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TECHNICAL DATA RECORD		PAGE 1 OF 72			
AUTHOR <i>W.R.M.</i> W. R. McCurnin (5)		DEPT. & GROUP NO. 733-33		DATE 11-4-63	
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J.L. Ballif *				AUTHORIZED CLASSIFIER SIGNATURE _____ DATE _____	
G.D. Calkins *		STATEMENT OF PROBLEM			
E.M. Chandler *		Evaluate the performance of two OMRE fourth core prototype fuel elements.			
J.R. Churchill *		ABSTRACT:			
A.C. Crawford *		Two full-scale prototype fuel elements of the OMRE fourth core design, OMRE 6-1 and 6-2, were fabricated and irradiated in the OMRE third core to test the fourth core design prior to the core loading. Thermo- couples indicated a rise in surface temperature on both test elements after 180 mwd of reactor operation. When the fuel element surface temperature on 6-1 reached the maximum allowable (760°F) the power level of the reactor was decreased to maintain 760°F. The power level was gradually decreased from 5.4 to 4.5 Mw. The test elements were then removed from the core and shipped to CDHC for postirradiation examination.			
R.M. Crawford *		The postirradiation examination revealed massive deposits of carbon- aceous material beneath four stainless steel bands used to hold the fuel plates together during assembly. The deposits had completely filled the space between the fuel plates and the box at the center two band locations and caused a distortion in the fuel element box at these locations. These deposits had caused a decrease in flow in the outer channels which had been indicated by the rise in surface temperature. The fuel plates and deposits were subjected to chloroform washing experiments which were not successful in removing or dissolving the hard deposits on the fuel plate surfaces.			
R.E. Forrester *		The fuel plates were examined to determine the fuel growth on both elements, the peak burnup of 6-1, and the integrity of nickel diffusion barrier bond of 6-1. The change in length of the clad fuel plate at the peak burnup location of 2300 Mwd/MTU in 6-1 was 0.49%. The change in length of the other clad fuel plates from 6-1 varied from 0.17 to 0.51%. The change in length of the clad fuel plates from 6-2 varied from 0.09 to 0.37%. The integrity of the nickel diffusion barrier bond was good with an average consumption of 0.66 mils at the 760°F location. The element was at operating temperature for 1500 hours and the predicted nickel consumption at this temperature would be 0.7 mils.			
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III. INTRODUCTION

A. Background (Objective - Purpose)

The design of the fourth core fuel elements for the OMRE utilizes Uranium-Molybdenum alloy plate clad with extended surface aluminum. Previous tests of alloy fuel elements at the OMRE¹⁰ utilized developmental fabrication techniques, one-third length fuel assemblies (except HT-1), and insufficient temperature monitoring. None of the test elements had achieved the design burnup requirements. The testing program had not yielded sufficient results to accurately predict the performance of a core loading of this design; therefore, it was decided to fabricate two full-scale prototype fuel elements and irradiate them in the third core. The purpose was to finalize fabrication procedures, determine inspection requirements, and to evaluate the irradiation performance of this design.

B. Design and Fabrication of Fuel Elements

1. Design Requirements and Limitations

The prototype fuel elements OMRE 6-1 and 6-2 were designed to operate in the OMRE third core at the maximum fourth core operating conditions. Due to the OMRE third core operating conditions, the fourth core prototype design temperatures and velocity were comprised. Table I presents the maximum fourth core operating conditions and the predicted prototype operating conditions in the third core.

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TABLE I

DESIGN OPERATING CONDITIONS FOR OMRE FOURTH CORE AND
PREDICTED PROTOTYPE PERFORMANCE IN OMRE THIRD CORE

	Fourth Core Fuel Element Hot Spot CP 13	(3) Third Core with 0% HB, 750°F OMRE Element Hot Spot Temp CP 13 6-1 CP18 6-2	
Max Surf Temp	750°F	737	722
Coolant Inlet Temp	600°F	600	600
Coolant Outlet Temp (Core Avg)	616°F	611	611
Coolant Outlet Temp (Max)	635°F	639	635
Coolant Velocity ft/sec	18	10.8	10.8
Avg Heat Flux BTU/hr-ft ²	23,800		
Peak Heat Flux BTU/hr-ft ²	96,000		
Peak Burnup MWD/MTU	11,500	6000*	10,000*
Fuel Enrichment % U-235	6	6	6

*Design Target Burnups

2. Mechanical Design

a. Fuel Element

Six extended surface, aluminum clad fuel plates were contained inside a square stainless steel box having outside dimensions consistent with standard OMRE fuel elements. Each of the six fuel plates were made up of three identical sections mechanically attached end to end. Figure 1 is a layout of the prototype fuel elements. Figure 2 presents a view of the major parts for 6-1 prior to final assembly. The six fuel plates were bound together with stainless steel bands 0.005 inches thick by 3/8 inches wide. The steel bands were used to hold the fuel plates together during assembly into the fuel element box. As can be seen in Figures 1 and 2, the edge runners of the plates were dimpled to maintain the plates centered in the box. This was done to prevent the fuel plates from nesting when adjacent plates become offset by more than the width of the side runners. Also, the dimples eliminate near stagnant coolant passages at the edges of the plates during the initial operating period in the reactor. Each fuel plate was supported at the bottom by a stainless steel hinge type locking beam and connected to the fuel plate end plugs with a stainless steel pin. The same hinge arrangement was plug welded to the box through pre-machined holes in the box. The leading edges of the six locking beams were tapered to reduce coolant turbulence. Figure 3

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FIGURE 1

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FIGURE NO. 2

MAJOR COMPONENTS OF OMRE 6-1 AND 6-2

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shows the locking beams on 6-1. The fuel element box, a standard third core fuel box made of 0.050 inch thick type 347 stainless steel, was formed from a single sheet and butt welded the full length of one side. Standard third core end hardware was used for the prototypes.

b. Fuel Plate

The U-3.5% Mo-0.5% Si alloy* was used as fuel in 6-1 and the U-3.5 Mo-0.1 Al alloy* was used as fuel in 6-2. The selection of these alloys as fuel for the prototypes was based on the results of an alloy development program carried out to provide a material with high creep strength and good thermal cycling stability under OMRE operating conditions. (4, 5)

The fuel was in the form of thin (0.102 inch) plates contained in finned (extended surface) type 1100 aluminum cladding extrusions. The fuel alloy was electrolytically plated with a layer of nickel (0.001 inch minimum) to prevent diffusion of uranium and fission products into the aluminum cladding where they might have contact with the coolant. The details of the cladding and fuel plates are presented in Figure 1.

* All alloy % used in this report are weight %.

3. Instrumentation

OMRE 6-1 had six 0.020 inch diameter stainless steel sheathed thermocouples imbedded in the aluminum fins at various locations. There was one coolant inlet thermocouple, one channel coolant thermocouple twelve inches from the top of the fuel plate, five channel exit thermocouples 1/4 inch from the top of the fuel plates, and two mixed coolant outlet thermocouples.

OMRE 6-2 had four 0.020 inch diameter sheathed thermocouples imbedded in the aluminum fins at various locations. There was one coolant inlet thermocouple, two channel outlet thermocouples and two mixed coolant outlet thermocouples.

Figure 1 shows the axial and channel location of the thermocouple hot junctions for both 6-1 and 6-2. Figure 4 is a photograph of the outlet end of the fuel bundle of 6-1 showing the thermocouple channel locations. The inlet thermocouple on 6-1 can be seen in Figure 3.

4. Fabrication

a. Fuel Plate

The details of the fuel plate components are shown in Figure 1. Reference 6 is a description of all of the fabrication and assembly procedures used to make 6-1 and 6-2.

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FIGURE NO. 3

INLET END OF FUEL BUNDLE
FROM OMRE FUEL ELEMENT 6-1

INLET T/C

FIGURE NO. 4

OUTLET END OF FUEL BUNDLE
FROM OMRE FUEL ELEMENT 6-2

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The uranium alloy cores for the fuel plates were vacuum induction melted and cast into graphite molds. The U-3.5 Mo-0.5 Si alloy used in 6-1 was cast into five plate molds and the U-3.5 Mo-0.1 Al alloy used in 6-2 was cast into both five and fifteen plate molds. All plates were cast to the nominal as-cast thickness, 0.102 inch, and machined to the length and width dimensions shown in Figure 1.

The aluminum cladding was a flat, extended surface, extruded tube of type 1100 F aluminum fabricated by Pacific Extrusions. The cladding was cut to length and the end plugs of type 6061 aluminum were machined to the dimensions in Figure 1. The cleaning and preparation of aluminum components is described in Reference 6.

The uranium alloy plates were electroplated with 0.001 to 0.002 inch of nickel. The relative thickness of nickel deposited was measured using an eddy current device (Dermatron Thickness Indicator).

The nickel coated fuel plate, end plugs and evacuation tube were slipped into the cladding and the end plugs heliarc welded to the cladding. After evacuating to 50 microns or less, the assembly was outgassed at 900°F

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for four hours. After outgassing, the evacuation tube was sealed by hot knifing. The outgassed and sealed assemblies were bonded by hot isostatic pressing. For development and evaluation of hot isostatic pressing refer to References 7 and 8. The plates for 6-1 were bonded by applying 6,500 to 7,800 psi argon at 1000°F for twenty to forty minutes. The plates for 6-2 were bonded by applying 7,000 to 8,500 psi argon at 1000°F for thirty-five minutes. After bonding, the fuel plates were machined to length and inspected. After visual and dimensional inspection, the fuel plates were subjected to a 250°F, 15 psi water autoclave test for twenty-four hours to determine if any pinhole leaks existed between the end plug and the fuel. The plates then were final machined and submitted for fuel element assembly.

b. Fuel Element Assembly

The assembly of the fuel elements is described in general in Reference 6. The major deviation from the description in Reference 6 and the assembly of the prototypes was the use of 0.005 inch thick stainless steel bands to hold the fuel bundle together. The following list contains the major steps in the fuel element assembly.

- a) Machine grooves in the fins for surface coolant inlet and the lower channel coolant thermocouples.
- b) Assemble plates in three plate subassemblies.
- c) Install thermocouples.
- d) Assemble fuel bundle.
- e) Using components shown in Figure 2, weld fuel bundle locking beams to the fuel box, weld lower end plug and the head extension to the fuel box.

5. Pre-irradiation Inspection and Measurements

In order to perform a comprehensive evaluation of the prototype performances, an extensive program was initiated to obtain all useful pre-irradiation data. Detailed records were maintained by the fabrication group concerning all phases of prototype fabrication. In addition to the fabrication records, the evaluation group required detailed dimensional, metallurgical, chemical, visual, and photographic data be taken and organized in a package useful for the post-irradiation examination and evaluation. An outline of the information which was gathered by the fabrication and evaluation groups and organized in the package, is presented below. The data which was used for the post-irradiation evaluation will be cited in that section of this report.

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- a. The following analysis, observations, and measurements were performed on the bare fuel plates:
- i. Chemical analysis of the uranium derby, the molybdenum pellets, the silicon and aluminum charge stock used in prototype fuel plate casting.
 - ii. Melting conditions including charge material, charge weights, melt cycle times, and melt temperatures including observations during heat preparations, melting and cooling periods.
 - iii. As-cast fuel plate thickness measurements (average thickness for six areas of fuel plate).
 - iv. Record of visual observations of as-cast fuel plates surfaces and photographs of machined fuel plates.
 - v. Radiographs of all fuel plates.
 - vi. Chemical analysis of two plates from each heat. Samples were taken from the top and bottom of each plate sampled. The samples were analyzed for molybdenum content, carbon content, uranium enrichment and silicon or aluminum content.
 - vii. Metallographic examination of one plate per heat (top and bottom samples from the casting).
 - viii. Machined fuel plate dimensions, if out of tolerance.

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- ix. Fuel plate density and weight. All 6-1 plates and three 6-2 plates were measured for full plate density.
- b. The following measurements, observations, or tests were made on the clad fuel plates:
 - i. The nickel plating thickness (average thickness for 8-15 areas of the fuel plate) and the weight of nickel deposited was determined and recorded. The nickel plating conditions were recorded.
 - ii. Hot pressure bonding parameters and evaluation.
 - iii. Water autoclave tests to determine if pinhole leaks existed between the end plug and fuel plates after pressure bonding.
 - iv. Clad plate dimensions were measured as follows:
 - 1) Width every inch
 - 2) Thickness every inch in three channels
 - 3) Length at seven locations
 - 4) Warpage every inch in center of plate
 - v. Record of visual inspection and photographs of the fuel plates.

Fuel plate orientation was carried throughout fabrication as follows; as the plates were removed from the casting mold the heat number, plate number, and top of casting were inscribed on the plate using a small electric vibrator. The plates were notched in the upper right hand corner prior to nickel plating. The evacuation

tube was placed over the notch during hot pressing. The plate and heat number were stamped in the side runner of the cladding next to the evacuation tube prior to machining of bonded plates.

C. Irradiation History

(9, 10)

1. Description of OMRE

The OMRE was designed to operate with terphenyl moderator-coolant over a range of power levels up to 12 MWT. The primary reactor fuel element (driver) for the first three cores consisted of a highly enriched plate type fuel element of UO_2 stainless steel cermet fuel cores clad with stainless steel. The OMRE operates with coolant upflow through the nuclear core. The average thermal neutron flux is 2×10^{13} nvt.

Radiation and high temperatures cause decomposition of the terphenyl moderator coolant. This damage results in the formation of multi-ring, high boiling organic compounds and also gases, mainly hydrogen, methane, ethane, and smaller amounts of other light hydrocarbons. The high boiling compounds are detrimental to the heat transfer properties of the coolant and are removed by a continuous purification system and fresh makeup added to the system as required.

2. Description of OMRE Third Core

Reference 11 is a description of the OMRE third core and gives the details of the core nuclear, thermal, and hydraulic parameters. This reference also lists the results of zero and low power tests of the initial loading of the third core. The primary objectives ⁽¹²⁾ of the operation of the third OMRE core were:

- a. To demonstrate the successful solution of the fuel element fouling problem observed on the second core driver elements.
- b. To irradiate a full scale prototype fuel element to generate data required for the development of fuel elements capable of operating at advanced organic reactor conditions.

The third core configuration is shown in Figure 5. The initial loading of the third core consisted of twenty-seven cermet fuel elements identical with first and second core elements ⁽⁹⁾, five dummy elements, a neutron source, one APM-UO₂ test element, one cermet type experimental element (Peak Temperature Experiment) and two fourth core prototypes (OMRE 6-1 and 6-2). The reactivity of the core, and of each of the test elements was determined from low power tests ⁽¹¹⁾.

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FIGURE NO. 5

OMRE CORE LAYOUT FOR CORE IIIA

3. Core 3A Parameters and Operating History⁽¹³⁾

Low power physics measurements for Core III-A⁽¹¹⁾ were made during the first part of July 1961, following initial criticality of this core configuration achieved on June 28, 1961. Moderate power (3.65 Mw) experiments began on July 14, 1961, with full power operation (6.35 Mw) on July 30, 1961.

Full power operation of the reactor with this core arrangement continued until October 9, 1961. During this period, the reactor power level was decreased periodically from 6.20 to 4.50 Mw, controlled by the limiting temperature conditions at first on one of the driver elements and later on test element 6-1. Low power operation, to measure post-power xenon effects, continued until October 11, 1962, at which time the reactor was shut down for removal of fuel elements for hot cell examination. The reactor had accumulated 282-Mwd exposure on the Core III-A loading.

Figure 6 presents the power level of the reactor, the accumulative power on the core, and the HB content during Core III-A operation. The initial coolant composition of Core III-A was as follows: 0% biphenyl, 12% ortho-terphenyl, 60.4% meta-terphenyl and 25.1% para-terphenyl. The HB content in the coolant was maintained between 1.1 and 9% throughout Core III-A by operation of the continuous purification system.

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FIGURE NO. 6

OMRE OPERATING PERAMETERS

4. Prototype Operating Temperatures

The first 32.3 Mwd of Core III-A power operation consisted of running reactor tests (14). During this period, the reactor power level did not exceed 3.5 Mw, however, the coolant flow rate was decreased from 7500 to 3500 gpm and the coolant inlet temperature varied from 500 to 600°F. The maximum temperature recorded on the prototypes was 739°F for T/C 76 on 6-1, and 713°F for T/C 86 on 6-2.

The reactor was operated at power levels from 6.2 at the first and decreasing to 5.8 Mw at the end of August. During this period of operation the maximum recorded temperature for 6-1 increased rapidly from 732°F to 752°F at which level it remained until August 19, at that time the reactor was shut down due to thermocouple failures on the controlling fuel elements. The reactor was operated in September and early in October at power levels from 5.4 early in September and decreasing to 4.5 mw. During this period, the hottest thermocouple on 6-1, T/C 76, increased to 760°F on September 24 (See Figure 7). This was the peak allowable recorded temperature for the prototypes. The reactor power level was then decreased gradually to maintain a peak temperature of 760°F on T/C 76. The reactor was shut down October 9 for removal of 6-1. Recorded temperatures from thermocouples 77 and 72 indicated a trend similar to T/C 76 except that the rise in temperature for T/C 77 occurred four days later than that for T/C 76 and the rise in temperature for T/C 72

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FIGURE NO. 7

INDICATED THERMOCOUPLE READINGS
FOR OMRE 6-1 & 6-2 FUEL ELEMENTS

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continued to increase even during the decrease in power level. The other thermocouples in 6-1 indicated in a manner similar to T/C 73 in Figure 7.

OMRE 6-2 operated in a similar manner to 6-1 with T/C 87 increasing at the same time as T/C 76 did (See Figure 7). It is interesting to note that T/C 86, which had followed a trend similar to 87, showed a marked decrease as the power level was reduced.

After removal of 6-1 and element 230 from the reactor core, an attempt was made to move 6-2 to another core position. While trying to remove the element from its core position, the element appeared to be stuck about two feet from the top of the fuel and approximately 200 to 300 pound force was required to remove it. An unsuccessful attempt was made to place it in another core position before removing it from the core.

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HOT CELL EXAMINATION OUTLINE

The following is an outline of the tasks performed during the hot cell examination of the OMRE 6-1 and 6-2.

For 6-1

1. As Received Fuel Element

- a. Overall photographs
- b. Enclosure box dimensional measurements

2. Fuel Element Disassembly

- a. Remove end hardware and examine coolant channels with a light source
- b. Mill out locking beams
- c. Remove fuel element box by use of the milling machine
- d. Remove the stainless steel bands
- e. Photograph fuel plates and box interior
- f. Take chemistry samples of organic materials

3. Examination of Individual Fuel Plates

- a. Complete visual examination and photographs of all plates
- b. Remove samples of organic film
- c. Measure fouling film thickness
- d. Clean the plates to remove adherent material
- e. Gamma scan selected plates
- f. Make detailed dimensional measurement of plates
- g. Strip the cladding and nickel from selected fuel plates and take dimensional and density measurements
- h. Section selected fuel plates for metallographic examination of nickel thickness and diffusion zone

4. Package and Remove Plates to Disposal Area

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For 6-2

1. As Received Fuel Element
 - a. Overall photographs
 - b. Enclosure box measurement
2. Fuel Element Disassembly
 - a. Remove end hardware and examine the coolant channels with light.
 - b. Mill out the locking beams
 - c. Remove the fuel element box by use of the milling machine
 - d. Remove the stainless steel bands
 - e. Photograph fuel plates and box interior
 - f. Take chemistry samples of organic material
3. Examination of Individual Fuel Plates
 - a. Complete visual examination and photographs of all plates
 - b. Remove samples of organic film
 - c. Measure fouling film thickness
 - d. Clean the plates to remove adherent materials
4. Package Fuel Plates and Remove to Disposal Area

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IV. Hot Cell Examination

A. Results (Statement of Findings)

1. Measurement of the fuel element boxes of both 6-1 and 6-2 showed that significant swelling had taken place in the area of the second and third bands of the fuel plates. (Figure 8). The swelling appeared to be more pronounced in width direction of the fuel plates. (Figure 8). 6-1 showed a maximum increase of 45 mils and 6-2 a maximum of 70 mils from nominal box dimensions. It should also be noted that 6-2 had scratch marks on the box resulting from its removal from the core by force (Figure 9).

2. Observation of the inlet screen from both elements showed the presence of some material that partially plugged the end of the screen area (Figure 10).

3. Removal of the end hardware from 6-1 and 6-2 revealed that all of the flow channels adjacent to the enclosure box were blocked (Figures 11 and 12).

4. Removal of the fuel element box disclosed massive deposits of primarily organic material under all of the bands holding the fuel plates together (Figures 13, 14, 15, 16, 17, and 18). The second and third bands of each element which were located in the highest temperature and neutron flux area showed the worst condition thus correlating to the position of the maximum dimensional changes for the enclosure box. After removal of the bands, the deposit underneath was determined to be slightly magnetic (Figure 19).

5. Chemical samples taken from the deposited material under the bands generally showed variations in ash contents ranging from about 13% to 70% ash, with a dependency on actual band location. Figure 20 shows the

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locations from which samples were taken and analyzed. The areas of highest temperature and flux showed the lowest ash content. The ash, in all cases regardless of location, ran about 50% by weight iron. The C/H ratios ranged from 1.70 to 2.69 without relation to position (see Table 2).

6. Analysis of the material caught in the screen of 601 (Figure 10) showed a very different result from the analysis of the buildup on or under the bands. It was almost insoluble in chloroform. A large proportion of the residue was also insoluble in nitric acid. It was deduced that part of the insoluble portion was silica (pure quartz) or other silicates (see Table 3 and Reference 12).

7. Postirradiation length measurements on the clad fuel plates showed a change in length of 0.51% in the central edge plates of 6-1 and 0.38% in the central edge plates of 6-2 (see Tables 4 and 5).

8. Postirradiation width changes were measured on clad fuel plates from 6-1 and range from 2 to 45 mils (see Tables 4 and 5).

9. Postirradiation length, width, thickness, and density measurements were made on two bare fuel plates, 3 and 17, from 6-1. The change in length was 0.24% and of width was 0.57% for plate 3. The change in both width and length on plate 17 was 0.38% (see Table 6).

10. Gamma scans were used to determine the point of maximum burnup and radiochemical analysis samples taken from that area has shown this to be 2300 MWD/MTU, for 6-1. (Figures 21, 22, 23).

11. Metallographic examination of the bond zone on plate 2 of 6-1 revealed (a) the fuel plate was bonded throughout except for some of the

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corners; (b) that the diffusion rate of the nickel into the aluminum was in agreement with predicted rates; (c) the nickel thickness measurements obtained during fabrication were error, about 50% (0.5 mils)

FIG 8 POSTIRRADIATION WIDTH
 DIMENSION OF FUEL ELEMENT BOX

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OMRE 6-1

OMRE 6-2

NOTE THE SCRATCH MARKS FROM THE GRID
PLATE OF THE REACTOR WHERE THE BOX HAD BULGED

FIGURE NO. 9

PHOTOGRAPHS SHOWING ALL FOUR SIDES OF THE
ENCLOSURE BOX OF FUEL ELEMENTS 6-1 AND 6-2

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FIGURE NO. 10

PHOTOGRAPHS SHOWING THE DEPOSITS COLLECTED
IN THE BOTTOM OF THE INLET SCREEN OF
FUEL ELEMENTS OMRE 6-1 AND 6-2

OMRE 6-2

OMRE 6-1

FIGURE NO. 11

COMPOSITE OF OMRE 6-2 OUTLET END

FIGURE NO. 12

COMPOSITE VIEW OF OUTLET END OF OMRE 6-1

OUTLET END

INLET END
OMRE 6-1

FIGURE NO. 13
FUEL BUNDLE AND PLATES OMRE 6-1

INLET END
OMRE 6-2

FIGURE NO. 14
FUEL ELEMENT BOX AND FUEL PLATES OF OMRE 6-2

FIGURE NO. 15
DEPOSITS ON AND UNDER
STAINLESS STEEL BANDS ON SIDE 3 OF OMRE 6-1

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FIGURE NO. 16

DEPOSITS ON SIDE 4 OF BAND 3 OF
FUEL ELEMENT OMRE 6-2

FIGURE NO. 17

DEPOSITS ON SIDE 1 OF BAND 3 OF OMRE 6-2

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FIGURE NO. 18
CRUD FOUND ON SIDE 4 OF BANDS OMRE 6-1

FIGURE NO. 19
A PIECE OF DEPOSIT CLINGING TO A MAGNET

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FIGURE NO. 20
LOCATIONS FROM WHICH SAMPLES OF
DEPOSIT WERE TAKEN

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**ANALYSIS OF CHLOROFORM INSOLUBLE DEPOSITS
ON FUEL ELEMENT 6-1**

Location of Sample	Ash (wt %)	Fe (wt % of Ash)	Atomic C/H Ratio
Element side 3, on band 1	(70.6) *	(50.6)	—
Element side 3, just upstream of band 1	(55.7)	(47.7)	—
Average around band 1	63.2	49.2	—
Element side 3, under band 2†	20.7	50.3	1.98
Element side 3, on and near band 2	15.2	42.8	1.99
Element side 4, on band 2	18.3 (19.5) Avg 18.9	55.0	1.70
Box side 3, near band 2	(26.4)	(59.2)	—
Box side 4, near band 2	17.4	52.6	1.85
Average around band 2	19.7	52.0	1.88
Element side 3, on band 3	7.4 (27.6) Avg 17.5	47.2 (58.0) Avg 52.6	2.38
Element side 3, under band 3†	13.5	47.6	2.63
Element side 3, near band 3†	15.3	56.2	2.48
Element side 4, on band 3	13.1 (18.7) Avg 15.9	62.4 (62.4) Avg 62.4	2.15
Box side 3, near band 3	10.1 (15.9) Avg 13.0	58.5 (59.1) Avg 58.3	2.08
Average around band 3	15.0	55.4	2.34
Chunks from plate 10,† about 5 in. from outlet end	31.1	48.8	1.61
Material scraped from fins† of plate 2, side 3	14.7	49.4	2.69
Material from element inlet screen	48.6	28.7§	2.06
Scrapings from OMRE expan- sion tank (No. 1997)	78.3**	58.1	2.21

*Values in parentheses are calculated from measurements on total samples as scraped from the element corrected for the chloroform soluble portion; all other values are from direct analyses of the chloroform insoluble portions.

†Fe₂O₃ detected by x-ray diffraction; other samples not checked

§The low iron content of this ash is attributed to the presence of small stones (silicates) making up about 59% of the ash weight (see text, Section II-3)

**Analysis of these scrapings at the OMRE indicated about 27% ash based on the total samples, which is in good agreement with the value 78.3% based on the chloroform insoluble fraction; the chloroform insoluble fraction was 35.2% of the total sample.

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TABLE 3

ESTIMATED PARTICLE SIZE
DISTRIBUTION OF MATERIAL
COLLECTED ON ELEMENT 6-1
INLET SCREEN

Size Range (μ)	Volume (%)
2000-3000	74.5
1000-2000	23.6
800-1000	1.2
400-800	0.7
100-400	0.01
100	0.0001

POSITION OF LENGTH MEASUREMENTS

1 1/16"	1-9/16"	1-1/2"	1-1/2"	1-1/2"	1-1/2"	1-1/2"	1-9/16"	1 1/16"
1	2	3	4	5	6	7	8	

POSITION OF WIDTH MEASUREMENTS

WIDTH DIMENSIONS						LENGTH DIMENSIONS					
POSITION	PRE	POST	ΔW	% CHG	AVG % CHG	POSITION	PRE	POST	Δ L	% CHG	AVG % CHG
PLATE #2	1	2.766	2.780	.014	.52	PLATE #16	1	12.508	12.540	.032	.26
	2	2.773	2.775	.002	.07		2	12.508	12.536	.028	.23
	3	2.781	2.785	.004	.15		3	12.260	12.280	.020	.16
	4	2.780	2.785	.005	.18		4	12.259	12.284	.025	.20
	5	2.779	2.798	.019	.71		5	12.261	12.290	.029	.24
	6	2.771	2.800	.029	1.09		6	12.509	12.538	.029	.24
	7	2.780	7.785	.005	.18		7	12.508	12.532	.024	.20
	8	2.770	2.790	.020	.75						
PLATE #17	1	2.768	2.787	.019	.71	PLATE #17	1	12.262	12.323	.061	.50
	2	2.782	2.799	.017	.64		2	12.262	12.325	.063	.52
	3	2.773	2.810	.037	1.39		3	12.757	12.820	.063	.52
	4	2.779	2.785	.006	.22		4	12.757	12.824	.067	.55
	5	2.780	2.807	.027	1.02		5	12.756	12.824	.068	.56
	6	2.776	2.799	.023	.86		6	12.258	12.320	.062	.51
	7	2.775	2.820	.045	1.70		7	12.259	12.310	.051	.42
	8	2.769	2.810	.041	1.55						
PLATE #3	1	2.777	2.762	.015	.54	PLATE #18	1	12.747	12.794	.047	.39
	2	2.790	2.770	.020	.72		2	12.748	12.810	.062	.51
	3	2.787	2.775	.012	.43		3	12.253	12.302	.049	.40
	4	2.782	2.782	.000	.00		4	12.251	12.294	.043	.35
	5	2.787	2.768	.019	.68		5	12.251	12.304	.053	.44
	6	2.785	2.769	.016	.57		6	12.752	12.815	.063	.52
	7	2.796	2.785	.011	.39		7	12.748	12.806	.058	.48
	8	2.773	2.775	.000	.00						
LENGTH DIMENSIONS											
POSITION	PRE	POST	Δ L	%CHG	AVG % CHG	POSITION	PRE	POST	Δ L	% CHG	AVG % CHG
PLATE #5	1	12.249	12.310	.061	.50	PLATE #1	1	12.503	12.532	.029	.24
	2	12.249	12.310	.061	.50		2	12.508	12.539	.031	.25
	3	12.754	12.803	.049	.40		3	12.256	12.284	.028	.23
	4	12.752	12.808	.056	.46		4	12.257	12.280	.023	.19
	5	12.751	12.801	.050	.41		5	12.259	12.283	.024	.20
	6	12.249	12.310	.061	.50		6	12.507	12.534	.027	.22
	7	12.248	12.315	.067	.55		7	12.505	12.538	.033	.27
PLATE #6	1	12.753	12.801	.048	.40	PLATE #2	1	12.256	12.315	.059	.49
	2	12.755	12.800	.045	.37		2	12.256	12.313	.057	.47
	3	12.258	12.300	.042	.35		3	12.758	12.820	.062	.51
	4	12.255	12.285	.030	.25		4	12.756	12.814	.058	.48
	5	12.252	12.300	.048	.40		5	12.757	12.818	.061	.50
	6	12.754	12.799	.045	.37		6	12.249	12.313	.064	.53
	7	12.752	12.801	.049	.40		7	12.248	12.318	.070	.58
						(Disregard for average)					
PLATE #4	1	12.520	12.497	.023	.19	PLATE #3	1	12.755	12.811	.056	.46
	2	12.524	12.498	.026	.21		2	12.754	12.815	.061	.50
	3	12.250	12.265	.015	.12		3	12.258	12.310	.052	.43
	4	12.248	12.260	.012	.10		4	12.256	12.304	.048	.40
	5	12.248	12.265	.017	.14		5	12.256	12.315	.059	.49
	6	12.523	12.498	.025	.20		6	12.758	12.810	.052	.43
	7	12.528	12.499	.029	.24		7	12.753	12.803	.050	.41

POSITION OF LENGTH MEASUREMENTS

POSITION OF WIDTH MEASUREMENTS

WIDTH DIMENSIONS											
POSITION	PRE	POST	Δ W	% CHG	AVG % CHG	POSITION	PRE	POST	Δ L	% CHG	AVG % CHG
PLATE #2	1	2.756	2.766	.010	.37	PLATE #5	1	12.239	12.275	.036	.30
	2	2.756	2.772	.016	.60		2	12.243	12.273	.032	.26
	3	2.755	2.775	.020	.75		3	12.748	12.795	.047	.39
	4	2.758	2.779	.021	.79		4	12.750	12.793	.043	.35
	5	2.759	2.813	.054	2.04		5	12.750	12.803	.053	.44
	6	2.760	2.795	.035	1.32		6	12.245	12.277	.032	.26
	7	2.760	2.775	.015	.56		7	12.243	12.265	.022	.18
	8	2.759	2.775	.016	.60						
PLATE #17	1	2.748	2.760	.012	.45	PLATE #6	1	12.749	12.795	.046	.38
	2	2.755	2.770	.015	.56		2	12.750	12.790	.040	.33
	3	2.757	2.770	.013	.49		3	12.256	12.285	.029	.24
	4	2.759	2.780	.021	.79		4	12.254	12.283	.029	.24
	5	2.760	2.780	.020	.75		5	12.259	12.277	.018	.15
	6	2.758	2.775	.017	.64		6	12.750	12.790	.040	.33
	7	2.756	2.775	.019	.71		7	12.748	12.794	.046	.38
	8	2.747	2.773	.026	.98						
LENGTH DIMENSIONS											
POSITION	PRE	POST	Δ L	% CHG	AVG % CHG	POSITION	PRE	POST	Δ L	% CHG	AVG % CHG
PLATE #1	1	12.500	12.526	.026	.21	PLATE #16	1	12.503	12.530	.027	.22
	2	12.500	12.525	.025	.20		2	12.504	12.515	.011	.09
	3	12.253	12.265	.012	.10		3	12.256	12.252	.004	.03
	4	12.250	12.260	.010	.08		4	12.253	12.250	.003	.02
	5	12.253	12.267	.014	.11		5	12.257	12.252	.005	.04
	6	12.500	12.522	.022	.18		6	12.501	12.516	.015	.12
	7	12.501	12.518	.017	.14		7	12.500	12.516	.016	.13
PLATE #2	1	12.249	12.280	.031	.25	PLATE #17	1	12.254	12.285	.031	.25
	2	12.243	12.287	.044	.36		2	12.258	12.305	.047	.39
	3	12.752	12.801	.049	.40		3	12.750	12.801	.057	.42
	4	12.751	12.806	.055	.45		4	12.753	12.798	.045	.37
	5	12.500	12.795	.045	.37		5	12.750	12.800	.050	.41
	6	12.250	12.297	.047	.39		6	12.256	12.295	.039	.32
	7	12.245	12.295	.050	.41		7	12.252	12.300	.048	.40
PLATE #3	1	12.747	12.785	.038	.31	PLATE #18	1	12.748	12.785	.037	.30
	2	12.748	12.774	.026	.21		2	12.749	12.830	.081	.67
	3	12.260	12.280	.020	.16		3	12.256	12.283	.027	.22
	4	12.253	12.283	.030	.25		4	12.249	12.277	.028	.23
	5	12.251	12.278	.027	.22		5	12.254	12.279	.025	.20
	6	12.749	12.780	.031	.25		6	12.749	12.804	.055	.45
	7	12.748	12.783	.035	.29		7	12.746	12.795	.049	.40
PLATE #4	1	12.500	12.526	.026	.21	PLATE #19	1	12.503	12.530	.027	.22
	2	12.500	12.526	.026	.21		2	12.504	12.515	.011	.09
	3	12.249	12.252	.002	.01		3	12.256	12.252	.004	.03
	4	12.245	12.250	.005	.04		4	12.253	12.250	.003	.02
	5	12.244	12.255	.009	.07		5	12.257	12.252	.005	.04
	6	12.497	12.516	.019	.15		6	12.501	12.516	.015	.12
	7	12.500	12.510	.010	.08		7	12.500	12.516	.016	.13

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LOCATION OF DIMENSIONS PLATE #3 AND PLATE #17

PLATE #3			PLATE #17		
LENGTH	DIMENSIONS	AVERAGE PREIRRADIATION	LENGTH	DIMENSIONS	
L-1	12.033	12.000 ± .005	L-1	12.047	
L-2	12.026	AVERAGE POSTIRRADIATION	L-2	12.045	
		12.029 12.046			
WIDTH	DIMENSIONS		WIDTH	DIMENSIONS	
W-1	2.660		W-1	2.657	
W-2	2.669	AVERAGE PREIRRADIATION	W-2	2.658	
W-3	2.663	2.645 ± .005	W-3	2.656	
W-4	2.656	AVERAGE POSTIRRADIATION	W-4	2.655	
W-5	2.659	2.660 2.655	W-5	2.656	
W-6	2.658		W-6	2.657	
W-7	2.656		W-7	2.651	
W-8	2.655		W-8	2.654	
THICKNESS	DIMENSIONS		THICKNESS	DIMENSIONS	
T-1 .108	T-10 .107		T-1 .107	T-10 .102	
T-2 .1085	T-11 .110	AVERAGE PREIRRADIATION	T-2 .110	T-11 .106	
T-3 .1085	T-12 .110	.109 .107	T-3 .112	T-12 .105	
T-4 .109	T-13 .109	AVERAGE POSTIRRADIATION	T-4 .108	T-13 .109	
T-5 .110	T-14 .111	.1092 .1077	T-5 .112	T-14 .108	
T-6 .111	T-15 .110		T-6 .111	T-15 .107	
T-7 .1095	T-16 .110		T-7 .107	T-16 .107	
T-8 .1095	T-17 .110		T-8 .107	T-17 .108	
T-9 .107	T-18 .1085		T-9 .108	T-18 .105	

TABLE 6

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DISCUSSION OF HOT CELL EXAMINATION AND RESULTS

OMRE 6-1 was discharged from the reactor due to increased surface temperature and examined at the hot cell. The element operated at maximum recorded temperatures of 735 to 760°F. Toward the end of the irradiation, the surface temperature was increasing and therefore was limiting the reactor power level. The recorded surface temperature continued to increase despite the decreases in core power.

OMRE 6-2 exhibited similar characteristics with maximum recorded temperatures of from 710 to 745°F. 6-2 was discharged from the reactor when it was discovered that the fuel box had swelled to the dimensions of the upper reactor grid plate. This condition was found during refueling operations when an attempt was made to shift its position. The sides of the fuel box were scraped when the element was pulled through the upper grid plate.

DISASSEMBLY AND VISUAL EXAMINATION OF OMRE 6-1

This fuel element was placed in AI's Components Development Hot Cell on October 17, 1961. The temperature on the sides of the as-received fuel element box was 170 to 185°F, determined by Tempilsticks, (temperature sensitive crayons). The temperature increased to a maximum of 200°F during the first half hour in the cell. All surfaces were coated with a wet, oily substance which did not drain or dry. It was found to be the shipping cask transport fluid, HB-40, (a mixture of hydrogenated terphenyls). The HB-40 film was present on all surfaces examined and because of it the fuel element heat transfer surfaces appeared to be fouled more than was actually the case. This point should be remembered when viewing Figures 9 to 19. The sides of the box were numbered as shown in Figure 8. Dimensions of the fuel element box were taken and are presented in Figure 8. The maximum width of the fuel box, 2.995 inches,

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was located on the upstream side of band number 3. This maximum dimension was in the width direction of the fuel plates.

The end hardware was removed from the fuel element using a power hacksaw. Visual examination of the fuel element using the Kollmorgen periscope indicated that all flow channels adjacent to the fuel element box were blocked. Using the periscope, a series of photographs were taken of the fuel element looking through the element from the outlet end with a light directed at the inlet end. Figure 12 is a composite of these photographs. One of the channels appeared to be partially blocked; but subsequent examination revealed that the coolant inlet thermocouple had dislodged from the center runner and was laying across the internal channel. Deposits had formed around the thermocouple and on the adjacent fuel plates, see Figure 13, Plates 10, 11, 12, Side 1, and Plates 13, 14, 15, Side 3. When looking through the fuel element as in Figure 12, the channel being 3 feet long, the thermocouple and deposits give the illusion that the channel was blocked.

The welds holding the locking beams were then milled out. The fuel element was set on the milling machine, and two corners of the box were milled off along their length. Sides 3 and 4 of the box were removed revealing the massive deposits on the stainless steel bands used to hold the fuel bundle together. Figure 15 shows the deposit on and under the bands. Chemical samples of the deposits on the fuel bundle bands and box were taken at the locations shown in Figure 20. The results of the chemical analysis are presented in Table 2. During sampling, it was determined that the deposits were magnetic, see Figure 19.

The stainless steel bands were removed and the fuel plates photographed individually. Figure 13 shows the fuel plates and the inside surfaces of the fuel box. The fuel plates were separated by milling out the stainless

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steel pins. Selected plates were then soaked in chloroform to remove the shipping cask fluid. Figure 24 shows the surface of Plate 8 before and after soaking in chloroform. Note the particles which are in the channels at the base of the fins after the chloroform soluble components had been removed. A thermocouple hot junction from the hottest plate is shown in Figure 25. Note the accumulation of deposits in the channels adjacent to the fin containing the thermocouple.

DISASSEMBLY AND VISUAL EXAMINATION OF OMRE 6-2

The fuel element was placed in the hot cell on November 11, 1962. After allowing the shipping cask fluid to dry, the element was visually inspected. The sides of the box were numbered as shown in Figure 8. During removal from the reactor, scrape marks were made on Sides 1 and 3 as shown in Figure 9. The width dimensions of the fuel element box were taken and are presented in Figure 8. The maximum width of the fuel box, 3.022 inches, was located just below band number 3. The maximum width was in the width direction of the fuel plates.

The disassembly, visual examination, and photographic examination of 6-2 was similar to 6-1 and is shown in Figures 9 to 16. Plate 8 was partially soaked in chloroform for one hour. Figure 26 shows the fuel plate as received and after soaking for one hour in chloroform. Figure 27 is a photograph of the side of the fins on plate 8 after treatment with chloroform. The blistering or flaky nature of the film on the sides of the fins was noted. Samples were taken from the steel bands and the inside of the box and submitted for chemical analysis.

FOULING FILM DISCUSSION

For completeness, the following discussion has been removed almost in

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BEFORE

AFTER

FIGURE NO. 24

PLATE 8 FROM OMRE 6-1
BEFORE AND AFTER SOAKING IN CHLOROFORM

HOT JUNCTION

FIGURE NO. 25

HOT JUNCTION OF THERMOCOUPLE 76 FROM OMRE 6-1

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FIGURE NO. 26

PLATE 8 FROM OMRE 6-2 WHICH HAD BEEN
PARTIALLY SOAKED IN CHLOROFORM

FIGURE NO. 27

BLISTERED DEPOSIT ON FINS AFTER
SOAKING IN CHLOROFORM

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context from reference 20:

The hot cell examination of both elements showed that both the increased surface temperature and the swelling of the fuel boxes were caused by massive organic deposits found on the inlet side of four 0.005" stainless steel bands used to hold the fuel bundles together. These deposits were heavier and harder on the bands near the center of the element where they were about 0.060" thick and completely filled the space between the bands and the aluminum cladding. Figure 11 shows the deposits formed on and under the steel bands. The deposits on the bands were magnetic and had a chemical composition similar to deposits formed on OMRE Core II driver elements.

The element as-received appeared to contain significant amounts of organic materials which appeared to be simply frozen coolant. This element was shipped in a cask containing HB-40 which is a poor solvent for terphenyls. Since chloroform will dissolve coolant, including most high boilers, but will not dissolve fouling films; stereophotographic examination of the element plates was made before and after soaking in chloroform and both the soluble and insoluble fractions were analyzed. The chloroform soluble portions were found to range from 21 to 60% of the total sample indicating that a very significant portion of the observed materials on element 6-1 was simply frozen coolant. Gas chromatographic analysis confirmed that the soluble materials were largely terphenyls, HB-40 and high boiler components. The compositions of the chloroform insoluble fractions are of primary interest since it is only these materials that are regarded as firm deposits at the temperature of reactor operation.

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Stereophotographic examination of the plates after washing with chloroform indicated that the normal film thickness is probably less than, or equal to, that on the stainless steel clad driver elements. The deposits on the inner plates were somewhat spotty but in general were so thin that samples for analysis could not be obtained by scraping. However, deposits were found on both outside plates of element 6-1 at each of the four positions where a stainless steel band, used to hold the plate in place, restricted the flow between the outside of the plate and inside of the element box. These bands (numbered 1 to 4, starting at the outlet end of the element) reduce the normal 30 mil coolant channel to less than 10 mils at these four points. Microscopic examination of these heavy deposits showed that large particles and fibers were trapped in these narrow channels and these accumulations probably accelerated deposition by a filtration action at first, and later by severe flow restriction, resulting eventually in nearly complete blockage of the channels. Thicker than normal deposits were also observed on one of the plates at a position where a surface thermocouple wire had become dislodged from its fin position resulting in restricted flow.

It is interesting to note from the table of analysis (Table 2), that the ash content of the deposit is at a minimum in the region of band 3 which is the region of maximum temperature and fast neutron flux (greatest burnup). The same trend is shown on other driver elements that were removed for examination with respect to the coolant technology work. If the scrapings from the OMRE expansion tank are typical of the larger circulating particles, it is evident from their high ash content that additional organic materials must have deposited together with these particles to produce the low ash films. Furthermore, the additional organic material appears to dilute the inorganic

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containing particles in proportion to the temperature and radiation flux in order to result in the ash profile along the element shown in the table #2. In this connection, it may be noted that two samples of thin films taken from driver elements known to have been deposited during holding time prior to power operation were shown to have ash contents from 70 to 80% which is very similar to the ash value of 78.6% for the particles which settled in the expansion tank. The source of the additional organic matter deposited may be smaller particles containing little organic matter, perhaps colloidal in size, or even soluble high molecular weight components of the coolant.

The material recovered from the inlet screen of element 6-1 was soaked in chloroform to separate soluble and insoluble materials. The material was 7.6% insoluble in chloroform. Microscopic examination of the chloroform soluble material show mainly large black particles of various sizes and textures although a number of other types of particles were also evident.

The ash from combustion of this sample was very different from all the other samples examined from element 6-1 in that some components could not be dissolved in acid. These acid-insoluble particles made up 28.7% of the total sample or 59% of the ash. The ash which was soluble in acid, a characteristic of the other samples, was about 20% of the total sample or, 41% of the ash. Iron as Fe_2O_3 , the form obtained after ashing, accounts for all of this acid-soluble ash. Optical properties of a few white particles indicated the presence of pure quartz (SiO_2), and additional evidence was obtained which indicated that other silicates were also present in the acid-soluble material.

The heterogeneous nature of the material collected on the inlet screen of 6-1 shows that large particles from various sources were present in the

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circulating OMRE coolant during Core III-A operations. An estimate of the particle size distribution of the material collected on the screen is given in Table 3. The 6-1 inlet screen was a 20-mesh screen made of 15 mil wire which give square openings of about 33 mil (840 microns). The estimate of particle size distribution given in Table 5 indicates that very few particles smaller than the screen openings were retained by the screen.

Fuel Plate Dimensional Measurements

The length of nine clad fuel plates from each element, plates 1 to 6 and 16 to 18, and the width of plates 2, 3, and 17 from OMRE 6-1 and plates 2 and 17 from OMRE 6-2 were taken and compared to the preirradiation measurements. The measurements and changes from pre to postirradiation are presented in Tables 4 and 5. The measurements were taken using a vernier caliper and are considered reproducible to ± 0.001 inches. The change in length was less than that observed on other test fuel elements containing aluminum clad, nickel diffusion barrier and U3.5 Mo fuel plates. The change in width is similar to that obtained from other test fuel elements and will be discussed in detail below.

Two fuel plates (3 and 17) were selected for more detailed dimensional inspection. The cladding and nickel diffusion barrier were removed chemically. The aluminum from plate 3 was removed using a solution of Oakite 160 (12 oz/gallon) heated to 150°F. The reaction was sluggish so sodium hydroxide pellets were added to the solution until dissolution of the aluminum was complete. The aluminum from plate 17 was removed using a 0.5M solution of sodium hydroxide. The solution was renewed three times and the plate soaked for thirty hours. There were several areas on the plate that the aluminum would not react. See Figures 28 to 30. Figure 30 shows a piece of deposit which had been underneath one of the stainless steel bands and could not be

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PLATE #3 SIDE 1

PLATE #3 SIDE 3

PLATE #17 SIDE 1

PLATE #17 SIDE 3

FIGURE NO. 28

BOTH SIDES OF FUEL PLATES #3 AND #17
AFTER STRIPPING

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FIGURE NO. 29

PLATE NO. 17

DEPOSIT LEFT ON PLATE AFTER CHEMICAL STRIPPING

FIGURE NO. 30

PLATE NO. 17

SAME DEPOSIT AS THAT SHOWN ABOVE FROM A
DIFFERENT ANGLE

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removed either chemically or mechanically. The plates then were placed in a solution of Enstrip A (12 oz/gallon) heated to 150°F to remove the nickel. Figure 28 shows the fuel plates after removing the nickel.

Both fuel plates were measured at the locations shown in Table 6. The length and width were measured with vernier calipers and the thickness measured with a micrometer. All measurements are considered accurate and reproducible to ± 0.001 inches. The fuel plates were then sectioned into five pieces using a diamond cutoff wheel. The archimedes density of each section was determined using air and octonal as the fluids. The location of the section within the plate and the density determinations are presented in Figure 31. The density of plate 17 was adversely affected by the undissolved aluminum and should be regarded as invalid.

The difference in the length increase measured on the clad plates from that measured on the bare plates, plate 3 average 59 mils clad vs. 29.5 mils bare and plate 17 average 62 mils clad vs. 46 mils bare requires some discussion. These differences 29.5 mils on plate 3 and 16 mils on plate 17 could only partially be accounted for by measurement accuracy, 1 mil on clad plates before irradiation and 1 mil after and 1 mil on the bare plate after. Five mils could be attributed to the fabrication tolerance of the bare plate. If all of these were in the proper relation a total of only 8 mils could be accounted for. The explanation for the remainder of the difference is that due to the difference in the coefficient of thermal expansion between the aluminum $14.2^{(15)}$ and the fuel material $22^{(16)}$, the clad at the temperature of exposure plastically adapted itself to the fuel plate and on cooling down the clad could not resume its original length. This effect has been demonstrated out of pile (see References 17 and 18) by metallographic examination of the nickel bond zone in the area of the end plugs. There was a

FIGURE NO. 31

	AVERAGE POSTIRRADIATION DENSITY	PREIRRADIATION DENSITY	% CHG
Plate #3	17.58	17.80	1.24
Plate #17	17.55	17.83	1.57

*DENOTES POSTIRRADIATION DENSITIES

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definite separation between the end plug and the fuel (17, 18).

The clad fuel plate width measurements are difficult to interpret for three reasons; first, although every attempt was made to remove the hard deposits along the edges, this was not entirely successful. Secondly, the dimples were located very close to the area measured both before and after irradiation and in some cases affected the postirradiation measurement. Thirdly, the fuel plate fabrication tolerance on the cladding materials allows for 0.020 inch clearance between the cladding and the fuel plate. This clearance is removed irregularly during bonding, leaving either one side or both sides of the plate with a dished area, see Figure 32. When the fuel grows this dished area would increase in dimension without the rest of the edge surface increasing. All measurements were made on the total edge surface rather than the dished area.

Gamma Scan and Burnup Analysis

Plates 2 and 3 from 6-1 were gamma scanned as shown in Figure 21. The zirconium-niobium peak was used for the gamma scans. The relative gamma intensity of plates 2 and 3 is shown in Figure 22 and 23. Four burnup samples were cut from plate 2 and analyzed radio-chemically. Quoted burnup is based on Cs^{137} using Sr^{90} as a check. The Cs^{137} half-life was assumed to be 28.6 years, and it was assumed to have a 6.15% fission yield. The peak burnup in 6-1 was 2,300 MWD/MTU. There were not a sufficient number of fuel plates gamma scanned to determine the element average burnup.

Metallographic Examination of the Nickel Diffusion Barrier Bond

Metallographic specimens were cut from plate 2 to determine the condition of the nickel bond zone. Plate 2 was selected due to the high temperature

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EDGE SIDE #2

EDGE SIDE #4

FIGURE NO. 32

PLATE NO. 5 1065-5

EDGE VIEW OF FUEL PLATE NO. 5
PRIOR TO DIMPLING

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(760°F) recorded during reactor operation. The diffusion rate of the nickel and aluminum had not been adequately determined at this temperature in pile. The samples were cut using a cutoff wheel. This method of cutting is considered inadequate, but was the best available at the time of examination. During the cutting operation, all samples showed a tendency for the cladding to separate from the nickel bond zone at the interface between the aluminum and the aluminum rich Al_3Ni phase. The specimens were mounted in bakelite and polished using 6 micron-diamond and one micron diamond paste. Figures 33 and 34 show typical areas of the bond zone. Figure 35 presents the nickel thickness measurements and the amount of nickel consumed during irradiation.

The metallographic examination revealed that (a) the fuel plate was well bonded throughout except for some of the corners, and (b) the nickel thickness measurement obtained during fabrication was in error. Figures 33, 34, and 35 illustrate these facts and show the diffusion products formed during the irradiation.

Figure 34 shows the distribution of the remaining nickel at the position of thermocouple 76. It is noteworthy that, for the most part, there seems to be more than enough nickel remaining as a diffusion barrier. The close study of the picture and the specimens has indicated that the original nickel thickness was less than the reported minimum of 0.0014". The discrepancy in nickel thickness was determined in a Core IV bond test series. In this test series it was the goal to determine a confidence level in the fuel plates which were bonded for Core IV fuel elements. The test plates were sectioned and examined at 500X to determine the various zone thicknesses present in the bond. The series consisted of ten enriched plates selected at random from the fourth Core plate fabrication stream to represent the various combinations of time,

OMRE 6-1
METALLOGRAPHY PLATE 2

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MET NO. 1

FUEL PLATE 2 SIDE 3

MET NO. 2

PREPARED BY CDHC

OMRE 6-1
METALLOGRAPHY FUEL PLATE 2

MET NO. 3

MET NO. 4

PREPARED BY CDHC

FIGURE NO. 33

OSTIIO'000021616

FIGURE NO. 34

PREPARED BY C.D.H.C.

COMPOSITE VIEW OF MET. 4
 (MAX. BURNUP AREA OF OMRE 6-1 PLATE 2)
 SHOWING NICKEL DIFFUSION BARRIER
 REMAINING AFTER 2300 ^{MWD}/MTU BURNUP
 MAG. 75 X

	Measured from Photographs			By Difference		Calculated Nickel Consumed in Diffusion Zones		Consumed Less .1 For Bonding	Original Nickel	
	Ni	Al ₃ Ni ₂	Overall	Al ₃ Ni	Al ₃ Ni ₂	Al ₃ Ni	Total		Postirradiation Calculated	Preirradiation Measured
A-1	0.4	2.3	3.3	0.6	.73	.11	.84	.74	1.24	1.70
B-1	0.2	2.3	2.8	0.3	.73	.06	.79	.69	1.19	1.70
A-3	0.4	2.3	2.8	0.1	.73	.01	.74	.64	1.14	1.40
E-1	0.4	1.8	3.0	0.8	.57	.15	.72	.62	1.12	1.75
G-1	0.4	1.7	2.7	0.7	.54	.13	.67	.57	1.07	1.75
E-3	0.2	1.7	2.6	0.7	.54	.13	.67	.57	.87	2.00
C-1	0.2	1.8	2.6	0.6	.57	.11	.68	.58	.88	1.70
D-1	0.4	1.8	2.4	0.2	.57	.04	.61	.51	1.01	1.70
E-1	0.2	1.7	2.4	0.5	.54	.09	.63	.53	.83	1.70
B-3	0.0	1.7	2.7	0.8	.54	.15	.69	.59	.89	1.40
C-3	0.0	2.2	3.2	0.8	.70	.15	.85	.75	.85	1.40
D-3	0.0	2.4	4.4	1.6	.76	.30	1.06	.96	1.06	1.40
H-1	0.4	2.0	3.2	0.8	.63	.15	.78	.68	1.18	1.75
I-1	1.5	1.8	4.2	0.9	.57	.17	.74	.64	2.24	1.75
F-3	2.0	2.4	5.0	0.6	.76	.11	.87	.77	2.87	2.00
J-1	0.3	2.0	3.0	0.7	.63	.13	.76	.66	1.06	2.25
K-1	0.2	2.3	3.0	0.5	.73	.09	.82	.72	1.02	2.25
L-1	0.4	2.0	2.7	0.3	.63	.06	.69	.59	1.09	2.25
G-3	0.4	2.3	3.1	0.4	.73	.08	.81	.71	1.21	2.25
H-3	0.5	2.2	3.2	0.5	.70	.09	.79	.69	1.29	2.25
M-1	0.4	1.5	2.5	0.6	.48	.11	.59	.49	.99	2.25
N-1	0.3	1.6	2.4	0.5	.51	.09	.60	.50	.90	2.25
I-3	0.4	1.7	2.8	0.7	.54	.13	.67	.57	1.07	2.25
J-3	0.2	2.0	2.7	0.5	.63	.09	.72	.62	.92	2.25
K-3	0.2	1.8	2.5	0.5	.57	.09	.66	.57	.86	2.25
O-1	0.7	1.5	2.6	0.4	.48	.08	.56	.46	1.26	2.25
P-1	0.4	1.8	2.6	0.4	.57	.08	.65	.55	1.05	2.25

ASSUMED DENSITY Ni
CONSUMPTION CALCULATION

Ni 8.90 gm/cm³
Al₃Ni₂ 4.78 gm/cm³
Al₂Ni 3.98 gm/cm³

FIGURE NO. 35

Ni AND DIFFUSION ZONE THICKNESS
FUEL PLATE #2

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Temperature and pressure involved in the isostatic pressure bonding of aluminum extrusions to the nickel plated fuel plates. The results of the tests showed that in all cases the plates were well-bonded. A statistical correlation made between the as-plated thickness and the measurements from the metallurgical specimens showed that the Dermitron, and eddy current device, was indicating 50% more nickel than was actually present. This was offset to a small degree by a lower than predicted nickel consumption during the bonding operation. It was predicted that 0.2 to 0.3 mils was consumed, whereas the test series showed about 0.1 mil was consumed.

Figure 35 presents the thickness measurements of the nickel diffusion zones as well as the calculated consumption of the nickel. The estimated time at diffusion temperature was 1,500 hours, The predicted nickel consumption (19) at 760°F for 1,500 hours would be 0.7 mils. If the temperature profile in the fuel plate, higher near the edges, is taken into account the nickel consumed during the irradiation is in excellent agreement with the predicted diffusion rate. Figure 34 is a low magnification view of metallographic sample 4. In this figure the black zone near the fuel is the free nickel remaining. The white zone present on side 3 near the center of the plate is the U NiAl inter-metallic formed when the free nickel has been completely consumed. The separation between the cladding and the bond zone on metallographic sample 4 occurred during the cutting operation.

V. CONCLUSIONS

Since the basic objective of the postirradiation examination was to determine the cause of the temperature anomaly which caused the removal of this element from the reactor, it can be said that it was a result of the buildup of the organic coolant on the stainless steel bands applied to this

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fuel element. These caused restriction in flow and subsequently, deformed the fuel element boxes.

The secondary objective of this work was to determine how the prototype of OMRE Core IV fuel elements would operate. This objective was also met. The examination showed that the presence of the belly bands to assist in the positioning of the fuel plates in the box was a detriment because of their tendency to collect organic and hence, cause both restrictions of flow and buildup. It also suggested that greater allowance for flow must be made around the sides of the fuel element. Also, another means of the positioning of the plates in the enclosure box is necessary to insure that the plates do not nest and then cause a coolant channel blockage. Except for these points, the design aspects of the element appeared to be acceptable.

The test also served to evaluate the stability of the fuel material and the diffusion barrier material. The fuel material held up well for the 2300 MWD/MTU that the element was exposed to. On the basis of the clad fuel plate dimensional changes, it was predicted that subsequent elements of this alloy and design would be capable of safe operation in the OMRE to a peak burnup of 5,000 MWD/MTU. The diffusion barrier was adequate for the use intended. It was, of course, less than anticipated because of the error in measurement of the original nickel coating, but did demonstrate that it has strength to maintain contact despite the thermal shock treatments it receives in the course of reactor operation and that the intermetallics formed as the nickel is consumed are extremely brittle.

This series of tests emphasizes once again the value that can be gained by the prototype irradiation or test of new fuel elements. It also indicates that considerable difficulty can be encountered on designs that, for all intent

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and purposes, appear sound and acceptable. It is most certainly recommended that this same procedure of irradiation of the prototype design be continued as a factor of safety for the proposed cores. The diffusion rate of the nickel in this experiment confirmed the predicted rate from other sites.

VI. FUTURE WORK

After preliminary evaluation of the results of the irradiation and post-irradiation examination of 6-1 and 6-2, it was decided to assemble one fuel element from the OMRE 9 series of test fuel elements using an alloy base fuel (U 3.5 Mo 0.1 Al) for irradiation in OMRE Core III. In addition, one additional element was selected from the OMRE-11 series also an alloy (U-10 Mo) fuel element. These elements incorporated the following design changes which were a direct result of the observation of the shortcomings of the 6-1 and 6-2:

- A. Elimination of the stainless steel bands.
- B. Reduced number of centering dimples from 7 to 4 or 5 per side of the fuel plate.
- C. Streamlining the flow entrance by modification of both the bottom end plug and the leading edge of the lower plates.
- D. Reduced runner width from 0.500 to 0.040 inches to enlarge the side channels and improve coolant flow in the side channels.
- E. The outer plates in the elements have been "upset" on the side runners to restrict fuel plate movement. This upset is made in a similar manner to the dimples used on 6-1, but limits the motion perpendicular to the flat surfaces of the plates rather than centering the plates in the box.

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F. Reduced fin height from 0.120" to 0.080" to simulate Core IV hydraulic conditions in Core III.

These elements were irradiated and have been examined at the hot cell. The evaluation of their performance is in progress.

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