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MATERIALS TESTING REACTOR
ENGINEERING TEST REACTOR

ANNUAL PROGRESS REPORT ON FUEL ELEMENT DEVELOPMENT

FOR FY 1961

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SUMMARY

This report summarizes progress in fuels and materials development on budgeted activity 04400209 during the period July 1960 to August 1961. Major areas of investigation include (1) a materials study by means of sample fuel plates containing uranium alloys or cermet, burnable poisons, non-uniform fuel and poison distributions and clad with various aluminum alloys, and (2) an engineering study of fuel element geometries optimized in heat transfer, hydraulics, and materials strength.

Up to 45 wt% U-Al alloys, 6 - 65 wt% UO_2 -Al and U_3O_8 -Al dispersions, including enrichments ranging from 20% - 93%, have been tested to 70% burnup in de-ionized water at 200°F in the MTR. Their performance at higher temperatures is still being investigated. Test results for the MTR conditions indicate that all of the compositions investigated to date will successfully withstand even the longest irradiation at these conditions if properly fabricated. Some high strength aluminum alloy claddings, not yet fully tested, show some peculiar surface effects which may be related to corrosion. Metallographic studies of irradiated cermet reveal a "reaction" (diffusion) zone produced around UO_2 particles in contact with aluminum. These zones are being studied by means of X-ray diffraction, electron microscopy and electron microprobe analysis.

From engineering studies has come promise of improved heat removal and lower pumping requirements for reactors through artificial roughening of fuel plates. Computer optimization studies and hydraulic tests have indicated 80% improvement in heat transfer or 60% less flow for the same heat load are obtainable for MTR conditions.

Heat transfer test results from 0.110" x 2.624" electrically-heated channels using heat fluxes up to 2.88×10^6 Btu/hr-ft², agree better with correlations based on bulk temperatures than with the more widely used modified Colburn equation.

In this range, a modified Colburn equation with a 20% safety factor, as is presently used, seems adequate. However, an equation based on the bulk coolant temperature could be used employing a smaller safety factor because of its greater accuracy.

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I. INTRODUCTION

The purpose of this report is to review the progress made in the Reactor Fuels and Materials Development Program at the MTR-ETR since the last report⁽¹⁾ was issued in August 1960. Inasmuch as the program is a continuing one, some data from the previous report have been included for comparison purposes.

The objectives of this project comprise a comprehensive development program aimed at the improvement of fuel elements for high flux test reactors and for investigation of new fuel compositions, distributions and geometries, and include increasing the fuel life in testing reactors, increasing the power density in these reactors, improving the flux distribution, and providing a means of safely reaching higher reactor operating power.

One means of extending the fuel element life is through the use of increased fuel loadings and burnable poisons. The previous report⁽¹⁾ has described the successful fabrication and irradiation of fuel plate samples which contain up to 45 weight per cent uranium alloyed with aluminum and up to 65 weight per cent UO_2 dispersed in aluminum by means of powder metallurgy. A wide variety of burnable poisons have been incorporated into the plates. These have been irradiated and the reactivity effects studied. Finally, work has been started on the use of non-uniform fuel loadings to give better neutron flux and power distributions in reactors.

In order for reactors to operate at higher power densities, it is necessary to develop better materials for the cores and claddings of their fuel elements. New fuel element geometries must also be developed with improved heat transfer and hydraulic characteristics. Sample fuel plates have been fabricated and tested which have over two times the ultimate tensile strength at ambient temperature as the fuel plates now in use in the MTR. Work on several new fuel element designs is underway.

Advanced testing reactor concepts call for much higher operating temperatures and power for the fuel elements than are now used. Consequently, this program is seeking to determine the stability of fuel materials, corrosion resistance of claddings and strength of fuel plate compositions under these more severe operating conditions.

It is expected that this program will culminate in the development of several proven fuel element designs suitable for more advanced testing reactors.

II. METALLURGICAL PROPERTIES

A. Materials

The sample fuel plate compositions which have been fabricated and irradiated to date under the Fuel Element Development program at the MTR-ETR are listed in Table I. These compositions have been divided into phases based upon the order of procurement, the first three phases being included in Table I. More detailed lists of compositions and their properties are given in the appendix.

1. Cladding Materials

It will be noted that all of the fuel plate samples listed here are clad with aluminum alloys and all but the thorium-containing plates use aluminum in the cores. Aluminum has been, and remains, the most popular base material for the fuel elements in research reactors because of its low cost, ease of fabrication, good neutron economy, and good heat transfer properties. Its poor mechanical properties as well as poor corrosion resistance to de-ionized water at temperatures above 400°F are its principle disadvantages. However, these properties can be improved by alloying additions and by the introduction of non-metallic dispersions through the use of powder metallurgy techniques.

In Figure 1 are plotted tensile strengths versus temperatures for a number of aluminum alloys which might possibly be used in testing reactors. In Table II, the nominal chemical compositions of the cladding materials used in this program are shown.

From these data, it can be seen that the APM materials, M257 and M470, have the best strength properties at elevated temperatures. Due to the absence of high cross section elements, their nuclear properties are excellent. However, the corrosion resistance of the aluminum powder metallurgy products is not as good as that of X8001(4,6).

Of the three commercial alloys listed, 1100, 5052 and 6061, the 6061 alloy has the best all-around set of properties for use in testing reactors at higher temperatures. 1100 aluminum is the most easily fabricated of all the alloys and has good corrosion resistance to de-ionized water below 400°F. Of course, the commercial alloys have the advantages of low cost and ready availability as compared with the experimental X8000 series alloys and the APM's.

2. Core Materials

The uranium-bearing core materials can be broken down into two classes - alloys and cermetes, each having certain advantages and disadvantages.

The alloys were easily worked when they contained less than 13 weight per cent uranium. But when uranium-aluminum alloys were prepared containing more than 13 weight per cent uranium, some fabrication difficulties were encountered. These hypoeutectic alloys were brittle

Figure 1

Tensile Strength vs. Temperature
for Selected Aluminum Alloys

TABLE I

SAMPLE FUEL PLATE COMPOSITIONS TESTED TO DATE

Core										Cladding		
Material	Wt % Fuel	% En- richment	U ²³⁵ (Grams)	Wt % Si	Poisons					Thick. (Mils)	Type Al	Thick. (Mils)
					B(Nat.)	B ₄ C	Dy ₂ O ₃	Ir	Gd ₂ O ₃			
U in Al Alloy	18	93								20	1100	15
↓	18	93								20	1100 + 0.5 Ni	15
	18	93								20	1100 + 1.0 Ni	15
	18	93			0.057%					20	1100	15
	18	93			0.07%					20	1100	15
	18	93			0.115%					20	1100	15
	18	93							0.0123	20	1100	15
	18	93			0.057%				0.013	20	1100	15
	19	93								20	X8001	15
	19	93								20	X8003	15
	19	93								20	5052	15
	19	93								20	1100	6
	19	93								20	6061	15
	19	93								20	M257	15
	19	93								20	X8002	15
	23	93								20	1100	15
	25	20								25	1100	15
	32	93								16	M257	8
	32	93								16	X8001	8
35	93			1					10	6061	15	
35	93			1					15	M257	20	
35	3								20	6061	15	
35	Nat.								20	1100	15	
45	93			3					10	6061	20	
45	93			3					10	M257	10	

Table I (Cont.)

Core										Cladding		
Material	Wt % Fuel	% En- richment	U ²³⁵ (Grams)	Wt % Si	Poisons					Thick. (Mils)	Type Al	Thick. (Mils)
					B(Nat.)	B ₄ C	Dy ₂ O ₃	Ir	Gd ₂ O ₃			
*U in Al Alloy		93	0.3		8 mg	x				20	1100	15
*		93	0.5		8 mg	x				20	1100	15
*		93	0.7		8 mg	x				20	1100	15
*		93	0.9		7 mg	x				20	1100	15
*		93	1.1		4 mg	x				20	1100	15
*		93	0.7		4 mg	x				20	1100	15
*		93	0.7		9 mg	x				20	1100	15
*		93	1.1		12 mg	x				20	1100	15
*		93	1.0							20	1100	15
*		93	0.8							20	1100	15
↓		93	0.5							20	1100	15
U in Al Alloy		93	0.3							20	1100	15
UO ₂ + Al Cermet	6.1	93								20	1100	15
	11.6	93								20	1100	15
	16.8	93								20	1100	15
	18.7	93			0.036%					20	1100	15
	18.7	93					0.951%			20	1100	15
	18.7	93			0.037%		0.51%			20	1100	15
	18.7	93			0.036%			1.275%		20	1100	15
	18.7	93			0.036%				0.012%	20	1100	15
	22.7	93								20	1100	15
	22.7	93			0.062%					20	1100	15
	22.7	93			0.123%					20	1100	15
	22.7	93							0.013%	20	1100	15
	22.7	93			0.062%				0.013%	20	1100	15
**	23.8	93								20	1100	15
**	23.8	93			0.08%					20	1100	15
**	27.3	93								20	1100	15
↓												

Table I (Cont.)

Core										Cladding		
Material	Wt % Fuel	% En- richment	U235 (Grams)	Wt % Si	Poisons					Thick. (Mils)	Type Al	Thick. (Mils)
					B(Nat.)	B4C	Dy2O3	Ir	Gd2O3			
UO2 + Al Cermet	30	93								15	1100	15
	32	80								15	1100	15
	39	20								45	1100	10
	40	60								15	1100	15
	42	40								20	1100	15
	45	93								10	1100	15
	52	30								20	1100	15
	54	20								25	1100	15
UO2 + Al Cermet	65	20								20	1100	15
U3O8 + Al Cermet	22.3	93			0.0018	0.0023				20	1100	15
U3O8 + Al Cermet	22.3	93								20	1100	15
U3O8 + Al Cermet	22.3	93								20	1100	15
ThO2	100									120	1100	15
98.5% ThO2 + 1.5% UO2	100									120	1100	15

* RMF Standards

** Duplex plates only

Note: A list by composition numbers is shown in tables XIV and XV of the appendix.

due to the presence of the intermetallic compound UAl_4 . It was known that rapid cooling and small additions of such elements such as silicon, tin or zirconium tend to suppress the peritectic reaction occurring at 750°C . This would prevent the more ductile UAl_3 from reacting with Al to produce UAl_4 . Thus, it was possible to hot roll U-Al alloys containing up to 45 weight per cent uranium. However, there was a tendency for edge cracking and segregation in these alloys during rolling so that a large amount of scrap was generated which had to be remedied.

TABLE II(2,4,5)
NOMINAL CHEMICAL COMPOSITION OF ALUMINUM MATERIALS
(Weight Per Cent Alloying Material)

Alloy	Cu	Si	Mn	Mg	Zn	Ni	Cr	Fe	Al_2O_3
1100		99% Minimum Aluminum							
5052				2.5			0.25		
6061	0.25	0.6		1.0			0.25		
X8001						1.0		0.5	
X8002						1.4		1.4	
X8003						1.4*		1.4*	
APM M257									6
APM M470									10

* In high purity aluminum

The scrap generated when making fuel plates with cermet cores was not so easily reclaimed. This material had to be returned for chemical recovery and could not be recycled directly to the melting stage as was the case with the alloy. Moreover, the cost of the uranium oxides was greater than that of the metal.

Off-setting these disadvantages of the oxides was the advantage that in making plates which contain more than 25 - 30 weight per cent uranium, much less scrap was generated. Also, when proper powder metallurgy techniques were used, a much better control over the microscopic and macroscopic distribution of the fuel in the plates was obtained.

B. Fabrication

The techniques used for fabrication of samples for the first two phases were discussed in the appendix of a prior report⁽¹⁾. The same general procedures illustrated in Figure 2 were used for the fabrication of the fuel plate samples for the third phase. All of these plates had alloy cores. While many of the plates in the third phase had high strength aluminum alloy claddings, those in the first two phases were all clad with 1100 aluminum. The effects of these materials on fuel plate fabrication are discussed below.

Figure 2

Figures 3 through 9 are designed to illustrate the effect of different material combinations on the cores at the ends of the fuel plates. Composition 19 in Figure 3 is the same as a regular MTR fuel plate. The fuel plates are customarily rolled at a temperature of 1100°F. At this temperature, the 1100 aluminum, used as a picture frame and cladding material, is much weaker and more ductile than the core alloy. Consequently, as the fuel plate assembly passes through the rolls, this 1100 aluminum tends to extrude through the rolls at the leading end of the core and back away from the core at the trailing end. Since the space between the rolls is fixed, the cladding tends to become thinner over the core ends. The core, of course, is thickened. This condition of core thickening, referred to as "dog boning," is undesirable because it tends to concentrate the fuel at the ends of the plates.

One means that has been used to improve this condition of "dog boning" is to use cermet cores. In Figure 3 are shown the cross sections of sample fuel plates cut through the ends of the plates to reveal the amount of core thickening. In this figure, as well as similar ones which follow, the different appearance in the macrographs is due to different etching properties of the compositions. The first three sections shown are of fuel plates with fuel loadings, claddings and cross sectional dimensions similar to those used by the MTR and ETR. As seen here, the use of cermet cores clearly reduces the amount of core thickening. However, an examination of the lower five micrographs on Figure 3 reveals that by using alloying elements such as silicon in the core alloys together with high-strength aluminum-based materials for picture frames and claddings, fuel plates containing high weight per cents of uranium alloy cores can be made whose fuel distribution compares favorably with those of cermet cored plates.

As previously mentioned, the amount of "dog boning" present in a fuel plate can be influenced by the hot strength of the cladding material. In Figure 4 are shown cross sections of a series of fuel plates all of which have 19 weight per cent uranium-aluminum alloy cores. Composition 53, with 6061 cladding and composition 56, with APM M257 cladding, are the best. Composition 64 is of interest since the cladding thickness is only 0.006 inch. It was not possible to fabricate sound plates of this type until APM M257 was substituted for 1100 Al in the picture frame. When 1100 aluminum was used, the core material would rupture the cladding at the leading and trailing ends.

In Figure 5, the cross section of two compositions made with unmodified 32 weight per cent uranium-aluminum alloy cores are shown. The "dog boning", while not excessive, is worse than in compositions 54 and 57 shown in Figure 6. The cross sections shown in Figure 6 are of interest since they show how much improvement can be made in core thickening by the use of silicon in the core material and by the use of high-strength claddings. Composition 32 is a fuel plate made for Phase II. It contained no silicon in the core while the cores of the other

Composition No.	Core		Cladding	Picture Frame
19	Alloy-18 wt% U + Al		1100 Al	1100 Al
13	Cermet-22.7 wt% UO ₂ + 62% B + Al		1100 Al	1100 Al
47	Cermet-22.3 wt% U ₃ O ₈ + 0.18% B		1100 Al	1100 Al
54	Alloy-35 wt% U + 1.4 % Si + Al		6061 Al	1100 Al
30	Cermet-40 wt% UO ₂ + Al		1100 Al	1100 Al
55	Alloy-45 wt% U + 3 wt% Si + Al		6061 Al	APM M257
28	Cermet-52 wt% UO ₂ + Al		1100 Al	1100 Al
35	Cermet-65 wt% UO ₂ + Al		1100 Al	1100 Al
		10X	HF Etch	

Figure 3 COMPARISON OF ALLOY AND CERMET CORE MATERIALS ON CORE THICKENING AT FUEL PLATE ENDS

Composition No.

Cladding

Picture Frame

53

6061 Al

1100 Al

56

APM M257

1100 Al

61

X8002 Al

1100 Al

62

X8003 Al

1100 Al

63

5052 Al

1100 Al

64

1100 Al

APM M257

73

X8001

1100 Al

10X

HF Etch

Figure 4

EFFECT OF CLADDING AND PICTURE FRAME MATERIALS ON CORE THICKENING AT FUEL PLATE ENDS
(Core Material: 19 wt% Uranium + Aluminum Alloy)

Core Material: 32 wt % Uranium + Aluminum Alloy

<u>Composition No.</u>		<u>Cladding</u>	<u>Picture Frame</u>
58		APM M257	1100 Al
60		X8001	1100 Al
	10 X	HF Etch	

Figure 5 EFFECTS OF CLADDING AND PICTURE FRAME MATERIALS ON CORE THICKENING AT FUEL PLATE ENDS

Composition No.

Cladding

Picture Frame

32

1100 Al

1100 Al

54

6061 Al

APM M257

57

APM M257

1100 Al

10X

HF Etch

Figure 6 EFFECT OF CLADDING AND PICTURE FRAME MATERIALS ON CORE THICKENING AT FUEL PLATE ENDS

(Core Material: 35 wt% Uranium + 1.4 wt% Silicon* +
Aluminum Alloy)

* Composition 32 contained no silicon

two compositions contained 1.4% silicon. When 45 weight per cent uranium is alloyed with aluminum, if it is to be used for fuel plate core material, it must be modified with an element such as silicon, tin or zirconium. Moreover, to be fabricated into fuel plates, it must be used with high-strength cladding and picture frame materials. In Figure 7 are shown two compositions made in this manner. The poor rolling properties of the core alloy here caused the variations in thickness, even in the center portion of the plates.

Finally, in Figures 8 and 9 are shown a series of fuel plate compositions in which high-strength aluminum alloys are used as cladding material. It is interesting to compare these with composition 19 shown in Figure 3. The only composition shown in Figures 8 and 9 in which the "dog boning" is nearly as bad as that shown in composition 19 is composition 58. Here the higher loaded core alloy was not modified with silicon and the cladding was only 0.008 inch thick.

In Figure 9, composition 53N is of interest for two reasons: (1) it illustrates a defect that is seen to a lesser degree in other plates, i.e., the stringering of the core into the joint between the picture frame and cladding, caused by the core not being properly seated in the picture frame before rolling, and (2) it shows an example of the use of nickel foil to promote bonding between the 6061 aluminum cladding and the other components of the fuel plate. It is this problem of producing a sound bond when using 6061 or 5052 aluminum alloys that makes them difficult to fabricate. However, the use of thin nickel foil has proven beneficial in promoting bonding and, thereby, reducing the reject rate in making these plates.

Making fuel plates clad with 6061 or 5052 aluminum was also complicated by the fact that certain of the alloying elements (i.e., Cu, Mg and Cr) in these materials are not permitted by the fuel element specifications to be present in the core alloy. Thus, the reject plates had to be chemically reprocessed instead of being remelted. This, of course, increases the cost.

The same problem existed with the use of the X8000 series alloys. Here the nickel and iron were not desired in the cores. Since the reject rate when using these alloys for cladding is much lower the problem was not so great.

The APM's, containing only Al_2O_3 in aluminum, present none of these problems. The reject rate is very low in making plates clad with APM. The reject plates can be remelted and the Al_2O_3 in the APM skimmed off as a dross from the surface of the bath. This helps to offset the high cost of the APM's (\$3.50 to \$8.00 per pound) when compared with commercial alloys (\$.50 per pound). Moreover, tests have shown that the alumina in the APM's would probably necessitate a head end separation step after dissolution but prior to solvent extraction during the chemical reprocessing of spent fuel plates. The total cost of the additional step would probably add only a small cost to the chemical reprocessing⁽⁷⁾.

Core Material: 45 wt % Uranium + 3 wt% Silicon + Al Alloy

<u>Composition No.</u>		<u>Cladding</u>	<u>Picture Frame</u>
59		APM M257	APM M257
55		6061 Al	APM M257

10 X HF Etch

Figure 7 EFFECT OF CLADDING AND PICTURE FRAME MATERIALS ON CORE THICKENING AT FUEL PLATE ENDS

Cladding Material: APM M257			
<u>Composition No.</u>		<u>Core</u>	<u>Picture Frame</u>
56		19 wt% U + Al Alloy	1100 Al
57		35 wt% U + 1% Si + Al Alloy	1100 Al
58		32 wt% U + Al Alloy	1100 Al
59		45 wt% U + 3% Si + Al Alloy	APM M257
	10X	HF Etch	

Figure 8 EFFECT OF CLADDING AND PICTURE FRAME MATERIALS ON CORE THICKENING AT FUEL PLATE ENDS

Cladding Material: 6061 Aluminum

<u>Composition No.</u>		<u>Core</u>	<u>Picture Frame</u>
53		19 wt% U + Al Alloy	1100 Al
53N ⁽¹⁾		19 wt% U + Al Alloy	6061 Al
54		35 wt% U + 1% Si + Al Alloy	APM M257
55		45 wt% U + 3% Si + Al Alloy	APM M257
	10X	HF Etch	

(1) The dotted line between core and cladding is nickel used to promote bonding.

Figure 9 EFFECT OF CLADDING AND PICTURE FRAME MATERIALS ON CORE THICKENING AT FUEL PLATE ENDS

The presence of silicon in fuel elements is undesirable as it causes trouble in the chemical reprocessing^(8,9). Consequently, in the newer sample fuel plates, tin has been substituted for silicon in the fuel plate cores.

The fuel plate samples made under Phase III, which contain boron as a poison, were made for reactivity calibration standards for use in the RMF (Reactivity Measurement Facility). The boron in these was present as B_4C dispersed in aluminum. This material, "binal", was then centered between two halves of core material so that the fuel plate was a five-layer sandwich instead of the usual three.

With the exception of these standards for the RMF, the sample fuel plates were inspected prior to irradiation in the same manner as has been described previously⁽¹⁾.

C. Mechanical Properties

In Table III are shown the average mechanical properties of the sample fuel plate compositions. A very limited number of tensile specimens have been tested to date so that these data must be considered as being preliminary. However, it is planned to test more specimens not only at ambient temperature but also at elevated temperatures in both the irradiated and unirradiated conditions.

The tensile specimens were all cut from the fuel plates, transverse to the rolling direction. With the exception of the specimen size, the testing was done in accordance with ASTM Designation: E8-57T. In order to be able to obtain four tensile specimens from one sample plate, the specimens were made with a 1-inch gage length and a 1/4-inch width. The thickness, of course, depended upon that of the fuel plate.

An examination of the tensile properties reveals that the compositions in which 1100 aluminum is used in the fully annealed condition as the cladding material have the poorest tensile properties. This, of course, is to be expected. The plates clad with APM M257 show the highest strength but the poorest ductility.

Plates with alloy core were somewhat stronger than those with cermet cores. This is not surprising since the tensile properties of the uranium-aluminum alloys are better than those of the uranium oxide-aluminum cermets⁽¹⁰⁾.

The 1100 clad plates have about the same tensile properties as that of pure metal. However, the plates clad with the higher strength materials have lower strength than the pure cladding material since the room temperature properties of the core materials are lower than those of the cladding materials.

TABLE III

ROOM TEMPERATURE MECHANICAL PROPERTIES OF SAMPLE FUEL PLATES

Core			Cladding		Microhardness - DPH			Tensile Properties			
Material	Wt % Fuel	Thick. (Mils)	Type Al	Thick. (Mils)	Cladding	Core		Number of Specimens	Yield Strength (0.2% Offset) (psi)	Ultimate Tensile Strength (psi)	% Elongation
						Matrix	Particle				
U-Al Alloys	18	20	1100-0	15	26	32	64	7	6,500	13,500	21
	18	20	1100 + 0.5 Ni	15	33	*43	*43				
	18	20	1100 + 1% Ni	15	36	*39	*39				
	18	20	1100-H	15	42	*53	*53	2	18,000	21,500	9
	19	20	X8001-0	15	36	47	120				
	19	20	X8002-0	15	45	47	120	3	20,500	25,500	9
	19	20	X8003-0	15	46	86	170	2	16,500	22,000	6
	19	20	5052-0	15	57	45	140	2	21,000	27,500	8
	19	20	6061-T6	15	50	39	240	2	15,000	24,500	16
	19	20	APM M257	15	67	*38	* 38	2	27,000	31,000	3
	19	20	1100-0	6	32	*80	* 80	3	6,500	13,500	22
	25	25	1100-0	15	27	40	190	2	9,000	12,000	13
	32	16	APM M257	8	74	52	220	2	15,500	20,500	11
	32	16	X8001-0	8	29	48	74				
	35	10	6061-T6	15	76	*70	* 70	4	13,500	21,000	4
	35	15	APM M257	20	77	*70	* 70	2	25,500	32,000	4
	35	20	1100-0	15	30	*55	* 55	2	18,500	15,000	7
	35	20	6061-T6	15	67	54	150	1	14,500	22,000	6
	45	10	6061-T6	20	40	25	110	3	12,500	17,000	9
	45	10	APM M257	10	65	36	140	1		30,500	1

Table III (Cont.)

Core			Cladding		Microhardness - DPH			Tensile Properties			
Material	Wt % Fuel	Thick. (Mils)	Type Al	Thick. (Mils)	Clad- ding	Core		Number of Speci- mens	Yield Strength (0.2% Offset) (psi)	Ultimate Tensile Strength (psi)	% Elonga- tion
						Matrix	Particle				
U ₃ O ₈ + Al Cermet	22.3	20	1100-0	15	* 27	30	160	2	4,500	10,000	6
UO ₂ +Al Cermet	65	20	1100-0	15	* 36	32	390	3	6,000	8,500	12
↓	6.1	20	1100-0	15	31	33	400				
	11.6	20	1100-0	15	47	36	390				
	16.8	20	1100-0	15	43	36	450				
	18.7	20	1100-0	15	31	31	430	9	6,000	13,100	18
	22.7	20	1100-0	15	29	37	460	7	7,500	12,000	14
	30	15	1100-0	15	30	35	200				
	32	15	1100-0	15	26	27	320	2	4,500	11,500	17
	39	45	1100-0	10	31	34	440	2	6,500	12,000	14
	40	15	1100-0	15	27	30	410	2	5,500	11,000	14
	42	20	1100-0	15	29	33	520	2	9,000	11,000	13
	45	10	1100-0	15	25	38	160				
	52	20	1100-0	15	29	24	550	2	8,500	10,000	8
	54	25	1100-0	15	28	36	550				

* Particles too fine to measure separately

III. EFFECTS OF IRRADIATION

A. Experimental Procedures

1. L-Piece Design

An aluminum housing (L-piece) with the outside configuration of a typical MTR fuel element was used to hold the sample fuel plates during irradiation. The L-piece, which was fitted with a removable end box, was described in IDO-16574⁽¹⁾. A fuel plate holder was used for positioning the sample plates in the L-piece. Eight of these holders could be placed in the L-piece.

Figure 10 shows a sample fuel plate holder. This particular holder accommodated twelve 0.050"-thick plates, but other holders were available for plates of different thicknesses. The plates were always arranged so the flow channels approximated those of a typical MTR fuel element. Short pieces of 0.10% Co-Al wire were used for flux monitoring by placing them in the flux plate wells. When the holders were stacked, the flux wires in one holder extended into the holder above. This allowed flux wire readings to be used for both the top of the holder containing the wires and the bottom of the holder above. The position of the flux plates and the number of flux wires have been varied, but no detectable differences in readings were noted.

Normal sample fuel plates were 0.050" thick. However, 0.032"-thick fuel plates have been used in studying cladding requirements. Also, 0.250"-thick plates, consisting of an ordinary plate contained in a 310 stainless steel jacket, have been used to study the irradiation stability of various fuels at elevated temperatures (to 425°F). Samples being tested are U-Al alloys, UO₂ dispersed in Al, and U₃O₈ dispersed in Al.

2. Burnup Calculations

Three methods for determining fuel burnup in the sample fuel plates have been used: (1) calculations from flux measurements, (2) isotopic analysis, and (3) RMF measurements. Good agreement has been found between the isotopic analysis and RMF measurements but the burnup calculated from the flux measurements has been consistently high⁽¹⁾. These calculations used the unperturbed flux data and a volume perturbation factor⁽¹¹⁾ to correct for local flux peaking in the vicinity of the flux wires.

In order to better estimate the flux distribution throughout each of the eight sample fuel plate holders in an experimental loading, a series of computations was made and various holder loadings irradiated to evaluate the methods of calculation.

The model used for the computations was a one-dimensional, slab geometry cell in a plane normal to the fuel plate faces. Previous flux measurements had indicated that the general unperturbed flux pattern was essentially flat in this direction, therefore, the model

- (1) Fuel Plate Holder
- (2) Center Partition (Integral part of holder)
- (3) Flux Plate (One on each side of the center partition)
- (4) Detail showing how center partition and flux wires extend from one holder into the holder above it.
- (5) Flux Wires
- (6) Slots for Fuel Plates

P.P. Co.-8-3885

Figure 10

Sample Fuel Plate Holder

used considered only half of the positions in the holder and the flux derivative at the right and left hand boundaries was set equal to zero. The left hand boundary was taken at the holder centerline and the right hand boundary was set at 12.70 cm from the centerline or approximately 9 cm from the outside of the L-piece. Figure 10 shows the type of holder from which the model was drawn.

The first cases were run using a four-group diffusion theory program for the IBM 650 - DMM and DMM-FAD^(12,13). These cases were run mainly to yield region-wise source values for use in a one-velocity, one-dimensional transport theory code for the IBM 704 - FLIP 1⁽¹⁴⁾.

The sample fuel plate descriptions used in the calculations were those of a standard MTR type plate with a core thickness of 0.020" and a cladding thickness of 0.015". The core contained 18 weight per cent uranium, 93.5% enriched, in aluminum with aluminum cladding.

A variety of loadings were investigated to study the effects of blank or low fuel content plates in various positions. Figure 11 gives the FLIP-1 flux for a loading containing a blank plate in position 1 and standard MTR plates in the other positions. Figures 12, 13, and 14 illustrate cases containing blank plates in various positions. All fluxes have been normalized to 1.00 in the number 1 position as this is the normal flux wire location. It can be seen that the presence of blank plates or those containing low U²³⁵ content, particularly in the outer positions of the holder have a noticeable effect on the relative flux in fuel plates throughout the holder.

In the loadings used to evaluate the calculational techniques, standard MTR plates and aluminum plates containing flux wires in various positions were used, and in some instances, flux wires were also placed on the edges of the holder. Table IV compares the results of these loadings with calculated values.

The burnups of some irradiated plates were re-calculated using the values of position-dependent flux in obtaining flux perturbation factors. These burnups are presented in Table V.

Preliminary calculations have been made to correct for flux distributions in the direction parallel to the fuel plate face (right angles to the horizontal direction used in the computations) and also vertically through the set of eight holders. In the vertical direction, the holders, as shown in Figure 10, extend past the ends of the fuel plates and, therefore, a water gap exists between adjacent plates in the vertical direction. The placement of the flux wires within the holder is such that most flux perturbations parallel to the fuel plate face can be accounted for without flux analysis. However, in the vertical direction, it is estimated that an additional three to five per cent correction can be gained by proper analysis. These calculations have indicated, therefore, that the major disagreement in former burnup determinations was due to flux perturbations in the direction normal to the fuel plate faces.

Figure 11 Flip 1 Flux Plot for Sample Fuel Plate Holder
Standard MTR Type Fuel Plates in Positions 2, 3, 4, 5 and 6

Figure 12 Flip 1 Flux Plot for Sample Fuel Plate Holder
Standard MTR Type Fuel Plates in Positions 2, 3, 4, 5 and 6

Figure 13 Flip 1 Flux Plot for Sample Fuel Plate Holder
Standard MTR Type Fuel Plates in Positions 2, 3, 5 and 6

Figure 14 Flip 1 Flux Plot for Sample Fuel Plate Holder
Standard MTR Type Fuel Plates in Positions 2, 3, 4 and 6

TABLE IV
COMPARISON OF FLUX VALUES - MACHINE CALCULATIONS vs. FLUX MEASUREMENTS

Loading Description	Flux Ratio	Values from Machine Calculations	Values from Flux Measurements
Blank in Position 1	$\frac{\phi 1}{\phi 7}$	0.902	0.920
Std. MTR in Positions 2, 3, 4, 5, 6		0.902	0.955
Blank in Position 1	$\frac{\phi 8}{\phi 7}$	0.892	0.893
Std. MTR in Positions 2, 3, 4, 5, 6		0.892	0.910
Blank in Positions 1,2,6	$\frac{\phi 1}{\phi 6}$	0.885	0.885
Std. MTR in Positions 3, 4, 5		0.885	0.860
		0.885	0.850
		0.885	0.891
Blank in Positions 1,6	$\frac{\phi 1}{\phi 7}$	0.835	0.852
Std. MTR in Positions 2, 3, 4, 5		0.835	0.830
		0.830	0.830
Blank in Positions 1,4	$\frac{\phi 1}{\phi 7}$	0.91	0.96
Std. MTR in Positions 2, 3, 5, 6		0.91	0.93
		0.97	
	$\frac{\phi 1}{\phi 4}$	1.03	1.04
		0.97	1.01
		0.97	0.92

TABLE V

COMPARISON OF FUEL BURNUP OF IRRADIATED SAMPLE FUEL PLATES
DETERMINED BY VARIOUS METHODS

Nvt (Unperturbed)	Fraction Burnup					
	Isotopic Analysis			RMF Deter- mination	Calculated from Flux Measurements	
	Method 1	Method 2	Method 3		Old Method	New Method
14.2×10^{20}	$0.513 \pm .007$	$0.525 \pm .010$	$0.517 \pm .012$	0.511	0.61	0.53
11.5×10^{20}	$0.422 \pm .008$	$0.423 \pm .015$	$0.420 \pm .016$	0.421	0.54	0.44
13.5×10^{20}	$0.476 \pm .007$	$0.478 \pm .010$	$0.471 \pm .011$	0.48	0.59	0.50

In order to compute accurately the burnup in a very homogeneous experiment such as the one described, it would be necessary to do a complete flux analysis on each loading. Also, in cases where severe unperturbed flux gradients occur across the experiment, more refined techniques would be necessary in which non-zero flux derivatives could be imposed at the boundaries. It is felt that for the experimental conditions described, the calculational techniques have provided a sufficiently accurate method of determining U-235 burnup.

3. Sample Examination

As described in IDO-16574,⁽¹⁾ pre-irradiation examination of the sample fuel plates consisted of measuring dimensions, weight, uniformity of fuel distribution in the core, location of the core, hardness of the core and cladding, thickness of the cladding, and the quality of the bonds between the core and the cladding.

Post-irradiation examination began by photographing the fuel plates in the MTR canal after removing them from the reactor. Plates selected for the Hot Cell examination were then measured, weighed, and sections mounted for photographing and hardness measurements.

B. RMF Measurements and Results

1. Objectives

The primary objectives of the RMF measurements, the RMF experimental procedure, and the data handling techniques for the sample fuel plates have been presented in a previous report⁽¹⁾. Subsequent to that report, RMF measurements have been made on representative plates of all items of Phase II and on plates of certain items of Phase III which were specially fabricated as RMF calibration standards. The specific objectives of these latest measurements were (1) to improve the accuracy of the technique, (2) to provide an estimate of fuel content before and after irradiation and an estimate of total burnup for various plates of the Phase II series, and (3) to provide a periodic check on the burnup and relative reactivity changes for a selected plate from each of those items containing burnable poisons.

2. Results

a. Accuracy

The previous report indicated three ways for improving accuracy. These were (1) to fabricate a more complete set of standards, (2) to redesign the RMF sample holder and positioning plates so that a greater range of fuel and poison sensitivities could be obtained, and (3) to take all measurements on the RMF's expanded scale.

Several additional standard plates have been fabricated to provide the basis for improved fuel and poison calibrations. Figure 15A shows the latest fuel response curves for the corner and center measurement positions. These are positions 1 and 2 as shown in Figure 15B. These curves are based on seven new fuel

Figure 15A RMF Fuel Calibration Curves

Figure 15B Schematic of RMF Core

calibration plates. Weighting factors for fuel, in $\mu\text{k/gm U}^{235}$ were obtained from these curves for five different ranges of fuel content. The factors are listed in Table VI. Weighting factors for l/v poison were determined from reactivities obtained by measuring three of the above fuel plates with widely differing fuel content to which a single boron tape had been attached. From these values, the responses of the plates without the boron tape were then subtracted and divided by the boron content of the tape to give the poison weighting factors in $\mu\text{k/mg boron}$. These factors are also shown in Table VI.

Redesigned RMF positioning plates and a modified sample holder were made and used during the early stages of the work herein reported. The measurement positions made available by these changes gave a much greater range of fuel and poison sensitivities than was previously possible. Unfortunately, the difficulties involved in changing the sample holder were so great that the setup was judged to be unacceptable for further use. All measurements used in this report were, therefore, made with the old experimental setup.

The expanded scale was used exclusively for all measurements. The reproducibility of several measurements on a sample taken on the same day was found to be about $\pm 0.7 \mu\text{k}$. However, measurements on standard samples show that there are day-to-day drifts in the RMF sufficient to require that some data scaling procedure be followed in order to compare sets of data taken at different times. For sets of data scaled to a standard plate (see previous report), the measurements on a given sample taken at widely differing times were found to be reproducible to about $\pm 1.3 \mu\text{k}$.

b. Estimates of Content and Burnup

Table VII compares initial plate content (fuel and poison) as given by the manufacturer with that calculated by the RMF for most items of Phase II; also included is an RMF estimate of the plate content after receiving the amount of irradiation given in the sixth column. Table VII gives the calculated content as a function of irradiation for plates of items 47, 48, and 49, based on the calibration weighting factors of Table VI.

c. Changes in Relative Reactivity

The changes in relative reactivity of those fuel plates containing burnable poisons are shown in Figures 16 through 19; a plate of item 47, which contains enriched fuel only, was included in each figure for purposes of comparison. In Figures 16, 17 and 18, the relative reactivities are obtained by dividing the net reactivity of each irradiated plate for a given time by its initial reactivity. In Figure 19, relative reactivities are obtained by dividing by the initial reactivity of the plate of item 47.

Figure 16 Fractional Change in Reactivity
(Reactivity Response Relative to Initial Readings)

Figure 17 Fractional Change in Reactivity
(Reactivity Response Relative to Initial Readings)

Figure 18 Fractional Change in Reactivity
(Reactivity Response Relative to Initial Measurements)

Figure 19 Fractional Change in Reactivity
(Reactivity Response Relative to Initial Measurements)

TABLE VI
WEIGHTING FACTORS FOR FUEL AND POISON

(Using U-235 and Boron)

$\mu k = 10^{-6} \Delta k/k$

Fuel Range (Grams)	Weighting Factor Fuel		Weighting Factor Poison	
	Corner Position	Center Position	Corner Position	Center Position
0.0-0.2	587.5	485.0	5.89	2.80
0.2-0.4	565.0	472.0	5.89	2.80
0.4-0.6	530.0	444.5	6.88	3.69
0.6-0.8	491.5	419.0	6.88	3.69
0.8-1.0	426.5	378.0	7.23	4.14

3. Discussion

The fuel calibration curves of Figure 15 are a considerable improvement over the previous calibration which was based in part on fuel tape data. Even though the estimates of fuel content used for the curves were derived from two different sources (the manufacturer for three plates, the Chemical Processing Plant Analytical Section for four plates), they seem to be fairly consistent. It should be noted, however, that the curves cannot be easily extrapolated to zero even though the effect of a blank aluminum plate has been subtracted from the reactivities used. This may indicate that the readings for the aluminum plate are biased. Various analyses of aluminum indicate that boron is present in varying quantities in all alloys of aluminum in common use. A contamination of 1 to 1.5 mg is common for the fuel plates which have been measured (including the fuel standards of Figure 15). If the aluminum plates being used as blank standards contained only 1 mg in excess of the fuel standards, this could easily account for the observed discrepancy. The poison weighting factors (Table VI) show a definite correlation between sensitivity to poison and quantity of fuel present. Previously, constant values for the poison weighting factors had been assumed since no information for poison response in the presence of quantities of U235 of less than about 0.9 gm were obtainable.

Although the fuel and poison calibrations are on a much sounder basis, other attempts to improve the measurement technique were less successful. The modified sample holder for use in the MTR was found to be mechanically unworkable. The long-term reproducibility for measurements on the expanded scale of $\pm 1.3 \mu k$ is the same as was previously obtained with the ordinary scale. Daily reproducibility of $\pm 0.7 \mu k$ is somewhat better than with the ordinary scale ($\pm 1.0 \mu k$). Thus, errors in reading are probably due to faulty sample positioning and an insufficient number of measurements of standard samples to insure proper

scaling of the data. For variations of $\pm 1.3 \mu\text{k}$, the maximum error in estimated content would be $\pm 0.015 \text{ gm U}^{235}$ and $\pm 0.9 \text{ mg boron}$; minimum detectability in the RMF is about 1 mg for U^{235} and 0.1 mg of boron (assuming $0.5 \mu\text{k}$ to be the minimum reproducibility of a measurement).

The principal importance of plotting the relative reactivity curves is to provide a useful check on the self consistency of the reactivity measurements and the flux data. The curves described below were at least qualitatively predictable with exceptions as noted. Certain of the most recent figures (for items 38, 39, 40, 41 and 47) show an initial downward curvature which was not formerly observed. No definite reason can be given for this variation. Measurements would have to be taken at shorter intervals to indicate more clearly the response in this region.

The relative reactivity curves for items 38 through 41 are somewhat inconclusive. Except for item 40, the curves show little variation from that observed for item 47 to which they are compared. This is probably because the macroscopic cross sections of the burnable poisons are insignificant when compared with that of the U^{235} . For each item, the relative changes in reactivity in the two positions were identical within experimental error. Item 40 (Figure 17) shows a peculiar response which is likely attributable to a faulty flux reading between the first and second readings. Any error in flux reading would, of course, be cumulative.

The curves of Figures 18 and 19 show the responses of three items (47, 48 and 49) whose fuel content is essentially the same. About 8 mg of boron are present in the latter two items but in the case of item 48, it has been added as elemental boron and in item 49 as boron carbide. The form in which the boron is present apparently has no significant influence on the reactivity responses observed; the burnup curves for items 48 and 49 are nearly identical. However, the quantity of poison used in these items has a more pronounced effect on their burnup curves than did the smaller amounts present in items 38 through 41. When expressed as a function of original reactivity (as in Figure 18), the plates containing poison consistently show a higher proportion of their original reactivity. When plotted as a function of the original reactivity of item 47, it is seen that the reactivities of items 48 and 49 converge to that of item 47 as their poison burns out. The net response of plates with this amount of added boron is noticeably dependent upon the position in which the plates are measured. This is due to relative differences in fuel and poison response. However, extrapolation of these reactivity responses to give the response in some hypothetical measurement condition is not possible because of the limited range of measurement conditions available in the RMF's highly thermalized center hole. An RMF lattice position would be necessary to approximate MTR conditions; at the present time, this is impossible. The fourth points of each of the curves appear at first glance to be faulty reactivity readings. However, it was discovered that the RMF measurements for these points were taken the same day that the plates were removed from the MTR. Thus, there is included a substantial poison

TABLE VII
ESTIMATES OF FUEL PLATE CONTENT

Plate Number	Manufacturer's Estimate		RMF Pre-Irradiation Estimates		RMF Post-Irradiation Estimates			U-235
	U-235 (grams)	Poison* Equivalent Boron (mg)	U-235 (grams)	Poison Equivalent Boron (mg)	Cumulative Irradiation (nvtx10 ⁻²⁰)	U-235 (grams)	Poison Equivalent Boron (mg)	U-235 Burnup %
22-3	0.816		0.819		21.17	0.180	0.69	78.0
24-4	0.815		0.802		20.54	0.214	0.72	73.3
25-5	0.832		0.812		22.50	0.185	1.20	77.2
28-6	0.848	0.32	0.838	1.14	†			
29-9	0.816	0.19	0.796	0.44				
30-9	0.866	0.09	0.838	0.17				
32-3	0.0142	0.33	0.016	0.85				
33-3	0.0621	0.33	0.058					
34-12	0.819	0.53	0.820	1.29				
35-4	0.820	0.54	0.819	1.13				
38-6	0.712	1.70	0.709	2.38	6.73	0.462	1.10	34.8
39-4	0.716	3.72	0.709	3.89	7.08	0.431	1.70	39.2
40-4	0.715	3.73	0.698	3.92	6.69	0.485	2.34	30.5
41-3	0.720	3.75	0.709	4.46	5.54	0.486	3.07	31.5
42-3	0.711	3.50	0.707	3.94	4.82	0.518	2.13	26.7
47-4	0.776		0.760	1.07	4.53	0.550	1.06	27.6
48-3	0.777	7.90	0.736	8.61	4.88	0.550	2.71	25.3
49-2	0.775	7.83	0.742	8.68	4.85	0.538	1.95	27.5

* Equivalent boron estimates (column 3) are obtained by assuming that absorption effects are proportional to thermal cross sections.

† Information not yet available for items 28 through 35.

effect due to the xenon transient. This result is also confirmed by the calculations for poison content in Table VII.

The calculated values of initial plate content given in Table VI check fairly well with the manufacturer's estimates. The U^{235} estimates agree on the average to within about 14 mg. The calculations for burnable poison expressed as equivalent boron agree to within 0.6 mg. These variations compare well with those predicted on the basis of reproducibility.

The response of U^{238} even in the lower enrichments is so small that its effect cannot be accurately measured. However, there seems to be some indication that resonance absorption is sufficiently large so that boron does not provide a realistic calibration for U^{238} . The poison effect of U^{238} is two to three times that predicted on the basis of its thermal cross section.

4. Conclusions of RMF Work

The RMF seems to provide a fairly accurate means of non-destructively analyzing the contents of the sample fuel plates. The calculated values for the initial U^{235} and equivalent boron content check reasonably well with the manufacturer's estimates. The U^{235} calculations for the irradiated plates should be nearly as accurate as for the unirradiated plates. However, fuel calibration suffers from the lack of a boron-free aluminum plate as a reference standard. Poison cross sections can be less accurately estimated for the following reasons: (a) The amounts of burnable poisons being used are too small for accurate detection in the RMF positions available at this time. (b) The presence of boron as a contaminant in the cladding material makes the poison calibration difficult and questionable.

Relative reactivity curves are useful primarily as a check on the consistency of the data. Errors in flux measurements can be detected as an offset in the curve, while an error in reactivity reading is indicated simply by a point not lying on the curve. Certain qualitative observations can also be made. But it is not possible to draw any significant conclusions for any other reactor where the neutron spectra or importance vary from that found in the measurement positions used in the RMF.

Some additional improvements in the measurement technique are now underway. Several blank aluminum plates of varying purities have been made so that the displacement effect of the aluminum can be properly evaluated. Several poison standards have also been made so that the dependence upon boron tape for poison calibration can be eliminated. The primary difficulty with the poison standards thus far has been the inability to obtain accurate chemical analyses of the boron content of the plates. It should be pointed out that calibration for non-1/v poisons is nearly impossible because of the lack of a measuring position in the lattice of the RMF.

TABLE VIII

ESTIMATES OF FUEL PLATE CONTENT vs. CUMULATIVE IRRADIATION

RMF ESTIMATES

Item Number	Cumulative Irradiation (nvt x 10 ⁻²⁰)	U ²³⁵ (grams)	Equivalent Boron (mg)
47	0.00	0.760	1.07
	0.86	0.704	1.94
	1.99	0.646	0.90
	3.04	0.605	4.94
	4.53	0.550	1.06
48	0.00	0.736	8.61
	0.86	0.696	6.69
	1.95	0.643	4.44
	3.32	0.589	8.18
	4.88	0.550	2.71
49	0.00	0.742	8.68
	0.86	0.696	6.69
	2.00	0.641	4.20
	3.33	0.591	8.01
	4.85	0.538	1.95

It is intended eventually to use the ARMF for the reactivity measurements. A positioning plate for use in the ARMF has already been fabricated and fuel and poison calibrations for that reactor are now being worked out. Fortunately, the ARMF greatly reduces the problems of accuracy noted for the RMF. Not only is the long term reproducibility better ($\pm 0.5 \mu k$) but the choice of fuel and poison sensitivities is more favorable. Use of the ARMF for irradiated plates at present is not feasible in most instances because the transfer tube from the MTR canal to the ARMF has not been completed.

C. Radiation Effects

1. Pictures of Fuel Plates Taken in MTR Canal

After each reactor cycle, the sample fuel plates were removed and photographed in the MTR canal. An attempt was made to keep all of the conditions the same from one time to the next but the varying conditions of the canal water affected the brightness of plate pictures in successive photographs.

The effect of irradiation on the external appearance of the fuel plates is shown in Figure 20 for six different aluminum alloy claddings - 1100 Al, 6061 Al, APM M257 Al, X8001 Al, X8003 Al, and 5052 Al. Except for the cladding material, all six plates in Figure 20 were identical. The core was a fully-enriched U-Al alloy containing 18 weight per cent uranium. It is interesting to note the outline of the core on all the irradiated plates. The mottled surface of the APM M257 plate after irradiation seems to be a characteristic of that alloy.

Figure 21 is a comparison of 6061 and APM M257 claddings during the irradiation of two plates with cores having a high uranium content (~ 45 wt %). The effect of the uranium content on the same cladding alloy during irradiation is shown for APM M257 in Figure 22. The core outline and especially the mottling of the M257 is quite evident in these photographs. The cause and effect of this is yet to be determined.

2. Alloys

Uranium-aluminum alloy fuel plates were fabricated from natural and fully-enriched uranium. Plates made from the natural uranium were 35 weight per cent uranium while the fully-enriched uranium was made into 18 to 23 weight per cent, 35 weight per cent, and 45 weight per cent uranium plates. Table IX shows the weight, thickness, and hardness changes as a function of U^{235} burnup for 18 to 23 weight per cent, fully-enriched uranium-aluminum plates. These data show that the dimensional stability and corrosion resistance of the plates have been good. It is interesting to note that the greatest hardness change has occurred in the matrix and the least in the cladding.

Fig. 20

Photos of Sample Fuel Plates as they appear under 7 feet of water in the MTR canal after being irradiated for various periods. All plates contain 18 wt% U-Al. alloy cores.

Unirradiated

8% U^{235} Burnup

20% U^{235} Burnup

35% U^{235} Burnup

50% U^{235} Burnup

A. 6061 Al Alloy Cladding

-
- 17

B. APM M257 Al Alloy Cladding

Figure 21 Appearance after Irradiation of Two Al Alloy Claddings on Fully-Enriched, 45 wt% U-Al Alloy Cores

8% U²³⁵ Burnup

20% U²³⁵ Burnup

35% U²³⁵ Burnup

A. 18 wt% U-Al Alloy Core

B. 32 wt% U-Al Alloy Core

C. 45 wt% U-Al Alloy Core

Figure 22 Appearance after Irradiation of APM M257-Clad Fuel Plates
Containing Cores with Different Uranium Percentages

TABLE IX
AVERAGE WEIGHT, SIZE, AND HARDNESS CHANGE
OF 18 - 23 WT %, FULLY-ENRICHED U-AL ALLOY FUEL PLATE
AFTER IRRADIATION

% U ²³⁵ Burnup	% Change in Weight	% Change in Thickness	% Change in Hardness		
			Cladding	Matrix	Particle
13 - 30	0.04	3.36			
30 - 50	0.31	2.17	70	391	182
50 - 83	0.38	1.98	30	380	375

The photomicrographs of specimens from 18 weight per cent U-Al alloy fuel which were irradiated to 51% and 69% U²³⁵ burnup are shown in Figure 23. The amount of fission gas buildup is small and the particles of intermetallic compounds exhibit surface irregularities. Most of the U-Al₄ particles have a region around them which could indicate the matrix is receiving fission damage since the particles have a higher U concentration. The regions are more pronounced as the burnup is increased as shown by Figure 23. The specimen with higher burnup also displays a longitudinal crack in the fuel core.

The 35 wt % natural U-Al alloy sample fuel plates were irradiated to a maximum of 27.7×10^{20} thermal neutrons/cm². Figure 24 shows the microstructure of these plates. The intermetallic particles tend to become rounded under irradiation. The fractures in the particles produced during rolling tend to become healed during irradiation. At the 85% burnup level, some porosity is evident.

3. Cermets

a. UO₂

The fuel plate program included plates containing up to 65 weight per cent UO₂ dispersed in aluminum. Irradiation of UO₂-Al cermets to a maximum burnup of 77% U²³⁵ has been accomplished. The average percentage change in weight, thickness, and hardness for UO₂ cermets vs. U²³⁵ burnup is shown in Table X (Table XVIII and XIX in the appendix lists the values before and after irradiation for each plate).

In general, these plates have shown about the same corrosion resistance as the alloy-cored plates, which was to be expected. They have proven to be slightly more stable. This is interesting because, as the photomicrographs show (Figures 26 - 35

M-692 24-13

HF Etched

500X

A. Unirradiated

M-569 22-15

HF Etched

500X

B. 51% U²³⁵ Burnup

M-659 22-16

HF Etched

500X

C. 69% U²³⁵ Burnup

Figure 23 Changes in Microstructure with Irradiation of
18 wt% Fully-Enriched U-Al Alloy

M-693 32-7

M-628 32-9

HF Etched

500X

A. Unirradiated

HF Etched

500X

B. 47% U^{235} Burnup

M-722 32-10

HF Etched

500X

C. 85% U^{235} Burnup

Figure 24 Change in Microstructure with Irradiation of
35 wt% Natural U-Al Alloy

there is some porosity to be found in the irradiated cermet-cored plates. The increase in hardness of the cladding and matrix material is about the same as was experienced in the alloy-cored plates. However, the UO_2 particles decrease in hardness upon irradiation.

TABLE X
AVERAGE WEIGHT, SIZE, AND HARDNESS CHANGES IN FUEL PLATES
WITH CORES OF UO_2 -Al CERMETS - AFTER IRRADIATION

Composition	% Change in Weight	% Change in Thickness	% Change in Hardness		
			Cladding	Matrix	Particle
UO_2 + Al (15 - 30% B.U.)	0.19	2.55	33	133	- 7
UO_2 + Al (30 - 50% B.U.)	0.31	1.70	57	199	4
UO_2 + Al (50 - 77% B.U.)	0.29	2.62	36	272	-39

20% enriched, 54 weight per cent UO_2 dispersed in Al indicates (Figure 25) nearly complete reaction of the UO_2 with the Al after 56% U^{235} burnup. Little evidence of porosity is noted, and the plate exhibited good stability.

A series of intermediate enrichment fuel compositions (30, 40, 60, and 80%) were irradiated to determine radiation stability and if any differences in reactivity throughout the burnup cycle could be correlated with the degree of enrichment.

Each enrichment was prepared by blending fully-enriched uranium-oxide with depleted material. The weight per cent of the UO_2 -Al core dispersion was then adjusted (32 - 54%) so that for each composition, the total U^{235} content remained constant. Irradiations were carried to 47% burnup of the U^{235} and reactivity measurements made at intervals during the irradiation. Within the sensitivity of the RMF, no significant differences were observed. The radiation damage observed on individual particles of UO_2 (apparently the particles from the fully-enriched starting material) was comparable to that found in fully-enriched samples containing the same total U^{235} and irradiated to the same burnup. This effect can be seen in Figures 25, 26, 27, 28, and 29.

Although these results would seem to indicate no advantage of intermediate enrichments, it should be noted that the maximum amount of U^{235} permitted in the samples for irradiation did not allow a very wide range of sensitivity for the RMF. Also, if all of the fuel

M-472 1-15

As Polished

520X

A. Unirradiated

M-263 1-21

As Polished

500X

B. 56% U^{235} Burnup

Figure 25 Microstructure of 20% Enriched, 54 wt% UO_2
Dispersed in Al

M-511 28-10

As Polished

520X

A. Unirradiated

M-726 28-1

As Polished

500X

B. 47% U^{235} Burnup

Figure 26 Microstructure of 30% Enriched, 52 wt % UO_2
Dispersed in Al

M-474 29-4

As Polished

520X

A. Unirradiated

M-708 29-1

As Polished

500X

B. 47% U^{235} Burnup

Figure 27 Microstructure of 40% Enriched, 42 wt% UO_2
Dispersed in Al

M-355 30-13

As Polished

500X

A. Unirradiated

M-706 30-1

As Polished

500X

B. 47% U²³⁵ Burnup

Figure 28 Microstructure of 60% Enriched, 40 wt% UO₂
Dispersed in Al

M-606 31-5

As Polished

520X

A. Unirradiated

M-724 31-7

As Polished

500X

B. 47% U^{235} Burnup

Figure 29 Microstructure of 80% Enriched, 32 wt% UO_2
Dispersed in Al

particles had a homogenized enrichment for any one composition, the radiation damage would have been less concentrated in any one particle.

Sample fuel plates containing fully-enriched 6.1 weight per cent to 16.8 weight per cent UO_2 were irradiated to 71% U^{235} burnup. Figure 30-A is a microstructure of a fully-enriched, 11.6 weight per cent UO_2 unirradiated sample for comparing with the irradiated plates. Figures 30-B through 32 show the extent of reaction for the different burnups; the higher the burnup, the greater the reaction zone and the greater the amount of cracking of UO_2 . Cracks were observed in some UO_2 particles extending between some of the gas pockets in the particles. The UO_2 particles lost their irregularity and exhibited two zones around the particles after irradiation. Additional samples containing loadings of UO_2 up to 65 weight per cent are being irradiated.

The change due to small additions of burnable poisons, such as B, B_4C , Dy_2O_3 , Gd_2O_3 and Ir, could not be detected in the microstructures in Figures 33 and 34. The effect of these poisons on the reactivity of the plates is being studied by use of the RMF. A duplex plate containing two different fuel compositions and a burnable poison in one-half showed no detectable change in Figure 35.

b. U_3O_8

Sample fuel plates were fabricated containing U_3O_8 dispersed in aluminum. Small quantities of natural B or natural B_4C were added to several plates to study the effect of burnable poisons. Figures 36 and 37 show the microstructures of these plates after irradiation to 25% U^{235} burnup. It is evident that the U_3O_8 particles reacted as much or more with the aluminum as did the UO_2 . It also appeared that the U_3O_8 had more porosity than the UO_2 which could be due to the fine stringering of the U_3O_8 powder in these particular samples. No effects of the poisons were evident.

It was desired to investigate the microstructure of identical plates exposed to a given irradiation at different rates. The work in this area has just been started but, as shown in Figure 38, there are possible rate effects on two plates of fairly close composition. The reaction zone in the plate with the higher irradiation rate ($\sim 1 \times 10^{14}$ n/cm² sec) was more pronounced than that irradiated at the lower rate ($\sim 0.7 \times 10^{14}$ n/cm² sec).

Not enough U_3O_8 plates were irradiated to give a representative comparison of percentage changes in weights, size, and hardness due to irradiation.

D. Effect of Heating Fuel Samples

To assist in studying the reaction zones around UO_2 and U_3O_8 fuel particles dispersed in aluminum, specimens from sample fuel plates were heat treated (600°C for 40 hours) to obtain reaction of fuel particles with aluminum. Not all of the specimens reacted and, in several cases, only a portion of the particles within a specimen reacted.

M-698 51-12

As Polished

A. Unirradiated

M-592 51-6

As Polished

500X

B. 38% U^{235} Burnup

Figure 30 Microstructure of Fully-Enriched 11.6 wt% UO_2
Dispersed in Al

An X-ray diffraction analysis made on a sample fuel plate which had been heat treated to produce the UO_2 -Al reaction indicated that Al and U-Al_4 were present, but no UO_2 could be detected, while another sample exhibiting little reaction indicated Al, UO_2 and U-Al_3 in detectable amounts. Another sample from the completely reacted specimen was selectively dissolved to remove the aluminum leaving intermetallic compounds and possibly UO_2 . A powder diffraction pattern on this sample indicated all U-Al_4 and no UO_2 .

A specimen cut from a heated sample fuel plate containing UO_2 dispersed in aluminum was examined by electron beam micro-analysis. The average of a number of X-ray intensity measurements indicated that the intensity ratios from the particles were 0.096 for Al and 0.547 for U. It has been noted in the literature that the reaction between UO_2 and Al results in Al_2O_3 and U-Al_4 with some U-Al_3 being possible⁽¹⁵⁾. The corresponding intensity ratios calculated for U-Al_4 are about 0.017 for Al and 0.73 for U (68 weight per cent U, 32 weight per cent Al). Therefore, the calculated and measured intensity ratios disagree if the constituent is U-Al_4 . A fair approximation to the measured values may be obtained if it is assumed that the particle consists of 70 - 80 volume per cent U-Al_4 and 20 - 30 volume per cent Al_2O_3 , but this does not agree with experimental evidence. Pure Al_2O_3 is known to exhibit visible fluorescence when struck by the electron beam but no optical fluorescence was noted during the investigation. Poor correlations is also obtained if it is assumed that the particle is represented by a mixed oxide and, therefore, contains a ternary compound of U, Al, and oxygen⁽¹⁶⁾.

Powders of 50 weight per cent, special-dense UO_2 (-325 mesh) and Al (-325 mesh) were pressed into a number of pellets having different densities and then rolled into sample fuel plates for reaction zone studies. After heat treating the plates the core of the sample, pressed at 75 tsi, had increased 25% in thickness, while the samples pressed at 25 and 50 tsi showed no thickness change. When the samples were examined metallographically, the 75 tsi sample indicated complete reaction of the UO_2 with Al, the 50 tsi sample showed a little reaction, and there was no reaction in the 25 tsi sample. Several more sample fuel plates which were heat treated are shown in Figure 39. The more highly-enriched, lower weight per cent UO_2 dispersion in Al showed much more reaction after heating at 600°C for 43 hours than did the lower-enriched, higher weight per cent sample which had been heated for 52 hours. It is apparent that the nature (i.e., particle size, method of preparation of the oxide, and O/U ratio) of the fuel particles definitely influences the U-Al reaction.

M-677 50-5

As Polished

500X

A. 22% U^{235} Burnup

M-585 50-10

As Polished

500X

B. 55% U^{235} Burnup

Figure 31 Microstructure of Fully-Enriched 6.1 wt% UO_2 Dispersed in Al

M-675

As Polished

500X

A. 30% U^{235} Burnup

M-460

As Polished

500X

B. 50% U^{235} Burnup

Figure 32 Microstructure of Fully-Enriched 16.8 wt% UO_2
Dispersed in Al

M-686 39-12

M-841 39-5

As Polished

520X

A. Unirradiated

As Polished

500X

B. 19% U^{235} Burnup

M-838 39-6

As Polished

500X

C. 37% U^{235} Burnup

Figure 33 Microstructure of Fully-Enriched 18.7 wt% UO_2
+ 0.951 wt% Dy_2O_3 Dispersed in Al

M-489 40-9

As Polished

500X

A. 19% U^{235} Burnup

M-844 40-10

As Polished

500X

B. 40% U^{235} Burnup

Figure 34 Microstructure of Fully-Enriched 18.7 wt% UO_2
+ 0.37 wt% B + 0.505 wt% Dy_2O_3 Dispersed in Al

As Polished

A. Upper Half of Plate - Fully Enriched 27.3 wt% UO_2
Dispersed in Al

As Polished

500X

B. Lower Half of Plate - Fully Enriched 23.8 wt% UO_2
+ 0.08 wt% B Dispersed in Al

Figure 35 Microstructure after Irradiation to 41% U^{235} Burnup
of a Duplex UO_2 Plate

As Polished

520X

A. Unirradiated

As Polished

500X

B. 25% U^{235} Burnup

Figure 36 Microstructure of Fully-Enriched 22.3 wt% U_3O_8 Dispersed in Al

As Polished

500X

- A. Fully-Enriched 22.3 wt% U_3O_8 + 0.0018 wt% B-Nat.
Dispersed in Al Irradiated to 24% U^{235} Burnup

M-658 49-9

As Polished

500X

- B. Fully-Enriched 22.3 wt% U_3O_8 + 0.023 wt% B_4C -Nat.
Dispersed in Al Irradiated to 20% U^{235} Burnup

Figure 37. Microstructures of U_3O_8 Cermet with Burnable Poisons
After Low Irradiation

As Polished

500X

A. Fully-Enriched 23.8 wt% UO_2 Dispersed in Al
Irradiated for 24 Weeks

M-460 52-8

As Polished

500X

B. Fully-Enriched 16.8 wt% UO_2 Dispersed in Al
Irradiated for 33 Weeks

Figure 38 Microstructure Comparison of Two Similar Plates Irradiated
to $\sim 48\%$ U^{235} Burnup at Different Rates

As Polished

250X

A. 43 Hours Heat Treatment. 60% Enriched, 50 wt% UO_2
Dispersed in Al

M-35 35-15

As Polished

500X

B. 52 Hours Heat Treatment. 20% Enriched, 65 wt% UO_2
Dispersed in Al

Figure 39 Microstructures of UO_2 Dispersed in Al and Heat-Treated
at 600°C

IV. PROTOTYPE STUDIES

Advances in both engineering and materials are tested in prototype form as a final pre-reactor proving medium. Current tests include multi-plate, rounded concentric square, roughened plate fuel elements and a renewable fuel shim rod. The advantage of the multi-plate element has been demonstrated and the manufacture of two fully-enriched elements is presently in progress. The rounded concentric square fuel element has been designed and a prototype for hydraulic evaluation is in construction. The roughened plate fuel element has been tested hydraulically (as reported below) and optimized in preparation for heat transfer tests. The renewable fuel shim rod has been tested hydraulically, is currently undergoing some minor engineering changes and should soon be ready for in-pile evaluation.

A. Roughened Heat Transfer Surfaces

Most test reactors depend on forced convection for cooling. As a potential method of increasing the efficiency of convective cooling, roughened fuel plates have been tested hydraulically. Artificial roughening of the heat transfer surface increases the turbulence (for a particular Reynolds number), thereby reducing the laminar film and enhancing the heat transfer. Several analogies between the heat transfer coefficient, h , and the friction factor, f , are available, the most common probably being the Colburn analogy:

$$\left(\frac{h}{V C_p}\right) \left(\frac{C_p \mu}{k}\right)^{2/3} = \frac{f}{2}$$

where

h	=	heat transfer coefficient, Btu/hr-ft ² -°F
V	=	velocity, ft/hr
ρ	=	density, lb/ft ³
C_p	=	heat capacity, Btu/lb-°F
μ	=	viscosity, lb/hr-ft
k	=	thermal conductivity, Btu/hr-ft ² -°F
f	=	friction factor

It should be possible to obtain a measure of the heat transfer coefficient by evaluating the friction factor. In order to do this, seven pairs of aluminum plates of ETR fuel plate dimensions have been roughened to differing degrees by knurling, as shown in Figure 40. The knurling put depressions in the plates which run at right angles to the direction of flow. Each pair of plates was assembled to form an ETR flow channel roughened on both inside surfaces. The friction loss was measured for the channels at Reynolds numbers from 2×10^4 to 1×10^5 . The resulting friction factors were considerably above those for a smooth tube, indicating that the heat transfer coefficient is correspondingly increased.

Scale

Plate

Mount

Scale

Plate

Mount

$$\epsilon/d = 0.025$$

$$\epsilon/d = 0.025$$

Figure 40 Sections of Plates Roughened by Knurling, mag=21X.
Scale shows 0.01 in.

$$\epsilon/d = 0.039$$

$$\epsilon/d = 0.60$$

Scale

Plate

Mount

$$\epsilon/d = 0.094$$

Scale

Plate

Mount

Figure 40 (Cont.) Sections of Plates Roughened by Knurling
Mag = 21X. Scale shows 0.01 in.

Vennard(17) analyzed the laminar film thickness and the distance the roughness must protrude, ϵ , to affect the friction factor. Table XI shows the degree of roughness, based on the work of Vennard, required to affect the friction factor in the Reynolds number range of interest. This work is applicable to the knurled plates only if the large areas between the knurl grooves can be considered protrusions. The roughness effect on the friction factor, f , would be expected to be proportional to the degree of roughness, ϵ/d . (ϵ/d is a dimensionless ratio of roughness protrusion height to hydraulic diameter.) This is the case in Figure 41 except for one set of data taken from plates with an ϵ/d of 0.025 (shown in the figure by Δ) that had a greater effect than anticipated. This discrepancy may very well be due to the choice of samples used in evaluating ϵ/d . Due to the roughening technique employed, the roughness may vary considerably over the length of the plate if the plate thickness is not held within very close tolerances.

The degree of roughness was optimized for reactor conditions on an IBM-650. Using the assumption that the film heat transfer coefficient increases proportionally to the friction factor, a friction factor of 0.025 was found to yield the minimum hot spot-hot channel wall temperature for the MTR. The roughness that produces this friction factor ($\epsilon/d = 0.060$) should reduce the hot spot-hot channel maximum in the MTR from 316°F to 225°F or permit pumping only 68% as much coolant or increasing the power 86% with existing hot spot-hot channel wall temperatures.

Table XII shows the potential power increase or coolant savings permitted by roughening the fuel plates or increasing the number of plates per element for both the MTR and ETR.

TABLE XI
RELATIVE ROUGHNESS VALUES

Reynolds Number	Undisturbed Laminar Film Thickness, in.	ϵ/d Inception of Roughness	ϵ/d Complete Turbulence
3×10^4	1.5×10^{-3}	1.78×10^{-3}	4.33×10^{-2}
10^5	5×10^{-4}	6×10^{-4}	1.44×10^{-2}

TABLE XII
FUEL ELEMENT OPTIMIZATION

	<u>MTR</u>	<u>ETR</u>
1. Hot element power - megawatts/liter	0.832	1.087
2. Metal-to-water ratio	0.6362	0.6655
3. Number of plates (standard)	19	19
4. Potential increase in power at same metal-to-water ratio		
a. Yielding existing hot element nominal wall temperature		
(1) With optimum roughness, 19 plates	(ϵ/d of .060) 81%	(ϵ/d of .015) 20%
(2) With optimum practical number of smooth plates	(32 plates) 46%	(28 plates) 16%
b. Yielding existing hot spot-hot channel wall temperature		
(1) With optimum roughness	(ϵ/d of .060) 86%*	(ϵ/d of .028) 33%
(2) With optimum practical number of plates	(32 plates) 47%	(30 plates) 25%
5. Potential reduction in pumping rate at same metal-to-water ratio		
a. Yielding existing hot element nominal wall temperature		
(1) With optimum roughness	(ϵ/d of .060) 66%	(ϵ/d of .015) 34%
(2) With optimum practical number of plates	(32 plates) 44%	(28 plates) 21%
b. Yielding existing hot spot-hot channel wall temperature		
(1) With optimum roughness	(ϵ/d of .060) 68%**	(ϵ/d of .028) 47%
(2) With optimum number of plates	(32 plates) 44%	(30 plates) 30%

* Yields outlet bulk temperatures exceeding saturation

** Yields outlet bulk temperatures at saturation if inlet pressure is maintained.

B. Heat Transfer and Hydraulics

Some of the aims of the Fuel Element Development program are to improve existing fuel element designs and to develop and test more advanced concepts. Fuel element designs are compared by evaluating their hydraulic and heat transfer potentials. Hydraulic evaluations of many fuel elements have been conducted by Phillips in the last few years⁽¹⁸⁾. The first heat transfer tests have concerned flat plate fuel elements in forced convection. It was hoped that one of the existing correlations, based principally on heat transfer data taken in circular tubes, would adequately predict forced convection heat transfer rates and temperatures in rectangular, high aspect-ratio flow channels. Several tests were run in an ETR flow channel (0.110" x 2.624" x 36" long). The data shown in Figure 42 were taken with a 21" hydraulic entrance length, 6" of it heated. The modified Colburn equation, shown in the figure, seems to correlate the data as well as any of the standard equations. It is apparent that heat transfer to the rectangular channels differs considerably from heat transfer to circular channels, particularly in the low power range. (Relative power is indicated by the 5, 10 and 15-volt data points that correspond approximately to 10^5 , 3.5×10^5 and 7×10^5 Btu/hr-ft², respectively.) This difference is seen better in Figure 43. Since extrapolation of any of the existing correlations to the high aspect ratio, rectangular flow channels seemed questionable, and establishing a new correlation is a long and tedious process, it was decided to measure the heat transfer rates and temperatures that would exist in the ETR under the most severe case. The power generation curve shown in Figure 4, IDO-16562⁽¹⁹⁾, was used to evaluate the bulk temperature at the hot spot for a given hot spot-heat flux. The coolant velocity was maintained at 35 ft/sec and the hot spot pressure was maintained at 170 psia. The data taken to date are shown in Figure 44. The modified Colburn equation seems to predict conditions fairly well over the convective range tested. Relating the three figures, it seems that for rectangular flow channels, the use of the modified Colburn equation below heat fluxes of 10^7 Btu/hr-ft² is questionable.

Above heat fluxes of 7×10^5 Btu/hr-ft², the use of the modified Colburn equation with a 20% safety factor, as recommended in IDO-16343⁽²⁰⁾ seems to be safe enough. Figure 44 indicates that the safe limits for the specific case of the ETR extends down to 3×10^5 Btu/hr-ft². The data indicate little dependence of the heat transfer coefficient on the film temperature. It appears that a correlation based on bulk coolant properties, such as the Dittus -Boelter equation, is more appropriate for ETR conditions.

The nucleate boiling data taken to date are quite limited but it looks like they may approach the Jens & Lottes correlation (see Figure 44). It is planned to continue the program until the burnout point is reached.

Figure 41 Effect of Surface Roughening on Friction Factor

Figure 42 Forced Convection Heat Transfer Data in a Simulated ETR Flow Channel

Figure 43 The Effects of Power Variation on the Accuracy of the Modified Colburn Equation as Applied to Rectangular Flow Channels

Figure 44 Heat Transfer to an ETR Flow Channel

V. CONCLUSIONS

During the past year, the Fuel Element Development program has shown that 45 weight per cent uranium-aluminum alloys can be satisfactorily used as core materials in nuclear fuel elements. The limiting factor for their effective use is the fuel element design in order that the heat generated can be removed. However, the thinner cores used with the higher weight per cent of uranium make it possible to use either thinner fuel plates or roughened fuel plates to achieve better heat transfer characteristics.

A number of high strength cladding materials have been investigated. The Aluminum Powder Metallurgy Products (APM's) appear to be the most promising of these because of their superior high temperature strengths and nuclear properties. However, a means must be found to improve their corrosion resistance to de-ionized water at 400°F or above. These high strength aluminum materials have also been shown to be useful in improving the fuel distribution in the fuel plates when used as claddings or picture frame material.

It has been shown that both UO_2 and U_3O_8 , when used in cermet cores with aluminum, exhibit similar radiation damage effects. While the rather low temperatures used for irradiation of the samples in this program to date have caused no gross distortion in the dimensions of the specimens, at higher temperatures this might be a problem. Consequently, the studies into the damage produced in UO_2 or U_3O_8 aluminum cermets by irradiation are continuing.

This program has shown that if it is desired to use oxide fuels of intermediate enrichments, then the isotopic concentration should not be adjusted by the blending of oxides of high and low enrichments. If the enrichment is adjusted in this manner, then the radiation damage is concentrated about the highly enriched particles. This is apt to have an adverse effect on the fuel element life.

VI. FUTURE WORK

A. Materials

In Tables XIII and XIV, the lists of fuel plate compositions for phases IV and V are given. These compositions were selected to further reactor technology by studying the effects of additional types of materials for fuel plate cores and claddings. Beryllium, for example, is being studied because of its superior moderator properties when compared with aluminum. Its low absorption cross section for neutrons would be advantageous in an MTR-type reactor.

In addition to studying the feasibility of fabricating these compositions and determining how well they withstand service in the reactor, other studies are also to be undertaken. For example, the effects of irradiation and temperature on the tensile properties of fuel plates is being determined.

X-ray diffraction studies are underway in an attempt to obtain an understanding of the damage mechanism which is produced on irradiation of uranium oxide-aluminum core materials. Capsule irradiations of various core materials are planned in order to determine if the materials are stable under various conditions of exposure during irradiation.

The amount of poison used in the fuel plates fabricated to date has been so small that it has been impossible to detect any change in metallurgical properties or in the reactivity. Consequently, it is planned to fabricate plates containing only poisons and plates containing larger amounts of poisons with fuel so that the radiation effects can be more readily determined.

A program to study the possibility of using thorium plus U^{233} as reactor fuels has been started. Under the Fuel Element Development program, the stability of this material in reactor service will be determined.

The photographs taken in the MTR canal of the irradiated fuel plates show some interesting effects on the cladding materials. It is planned to improve the corrosion testing procedures as well as the ultrasonic inspection equipment in order to investigate these effects of radiation almost immediately after leaving the reactor.

B. Prototypes

An improved MTR-type fuel element using 32 fuel plates instead of the 19 in the MTR and ETR is about ready for hydraulic testing prior to insertion in the reactor.

A dummy fuel element with an external configuration of an MTR element but with a cross-sectional geometry of a nest of concentric rounded squares is nearing completion. This dummy element is to be tested in order to determine its hydraulic characteristics.

TABLE XIII

PHASE IV SAMPLE FUEL PLATES

Composi- tion	Core Material	Core Thickness (mils)	Clad Material	Clad Thickness (mils)	P.F. Material
74	50 wt% U ²³⁵ , fully enriched, 3 wt% Sn, Al	8	APM 257	12	APM 257
75	50 wt% U ²³⁵ , fully enriched, 3 wt% Sn, Al	8	APM 257 X8001	12 5	APM 257
76	18 wt% U, fully enriched, Al	20	APM 470	15	APM 470
77	50 wt% U ²³⁵ enriched, 3 wt% Sn, Al	8	APM 470	12	APM 257
78	18 wt% U, fully enriched, Al	20	APM 583	15	APM 257
79	50 wt% U, fully enriched, 3 wt% Sn, Al	8	APM 583	12	APM 257
80	18 wt% U, fully enriched, Al	20	2% B as B ₄ C "Binal" 1100 Al	1 14	APM 257
81	18 wt% U, fully enriched, 0.4 wt% Si, 0.2 wt% Cu, .6 wt% Mg, 0.2 wt% Cr + Al	20	6061 Al	15	APM 257
82	18 wt% U, fully enriched, 0.6 wt% Ni, 0.4 wt% Fe, + Al	20	X8001	15	1100 Al

TABLE XIV

PHASE V SAMPLE FUEL PLATES

Composition	Core Material	Core Thickness (mils)	Clad Material	Clad Thickness (mils)
87	32 wt% UO_2 , fully enriched 8 wt% BeO + 1100 Al	20	1100 Al	15
88	30 wt% U-Al alloy, fully enriched + 1100 Al	10	Be	20
89	18 wt% U-Al alloy, fully enriched	20	Be-Al*	15
90	Th + 1.5% U	70	APM 257	15
91	63.5% (ThO_2 + 1.5% UO_2) fully enriched + Al	70	APM 257	15
92	47 wt% UC, fully enriched + 1100 Al	8	APM 257	20
93	47 wt% UN, fully enriched + 1100 Al	8	APM 257	20
94	47 wt% U_3Si , fully enriched + 1100 Al	8	APM 257	20

* 40 wt% Be, 60 wt% Al

A program to study the possibility of the use of non-uniformly distributed fuel in ETR elements is being initiated. This will involve a computer program to determine the optimum fuel loading as well as a feasibility study on the fabrication methods for these elements.

Finally, dummy fuel elements of either the MTR or ETR type are to be made using some of the high strength fuel plate compositions which have been developed. These are then to be tested hydraulically in order to demonstrate their improved properties.

VII. ACKNOWLEDGMENTS

The authors and staff wish to thank the Plant Engineering Section for their hydraulic test work, the MTR Hot Cell Section for the work performed on the irradiated samples, and the CPP Analytical Laboratory for the large number of chemical determinations they have performed for this program. Without the support from these groups and many others, this project would not be possible.

VIII. REFERENCES

1. Francis, W. C., Craig, S. E., "Progress Report on Fuel Element Development and Associated Project," Phillips Petroleum Company, IDO-16574, August 16, 1960
2. Alcoa Aluminum Handbook, Aluminum Company of America, Pittsburgh, Pa., 1959
3. Binger, W. W., Aluminum Company of America, New Kensington, Pa., personal communication
4. Towner, R. J., "Alcoa's APM Alloys," Aluminum Company of America, Pittsburgh, Pa., September 15, 1960
5. Lubsinger, R. J., "Summary Report on the Corrosion of Aluminum in High Temperature Dynamic Water System," General Electric Company, Richland, Wash., HW-59778, Rev., February 1, 1961
6. Draley, J. E., Ruther, W. E., "Corrosion Resistance and Mechanical Properties of Aluminum Powder Products," Argonne National Laboratory, Lemont, Ill., ANL-5927, March 1959
7. Rohde, K. A., Phillips Petroleum Company, private communication
8. Slansky, C. M., Phillips Petroleum Company, private communication
9. Daniel, N. E., Foster, E. L., Dickerson, R. F., "Effects of Ternary Additions on Aluminum - 35 Wt % Uranium Alloys," Battelle Memorial Institute, BMI-1388, October 27, 1959
10. Cunningham, J. E., Beaver, R. J., Thurber, W. C., and Waugh, W. C., "Fuel Dispersion in Aluminum-Base Elements for Research Reactors," Paper presented at Fuel Element Conference, Paris, 1957
11. Lewis, W. B., Phillips Petroleum Company, private communication
12. Leshan, E. J., Levit, R. J., and Franklin, Joel, "Diffusion Multi-group Multiregion:DMM," IBM 650 Program Library, File No. 8.2.015
13. Brown, A. W., Phillips Petroleum Company, Computer Library Program Number 10-048, 1960
14. Anderson, B. L., Davis, J. A., Gelbard, E. M., Jarvis, P. H., "FLIP - An IBM-704 Code to Solve the P_L and Double P_L Equations in Slab Geometry," Westinghouse Electric Corporation, WAPD-TM-134, March 1959
15. Waugh, R. C., "The Reaction and Growth of Uranium Dioxide-Aluminum Fuel Plates and Compacts," ORNL-2701, March 23, 1959
16. Moll, S. H., Advanced Metals Research Corporation, Somerville, Mass., private communication

References (Cont.)

17. Vennard, J. K., "Elementary Fluid Mechanics," 3rd Edition, pages 202-203, Wiley Publishers, New York (1954)
18. Beck, J. G., "Hydraulics of Modified Fuel Elements for the ETR," Phillips Petroleum Company, IDO-16465, November 1959
19. Walker, V. A., "Heat Transfer in ETR Fuel Assemblies for Cycle 13," Phillips Petroleum Company, IDO-16562, November 6, 1959
20. Nertney, R. J., "Calculated Surface Temperatures for Nuclear Systems and Analysis of Their Uncertainties," Phillips Petroleum Company, IDO-16343, June 1, 1957

APPENDIX - DATA

TABLE XV
PHASE I SAMPLE FUEL PLATES

Composition No.	Plate Composition	Core Thickness (mils)	Purpose							Status			Cladding Thickness (mils) *
			Fuel Stability	Poison Investigation	Fabrication Techniques	High Strength	Graded Fuels	Fertile Material	Calibration Standards	Fabricated	Irradiated	Post-Irradiation Examined	
1	54 wt% UO ₂ , 20% enriched in Al	25	X							X	X		15
2	25 wt % U, 20% enriched in Al alloy	25	X							X	X		15
3	18 wt % U, 93.5% enriched in Al alloy	20			X	X				X	X	X	15
4	22.7 wt% UO ₂ , 93.5% enriched in Al	20	X							X	X	X	15
5	30 wt% UO ₂ , 93.5% enriched in Al	15	X							X	X	X	15
6	45 wt% UO ₂ , 93.5% enriched in Al	10	X							X	X	X	15
7	Upper ½ plate - 23 wt% U, 93.5% enriched in Al alloy Lower ½ plate - 18 wt% U, 93.5% enriched in Al alloy	20			X		X			X	X		15
8	Upper ½ plate - 27.3 wt% UO ₂ , 93.5% enriched in Al Lower ½ plate - 23.8 wt% UO ₂ , 93.5% enriched in Al	20			X		X			X	X		15

Note: One or more plates of each item listed above have been irradiated for at least one cycle in the MTR.

* Material: 1100 Al

TABLE XV (Cont.)

Composition No.	Plate Composition	Core Thickness (mils)	Purpose						Status			Cladding Thickness (mils) *	
			Fuel Stability	Poison Investigation	Fabrication Techniques	High Strength	Graded Fuels	Fertile Material	Calibration Standards	Fabricated	Irradiated		Post-Irradiation Examined
9	Upper $\frac{1}{2}$ plate - 23 wt % U 93.5% enriched in Al alloy Lower $\frac{1}{2}$ plate - 18 wt% U, 93.5% enriched plus .07 wt% B in Al alloy	20		X	X		X			X	X		15
10	Upper $\frac{1}{2}$ plate - 27.3 wt% UO_2 , 93.5% enriched in Al Lower $\frac{1}{2}$ plate - 23.8 wt% UO_2 , 93.5% enriched plus .08 wt% B in Al	20		X	X		X			X	X		15
11	18 wt% U, 93.5% enriched plus .057 wt% B in Al alloy	20		X	X					X	X	X	15
12	18 wt% U, 93.5% enriched plus .115 wt% B in Al alloy	20		X	X					X	X	X	15
13	22.7 wt% UO_2 , 93.5% enriched plus .062 wt% B in Al	20		X	X					X	X	X	15
14	22.7 wt% UO_2 , 93.5% enriched plus .123 wt% B in Al	20		X	X					X	X	X	15
15	18 wt% U, 93.5% enriched plus .0123 wt% Gd_2O_3 in Al alloy	20		X	X					X	X	X	15
16	18 wt% U, 93.5% enriched plus .057 wt% B plus .013 wt% Gd_2O_3 in Al alloy	20		X	X					X	X	X	15

Note: One or more plates of each item listed above have been irradiated for at least one cycle in the MTR.

* Material: 1100 Al

TABLE XV (Cont.)

Composition No.	Plate Composition	Core Thickness (mils)	Purpose							Status			Cladding Thickness (mils)*
			Fuel Stability	Poison Investigation	Fabrication Techniques	High Strength	Graded Fuels	Fertile Material	Calibration Standards	Fabricated	Irradiated	Post-Irradiation Examined	
17	22.7 wt% UO_2 , 93.5% enriched plus .013 wt% Gd_2O_3 in Al	20		X	X					X	X	X	15
18	22.7 wt% UO_2 , 93.5% enriched plus .062 wt% B plus .013 wt% Gd_2O_3 in Al	20		X	X					X	X	X	15
19	18 wt% U, 93.5% enriched in Al alloy	20							X	X	X	X	15
20	100% ThO_2	120			X			X		X	X		15
21	98.5% ThO_2 plus 1.5 wt% UO_2	120	X		X			X		X	X		15

Note: One or more plates of each item listed above have been irradiated for at least one cycle in the MTR.

* Material: 1100 Al

TABLE XVI
PHASE II SAMPLE FUEL PLATES

[illegible]

TABLE XVI (Cont.)

Composition No.	Plate Composition	Clad Material	Clad Thickness(mils)	Core Thickness(mils)	Purpose									Status	
					Fuel Stability	Poison Investigation	Fabrication Techniques	High Strength	Corrosion Resistance	Clad Materials	Clad Thickness	Fertile Material	Calibration Standard	Fabricated	Irradiated
31	32 wt% UO_2 , 80% enriched in Al	1100	15	15	X									X	X
32	35 wt% U, natural in Al alloy	1100	15	20	X									X	X
33	35 wt% U, 3% enriched in Al alloy	6061	15	20	X		X						X		
34	39 wt% UO_2 , 20% enriched in Al	1100	10	45	X									X	
35	65 wt% UO_2 , 20% enriched in Al	1100	22.5	20	X		X							X	
38	18.7 wt% UO_2 , 93.2% enriched in Al + 0.036 wt% B	1100	15	20	X	X	X							X	X
39	18.7 wt% UO_2 , 93.2% enriched + 0.95 wt% Dy_2O_3 in Al	1100	15	20	X	X	X							X	X

TABLE XVI (Cont.)

Composition No.	Plate Composition	Clad Material	Clad Thickness (mils)	Core Thickness (mils)	Purpose									Status	
					Fuel Stability	Poison Investigation	Fabrication Techniques	High Strength	Corrosion Resistance	Clad Materials	Clad Thickness	Fertile Material	Calibration Standard	Fabricated	Irradiated
40	18.7 wt% UO_2 , 93.2% enriched + .037 wt% B + .51 wt% Dy_2O_3 in Al	1100	15	20	X	X	X							X	X
41	18.7 wt% UO_2 , 93.2% enriched + .036 wt% B + 1.275 wt% Ir in Al*	1100	15	20	X	X	X							X	X
42	18.7 wt% UO_2 , 93.2% enriched + .012 wt% Gd_2O_3 + .036 wt% B in Al	1100	15	20	X	X	X							X	X
47	22.3 wt% U_3O_8 , 93.2% enriched in Al	1100	15	20	X	X	X							X	X
48	22.3 wt% U_3O_8 , 93.2% enriched + 0.18 wt% B natural in Al	1100	15	20	X	X	X							X	X
49	22.3 wt% U_3O_8 , 93.2% enriched + 0.23 wt% B_4C natural in Al	1100	15	20	X	X	X							X	X

* Original specifications called for 1.275 wt% Ir_2O_3 but due to fabrication difficulties, an equivalent amount of Ir metal was substituted.

TABLE XVI (Cont.)

Composition No.	Plate Composition	Clad Material	Clad Thickness (mils)	Core Thickness (mils)	Purpose									Status	
					Fuel Stability	Poison Investigation	Fabrication Techniques	High Strength	Corrosion Resistance	Clad Materials	Clad Thickness	Fertile Material	Calibration Standard	Fabricated	Irradiated
50	6.1 wt% UO ₂ , 93.2% enriched in Al	1100	15	20									X	X	X
51	11.6 wt% UO ₂ , 93.2% Enriched in Al	1100	15	20									X	X	X
52	16.8 wt% UO ₂ , 93.2% enriched in Al	1100	15	20									X	X	X

TABLE XVII
PHASE III SAMPLE FUEL PLATES

Composition No.	Plate Composition	Clad Material	Clad Thickness(mils)	Core Thickness(mils)	Purpose									Status	
					Fuel Stability	Poison Investigation	Fabrication Techniques	High Strength	Corrosion Resistance	Clad Materials	Clad Thickness	Fertile Material	Calibration Standard	Fabricated	Irradiated
53	19 wt% U, 93% enriched in Al alloy; 1100 Al picture frame	6061	15	20			X	X		X				X	X
53N	19 wt% U, 93% enriched in Al alloy; 1100 Al picture frame, Ni foil used to promote bonding	6061	15	20			X	X		X				X	X
54	35 wt% U, 93% enriched + 1 wt% Si in Al alloy; APM M257 Al picture frame	6061	10	15	X		X	X		X	X			X	X
55	45 wt% U, 93% enriched + 3 wt% Si in Al alloy; APM M257 Al picture frame	6061	20	10	X		X	X		X				X	X
56	19 wt% U, 93% enriched in Al alloy; 1100 Al picture frame	APM M257	15	20			X			X				X	X

TABLE XVII (Cont.)

Composition No.	Plate Composition	Clad Material	Clad Thickness(mils)	Core Thickness(mils)	Purpose									Status	
					Fuel Stability	Poison Investigation	Fabrication Techniques	High Strength	Corrosion Resistance	Clad Materials	Clad Thickness	Fertile Material	Calibration Standard	Fabricated	Irradiated
57	35 wt% U, 93% enriched + 1% Si in Al; 1100 Al picture frame	APM M257	20	15	X		X	X		X	X			X	X
58	32 wt% U, 93% enriched in Al alloy; 1100 Al picture frame	APM M257	8	16	X		X	X		X	X			X	X
59	45 wt% U, 93% enriched + 3% Si in Al alloy; APM M257 picture frame	APM M257	20	10	X		X	X		X				X	X
60	32 wt% U, 93% enriched in Al alloy; 1100 Al picture frame	X8001	8	16	X		X		X	X	X			X	X
61	19 wt% U, 93% enriched in Al alloy; 1100 Al picture frame	X8002	15	20			X		X	X				X	X

TABLE XVII (Cont.)

Composition No.	Plate Composition	Clad Material	Clad Thickness (mils)	Core Thickness (mils)	Purpose									Status	
					Fuel Stability	Poison Investigation	Fabrication Techniques	High Strength	Corrosion Resistance	Clad Materials	Clad Thickness	Fertile Material	Calibration Standard	Fabricated	Irradiated
62	19 wt% U, 93% enriched in Al alloy; 1100 Al picture frame	X8003	15	20			X		X	X				X	X
63	19 wt% U, 93% enriched in Al alloy; 1100 Al picture frame	5052	15	20			X	X		X				X	X
64	19 wt% U, 93% enriched in Al alloy; APM M257 picture frame	1100	6	20			X				X			X	X
65	0.3 gram U ²³⁵ + 8 mg B	1100	15	20									X	X	Not to be Irradiated
66	0.5 gram U ²³⁵ + 8 mg B	1100	15	20									X	X	
67	0.7 gram U ²³⁵ + 8 mg B	1100	15	20									X	X	
68	0.9 gram U ²³⁵ + 7 mg B	1100	15	20									X	X	
69	1.1 grams U ²³⁵ + 4 mg B	1100	15	20									X	X	

TABLE XVII (Cont.)

Composition No.	Plate Composition	Clad Material	Clad Thickness (mils)	Core Thickness (mils)	Purpose									Status	
					Fuel Stability	Poison Investigation	Fabrication Techniques	High Strength	Corrosion Resistance	Clad Materials	Clad Thickness	Fertile Material	Calibration Standard	Fabricated	Irradiated
70	0.7 gram U ²³⁵ + 8 mg B	1100	15	20									X	X	Not to be Irradiated
71	0.7 gram U ²³⁵ + 9 mg B	1100	15	20									X	X	
72	1.1 gram U ²³⁵ + 12 mg B	1100	15	20									X	X	
73	19% U, 93% enriched + Al; 1100 Al picture frame	X8001	15	20			X		X	X	X			X	X

TABLE XVIII

MICROHARDNESS AND IRRADIATION DATA ON SAMPLE FUEL PLATES

Plate Composition	Composition No.	Plate No.	Average Thermal Neutron Flux $\times 10^{-14}$	No. Cycles in MTR	Total Exposure $20^{(1)}$ $\text{nvt(th)} \times 10^{-20}$	% Burnup U^{235}	Cladding Hardness			Matrix Hardness			Particle Hardness		
							Pre DPN	Post DPN	% Hardness Change	Pre DPN	Post DPN	% Hardness Change	Pre DPN	Post DPN	% Hardness Change
54 wt% UO_2 , 20% enriched + Al cermet core 1100 Al clad	1	21	1.09	8	12.05	56	28	44	57	36	250	590	550	360	- 35
		25	0.86	16	19.01	73									
18 wt% U, 93.5% enriched + Al alloy core 1100 Al clad	3	✓ 4	1.07	4	5.89	33	22	34	54	33	150*	350	38	150*	290
		✓ 6	1.05	6	8.69	45		37	68		160*	380		160*	320
22.7 wt% UO_2 , 93.5% enriched + Al cermet core 1100 Al clad	4	✓ 15	0.88	3	3.66	23	26	33	27	33	93	180	410	150	63
		✓ 18	1.04	8	11.48	55		35	35		110	230		410	
30 wt% UO_2 , 93.5% enriched in Al cermet core 1100 Al clad	5	✓ 10	0.70	4	3.86	23	30	51	70	35	130	270	200	380	90
		17	0.80	19	21.07	77									
45 wt% UO_2 , 93.5% enriched in Al cermet core 1100 Al clad	6	✓ 24	0.59	3	2.45	15	25	44	76	38	120	220	160	280	80
		✓ 22	0.90	7	8.66	45		83	230		230	510		320	100
Upper $\frac{1}{2}$ 27.3 wt%, Lower $\frac{1}{2}$ 23.8 wt% U, 93.5% enriched + Al alloy core 1100 Al Clad	8	17	0.81	8	9.01	46	34			32			200		
		21	0.40	8	4.48	27				32			200		

(1) Based on average 16-day cycle.

✓ Reported in past report

* Particles too small for individual measurements - average values

TABLE XVIII (Cont.)

Plate Composition	Composition No.	Plate No.	Average Thermal Neutron Flux $\times 10^{-14}$	No. Cycles in MTR	Total Exposure $nvt(th) \times 10^{-20}$	% Burnup U^{235}	Cladding Hardness			Matrix Hardness			Particle Hardness		
							Pre DPN	Post DPN	% Hardness Change	Pre DPN	Post DPN	% Hardness Change	Pre DPN	Post DPN	% Hardness Change
Upper $\frac{1}{2}$ 27.3 wt%, lower $\frac{1}{2}$ 23.8 wt% U+.08 wt% B, 93.5% enriched + Al alloy core, 1100 Al clad	10	1	0.80	7	7.75	41	29	45	55	35	100	190	130	390	160
		18	0.80	8	8.83	45					37			150	
18 wt% U, 93.5% enriched + .057 wt% B in Al alloy core, 1100 Al clad	11	5	0.99	4	5.49	31	26	43	65	37	160*	330	77	160*	110*
		2	0.88	6	7.26	39		34	31		130*	250		130*	170*
18 wt% U 93.5% enriched in Al alloy core + .115 wt% B, 1100 Al clad	12	4	1.07	4	5.89	33	22	35	59	33	129*	291	33	139*	291
		5	1.05	6	8.69	44		32	45		139*	321		139*	321
22.7 wt% UO_2 , 93.5% enriched in Al matrix + .062 wt% B, 1100 Al clad	13	3	1.04	4	5.72	32	23	37	61	32	108	237	445	249	- 44
		7	1.10	7	10.61	51		35	52		106	231		253	- 43
22.7 wt% UO_2 , 93.5% enriched in Al matrix + .123 wt% B 1100 Al clad	14	4	1.01	4	5.57	31	29	56	93	38	114	200	473	180	- 66
		5	1.11	5	7.64	40		50	72		148	299		430	- 9
18 wt% U, 93.5% enriched in Al alloy + .0123 wt% Gd_2O_3 , 1100 Al clad	15	2	1.19	4	6.56	36	19	31	63	25	141*	464	25	141*	464
		4	1.09	6	9.00	46		45	137		161*	544		161*	544

* Particles too small for individual measurements - average values

TABLE XVIII (Cont.)

Plate Composition	Composition No.	Plate No.	Average Thermal Neutron Flux $\times 10^{-14}$	No. Cycles in MTR	Total Exposure $\text{nvt(th)} \times 10^{-20}$	% Burnup U^{235}	Cladding Hardness			Matrix Hardness			Particle Hardness		
							Pre DPN	Post DPN	% Hardness Change	Pre DPN	Post DPN	% Hardness Change	Pre DPN	Post DPN	% Hardness Change
18 wt% U, 93.5% enriched + .057 wt% B + .013 wt% Gd_2O_3 in Al, 1100 Al clad	16	3	1.20	4	6.65	36	18	34	89	29	125*	331*	29	125	331
		4	1.09	6	9.00	46		32	78		139*	495*		139	495
22.7 wt% UO_2 , 93.5% enriched + 0.013 wt% Gd_2O_3 in Al cermet core + 1100 Al clad	17	✓5	0.87	3	3.62	22	33	49	48	32	110	240	690	150	- 78
22.7 wt% UO_2 , 93.5% enriched + .062 wt% B + .013 wt% Gd_2O_3 + Al cermet core, 1100 Al clad	18	✓3	1.04	5	7.16	39	31	49	58	32	130	312	370	280	- 24
18 wt% U, 93.5% enriched in Al alloy core 1100 Al clad	19	31	0.97	3	4.00	24	22	26	18	26	120*	361	77	120	56
		33	1.04	7	10.09	50		40	82		170*	550		170	121
100% ThO_2 core 1100 Al clad	20														

* Particles too small for individual measurements - average values

TABLE XVIII (Cont.)

Plate Composition	Composition No.	Plate No.	Average Thermal Neutron Flux $\times 10^{-14}$	No. Cycles in MTR	Total Exposure $\text{nvt(th)} \times 10^{-20}$	% Burnup U235	Cladding Hardness			Matrix Hardness			Particle Hardness		
							Pre DPN	Post DPN	% Hardness Change	Pre DPN	Post DPN	% Hardness Change	Pre DPN	Post DPN	% Hardness Change
98.5 wt% ThO ₂ + 1.5 wt% UO ₂ core, 1100 Al clad	21														
18 wt% U, 93.5% enriched + Al alloy core, 1100 Al clad	22	15	1.26	6	10.49	51	42	55	31	53*	180	240	53*	210	300
		16	1.03	12	17.03	69		72	71		200	280		240	350
		22	0.81	6	6.72	37									
18 wt% U, 93.5% enriched + Al alloy core 1100 Al + 0.5 wt% Ni clad	24	7	0.81	6	6.72	37	33			43*			43*		
		10	1.38	6	11.41	54		33	0		180	320		210	390
		11	1.16	11	17.61	70		51	55		210	390		240	460
		12	1.05	16	23.22	80									
18 wt% U, 93.5% enriched + Al alloy core 1100 Al + 1% Ni clad	25	7	1.29	6	10.66	52	36	33	- 8	39*	300	670	39*	-	-
		9	0.99	19	25.99	83									
		12	0.81	6	6.72	37									
52 wt% UO ₂ , 30% enriched + Al cermet core 1100 Al clad	28	1	0.83	8	9.15	47	29			24			550		
		2	0.87	2	2.41	15									
42 wt% UO ₂ , 40% enriched + Al cermet core 1100 Al clad	29	1	0.83	8	9.20	47	29			33			520		
		2	0.57	3	2.35	15									

* Particles too small for individual measurement - average values

TABLE XVIII (Cont.)

Plate Composition	Composition No.	Plate No.	Average Thermal Neutron Flux $\times 10^{-14}$	No. Cycles in MTR	Total Exposure nvt(th) $\times 10^{-20}$	% Burnup U ²³⁵	Cladding Hardness			Matrix Hardness			Particle Hardness		
							Pre DPN	Post DPN	% Hardness Change	Pre DPN	Post DPN	% Hardness Change	Pre DPN	Post DPN	% Hardness Change
40 wt% UO ₂ , 60% enriched + Al cermet core, 1100 Al clad	30	1	0.83	8	9.20	47	27			30			410		
		4	0.42	4	2.30	15									
32 wt% UO ₂ , 80% enriched + Al cermet core 1100 Al clad	31	7	0.84	8	9.34	47	26			27			320		
		12	0.53	6	4.37	26									
35 wt% U, natural in Al alloy 1100 Al clad	32	6	1.31	10	18.05	71	30	50	67	55*	76	38	55*	243	342
		9	0.83	8	9.20	47									
		10	1.06	19	27.68	85									
35 wt% U, 3% enriched + Al alloy core 6061 Al clad	33	6	0.63	12	10.52	51	67			54			150		
		7	0.65	5	4.47	26									
39 wt% UO ₂ , 20% enriched + Al cermet core 1100 Al clad	34	2	0.64	12	10.61	52	31			34			440		
		5	0.69	4	3.84	23									
65 wt% UO ₂ , 20% enriched + Al cermet core 1100 Al clad	35	3	0.63	12	10.55	52	36			32			390		
		7	0.67	4	3.72	23									

* Particles too small for individual measurements - average values

TABLE XVIII (Cont.)

Plate Composition	Composition No.	Plate No.	Average Thermal Neutron Flux $\times 10^{-14}$	No. Cycles in MTR	Total Exposure nvt(th) $\times 10^{-20}$	% Burnup U ²³⁵	Cladding Hardness			Matrix Hardness			Particle Hardness		
							Pre DPN	Post DPN	% Hardness Change	Pre DPN	Post DPN	% Hardness Change	Pre DPN	Post DPN	% Hardness Change
18.7 wt% UO ₂ , 93.5 % enriched + .036 wt% B + Al cermet core 1100 Al clad	38	5	0.70	3	2.89	18	30			31			480		
		13	0.57	12	9.40	48									
18.7 wt% UO ₂ , 93.5% enriched + .951 wt% Dy ₂ O ₃ + Al cermet core 1100 Al clad	39	5	0.43	5	3.01	19	30	38	27	32	54	69	380	670	76
		6	0.48	10	6.62	37		34	13		55	72		470	19
		8	0.56	23	17.72	70									
18.7 wt% UO ₂ , 93.5% enriched + .037 wt% B, + .91 wt% Dy ₂ O ₃ + Al cermet core, 1100 Al clad	40	9	0.72	3	3.00	19	32	34	6	37	59	59	450	-	
		10	0.68	8	7.51	40		39	22		62	68		440	- 2
		11	0.70	21	20.33	75									
18.7 wt% UO ₂ , 93.5% enriched + .036 wt% B + 1.275 wt% Ir + Al cermet core, 1100 Al clad	41	9	0.87	3	3.60	22	29			25			400		
		12	0.82	16	18.15	71									
18.7 wt% UO ₂ , 93.5% enriched + .0115 wt% Gd ₂ O ₃ + .036 wt% B + Al cermet core, 1100 Al clad	42	12	0.89	16	19.64	74	30			32			450		
		14	0.90	3	3.75	23									

TABLE XVIII (Cont.)

Plate Composition	Composition No.	Plate No.	Average Thermal Neutron Flux $\times 10^{-14}$	No. Cycles in MTR	Total Exposure $\text{nvt(th)} \times 10^{-20}$	% Burnup U235	Cladding Hardness			Matrix Hardness			Particle Hardness		
							Pre DPN	Post DPN	% Hardness Change	Pre DPN	Post DPN	% Hardness Change	Pre DPN	Post DPN	% Hardness Change
22.3 wt% U ₃ O ₈ , 93% enriched + Al cermet core, 1100 Al clad	47	10	0.99	3	4.13	25	26	35	35	30	150	400	140	-	-
		11	0.95	8	10.57	52									
22.3 wt% U ₃ O ₈ , 93% enriched, .18 wt% B + Al cermet core, 1100 Al clad	48	8	0.98	3	4.05	24	30	37	23	29	130	350	178	-	-
		11	0.95	8	10.55	52									
22.3 wt% U ₃ O ₈ , 93% enriched, .23 wt% B ₄ C + Al cermet core 1100 Al clad	49	9	0.80	3	3.30		26	41	58		140	230	42*	180	330
		11	0.82	8	9.10	47				42*					
6.1 wt% UO ₂ , 93% enriched + Al cermet core 1100 Al clad	50	5	0.71	5	4.89	29	31	38	23	33	43	30	400	35	- 91
		10	0.69	12	11.50	55		31	0		40	21		-	-
11.6 wt% UO ₂ , 93% enriched + Al cermet core 1100 Al clad	51	6	0.84	6	6.98	38	47	32	-32	36	52	44	390	69	- 82
		14	0.79	16	17.42	70									

* Particles too small for individual measurements - average values

TABLE XVIII (Cont.)

Plate Composition	Composition No.	Plate No.	Average Thermal Neutron Flux $\times 10^{-14}$	No. Cycles in MTR	Total Exposure $\text{nvt}(\text{th}) \times 10^{-20}$	% Burnup U^{235}	Cladding Hardness			Matrix Hardness			Particle Hardness		
							Pre DPN	Post DPN	% Hardness Change	Pre DPN	Post DPN	% Hardness Change	Pre DPN	Post DPN	% Hardness Change
16.8 wt% UO_2 , 93% enriched + Al cermet core, 1100 Al clad	52	6 8 10	0.63 0.66 0.62	6 11 21	5.20 9.99 17.95	30 50 71	43	39 41	-10 -5	36	43 57	19 58	450	200 400	-56 -11
19 wt% U, 93% enriched + Al alloy core 6061 Al clad	53	27	0.81	6	6.72	37	50			39			240		
45 wt% U, 93% enriched + 3% Si + Al alloy core, 6061 Al clad	55	1	0.51	4	2.82	18	40			25			110		
19 wt% U, 93% enriched + Al alloy core APM M257 clad	56	1 9	0.76 0.81	3 6	3.16 6.72	20 37	67			38*			38*		
30 wt% U, 93% enriched in Al alloy core APM M257 clad	58	7	0.85	9	10.55	52	74			52			220		
45 wt% U, 93% enriched + 3% Si + Al alloy core, APM M257 clad	59	2	0.80	3	3.34	21	65			36			140		

* Particles too small for individual measurements - average values

TABLE XVIII (Cont.)

Plate Composition	Composition No. Plate No.	Average Thermal Neutron Flux $\times 10^{-14}$	No. Cycles in MTR	Total Exposure $\text{nvt}(\text{th}) \times 10^{-20}$	% Burnup U^{235}	Cladding Hardness			Matrix Hardness			Particle Hardness		
						Pre DPN	Post DPN	% Hardness Change	Pre DPN	Post DPN	% Hardness Change	Pre DPN	Post DPN	% Hardness Change
32 wt% U, 93% enriched in Al alloy core X8001 Al clad	60	4	0.77	2	2.14	14								
		8	0.78	5	6.47	36	29		48			74		
19 wt% U, 93% enriched in Al alloy core X8003 Al clad	62	4	0.78	6	6.47	36	46		86			100		
19 wt% U, 93% enriched in Al alloy core 5052 Al clad	63	1	0.74	2	2.04	13	57		45			140		
19 wt% U, 93% enriched + Al alloy core X8001 Al clad	73	5	0.78	6	6.47	36	36		47			120		

TABLE XIX

DIMENSIONS AND WEIGHT DATA ON SAMPLE FUEL PLATES

Composition	Plate No.	Dimensions							Weight		
		Average Length		Average Width		Average Thickness		% Change	Before Irrad.	After Irrad.	% Change
		Before Irrad.	After Irrad.	Before Irrad.	After Irrad.	Before Irrad.	After Irrad.				
1	21	2.870	2.876	2.310	2.311	0.057	0.0545	- 4.38	19.127	18.9176	- 1.09
1	25	2.870	2.874	2.310	2.312	0.057	0.0570	0	19.0611	18.9682	- 0.48
5	17	2.870	2.875	2.311	2.316	0.045	0.0477	+ 6.0	13.7905	13.8340	+ 0.31
8	17	2.870	2.877	2.311	2.317	0.051	0.0530	+ 3.92	15.5868	15.8359	+ 1.59
8	21	2.870	2.879	2.311	2.317	0.051	0.0523	+ 2.55	15.6404	15.6716	+ 0.20
10	1	2.890	2.884	2.320	2.318	0.052	0.0525	+ 0.95	16.0080	15.9828	- 0.16
10	18	2.870	2.880	2.311	2.314	0.051	0.0531	+ 4.12	15.5788	15.6422	+ 0.40
22	15	2.874	2.878	2.312	2.314	0.052	0.0514	- 1.15	15.7700	15.8105	+ 0.26
22	16	2.874	2.874	2.311	2.311	0.052	0.0520	0	15.7500	15.8001	+ 0.32
22	22	2.874	2.876	2.311	2.314	0.052	0.0545	+ 4.81	15.9300	16.0604	+ 0.82
24	7	2.874	2.884	2.312	2.317	0.050	0.0546	+ 9.20	15.5110	15.6544	+ 0.92
24	10	2.874	2.872	2.311	2.313	0.050	0.0495	- 1.00	15.3200	15.3576	+ 0.24
24	11	2.874	2.879	2.312	2.316	0.050	0.0520	+ 4.00	15.5500	15.5831	+ 0.21
24	12	2.874	2.878	2.312	2.318	0.050	0.0530	+ 6.00	15.3410	15.4418	+ 0.66
25	7	2.874	2.870	2.313	2.312	0.050	0.0499	- 0.20	15.4400	15.4792	+ 0.25
25	9	2.874	2.877	2.312	2.318	0.050	0.0531	+ 6.20	15.4500	15.5640	+ 0.74
25	12	2.875	2.881	2.313	2.3155	0.050	0.0530	+ 6.00	15.4100	15.5281	+ 0.77
28	1	2.876	2.878	2.312	2.320	0.051	0.0533	+ 6.47	17.1700	17.2664	+ 0.56
28	2	2.877	2.880	2.317	2.320	0.051	0.0523	+ 2.55	17.2100	17.2502	+ 0.23
29	1	2.876	2.878	2.314	2.319	0.051	0.0533	+ 4.51	16.6100	16.6831	+ 0.44
29	2	2.876	2.881	2.316	2.318	0.051	0.0525	+ 2.94	16.6200	16.6492	+ 0.17
30	1	2.874	2.882	2.316	2.320	0.049	0.0487	- 0.61	14.7800	14.8730	+ 0.63
30	4	2.876	2.879	2.315	2.319	0.048	0.0606	+26.25	14.8300	14.8666	+ 0.25

TABLE XIX (Cont.)

Composition	Plate No.			Dimensions					Weight		
		Average Length		Average Width		Average Thickness		% Change	Before Irrad.	After Irrad.	% Change
		Before Irrad.	After Irrad.	Before Irrad.	After Irrad.	Before Irrad.	After Irrad.				
31	7	2.874	2.878	2.313	2.320	0.046	0.0477	+ 3.69	14.4400	14.5243	+ 0.58
31	12	2.875	2.883	2.313	2.3195	0.046	0.0494	+ 7.39	14.4350	14.5042	+ 0.48
32	6	2.875	2.881	2.313	2.314	0.049	0.0496	+ 1.22	16.0960	16.1187	+ 0.14
32	9	2.875	2.880	2.312	2.317	0.050	0.0521	+ 4.20	16.1850	16.1591	- 0.16
32	10	2.874	2.876	2.312	2.314	0.050	0.0529	+ 5.80	16.0720	16.1120	+ 0.25
33	6	2.872	2.881	2.314	2.315	0.047	0.0546	+16.17	16.9860	17.1598	+ 1.02
33	7	2.873	2.875	2.312	2.314	0.047	0.0548	+17.95	17.0760	17.1502	+ 0.43
34	2	2.872	2.878	2.310	2.320	0.066	0.0691	+ 4.69	22.5500	22.6355	+ 0.38
34	5	2.876	2.880	2.315	2.316	0.066	0.0684	+ 3.63	22.6300	22.6735	+ 0.19
35	3	2.875	2.880	2.312	2.315	0.065	0.0667	+ 2.62	21.9700	22.0690	+ 0.45
35	7	2.874	2.8765	2.312	2.314	0.065	0.0680	+ 4.61	21.9710	22.0163	+ 0.21
38	5	2.875	2.883	2.312	2.317	0.051	0.0521	+ 2.15	15.6400	15.6807	+ 0.26
38	13	2.875	2.883	2.312	2.317	0.051	0.0530	+ 3.92	15.6400	15.6831	+ 0.27
39	5	2.874	2.881	2.312	2.318	0.052	0.0517	- 0.58	15.7110	15.7239	+ 0.08
39	6	2.875	2.878	2.312	2.315	0.051	0.0521	+ 2.16	15.7260	15.7451	+ 0.12
39	8	2.875	2.880	2.313	2.320	0.052	0.0541	+ 4.03	15.7582	15.9070	+ 0.94
40	9	2.876	2.882	2.313	2.316	0.051	0.0505	- 0.98	15.6260	15.6607	+ 0.22
40	10	2.874	-	2.312	2.316	0.051	0.0519	+ 1.76	15.5670	15.6255	+ 0.38
40	11	2.875	2.882	2.312	2.320	0.051	0.0549	+ 7.64	15.5640	15.7432	+ 1.15
41	9	2.875	2.879	2.316	2.314	0.051	0.0525	+ 2.94	15.6003	15.6246	+ 0.15
41	12	2.875	2.877	2.316	2.3205	0.051	0.0527	+ 3.33	15.4773	15.6108	+ 0.86
42	12	2.876	2.879	2.314	2.3205	0.051	0.0542	+ 6.27	15.5720	15.7226	+ 0.95
42	14	2.879	2.881	2.313	2.319	0.051	0.0521	+ 2.15	15.6820	15.7352	+ 0.34
47	10	2.876	2.876	2.314	2.316	0.050	0.0500	0	15.2570	15.3039	+ 0.31
47	11	2.878	2.881	2.318	2.320	0.050	0.0522	+ 4.40	15.2590	15.3443	+ 0.55
48	8	2.878	2.877	2.318	2.315	0.051	0.0505	- 0.98	15.4700	15.5533	+ 0.54
48	11	2.876	2.879	2.316	2.322	0.051	0.0528	+ 3.52	15.3000	15.3943	+ 0.62

TABLE XIX (Cont.)

Composition	Plate No.	Dimensions							Weight		
		Average Length		Average Width		Average Thickness		% Change	Before Irrad.	After Irrad.	% Change
		Before Irrad.	After Irrad.	Before Irrad.	After Irrad.	Before Irrad.	After Irrad.				
49	9	2.876	2.875	2.317	2.315	0.051	0.0508	- 0.39	15.4760	15.5243	+ 0.31
49	11	2.876	2.878	2.316	2.318	0.051	0.0533	+ 4.50	15.3550	15.4478	+ 0.60
50	5	2.874	2.874	2.312	2.315	0.051	0.0508	- 0.39	15.2550	15.2791	+ 0.16
50	10	2.874	2.874	2.312	2.313	0.050	0.0510	+ 2.00	15.2010	15.2394	+ 0.25
51	6	2.875	2.876	2.312	2.314	0.051	0.0505	- 0.98	15.3500	15.3811	+ 0.20
51	14	2.875	2.877	2.312	2.3165	0.051	0.0525	+ 2.94	15.3700	15.4748	+ 0.68
52	6	2.875	2.876	2.312	2.312	0.051	0.0505	- 0.99	15.5400	15.5665	+ 0.17
52	8	2.875	2.879	2.312	2.316	0.051	0.0517	+ 1.37	15.5400	15.5573	+ 0.11
52	10	2.875	2.876	2.312	2.316	0.051	0.0528	+ 3.52	15.4300	15.5281	+ 0.63
53	27	2.865	2.8805	2.300	2.309	0.051	0.0526	+ 3.13	15.6150	15.3597	- 1.63
55	1	2.875	2.877	2.309	2.307	0.050	0.0504	+ 0.80	15.7364	15.7923	+ 0.35
56	1	2.880	2.878	2.310	2.301	0.049	0.0537	+ 9.59	15.8180	15.8644	+ 0.27
56	9	2.876	2.881	2.302	2.309	0.049	0.0529	+ 7.96	15.8280	15.9359	+ 0.68
58	7	2.877	2.880	2.316	2.298	0.033	0.0349	+ 5.75	10.4866	10.5782	+ 0.92
59	2	2.865	2.865	2.295	2.2985	0.050	0.0527	+ 5.40	15.7450	15.8014	+ 0.36
60	4	2.877	2.872	2.311	2.307	0.034	0.0350	+ 2.94	10.8340	10.8535	+ 0.18
60	8	2.866	2.869	2.309	2.313	0.034	0.0357	+ 5.00	10.7280	10.8490	+ 1.12
62	4	2.878	2.8765	2.310	2.3155	0.050	0.0554	+10.80	15.6409	15.7834	+ 0.91
63	1	2.880	2.871	2.312	2.303	0.049	0.0502	+ 2.44	14.9296	14.9372	+ 0.05
73	5	2.886	2.878	2.310	2.305	0.050	0.0531	+ 6.20	15.4555	15.5871	+ 0.85