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ANL-5377

METALLURGY AND CERAMICS

UNITED STATES ATOMIC ENERGY COMMISSION

MECHANICAL STABILIZATION OF URANIUM
FUEL ELEMENTS.

Final Report—Metallurgy Program 5.1.12

By
K. F. Smith
S. T. Zegler
R. M. Mayfield

Price \$0.40

Available from the
Office of Technical Services
Department of Commerce
Washington 25, D. C.

November 1956

Argonne National Laboratory
Lemont, Illinois

Technical Information Service Extension, Oak Ridge, Tenn.

CLASSIFICATION CANCELLED
DATE FEB 11 1957
For The Atomic Energy Commission
H. F. Canale
Chief, Declassification Branch *mcL*

ANL-5377
Metallurgy and Ceramics

ARGONNE NATIONAL LABORATORY
P. O. Box 299
Lemont, Illinois

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Final Report - Metallurgy Program 5 1.12

Portions of the material contained in this report have been given in the following reports:

ANL-4825, pages 83, 84
ANL-4860, pages 87, 88
ANL-5036, pages 12-14
ANL-5097, pages 18-21
ANL-5153, pages 20, 21
ANL-5257, page 43
ANL-5338, pages 74, 75
ANL-5439, pages 25, 27-29
TID-5185 (Pt. 1), pages 200-207

METALLURGY DIVISION

November 1956

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

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MECHANICAL STABILIZATION OF URANIUM FUEL ELEMENTS

by

K. F. Smith, S. T. Zegler, and R. M. Mayfield

I. SUMMARY

A study of the mechanical restraint of cylindrical specimens of uranium under thermal cycling has been concluded.

Various degrees of restraint were accomplished by the use of containing jackets of different materials, with occasional assistance of minor alloying of the uranium with zirconium.

The ratio of clad cross-sectional area to core cross-sectional area is a means employed for expressing the effectiveness of restraint provided by a given material.

Unalloyed zirconium was found ineffective as a jacketing material in any thickness for use at 550°C or higher.

Type 347 stainless steel was an effective restraining material to 800°C in clad-to-core area ratios of 22 per cent or higher, provided means are used to provide mechanical separation of clad and core above 730°C to prevent alloying between uranium and steel.

Tantalum is an effective restraining material to 800°C in clad-to-core area ratios as low as 11 per cent, and probably as low as 7 per cent. Although not suitable for reasons of physics for thermal type reactors, results suggest investigation of niobium, which has similar properties, for those applications.

Considerably reduced propensity for growth, increased grain size, and increased thermal expansion have been observed for uranium which has been thermal cycled under complete restraint.

The graph of Fig. 12 summarizes the findings on minimum acceptable jacket thickness for each material.

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II. INTRODUCTION

The dimensional instability of uranium as used in fuel elements of nuclear reactors is the source of many difficulties in the design of those elements. Under conditions of neutron bombardment, the crystal structure of uranium is such that internal stresses are set up, resulting in strains which change the external dimensions of most fabricated shapes of the material. This dimensional instability may take the form of (1) growth in some particular direction, (2) local roughening of the surface, or (3) low-order density changes. These effects may occur alone or in various combinations.

Various means have been used to cope with this dimensional instability, each device having its own particular merits and its disadvantages. Among the avenues of approach to the problem, different types of heat treatment, fabrication, alloying, compacting, and jacketing of the uranium have been employed, as well as some ingenious devices of design and assembly of elements for cancelling out a portion of such deformation.

The dimensional stability of uranium under irradiation, while quantitatively different, bears resemblance to that observed under thermal cycling, and it is reasonable that the stresses developed against a containing jacket would be of similar order of magnitude. Since measurements after thermal cycling are much more easily made than those after irradiation, this examination was based on the deformation obtained by thermal cycling.

The present report deals with a study of jacketing, or enclosure of the core material by a strong cladding, not necessarily metallurgically bonded to the core, which would provide sufficient strength at service temperatures to inhibit the external deformation of the clad core to a greater or less degree. Determinations of required thickness of jacket have been made for specific conditions of maximum cycling temperature, type of fabrication and heat treatment of uranium core, and choice of cladding material. The study also includes a brief examination of what changes occur in the uranium core as a result of complete restriction by extra heavy jackets.

Jacketing materials investigated were pure zirconium, Type 347 stainless steel, and tantalum, the latter of possible interest only in fast reactors. However, results of these tests may be carried over to other materials of equivalent tensile and creep strength, at least in the manner of the amount of restraining force provided.

The materials for jacketing are considered in order of increasing degree of restraint.

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III RELATION OF RESTRAINT TO JACKET THICKNESS

In reactor design physicists take into account among other critical ratios, the relation of the quantity of fissionable material to the quantity of structural or diluent material lying in the high flux regions. If a certain cladding material has been specified along with certain maximum temperatures, designers will be assigned a maximum percentage figure for the ratio of clad-to-uranium core volume which may not be exceeded if power specifications are to be met. If a jacket is to be used as a restrictive force against distortion of the fuel material it then becomes important to know what thickness of each jacketing material is necessary to restrain the fuel element to a given dimensional tolerance

Data for the cladding materials investigated have therefore been interpreted in terms of the area ratio of clad-to-core which is actually the volume ratio for a fuel element if end effects can be neglected. All the specimens investigated were right circular cylinders, and, since end effects were excluded the ratio of the remaining circumferential cladding to the core could be calculated using the ratio of areas in a cross section. This ratio has been used in the comparative evaluation of specimens and materials.

Experimental data have been reported in "Test Units" within which identical testing conditions prevailed. The reporting of the units is arranged in order of materials.

A NaK bomb heated by an induction coil with an On-Off cycle was used for all testing in Test Units No. 1 through No. 7 (see ANL-4848). Automatic recording of time-temperature was employed on this induction cyler.

The terms "alpha cycling" "beta cycling" etc. as used in the following pages are understood to indicate the uranium phase attained at maximum temperature of cycling. The minimum temperatures in all tests reported here were either 100° or 150°C

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Fig. 1 Restraining Effect of Zirconium Jackets

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A. Zirconium Jackets

1. Test Unit No. 1 - Alpha Cycling of Uranium to 500°C

- a. Core material - uranium rolled from salt at 600°C.
- b. Core size - nominal 1.36" diameter, 4" long.
- c. Jacket material - zirconium.
- d. Clad-to-core fit - snug, pushed through die, probably no diffusion bond.
- e. Jacket thicknesses - 15, 20, and 35 mils.
- f. Clad-to-core area ratios - 4.5%, 6%, and 10%.
- g. Number of thermal cycles - 110.
- h. Maximum cycling temperature - 500°C.
- i. Conclusions (see Table I and Fig. 1):
 - (1) Zirconium jackets provide some restriction of growth of uranium.
 - (2) A clad-to-core ratio of 10% provides about 90% growth restriction of alpha-rolled uranium.

Table I.

DIMENSIONAL EFFECT OF CYCLING ZIRCONIUM-CLAD ALPHA-ROLLED URANIUM (See Fig. 1.)

Slug No.	Can Wall Thickness (In.)	Area Ratio	Size Before Cycling (In.)		Size After Cycling (In.)		Change in Dimensions (In.)			
			Length	Diameter	Length	Diameter	Length	%	Diameter	%
Bare	0.0	0	3.999	1.365	4.104	1.349	+0.105	2.63	-0.016	-1.17
1	0.015	4.5	3.875	1.358	3.970	1.340	+0.095	2.45	-0.018	-1.33
2	0.020	6	4.002	1.359	4.067	1.346	+0.065	1.62	-0.013	-0.96
3	0.035	10	4.002	1.368	4.012	1.361	+0.010	0.25	-0.007	-0.51

Note: The dimensions listed in Table I were taken after the jackets were removed.

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2. Test Unit No. 2 - Beta Cycling of Uranium to 730°C.

- a. Core material - Hanford quality uranium, beta annealed 2 hours at 750°C, furnace cooled.
- b. Core sizes - (1) single rod: 0.242" diameter, 0.971" long.
(2) bundle of eleven wires: each 0.062" diameter, 0.971" long.
- c. Jacket material - No. 3 grade zirconium, swaged (see Fig. 2)
- d. Clad-to-core fit - (1) rods: 9% excess space.
(2) wires; 59% excess space.
- e. Jacket thicknesses - 10, 20, 30, and 50 mils.
- f. Clad-to-core area ratios - (1) rod: 17%, 35%, 54% and 94%.
(2) wires: 24%, 49%, 75%,
and 130%.
- g. Number of thermal cycles - 200.
- h. Maximum cycling temperature - 730°C.
- i. Heating time - 5-7 minutes.
- j. Cooling time - 15-20 minutes.
- k. Deformation range - 6.03% on length, -0.7 to 13.7% on diameter.
- l. Conclusions: (1) Instability of uranium to beta cycling is considerably greater than upon alpha cycling.
(2) Zirconium jackets are ineffective in totally restricting uranium upon beta cycling, even though considerable free space was provided into which the core material could expand laterally (see Fig. 3).
(3) Zirconium jackets are also ineffective in preventing surface roughening and warping transmitted to the cladding by the enclosed uranium.

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Macro No. 15662

Fig. 2. Sketch of design of zirconium assemblies.

Fig. 3. Appearance of Zirconium Assemblies After 200 Cycles (100°C-730°C).

Set No. 1 (solid uranium rod)

(1)

(2)

Set No. 2 (uranium wires)

1X

Macro No. 14,690

(1) Empty jacket

(2) Stainless steel jacket

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3. Test Unit No. 3 - Gamma Cycling of Uranium and U-2 w/o Zr to 800°C.

- a. Core materials - (1) Hanford quality uranium, gamma annealed 2 hours at 800°C, furnace cooled.
(2) Uranium - 2% by weight Zr alloy annealed 1 hour at 800°C, 1 hour at 575°C, air cooled.
- b. Core sizes - (1) Single rod: 0.242" diameter, 0.971" long
(2) Bundle of eleven wires: each 0.062" diameter, 0.971" long.
- c. Jacket material - No. 3 grade zirconium, swaged.
- d. Clad-to-core fit - (1) rods; 9% excess space.
(2) wires; 59% excess space.
- e. Jacket thicknesses - 10, 20, 30, and 50 mils.
- f. Clad-to-core area ratios - (1) rod: 17%, 35%, 54%, and 94%.
(2) wire: 24%, 49%, 75%, and 130%.
- g. Number of thermal cycles - 200.
- h. Maximum cycling temperature - 800°C.
- i. Heating time - $3\frac{1}{2}$ to $4\frac{1}{2}$ minutes.
- j. Cooling time - 17-18 minutes.
- k. Deformation range - same or greater than in Test Unit No. 2.
- l. Conclusions (see Fig. 4):
 - (1) Zirconium unsuitable for jackets in gamma cycling.
 - (2) 2 w/o Zr alloying of uranium is ineffective in helping to restrain deformation during gamma cycling.

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Fig. 4. Appearance of Zirconium Assemblies After 200 Cycles (100°C-800°C).

Set No. 1 (solid uranium rod)

Set No. 2 (uranium wires)

Set No. 3 (U-2 w/o Zr alloy rod)

(1)

Macro No. 14,689

1X

(1) Empty jacket

B. Type 347 Stainless Steel Jackets

1. Test Unit No. 4 - Alpha Cycling of Uranium to 550°C.

- a. Core materials - Hanford quality uranium:
 - (1) Alpha rolled 89% at 300°C.
 - (2) Rolled as in (1) and beta quenched (1/2 hour 725°C, water quenched and annealed 2 hours at 575°C).
 - (3) Rolled as in (1) and beta annealed (1 hour at 725°C, furnace cooled to room temperature in 4 hours).
- b. Core size - 0.36" diameter and 1.37" long.
- c. Jacket material - 347 SS, cold-drawn, stress-relieved at 800°C.
- d. Clad-to-core fit - clad drawn over core - no free movement, but no diffusion bond.
- e. Jacket thicknesses - 5, 8, 10, 15, and 20 mils.
- f. Clad-to-core area ratios - 5.6%, 9%, 11%, 17%, and 23%.
- g. Number of thermal cycles - 700.
- h. Maximum cycling temperature - 550°C.
- i. Heating time - 5-7 minutes.
- j. Cooling time - 20-25 minutes.
- k. Deformation range - (1) Many ruptures in case of alpha-rolled cores.
 - (2) Limited deformation without rupture in case of beta-quenched and beta-annealed cores (see Fig. 5).
- l. Conclusions: Very low distortion for heavier jackets.

Fig. 5: Percent Elongation of Stainless Steel Jackets containing Beta-Quenched and Beta-Annealed Uranium after 700° Cycles (100° C-550° C).

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2. Test Unit No. 5 - Beta Cycling of Uranium to 725°C.

- a. Core materials - Same as for Test Unit No. 4.
- b. Core size - Same as for Test Unit No. 4.
- c. Jacket material - Type 347 stainless steel, cold-drawn, stress-relieved at 800°C.
- d. Clad-to-core fit - clad drawn over core - no free movement, but no diffusion bond.
- e. Jacket thicknesses - 8, 10, and 15 mils.
- f. Clad-to-core area ratios - 9%, 11%, and 17%.
- g. Number of thermal cycles - 700 to 550°C; 50 to 725°C for those specimens which survived Test Unit No. 4.
- h. Maximum cycling temperature - 725°C.
- i. Heating time - 5-7 minutes.
- j. Cooling time - 15-20 minutes.
- k. Deformation range - (1) One rupture (10 mil), one 0.46" in length, -4 to +2 mils in diameter (10 mil) for alpha rolled (see Fig. 6)
(2) For beta quenched and annealed, no ruptures, -0.13% to 0.33 in length, to 15 mils in diameter.
- l. Conclusion: (1) Instability of uranium on beta cycling is considerably greater than upon alpha cycling.
(2) Stainless steel jackets of 15 mils or less in thickness are ineffective in totally restraining deformation.

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2X

Fig. 6. Representative example of wall rupture in stainless steel assemblies containing beta-quenched uranium upon alpha-beta phase cycling (125°C - 725°C). Assembly No. 42.

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3. Test Unit No. 6 - Gamma Cycling of Uranium to 800°C.

- a. Core material - Normal uranium, beta quenched. (4 hours at 725°C, water quenched)
- b. Core size - $3/8$ " diameter, one inch long.
- c. Jacket material - Type 347 stainless steel, as rolled.
- d. Clad-to-core fit - Core wrapped in 3 wraps of 0.0015" Zr foil for separation - 6% excess space.
- e. Jacket thicknesses - 13, 17, 21, 25, 29, 32, 39, and 47 mils.
- f. Clad-to-core area ratios - 14, 19, 24, 28, 34, 37, 45, and 56%.
- g. Number of thermal cycles - 500.
- h. Maximum cycling temperature - 800°C.
- i. Heating time - 3 minutes.
- j. Cooling time - 16 minutes.
- k. Deformation range - length, slightly on 21-mil capsule only. Diameter, $1/5$ mil to $2-1/5$ mils (see Fig. 7).
- l. Conclusions: (1) Approximately 22% clad-to-core ratio of Type 347 stainless steel will restrain uranium to 800°C.
(2) Mechanical separation of uranium and stainless steel by zirconium at 800°C will prevent formation of low melting eutectic.

Fig. 7

C. Tantalum Jackets

1. Test Unit No. 7 - Gamma Cycling of Uranium to 800°C.

- a. Core material - Normal uranium, beta quenched (4 hours at 725°C, water quenched).
- b. Core size - $3/8$ " diameter, one inch long.
- c. Jacket material - Fansteel tantalum.
- d. Clad-to-core fit - 6% excess space, no diffusion bond (before or after cycling).
- e. Jacket thicknesses - 10, 15, and 20 mils.
- f. Clad-to-core area ratios - 11, 16, and 22.5%.
- g. Number of thermal cycles - 500.
- h. Maximum cycling temperature - 800°C.
- i. Heating time - 3 minutes.
- j. Cooling time - 16 minutes
- k. Deformation - none on any capsule. Uranium extruded through end holes on two capsules. This may have helped to avoid capsule deformation, but significantly no deformation appeared on the capsule with the thinnest wall (Fig. 8), even though no extrusion took place.
- l. Conclusions:
 - (1) Tantalum will restrain uranium to 800°C in clad-to-core ratios of 11% and probably as low as 7% (see Fig. 9).
 - (2) For thermal reactors the investigation of niobium is suggested.

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1.5X

Fig. 8. Side and bottom views of the tantalum-canned, beta-quenched uranium specimens after 500 cycles between 100° and 800°C. The numbers refer to the can wall thickness in inches.

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Fig. 9

Deformation on Diameter of Capsules Jacketed in Type 347 Stainless Steel
and in Tantalum After 500 Cycles Between 100° and 800°C

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IV. EFFECT OF COMPLETE RESTRAINT ON URANIUM1. Test Unit No. 8 - Alpha Cycling of Uranium in Heavy Jackets

- a. Core material - Uranium, rolled at 300°C, annealed 2 hours at 600°C.
- b. Core size - $3/8$ " diameter, one inch length.
- c. Jacket material - stainless steel (see Fig. 10)
- d. Clad-to-core fit - "close fit."
- e. Jacket thicknesses - $3/16$ " (0.1875").
- f. Clad-to-core area ratio - 300%.

	<u>Restrained by jacket</u>	<u>After remov- ing jacket</u>
g. Number of thermal cycles	350 - 2000	200
h. Maximum cycling temp.	550°C	550°C
i. Heating time	5 min	5 min
j. Cooling time	5 min	2 min
k. Holding time at temp.	5 min	5 min
l. Deformation - All internal, none external.		
m. Effect of restrained cycling -		
(1) Increase in grain size (see Table II).		
(2) Development of microcracks or voids.		
(3) Reduction of growth under subsequent free cycling (see Table II).		
(4) Increase in longitudinal coefficient of thermal expansion (see Table II).		
(5) Probable increase in randomization of crystal orientation.		

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Fig. 10: Restrained cycling container.

Table II
STRUCTURAL CHANGES IN URANIUM
UNDER RESTRAINED CYCLING

Spec. No.	Cycles Under Restraint	Grain Size (mm) Prior to Free Cycling	Growth Values- $G_t^{(1)}$ (Free Cycling 0-200X)	T.E.C. ⁽²⁾ 25-100°C After Free Cycling
15A	NONE (Control)	0.02	579	5.3
22A	350	0.03	542	6.4
23A	1000	0.04	390	9.7
25A	2000	0.045	106	12.5

(1) $G_t = \frac{1}{L} \cdot \frac{dL}{dN} \cdot 10^6$ microinches/inch/cycle.

(2) Thermal expansion coefficient, inches/inch/°C.

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2. Discussion of Complete Restraint

The purpose of this investigation (Test Unit No. 8) was to determine if changes in internal structure would occur during restrained cycling and what effect such changes might have on the growth rate on subsequent free cycling.

No dimensional changes were noted in the heavy jacket during cycling or in the specimen after removal from the jacket, but changes in structure occurred as shown by differences in grain size, thermal expansion coefficient, and free cycling growth (see Table II). Free cycling of this material for the number of cycles here executed as restrained would have resulted in 70 per cent reduction of area.

The results of the metallographic examination are shown in Fig. 11. Specimen 23A, after 1000 cycles under restraint, revealed fine microcracks upon mechanical polishing. The discontinuous microcracks were located at the site of inclusions and, in some cases, extended out into the matrix. Upon heat tinting, it was found that the microcracks were intergranular in most cases. These cracks are too fine to be seen in the photograph at 100X, Fig. 11-c.

Specimen 25A, after 2000 cycles under restraint, showed larger and more abundant microcracks upon mechanical polishing. As before, these cracks were located generally in the vicinity of inclusions, being intergranular after developing the grain structure by heat tinting. These larger cracks show up in the form of polishing pits in Fig. 11-d.

This same phenomenon, cracks or voids in the microstructure after thermal cycling, has been noted in previous specimens after sustained free cycling. In such cases, the voids were larger and elongated due to growth of the specimen. Since there is no large over-all movement in the restrained cycling, the cracks would not be expected to open up or enlarge so readily since their formation is dependent upon the "kneading" action of the individual grains upon cycling.

The decrease in free cycling growth rate could be ascribed to the increase in grain size and the presence of microcracks or voids that occurred during the restrained cycling. The grain size change was slight, between 1000 and 2000 cycles under restraint, but the microcracks became more pronounced. Any randomization of the orientation that may have occurred, as indicated by the thermal expansion values, would also be a contributing factor. No orientation studies, as such, were made.

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Fig. 11. Alpha Cycling of Uranium in Heavy Jackets
(Transverse Sections - Electrolytically Polished)

11-a. Specimen 5A. Annealed (Control)
Grain Size, 0.02 mm.

M-11741 Polarized Light 100X

11-b. Specimen 22A. 350X restrained
Grain Size, 0.03 mm.

M-12372 Polarized Light 100X

11-c. Specimen 23A. 1000X restrained.
Grain Size, 0.04 mm.

M-12409 Polarized Light 100X

11-d. Specimen 25A. 2000X restrained.
Grain Size, 0.045 mm.

M-12796 Polarized Light 100X

V. GENERAL DISCUSSION OF RESTRAINT OF URANIUM

Table III and Fig. 12 summarize the work of this project related to jacket thickness as a variable in restraint of uranium under thermal cycling.

Zirconium is not suited to restrain completely the deformation of uranium at temperatures 550°C and above, but will serve to reduce it. A thickness of zirconium jacket representing only 10 per cent of the core area has been shown to reduce deformation by 90 per cent. Thicker jackets, however, do not provide much additional restraint. Evidently the creep strength of unalloyed zirconium at these temperatures is too low to provide sufficient restrictive force.

Type 347 stainless steel is a better jacketing material and good stability is indicated for clad-to-core area ratios of 22 per cent or higher, even at 800°C. However, to prevent formation of a low-melting eutectic with the uranium, it is essential to provide some kind of mechanical separation of the two for temperatures above approximately 730°C. This separation was provided in these tests by wrapping the uranium slugs (and capping ends) in zirconium foil, as described under Test Unit No. 6.

The inclusion of tantalum as a test material was suggested by its fortuitous combination of high strength and high thermal conductivity. Moreover, its similarity to niobium, a more suitable material for thermal reactors, might justify some extrapolation of results. The restrictive power of tantalum in these tests justifies the belief that clad-to-core area ratios of only 7-10 per cent would be as effective as 22 per cent is for stainless steel. No jackets of this gauge were made, but a study of the very small deformations shown in Fig. 8 provides some basis for an estimate. Some idea of the restraint provided by tantalum may be gained from Fig. 8, which shows extrusion of the uranium through a 1/16" hole in the capsule which had been drilled to allow circulation of the heat transfer medium through the capsule. No such extrusion appeared in the case of the stainless steel capsules, probably because of the protecting wrap of zirconium.

In Test Units Nos. 6 and 7 a microscope comparator was used for measuring deformation. All other Test Units employed micrometer calipers for this purpose.

Indications from Test Unit No. 8 are that a method for randomizing the structure of uranium by cycling under heavy restraint might possibly be developed. At least the indication is that the internal force on the jacketed specimens should become less as the cycling progresses. The fact that sudden distortion of jacketed specimens sometimes arrives late in the cycling process may be explained by the weakening of the jacket rather than by increased internal force from the uranium.

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Table III.

APPROXIMATE CLAD-TO-CORE AREA RATIOS
REQUIRED TO STABILIZE URANIUM
CYLINDERS DIMENSIONALLY

Maximum Cycling Temp. (°C)	Jacketing Material		
	Zirconium	347 Stainless	Tantalum
550 (alpha)	> 10%	20%	-
730 (beta)	>130%	20%	-
800 (gamma)	>130%	22%	7-10%

Fig 12 Approximate Clad-to-Core Area Ratios for Adequate Stability
of Uranium Cylinders Under Thermal Cycling

ACKNOWLEDGEMENT

Acknowledgement is hereby made to Mr. A B Shuck for his care in the preparation and encapsulment of the uranium and uranium alloy cores used in these tests.

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APPENDIX

Original Data Tables

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Table IV.

MAXIMUM DIMENSIONAL CHANGES IN ZIRCONIUM JACKETS UPON
CYCLING BETWEEN 100°C AND 730°C (TEST UNIT NO. 2)

Assembly No.	Uranium	Jacket Wall Thickness (in.)	Jacket Dia. (in.)	Per Cent Changes in Dimensions						Comments
				After 50 cycles		After 100 cycles		After 200 cycles		
				Length(1)	Dia.	Length(1)	Dia.	Length(1)	Dia.	
7-0 7-00	Empty Empty	0.020 0.020	0.289 0.288	0.51	+0.3	0.39	+1.0	0.12	+1.4	
7-1 7-2	Beta Annealed (2) FBR Fuel Rods (0.242" Dia. x 0.971" Long)	0.010 0.010	0.270 0.266	0.80	$\frac{+3.8}{-0.8}$	1.20	$\frac{+5.6}{-1.6}$	Too warped to measure	$\frac{+13.7}{-2.2}$	Badly warped and wrinkled
7-3 7-4		0.020 0.020	0.288 0.290	0.83	$\frac{+1.0}{-1.4}$	2.17	$\frac{+3.2}{-1.7}$	2.21	$\frac{+6.3}{-3.5}$	Badly warped
7-5 7-6		0.030 0.030	0.308 0.308	1.26	$\frac{+1.0}{-1.0}$	4.06	$\frac{+1.8}{-0.6}$	6.03	$\frac{+4.5}{-0.6}$	Warped
7-7 7-8		0.050 0.050	0.350 0.349	0.75	+0.5	1.46	$\frac{+1.3}{-1.0}$	4.22	$\frac{+2.3}{-1.2}$	Warped
7-9(3) 7-10(3)		0.020 0.020	0.287 0.288	0.20	+0.3	0.12	+0.9	-0.24	$\frac{+1.0}{-0.7}$	
7M-1 7M-2	Beta Annealed (2) Wires (0.062" Dia. x 0.971" Long)	0.010 0.010	0.267 0.269	0.67	$\frac{+4.4}{-3.4}$	1.33	$\frac{+6.4}{-4.0}$	3.43	$\frac{+7.5}{-4.1}$	Badly warped and wrinkled
7M-3 7M-4		0.020 0.020	0.288 0.289	0.83	$\frac{+2.5}{-1.8}$	0.86	$\frac{+3.9}{-2.5}$	2.25	$\frac{+4.5}{-3.5}$	Warped
7M-5 7M-6		0.030 0.030	0.309 0.309	0.91	$\frac{+1.6}{-1.0}$	1.26	$\frac{+2.6}{-1.6}$	3.39	$\frac{+4.9}{-1.9}$	Warped
7M-7 7M-8		0.050 0.050	0.348 0.348	0.67	$\frac{+0.9}{-0.3}$	0.67	$\frac{+1.8}{-0.6}$	3.23	$\frac{+2.9}{-1.2}$	

- (1) Initial Fiducial Length 1.000".
 (2) 2 hours at 750°C; furnace cooled.
 (3) Jacket material, 347 stainless steel.

Table V

MAXIMUM DIMENSIONAL CHANGES IN ZIRCONIUM JACKETS UPON
CYCLING 200 TIMES BETWEEN 100°C AND 800°C
(TEST UNIT NO. 3)

Assembly No.	Uranium	Jacket Wall Thickness (in.)	Jacket Dia. (in.)	Per Cent Change in Dimensions		Comments
				Length(1)	Diameter	
8-0 8-00	Empty Empty	0.020 0.020	0.289 0.289	0.87	+ 1.00	
8-1 8-2	Gamma Annealed	0.010 0.010	0.270 0.269	7.19	$\frac{+12.0}{- 1.5}$	Warped and wrinkled
8-3 8-4	(2) EBR Fuel Rods	0.020 0.020	0.288 0.288	6.44	+ 5.5	Warped and wrinkled
8-5 8-6	(0.2425" Dia. x	0.030 0.030	0.310 0.310	8.28	+ 4.8	Warped
8-7 8-8	0.971" Long)	0.050 0.050	0.350 0.351	6.67	+ 3.2	Warped
8M-1 8M-2	Gamma Annealed	0.010 0.010	0.267 0.270	2.16	+15.9	Warped and wrinkled
8M-3 8M-4	(2) Wires (0.062"	0.020 0.020	0.289 0.289	4.37	+11.1	Warped
8M-5 8M-6	Dia. x	0.030 0.030	0.310 0.310	5.83	$\frac{+ 4.2}{- 1.6}$	Warped
8M-7 8M-8	0.971" Long)	0.050 0.050	0.349 0.350	5.60	$\frac{+ 2.1}{- 1.2}$	

(1) Initial Fiducial Length 1.000".

(2) 2 hours at 800°C; furnace cooled.

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Table VI

MAXIMUM DIMENSIONAL CHANGES IN ZIRCONIUM JACKETS CONTAINING U-2 w/o ZR
ALLOY UPON CYCLING BETWEEN 100°C AND 800°C
(TEST UNIT NO. 3)

Assembly No.	Uranium	Jacket Wall Thick-ness (in.)	Jacket Dia. (in.)	Per Cent Changes in Dimensions						Comments	
				After 50 cycles		After 100 cycles		After 200 cycles			
				Length(1)	Dia.	Length(1)	Dia.	Length(1)	Dia.		
8Z-1	Gamma-Iso Treated (2) U-2 w/o Zr alloy (0.242" Dia. x 0.969" Long)	0.010	0.269	0.51	+0.3	1.61	$\frac{+1.8}{-0.4}$	3.73	$\frac{+4.4}{-2.2}$	Badly checked surfaces	
8Z-2		0.010	0.269								
8Z-3		0.020	0.289	1.32	Nil	3.03	$\frac{+0.3}{-0.9}$	8.87	$\frac{+2.4}{-1.4}$	Checked sur-faces	
8Z-4		0.020	0.289								
8Z-5		0.030	0.310	1.17	Nil	2.79	$\frac{+0.3}{-0.6}$	8.41	+2.3	Checked sur-faces	
8Z-6		0.030	0.310								
8Z-7		Long)	0.050	0.348	0.47	Nil	1.57	-0.6	4.91	$\frac{+1.4}{-0.3}$	.
8Z-8			0.050	0.349							

(1) Initial Fiducial Length 1.000".

(2) 1 hour at 800°C; 1 hour at 575°C; air cooled.

Table VII

DIMENSIONAL CHANGES IN STAINLESS STEEL JACKETED STUGS UPON THERMAL CYCLING
(TUNTS UNITS NOS. 4 AND 5)

Assembly No. (1)	Jacket Wall Thickness (in.)	ALPHA PHASE CYCLING (100°C-550°C) (2)											ALPHA-BETA PHASE CYCLING (125°C-725°C) (50 CYCLES)					
		n Cycles		Mean Change in Dia. (mils)			Change in Median Lengths (mils)			Change in Median Length			n Cycles		Change in Dia. Range (mils)	Change in Lengths (mils)	Per Cent Change in Lengths	Comments
		Dia. (in.)	Length (in.)	100x	300x	700x	100x	300x	700x	100x	300x	700x	Dia. (in.)	Length (in.)				
1A	0.005	0.3853	1.4964	0.0	0.9	1.7	0.4	1.5	2.5	0.06	0.10	0.17						
2A	0.005	0.3850	1.4979	0.4	1.0	1.4	0.6	1.7	2.1	0.04	0.11	0.14						
1Q	0.005	0.3849	1.4947	0.0	0.6	1.0	1.2	2.7	3.3	0.08	0.17	0.22						
2Q	0.005	0.3853	1.4967	0.0	0.3	1.2	0.6	1.4	2.7	0.04	0.13	0.18						
1R	0.005	0.3852	1.4938	-0.4*	N.C.	N.C.	*	-	-	-	-	-						
2R	0.005	0.3854	1.4981	-0.0*	N.C.	N.C.	*	-	-	-	-	-						
1AT	0.0075	0.3854	1.5322	0.1	0.3	0.5	0.8	0.3	0.6	0.05	0.02	0.04						
2AT	0.0075	0.3854	1.5292	0.2	0.2	0.4	-0.4	2.3	0.5	-0.03	0.15	0.03						
1QT	0.0075	0.3876	1.5150	-2.1	-1.9	-1.8	15.3	16.4	16.2	1.00	1.08	1.07						
2QT	0.0075	0.3878	1.5113	-2.2	-1.6	-1.6	17.6	18.5	18.9	1.16	1.22	1.25						
1RT	0.0075	0.3857	1.5298	0.4*	N.C.	N.C.	*	N.C.	N.C.	-	-	-						
2RT	0.0075	0.3857	1.5292	1.0*	N.C.	N.C.	*	N.C.	N.C.	-	-	-						
3A	0.008	0.3849	1.5052	0.2	0.7	1.1	0.9	1.0	1.7	0.06	0.06	0.11	0.3850	1.507	- 2.0	14.0	4.0	0.26 Rupt. Wall
4A	0.008	0.3853	1.5084	0.2	0.4	0.5	0.7	1.7	1.9	0.05	0.11	0.13	0.3858	1.510	1.0	6.0	2.0	0.13 Rupt. Wall
3Q	0.008	0.3851	1.5060	0.1	0.3	0.6	1.8	2.4	2.6	0.12	0.16	0.17	0.3857	1.509	- 9.0	9.0	2.0	0.13 Rupt. Wall
4Q	0.008	0.3849	1.5033	-0.1	0.4	0.5	2.1	2.7	3.1	-0.14	0.18	0.20	0.3854	1.506	-13.0	10.0	5.0	0.33 Rupt. Wall
3R	0.008	0.3859	1.5064	-1.4	*	N.C.	33.2	*	*	2.20	-	-						
4R	0.008	0.3854	1.5050	-1.9	-2.7	*	27.3	40.3	*	1.81	2.68	-						
5A	0.010	0.3845	1.5007	0.3	0.5	0.8	-0.7	-0.3	0.0	-0.05	-0.02	0.0	0.3853	1.501	- 5.0	7.0	2.0	0.13 Rupt. Wall
6A	0.010	0.3847	1.4994	0.2	0.4	0.7	-0.2	-0.4	0.6	-0.01	-0.02	-0.03	0.3854	1.500	- 2.0	10.0	1.0	0.07 Rupt. Wall
5Q	0.010	0.3848	1.4955	0.2	0.3	0.6	0.0	0.7	1.1	0.0	0.04	0.07	0.3854	1.497	- 1.0	8.0	0.0	0.00 Rupt. Wall
6Q	0.010	0.3845	1.4981	0.3	0.4	0.7	-0.1	1.1	1.2	-0.0	0.07	0.08	0.3852	1.499	- 2.0	10.0	0.0	0.06 Rupt. Wall
5R	0.010	0.3847	1.5002	-0.6	-1.2	-1.3	19.5	32.4	38.1	1.30	2.16	2.54	0.3834	1.538	- 1.0	1.0	1.0	0.07 Rupt. Weld
6R	0.010	0.3846	1.4950	-0.6	-1.1	-1.1	18.7	30.0	35.9	1.25	2.01	2.40	0.3835	1.532	- 4.0	2.0	-7.0	-0.46 No Rupt.
7A	0.016	0.3850	1.5061	0.2	0.5	0.4	-0.2	0.2	0.3	-0.01	0.01	0.02	0.3854	1.510	0.0	9.0	-2.0	-0.13 No Rupt.
8A	0.016	0.3851	1.5082	0.1	0.4	0.4	-0.5	-0.4	-0.4	-0.03	-0.03	-0.03	0.3855	1.508	- 1.0	12.0	2.0	0.13 No Rupt.
7Q	0.016	0.3852	1.5018	0.1	0.3	0.3	0.4	0.8	0.8	0.06	0.05	0.05	0.3855	1.503	0.0	14.0	1.6	0.07 No Rupt.
8Q	0.016	0.3852	1.5048	0.2	0.3	0.4	1.0	1.2	0.9	0.07	0.08	0.07	0.3856	1.506	- 1.0	15.0	2.0	0.13 Rupt. Weld
7R	0.016	0.3857	1.5030	-0.4*	N.C.	N.C.	*	*	*	-	-	-						
8R	0.016	0.3851	1.5003	-0.1	0.4**	*	9.7	**	*	0.65	-	-						
9A	0.020	0.3847	1.4987	0.3	0.4	0.5	-0.4	0.0	-0.4	-0.03	0.00	-0.03						
10A	0.020	0.3847	1.4978	0.3	0.5	0.5	-0.6	0.5	0.4	0.04	0.04	0.03						
9Q	0.020	0.3847	1.4964	-0.1	0.2	0.2	-0.4	0.0	0.0	0.03	0.00	0.00						
10Q	0.020	0.3844	1.4981	0.2	0.3	0.4	0.0	0.4	0.4	0.0	0.03	0.03						
9R	0.020	0.3848	1.4975	-0.2**	0.1*	N.C.	**	*	-	-	-	-						

NOTES (1) Suffix Designation A - Annealed 1 hour at 725°C.
Cooled to room temperature in 4 hours.
Q - 1/2 hour at 725°C, water quenched.
Annealed 2 hours at 575°C.
R - As rolled 300°C.

(2) Legend C - Cycled.
NC - Not Cycled.

* Total rupture of welds.
** Partial rupture of welds.