NAA-SR-3887

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SODIUM REACTOR EXPERIMENT FUEL IRRADIATION EXPERIENCE

AEC Research and Development Report

Sep '59

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.

Price $1.00.
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Washington 25, D. C.

NSA 13-21184

NAA-SR-3887
METALLURGY AND CERAMICS
38 PAGES

SODIUM REACTOR EXPERIMENT
FUEL IRRADIATION EXPERIENCE

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A DIVISION OF NORTH AMERICAN AVIATION, INC.
P.O. BOX 309 CANOGA PARK, CALIFORNIA

CONTRACT: AT(11-1)-GEN-8
ISSUED: SEP 1 5 1959

DISTRIBUTION

This report has been distributed according to the category "Metallurgy and Ceramics" as given in "Standard Distribution Lists for Unclassified Scientific and Technical Reports" TID-4500 (14th Ed.), October 1, 1958. A total of 605 copies was printed.

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ABSTRACT

Nondestructive examinations of the unalloyed uranium fuel in the Sodium Reactor Experiment (SRE) showed no increase in cladding diameter after 850 Mwd/Tonne calculated maximum burnup. Some clad stretching is evident at 950 Mwd/Tonne. Destructive examinations at maximum burnups of 65, 105, 390, and 850 Mwd/Tonne showed progressive irradiation-induced dimensional changes. Data showed maximum changes in diameter of 1.7%, in length of 2.9%, and in density of -2.6% for the highest burnup. Surface conditions indicated progressive roughening with increasing fuel material burnup level. All surface and dimensional characteristics appeared to be directly related to burnup. Some relationship was found between surface roughening and fuel element surface temperature. The SRE fuel element design appears to be performing well. Fuel element cladding examinations indicated no apparent change in ductility after exposure to surface temperatures of about 850°F, with subsequent cycling resulting from startup and shutdown of the reactor.

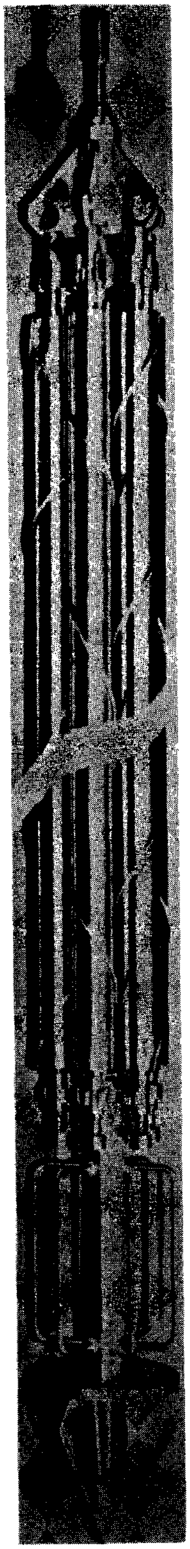
I. INTRODUCTION

The objective of the metallic-base fuel program is to develop fuel elements that will be economically feasible for sodium graphite reactors (SGR). The fuel material must have capabilities of long burnup, low fabrication cost, and be easily reprocessed. In order to properly utilize the sodium coolant in SGR's, the fuel must operate at high surface and center temperatures and high surface heat flux. The fuel should have a high uranium density and a low parasitic neutron cross section. The operational philosophy of this program has been that the irradiation of full-size elements, after proper small capsule backup effort, is the most effective way of determining the limitations of the fuel element under desired operating conditions.

As part of the SRE, a fuel program was established to evaluate the fuel core initially selected for use in the reactor. This phase of the investigation deals with the unalloyed uranium fuel which makes up the first SRE core and the evaluation of the fuel element design. Because of the high operating temperatures (surface and central) employed in the SRE, and because of the limited amount of operational experience, the first core loading is being considered experimental. For this reason, this evaluation work is included as part of the SGR experimental fuels program.

Irradiation growth and swelling appear to be the greatest limiting factors on the life of metal fuels. Irradiation growth, resulting from the anistropic properties of alpha uranium, causes a change in shape with only small density changes. Irradiation swelling, which is thought to be caused by nucleation and growth of small bubbles of fission gas, also causes gross density decreases

The overall metal fuel program has the goal to overcome these problems by the development of satisfactory alloys and fabrication methods.



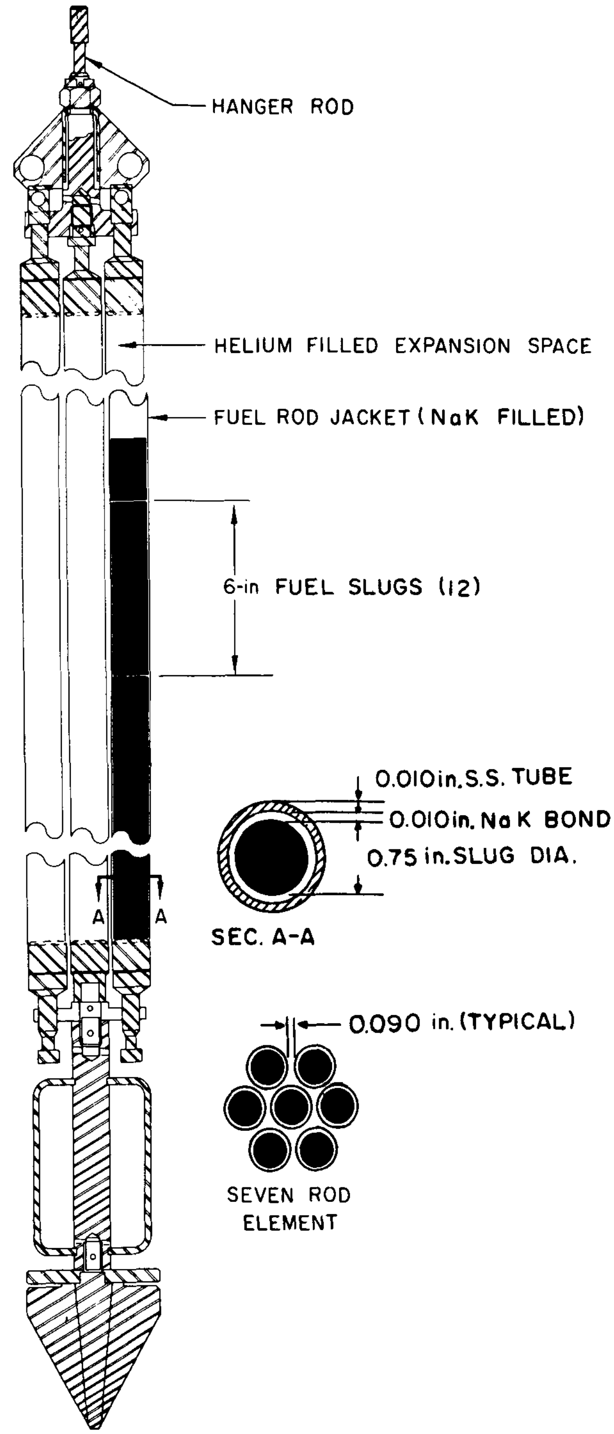


Figure 1. SRE Fuel Element

II. PROCEDURE

A. GENERAL

The selection of alpha-rolled, beta-heat treated uranium as a fuel for the first SRE core was made in 1954, after extensive thermal cycling tests[1] and consideration of in-pile irradiation results from other sites.[2,3,4]

An alternate fuel, U - 2 wt % Zr alloy, was discarded at that time, in favor of the unalloyed uranium, because of the sensitivity of the U - 2 wt % Zr alloys to fabrication variables. It was originally expected, from experimental results, that the high fuel slug temperatures, 500 to 1200°F, might decrease the irradiation growth. This fact has not as yet been demonstrated. In the original proposal, the expected life of SRE Core I was 2500 Mwd/Tonne max.

B. DESCRIPTION OF ELEMENTS

The standard SRE fuel elements are seven-rod fuel clusters containing NaK-bonded uranium slugs in Type 304 stainless steel jackets. The active fuel length is 72 in. The 0.750-in. diameter by 6.0-in. long slugs of unalloyed uranium are bonded by 0.010 in. of NaK to the 0.010-in. stainless steel jacket for purposes of heat transfer (see Figure 1). The fuel element channels through which the sodium coolant flows are 2.80 in. in diameter. The spacing between fuel rods for sodium circulation is maintained by spirally wrapped wires, 0.092 in. in diameter. End fittings position the rods and the element in the channel and regulate the flow of the coolant.

The SRE core was designed for a fuel loading of 37 seven-rod fuel elements. The seven-rod element is designed to provide adequate heat transfer surface to limit the center fuel temperature to 1200°F when the SRE is operating at 20 Mwt.

The metal procurement and fabrication of the α-rolled, β -heat treated uranium are covered in detail in NAA-SR-3456,[5] so will not be discussed here, except to indicate that every effort was made to process the metal with the best practice available, and that detailed records were kept on all phases of fabrication, from reduction of UF_6 to final assembly of the fuel elements. Each fuel slug in the SRE can be traced to a detailed chemical analysis and a set of fabrication conditions.

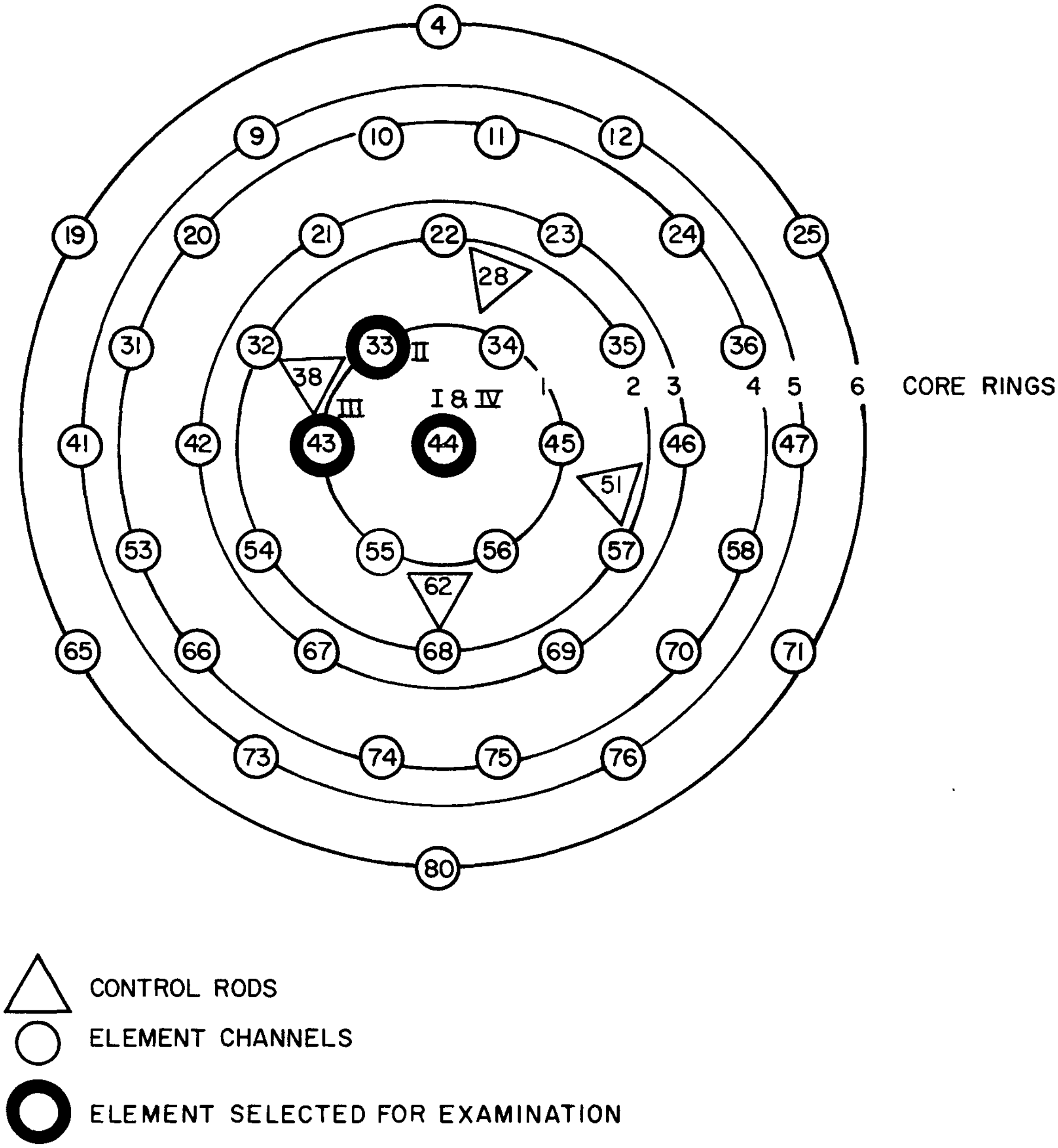


Figure 2. SRE Core Configuration

C. IRRADIATION CONDITIONS AND SCHEDULE

The operating conditions of the SRE are shown in Table I. The majority of the core burnup represented in this evaluation took place at or near these conditions. Figure 2 shows the layout of the core face. The center channel and the channels in the first ring have the highest power output.

TABLE I

SRE CONDITIONS

Type	- Thermal Heterogeneous
Capacity	- 20 Mwt
Moderator	- Graphite
Coolant	- Sodium
	T_{in} = 525°F (actual)
	T_{out} = 850°F (actual)
	Flow = 800 to 1200 gpm
Fuel Loading	- Core I
	2.78% Enriched (U^{235}) Unalloyed Uranium
	Weight - 3000 kg
Fuel Element	- No. of Elements - 43
	Rods/Element - 7
	Overall Length - 8 ft 6 in.
	Active Length - 6 ft
Flux	- Core I
	Max. thermal neutron flux density - 1.5 x 10^{13} nv
	Average thermal neutron flux density - 1.0 x 10^{13} nv
	Cell spacing 11 in. on triangular lattice array

These fuel channels are used for standard elements to be evaluated, and experimental fuel elements containing thermocouples which read center fuel temperatures at varying distances into the reactor core. The temperature profile can also be calculated from channel power and sodium temperature data. Figure 3 compares the calculated with the measured fuel temperature in the center channel and the first ring channels of the SRE at a power of 20 Mwt. Records are kept of the

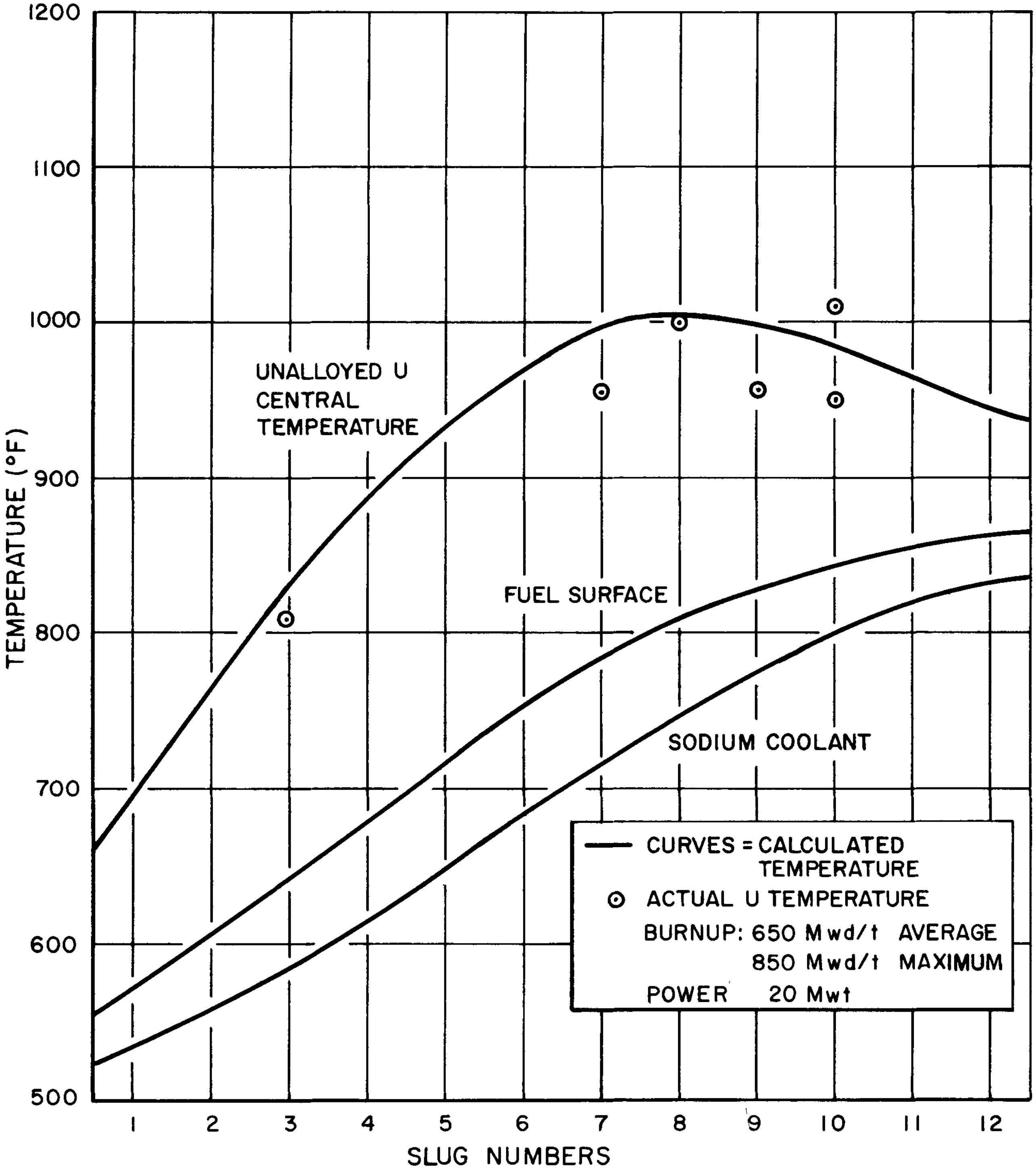


Figure 3. Typical Fuel Temperatures vs Slug Numbers for MC-1-1 Fuel Element

cumulative thermal power history of the reactor fuel. Figure 4 represents the reactor power and fuel temperature conditions during a typical SRE power run.

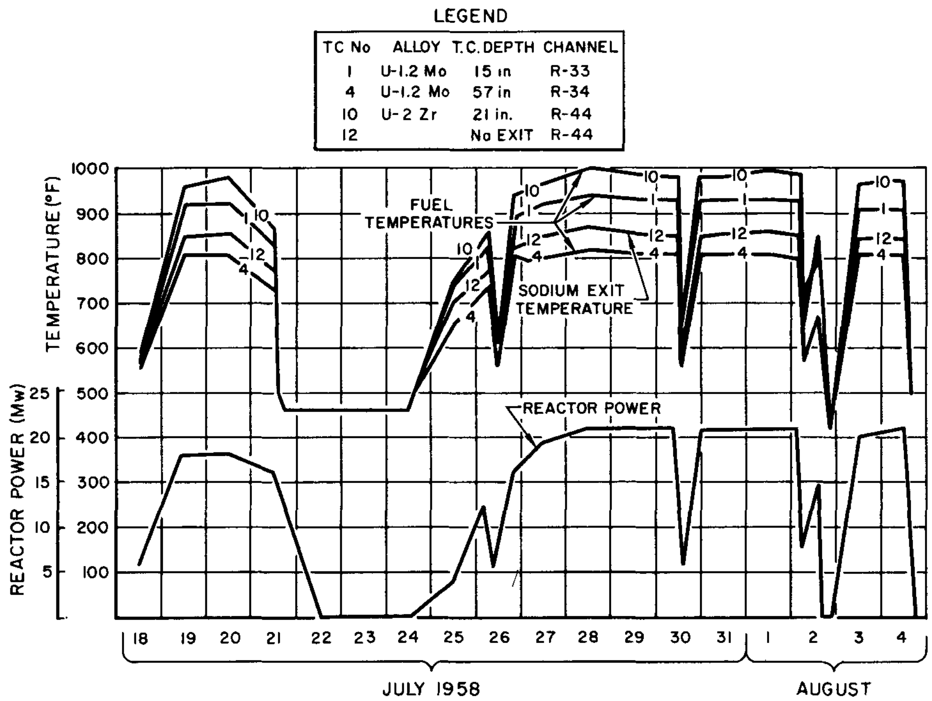


Figure 4. Typical SRE Power Run Showing Temperature and Power Relations

The irradiation program was set up to evaluate, by means of destructive and nondestructive examination, fuel elements making up the first SRE core. It was designed to study elements at varying levels of burnup and to ascertain the fuel performance under these conditions. Destructive examinations were scheduled at 65, 105, 390, and 850 Mwd/Tonne maximum* and beyond. The basis of selection of these burnup levels was as follows:

1) 65 Mwd/Tonne represented the end of the low power and temperature tests. During this time, the reactor probably did not go over 750°F. This was essentially the zero point.

2) 105 Mwd/Tonne represents the end of the first power run. An examination was desired to check the element integrity.

3) 390 and 850 Mwd/Tonne were part of the continuous high power evaluation.

*The average burnup of the fuel is calculated from operating data. The maximum burnup fuel slug in an element rod is obtained by multiplying the average fuel rod burnup figure by 1.3, the peak to average ratio.

The elements for evaluation were selected from the position of highest available flux, in order to obtain the greatest burnup in the shortest time. The first and fourth elements were from R-44, the center channel. The second and third elements examined were from the first reactor ring (see Figure 2).

D. HOT CELL EXAMINATION

The hot cell examinations of the fuel elements were of two types: (1) nondestructive, and (2) destructive. Below are descriptions of the procedures followed in each method.

1. Nondestructive Examination

A special technique for viewing fuel elements within the reactor face was developed, using a television camera mounted in the shield plug adapter ring. The elements are raised by the cask hoist and viewed as required. The operators are able to detect any gross cladding defects or mechanical abnormalities by remote viewing. Figure 5 shows the schematic arrangement of the apparatus.

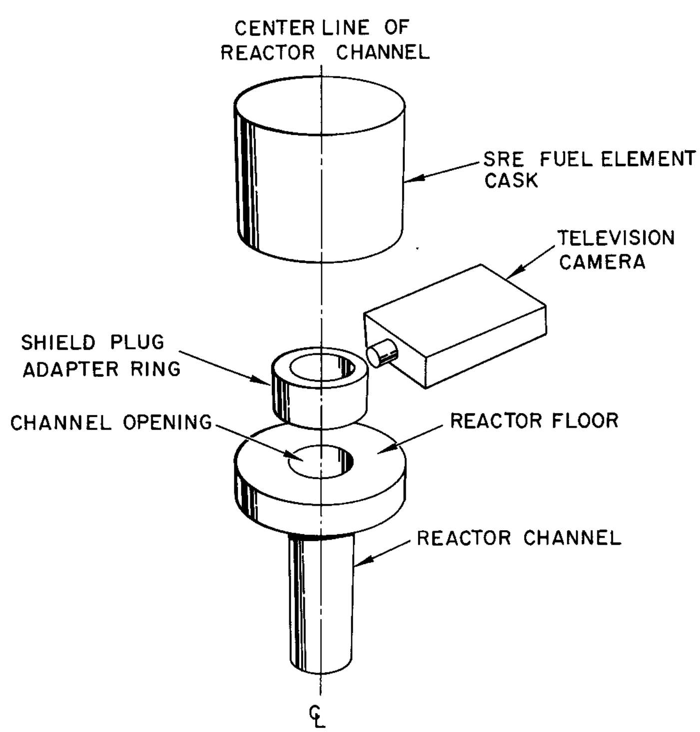


Figure 5. TV Examination of SRE Fuel - Schematic

Figures 6, 7, and 8 are the top, middle, and bottom, respectively, of a fuel element, as viewed on the TV screen. Note the adherence of beads of sodium coolant on the cladding. This technique has proved useful in checking fuel elements suspected of being defective.

The more detailed nondestructive examination consisted of the following in a hot cell:

a) straightness determination

b) snap gauging for cladding diameter measurement

c) visual observation for gross abnormalities and/or cladding integrity.

The elements selected for this type of examination were looked at after each reactor shutdown. Generally, this was the periodic test of the fuel element to determine external indications of the internal swelling or growth.

The straightness was determined by viewing the fuel element in a vertical position with a surveyor's transit. The snap gauging operation, a measurement of outside fuel cladding diameter, was accomplished by a set of snap gauges actuated in-cell by a master-slave manipulator. The gauging took place on the elements on the side located nearest the reactor center. Thus, with each examination, three rods were gauged, starting from the top of the element rod, every 10 in. down the rod. The element rods required some physical separation, in order for the gauge to slip over the tube. The visual examination consisted of the observation of the fuel element with a 10 X telescope, with field glasses through the shielded glass window, and with magnifying glasses located in the cell.

2. Destructive Examination

The destructive examination consisted of the following:

a) Disassembly and decanning, including fission-product analysis in the gas-filled expansion void and in the NaK bond

b) Visual and photographic examination

c) Dimensional measurement for length, diameter, and warp

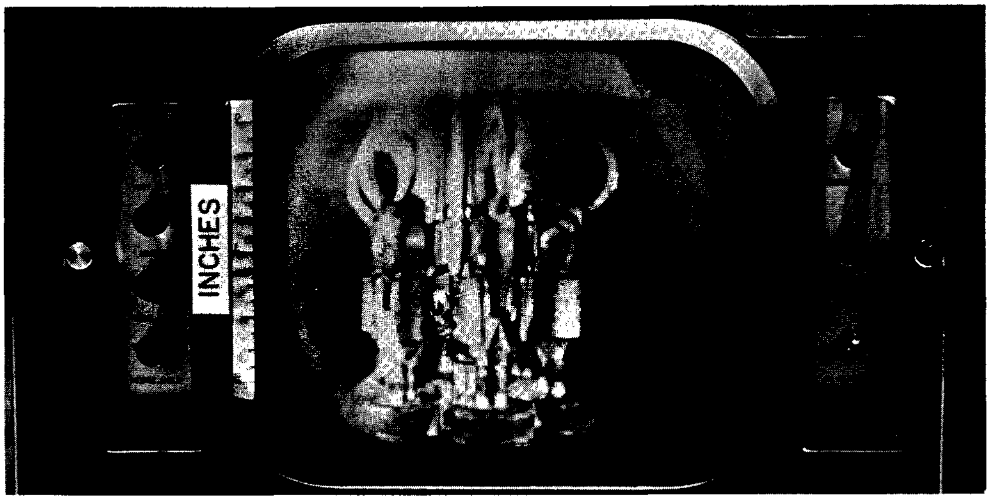


Figure 6. TV Examination of SRE Fuel - Top of the Element

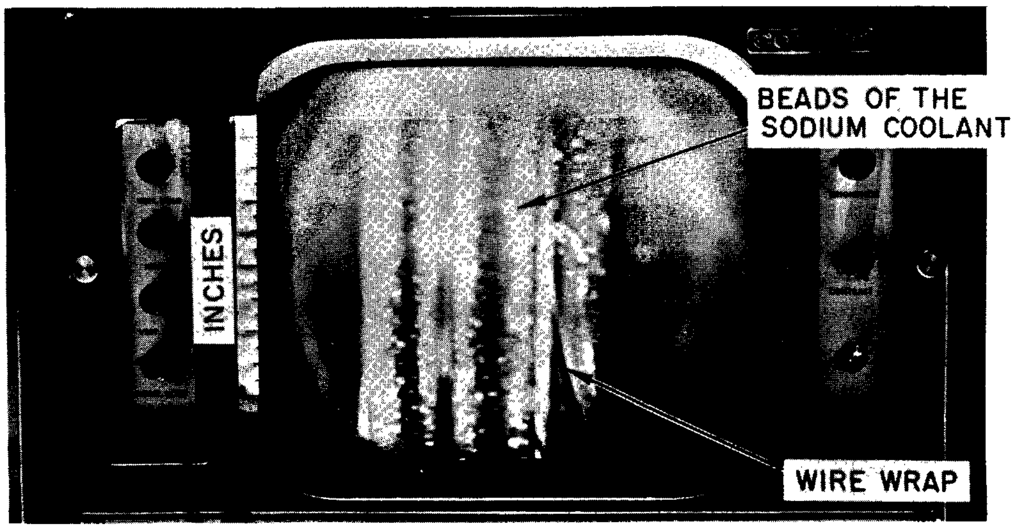


Figure 7. TV Examination of SRE Fuel - Middle of the Element

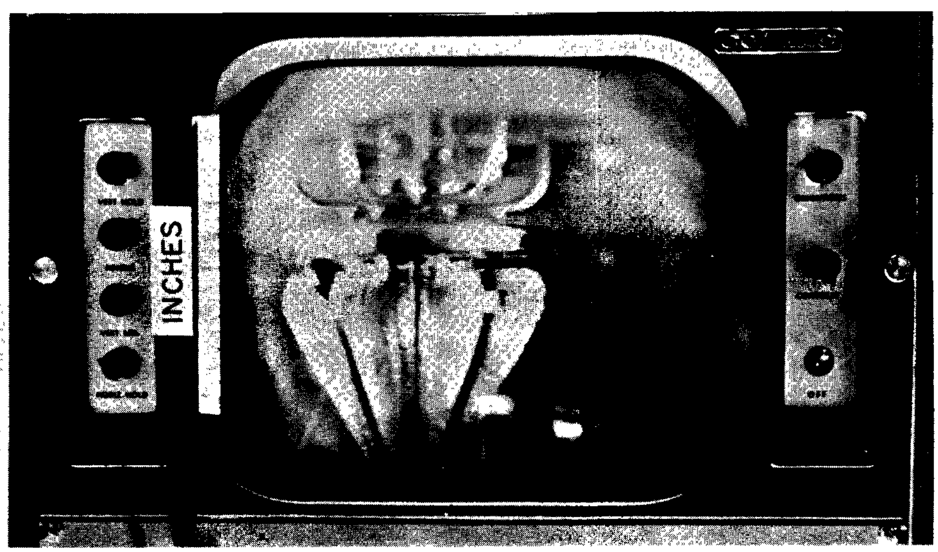


Figure 8. TV Examination of SRE Fuel - Bottom of the Element

d) Surface measurement

e) Density determination

f) Burnup analysis by gamma-radiation detection techniques and radiochemical analysis

g) Metallographic examination

This examination required the disassembly of the fuel cluster, then the decanning of the fuel element rod to allow measurement of each individual fuel slug. Each slug was considered as a unit, and had a corresponding temperature and burnup associated with it. After the opening of the rod, the NaK bond material was digested in an alcohol-kerosene solution, the individual slugs were cleaned, and were then stored under kerosene in the cell. After decanning and cleaning, visual examination and photography were completed to show surface variation and any gross defect. Each slug was given a thorough visual examination, both with the unaided eye and with a 10 X telescope. Dimensional measurements were then taken. Diameters were read at five equispaced points, then the slug was rotated 90° and the measurements were repeated. Three length measurements were made, one on the central axis and two at opposite points on the circumference. The density measurements, using the Archimedes method, were carried out on a direct-weighing balance, adapted for remote operation.

An experimental setup was in use to read gamma-ray intensity for determining relative burnup from each of the individual slugs from the fuel rod. The slug was centered in the hot cell, in front of a 1/8-in. diameter hole running through the shielded wall. A scintillation detector was located at the other end of the hole, and operated a gamma spectrometer, set to record only gamma-ray energies in excess of 700 kev. This provided only relative information, however, and thus a radiochemical burnup determination is necessary to convert the data from gamma scanning to absolute burnup figures. The radiochemical analysis work is now underway.

Sections from the representative slugs were taken for hot metallographic examinations. These were examined for structure, gas voids, and any apparent damage or abnormality.

The stainless steel cladding was visually examined and subjected to bend tests, in order to qualitatively determine if carburization had taken place or if the cladding physical properties had in any way been impaired by the extended high temperature exposure.

nd

III. RESULTS

The results are presented in two parts. Part A presents the cumulative results from four destructive examinations and their reflection on the SRE fuel element performance. Part B presents specific results of the fourth destructive examination. This is the most recent and the highest burnup destructive examination, and therefore merits individual attention.

A. CUMULATIVE RESULTS OF FOUR DESTRUCTIVE EXAMINATIONS

Figures 9, 10, and 11 show the change in warp, length, and diameter of the fuel slugs with respect to maximum burnup. Table II indicates the results of all four examinations. These results are summarized by averaging the results from the four slugs in the top, middle, and bottom fuel rod sections, and tabulating these values. Since density changes were not measured during the first three examinations, calculated volume changes are included for all tests. An extra column is provided in Table II for the volume change obtained by density measurements for the 850 Mwd/Tonne maximum examination.

The following is a brief summary of the results shown in Figures 9, 10, and 11:

1) Warp

   There was a sharp rise in the warp with increasing fuel rod burnup, to a level of 105 Mwd/Tonne, at which point a leveling occurred.

2) Length

   The general tendency was toward an increase in length with increasing burnup of the rod.

3) Diameter

   There was a general trend toward increasing diameters with increasing burnup of the rod.

4) Surface

   The surface roughness appeared to increase at the center and the bottom, as a direct function of burnup. The top slugs, where the surface temperature was maximum, tended to remain relatively smooth.

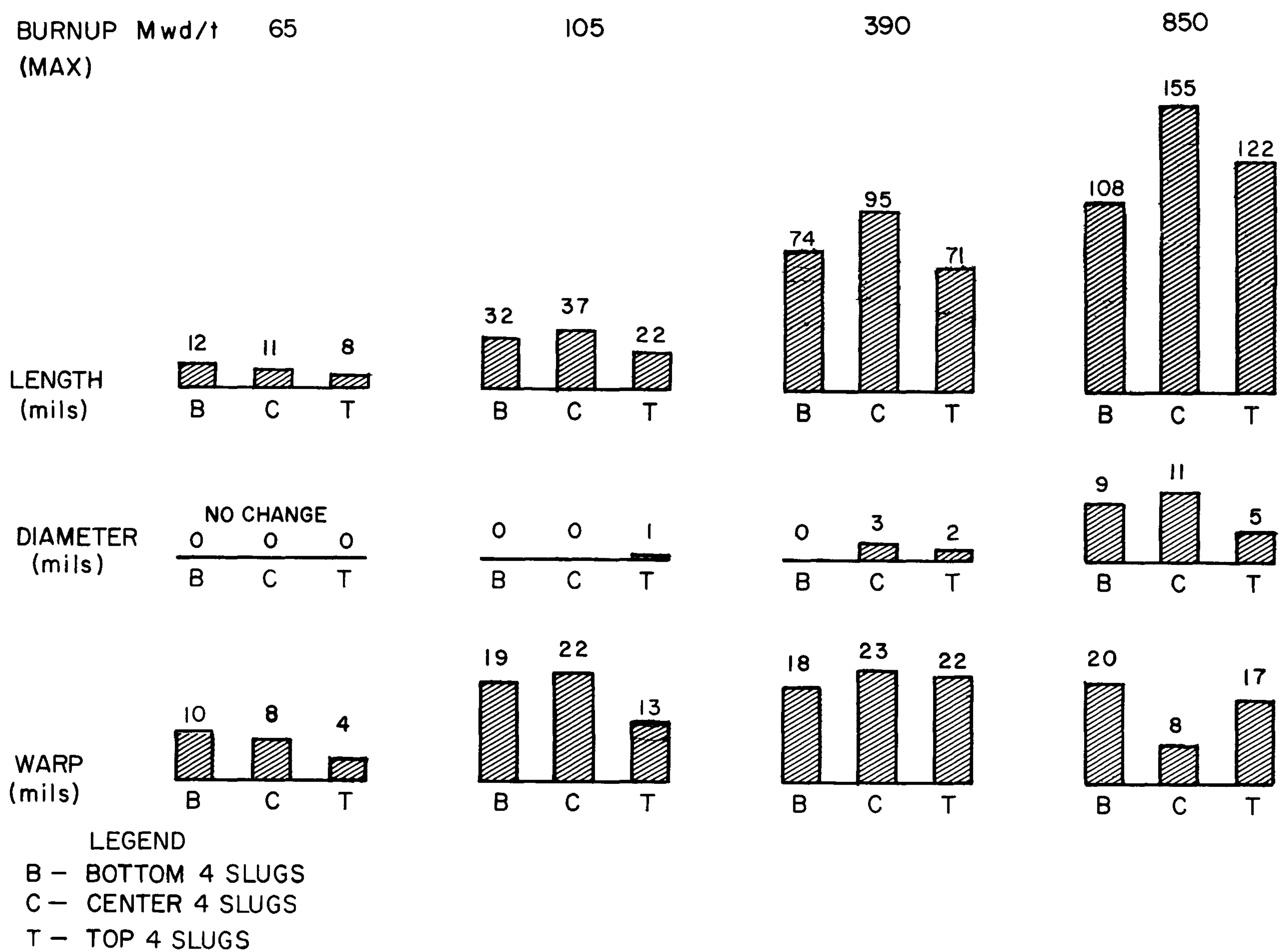


Figure 9. Average Changes in Length, Diameter, and Warp vs Burnup for Standard Unalloyed Uranium Fuel From SRE

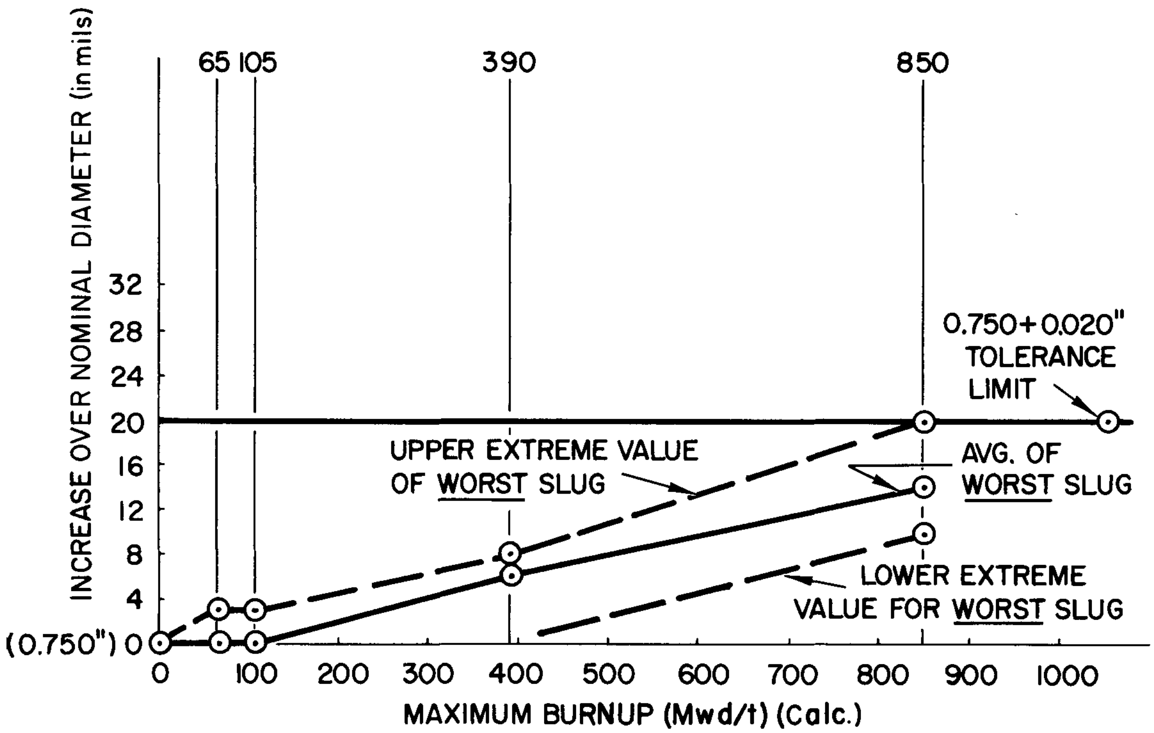


Figure 10. Diameter Increase vs Burnup of Unalloyed Uranium

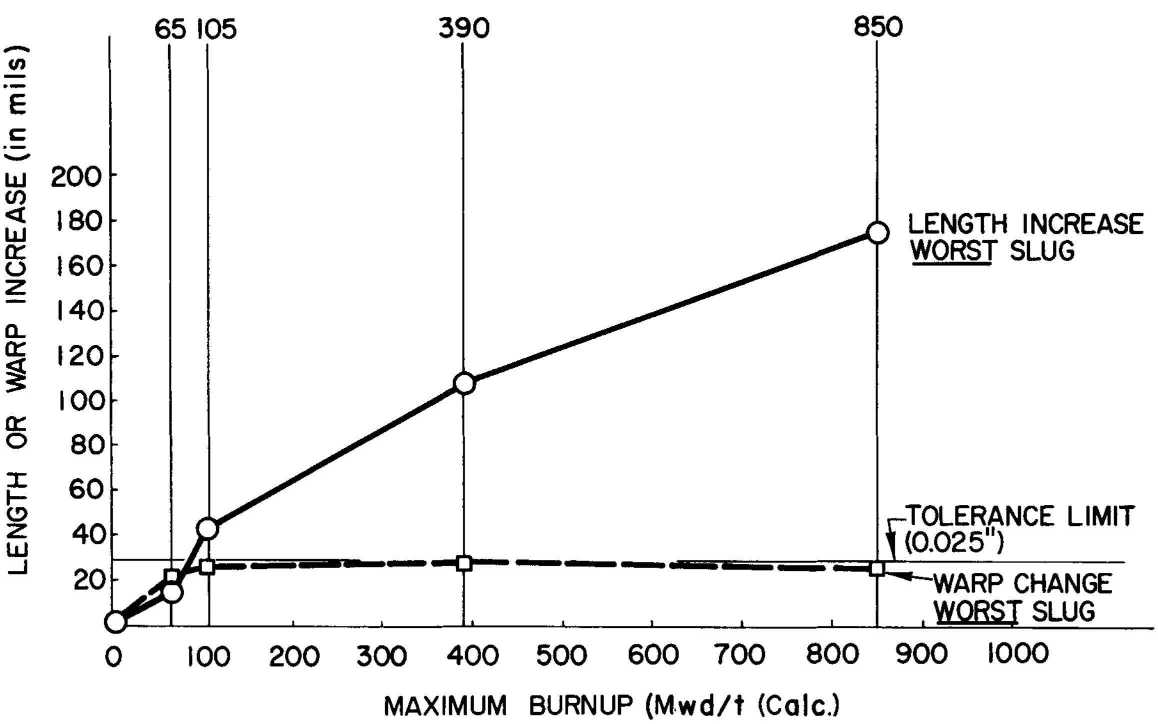


Figure 11. Length and Warp Increase vs Burnup of Unalloyed Uranium

TABLE II

SRE CUMULATIVE IRRADIATION RESULTS

Calc. Burnup			Change in Length (ΔL) (mils)			Change in Diameter (ΔD) (mils)			Change in Volume (ΔV) (Calc.) (%)			Actual Warp (mils)		
Max.	Average		B	C	T	B	C	T	B	C	T	B	C	T
65	50	max./slug	17	12	9	0	-2	0	0.3	0.2	0.1	18	20	10
		average	12	11	8	0	0	0	0.2	0.2	0.0	10	8	4
105	80	max./slug	38	42	29	1	1	2	0.8	0.9	0.9	24	26	25
		average	32	37	22	0	0	1	0.6	0.6	0.5	19	22	13
390	300	max./slug	89	108	86	1	5	4	1.7	3.2	2.4	22	26	27
		average	74	95	71	0	3	2	1.3	2.5	1.8	18	23	22
850	650	max./slug	151	175	161	11	13	9	5.5	6.1	5.1	24	17	21
		average	108	155	122	9	11	5	4.1	5.6	3.4	20	8	17
		max./slug*							1.1	2.6	2.4			
		average*							0.5	2.3	1.8			

B = bottom 4 slugs
C = center 4 slugs
T = top 4 slugs
* Volume change based on actual density measurements at 850 Mwd/Tonne max.

Figure 12. Typical Views of Fuel Element R-33 After 390 Mwd/Tonne Burnup Showing Black Residue Adhering to the Cladding After Washing

B. EXAMINATION OF AN UNALLOYED URANIUM ROD

The following results were from an unalloyed uranium rod that was part of a mixed alloy fuel element, examined after 850 Mwd/Tonne maximum burnup.

1. Nondestructive Examination

The straightness and outside diameter measurements of the cladding tube indicated the element to be within inspection tolerance. The visual examination showed no abnormalities in the cladding surface. There was, however, a thin black surface coating visible on the washed element, thought to be nickel oxide (see Figure 12 for photograph of similar element). This coating was more noticeable in the higher burnup areas of the rod. The same coating has been noted previously, on rods with both long and short irradiation exposure times.

2. Destructive Examination

Table III shows the actual data from the destructive examinations of the unalloyed uranium rod No. 204 at 850 Mwd/Tonne maximum burnup. Figure 13

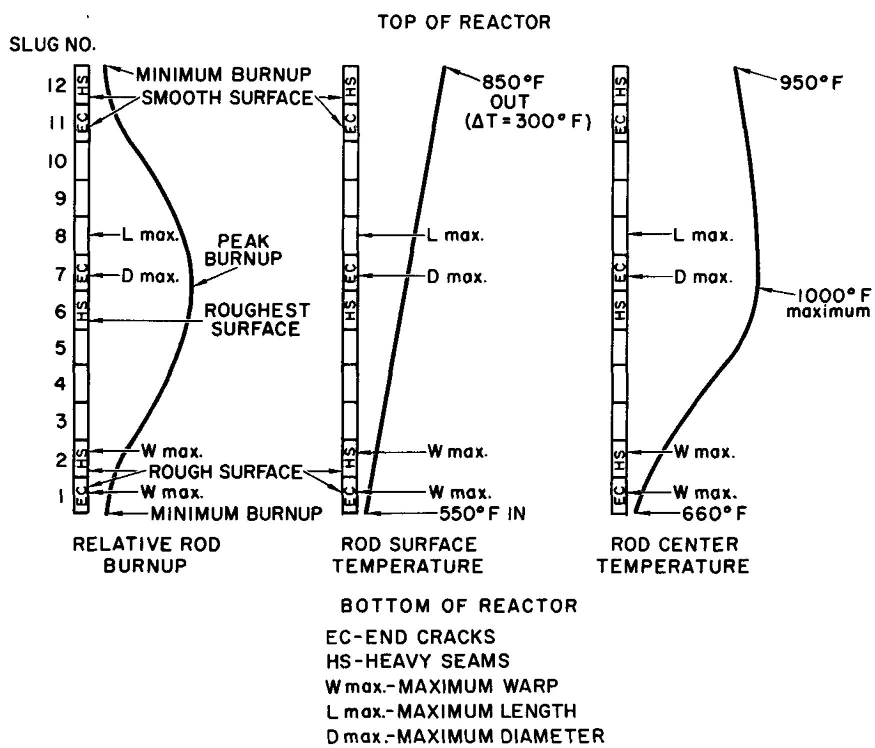


Figure 13. Location of Extreme Dimensional Change Values in an Unalloyed Uranium Fuel Rod From MC-1-1

TABLE III

DENSITY AND DIMENSIONAL DATA FOR UNALLOYED URANIUM FUEL ROD

Slug Position	Slug No.	Warp (in.)	Length (in.)	Diameter (in.)	Density (gm/cm^3)	Change (%) Diameter (ΔD)	Change (%) Length (ΔL)	Change (%) Density ($\Delta \rho$)
Nominal		0.003 max. single throw	6.000 ±0.010	0.750 ±0.002	19.00 ± 0.05			
1	7932-4	0.026	6.035	0.759	18.99	1.2	0.6	-0.1
2	7733-5	0.026	6.120	0.757	18.96	0.9	2.0	-0.2
3	8933-3	0.021	6.124	0.759	18.91	1.2	2.1	-0.5
4	8933-4	0.012	6.151	0.761	18.79	1.5	2.5	-1.1
5	8933-5	0.020	6.172	0.761	18.65	1.5	2.9	-1.8
6	7723-1	0.002	6.172	0.762	18.57	1.6	2.9	-2.2
7	7931-18	0.012	6.105	0.763	18.50	1.7	1.8	-2.6
8	8933-6	0.010	6.175	0.757	18.53	0.9	2.9	-2.5
9	8933-7	0.018	6.161	0.759	18.54	1.2	2.7	-2.4
10	8933-8	0.022	6.139	0.753	18.61	0.4	2.3	-2.1
11	9331-17	0.022	6.112	0.752	18.75	0.3	1.9	-1.3
12	7923-1	0.017	6.075	0.756	18.73	0.8	1.3	-1.4
Average		0.017	6.128	0.758	18.71	1.1	2.2	-1.5
Maximum		0.026	6.175	0.763	18.99	1.7	2.9	-2.6
Minimum		0.002	6.035	0.752	18.50	0.3	0.6	-0.1

Fuel Element MC-1-1
Rod No. 204
Channel R-44
Unalloyed Uranium, α-Rolled, β-Heat Treated
Burnup – Average, 650 Mwd/t; Maximum, 850 Mwd/t

summarizes the data by indicating the location of the points of extreme dimensional change with respect to relative burnup, central, and surface temperature. These results mention defects which were present in the fuel slugs, as shown by Figure 13. The fuel slug defects were heavy seams and end cracks that were intentionally placed in the rod to determine their effect on the performance of the slugs. Below is a brief summary of results:

a. Warp

1) Maximum warp (W max.) was found in slugs at both the bottom and top of the rod (see Figure 13).

2) There was no apparent correlation between the original defects (heavy seams (HS) and end cracks (EC)) and the warp.

b. Length

1) Generally, the Δ L increased toward the center slugs. The range of length increases was from 0.030 to 0.175 in. in 6 in. (see Table III).

2) The maximum length (L max.) was found near the center of the rod, indicating an increase of 0.175 in. or a ΔL of 2.9% maximum. The average Δ L was 2%.

3) Both ends of all slugs exhibited some concavity. The center slug was measured as having 0.020 in. concavity on each end.

4) There was no apparent correlation between original defects and length increases.

c. Diameter

1) The ΔD increased toward the middle of the rod (see Table III) (maximum diameter - D max.).

2) Except for the top slug, there was no correlation between original defects and the change in diameter. The top slug contained a heavy seam defect which opened up 10 to 20 mils and affected the diameter measurement.

d. Volume Change

Volume change (ΔV), calculated from dimensional measurements at the points of maximum diameter and the corresponding length, was less than 8%. The average calculated change in volume was 4.2%. The volume change calculated from the measurement of density indicated a maximum of 2.6% and an average of 1.5%.

e. Surface

The surfaces of the slugs were characterized by a gradation of "orange peel" or "sandblasted" condition of roughening. The roughest slugs were found in the center of the rod. There were no pronounced bumps or other extreme abnormalities noted in the slugs, except at the top slug containing a heavy seam.

f. General

1) Even though some extreme values of diameter change were found, no external evidence was visible or measurable that indicated damage to the stainless steel cladding.

2) The typical fabrication defects placed in six of the slugs did not appear to affect the demensional measurements, except in the case of the top slug containing a heavy seam.

IV. DISCUSSION OF RESULTS

This discussion is basically concerned with SRE fuel experience on standard unalloyed uranium, as used in the first core. The first three destructive examinations were of rods from standard fuel clusters. The fourth examination, however, was made on a rod from an experimental element, MC-1-1. Since the MC-1-1 rod was fabricated from the same fuel as the first core and had the same reactor history, this rod was assumed to be fully representative of the SRE reactor core elements at this burnup. There were, however, six defected slugs included in this rod. These slugs were part of an overall program of evaluating the performance of slugs thought to be of lower quality than specified originally at the time of fuel procurement. Reference to Figure 13 will show their location, and further reference in the text will indicate their importance.

A. NONDESTRUCTIVE EXAMINATION

The nondestructive examinations of these four elements took place in the SRE hot cell, as described in the procedure. No external indication of dimensional change, or of any structural deformity or surface defect on the tubes, was found. Subsequent nondestructive examinations, at 950 Mwd/Tonne and 1010 Mwd/Tonne maximum burnup, have shown an increase in cladding diameter of 2 to 3 mils, presumably from fuel swelling or growth. Figure 14 shows the location of the diameter change. Destructive examination of a rod with this cladding increase is under way to verify the cause of the change.

1. Warp

The warp measurement tended to increase during the first two irradiation periods. It then appeared to level off, and perhaps even decrease, in the fourth examination. As the fuel burnup increased, the slug diameter increased, particularly in the area of maximum burnup (middle section of the element). It is possible that diameter increases of the fuel slug, and the corresponding cladding restraint, has caused the warp to decrease, because there is no space left in the cladding. This would explain the apparent decrease in the warp, during the higher burnup examinations, at the points of maximum burnup. The warping tendency still appears to be present in the lower burnup areas. Since warp is thought to be a function of stress, introduced during fabrication and with resulting preferred orientation,

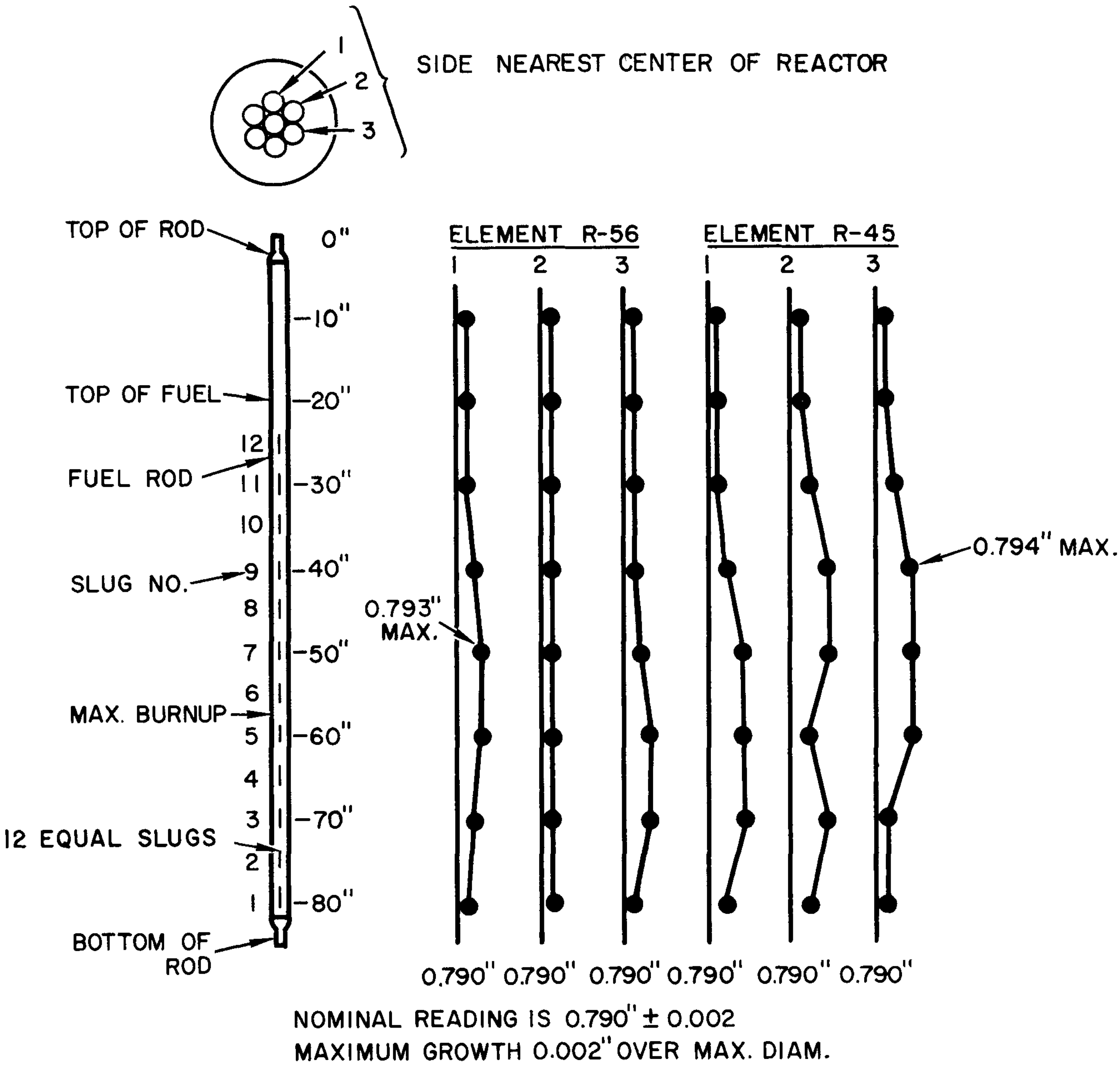


Figure 14. External Snap Gauge Readings on Unalloyed Uranium Fuel Elements

it is also possible that extended exposure to high temperature could anneal this effect, especially in the center of the rod.

2. Length

In general, the extreme values of length increases found in examination No. 4 were as would have been predicted from previous examination results. It appears that the length increased in direct proportion to burnup, with no effect of temperature evident. At the 650 Mwd/Tonne average (850 max.) the growth rate equaled 32% Δ L/total at. % burnup, as predicted by Kittle et al at ANL.[2,3]

The length measurements were influenced to some degree by the presence of slug concavity. This condition is illustrated by Figure 15. The maximum burnup slugs showed 0.020 in. concavity on each end, or a total of 0.040 in. The condition was pronounced enough to be plainly visible to the unaided eye during visual examination. The photograph illustrating this is from the third examination, 390 Mwd/Tonne maximum, and the condition appears to be even more apparent in the 850 Mwd/Tonne maximum burnup examination. The stamped identification numbers were still very legible, despite the dishing or concavity.

3. Diameter

The diameter in examination No. 4 ranged from 0.748 in., near the end of the rod, to 0.770 in., in the center of the rod. This extreme diameter measurement represents one of two high points. Diameter measurements taken adjacent to these points indicated values of 0.005 in. less than the extremes. Thus, the extreme measurements appear to be high point areas, rather than a general condition. This condition was clearly indicated by using the extreme values in calculating volume change. This was about 8%. With actual density measurements, the maximum volume change was 2.6%, and the overall average was 1.5%.

4. Density

The volume change was determined by density measurements for the fourth examination (850 Mwd/Tonne). Previous to this time, density determination apparatus was not available at the SRE hot cell. For the first three examinations, the relationship that twice the diameter change plus the length change approximates the volume change was used. The density change is almost an

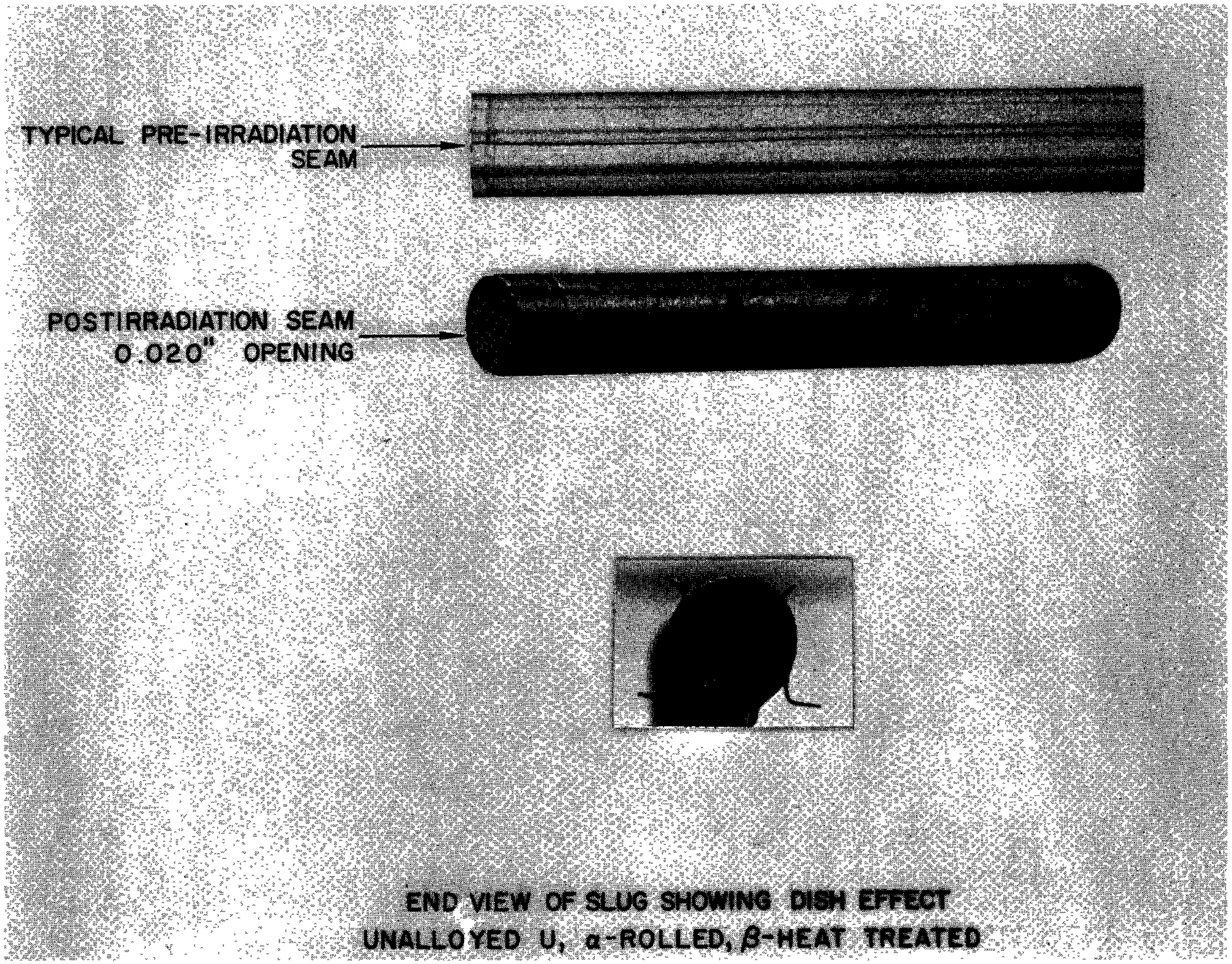


Figure 15. Typical Slug Defects and Slug Concavity

inverse relation to the change in volume in the low range of values. Thus, the magnitudes of Δ V and $\Delta \rho$ (in %) approximate one another closely.

Density changes were greatest for fuel slugs having the highest temperatures and burnup.

5. Surface

Examination No. 4 indicated the progressive nature of the surface roughness change. It showed that the surface at the highest burnup and at the maximum slug central temperature was the roughest. The four slugs located at the top of the rod were characterized by a relatively smoother surface, as seen in Figure 16, the composite photograph. This photograph represents the center

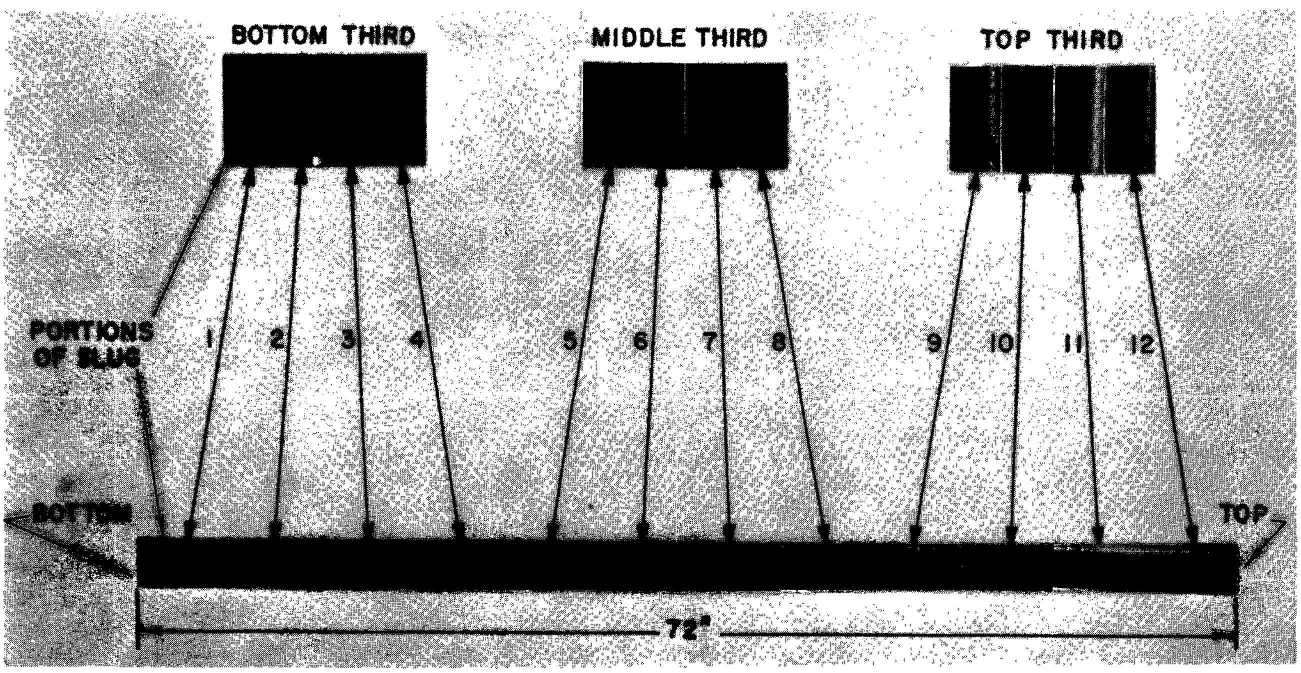


Figure 16. Composite Photograph of Unalloyed Uranium Rod From MC-1-1

1 in. of each of the fuel slugs in the rod of unalloyed uranium (850 Mwd/Tonne maximum burnup). While the composite is artificial, in that 12 in. or less represents 6 ft of fuel, it is nevertheless a true indication of the variation of surface roughness from top to bottom of the rod. The three groups of four slugs each were selected because they showed similarities in results and appeared to be logical groupings.

The surface roughness affected the diameter measurement to a marked degree. Reference to Figure 16 again indicates this variation of surface roughness that exists from top to bottom. Therefore, when placing slugs in the measurement jig, the dial indicator actuating plunger may contact only the high surface peaks or wrinkles. The average diameter for each slug is a result of ten measurements, taken at equal length increments and averaged. The averages of the measured values are indicated in Table III.

The recognition of the slug surface roughness condition and its effect on the measurement has emphasized the need for a means of better assessing the overall surface roughness. Several methods have been suggested, such as profilometers or comparative surface gauges. The latter method probably represents a practical way to make a comparison in a hot cell. This takes two steps toward defining surface variation: (a) the qualitative measurement of surface differences, and (b) the reduction of the subjectivity in assessing this characteristic. Future work will make an effort to place a qualitative number on each surface.

6. Defect Slugs From Examination No. 4

As was indicated, the unalloyed uranium rod in examination No. 4 contained six defect slugs. These slugs were located at the top, middle, and bottom of the rod. They represented two typical types of fabrication defects, heavy seam and end cracking, of the type encountered in fabrication. Figure 15 shows the postirradiation results from a heavy seam defect. The seam opening was 0.020 in. This results in a diameter increase of 0.006 in. The other five defect slugs examined indicated no growth or effect due to the defect that could be dimensionally measured. The defect slug with the heavy seam that opened up appeared to be nontypical, in that it was actually deeper than had been anticipated when selected for irradiation.

7. Cladding

The decanning operation cuts sections of the stainless steel cladding from the fuel rod like a pipe cutter. Several of these sections were carefully examined under low-power magnification. The examination showed no cladding defects or discontinuities. In addition, sections of the tube were flattened in an air-operated vice, and examined for cracking. There was no evidence of cracking or any malfunction. The conclusion drawn was that the cladding showed no carburization and that it still retained its ductility.

8. Burnup Analysis

The burnup information for these examinations has been arrived at by calculation, using reactor operations data. In order to verify the maximum burnup values, slugs have been sent to an outside contractor for analysis. Preliminary analytical results indicated good agreement with the calculated results. The current practice of gamma scanning appears to be a very effective means of determining relative burnup. As the final analytical results are received, verification of the gamma scan results will be possible.

9. Metallographic Examination

The preliminary metallographic examination of the unalloyed uranium in test No. 4 indicated that there were no gross voids, defects, or changes in microstructure. The observation indicated, in addition, the following:

a) The cross section of the unalloyed uranium had a very rough surface.

b) Many twins and some subgrains were evident in this unalloyed uranium.

10. Fission Gas Analysis

The measurement of fission-product gases was not made in this series of examinations because the required equipment was not yet available. This determination is to be included as part of the program, and will be carried out in the future examinations.

11. NaK Sampling

Samples of the reacted NaK bonding material were taken from the fuel rod, and analysis indicated the presence of fission products. This quantity appears very much as predicted from previous examinations.

12. General Observations

From the information resulting from the first four destructive examinations, it appears possible to predict the lifetime of the SRE Core I. Figure 10, a plot of the diameter increases vs burnup, can be extrapolated to higher burnups. By extrapolating the extreme diameter of the worst slug linearly, an estimate of 1200 Mwd/Tonne maximum has been made. This estimate assumes that an 8 to 10 mil stainless steel cladding diameter increase is permissible. Examinations of the cladding have indicated satisfactory ductility, and therefore a diameter increase of 8 to 10 mils over nominal appears to be safe. This diameter change allows a margin of safety for additional dimensional change without rupture if an emergency condition should arise. It will be several months before verification of this prediction will be possible.

The present temperature conditions of the SRE do not appear to cause accelerated radiation damage. The indication of swelling thus far encountered has been weighted on the high side, because volume increases have been calculated from dimensional measurements. The actual density measurements have shown lower overall volume increases, because the effects of localized surface expansion and roughness have been averaged out.

Another more general observation resulting from these examinations is the satisfactory performance of the fuel element design. The hardware itself has functioned very well. Minor modifications have been suggested for the second core, but the basic fuel element configuration appears to be acceptable. There are several areas where additional experimental work might be undertaken, such as determining whether the wire wrap is really necessary. Elimination of this would probably make the fuel element fabrication procedure easier and reduce the amount of stainless steel in the core. Also, the provision of variable or adjustable fuel element orifice plates might allow improved temperature control on individual elements.

The performance of the fuel cladding has appeared to be satisfactory. The limitations in the fuel element have thus far been associated with the fuel dimensional changes (diameter) rather than the cladding. The temperatures of operation have not yet reached a point where the cladding material problems have been a limiting factor.

V. CONCLUSIONS

A. OBSERVATIONS ON THE FUEL ELEMENT AS A WHOLE

1) The SRE fuel elements appear to be operating satisfactorily, as far as structural features are concerned. The limiting factor at this time appears to be the behavior of the fuel material.

2) Slug dimensional increases and density decreases are filling the 0.010-in. NaK-bond annulus, and could ultimately rupture or cause the element to stick in the fuel channel.

B. OBSERVATIONS WITH RESPECT TO THE FUEL MATERIAL

1) The fuel has undergone dimensional changes (length and diameter), and has decreased in density. These changes are a maximum at the point of highest burnup. These changes have not as yet endangered the element at 850 Mwd/Tonne max. burnup.

2) The presence of the fuel slug fabrication defects (heavy seams and end cracking) did not appear to impair fuel slug performance under irradiation.

VI. FUTURE WORK

As is obvious, this can only be an interim report of the experience to date. The proposed future program calls for the following additional steps:

a) The continuing nondestructive and destructive examinations, as required, until termination of the operation of the first core;

b) The destructive evaluation of elements of the first core, based on a statistical sampling;

c) The nondestructive and destructive examination of the thorium 7.6 wt % uranium fuel selected for the SRE second core loading;

d) The continuing irradiation and evaluation of a variety of promising fuel materials;

e) The introduction of fuel elements with increased NaK bond annulus, to compensate for fuel diameter increase and volume change.

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