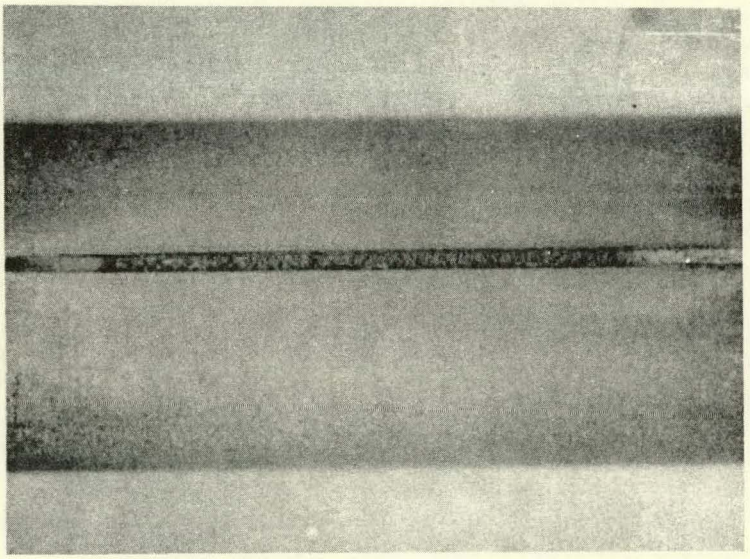
SAMPLE NO. 11 546°F STEAM-WATER
WEIGHT CHANGE: -13mg

606-16

FIGURE 17 (4X MAGNIFICATION) COLD SWAGED SAMPLES NO. 3 AND NO. 11 AFTER 1000-HOUR FLOW TESTING



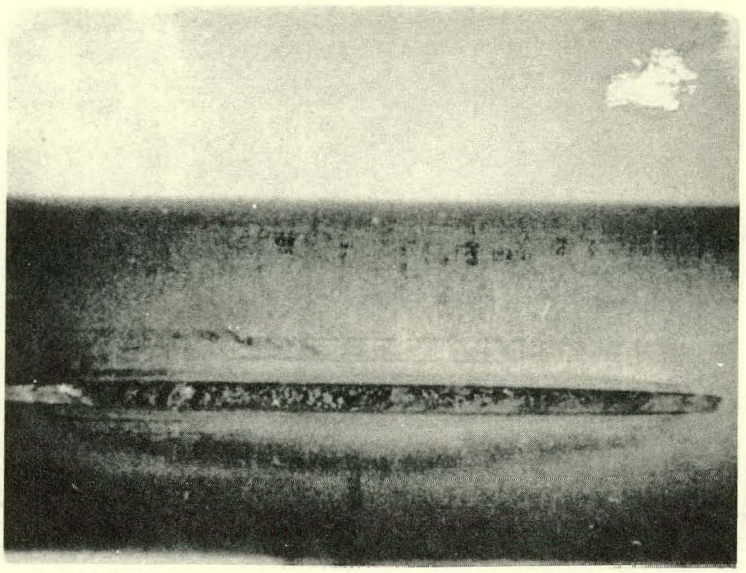
SAMPLE NO. 2 -536°F WATER
WEIGHT CHANGE: +6 mg



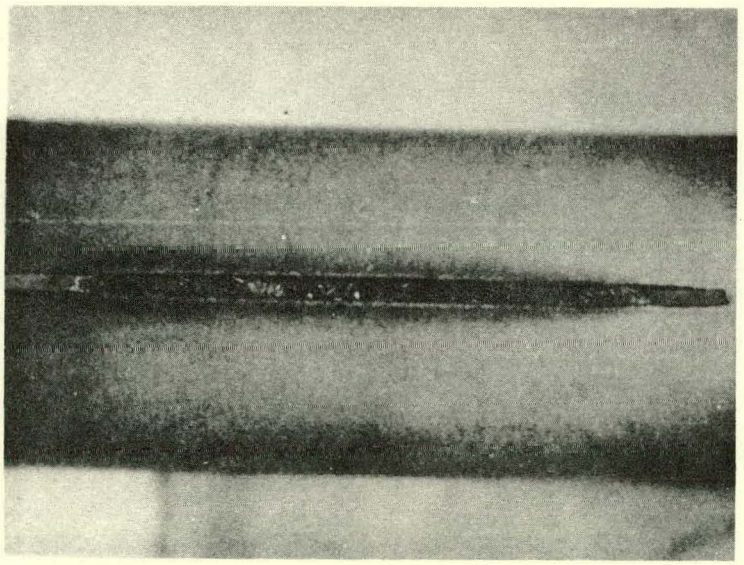
SAMPLE NO. 10 546°F STEAM WATER
WEIGHT CHANGE: +6mg

606-17

FIGURE 18 (4X MAGNIFICATION) COLD SWAGED ANNEALED SAMPLES NO. 2 AND NO. 10 AFTER 1000-HOUR FLOW TESTING



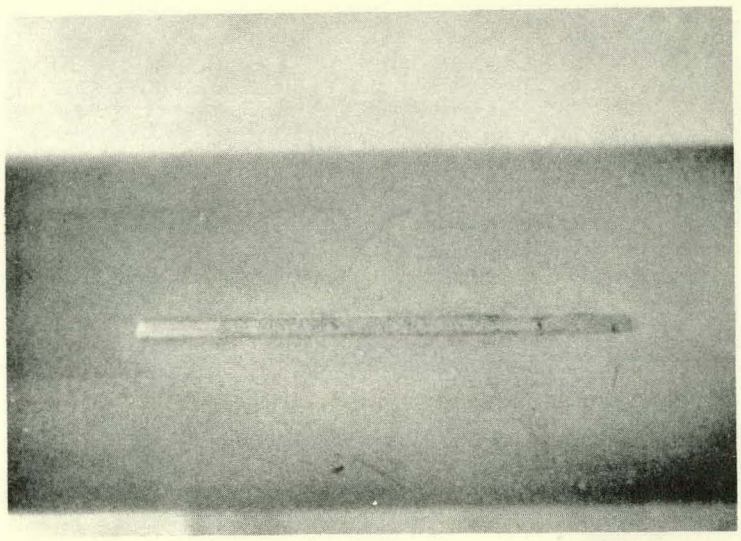
SAMPLE NO. 5 536°F WATER



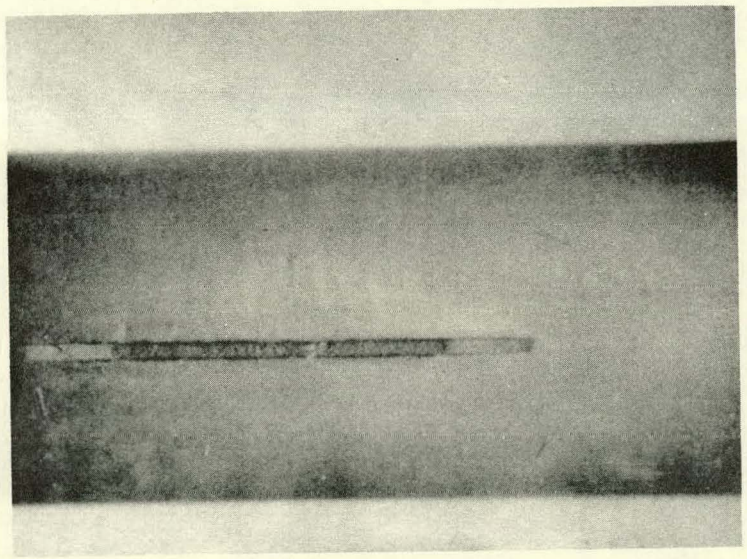
SAMPLE NO. 13 546°F STEAM-WATER
WEIGHT CHANGE: +44 mg

606–18

FIGURE 19 (4X MAGNIFICATION) COLD SWAGED-ANNEALED SAMPLES (WITH ½% CaO ADDED TO UO_2) NO. 5 AND NO. 13 AFTER 1000-HOUR FLOW TESTING (Note slight swelling)



SAMPLE NO. 7 536°F WATER
WEIGHT CHANGE: +13 mg



SAMPLE NO. 15 546°F STEAM-WATER
WEIGHT CHANGE: +22 mg

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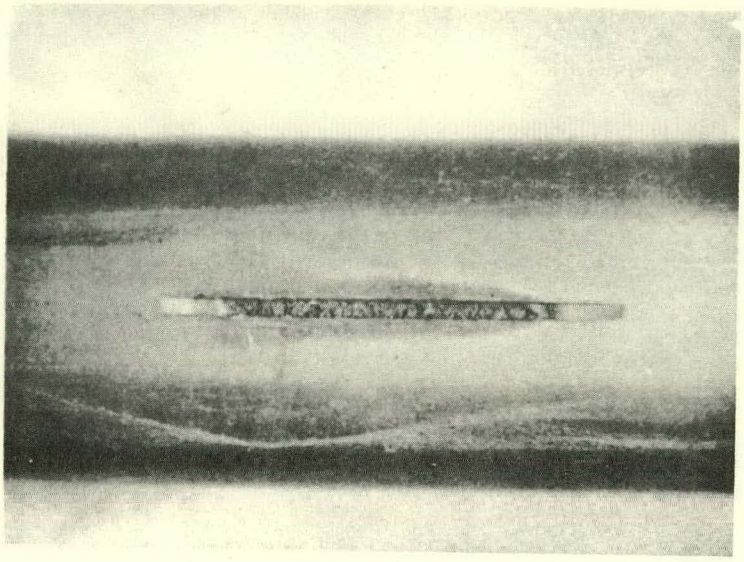
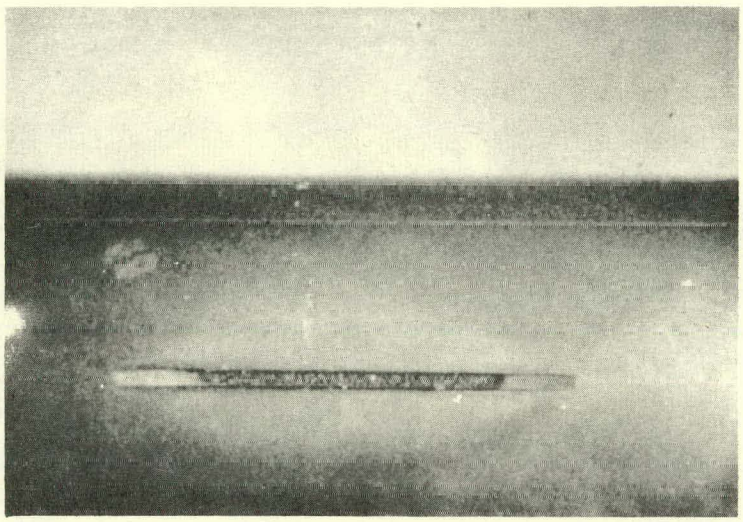
FIGURE 20 (4X MAGNIFICATION) COLD SWAGED-ANNEALED SAMPLE (WITH ½% TiO_2 ADDED TO UO_2) AFTER 1000 HOUR FLOW TESTING



SAMPLE NO. 8 536°F WATER WEIGHT
WEIGHT CHANGE: +2 mg



SAMPLE NO. 16 546°F STEAM-WATER
WEIGHT CHANGE: +10 mg

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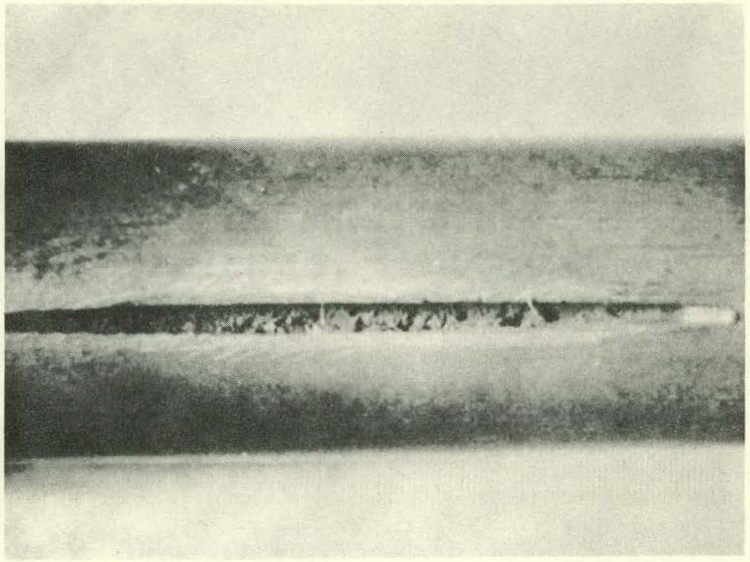
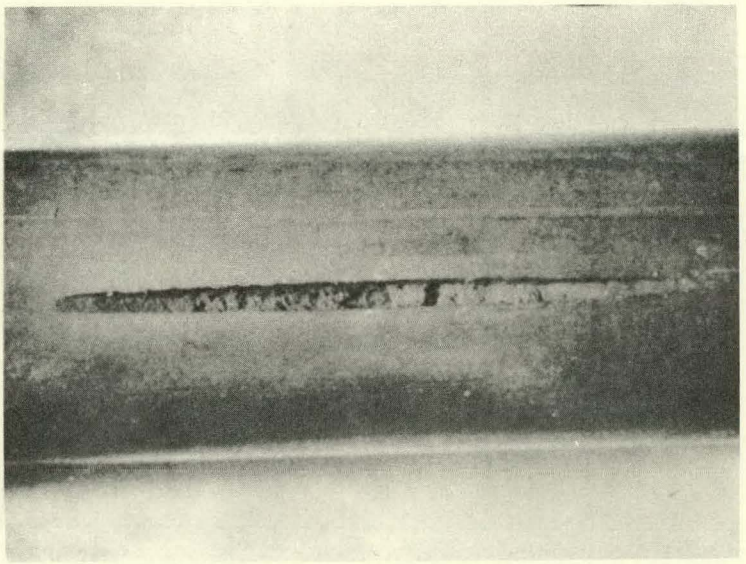
FIGURE 21 (4X MAGNIFICATION) HOT SWAGED EROSION FLOW SAMPLES NO. 8 AND NO. 16 AFTER 1000 HOURS FLOW TESTING



SAMPLE NO. 13-2 536°F WATER
WEIGHT CHANGE: -239 mg



SAMPLE NO. 14-2 546°F STEAM-WATER
WEIGHT CHANGE: -27 mg

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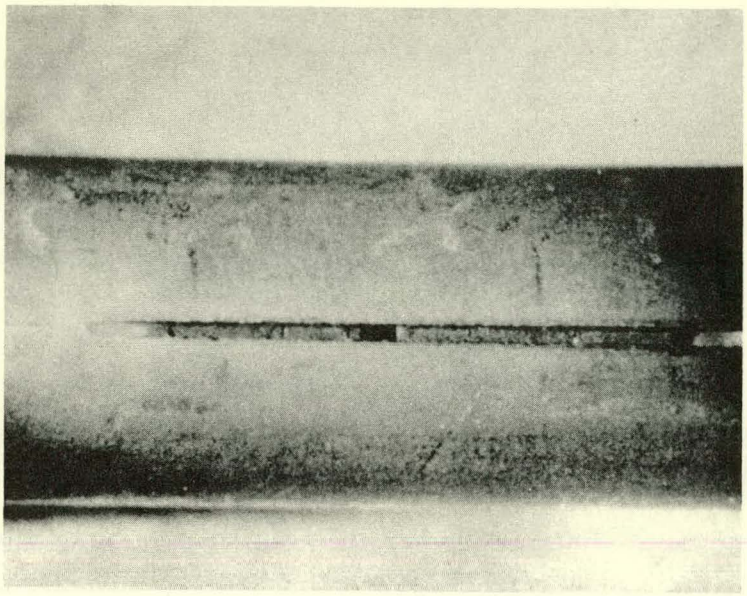
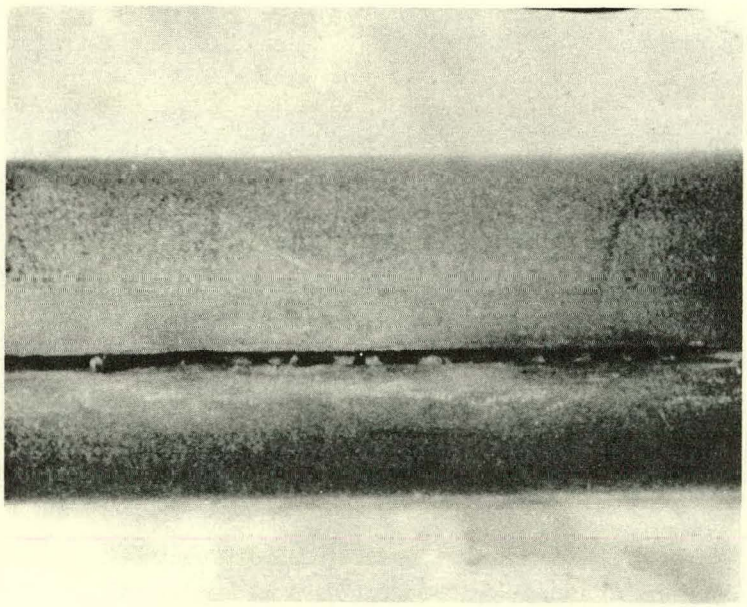
FIGURE 22 TANDEM ROLLED - ANNEALED SAMPLES WITH ½% TiO_2 ADDED TO UO_2 NO. 13-2 AND 14-2 AFTER 1000-HOUR FLOW TESTING



PELLET SAMPLE NO. 1 2 536°F WATER
WEIGHT CHANGE: -25 mg



VIBRATORY COMPACTED SAMPI F NO. 10-2

546°F STEAM-WATER
WEIGHT CHANGE: -171 mg

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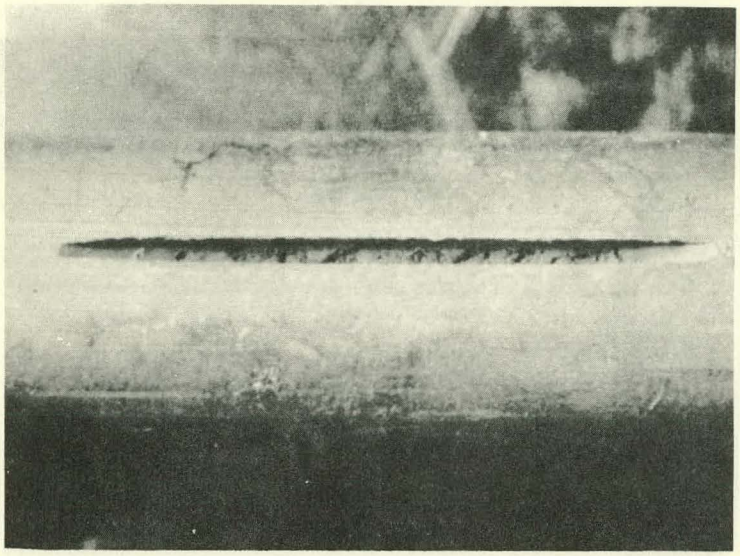
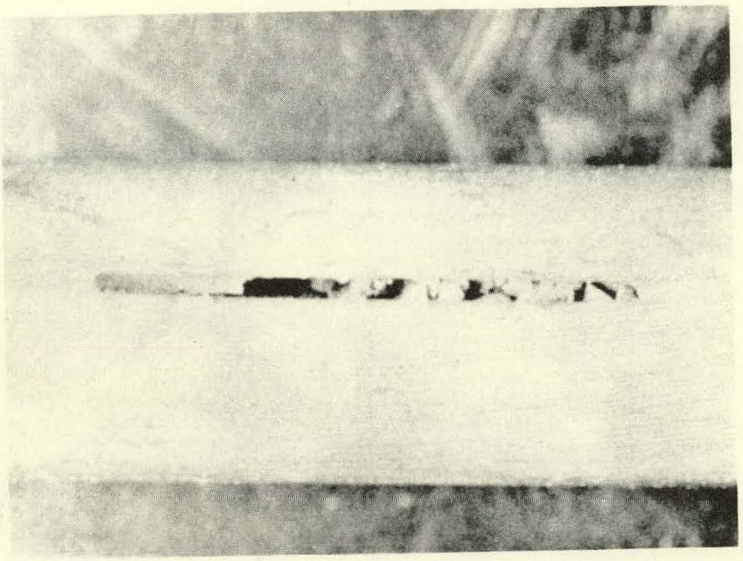
FIGURE 23 PELLET SAMPLE NO. 1-2 AND 65% DENSE VIBRATORY COMPACTED SAMPLE NO. 10-2 AFTER 1000 -HOUR FLOW TESTING.



SAMPLE NO. 15-2 536°F WATER
WEIGHT CHANGE: +3.4 mg



SAMPLE NO. 16-2 546°F STEAM-WATER
WEIGHT CHANGE: 1412 mg

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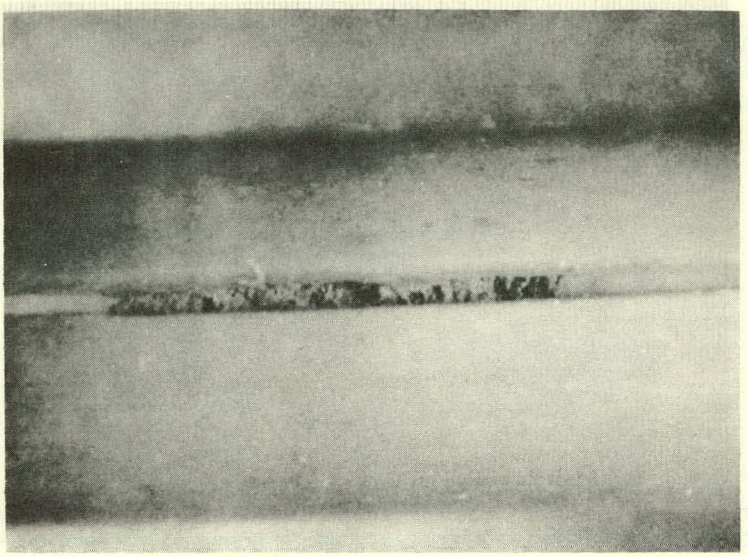
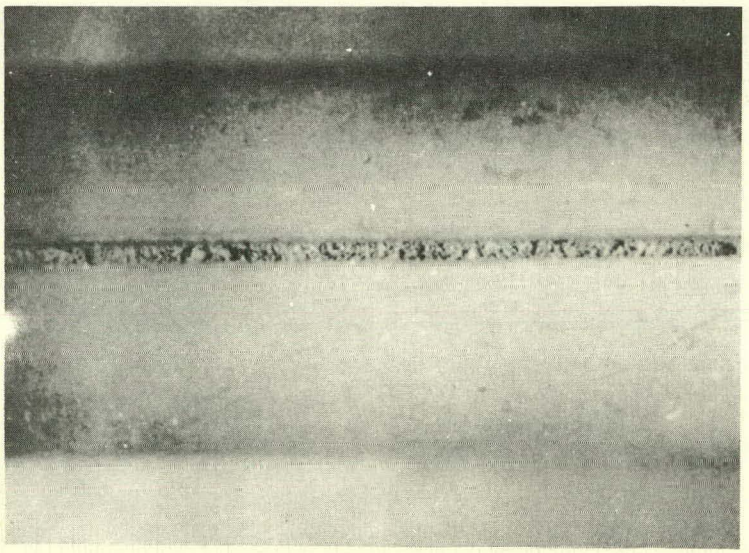
FIGURE 24 4X MAGNIFICATION) 92% DENSE VIBRATORY COMPACTED SAMPLES NO. 15-2 AND 16-2 AFTER 1000-HOUR FLOW TESTING



TANDEM ROLLED SAMPLE 11-2
WEIGHT CHANGE: -66 MG



COLD SWAGED-ANNEALED SAMPLE 2
WEIGHT CHANGE: +7MG

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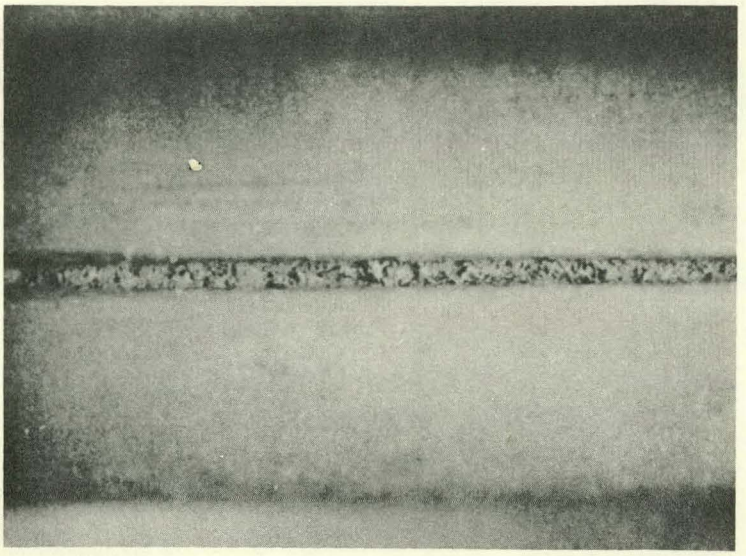
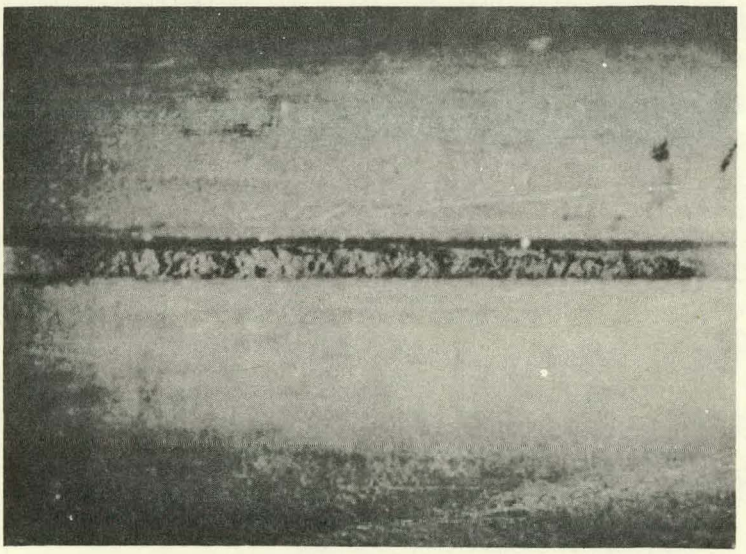
FIGURE 25 (5X MAGNIFICATION) TANDEM ROLLED SAMPLE NO. 11-2 AND COLD SWAGED-ANNEALED SAMPLE NO. 2 AFTER 4000-HOUR FLOW TESTING.



COLD-SWAGED SAMPLE 3 (6X-MAGNIFICATION)
WEIGHT CHANGE : -12 MG



HOT SWAGED SAMPLE 8 (10X-MAGNIFICATION)
WEIGHT CHANGE: +5MG)

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FIGURE 26 COLD SWAGED SAMPLE NO.3 AND HOT SWAGED SAMPLE NO. 8 AFTER 4000-HOUR FLOW TESTING

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