ANL-6028
Metallurgy and Ceramics
(TID-4500, 15th Ed.)
AEC Research and
Development Report

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois

THERMAL CYCLING OF EBR-I, MARK III FUEL

by

G. K. Whitham and E. S. Sowa

Idaho Division

April 1960

Operated by The University of Chicago
under
Contract W-31-109-eng-38

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

THERMAL CYCLING OF EBR-I, MARK III FUEL

by

G. K. Whitham and E. S. Sowa

ABSTRACT

A brief description of the EBR-I, Mark III fuel fabrication process is followed by an exposition of the thermal cycling tests on fuel samples by Reactor Engineering and the Idaho Divisions. All samples tested were received from the ANL Metallurgy Division and fabricated in the Lemont shop. Results of these thermal cycling tests, coupled with observations made by the Metallurgy Division on the irradiation behavior of the fuel, resulted in the selection of the optimum heat treatment subsequently used in the fabrication of the Mark III core loading.

INTRODUCTION

The EBR-I, Argonne National Laboratory's Experimental Breeder Reactor No. 1, was operated for four years through two core loadings to produce 4 million kwh of heat. It was used to demonstrate the ability of a fast reactor system to breed nuclear fuel and to prove that NaK-cooled systems could be operated reliably. In normal operation the plant was quite stable and largely self-regulating.

However, evidence was obtained which showed that the reactor had a prompt positive coefficient of reactivity. The combination of this coefficient with delayed negative coefficients led to instability under operating conditions more severe than the designed operating conditions. A study of kinetic characteristics was undertaken as a last set of experiments on the reactor. Together with associated studies, this led to the belief that the prompt positive coefficient of reactivity was associated with the inward bowing of the fuel rods in the reactor core. Before studies could be completed, they were terminated by a partial melting of the fuel elements.

Since the stability of any reactor, either thermal or fast, poses an important problem, it was felt that observance of the positive coefficient in the fast EBR-I reactor merited further investigation. Accordingly, a third loading (Mark-III) was fabricated with design efforts concentrated on minimizing or eliminating rod-bowing. Provision was also made for greater flexibility in coolant-flow arrangement by adding the option of using parallel coolant flow through the core and inner blanket in addition to the previous series flow arrangement.

FUEL FABRICATION

The extrusion process was chosen for the third fuel loading because it could effect a metallurgical bond between the Zircaloy-2 cladding and the U-2 w/o Zr core.(1) This type of bond would insure maximum rigidity together with excellent heat transfer. After consideration of several methods of extruding ribs directly on the rods, the decision was made to extrude a conventional round rod with emphasis on maximum yield per billet, particularly with respect to the enriched metal. The ribs, deemed necessary for a rigid core configuration, would be welded on later by ANL during assembly of the fuel rods.

Two extrusion billet sizes were developed, one for fabricating the enriched fuel rods, and one for blanket rods. The maximum billet size for the enriched extrusions was limited principally by criticality considerations; however, tools available for the extrusion step in fabrication also presented a problem. The enriched billet developed was 2 in. in diameter by $9\frac{3}{4}$ in. in overall length. Since there were no criticality limitations on the blanket billets, the objective were simply to develop the largest billet that could be extruded into a rod and still meet the clad thickness and uniformity specifications. The final blanket billet developed was $2\frac{3}{4}$ in. in diameter by 9 in. in overall length. The finished rod specifications were 0.406 to 0.408 in. OD.

Cladding components were machined from pre-extruded Zircaloy-2 tube stock from a large forged ingot supplied by ANL.(2) All were prepared at ANL and shipped to Nuclear Metals, Inc., with either an as-cast or a rough-machined surface, and/or an as-cast or heat-treated structure.

Accessories, such as copper-nickel alloy for nose plugs and cutoffs, were cast in large-diameter molds, extruded into rod stock, and machine-finished to the component specifications. Copper extrusion cans, end plugs, and evacuation tubes, were prepared by conventional techniques.

Before assembly, all billet components were mechanically or chemically cleaned. The components were assembled into extrusion billets immediately following air drying, then connected to a vacuum system by means of a copper evacuation tube at the end of the billet. After holding at 800°F for one-half hour for additional outgassing, the tubes were sealed off hot by pinching the evacuation tube closed, then removing the remainder by torch cutting. After preheating for $1\frac{1}{2}$ hr in a 1225°F furnace, the billets were inserted into the 2-in. diameter liner and extruded through a 0.453-in. diameter die. All extrusion tools were preheated to 900°F and lubricated with a colloidal suspension of graphite and oil to facilitate the process.

The next step was to pickle away the copper extrusion jacket in a 50% nitric acid - 50% water solution. Rods were then swaged to a finished size of 0.406 - 0.408 in The average amount of cold working was approximately 6%. Swaging plus cold working reduced the core material in a ratio of forty to one. In terms of uniform core and cladding for extrusion, the acceptable lengths varied from 137 to 146 in. These rods were sent to ANL for fabrication into final fuel elements.

At ANL the U^{235} rods were cut into appropriate lengths for core sections. The natural uranium rod was cut into lengths for upper and lower blanket sections to be used for the breeding sections of fuel rods.[3] Natural uranium blanket sections were zone-welded to the U^{235} core. The U^{238} rod was also cut into full-length blanket rods. These three-piece fuel rods and blanket rods were then passed through an automatic spot-welding machine that simultaneously welded on three equally spaced Zircaloy-2 wires to form the support ribs. The completed uranium sections were welded to the lower Zircaloy tip and the upper Zircaloy handle section.

A rather broad testing program was undertaken when the first extruded material was available. The Metallurgy Division undertook nondestructive testing[4] and irradiation testing,[5] while Reactor Engineering and the Idaho Division pursued thermal cycling tests.

EXPERIMENTAL EQUIPMENT (Idaho Division)

The Idaho Division used two thermal cycling units, each designed to handle 2-in.-long samples. The small unit handled one slug; the larger cycler accommodated eight 2-in.-long slugs. Figure 1 shows the smaller unit which consisted of: (1) a water-cooled cold tank and (2) an insulated, electrically heated hot tank, both of which were filled with NaK. A long metal bellows (4) was used to insure containment of the argon blanket gas in the system. The travel of the shaft was set by the length of the slot (5). Since the change in gas volume caused by the bellows movement was considerable, an argon ballast tank (6) reduced this pressure change in the system. The timing cycle was set by the motor-driven cam and microswitch (3), which operated the solenoid valves (7), controlling the air to the drive air-piston (8).

The first samples tested were cut from the long, extruded rods as received from Nuclear Metals. The 2-in.-long samples were polished on the ends to remove any burrs or ridges and to facilitate the micrometer readings of total length. A line was scribed the length of the sample and the ends were marked for identification.

In subsequent measurements, all micrometer measurements were made independently to an accuracy of 0.001 in. The readings were compared and any deviations were cross-checked until agreement was reached. Measurement of the total length was difficult after cycling because of the crowned uranium surface at the ends. During early tests, diameter measurements made on the ends were difficult because of a slight flare. As discussed later, zirconium end-caps (zone-melted on each end) resolved this difficulty

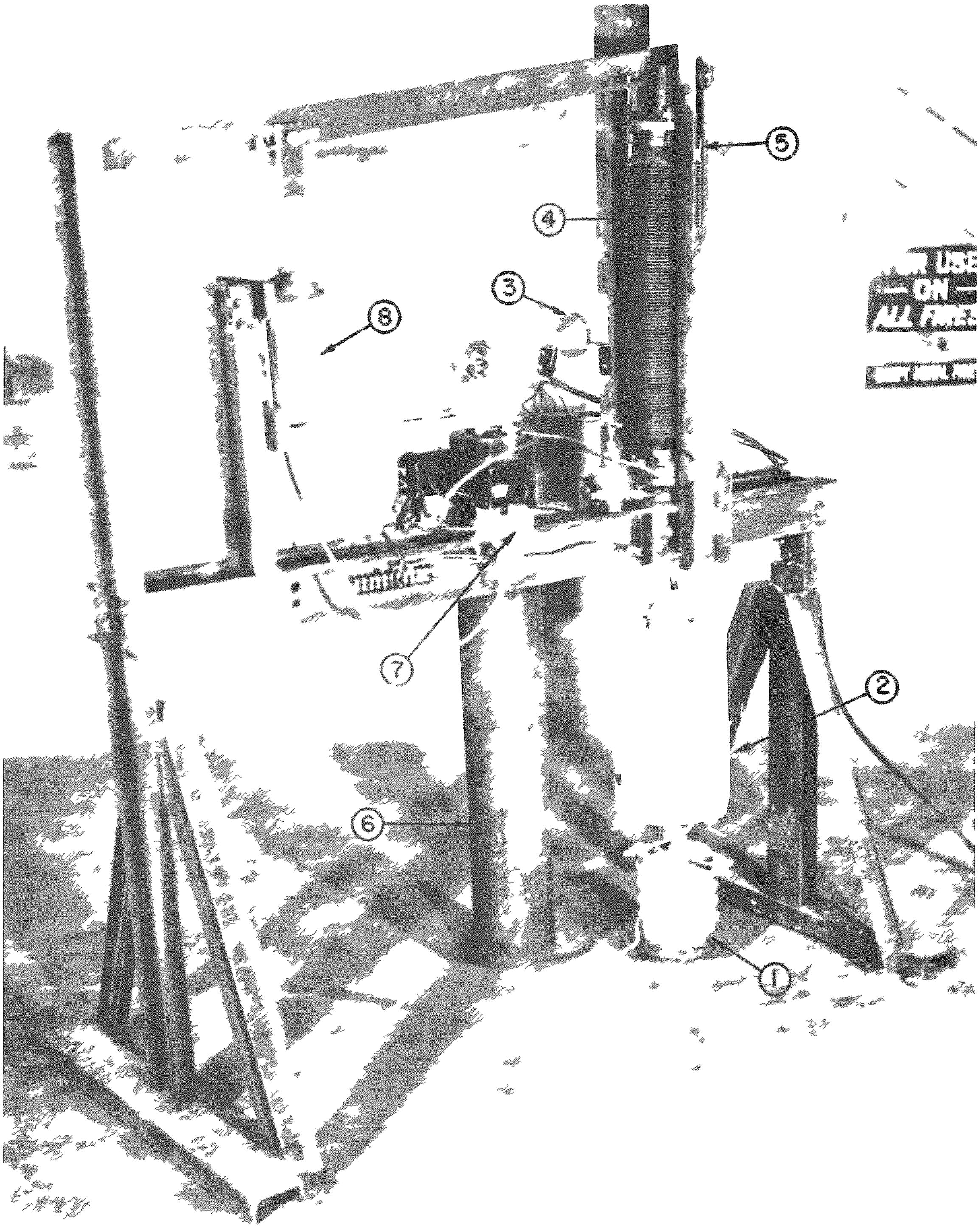


Fig. 1 Idaho Division Thermal Cycling Unit

EXPERIMENTAL EQUIPMENT (Reactor Engineering Division)

The Reactor Engineering thermal-cycling unit consisted of a long, cylindrical tank filled with NaK (see Figs. 2 and 3). The upper section of the cylinder was surrounded by heaters and insulation, providing a high-temperature heating zone. The lower section of the cylinder was uninsulated and unheated.

Transfer of samples was done by moving a basket containing them up and down from one zone to the other. The basket was suspended from a long rod, the upper end of which was connected to a motor-driven cable. The cable entered a long, cylindrical gas-blanket region through a seal in the top of the cylinder.

A thermocouple moved with the basket, providing a variable signal and permitting the amplitude of the cycles to be recorded on a potentiometer. Timing and control of the cycles was performed by electronic circuits.

EXPERIMENTAL TESTS (Idaho Division)

The first slug was supplied to Idaho with machined ends of exposed uranium. During Run 1 (see Table I), the temperature difference was from 350 to 30°C, with travel time of one second from the hot tank to the cold tank. Residence time in each tank was 15 sec.

This temperature difference was considered too small for fuel elements, so in Run 2 the temperature of the hot tank was raised and the cycler operated from 420 to 25°C. This slug was furnished with cup-shaped, Zircaloy-2 end caps recessed into the uranium, and a heliarc end-weld sealed them to the Zircaloy-2 cladding.

The third sample was identical with that in Run 2, but the temperature difference was from 500 to 35°C, which was considered necessary for adequate testing of the core material. Total thermal cycles exceeded 1000 on this run. Final examination showed the uranium had bulged out about $\frac{3}{32}$ in. on each end, forcing off both end caps (see Fig. 4). The diameter in the middle of the slug had grown about 0.020 in. The overall length appeared to have shortened and the bowing was approximately $\frac{1}{16}$ in. as evidenced by rolling on a flat surface. Inspection at 10X magnification showed the 0.020-in.-thick Zircaloy-2 surface covered with hairline cracks. Several large cracks ran the length of the slug. The black color was caused by an oxide surface which resulted from the scavenging of oxygen from the NaK in the cycler.

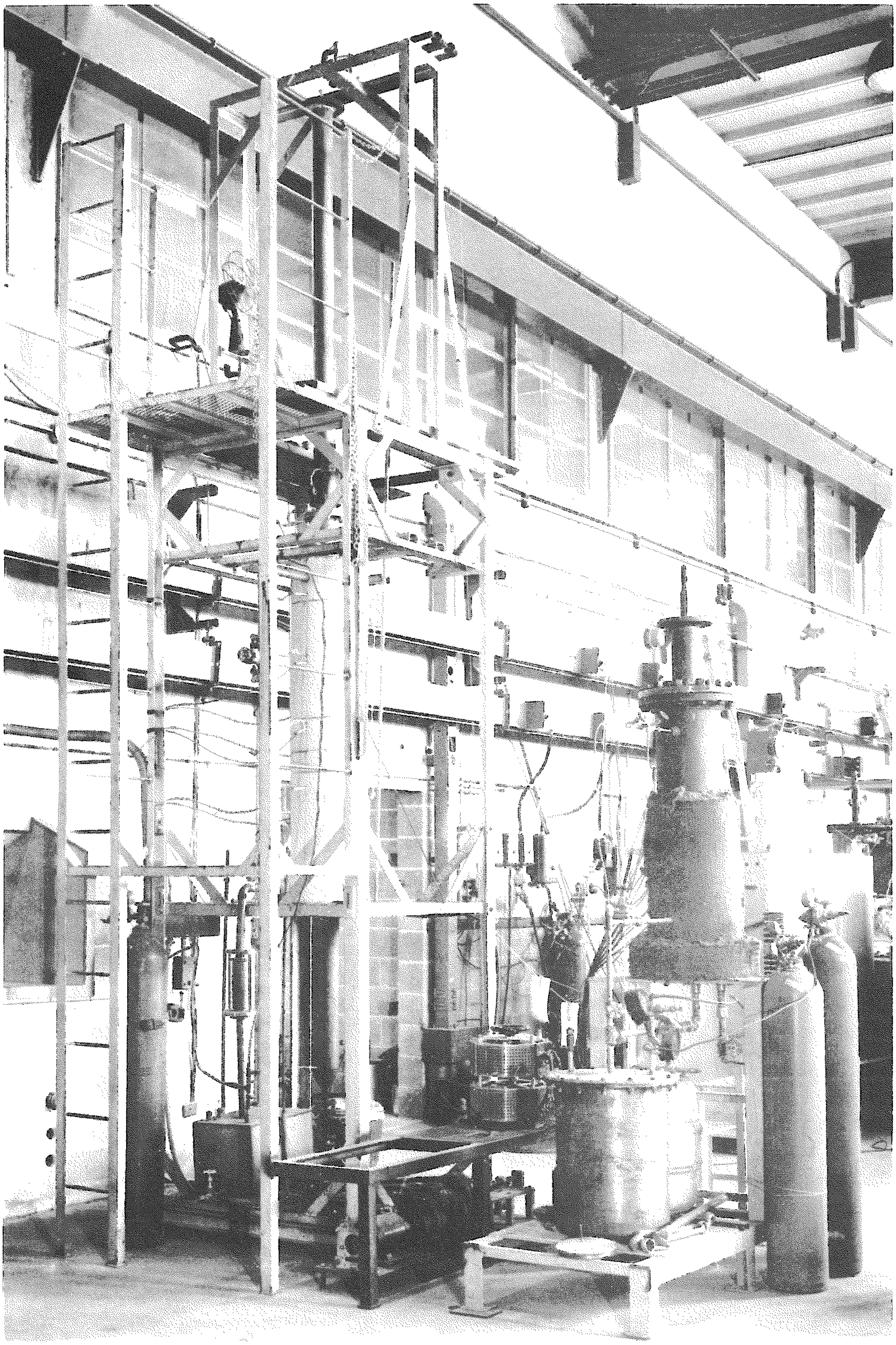


Fig. 2 Reactor Engineering Division Thermal Cycling Unit

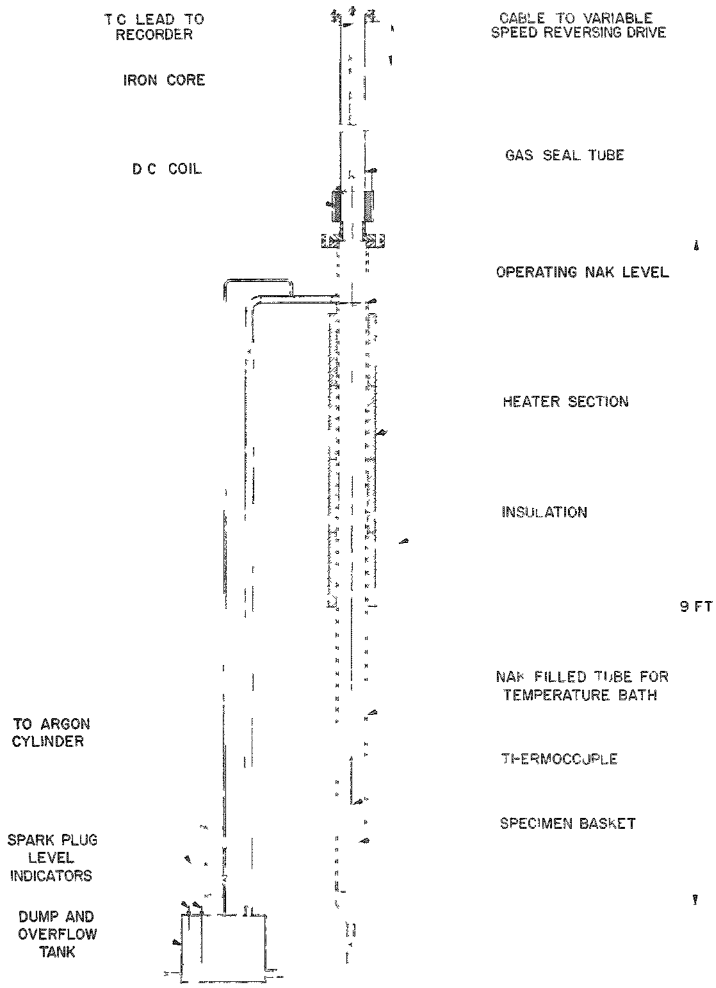


Fig. 3 Schematic of Reactor Engineering Division Thermal Cycle

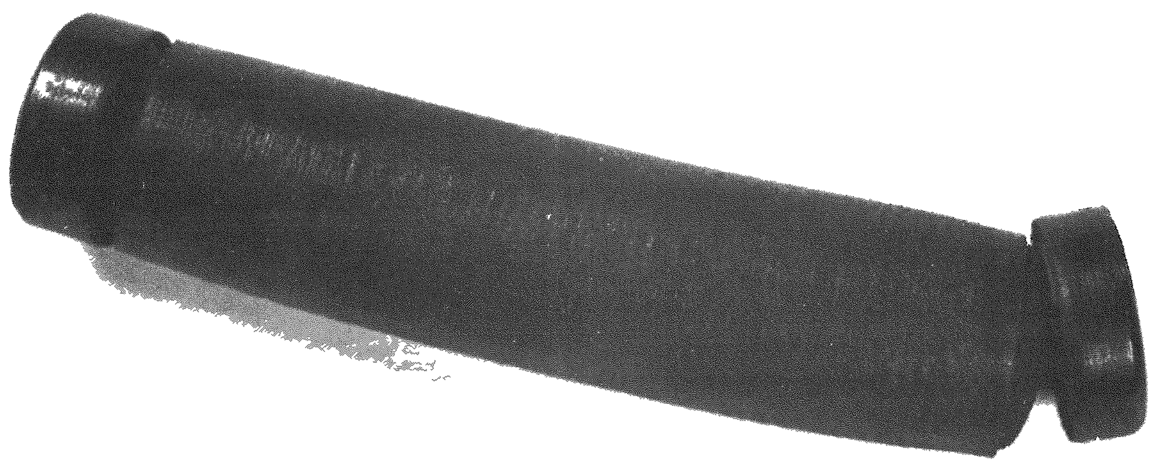


Fig. 4 First Slug Supplied to Idaho after 1000 Cycles between 35 and 500°C

It was apparent from these tests that the grain structure of the uranium had been given a preferred orientation by working the metal into rods; therefore, a suitable heat treatment seemed necessary to restore the uranium to a random grain structure. As a result of these data, all subsequent slugs were subjected to some type of heat treatment.

The fourth slug was placed in a stainless-steel capsule and blanketed with argon gas before seal-welding the final closure. This capsule and slug received the following heat treatment: furnace-heated to 800°C, held at temperature one hr, then furnace-cooled to room temperature. This stabilized the uranium considerably and the heliarc welded end-caps stayed intact during this test. At this time, the Metallurgy Division selected three heat treatments (A, B, and C) for subsequent trials so the best one could be used for final fabrication.

HEAT TREATMENT

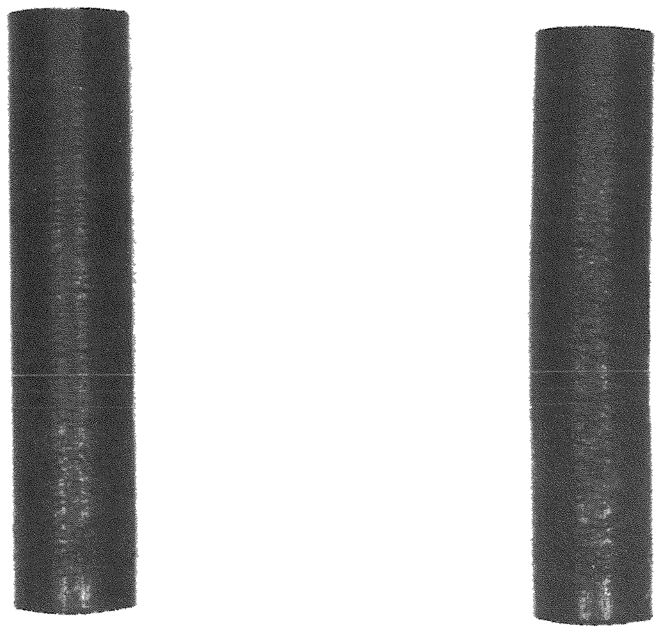
A. Held at 800°C for 15 min; cooled to 500°C. Held at 500°C for 1 hr; air-cooled to room temperature.

B. Held at 800°C for 15 min; cooled to 690°C for 1 hr; air-cooled to room temperature.

C. Held at 800°C for 15 min; water quenched. Held at 690°C for 1 hr; water quenched.

In Runs 5 through 8 (see Table I) three slugs with heat-treatment "B" and one without any treatment were tested. These slugs all had "as machined" ends. These four tests had one thing in common: both ends of the slugs flared out enough to make diameter measurements impossible unless the micrometer measurements were taken about $\frac{3}{8}$ in from the end of the slugs. A slight bulging or crowning of the uranium end-surfaces made the final total-length measurement difficult to make and interpret. The results of these tests can be seen in Fig. 5, which shows the wrinkled surface of slugs from Runs 6 and 7.

The results of Run 9 (see Table II) still showed definite shortening in length with increased diameter. After some deliberation, it was decided that the thermal shock given these samples by the fast travel speed of the cycler was considerably more severe than any thermal shock encountered in reactor operation. The cycler was therefore changed from a one to ten-sec. travel time from hot tank to cold tank. Residence time in each tank was kept the same so that samples would reach tank temperature. It was believed that the reduced thermal shock would also reduce the bimetal effect, which is no doubt the controlling factor in the dimensional changes encountered during thermal cycling in fuel fabricated with this type of coextruded bond.



Run #6 Run #7

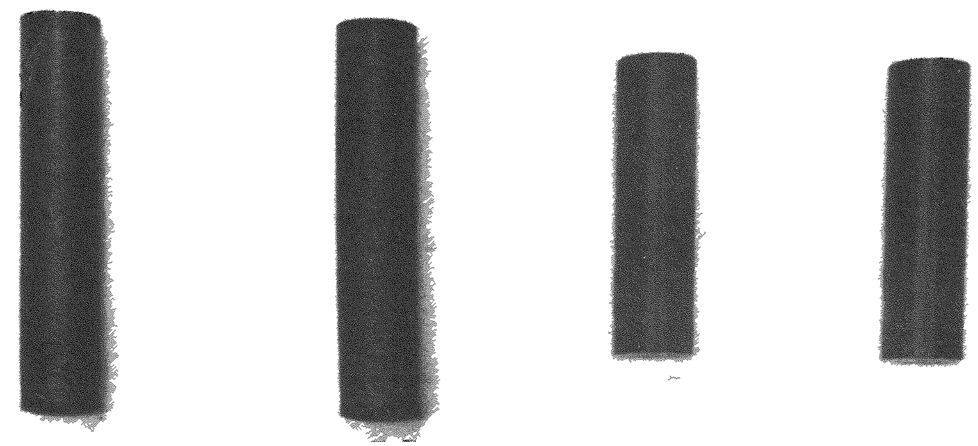
As Machined Ends

Fig. 5 Thermal Cycled Slugs with "B" Heat Treatment

Twenty-four samples were tested with reduced thermal shock conditions and a temperature difference still between 500 and 35°C. These data are repetitious; therefore, only two typical runs will be dealt with and tabulated here.

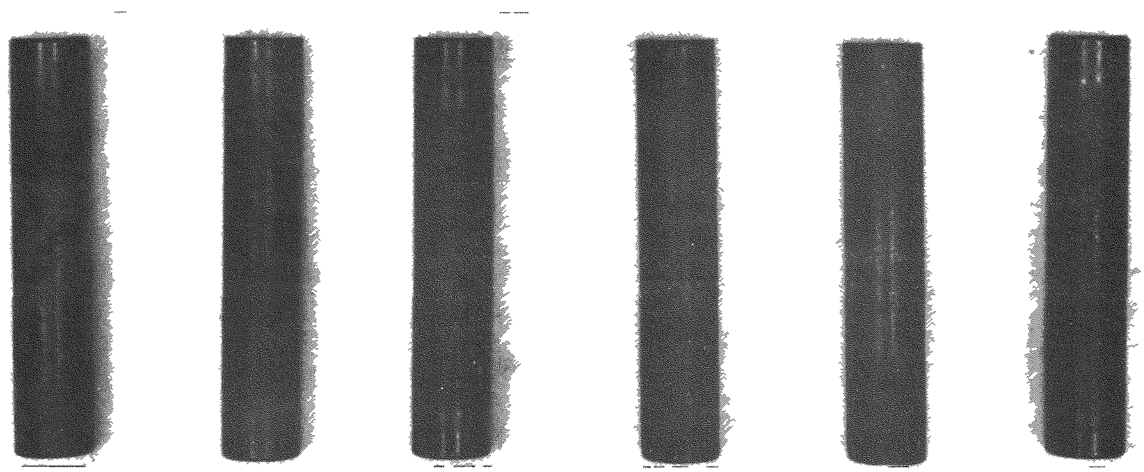
On subsequent tests, in order to obtain satisfactory micrometer measurements, it was elected to use the zone-melting technique developed by Argonne National Laboratory's Metallurgy Division, i.e., to bond the entire interface of uranium to a Zircaloy-2 end cap. It was felt that this technique would eliminate the end-flaring observed on all previous tests. Since this technique was to be used in final rod fabrication, it was felt that bonding the end caps would produce a sample equivalent to the final assembly. The next slugs received from Metallurgy had $\frac{1}{8}$-in.-thick, zone-melted end caps and received heat treatment "A." Comparison of the one slug tested in Run 9 (fast cycling rate,"B" heat treatment) and slugs tested at the slower cycling rate used in Run 10 showed a big difference in growth rate (see Table II). From results obtained thus far, the slower cycling rate seemed to resemble actual reactor operating conditions more closely. Accordingly, requirements for final fabrication were frozen on this basis. Considering irradiation(5) and thermal cycling data, it was decided to use the "B" heat treatment for final fabrication.

All of the last series of slugs (see Table IV) to be run used material the same as that used in the fabrication of the Mark-III loading. This material received two "B" heat treatments during fabrication to remove any differences between 20:1 and 40:1 reductions for core and blanket rods, respectively. Slugs 4, 5, and 6 were taken from $2\frac{3}{4}$-in. material that was reduced 40:1 for blanket material. Figure 6 shows these six slugs after 1000 cycles. The surface showed only slight imperfections between the $\frac{1}{8}$-in.-thick Zircaloy-2 end caps.



Run #6 Run #7
As Machined Ends
"B" Heat Treatment

Zircaloy-2
Corrosion Samples



1 2 3
Final Core Material

4 5 6
Final Blanket Material

Fig. 6 Material Selected for Mark III Loading after Thermal Cycling (1000 Cycles between 35 and 500°C)

Two Zircaloy-2 samples were run at 500°C for 50 hours to measure the effect of NaK corrosion or oxidation. The final appearance and the weight gain showed (see Fig. 6) that the only effect was the production of a solid oxide layer. The two samples had original weights of 21.0937 and 21.0941 g. After the run they showed gains of 4.9 and 3.1 mg, respectively. Careful handling of these specimens showed the oxide layer was formed from getter action in the NaK, and not from oxidation during chemical cleaning and removal of the NaK alloy from the slugs.

From Run 12 (Table IV), it can be seen that the blanket material showed less growth rate and gave more consistent data than the core material. All thermal cycling growth rates seemed high in comparison to the material used in the two previous EBR-I loadings.

EXPERIMENTAL TESTS (Reactor Engineering Division)

Concurrently, thermal cycling tests were conducted by the Reactor Engineering Division on long samples of the coextruded element material. The first test was tried on a full-scale element as shown in Fig. 7. Prior to thermal cycling, the element was heat treated for 1 hr at 800°C, followed by an isothermal quench into lead at 500°C. It was held at 500°C for 1 hr, then air-cooled to room temperature. The pre-cycling test consisted simply of running a profile trace of the element, from which it was determined that the maximum deviation from a straight cylinder was 0.007 in. The element was subsequently cycled a total of 200 times between 35 and 550°C. The transfer time was 1 min from one temperature zone to the next, with a 5 min holdup time in each zone.

After cycling was completed, the element was removed from the cycler for examination. The final appearance is shown in Fig. 8. It was found that the maximum deviation from a straight line now was $\frac{5}{16}$ in.

Following this initial test, two more elements with welded side ribs(3) were prepared for cycling. These two elements were heat treated by furnace-cooling from 800°C. In addition, the elements were suspended from their upper ends during this test, since it was conjectured that a portion of the bowing of the first element was caused by its entire weight resting on its lower end. Cycling was conducted between 50 and 550°C for a total of 203 cycles. The appearance of the elements before and after testing can be seen in Figs. 9 and 10. It is apparent that a very significant warping of the elements occurred despite the fact that they were suspended; the weight does not appear to contribute to the bowing. On one element a portion of a rib was detached from the cladding. The cycling holdup time was again 5 min, with a 1 min transition interval from one temperature zone to the next.

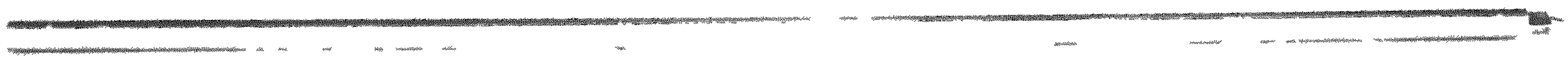


Fig. 7 First Full Length Fuel Element Supplied to Reactor Engineering Division before Cycling

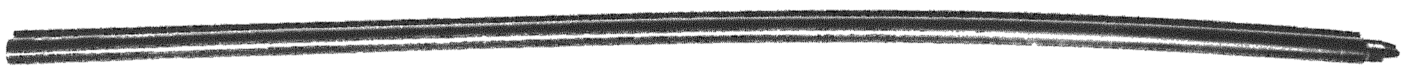


Fig. 8 First Full Length Fuel Element Supplied to Reactor Engineering Division after Cycling (200 Cycles between 35 and 550°C)

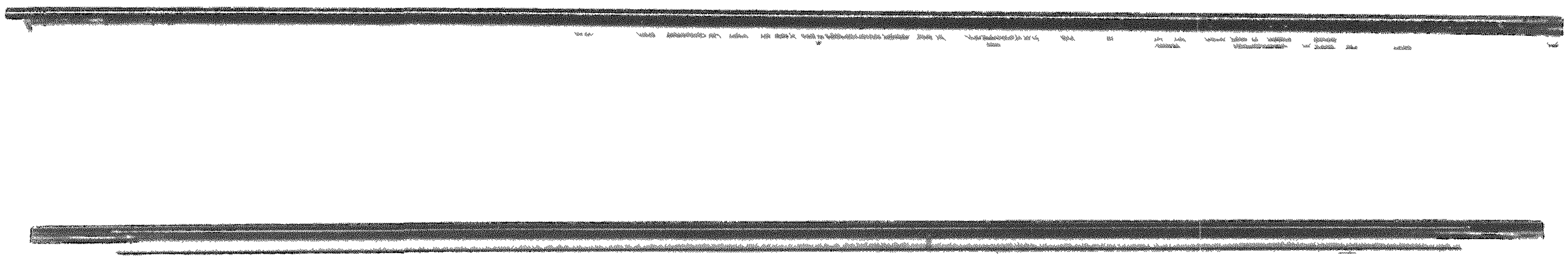


Fig. 9 Second Group of Two Elements before Cycling

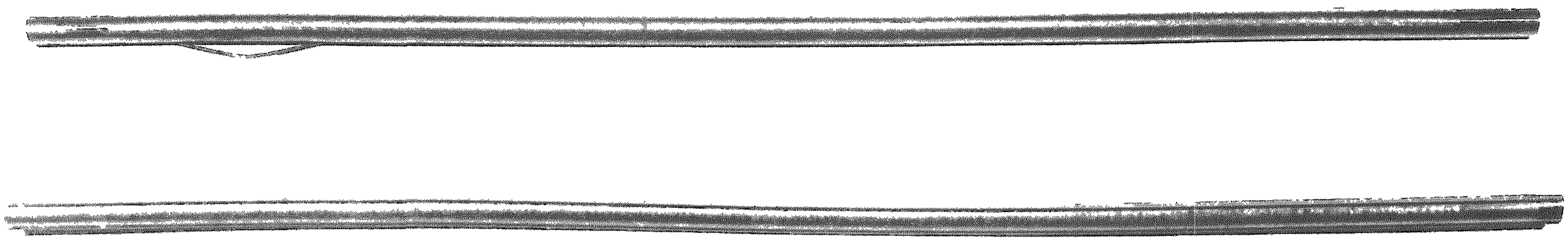


Fig. 10 Second Group of Two Elements after 203 Cycles between 50 and 550°C

The influence of these developments resulted in an attempt to stabilize the alloy by various heat treatment methods. A series of 11 6-in. samples was prepared by the Metallurgy Division. Nine of these samples were divided into three groups of three samples per group, and each group was given a heat treatment: A, B, or C, as previously described.

One sample from each group was selected and its Zircaloy-2 cladding machined off. Two additional samples were included, one a plain swaged Zircaloy-2 rod, and the second a non-heat treated sample with cladding removed. The appearances of these samples before cycling can be seen in Fig. 11.

These specimens were cycled between 50 and 550°C for a total of 203 cycles with the same transfer and holding times as during the previous test. The post-cycling appearances are shown in Fig. 12. Table V lists the results of measurements made before and after cycling.

REACTOR PERFORMANCE

A number of selected EBR-I, Mark III fuel rods, which were removed from positions extending from the reactor core center to edge have been measured to determine dimensional changes after 1,135 Mwh of reactor operation. The maximum growth of each rod occurred in the top quarter of the fuel section and dropped sharply to the upper blanket diameter at the fuel-blanket junction. None of the blanket sections measured showed appreciable growth. Rod growth was greatest for rods near the center of the reactor and decreased toward the outer edge of the reactor core.

In the center subassembly, the maximum diametral growth of rods measured varied from 0.006 to 0.005 in. The maximum growth in the rods from core subassemblies surrounding the center subassembly ranged from 0.004 in. at the face adjacent to the center subassembly to 0.0015 in. in the outermost fuel rods.

Temperatures measured at the center of the fuel slug increased from 482°C at the reactor vertical center line to 497°C in the upper half of the fuel slug, and dropped sharply at the fuel-blanket boundary. Coolant temperature increased from 250°C at the bottom of the coolant channel to 400°C at the top.

While these rods have been in the reactor, there have been 232 start-ups at 500 kw or above, of which 147 were with the reactor inlet coolant at 230°C (normal inlet temperature for high-temperature operation). The remainder of the reactor operation was at lower inlet temperature.

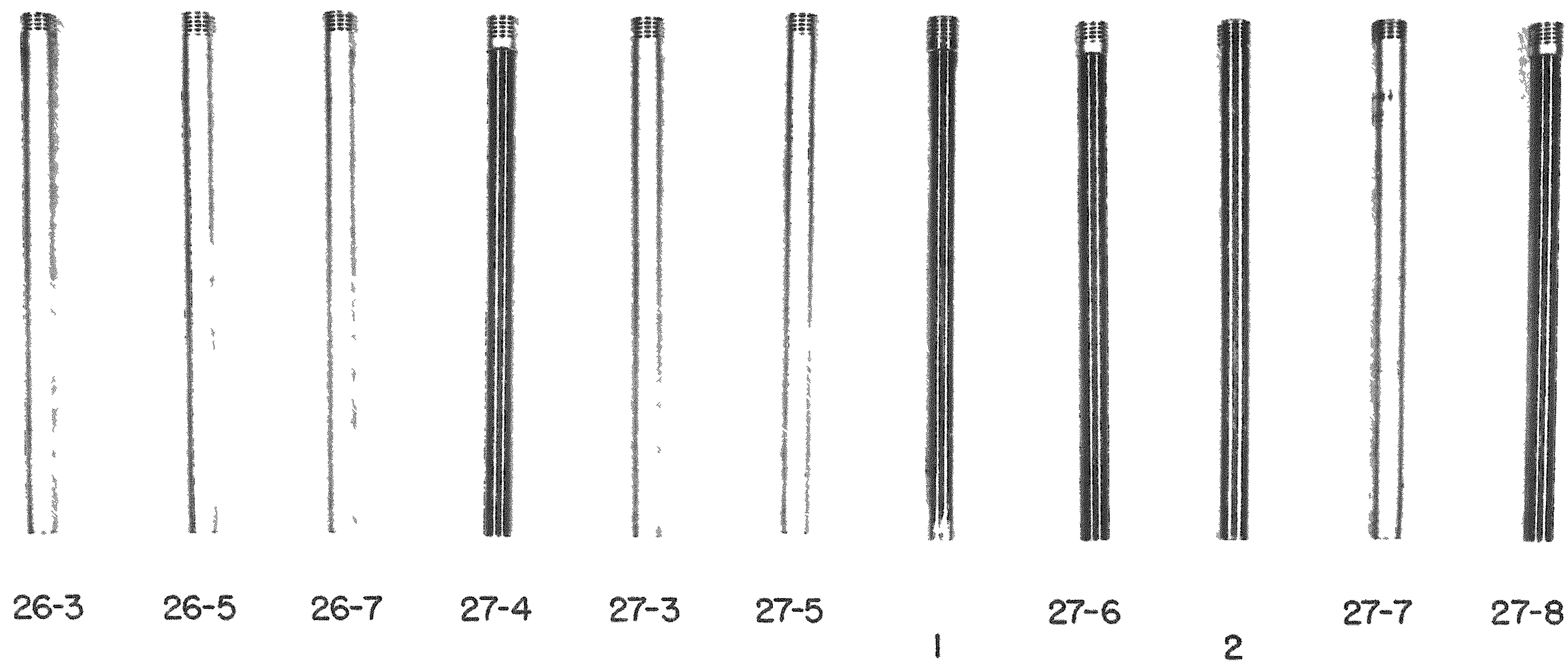


Fig. 11 Heat Treated Samples before Cycling

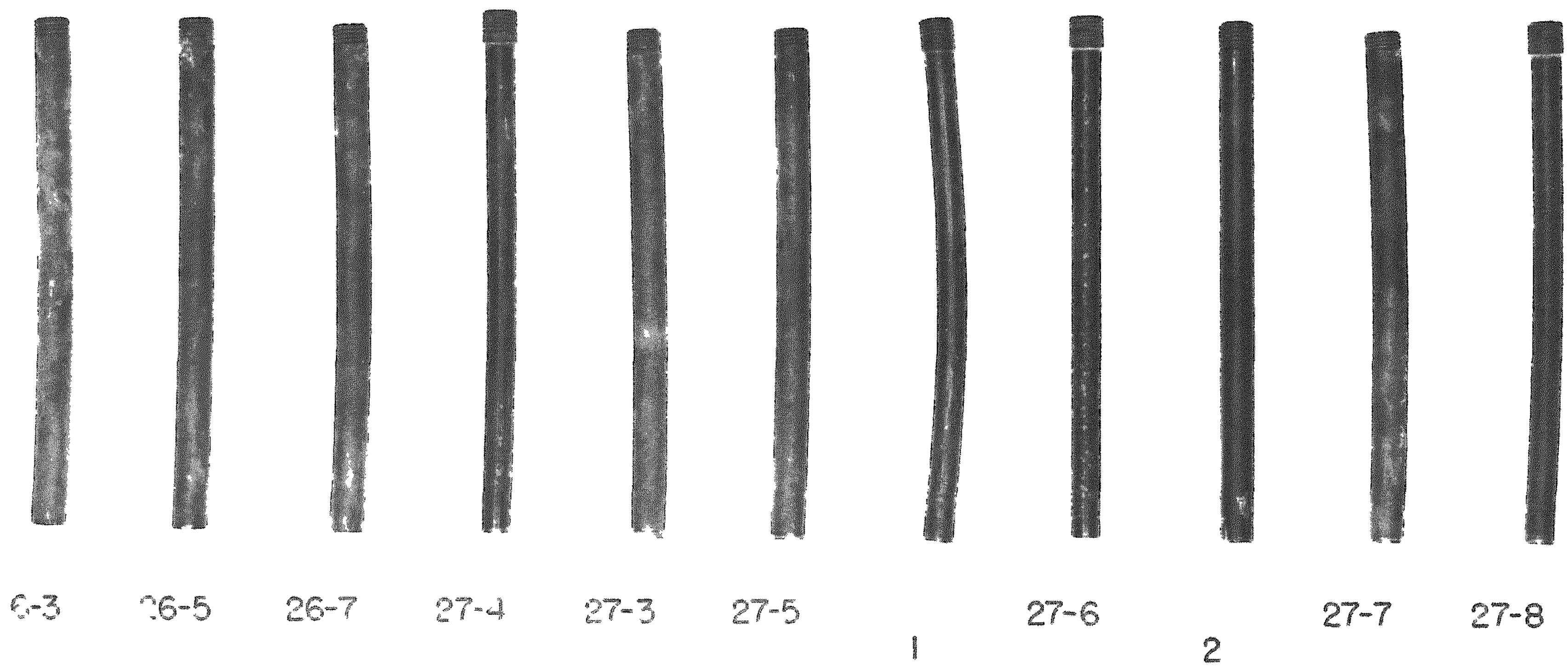


Fig. 12 Post-cycling Appearance of Heat-treated Samples

RESULTS AND DISCUSSION

In all of the tests conducted, both at the Idaho Division and Reactor Engineering Division, it was apparent that rapid cycling resulted in dimensional changes to the elements. It was necessary, therefore, to use a cycling rate comparable to that expected in the reactor to obtain realistic results. The tests showed that the coextruded material as received from the extrusion process was not dimensionally stabilized for thermal cycling or irradiation damage. Consequently, three heat treatments were chosen for subsequent tests and the "B" heat treatment was finally selected, based upon the test results as the best compromise to compensate for the bimetal effect and radiation damage. It should be understood that this treatment would not necessarily be used for unclad uranium, but was acceptable for the material under investigation.

In general, the effect of thermal cycling damage was apparent as bowing in long rods, a slight shortening of total length, and a corresponding increase in diameter. In none of the samples cycled was there any sign of torsional warpage. Table V does show that some influence is exerted by the cladding, and it would be expected that this effect could become more pronounced with increasing severity of cycling conditions.

REFERENCES

1. Sawyer, H. F., Coextrusion of Zircaloy Clad U-2 w/o Zr Rod for the EBR-I Mark III Core Loading, NMI-4801 (April 30, 1950).

2. Macherey, R. E., Carson, N. J., Salley, R. L., and Beatty, R. A., Fabrication of Fuel and Rod Stock for EBR-I, Mark III, ANL-5895 (unpublished).

3. Noland, R. A., Stone, C. C., McCuaig, F D., and Walker, D. E., The Manufacture of EBR-I, Mark III Fuel and Blanket Rods, ANL-5917 (unpublished).

4. Beck, W. N., Renken, C. J., Meyers, R. C., and McGonnagle, W. J., Nondestructive Testing of EBR-I, Mark III Fuel Elements and Components, ANL-5893 (May 1959).

5. Kittel, J. H., Irradiation of Extrusion Clad Core Alloy for EBR-I, Mark III, ANL-5918 (October 1959).

Table I

RESULTS OF RUNS 1 THROUGH 8

Run No.	Slug No.	Total Cycles	Growth/in. Length	Growth/in. Diameter	Total Growth Length, μ in./in./cycle	Total Growth Diameter, μ in./in./cycle	Temperature Range, °C
1	1	500	-0.00125	-0.0005	- 2.5	- 1.5	350 - 30
2	2	500	0.00242	0.0013	- 4.5	1.7	420 - 25
3	3	112	0.0022176	-	9.9	-	550 - 35
3	3	1267	-	0.197	end caps off	39	550 - 35
4	4	480	0.009	0.0089	-19	18	550 - 25
4	4	1132	0.0206	0.028	-20	25	550 - 25
5	5	200	0.0005	0	- 2.5	0	500 - 30
5	5	484	0.0005	0	- 2.5	0	500 - 30
5	5	1020	0.0035	0.002	- 3.5	2	500 - 30
6	6	144	0.000525	0	3.6	0	500 - 30
6	6	498	0.0011	0	2.2	0	500 - 30
6	6	1266	0.0034	0.0057	3.4	5.7	500 - 30
7	7	236	0.001225	0.001	5	4.2	550 - 30
7	7	468	0.00015	0.012	.3	25	550 - 30
8	8	200	0.000	0.0025	0	12.5	500 - 30
8	8	504	0.00155	0.0025	3.1	5	500 - 30
8	8	1868	0.00255	0.0065	1.3	3.4	500 - 30

Table II

RESULTS OF RUNS 9 AND 10 FOR THE TEMPERATURE RANGE BETWEEN 500 AND 35°C

Run No.	Slug No.	Total Cycles	Growth/in. Length	Growth/in. Diameter	Total Growth Length, μ in./in./cycle	Total Growth Diameter, μ in./in./cycle
9	B-1	500	-0.005	0.00925	-10	7.7
9	B-1	1000	-0.0275	0.0425	-27	16.6
10	A-1	200	-0.00065	None	- 3.25	None
10	A-1	500	-0.00215	0.00175	- 5.3	3.5
10	A-1	1016	-0.0077	0.00625	- 7.6	6
10	A-2	200	-0.00065	None	- 3.25	None
10	A-2	500	-0.00185	0.00175	- 3.7	3.5
10	A-2	1016	-0.002	0.006	- 1.9	5.7
10	A-3	200	-0.00065	0.00025	- 3.25	1.2
10	A-3	500	-0.00335	0.001	- 6.7	2
10	A-3	1016	-0.0068	0.00575	- 6.6	5.5
10	B-2	200	-0.0008	None	- 4	None
10	B-2	500	-0.00235	0.00125	- 4.7	2.5
10	B-2	1016	-0.0093	0.0075	- 9.2	7.2
10	B-3	200	-0.00055	None	- 2.75	None
10	B-3	500	-0.00145	0.00075	- 2.9	2.5
10	B-3	1016	-0.00755	0.003	- 7.4	2.9
10	C-1	200	-0.0005	None	- 2.5	None
10	C-1	500	-0.00085	0.00025	- 1.7	0.5
10	C-1	1016	-0.00425	0.003	- 4.1	2.9
10	C-2	200	-0.0006	None	- 3	None
10	C-2	500	-0.00085	None	- 1.7	None
10	C-2	1016	-0.00435	0.00275	- 4.2	2.6
10	C-3	200	-0.0009	None	- 4.5	None
10	C-3	500	-0.0014	0.00025	- 2.8	0.5
10	C-3	1016	-0.0055	0.003	- 5.4	2.9

Table III

RESULTS OF RUN 11 FOR THE TEMPERATURE RANGE BETWEEN 500 AND 35°C

Slug No.	Total Cycles	Growth/in. Length	Growth/in. Diameter	Total Growth Length, μ in./in./cycle	Total Growth Diameter, μ in./in./cycle
3	200	-0.00171	0.0005	- 8.5	2.5
3	500	0.00349	-0.00274	6.98	-5.48
3	1080	0.01302	-0.00749	13.02	-7.49
A-1	200	-0.0004	-0.000976	- 2	-4.88
A-1	500	-0.00085	0.000611	- 1.70	1.222
A-1	1080	-0.003	0.00451	- 3	4.51
A-2	200	-0.00025	0.000489	- 1.25	2.445
A-2	500	-0.00105	0.001215	- 2.1	2.430
A-2	1080	-0.00425	0.002925	- 4.25	2.925
A-3	200	-0.00085	-0.0003665	- 4.25	-1.8325
A-3	500	-0.00145	0.001098	- 2.90	2.196
A-3	1080	-0.0037	0.00674	- 3	6.74
B-3	200	-0.0002	No Change	- 1	No Change
B-3	500	0.00065	0.000487	1.30	0.974
B-3	1080	0.00225	0.0017	2.25	1.7
C-1	200	No Change	-0.0001214	No Change	-0.607
C-1	500	0.0015	-0.016	3.0	-32
C-1	1080	0.0042	-0.0127	4.2	-12.7
C-2	200	-0.00025	-0.000364	- 1.25	-1.82
C-2	500	0.001775	-0.000121	3.550	-0.242
C-2	1080	0.0048	-0.001815	4.8	-1.815
C-3	200	-0.00015	-0.000727	- 0.75	-3.635
C-3	500	0.001375	-0.000971	2.750	-1.942
C-3	1080	0.00385	-0.0034	3.85	-3.4

Table IV

RESULTS OF RUN 12 FOR THE TEMPERATURE RANGE BETWEEN 500 AND 35°C

Slug No.	Total Cycles	Growth/in. Length	Growth/in. Diameter	Total Growth Length, μ in./in./cycle	Total Growth Diameter, μ in./in./cycle
#1 core	200	-0.00095	0.00125	-4.75	6
#1 core	447	-0.002	0.00225	-4.47	4.57
#1 core	1004	-0.006	0.0055	-6	5.4
#2 core	200	0.00065	-0.0005	3.25	-2.47
#2 core	447	0.00135	-0.00075	3.02	-1.53
#2 core	1004	0.00175	-0.00075	1.75	-0.73
#3 core	200	-0.0009	0.00175	-4.5	7.54
#3 core	447	-0.007	0.002	-3.35	4.4
#3 core	1004	-0.00565	0.005	-5.6	4.94
#4 blkt	200	-0.0004	No Change	-2	No Change
#4 blkt	447	-0.00055	0.001	-1.1	2.2
#4 blkt	1004	-0.00235	0.00275	-2.3	2.92
#5 blkt	200	-0.0011	0.0005	-5.5	2.47
#5 blkt	447	-0.0016	0.00175	-3.5	3.8
#5 blkt	1004	-0.0035	0.003	-3.5	2.97
#6 blkt	200	-0.00065	0.00025	-3.25	1.2
#6 blkt	447	-0.00095	0.001	-2.1	2.2
#6 blkt	1004	-0.00265	0.00325	-2.5	3.22

Blkt = Blanket Material

Core = Core Material

Table V

RESULTS OF TESTS WITH SAMPLES HAVING DIFFERENT HEAT TREATMENT

Heat Treatment	Rod No.	Diameter, in.			Length, in.			Total Indicator Run Out		
		Before	After	Diff.	Before	After	Diff.	Before	After	Diff.
A	26-3	0.393 0.400	0.400 0.407	0.007	6.002	5.868	-0.144	0.004	0.110	0.106
A	27-3	0.395 0.400	0.401 0.407	0.006 0.007						
B	26-5	0.399 0.402	0.404 0.406	0.005 0.004	6.006	5.910	-0.096	0.003	0.073	0.070
B	27-5	0.400 0.401	0.404 0.406	0.001 0.005	6.001	5.880	-0.121	0.0035	0.095	0.092
C	26-7	0.400 0.403	0.406 0.408	0.005 0.006	6.002	5.875	-0.127	0.006	0.130	0.124
C	27-7	0.400 0.404	0.402 0.408	0.002 0.004	6.005	5.925	-0.080	0.0025	0.128	0.126
The following three had the Zircaloy clad removed.										
A	27-4	0.344 0.345	0.344 0.345	None	6.005	6.045	0.040	0.002	0.082	0.080
B	27-6	0.344 0.345	0.344 0.345	None	6.004	6.038	0.034	0.002	0.007	0.005
C	27-8	0.343 0.344	0.344 0.346	0.001 0.002	6.002	6.053	0.051	0.001	0.140	0.139
-	#1	0.375 0.382	0.350 0.360	-0.018 -0.25	6.048	6.042	-0.006	0.005	0.187	0.182
-	#2	0.403 0.404	0.403 0.404	None	6.033	6.031	-0.002	0.0095	0.015	0.005

APPENDIX

A cutaway diagram is included as Fig. 13 to show some of the general construction details of the larger cycling unit used by the Idaho Division.

The top thermocouple extended down the small central support tube and was attached to the top of the sample basket. The residence time of the sample basket in each tank was recorded on a temperature recorder receiving its signal from this thermocouple.

The bellows guide was found necessary to achieve a proper support and alignment of the long bellows assembly; this guide materially increased the life of the bellows.

The main support tube for the entire assembly was a single stainless steel pipe with milled slots in the region of the hot and cold tanks. This continuous tube eliminated the possibility of the sample basket catching or hitting any edge as it stroked up and down.

The vent tube in the hot tank was used during the NaK filling and later connected to the argon ballast tank referred to in the description in Fig. 1.

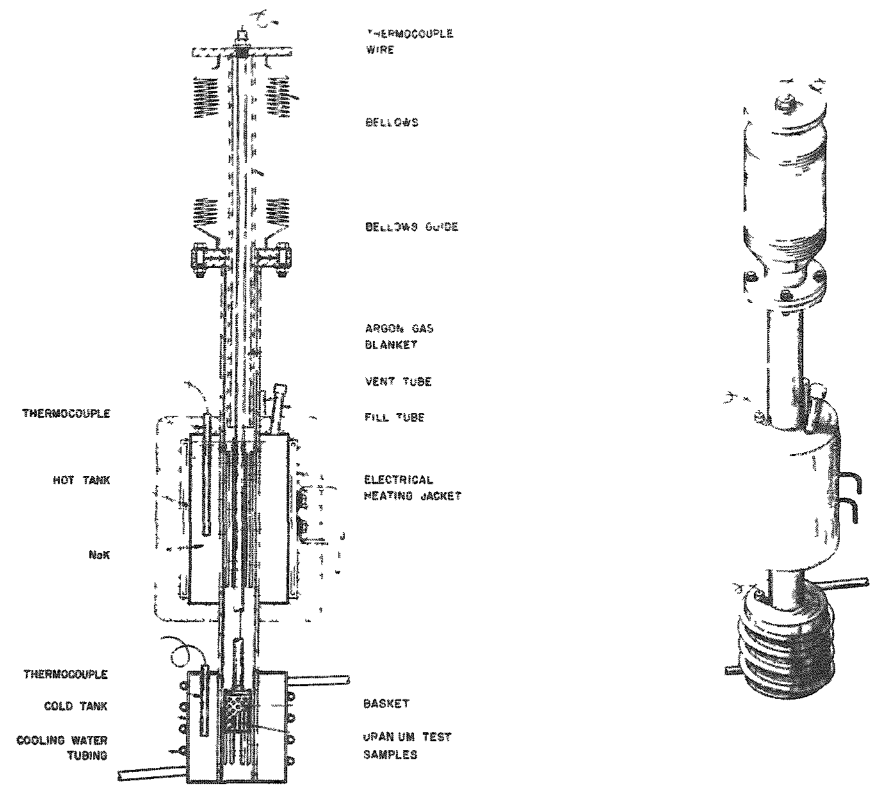


Fig. 13. Thermal Cycling Device