PROGRESS REPORT ON FUEL ELEMENT DEVELOPMENT AND ASSOCIATED PROJECTS

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S U M M A R Y

The fuel development program at the MTR has sought to develop improved, economical, long-life fuel assemblies through a comprehensive study of various fuel compositions, enrichments, claddings, burnable poisons, fuel and poison distributions, and fuel element geometry optimization.

The core materials, including uranium-aluminum alloys, uranium oxide-aluminum cermet, thorium, thorium oxide, boron, gadolinium, dysprosium, and iridium, are tested in pilot-plant scale by irradiating them as sandwich-type sample fuel plates.

In the procurement of these sample plates, fabrication techniques were developed and evaluated for incorporation of all the fuels and poisons (except Ir_2O_3) into cores of aluminum or aluminum alloys. Methods were developed to minimize "dog-boning" and to produce graded fuels.

Some of the sample plate compositions have been irradiated to high burnup, i.e., over 50% of the U^{235} content, and have operated successfully in the MTR for 7 or more cycles. The irradiated uranium-aluminum alloy and uranium oxide-aluminum cermet fuel plates have shown excellent dimensional stability and good corrosion resistance to long term irradiation. However, some of the thorium oxide fuel plates failed during one cycle of irradiation because of blistering, rupturing, or forming of pinholes in the cladding. The isostatic bonding procedure used to bond aluminum plates to the ThO_2 cores is apparently not adequate for reactor use.

The sample fuel plate work has demonstrated the suitability of high weight percent UO_2 -Al fuels for testing reactors, indicated the potential of systematically varying the fuel loading within a single plate, and experimentally verified the applicability of burnable poisons for reducing reactivity changes resulting from fuel burnup. The RMF has proven an excellent non-destructive analytical tool for determination of fuel and poison burnup.

This program has stimulated several new developments and revealed many interesting facts in the fabrication and testing of reactor fuel materials. For example: (1) ultrasonic inspection has proven to be an excellent non-destructive method for determination of small voids in the core and unbonded cladding not otherwise detected by radiographing, (2) the ultrasonic inspection of irradiated fuel plates in the MTR canal is feasible, and (3) analytical procedures were developed for the determination of the small quantities of gadolinium added to the cores.

The prototype studies consisted of theoretical and experimental evaluations of the hydraulic and heat transfer characteristics, the structural properties, the economics and the reactor operating characteristics of various full-sized fuel assemblies and shim rods. The results of the sample fuel plate studies have been incorporated in these prototypes to obtain optimum practical designs for testing reactors. The fuel element geometries investigated include plates, tube bundles, hexagonal honeycomb, and concentric cylinders.

An MTR shim rod with renewable fuel and poison sections was designed, tested hydraulically, and is now considered ready for final in-pile testing. This rod outlasts the existing shim rods, is cheaper and allows more operational flexibility.

A theoretical analysis, hydraulic tests and a mechanical evaluation have shown that an improvement can be made in plate-type fuel elements by using an increased number of thinner, high-strength fuel plates in the fuel element. An in-pile prototype test of such an element is now planned.

An analysis of roughened surfaces indicates that economy or increases in reactor power may be gained through the use of roughened heat transfer surfaces in non-boiling, water cooled reactors. Preliminary hydraulic tests have been performed and indicate that practical roughened surfaces may be formed. Out-of-pile heat transfer tests are now planned.

The theoretical analysis of geometries indicates that tube bundles, honeycomb and concentric cylinder designs come close to eliminating wasted space and hot spots in a reactor element. Out-of-pile tests of a tube bundle element have shown that fabrication techniques of this type element must be improved. No reasonable fabrication techniques for a honeycomb element have yet been demonstrated. A fuel element composed of concentric square cylinders having rounded corners has been designed and fabrication of a dummy prototype is in progress.

The current fuel development program seeks to extend the materials and prototype studies. Combinations of fuels and poisons in non-uniform distributions and the high temperature applications of aluminum fuels are being evaluated.

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I. INTRODUCTION

Early in the operational stages of the MTR it was realized that several advantages might accrue from changes in fuel materials and in fabrication and assembly techniques. Therefore, a fuel element development program was proposed in 1954 having as its major objectives the development of long-life fuel assemblies for the general AEC reactor program and the performance improvement of the MTR type fuel element. This proposal included: 1) improvement in power (flux) distribution, 2) lower cost, 3) improved operability of both fuel elements and shim rods, and 4) possible high power operation.

The fuel development program at the MTR-EIR, beginning in 1955, has stressed application and embraces a materials study and a full scale prototype design and testing program. The materials study is based on small test plates containing various fuel compositions and enrichments, claddings, burnable poisons, and non-uniform fuel and poison distributions. The prototype program involves various fuel geometries with associated heat transfer and hydraulic evaluations; and a design and test of an MTR shim rod with renewable fuel and poison sections.

Although the MTR has operated quite successfully using plate type elements since it first went critical in March 1952, investigation of other geometries has been stimulated by one increase in operating power from 30 to 40 Mw and a proposed increase to 60 Mw. The split cycle operation of the MTR for refueling has spurred work towards higher fuel loading and burnable poisons. Experience with fuel loadings of 20% enriched uranium and plutonium has stimulated new techniques in fabrication, shown the desirability for higher weight per cent, and has enhanced the potential of the oxide fuel and of powder metallurgy fabrication. The history of the EIR startup with its fuel element and control rod problems has further substantiated the need for a program geared closely to reactor operation.

This report reviews the progress to date and describes a realistic continuing program. The work effort is logically divided into the following activities: 1) sample fuel plates, 2) full scale fuel elements, and 3) shim rod improvement.

II. SAMPLE FUEL PLATES

A. Experiment Design

1. Fuel Plate

The sample fuel plate irradiation study was initiated as one part of the Fuel Element Development Program at the MTR to provide information on reactor fuel materials for application to full scale elements. The bulk of the development work has been directed toward economic and performance improvement of MTR-ETR type fuel elements. The use of sample fuel plates provides a "pilot plant" approach which not only gives information on reactor fuels selection, but also evaluates fabrication techniques, and yields, from Reactivity Measurement Facility studies, data applicable to reactor use on fuel and poison burnup behavior. The dimensions and U^{235} loadings of the sample fuel plates were determined from the requirements of the RMF and the size limitations of the experiment.

a. RMF Requirements

Originally it was estimated that the RMF would need 10 grams of U^{235} in each composition at the end of irradiation to obtain adequate sensitivity (1% excess reactivity accuracy) throughout the range of burnup. This necessitated sample fuel plates of MTR fuel plate size or required the reading of several plates at a time in the RMF. Later estimates reduced the limit to approximately 1 gram of U^{235} .

b. Dimensions and Fuel Loading

The fuel loading per unit area was based on an MTR fuel plate loading of 0.178 gm/in^2 . This, together with a flow channel width of approximately 0.110" between the plates, insured proper heat removal during irradiation in the MTR. Also, dimensional limitations to be discussed later, resulted in final overall dimensions of 2.312" x 2.875" with varying core and cladding thickness to give the required loading.

c. Compositions

The sample fuel plate compositions are divided into phases based upon order of procurement (Tables I, IX and X). Table I lists the initial areas of investigation in the materials study. Twenty-one compositions were chosen to evaluate properties in two general fields: fabrication and reactor use. Considerable interest has been displayed in the use of UO_2 as a reactor fuel for MTR-ETR type fuel elements. For this reason UO_2 was chosen for investigation of its irradiation behavior and the feasibility of powder metallurgy fabrication. The weight per cent of UO_2 was varied from an MTR equivalent loading of 23% to 54% in order to determine relationships between radiation damage and weight per cent, and to develop fabrication techniques that would eliminate the possibility of fuel lumping at the ends of the core (dog-boning) during

TABLE I

SAMPLE FUEL PLATE COMPOSITIONS FOR PHASE I

Core Material	Per Cent Enrichment	wt% of Fuel	wt% of Poisons		Core Thickness in Mills
			B(Nat)	Gd ₂ O ₃	
UO ₂ (Powder) + Al (Powder)	20	54.0			25
	93.5	22.7			20
	93.5	30.0			15
	93.5	45.0			10
	93.5	22.7	0.062		20
	93.5	22.7	0.123		20
	93.5	22.7		0.013	20
	93.5	22.7	0.062	0.013	20
	{ 1/2 core 93.5	27.3			
	{ 1/2 core 93.5	23.8			
U + Al Alloy	20	25			25
	*93.5	18			20
	93.5	18			20
	93.5	18	0.057		20
	93.5	18	0.115		20
	93.5	18		0.0123	20
	93.5	18	0.057	0.013	20
	{ 1/2 core 93.5	23			
	{ 1/2 core 93.5	18			
	{ 1/2 core 93.5	23			
ThO ₂ (Powder)		100			120
ThO ₂ (Powder) + UO ₂	93.5	98.5% ThO ₂ 1.5% UO ₂			120

Claddings for all Phase I sample plates were 1100 Al, .015 inch thick.

* Cold Rolled

rolling of the higher weight per cents. The uranium-aluminum alloys provided a means of investigating MTR type plates to very high burnups and also of studying non-uniform fuel loading with uranium alloys. The ThO_2 compositions were chosen to study the use of thorium as a breeder fuel in flat plate designs.

The burnable poisons were incorporated in both the UO_2 -Al powder cores and the U-Al alloy cores. The poison weights chosen in this phase serve as standards for determining apparent cross section values and burnup rates for use in excess reactivity calculations for an MTR core loading.

2. Holder and L-Piece

a. L-Piece Design

It was decided that the flux and coolant flow necessary for successful operation of the experiment could be provided by a core position. An aluminum housing (L-piece) with the outside configuration of a typical MTR fuel element was designed to hold the experiment. The L-piece was fitted with one removable end box to give access to the machined interior (inside dimensions are 2.516" x 2.625" x 26.75"). The end box was held in place by a stainless steel locking mechanism fastened in the housing with machine screws. A screw and wedge type mechanism was used to force small balls from conical holes in the end box into matching holes in the housing. This arrangement formed a secure lock between the end box and the housing. Figure 1 shows the removable head with the locking mechanism and Figure 2 shows the components making up the test assembly.

b. Holder Design

Figure 3 shows the fuel plate holder loaded with sample plates. Eight of these holders can be placed inside the L-piece. The fuel plate holder consists of two side plates with milled slots to accommodate three partitions and twelve of the 0.040" to 0.050" fuel plates or eight of the 0.150" ThO_2 fuel plates. With these loadings the flow channel sizes through the holders approximate those for a typical MTR fuel element. The partitions and a stop for the plates to rest upon are joined to the side plates by welding. Fuel plate and flux monitor retainers are hinged to the side plates and are held closed by a spring latch which clamps over the center partition. Holes drilled into the top of the side piece hold 1/2" and 3/4" flux wires. The flux monitors were located such that they provided integrated flux measurements for the top of one holder and the bottom of the holder above it when they are positioned in the L-piece.

3. Reactor Suitability

To insure the operational safety of the experiment in the reactor, heat transfer calculations were made and prototypes were hydraulically tested.

a. Hydraulics

The hydraulic tests were performed in the MTR single element hydraulic loop which was designed to simulate reactor flow conditions through an element. A variety of loadings expected to be encountered in actual operation were tested, but due to the large number of tests needed to evaluate the experiment in which plates of different total thickness were used, only those plates having overall thicknesses of 0.050 in. and 0.150 in. were used in determining overall (core) pressure drops vs. coolant flow through the L-piece. One holder was loaded with 0.150 in. plates representing the thorium compositions and the other seven were loaded with 0.050 in. plates. The holders were then moved throughout the L-piece in order to find the flow conditions to be expected and to find the optimum location for the thorium compositions. It was found that at the MTR operating core pressure drop of 40 psi, the flow through the L-piece was not greatly affected by the position of the thorium plates, although the top position showed slight advantage. On this basis, it was decided to load the L-piece with the thorium plates always in the number one, or top, position.

Further hydraulic tests were made to correlate coolant velocity with sample plate size so that the results of the prior tests could be applied to experiment loadings containing several plate sizes.

b. Heat Transfer

Using the hydraulic data, heat transfer calculations were made, including a hot-spot hot-channel analysis.⁽²⁾ It was found that the experiment could safely be placed in a peak neutron flux field of 4×10^{14} n/cm²-sec.* For the worst condition the hot-spot hot-channel analysis gives a film ΔT of 168°F, a bulk water temperature rise of 66.4°F and a maximum sample plate temperature of 346°F.

Reactor position L-51 was used for the irradiation of the sample fuel plates. Flux measurements in this L-piece show that the average value of the flux varies between 0.9×10^{14} n/cm²-sec for the top and bottom positions and 1.6×10^{14} n/cm²-sec for the center positions. Those plates located in the center positions are expected to have an average wall temperature of approximately 145°F during irradiation.

B. Sample Procurement

Negotiations with potential vendors selected from among the most active fuel element fabricators indicated little interest in supplying the sample fuel plates shown in Figure 4.

A contract was eventually arranged with Sylvania Electric Products Inc. (later Syl-Cor) to furnish these items with an estimated project completion time of six months. Delays in contractual negotiations, problems in procurement of fuel materials, and unexpected fabrication difficulties necessitating additional development work resulted in the following time schedule.

* In this report, neutron flux refers to the thermal neutron flux.

FIG. 1
REMOVABLE END BOX FOR EXPERIMENTAL L-PIECE
PHOTOGRAPH SHOWS STAINLESS STEEL INSERT

EXPERIMENTAL DESIGN FOR FUEL PLATE IRRADIATION

FIG. 2
COMPONENTS OF TEST ASSEMBLY

PP CO.

FIG. 3
SAMPLE FUEL PLATE HOLDER LOADED WITH PLATES

FIG. 4
TYPICAL SAMPLE FUEL PLATE

PP CO.

1. Design of fuel plate holder, L-piece and specification of composition.	Fall 1955
2. Contract signed.	Feb. 1956
3. First shipment of plates.	May 1957
4. Start of irradiation program.	Dec. 1957
5. Last shipment of plates.	May 1958
6. Completion of Phase I irradiations and post irradiation examinations.	Dec. 1959

The sample procurement schedule illustrates the very real need for facilities to supply test specimens for reactor experimental programs. The developmental nature, small quantity production of any single item, and custom handling make sample fabrication unattractive to most fuel element suppliers.

C. Sample Fuel Plate Fabrication

The procedures used for the fabrication of the sample fuel plates were essentially those used for the fabrication of full-size plates. The length of the plate was the only dimension greatly changed. Hence, the fabrication of the plates is on a pilot plant scale and the information obtained should be directly applicable to full-size fuel plates. The basic fabrication procedures are described in Appendix A of this report.

One of the major problems of fabrication which exists in the manufacturing of fuel plates is "dog boning". This term describes the condition where the ends of the fuel cores are thickened and the cladding thickness is correspondingly reduced. This phenomenon is caused by differences in the mechanical properties of the core and the cladding materials. If the cladding material is much softer than the core, as is the case when 1100 Al is used to clad U-Al alloys, the cladding material will be extruded ahead of the core as the leading edge enters the rolls. As the trailing edge of the core passes through the rolls, the cladding material is extruded to the rear so that the plate tends to "dog bone" at both ends.

In plates with alloy cores containing less than 20 wt% uranium, "dog boning" is normally not a problem. In the fabrication of sample fuel plates, it has been found that if 2-1/2 in. diameter rolls are used the cladding will be completely torn away at the end of the core so that the core is exposed, while if plates of the same materials are rolled at the same temperature on 8 in. rolls a satisfactory plate can be produced.

When, more than 25% uranium is used in the alloy core with a cladding of 1100 aluminum, it becomes very difficult to maintain a uniform core thickness. However, if a cladding material is used with a tensile strength

more nearly that of the core material, a more uniform core thickness can be maintained. For example, by using 6061 aluminum cladding over 35% U-Al cores, with 6061 picture frames, the "dog boning" of the core amounts to 25 to 30%. If this same alloy material is used for cores and 1100 aluminum is used for the cladding and picture frames, the "dog boning" will amount to about 75 to 80% of the core thickness.

Certain difficulties, however, were associated with the use of 6061 aluminum in fuel plates. If the alloy was used for both the picture frame and the cladding, it was not possible to produce a predictable bond, and the cores often exhibited gross distortion of the rectangular shape. These problems were solved by the use of 1100 aluminum picture frames with 6061 aluminum cores. With this combination of 6061 aluminum and 1100 aluminum, the core "dog boning" was not reduced as much as with all 6061 (35 to 40% instead of 25 to 30%). However, bonding was consistently very good and the cores showed little or no distortion of the rectangular shape. When this combination was used for plates containing either UO_2 -Al or U_3O_8 -Al cores, it was difficult to confine the fuel to the core area. During the first hot rolling pass the 1100 frame was elongated approximately 75% more than the 6061 cladding, and this large relative movement resulted in the oxide particles from the core being embedded in the cladding as the cores were shifted by the picture frame.

The fuel element development program has demonstrated the feasibility of manufacturing fuel plates containing segments having different fuel contents. No unusual fabrication difficulties were encountered during the manufacture of either graded UO_2 -Al fuel plates or graded U-Al alloy fuel plates. The compositions which have been fabricated are included in Table I.

Fabrication experience has been gained in the addition of the following poisons in fuel core compositions:

1. B - up to 0.115 wt% in U-Al alloy and up to 0.123 wt% in UO_2 -Al cermet. (Phase I)
2. Gd_2O_3 - up to 0.013 wt% in U-Al alloy and UO_2 -Al. (Phase I)
3. Dy_2O_3 - up to 0.951 wt% in UO_2 -Al cermet (Phase II)
4. Ir_2O_3 - 1.43 wt% in UO_2 -Al cermet (Phase II)
5. Ir - 1.275 wt% in UO_2 -Al cermet (Phase II)
6. B_4C - 0.0023 wt% in U_3O_8 -Al cermet (Phase II)

No unusual fabrication difficulties resulted from the use of Gd_2O_3 and Dy_2O_3 . Boron has been difficult to disperse uniformly and difficult to analyze chemically. When plates containing Ir_2O_3 were annealed at 600°C for one hour, small blisters were produced. When Ir metal was substituted for the Ir_2O_3 no trouble was encountered. Plates containing more than one type of poison have been fabricated and no difficulties were encountered which had not been experienced in the use of each poison individually.

D. Sample Examination

1. Pre-Irradiation Examination

When the sample fuel plates were received they were subjected to a series of tests designed to determine their suitability for irradiation in the MTR, and to establish their metallurgical properties prior to irradiation so that the radiation effects could be evaluated. The following properties of the fuel plates were measured: dimensions, weight, uniformity of fuel distribution in the core, location of the core, tendency for blister formation in the cladding, hardness of the "core" and cladding, thickness of the cladding, and the quality of the bonds between the core and the cladding. The dimensions of all the fuel plates were carefully measured using a vernier caliper and a micrometer. After this the plates were weighed. Radiographs of the plates, which had been supplied by the manufacturer were examined in order to determine the size, shape, and location of the cores within the "picture frames". Also, an attempt was made to evaluate the distribution of the fuel in the cores as well as to check for other defects. To check for minute surface defects each plate was given a fluorescent penetration "Zyglo" test. All of the plates were given a blister test. This test consisted of holding the plates for at least three days at a temperature of 300°F.

One plate of each composition, chosen at random, was cut up and prepared for metallographic examination. Standard techniques were used for this examination. The purposes of this examination were to check the quality of the bonds between the cladding and core, to determine the thicknesses of the core and claddings, and to ascertain the uniformity of the fuel distribution in the cores. Moreover, it was desired to be able to compare the microstructures of the plates before and after irradiation in order to study the radiation effects.

The metallographic mounts were subsequently used as the specimens for microhardness measurements. Using a "Tukon" microhardness tester the hardnesses of the cladding, matrix, and core particles were determined on each of the plates. Finally to evaluate thoroughly the quality of the bonds between the cladding and the core of the plates it was desired to inspect them ultrasonically. Because of delays in procuring this equipment and putting it into operation, some plates were irradiated without the ultrasonic inspection. The remaining plates, with the exception of the unbonded thorium plates, were checked with this equipment. Several plates from each composition were sent to the CPP Analytical Laboratory for quantitative analysis of fuel and poisons. A new method of gadolinium determination was developed for the program by this laboratory. The procedure is given in Appendix B.

2. Post-Irradiation Examination

Upon completion of irradiation and post-irradiation inspection in the canal, selected specimens of the sample fuel plates were transferred to the MTR hot cell for examination. In the hot cell the plates were

first weighed, measured, and photographed. After this they were descaled by a hot caustic dip followed by a nitric acid dip, and a rinse in clear, cold water. The plates were then rapidly dried and reweighed.

Sections both parallel and perpendicular to the rolling direction were cut from the plates, mounted in bakelite, and prepared for metallographic examination. After taking photomicrographs of the specimens, microhardness measurements were made using a "Tukon" microhardness tester.

Some difficulty was encountered in these operations since it was discovered that the bakelite used as a mounting material tended to fall apart after having been exposed to the "hot" specimens for three or four weeks. Figure 5 shows two of these metallographic mounts.

3. Results

a. Radiographs and Ultrasonics

The results of radiography and "Zyglo" tests showed that all of the sample plates received were sound. Of one hundred unirradiated plates from the first group of sample fuel plates inspected with the ultrasonic scanner, three were found to give indications of serious defects.

In one plate an area of about three-quarters of an inch in diameter located in one corner had poor sound transmission properties. Figure 6A is a photomicrograph of a section cut through this area. The defect which was most noticeable to the scanner is the lack of a metallurgical bond on one side at the interface between the core and cladding. Two other defects can also be seen. One is the void between the picture frame and the cladding. The other is that the core is not centered in the plate. The ultrasonic scanner could detect the voids between the cores and the picture frames. However, none of the non-destructive tests used were capable of checking the cladding thickness.

Figure 6B is typical of the results achieved by the radiographic inspection of the sample plates. This plate, a typical MTR fuel composition, is the same one which was later found to be defective by the use of ultrasonics (Figure 6A). However, the only defect shown in the radiograph is a slightly uneven fuel distribution in the core, due to a slight amount of "dog boning".

Another type of fabrication anomaly which could not be detected by non-destructive examination is the double core phenomenon shown in Figure 7. This plate passed all pre-irradiation inspections, was irradiated successfully to 29% burnup and passed all post-irradiation examinations. The defect was found only when the plate was cut in the hot cell for metallographic inspection. The main objections to defects of this type are the reduced clad thickness and the possibility of non-uniform fuel distribution.

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FIG. 5
PHOTOGRAPHS TAKEN IN HOT CELL SHOWING DAMAGE TO BAKELITE
MOUNTS BY IRRADIATED SPECIMEN

FIG. 6A

PHOTOMICROGRAPH SHOWING UNBONDED AREAS DETECTED BY
ULTRASONIC INSPECTION
(18 Wt % 93.5 % ENRICHED IN Al ALLOY 100X, HF etched)

PPCo.

FIG. 6B

RADIOGRAPH OF DEFECTIVE PLATE SHOWN IN PRECEDING FIGURE
(PLATE WAS CUT ALONG DOTTED LINE TO OBTAIN SAMPLE SHOWN IN FIG. 6A)
(PHOTOGRAPH SLIGHTLY ENLARGED)

FIG. 7
PHOTOMICROGRAPH SHOWING DOUBLE CORE
(75X)
(30 Wt. % UO_2 , 93.5 % ENRICHED IN Al MATRIX , 29% BURNUP

b. Surface Conditions and Corrosion

The only visual change in most of the sample fuel plates from their exposure in the reactor was a slight brown stain on the surface of the plates. In Figure 8 are shown typical irradiated plates before and after cleaning with caustic. The stain was easily removed by the caustic descaling solution.

Figure 9 illustrates sample fuel plates whose surfaces showed the greatest amount of corrosion. In spite of the appearance of these plates there was no appreciable weight change during the irradiation. It is interesting to note the core outline of the plates.

One fuel plate which had a core with the same composition as used in the MTR fuel plates, but with 0.057 weight per cent boron and 0.013 weight per cent Gd_2O_3 , also failed under test. Figures 10 through 13 are views of this plate. The blistering was probably caused by conditions such as those shown in Figure 6, i.e., voids between picture frame and core or unbonded areas between core and cladding. This plate had not been ultrasonically inspected.

Table II gives the average effects of irradiation upon the dimensions and weights of the sample fuel plates. Inasmuch as there has been little change it can be concluded that the plates have shown excellent corrosion resistance and dimensional stability. The detailed pre- and post-irradiation data are given in Appendix C.

TABLE II
AVERAGE WEIGHT AND VOLUME CHANGES

Compositions	% Change in Vol.	% Change in Wt.
U^{235} + Al (15-30% Burnup)	-0.30%	0.05%
U^{235} + Al (30-50% Burnup)	0.43%	0.01%
UO_2 + Al (15-30% Burnup)	0.01%	0.11%
UO_2 + Al (30-54% Burnup)	0.19%	-0.27%

c. Metallography

Figures 14 through 17 are photomicrographs of cross sections of typical sample fuel plates taken before and after irradiation. The most striking change in the microstructure after irradiation was the formation of the light grey area around the UO_2 particles in the UO_2 -Al fuel plates. This can be seen in Figures 14 and 15. The appearance of this phase is very similar to that produced by heating UO_2 -Al as reported by Waugh at ORNL⁽⁴⁾. However, when produced by heating it is also accompanied by swelling of the plates. No swelling of the irradiated plates was observed. Moreover, the temperature reached in the cores of the sample fuel plates was calculated to have been 150°C or less. This is far below the temperatures of 500 to 600°C used to produce the reaction by heat alone. During hot rolling and blister testing the plates were not held at elevated temperature long enough to produce the UO_2 -Al interaction and therefore there is no evidence of this grey zone in the unirradiated fuel. There is little evidence of corrosion and no indication of microscopic diffusion into the cladding.

Table III summarizes the results of the microhardness testing. These data show that while there was a nominal hardness increase in the cladding after irradiation, there was a much larger hardness increase in the matrix. Detailed hardness data are given in Appendix C. In general, the hardness of the cladding, matrix, and U-Al particles have increased with irradiation while the hardness of the UO_2 particles has decreased.

TABLE III
AVERAGE HARDNESS CHANGES

Compositions	% Hardness Change in Clad	% Hardness Change in Matrix	% Hardness Change in Particle
U^{235} + Al (15-30% Burnup)	57%	350%	190%
U^{235} + Al (30-50% Burnup)	71%	390%	220%
UO_2 + Al (15-30% Burnup)	62%	230%	-38%*
UO_2 + Al (30-54% Burnup)	96%	390%	-4.9%*

* Negative values indicate a decrease in hardness. Some of the particles were too small to obtain a hardness measurement. For these cases the measurements were taken in the matrix at a point where a heavy concentration of the fine particles was located.

BEFORE DESCALING

AFTER DESCALING

PP CO.

FIG. 8
TYPICAL SURFACE CONDITIONS OF IRRADIATED PLATES

P P CO.

FIG. 9
PHOTOGRAPHS SHOWING SCALE ON FUEL PLATES
BEFORE DESCALING

FIG. 10
BLISTER ON PLATE OF MTR COMPOSITION AFTER 34 % BURNUP

FIG. 11
REVERSE SIDE OF PLATE SHOWN IN FIGURE 10

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FIG. 12
EDGE VIEW OF PLATE SHOWN IN FIGURES 10 AND 11

FIG. 13
EDGE VIEW OF PLATE SHOWN IN FIGURES 10 THROUGH 12 AFTER
BEING SECTIONED AND MOUNTED
FOR METALLURGICAL EXAMINATION (50 X)

P P CO.

BEFORE IRRADIATION
(325 X)

AFTER 22% FUEL BURNUP
(325 X)

AFTER 54% FUEL BURNUP
(325 X)

FIG. 14
CHANGES IN MICROSTRUCTURE OF OXIDE FUEL CORE
WITH IRRADIATION
(22.7 Wt.% UO_2 , 93.5 % ENRICHED, IN AL. MATRIX)

BEFORE IRRADIATION
(325 X)

AFTER 15% FUEL BURNUP
(325 X)

AFTER 44% FUEL BURNUP
(325 X)

FIG. 15
CHANGES IN MICROSTRUCTURE OF OXIDE FUEL CORE
WITH IRRADIATION
(45 Wt.% UO_2 , 93.5 % ENRICHED, IN AL. MATRIX)

BEFORE IRRADIATION
(325 X)

AFTER 24% FUEL BURNUP
(325 X)

AFTER 50% FUEL BURNUP
(325 X)

FIG. 16
CHANGES IN MICROSTRUCTURE OF TYPICAL MTR FUEL
COMPOSITION WITH IRRADIATION
(18 Wt.%, 93.5 % ENRICHED, IN Al ALLOY)

BEFORE IRRADIATION
(325 X)

AFTER 36% FUEL BURNUP
(325 X)

AFTER 46% FUEL BURNUP
(325 X)

FIG. 17
CHANGES IN MICROSTRUCTURE OF FUEL ALLOY PLUS
POISON MATERIAL WITH IRRADIATION
(18 Wt.% 93.5 % ENRICHED IN Al ALLOY PLUS
0.057 Wt.% B PLUS 0.013 Wt.% Gd_2O_3)

P.P. CO.

The hardness increase in the matrix is approximately the same for the U-Al cores as for the UO₂-Al dispersions. The large increase in the matrix hardness over the cladding is apparently principally caused by the effects of fission fragments. Some of the increase in hardness may be due to alloying of fission products in the U-Al system and to the formation of Al₂O₃ in the cermet cores. However, because of the limited amount of data and the experimental errors involved, no quantitative conclusions can be made at this stage. Improvements in micro techniques now becoming available may assist in determining the composition of some of these interaction areas in the core material.

E. Irradiation Experience

After the first few cycles of irradiation, several changes in the experiment design and handling techniques were made to improve the operation of the experiment. Plate holders were modified to permit relief of differential coolant pressures existing between adjacent channels which had caused buckling in some of the plates. Tools were modified to provide better underwater handling. The fuel plates holder design was changed (see Figure 18) to eliminate the fuel plate retainers and to place the flux monitors in blank aluminum plates to make flux measurements possible in any holder position.

An analysis of the integrated flux data for position L-51 was made to derive methods by which reasonable predictions of the integrated flux could be made at each of the eight vertical positions within the L-piece, both on the core side and the reflector side. Of prime importance was the reduction of the number of measurements being made for each cycle of irradiation. During the first cycles of irradiation, flux maps were made of the individual holders in order to determine flux gradients existing around the plates and to use the resulting information in the calculation of volume perturbation factors for the sample plates.⁽³⁾

The number of monitors were reduced from nine per holder to two per holder once a correlation between the relative fluxes of the holder positions and the monitor positions had been made. Due to the severe gradients existing horizontally and vertically in the corner position of the core, the plates used for RMF measurements were placed closest to the two flux monitors to insure the maximum accuracy of integrated flux measurements for these plates.

A procedure was then developed which required core and reflector flux monitors only at vertical positions 2, 5, and 8. From the integrated flux measurements at these positions, the core and reflector integrated flux can be reasonably predicted for the remaining ten locations. The procedure is based on the observation and assumption that the integrated flux measurements for the core side and $\left[1 - \frac{\phi_{\text{reflector side}}}{\phi_{\text{core side}}}\right]$ have Gaussian shaped distributions over the eight holder positions. Figure 19 shows a typical fit by the new method as compared to the actual measured values.

Since one of the purposes of the program was to irradiate different compositions to extreme fuel burnups in order to aid in the evaluation of materials and fabrication techniques for reactor use, several plates were irradiated for at least seven cycles in the MTR to fuel burnups in the 44-54 per cent range. To provide an irradiation history for each composition, low and intermediate burnups were attained in the 13-20 per cent and 30-40 per cent ranges. Once these goals were achieved, several plates were reinserted in the reactor for three more cycles. These plates have remained dimensionally stable with no apparent fission gas release or excessive corrosion.

During the course of testing the Phase I sample fuel plate compositions, it became apparent that it would be convenient to have a means of inspecting the bond between the core and the cladding of the irradiated plates. Consequently, the ultrasonic scanner was modified for use in the MTR canal. A view of this equipment is shown in Figure 20. The principal modification was lengthening the search tubes to ten feet. The lead cables were shortened so that the distance from the instrument to the transducers remained the same, thus leaving the unit electrically balanced. These modifications proved to be successful. However, to be entirely practical, it is necessary to make additional refinements in the equipment so that the exact position of defects in the sample fuel plates may be determined.

A fission break was detected in the L-51 reactor position during reactor cycle 113, and the experiment was discharged from the reactor. Inspection of the eight unbonded thorium plates revealed that two of the plates had blistered and ruptured (Figure 21) and one plate had blistered without rupturing (Figure 23). The ruptured plates allowed small quantities of radioactive materials to enter the coolant stream. The sample fuel plates which contained ThO_2 and UO_2 and which had been irradiated for one cycle were then visually examined. Three of these plates had also failed, but in a different manner. The ThO_2 - UO_2 plates had developed pin holes, as shown in Figure 22. Both the ThO_2 and the ThO_2 - UO_2 plates had doubtlessly released small quantities of radioactive material into the coolant stream during their first cycle of operation; however, this material was not detected because of simultaneous failures of larger experiments in the reactor.

All of these ThO_2 plates had been fabricated in the manner described in Appendix A. The 30 ThO_2 and ThO_2 - UO_2 plates were blister tested at 300°F for three days. Four of these plates developed blisters and were rejected. Six additional plates were rejected for other manufacturing deficiencies. The remaining 20 plates passed not only the blister test and visual examination but also the "Zyglo" test. One satisfactory plate of each composition was held as an RMF standard and one plate of each composition was cut for pre-irradiation examination. The remaining plates were irradiated and 37% of these plates failed during their first cycle in the reactor. The failure of these plates cannot be attributed to temperature alone, since the calculated normal operating temperatures of these plates were less than 127°F and all of the irradiated plates withstood blister testing at 300°F. The pinholes which developed in the

FIG. 18
MODIFIED SAMPLE FUEL PLATE HOLDER

FIG. 19
TYPICAL FIT FOR OBSERVED AND PREDICTED INTEGRATED
FLUX VALUES

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FIG. 20
ULTRASONIC SCANNING EQUIPMENT INSTALLED IN THE MTR CANAL

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FIG. 21
CLADDING SEPARATION FROM
ThO₂ PLATE AFTER ONE CYCLE
IN THE MTR
(PLATE 20-9)

FIG. 22
HOLES IN CLADDING OF
ThO₂-UO₂ PLATE AFTER ONE
CYCLE IN THE MTR
(PLATE 21-9)

FIG. 23
ThO₂ PLATE BLISTERED ON
BOTH SIDES, BUT CLADDING
DID NOT RUPTURE
(PLATE 20-16)

PP CO.

ThO₂-UO₂ plates also must have been caused by irradiation, corrosion or rapid reactions between the fuel and clad since structural defects of this type would have been detected prior to irradiation by the "Zyglo" test. This unsatisfactory irradiation experience indicates that for thorium to be a satisfactory material for use in clad plates, bonding must be accomplished between the fuel core and clad. Therefore further work with unbonded ThO₂ in aluminum cladding is not contemplated. However, thorium metal clad in aluminum will be investigated in Phase III of this program.

In all, the experiment design has proven satisfactory for the irradiation program. Sufficient heat removal is achieved without auxiliary equipment, and the plates are easily handled during loading and unloading of the L-piece.

F. RMF Measurements and Results

1. Objectives

The primary objective of the RMF measurements on the sample fuel plates was to provide a periodic check on changes in relative reactivity worths of the samples and to determine the fuel and poison content of the plates during the progress of their irradiation. This information would provide a valuable corroboration of theoretical burnup calculations and incidentally check the accuracy of the flux measurements. Chemical analysis of the plates was not feasible since the plates would then of necessity, be destroyed and lost to further irradiation. In addition, adequate facilities for analysis of the irradiated plates were not available for the scope of analysis required.

To accomplish these objectives, measurements of sample fuel plates in the RMF have been directed in three channels of activities: (1) pre-irradiation reactivity measurements of all plates; (2) measurement of selected plates following periods of MTR irradiation; and (3) developing a procedure for evaluating the reactivity measurements. Pre-irradiation measurements were useful in selecting the most nearly identical pair of plates from each composition. One of these was retained as an unirradiated standard and the other subjected to irradiation in the MTR with the remaining plates of the same type. The reactivity measurements on the other plates served to provide a basis of comparison after irradiation should this be found desirable, and also indicated the degree of uniformity in a set of plates. The one plate chosen as the irradiated plate to be checked was measured, following intervals of MTR irradiation, along with the unirradiated standard. This permitted following the changes in relative sample worths with irradiation; also fuel and/or poison burnout could be determined if a suitable calibration procedure was worked out.

2. The Reactivity Measurement Facility

The RMF is a light-water moderated and reflected low power critical assembly located at the end of the MTR canal. Its special features include a 7 in. x 7 in. center water hole and a calibrated

regulating rod capable of measuring reactivity changes reproducibly down to about $1 \mu k$ ($10^{-6} \Delta k/k$).

In the water hole, the relative importance of fast and slow neutrons varies from position to position. This enables the effects of fuel and poison to be separated by measuring a sample in at least two positions, assuming a two-group theory is applicable. For relatively small differences in fuel and/or poison content, the reactor's response in a given position is adequately described by the relationship:

$$\rho_n = W_{f_n} \Sigma_f + W_{p_n} \Sigma_p \quad (1)$$

where ρ_n is the reactivity response in position n

W_{f_n} is a weighting factor for fuel at n

W_{p_n} is a weighting factor for poison at n

Σ_f represents the quantity of fuel in the sample

Σ_p represents the quantity of poison in the sample

If a suitable set of standard fuel and poison samples is available, the weighting function W_{f_n} and W_{p_n} can be determined for the desired range

of fuel and poison content. Once these are obtained for at least two experimental positions fuel and poison content of an unknown sample may be found by measuring the sample in these positions, substituting reactivities ρ_1 and ρ_2 so obtained in equation (1), and solving simultaneously for Σ_f and Σ_p .

$$\Sigma_f = \frac{\rho_1 W_{p_2} - \rho_2 W_{p_1}}{W_{p_2} W_{f_1} - W_{p_1} W_{f_2}}, \quad (2)$$

and

$$\Sigma_p = \frac{\rho_2 W_{f_1} - \rho_1 W_{f_2}}{W_{p_2} W_{f_1} - W_{p_1} W_{f_2}}. \quad (3)$$

3. Procedure

The sample holders used for the RMF measurements had three slots; a grid located in the RMF center hole provided three positions which would accept the sample holder making a total of nine possible positions for the individual plates relative to the RMF core. Two positions were chosen which gave the greatest variation in fuel sensitivity, one being near the center and one near a corner. All subsequent measurements were made in these reactor positions.

Appropriate standards were utilized each time a group of test plates was measured. Irradiated plates were measured in conjunction with their corresponding unirradiated standards so that relative reactivity changes corrected for RMF drift could be obtained. One plate containing a representative quantity of U^{235} was measured repeatedly each time a series of test samples were run in the RMF. The average of the measurements taken for this standard for any given day provided the basis for comparing measurements taken at widely differing times. A plate containing aluminum only, was also measured periodically as a correction for water displacement.

The determination of the weighting functions W_{f_1} , W_{f_2} , W_{p_1} , W_{p_2} requires adequate standards to cover the range of fuel and poison content encountered. The problem is complicated by the fact that both the W_f and W_p vary with fuel content. RMF measurements and subsequent destructive chemical analysis of a representative group of test plates provided the basis for an adequate calibration for plates containing .88 to 1.12 gm U^{235} . This range for fuel calibration was insufficient, however, since burnup in some of the plates was as great as 60%, based on flux data. This meant that only about 0.4 gm of U^{235} remained.

To extend the range of fuel calibration, three approaches were suggested: (1) procurement of additional plates to extend the range; (2) use of enriched uranium-impregnated polyethylene tapes in lieu of standard plates; and (3) extrapolation of available fuel plate data using a least squares fit to some appropriate function. Additional plates containing a wider range of fuel content were ordered but have not been received. Various combinations of fuel tapes were measured in the RMF by attaching them to blank aluminum plates identical in size with the test plates. This method was found to have several drawbacks. The measurements were very position sensitive and varied with placement of the tape and orientation of the plate in the holder. There was also some indication that the distribution of uranium in the tapes was not sufficiently uniform for the accuracy desired. A least squares fit of the form $\rho = \rho_0 (1 - e^{-\lambda \Sigma})$ was calculated using the RMF reactivity values for ρ and the available chemical analysis data for Σ . The theoretical curves fit the limited data well for both RMF positions.

Calibration for poison was done primarily with 1% natural boron impregnated polyethylene tape using the same procedure as with the fuel tape. The boron tapes were attached on representative standard sample fuel plates so that the weighting functions for poison would be determined in the presence of fuel. This proved to be adequate for amounts of boron up to about 15 mg. For greater amounts of boron, higher concentrations of boron in the tape would be required. Reactivity measurements were taken on an additional group of sample fuel plates containing varying amounts of boron. Chemical analyses of the plates by two independent methods gave estimated boron content which differed by as much as 50% and these in turn differed from the manufacturers specifications.

4. Data

RMF measurements were made on 21 different items used in the test series. The results for several representative plates are given in Table IV-A. The net reactivities obtained for the plates for both positions are given in columns 3 and 4. U^{235} content and poison content (equivalent boron) calculated from the reactivities are given in columns 5 and 6. Table IV-B lists the weighting function used in these calculations. The W_f were obtained from the slopes of the fuel calibration curves of Figure 24. The W_p are the slopes of the poison calibration curves, Figure 25. Table V-A compares RMF values of U^{235} and boron content with chemical analysis values for 4 different unirradiated plates. Chemical analysis of boron content was obtained by two independent methods. Table V-B compares the fraction burnup as determined by 3 different stoichiometric-isotopic distribution analysis with the equivalent values determined by RMF measurements and calculated from flux measurements. The fraction burnup obtained from flux measurements, as reported in Table V-B, was calculated by standard techniques using an average volumetric flux perturbation factor. Burnups calculated in this manner are too high, presumably because the flux wires are in positions where the local flux is a maximum and therefore yield peak flux values instead of volumetric average flux values. All burnup values reported in other parts of this report allow for this effect. The agreement between the analytically determined values and the RMF values is good for both the irradiated and unirradiated plates.

Figures 26, 27A and 27B show relative reactivity changes with nvt for typical plates containing fuel only, and for plates containing fuel and burnable poisons. Figure 28 shows the fractional decrease in fuel content of several typical plates as a function of nvt.

5. Discussion

The uncertainty in results has been estimated from reproducibility measurements and from the fit of the data to smooth curves to be 5 to 15% for fuel and on the order of 50% for boron. Fluctuations in results are attributed to a considerable extent to the relative fuel and poison sensitivities in the positions used and, in the case of boron and/or fission products, to the small quantities involved. A more detailed analysis of errors will be given in a later report.

The results of the work completed thus far have suggested changes in experimental procedures which should help to reduce the errors inherent in the calculations of fuel and poison content of irradiated plates. A more complete set of standards is essential to any real improvement. Also the holder positions now available for sample measurements do not provide sufficiently different weighting functions for either fuel or poison. With $W_{p1}/W_{p2} = 1.67$, very small errors in the reactivities are sufficient to cause large errors in the calculated content. This has been remedied in part by redesigning the sample holder and the position plates so that the plates may be moved closer

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FIG. 24
 RMF FUEL CALIBRATION CURVES

FIG. 25
RMF POISON CALIBRATION CURVES

TABLE IV-A

RMF ANALYSES OF REPRESENTATIVE IRRADIATED TEST PLATES

Plate Composition	Unperturbed nvt $\times 10^{-20}$	Net Reactivity		Content*	
		Corner Position	Center Position	U^{235} (g)	Equiv. B (Nat) (mg)
45 wt% UO_2 , 93.5% Enriched in aluminum	0.00	4.171	3.567	1.125	0.0
	1.12	3.972	3.415	1.09	0.0
	2.18	3.767	3.238	1.03	2.5
	3.26	3.545	3.071	1.00	2.2
	5.52	3.214	2.766	0.88	1.0
	7.40	3.396	2.941	0.83	2.1
	11.54	2.910	2.522	0.65	1.9
22.7 wt% UO_2 , 93.5% Enriched Plus 0.062 wt% B in Al	0.00	3.383	2.964	0.99	4.0
	1.87	3.111	2.712	0.89	2.9
	4.29	3.316	2.915	0.85	5.5
	6.30	2.929	2.601	0.78	6.4
	8.95	2.921	2.527	0.65	3.4
	12.46	2.431	2.109	0.55	3.2
22.7 wt% UO_2 , 93.5% Enriched Plus 0.123 wt% B in Al	0.00	3.162	2.840	1.00	7.7
	1.87	2.992	2.663	0.92	5.9
	4.29	3.310	2.915	0.85	5.8
	6.30	3.037	2.655	0.76	4.2
	8.95	3.029	2.650	0.70	5.3
	12.84	2.392	2.080	0.54	3.4
22.7 wt% UO_2 , 93.5% Enriched Plus 0.062 wt% B plus 0.013 wt% Gd_2O_3 in Al	0.00	3.259	2.891	0.99	5.9
	1.42	3.152	2.776	0.94	4.6
	3.33	2.935	2.599	0.87	5.1
	4.82	3.225	2.841	0.83	5.7
	9.54	2.904	2.532	0.66	4.6
	13.43	2.283	1.981	0.51	3.0

TABLE IV-B

WEIGHTING FACTORS FOR U^{235} AND BORON

Fuel Range (g)	W_F ($\Delta k/k/g$)		W_D ($\Delta k/k/mg$)	
	Corner Position	Center Position	Corner Position	Center Position
0.5 to 0.7	4.85	4.10	0.0693	0.0417
0.7 to 0.9	4.35	3.70	0.0693	0.0417
0.88 to 1.13	3.709	3.172	0.0693	0.0417

* Calculated from reactivity measurements.

TABLE V-A

COMPARISON OF RMF AND CHEMICAL ANALYSES OF UNIRRADIATED TEST PLATES

Plate Composition	Net Reactivity		RMF Determination		Chemical Analysis		
	Corner Position	Center Position	U ²³⁵ (g)	B (Nat) (mg)	U ²³⁵ (g)	B (Nat) (mg)	
						Method A	Method B
18 wt% U, 93.5% Enriched Plus 0.057 wt% B in Al Alloy	3.562	3.101	1.019	3.1	1.004	3.8	2.5
	3.529	3.060	0.998	2.4	0.995	2.0	2.3
22.7 wt% UO ₂ , 93.5% Enriched Plus 0.123 wt% B in Al	2.961	2.622	0.894	5.1	0.915	3.3	4.2
	2.985	2.651	0.909	5.6	0.919	5.2	4.0

TABLE V-B
COMPARISON OF FUEL BURNUP OF IRRADIATED SAMPLE FUEL PLATES
DETERMINED BY VARIOUS METHODS

Plate Composition	nvt (Unperturbed)	Fraction Burnup				
		Isotopic Analysis			RMF Determination	Calculated from Flux Measurements
		Method 1	Method 2	Method 3		
22.7 wt% UO ₂ 93.5% Enriched in Al	14.2 x 10 ²⁰	0.513 ± 0.007	0.525 ± 0.010	0.517 ± 0.012	0.511	.61
45 wt% UO ₂ 93.5% Enriched in Al	11.5 x 10 ²⁰	0.422 ± 0.008	0.423 ± 0.015	0.420 ± 0.016	0.421	.54
18 wt% U 93.5% Enriched in Al alloy	13.5 x 10 ²⁰	0.476 ± 0.007	0.478 ± 0.010	0.471 ± 0.011	0.489	.59

to the reactor's fuel, a position in which W_p is appreciably greater. Finally, some increase in accuracy will result from taking all measurements on the RMF's expanded scale.

Despite the inherent uncertainties in the calculations of fuel content, it should be noted from Figure 28 that the relative change in U^{235} content of several plates of different compositions and poison content plotted as a function of neutron exposure agree very well with each other. This indicates that the calculation from RMF measurements in two positions is reasonably adequate for fuel determination.

The curves of Figure 26 show that in the center experimental position the relative fuel content of the plates as determined from reactivity measurements alone agrees well with that determined by the more complicated calculation procedure. This is true because of the high sensitivity of the RMF to fuel relative to poison in this position and the relatively low fission product poison cross section. Furthermore, this suggests that upon proper calibration, fuel burnup can be read directly from a single post-irradiation measurement in the RMF on each plate. Assuming that each fission produces poisons having a total cross section of 100 barns, a fuel plate of the type used here when burned out to 50% has a poison cross section equivalent to about 3 mg of natural boron. This quantity of poison reduces the reactivity of the plates by about 6%.

6. Results and Conclusions of RMF Measurements

Nondestructive techniques have been developed for the RMF which yield accurate values of the fuel content, poison content and burnup of sample fuel plates containing between 0.5 g and 1.13 g U^{235} and less than 10mg equivalent boron. The fuel burnup data determined by the RMF are more accurate than the corresponding values determined from integrated flux and initial fuel content data. The determination of fuel in unirradiated plates by the RMF often yields data more accurate than that furnished by the sample fuel plate manufacturer.

G. Burnable Poison Irradiation Program

The goals of the irradiation program of sample plates containing poisons are (1) to develop suitable fabrication techniques, (2) to demonstrate reactor suitability, and (3) to determine the types and quantities of poisons needed to achieve longer cycle life and better reactor control.

A theoretical study was initiated to minimize reactivity changes over the desired operating time of the core. The reactivity changes due to fuel burnup and the buildup of fission poisons were approximately balanced by the changes due to the burnup of added poisons. In this analysis, the reactivity worth of fuel was assumed to be a linear

FIG. 26
FRACTIONAL CHANGE IN REACTIVITY OF FUEL PLATES
(CENTER POSITION)

FIG. 27-A

FRACTIONAL CHANGE IN REACTIVITY OF FUEL PLATES CONTAINING BURNABLE POISONS (CORNER POSITION)

FIG. 27-B

FRACTIONAL CHANGE IN REACTIVITY OF FUEL PLATES CONTAINING LARGE AMOUNTS OF BORON

FIG. 28
FUEL BURNOUT IN MTR IRRADIATED PLATES

function of the mass of fuel, and the reactivity worth of poison was assumed to be a linear function of the mass of poison (i.e., no self-shielding). Fig. 29-A shows the individual reactivity changes of fuel and poisons, calculated using the above assumptions, as a function of ETR operating time at constant flux. The individual reactivity worths of selected amounts of poisons and fuel in Fig. 29-A were then added algebraically to produce the total reactivity curves shown in ETR Fig. 29-B. The composition for which this analysis was made is approximately that of sample plate composition #18.

The flattened total reactivity curve of Fig. 29-B is indicative of the results obtainable from burnable poisons. However, before the optimum benefits of burnable poisons may be accrued, it is necessary to analyze critically the assumptions upon which Figures 29-A and 29-B are based. The RMF provides the initial experimental data, as typified by Figures 24, 25, 26, 27-A and 27-B, needed for this analysis.

Fig. 24 shows that even for relatively thin plates (.050 in.) having moderate fuel loadings the reactivity worth of the fuel is not directly proportional to the mass of fuel present. Fig. 24 also reveals that the amount of self-shielding is not only dependent upon the amount of fuel but also upon the distribution of fuel in (or upon) the plates. The reactivity worth of U^{235} impregnated tapes attached to the outside of the fuel plates was consistently greater than the reactivity worth for the same amount of U^{235} dispersed within the core of the sample fuel plate.

Although it is not indicated in Fig. 25, the RMF data shows that there is also considerable self-shielding by poison in the sample fuel plates investigated. There is also a mutual shielding by fuel and poison and, therefore, the reactivity worth of the combination is not the algebraic sum of the individual reactivities. A quantitative evaluation of the shielding by poisons cannot be made until more precise RMF poison and fuel standards have been obtained.

The RMF experimental data on irradiated plates, as shown in Figures 26, 27-A, 27-B and 28, were taken sometime after irradiation and some of the fission product poisons (chiefly Xe^{135}) had decayed away. Hence, the experimental reactivity curve for fuel as a function of irradiation time (Fig. 26) coincides better with the predicted reactivity curve for U^{235} (Fig. 29-A) than with the predicted reactivity curve for fuel and associated fission products (Fig. 29-B).

In addition to the differences between the predicted reactivity curves (Fig. 29-B) and the measured reactivity values (Fig. 27-A) which are caused by shielding and fission product poison decay, there is an effect due to the difference in the flux spectra in the two positions of the RMF, the experimental irradiation facility and the reactor core represented in Fig. 29-B. The irradiation flux spectrum has a pronounced effect upon the relative burnup rates of poisons and fuels as shown by variations in absorption cross sections with neutron

energy. Also, the total reactivity worth of combinations of fuel and poisons is strongly dependent upon the flux spectra, as indicated in Fig. 27-B. In this figure, the reactivity worth of a sample plate containing U^{235} and a large amount of poison is plotted as a function of irradiation time. Even though the curves for the corner position ($\Phi_{\text{thermal}}/\Phi_{\text{fast}} = 40$) and for the center position ($\Phi_{\text{thermal}}/\Phi_{\text{fast}} = 64.5$) are normalized to have the same value prior to irradiation, they differ considerably after irradiation. Also it is reasonable to assume that the reactivity worth of this plate while being irradiated in L-51 ($\Phi_{\text{thermal}}/\Phi_{\text{fast}} = 11$) would be considerably different from that shown in Fig. 27-B.

As more data are obtained on the combined effects of fuel and burnable poisons, the burnable poisons will be integrated into both new and existing geometries. Some of the required data should be obtained from the investigation of Phase II compositions (Table IX) which is now in progress.

FIG. 29-A
REACTIVITY vs. ETR REACTOR TIME FOR FUEL, FISSION
PRODUCTS, AND VARIOUS POISONS

FIG. 29-B
TOTAL REACTIVITY vs. ETR REACTOR TIME FOR
FUEL, FISSION PRODUCTS, AND BURNABLE POISONS

III. PROTOTYPE STUDIES

A theoretical analysis (to be published separately) of the hydraulic and heat transfer characteristics of parallel flow, heterogeneous fuel elements indicates that for optimum operation every flow channel in the element should have the same hydraulic diameter. It is further shown, that for equivalent elements (those elements fitted into the same total space, having the same equivalent diameters, the same clad thickness, and the same fuel content and composition), there is very little if any advantage of one geometrical design over any other geometrical design except those advantages directly caused by the elimination of wasted space and of local hot-spots. Wasted space includes such things as mechanical braces and spacers (e.g., side plates), those portions of the fuel element which do not contain fuel or which have extra thick cladding, and those distorted flow channels which result on the outside of the element when a geometry such as the hexagonal-honeycomb is forced to fit in a square area. Local hot-spots are typified by the reduction of the heat transfer coefficient in sharp corners and between adjacent tubes. Therefore, the optimum parallel flow fuel element is one which is strong, easy to fabricate and which has no wasted space and no local hot spots. As yet, such an optimum element has not been designed. Currently, the types of fuel elements most commonly used for testing reactors are the flat and curved plate elements and the tubular elements.

A. Plate Type Elements

The plate type fuel elements have the advantage of being a proven design for which fabrication techniques are well developed. However, since plates are weak structurally, heavy side plates are required to withstand the hydraulic forces within the reactor. Further improvement in the plate designs are being developed through the use of a greater number of thinner plates, slotted side plates and through the use of modified end boxes or plate spacings to obtain a more uniform flow distribution. Modifications of the plate design have been proposed for those special cases involving cylindrical cores, i.e., the circular segment and the involute element.

Four MTR "dummy" fuel elements having 22, 24, 30, and 32 plates have been tested hydraulically. The element specifications are shown in Table VI. The measured hydraulic data for the four elements and a standard MTR element are shown in Figures 30 and 31. Calculations based on these curves show that if the plate thickness is reduced and the number of plates is increased there will be an advantage in the heat transfer capabilities of the fuel element that should allow cooler operation and/or an increase in power (see Table VI).

Velocity measurements were made on three of the outer channels and two of the center channels of the 32 plate element. The results of these measurements show an average velocity of 29.2 ft/sec with a minimum measured velocity of 27.0 ft/sec. This gives a difference of 7% between the average and minimum measured velocity. A similar test on the 30 plate element gave an average of 27.9 ft/sec with a minimum measured

TABLE VI

HEAT TRANSFER AND HYDRAULIC DATA FOR VARIOUS FUEL PLATE COMBINATIONS

	Std. MTR	D-1	D-4	D-5	D-8
Number of Plates	19	24	32	22	30
Type of Aluminum	1100	6061	6061	1100	1100
Outer Plate Thickness (inches)	.0625	0.050	0.050	0.0625	0.0625
Inner Plate Thickness (inches)	.050	0.040	0.040	0.050	0.050
Nominal Channel Width	116	0.091	0.057	0.093	0.053
Flow at 40 psi Drop; Measured gpm Through Element	568	505	370	505	322
Flow at 40 psi Drop; Measured ft/sec Through Element	33	29.5	25.6	31.7	25.6
Flow at 40 psi Drop; Calculated gpm Through Element	590	540	391	524	338
Flow at 40 psi Drop; Calculated ft/sec Through Element	34.3	31.5	27.0	32.9	26.8
Maximum Wall Temperature ($^{\circ}\text{F}$) at Standard MTR Loading Assuming ϕ_{max} for MTR is 8×10^5 Btu/hr-ft ² and the Distribution is Chopped Cosine	228	217	210	219	218
% Increase in Power at Standard MTR Wall Temperature Based on Measured Flow with no Hot-Spot Hot-Channel Analysis		12%	20%	10%	11%

FIG. 30
TOTAL FLOW THROUGH FUEL ELEMENT
TEST ASSEMBLY vs. TOTAL PRESSURE DROP

FIG. 31
INTERNAL FLOW VS. FUEL ZONE PRESSURE DROP
i.e. TOTAL ΔP LESS END BOX ΔP's

velocity of 25 ft/sec. This gives a difference of 10% between the average and the minimum measured velocities. These maximum channel to channel velocity deviations compare favorably with the 30% minimum to average deviation measured in the standard MTR fuel element and offer a potential improvement evident in the hot-spot hot-channel analysis.

Destruction tests were also attempted on two of these elements. For the 30 plate element the maximum pressure differential across the assembly was 130 psi with 805 gpm of water flowing through the assembly. This flow rate is 190% of the 40 psi flow rate. For the 32 plate element the maximum pressure was 119 psi with 860 gpm of water flowing through the assembly. This flow rate is 175% of the 40 psi flow rate. Visual inspection after these tests revealed no mechanical damage to either of these elements.

As a result of these tests a 32 plate fuel element, utilizing slotted side plates and T-6 condition 6061 aluminum cladding, will be tested in the MTR. A 28 plate fuel insert, of similar design, for the MTR renewable shim rod is also proposed.

To test the feasibility of reducing the plate thickness without loss of structural strength, static pressure tests were run on a 6061 aluminum element and on a 1100 aluminum element. The test apparatus shown in Figure 32 applies an internal static pressure and measures the deflection of the outer plate. The test results obtained both at room temperature and at temperatures approximating the maximum plate temperatures encountered in reactor operation are shown in Figures 33 and 34. Within the proportional (elastic) limit there is no advantage of one aluminum alloy over another. Once this value is exceeded, however, the stronger alloy results in less permanent deflection and the initial permanent set occurs at a higher pressure. The thin 6061 aluminum plates appear sufficiently strong. However, an additional gain in strength is potentially available through the use of mechanical assembly, i.e., pinning or roll swaging which allows the 6061 cladding to be maintained in the T-6 condition. A summary of the results is given in Table VII-A, B and C.

During these static pressure tests, the maximum deflection was obtained from the external plate having the high pressure on the convex side of the plate. Therefore, it is the data which are presented in Table VII-A and Figures 33 and 34. The elastic deformation of these plates was most nearly that theoretically predicted for a flat plate with all edges fixed (see Table VII-B). The deflections shown in the table were calculated from the following equations:

All edges fixed

$$y_{\max} = \frac{0.028 w b^4}{E t^3 (1 + 1.056 \alpha^5)} \quad (1)$$

where

$$\begin{aligned} w &= \text{pressure (lb/in}^2\text{)} \\ b &= \text{width of plate (in.)} \\ E &= \text{modulus of elasticity (lb/in}^2\text{)} \\ t &= \text{thickness (in.)} \\ \alpha &= \text{ratio of width to length} \\ y_{\max} &= \text{maximum deflection (in.)} \end{aligned}$$

TABLE VII-A

EFFECT OF ALLOY AND THICKNESS ON FUEL PLATE STRENGTH

(Values shown are based on static pressure tests)

Material (Al)	Thickness	Max Deflection at 10" Hg	First Permanent Deflection (in.Hg)	Permanent Deflection at 20" Hg	Pressure at Plate Reversal (in.Hg)
6061	0.050"	0.007"	26	0	45
6061	0.040"	0.013"	9	0.005"	30
1100	0.0625"	0.004"	17	0.002"	33
1100	0.050"	0.007"	13	0.013"	21

TABLE VII-B
COMPARISON OF OBSERVED AND THEORETICAL ELASTIC DEFORMATIONS

Plate Material	Plate Thickness (in.)	Temperature (°F)	Observed Deflection (in.)	Calculated Deflection (in.)	
				Fixed Edges	Simply Supported Edges
1100 Al	.050	75	.018	.010	.050
6061 Al	.040	75	.024	.017	.085
1100 Al	.0625	75	.012	.006	.030
6061 Al	.050	75	.022	.015	.075
1100 Al	.050	365	.022	.011	.055
6061 Al	.040	365	.036	.016	.080

TABLE VII-C

COMPARISON OF OBSERVED AND THEORETICAL INELASTIC DEFORMATION PRESSURES

Plate Material	Plate Thickness (in.)	Temperature (°F)	Yield* Strength (psi)	Observed** Pressure (psi)	Calculated Minimum Pressure for First Permanent Deformation (psi)		
					Fixed Edges	Simply Supported Edges	Arch with Simply Supported Ends
1100 Al	.050	75	5,000	6.4	3.6	2.4	119
6061 Al	.040	75	8,000	4.4	3.8	2.4	61
1100 Al	.0625	75	5,000	8.3	5.7	3.8	232
6061 Al	.050	75	8,000	12.8	5.8	3.9	119
1100 Al	.050	365	3,200	2.0	2.3	1.6	110
6061 Al	.040	365	5,100	1	2.4	1.6	57

* "Metals Handbook", 1948 edition, published by The American Society for Metals.
(annealed values)

** This observed pressure is the minimum observed pressure capable of causing inelastic deformation of the plates. Since the lateral differential pressures were increased in increments of approximately 0.5 psi, the true pressure at which inelastic deformation first occurred may be as much as 0.5 psi lower than the numbers quoted in this column.

FIG. 32

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STATIC PRESSURE DEFLECTION MEASUREMENT RIG
THE APPARATUS FOR MEASURING DEFLECTION
OF FUEL PLATES WITH APPLIED PRESSURE

FIG. 33
STATIC PRESSURE TESTS ON DUMMY FUEL ELEMENTS
MAXIMUM DEFLECTION

FIG. 34
STATIC PRESSURE TESTS ON DUMMY FUEL ELEMENTS
PERMANENT DEFLECTION

Edges simply supported (hinged)

$$y_{\max} = \frac{0.142 \, w b^4}{E t^3 (1 + 2.21 \, \alpha^5)} \quad (2)$$

The deflections in Table VII-B correspond to values of the pressure such that the points lie on the linear portion of the curves, Figure 33. The brazed fuel plates tested were approximately one half as stiff as theory predicts for fixed end plates. Therefore, the following preliminary equation is recommended for elastic deflection calculations on plates of this type.

$$y_{\max} = \frac{0.056 \, w b^4}{E t^3 (1 + 1.056 \, \alpha^5)}$$

Previous investigations have shown that the elastic deflection of flat ETR type plates is best calculated by the formula for flat plates having simply supported edges.

A comparison between the observed and calculated pressures at which plastic deformation first takes place is given in Table VII-C. The Calculated Pressures were obtained from the following equations:

All edges fixed

$$w = \frac{S t^2 (1 + 0.623 \, \alpha^6)}{0.5 \, b^2}$$

Simply supported edges

$$w = \frac{S t^2 (1 + 1.61 \, \alpha^3)}{0.75 \, b^2}$$

Arch with simply supported ends

$$w = \frac{E t^3 \left[\frac{\pi^2}{\alpha^2} - 1 \right]}{12 \, r^3 (1 - \nu^2)}$$

where

S = yield strength (lb/in²)
 r = radius of curvature (in.)
 ν = poisons ratio

This comparison again shows that the behavior of the plates is most nearly described by fixed end, flat plate theory. With the possible exception of the .050 inch, 6061 Al plate at room temperature, none of the plates exhibited significant arch strength. This lack of arch strength may be partially caused by the fact that the static pressure inside the fuel element causes some outward force on the ends of the fuel plate, thus tending to put the plate under tension.

This comparison also shows that the actual effect of temperature on the start of plastic deformation is over twice as great as theory predicts.

The values of pressures given in Table VII-C represent the onset of plastic deformation and not the onset of plate failure which may be obtained from the sharp deflections in Figures 33 and 34. Plate failures occurred at considerably higher deflections because a small amount of plastic deformation will redistribute the stresses within the plate and will work harden the metal, thereby producing greater failure strengths than simple theory predicts.

The above analysis does not consider the possible effects of differences in the core and the cladding materials, nor does it consider the possibility of the fuel plates retaining some of their work, thermal and age hardening during the brazing process.

B. Hexagonal-Honeycomb Type Element

The hexagonal-honeycomb type fuel element has been investigated because of its high heat transfer area, low metal to water ratio and excellent structural characteristics. This type of fuel element is currently quite difficult to construct and little is known about possible hot spots in the corners of the hexes. Also, the full advantages of the hexagonal arrangement cannot be realized in an existing reactor core which was designed for square fuel elements (see Figure 35-A).

C. Tube Bundle Type Element

The tube bundle appears to be an attractive type of heterogeneous fuel element. It has the highest heat transfer area and lowest metal to water ratio of any element considered. Other advantages inherent in this design are increased strength and possibly higher power operation. The tube bundle is potentially strong enough to eliminate the necessity of side plates. However, completely satisfactory fabrication techniques are yet to be developed and considerable uncertainty exists about the magnitude of the circumferential temperature gradients on the outside of the tubes (see Figure 35-B).

D. Concentric Rounded Square Fuel Element

A concentric rounded square fuel element (Figure 36) has been designed and fabrication of a full-scale dummy element has been started. This design is a compromise which has very little wasted space, which should be fairly strong and should present no major fabrication difficulties. Although this design is most efficient when fitted into a square area (e.g., the ETR) it may also be fitted into other areas such as the MTR and cylindrical segment shapes.

E. Tubular MTR Fuel Element

1. Design

Arrangements made with The Martin Company to install their tube bundle design in an MTR envelope resulted in an assembly containing sixty-four fuel tubes each 0.302 in. in diameter as shown in Figures 37

FIG. 35-A
HEXAGONAL HONEYCOMB

FIG. 35-B
TUBE BUNDLES

NOTE :

DOTTED TUBES SHOW CLOSEST
APPROACH OF ADJACENT BUNDLES

PP CO. - C - 2667

CROSS SECTION

DETAIL

PPCo. - A - 2919

FIG. 36
CONCENTRIC ROUNDED SQUARE FUEL ELEMENT

and 38. The fuel in the tubes consists of cored pellets of UO_2 and aluminum, fabricated by powdered metallurgy techniques, which were slipped over an aluminum tube that subsequently became the inner cladding. A second aluminum tube was slipped over the outside of the fuel and the assembly was then evacuated and drawn to final size.

Pre-test inspection revealed distortion of tubes during assembly into the bundle permitting some contact between the tubes. This is illustrated in Figure 39. Considerable variation was also observed in the size of the brazed joint between tubes.

2. Tests

a. Hydraulics

Hydraulic tests were conducted in a single element flow test loop. The flow data from these tests are compared with similar data from production plate type element in Figure 40. The coolant velocities through the corner tubes calculated from the pressure drop measurements are shown in Figure 41. The two tubes located on the concave side of the element indicate a velocity decrease of 12-15 percent below average while the tubes adjacent to the convex side indicated approximately average velocities. The unequal flow distribution is largely caused by the top end box not being concentric with the center of the fuel section. The velocity outside the tubes is approximately the same as that inside the tubes. Under normal MTR flow conditions, these values are 30.2 ft/sec outside the tubes and 30.7 ft/sec average inside compared to 33 ft/sec with the 30% minimum to average variation in the MTR plate element.

The hydraulic data reported here were obtained by testing two "dummy" elements. These were similar to "live" elements in all respects except for the substitution of normal or depleted uranium for the enriched material. In the test of one of these elements, some of the brazed joints between the tubes broke, freeing one end of several tubes (see Figure 42). The brazed joint between the bundle and the shell also broke loose during this test permitting the tube bundle to drop to the lower end box. The second element was tested to 128% of normal flow rate without incident. No vibrations of the tubes were detected during these tests.

b. Heat Transfer

The bulk water temperature rise and maximum wall temperature under reactor conditions were calculated from the flow rates obtained in the hydraulic tests and from the application of a hot-spot hot-channel analysis performed in accordance with the procedure described in IDO-16343(2). Because of the distortion noted in the tube bundle, three cases of mechanical distortion were considered for analysis:

- (a) Each tube was distorted mechanically, moving toward an adjacent one by 0.015 in.

- (b) Three tubes came together for a distance of two inches at the center (lengthwise) of the tubes.
- (c) Four tubes came together for a distance of two inches at the center.

The results of these analyses are summarized in Table VIII. The estimated distortion results in maximum wall temperatures which are far in excess of those allowed in the MTR. Therefore, any satisfactory tube bundle fuel element must be fabricated and handled in such a manner as to insure freedom from gross mechanical distortion. The comparison of the tube element with the MTR element favors the latter if the circumferential temperature gradient is calculated by the method of Deissler and Taylor⁽⁶⁾. However, there is some doubt as to the reliability of this method. If the circumferential temperature gradient is neglected or is calculated by a modification of the Deissler and Taylor procedure, then this tube element and the standard MTR element are approximately equal.

Because of the weakness apparent in the tube assembly, "live" elements of this design were not considered satisfactory for reactor tests. Improved fabrication techniques and controls should result in a satisfactory element. Confining the fuel tubes in an MTR element for testing purposes imposes severe restrictions on the performance of the tubular element. Without the MTR shell, more tubes could be included in the bundle and the performance would be improved.

F. Modified MTR Shim Rod

As a part of the Fuel Element Development Program, an improved MTR shim rod has been designed and a prototype has been tested out of pile. This new shim rod is expected to meet or exceed all design requirements; the out-of-pile tests have already shown that it can meet satisfactorily the heat transfer requirements for operating power levels to 60 Mw. The Safeguard Committee has reviewed this design and accepted it in principle. The testing program can now proceed into the in-pile phase for operational evaluation. Savings of about \$25,000 yearly on a five year basis for component cost are expected, and in addition there are attractive potential operational advantages.

The design employs an outer housing (structure) which is essentially a permanent component and not expendable upon completion of burnup in the fuel and poison sections. The poison section surface area is 2% greater than that currently in use, which should mean slightly more negative reactivity "worth" for control. It is removable from the housing, and can be inverted and re-inserted for extended life and more even burnup. A study will be made to determine if this removal and re-insertion may be accomplished without prior replacement of an adjacent fuel element with a dummy Cd block. If the study indicates that this is possible, then the replacement of the Cd poison (and fuel) section may be executed without the removal of the upper grid. The poison and fuel sections only are expendable for reasons of burnup; (the spacer may require infrequent replacing because of physical wear). New methods of fabrication are utilized for the poison section which will eliminate the possibility of inward ballooning of the inner sandwich layer.

The fuel section containing 150 grams of U^{235} in sixteen plates can be removed from the housing and a new (or Xe^{135} depleted) one re-inserted, in a manner similar to the Cd poison section replacement.

FIG. 37
MTR TUBULAR FUEL ELEMENT

FIG. 38
TUBULAR FUEL SECTION - TOP VIEW

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FIG. 39
TUBULAR FUEL SECTION
SECTION OF TUBE BUNDLE AFTER REMOVAL FROM BOX
SHOWING UNEVEN TUBE SPACING, ENLARGED

FIG. 40
HYDRAULIC TESTS
FLOW THROUGH ELEMENTS VS. OVERALL PRESSURE DROP FOR
MTR PLATE AND TUBULAR FUEL ELEMENTS

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FIG. 41
FLOW DISTRIBUTION TEST MTR TUBULAR ELEMENT

PP CO.-B-2668

FIG. 42
TUBULAR FUEL SECTION-TOP VIEW
ENLARGEMENT SHOWING EXCESS BRAZE MATERIAL AND JOINT FAILURE

TABLE VIII
SUMMARY OF HEAT TRANSFER CALCULATIONS
ON TUBULAR MTR FUEL ELEMENT COMPARED
WITH MTR PLATE ELEMENT

Maximum Wall Temperature Calculated for the Following Conditions		Tube	Plate
1.	Without hot-spot hot-channel factors ($F_h \propto F_b$)*	217°F ¹ 189°F ² 193°F ³	197°F
2.	With $F_h \propto F_b$ but neglecting mechanical distortion	348°F ¹ 303°F ² 310°F ³	292
3.	With $F_h \propto F_b$ including 0.015 in. distortion	417°F ¹	
4.	Without $F_h \propto F_b$ but assuming three tubes touch for 2 in. at center	288°F ¹	
5.	Same as 4 but with $F_h \propto F_b$	472°F ¹	
6.	Without $F_h \propto F_b$ but assuming four tubes touch for 2 in. at center	256°F ¹	
7.	Same as 6 but with $F_h \propto F_b$	583°F ¹	

*
$$F_h = \frac{\Delta T_{\text{film-max}}}{\Delta T_{\text{film-nominal}}}$$

$$F_b = \frac{\Delta T_{\text{bulk-max}}}{\Delta T_{\text{bulk-nominal}}}$$

1. Circumferential temperature gradient estimated by the method of Deissler and Taylor⁽⁶⁾ is included in maximum wall temperature.
2. No circumferential temperature included.
3. Circumferential temperature gradient estimated by a modification of the Deissler-Taylor method.

The housing features improved coolant exit ports which eliminate the partial obstruction of the coolant flow by the lower grid bearing. This interference was disclosed during the early test work and may be the cause of boiling experienced in the shim rod. Current shim rods reflect a change which overcomes this early design deficiency.

Procurement of fully fueled and operational prototypes and complete in-pile testing are recommended.

G. MTR Oxide Fuel Element

An MTR oxide fuel element, of standard dimensions, was purchased from Syl-Cor. The element contained 1000 grams of 20% enriched fuel in a UO_2 -aluminum dispersion (about 60 w/o UO_2). The element was tested hydraulically up to a 50 psi drop through the element (normal MTR operation requires a ΔP of 40 psi) with no visible damage. The element was then run for 3 cycles in MTR positions 21 and 29 with a 37% burnup of the enriched material.

There was no detectable failure of the element and, although the post-irradiation tests are not yet complete, it is felt that this test in conjunction with 54% burnups safely completed on similar compositions in the sample fuel plates has adequately demonstrated the feasibility of UO_2 fuel elements in testing reactors of the MTR type.

H. Poison Section Fabrication

A short, preliminary investigation into the feasibility of forming poison sections by a roll-swaging technique was made. A cadmium core was placed between two concentric aluminum tubes. Short aluminum core filler pieces were placed at either end of the cadmium core. These concentric tubes were then cold swaged to form one solid tube with the cadmium completely sealed in aluminum. A radiograph of the completed tubes revealed no voids between the cadmium and aluminum. Photomicrographs of sections through the core revealed a very tight mechanical bond between the cadmium and the aluminum even though this method did not form metallurgical bonds. The bonds between the aluminum cladding and the aluminum core filler pieces were not perfect. Additional hot swaging may be required to overcome this deficiency. The swaging method of fabrication appears to offer an excellent potential for containing the cadmium in the reactor.

I. Roughened Heat Transfer Surfaces

The effects of roughening a hydraulic-heat transfer surface are to increase the friction factor (pressure drop) and to increase the heat transfer coefficient. If the surface roughening is not too extreme, the increases in the friction factor and heat transfer coefficient are approximately proportional, specifically,

$$h = 1/2 V_p C_f (P_r)^{-2/3}$$

FIG. 43
MODIFIED MTR SHIM ROD WITH REMOVABLE FUEL
AND POISON SECTIONS

FIG. 44
PP CO.
MODIFIED MTR SHIM ROD WITH ADDITIONAL SLOTS.
ADDITIONAL SLOTS WERE CUT TO RELIEVE OBSTRUCTIONS CAUSED
BY REACTOR GRID GUIDE BEARINGS AT CERTAIN ROD POSITIONS

Because pressure drop, heat transfer coefficient and pumping power are related directly to V^n by different values of n , (i.e., $h \sim V^f$, $\Delta P \sim V^2$ and $W_{\text{pump}} \sim V^3$) and since the pressure drop that occurs in the active fuel core is only a fraction of the total primary coolant pressure drop, it is theoretically possible to obtain increases in allowable reactor power and/or reductions in primary pumping power by changing from smooth to roughened heat transfer surfaces.

Preliminary hydraulic tests are being run to determine the types of surfaces that appear most practical for reactor use. When these tests are completed, heat transfer tests will be conducted on the most promising surface. Recommendations concerning in-pile tests will depend upon the results of these heat transfer tests.

IV. ASSOCIATED PROJECTS

Investigations being conducted at the MTR along somewhat different lines but which are associated with the fuel element development program are summarized briefly below because overall integration of these programs permits the maximum utilization of the data with a minimum in cost and manpower.

A. High Temperature Oxide Fuel Development

A statistically designed capsule irradiation program has been undertaken as part of the ORNL Experimental Gas Cooled Power Reactor (EGCR) fuel development program. A total of sixteen lead-type capsules are to be irradiated in the ETR reflector for periods varying from 6 to 44 months. Figure 45 illustrates the three cylinder arrangement involving the UO_2 fuel pellets and stainless steel container, the NaK vessel, and the thermal barrier gas vessel. The operating parameters are indicated in the table. The controlling values are the 1300°F and 1600°F fuel can temperatures obtained by varying the He-N_2 gas mixture in the thermal barrier system. The first capsule of the series was inserted in February 1959. Six more were inserted in July 1959, four in December 1959, and four in May 1959.

The radiation stability of fuel as determined by reactor lifetime and by a complete post-irradiation metallurgical examination, including fission gas buildup, will serve as proof of the fuel element design for the EGCR and will provide some basic experimental data for the fuel element development program.

B. Radiation Damage Studies

Post-irradiation examination of reactor fuel materials is one portion of a program to study the radiation effects on reactor materials (including fuels as well as materials of construction for reactors and reactor experiments). Fuel plate samples irradiated for stability tests serve both projects. Studies of radiation damage to materials like aluminum, stainless steel, beryllium, etc., also serve to advance the knowledge of fuel element materials. Considerable work has been conducted at the MTR to determine changes in mechanical properties of metals with radiation. Studies are now contemplated to correlate these observations with an explanation of the damage mechanism.

C. Heat Transfer and Hydraulics

A fuel element development program which aims to test the best geometry (in which has been incorporated the best fuel material) for a particular reactor design, must involve theoretical and experimental work in heat transfer and hydraulics. For this purpose hydraulic facilities have been provided at the MTR-ETR and have served in proof testing new element designs and in determining the value of improvements to existing designs. Some in-pile heat transfer measurements have been made under a separate budgeted activity and additional out-of-pile work is proposed. A small 220 kw electrically heated loop is being assembled at the MTR-ETR

FUEL GEOMETRY	PELLET DENSITY (% THEO.)	ENRICHMENT	AVERAGE NEUTRON FLUX PERTURBED (N/cm ² - sec.)	DESIGN POWER BTU/hr. - ft.	BURN - UP		CLAD TEMPERATURE (°F)	IRRADIATION TIME (DAYS)
					RATE (MW/MT)	TOTAL (MWD/MT)		
SOLID PELLETS	95	NAT. 1%	5×10^{13}	35,000	12.5 - 16.5	3000	1300	175 - 990
CORED PELLETS						6000		
CORED W/ BUSHING						13000		

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FIG. 45
OXIDE FUEL IRRADIATION - EGCR PROGRAM

with possible later modification to a 600 kw loop. Heat transfer data in forced convection, nucleate boiling and burnout is possible in this loop using geometries of interest in the fuel element development program.

D. Vibration Tests

Discussions between members of the Reactor Engineering Section and the Instrument Development Section in October 1955, led to a cooperative effort to develop techniques for measuring fuel element vibration caused by pressure fluctuations along the fuel geometries* as a result of coolant flow. A hydraulic test fixture was available on a part-time basis for the flow tests.

Three approaches to the detection and measurement of the amplitude and frequencies of vibration were investigated:

1. An electro-mechanical "probe" transducer,
2. An electro-mechanical "proximity" transducer,
3. An ultrasonic transducer.

All three transducers with suitable amplifiers and associated circuitry were used with a General Radio Vibration analyzer connected to a Sanborn strip chart recorder.

The probe type transducer was used only for calibration testing since it produced loading on the vibrating elements and required drilling access ports in the housing and in the plates.

The proximity type transducer offered the best means of obtaining data in a short time with the least auxiliary equipment but had the disadvantage of limited transmission distance and required access ports similar to those used with the probe-type pickup.

The ultrasonic method had the distinct advantage of non-loading and requiring no access ports. However, this method required considerable development effort.

The ultrasonic system was built as described in IDO-16297⁽⁵⁾. Preliminary tests using vibrating strings in air and moving plates in a water filled tank yielded very promising results. However, tests of actual fuel elements in the hydraulic test fixture proved that considerable refinement of the acoustic coupling tank and that shielding from direct electrical pickup were necessary. Some difficulty was experienced because of the presence of standing waves.

* These tests have been applied to new geometries now under study and to plate type elements.

Some tests of fuel elements in a second hydraulic test fixture at the ETR during the latter part of 1958 yielded good results from the instrumentation and also proved that newer fuel element designs were much less likely to develop large vibration amplitudes.

Further work on refinement of the ultrasonic method is planned in the Instrument Development Section. An apparatus will be utilized which can impress known frequencies and amplitudes of vibration on fuel plates. Gated, rather than continuous wave transmission, and redesign of the coupling tank to minimize standing waves is planned.

Vibration testing of fuel elements is now particularly valuable with technology striving for longer-life fuel elements and higher velocity coolant flows.

V. CONCLUSIONS AND FUTURE DEVELOPMENT OF FUEL ELEMENTS

A. Fabrication

The sample fuel plate fabrication program has demonstrated satisfactory techniques for incorporating combinations of poisons into both alloy and cermet fuels. High weight per cent alloys (35%U) and cermets (65%U) have been satisfactorily produced and methods of producing even higher weight per cent alloys are being investigated.

The satisfactory results from fabrication of graded fuel plates have led to the current program of endeavoring to extend these techniques to full size fuel plates containing a large number of varying fuel compositions.

The initial fabrication work with high strength aluminum alloy claddings showed considerable success. Therefore, future work is proposed to develop fabrication techniques for fuels clad with high strength, high temperature, corrosion resistant alloys. Also, fabrication techniques will be evaluated for producing thinner cladding.

B. Materials

1. Fuels and Poisons

The sample fuel plate program has demonstrated the feasibility of high weight per cent UO_2 -Al cermets as reactor fuels in clad elements. Also high fuel burnups (50 - 60%) may be safely obtained. Future work will endeavor to increase the burnup to determine the ultimate safe limit and to develop a more fundamental understanding of the mechanism of irradiation damage.

The reactor suitability of burnable poisons has been demonstrated by their successful irradiation in the MTR. The RMF was able non-destructively to determine the amount of fuel and poison in both irradiated and unirradiated plates and to determine the relative reactivity changes. These measurements generally confirm the value of burnable poisons in controlling reactivity change with burnup. However, a strong interdependence was found between the reactivity, neutron flux spectra, concentration of fuel and the concentration of poison. This interdependence will be further investigated in the future work.

The feasibility and irradiation stability of graded fuel plates has been partially demonstrated by the successful irradiation of sample plates containing two fuel compositions. A theoretical and experimental program is proposed to evaluate the full potential of graded fuel plates and to demonstrate their worth in existing and proposed reactors.

The instability of unbonded sample fuel plates containing ThO_2 has been demonstrated. Therefore, it is proposed to investigate the possibilities of using thorium in other forms (such as metallic Th) in plate type fuel elements.

Unbonded ThO_2 sample fuel plates were not stable even under low exposures in the reactor.

2. Cladding Materials

Static pressure tests have shown that fuel elements fabricated from thin, hardened aluminum alloys possess structural characteristics equal to or better than thicker plates made of soft aluminum. Therefore future sample fuel plate tests are proposed (see Table X) to determine the irradiation suitability of various stronger aluminum alloys. Even though corrosion of 1100 Al is no problem in the MTR and ETR, aluminum alloys having increased high temperature corrosion resistance will be evaluated for possible use in more advanced reactors. Also, during Phase III of the Fuel Element Development Program, the irradiation suitability and mechanical properties of thinner claddings will be determined.

At present the investigation of cladding materials is primarily being limited to aluminum and aluminum alloys. This has not precluded the consideration of other materials which show promise of improving the performance or extending the range of operation.

C. Prototypes

A theoretical analysis and out-of-pile tests of an improved MTR type element using a greater number of thin, high strength plates have partially demonstrated the reactor suitability and advantages of this type element. It is therefore planned to test full size elements of this design in the MTR.

Evaluation and out-of-pile testing of a renewable shim rod have shown that this new shim can increase reactor operational flexibility and save at least 25,000 dollars/year in MTR operating costs. Therefore, complete in-pile proof-testing is proposed. Out-of-pile testing of a tube-bundle element enclosed in an MTR shell demonstrated that fabrication techniques must be improved before this type element is satisfactory for reactor use. However, the theoretical analysis of this geometry is very favorable. Therefore, further development of tube bundle fabrication is proposed.

Operational testing of a full scale oxide fuel element in the MTR has demonstrated the reliability of UO_2 -Al plate type fuel elements.

The design of flat and curved plate type fuel elements will continue to be improved as new information and materials become available. However, the general theoretical analysis indicates the limitations of this design. Therefore, current studies of fuel element geometries for the MTR and ETR are being directed more toward other geometries such as the tube bundle, hexagonal honeycomb, and nest of concentric rounded squares, all of which offer improved heat transfer and hydraulic characteristics and improved strength.

None of the fuel element geometries yet considered have all of the characteristics which an ideal fuel element should possess, i.e., simplicity of construction, high mechanical strength, no wasted space, and ease of reprocessing the fuel. Therefore, new fundamental ideas on geometrical configurations are being sought.

TABLE IX

SAMPLE FUEL PLATE COMPOSITIONS FOR PHASE II

Core Material	% En- richment	wt% of Fuel	wt% of Poisons					Cladding Material	Core Thick- ness
			B(Nat)	B ₄ C	Dy ₂ O ₃	*Ir Metal	Gd ₂ O ₃		
U in Al Alloy	93.5	18						1100 Al H16	20
"	93.5	30						6061 Al T6	16
"	93.5	18						1100 Al + 0.5% Ni	20
"	93.5	18						1100 Al + 1.0% Ni	20
"	30	45						1100 Al	20
"	40	45						1100 Al	20
"	3	35						1100 Al	20
UO ₂ (Powder) + Al (Powder)	30	52						1100 Al	20
"	40	42						1100 Al	20
"	60	40						1100 Al	15
"	80	32						1100 Al	15
"	20	39						1100 Al	45
"	20	65						1100 Al	20
"	93.5	18.7	0.036					1100 Al	20
"	93.5	18.7			0.951			1100 Al	20
"	93.5	18.7	0.037		0.505			1100 Al	20
"	93.5	18.7	0.036			1.275		1100 Al	20
"	93.5	18.7	0.036				0.012	1100 Al	20
"	93.5	6.1						1100 Al	20
"	93.5	11.6						1100 Al	20
"	93.5	16.8						1100 Al	20
U(Nat)-Al Alloy		35						1100 Al	20
U ₃ O ₈ (Powder) + Al (Powder)	93.5	22.3						1100 Al	20
"	93.5	22.3	0.002					1100 Al	20
"	93.5	22.3		0.002				1100 Al	20
Thorium		100						1100 Al	70
"		100						Zr	70
Th + U	U-93.5	U-2%						1100 Al	70
"	U-93.5	U-2%						Zr	70

* Ir metal was substituted for Ir₂O₃ when the latter failed during blister testing.

TABLE X

SAMPLE FUEL PLATE COMPOSITIONS FOR PHASE III

Core Material	% En- richment	wt% of Fuel	U ²³⁵ (gram)	wt% of Si	B(Nat) (mg)	Cladding Material	Cladding Thickness (mills)	Core Thickness (mills)
U in Al alloy	93.5	18				6061 Al	15	20
	93.5	35		1		6061 Al	10	15
	20	45		3		6061 Al	15	20
	93.5	18				AMP-M297	15	20
	93.5	35		1		AMP-M297	10	15
	93.5	30				AMP-M297	8	16
	20	45		3		AMP-M297	15	20
	93.5	30				X8001 Al	8	16
	93.5	18				X8002 Al	15	20
	93.5	18				X8003 Al	15	20
	93.5	18				5052 Al	15	20
	93.5	18				1100 Al	6	20
			0.3		4.0	1100 Al	15	20
			0.5		4.0	1100 Al	15	20
			0.7		4.0	1100 Al	15	20
			0.9		4.0	1100 Al	15	20
			1.1		4.0	1100 Al	15	20
			0.7		8.0	1100 Al	15	20
			0.7		12.0	1100 Al	15	20
			1.1		12.0	1100 Al	15	20

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ACKNOWLEDGMENTS

Because the work covered in this report extends over several years and so many individuals and groups have contributed valuable assistance, it is impossible to give adequate personal credit.

The authors and staff especially wish to thank the Plant Engineering Section for their hydraulic test work and for their reduction of the hydraulic data. The efforts of Division Engineering in designing "L" pieces and test holders and their engineering work on the renewable shim rod are particularly appreciated. The MTR Hot Cell Section and the CPP Analytical Laboratory have not only performed the standard determinations but also developed new procedures and offered valuable advice. Finally, special thanks are due to the Electronics Group for their developments in vibration measurements and for advice in selecting ultrasonic inspection equipment.

APPENDIX A

Sample Fabrication

The following notes in the fabrication procedure were furnished by the vendor and are either directly reprinted from the vendor's report or rephrased with added comments by the author.

Those cores containing uranium in the form of an oxide were prepared by the powder metallurgy technique subsequently enclosed by the conventional picture frame technique and finally hot rolled to effect core to clad bond and ultimate desired thickness. The remainder of the uranium bearing plates contained uranium metal alloyed with aluminum. These were processed by melting, casting, breakdown rolling, shearing blanks, picture framing and finish rolling. Finally, procedures for preparing test fuel plates containing ThO_2 cores had to be developed.

Each item of enriched material was handled as an individual batch so that positive identification could be maintained. Since each picture frame contained three cores, a batch for the powder metallurgy plates generally consisted of five picture frame units, or fifteen cores. For the wrought alloy plates, a batch consisted of one or more ingots of the same compositions which would yield enough cores to satisfy a complete item.

1. Powder Metallurgy Core Preparation

a. Materials

The aluminum powder employed for this work was obtained from Alcoa. It was designated as HP-120 and was received as -20 mesh containing approximately 40% -325 mesh particles. The chemical analysis of this powder showed 99.87% aluminum, the remainder primarily Al_2O_3 , iron, and silicon.

The uranium dioxide powder employed was prepared by the steam oxidation of uranium metal. Approximately 60% was -325 mesh and the balance was -80 to +325 mesh.

The boron was supplied by City Chemical Corporation, New York, was Grade A crystalline elemental boron powder being 100% -325 mesh (average particle size 2.3 microns).

The gadolinium oxide was supplied by Lindsay Chemical Company, West Chicago, Illinois. This material was all -325 mesh (average particle diameter 2.1 microns).

b. Blending and Compacting

Each mixture was blended for two hours in a glass jar containing a screen baffle. Subsequent to blending, individual charges were weighed out and compacted at 30 psi into 2" x 1/2" pieces employing a small V-block die. The completed as-pressed compacts were used directly for picture frame assembly and fabrication to finished plates.

2. Wrought Alloy Core Preparation

a. Materials

The aluminum melt stock employed for this work was obtained from Alcoa in the form of Grade 5-A pig as a 50 pound ingot.

The natural uranium metal melt stock was in derby form. The enriched uranium metal was supplied through Phillips Petroelum Company by ORNL.

In addition to the uranium and aluminum melt stock, boron and gadolinium oxide additives were included in some of the melts. The same boron and gadolinium oxide employed for the powder metallurgy specimens were used as additions for the melting and casting phases.

b. Melting and Casting

The desired quantity of aluminum melt stock was cut from the aluminum pig and caustic dipped to assure cleanliness. The desired quantity of uranium melt stock was weighed out and pickled in nitric acid to remove excessive surface oxide. These pieces were then wrapped in aluminum foil to help prevent further oxidation during their addition to the melt. In the event that the melt was to contain either boron or gadolinium oxide or both, the required quantities of these additives were mixed with some Alcoa H.P. 120 aluminum powder and compacted into 1/2" x 1/2" x 2" pieces.

Subsequent to charge preparation, the aluminum melt stock was placed in a graphite crucible and induction melted in air. When the melt reached a temperature of approximately 950°C, the required quantity of uranium melt stock was added. Approximately ten minutes after the addition of the uranium the melt was stirred with a graphite rod to insure complete alloying of the uranium with the aluminum. The melt was finally heated to approximately 1100°C. If no further additions were to be made to the melt, it was stirred at 1100°C, allowed to cool to about 1040°C and tilt poured into a preheated copper mold containing a preheated ceramic hot top.

In the case of those ingots containing boron and/or gadolinium oxide, the compacts composed of aluminum powder along with boron and/or gadolinium oxide were added to the melt at 1100°C.

As a means of determining the quantity of uranium, boron and gadolinium oxide in each melt, chemical analysis was performed on a minimum of four samples from each ingot.

Early results revealed no difficulty in obtaining the specified uranium content, but the boron content was found to be quite low in comparison with what had been added. It was therefore necessary to add an excess of boron to each melt to compensate for losses.

As a means of determining the quantity of gadolinium oxide present a 1/2" x 3" x 3" ingot was forwarded to Phillips Petroleum Company for evaluation. Four samples taken from the ingot gave values indicating that the desired wt.% was essentially present and that the uniformity of distribution was satisfactory.

c. Hot Rolling

Subsequent to melting and casting, the ingots were scalped to prepare for hot rolling.

The ingots were next preheated for 30 minutes at a temperature of about 590°C. Each ingot was then hot rolled from 0.500" to either 0.098" or 0.115" dependent upon the core size of the finished test fuel plate. A reduction of about 10% per pass was employed along with a five minute reheat at 590°C between each pass.

At the 0.098" or 0.115" thickness, each hot rolled slab was radiographically evaluated for homogeneity.

Each slab was finally sheared into 1/2" x 2" core blanks in preparation for picture frame assembly.

3. Picture Frame Assembly

The picture frame finally selected for use was a 5" square containing three 1/2" x 2" openings spaced 1/4" apart. The 1/2" x 2" size was chosen as a die because this size was on hand. This configuration allowed adequate edge and end clad on the assembled unit.

a. Rolling the Picture Frame Units

Since the finished test fuel plates were specified to contain cores 1-7/8" x 2-7/16" and the initial core pieces were 1/2" x 2", it was necessary to cross roll the picture frame unit to obtain the 2-7/16" dimension from the 2" dimension. Therefore, after preheating the picture frame unit for thirty minutes at 590°C in an argon atmosphere, the unit was cross rolled employing an 18 percent reduction. After reheating, the 1/2" dimension was elongated to the 1-7/8" dimension by normal rolling. Reductions of 20% per pass were employed along with a reheat of about five minutes at 590°C in air between each pass.

Each unit was hot rolled to approximately 0.003" thicker than specified finish size. Final thickness was obtained by a cold pass which assured proper thickness and yielded a higher quality surface.

b. Finishing

After cold finishing, each picture frame unit containing three core pieces was radiographed to qualitatively evaluate the cores and to locate the cores for the purpose of finish-trimming the individual test fuel plates.

Utilizing the radiographs and templates the picture frame units were marked and three finish size test fuel plates were sheared from each. Since radiographs of the finished plates were required, each finish-sheared test fuel plate was radiographed and evaluated.

Finally, each finished test fuel plate was subjected to a blister anneal of one hour at 600°C.

4. Thoria and Thoria-Urania Fuel Plates

Due to the brittle nature of compacted and sintered thoria tiles, roll cladding was not considered as a feasible fabrication technique. Since it was necessary to obtain a good aluminum-to-aluminum bond between the picture frame and cover plates, a hot pressing procedure was used.

Picture frames employed for this fabrication procedure were about 0.123" x 3" x 9" and contained two cavities to accommodate two batches of five core pieces. The cover plate stock was 0.017" x 3" x 9". After caustic cleaning of the picture frame and cover plates, the unit was assembled in a conventional manner and welded continuously about the outer edge to form a seal. One end of the picture frame was prenotched to accommodate an evacuation tube which was also sealed in position by welding. Upon completion of welding, the tandem picture frame unit was sandwiched between two aquadag coated steel plates and placed into a die located in a 500 ton capacity hydraulic press. The die was composed of four pieces, two sides and a top and bottom. Each segment was heated with calrod type heaters. After placing the unit in the die, a mechanical pump was attached to the evacuation tube and pumping initiated. This was carried out for a period of about 2-1/2 hours while the unit and die were brought up to a temperature of about 590°C. At this time, a pressure of approximately 8 tsi was applied and held for 15 minutes. The pressure was then released and the unit was allowed to cool in the die to room temperature before removal. If removed before cooling, large blisters and accompanying fractures of the core were encountered.

After hot pressing and cooling, the unit was removed from the die and radiographed, dimensionally checked, and cut to finish specified size. Since no metallurgical bond was anticipated between the core and clad, no final blister anneal was employed on these plates.

APPENDIX B

Gadolinium Analysis

The Sylvania aluminum-uranium ingot identified as number 6-15 has been analyzed for gadolinium. Samples were cut from each of the four corners. Results, in terms of weight per cent Gd_2O_3 , are as follows: 0.011₅, 0.012₁, 0.012₁ and 0.012₁. These compare favorably with the "made-up" content of 0.0123% Gd_2O_3 . Each sample was chemically processed to separate gadolinium; the separated gadolinium phase was analyzed in duplicate by emission spectrography. At this time the estimated (predicted) standard deviation for a result obtained in the above manner is 10%. Experimental work now in progress is designed to establish the estimate of reliability more closely.

In the analytical method, the sample is dissolved in aqua regia. The matrix uranium and aluminum are separated; uranium by liquid-liquid extraction, aluminum by precipitation of the rare earth fraction at high pH at which aluminum remains in solution as aluminate. Cerium is added to serve both as a carrier and an internal standard before dissolution commences. The rare earth fraction is washed, dissolved to a known volume, and the gadolinium to cerium ratio is determined by an A.C. spark, rotating graphite disc spectrographic method. The method was developed by G. W. Boyes, J. H. Sikes, M. C. Elliott, and J. E. Rein.

APPENDIX C - DATA

TABLE XI

PHASE I SAMPLE FUEL PLATES

Composition No.	Plate Composition	Core Thickness (mills)	Purpose							Status		
			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	
2	25 wt% U, 20% enriched in Al alloy	25	X							X	X	
3	18 wt% U, 93.5% enriched in Al alloy (cold rolled)	20			X	X				X	X	X
4	22.7 wt% UO_2 , 93.5% enriched in Al	20	X							X	X	X
5	30 wt% UO_2 , 93.5% enriched in Al	15	X							X	X	X
6	45 wt% UO_2 , 93.5 enriched	10	X							X	X	X
7	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 in Al alloy	20			X		X			X	X	
8	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 in Al	20			X		X			X	X	

APPENDIX C - DATA
TABLE XI (CON'T)
PHASE I SAMPLE FUEL PLATES

Composition No.	Plate Composition	Core Thickness (mills)	Purpose							Status		
			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	
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	
11	18 wt% U, 93.5% enriched plus .057 wt% B in Al alloy	20		X	X					X	X	X
12	18 wt% U, 93.5% enriched plus .115 wt% B in Al alloy	20		X	X					X	X	X
13	22.7 wt% UO_2 , 93.5% enriched plus .062 wt% B in Al	20		X	X					X	X	X
14	22.7 wt% UO_2 , 93.5% enriched plus .123 wt% B in Al	20		X	X					X	X	X
15	18 wt% U, 93.5% enriched plus .0123 wt% Gd_2O_3 in Al alloy	20		X	X					X	X	X

APPENDIX C - DATA
TABLE XI (CON'T)
PHASE I SAMPLE FUEL PLATES

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

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

Material: 1100 Al

All clad thicknesses were 15 mils.

TABLE XII

EXPERIMENTAL DATA FOR IRRADIATED PLATE HAVING COMPLETED POST-IRRADIATION EXAMINATION

IRRADIATION AND TUKON HARDNESS DATA

Plate Composition	Composition No.	Plate No.	Total Nvt	% Burnup	No. of Cycles in MTR	Average Flux	Cladding Hardness			Matrix Hardness			Particle Hardness		
							Pre	Post	% Hardness Change	Pre	Post	% Hardness Change	Pre	Post	% Hardness Change
18 wt% 93.5% Enriched in Al Alloy (Cold Rolled)	3	4	7.85×10^{20}	32	4	1.20×10^{14}	22	34	54	33	*146	345	38	*	*
	3	6	11.58×10^{20}	44	6	1.22	22	37	68	33	*163	394	38	*	*
22.7 wt% UO ₂ , 93.5% Enriched, in Al Matrix	4	15	4.88×10^{20}	22	3	.91	26	33	27	33	93	182	412	150	-64
	4	18	15.30×10^{20}	54	8	1.07	26	35	35	33	114	245	412	412	---
30 wt% UO ₂ , 93.5% Enriched, in Al Matrix	5	10	5.15×10^{20}	23	4	.76	30	51	70	35	127	263	200	375	87
45 wt% UO ₂ , 93.5% Enriched, in Al Matrix	6	24	3.26×10^{20}	15	3	.67	25	44	76	38	118	210	157	283	80
	6	22	11.54×10^{20}	44	7	1.03	25	83	232	38	230	505	157	318	103
18 wt% U, 93.5% Enriched, in Al Alloy plus 0.057 wt% B	11	5	7.32×10^{20}	31	4	1.09	26	43	65	37	*163	341	77	*	*
	11	2	9.68×10^{20}	39	6	.98	26	34	31	37	*129	249	77	*	*

TABLE XII (CON'T)

EXPERIMENTAL DATA FOR IRRADIATED PLATE HAVING COMPLETED POST-IRRADIATION EXAMINATION

IRRADIATION AND TUKON HARDNESS DATA

Plate Composition	Composition No.	Plate No.	Total Nvt	% Burnup	No. of Cycles in MTR	Average Flux	Cladding Hardness			Matrix Hardness			Particle Hardness		
							Pre	Post	% Hardness Change	Pre	Post	% Hardness Change	Pre	Post	% Hardness Change
18 wt% U, 93.5% Enriched, in Al Alloy plus 0.115 wt% B	12	4	7.85×10^{20}	33	4	1.20×10^{14}	22	35	59	33	*129	291	33	*	*
	12	5	11.58×10^{20}	44	6	1.22	22	32	45	33	*139	321	*33	*	*
22.7 wt% UO ₂ , 93.5% Enriched, in Al Matrix plus 0.062 wt% B	13	3	7.63×10^{20}	32	4	1.27	23	37	61	32	108	237	445	249	-44
	13	7	14.14×10^{20}	51	7	1.19	23	35	52	32	106	231	445	253	-43
22.7 wt% UO ₂ , 93.5% Enriched, in Al, Matrix Plus 0.123 wt% B	14	4	7.42×10^{20}	31	4	1.22	29	56	93	38	114	200	473	180	-66
	14	5	10.19×10^{20}	40	5	1.20	29	50	72	38	148	299	473	430	-9.1
18 wt% U, 93.5% Enriched, in Al Alloy plus 0.0123 wt% Gd ₂ O ₃	15	2	8.75×10^{20}	36	4	1.20	19	31	63	25	*141	464	25	*	*
	15	4	11.99×10^{20}	46	6	1.14	19	45	137	25	*161	544	25	*	*
18 wt% U, 93.5% Enriched, in Al Alloy plus 0.013 wt% Gd ₂ O ₃	16	**3	8.75×10^{20}	36	4	1.20	18	34	89	29	*125	331	29	*	*
	16	4	11.99×10^{20}	46	6	1.14	18	32	78	29	*139	495	29	*	*

TABLE XII (CON'T)

EXPERIMENTAL DATA FOR IRRADIATED PLATE HAVING COMPLETED POST-IRRADIATION EXAMINATION
IRRADIATION AND TUKON HARDNESS DATA

Plate Composition	Composition No.	Plate No.	Total Nvt	% Burnup	No. of Cycles in MTR	Average Flux	Cladding Hardness			Matrix Hardness			Particle Hardness		
							Pre	Post	% Hardness Change	Pre	Post	% Hardness Change	Pre	Post	% Hardness Change
22.7 wt% UO ₂ , 93.5% Enriched, in Al Matrix plus 0.013 wt% Gd ₂ O ₃	17	5	4.82 x 10 ²⁰	22	3	.96 x 10 ¹⁴	33	49	48	32	105	228	690	152	-78
22.7 wt% UO ₂ , 93.5% Enriched, in Al Matrix plus 0.062 wt% B plus 0.013 wt% Gd ₂ O ₃	18	3	9.54 x 10 ²⁰	38	5	1.18	31	49	58	32	132	312	370	282	-24
18 wt% U, 93.5% Enriched, in Al Alloy	19	31	5.33 x 10 ²⁰	24	3	1.21	22	26	18	26	*120	361	77	*	*
	19	33	13.45 x 10 ²⁰	50	7	1.14	22	40	82	26	*165	532	77	*	*

* Particles are too small for individual measurements. Average values for matrix and particles are given.

** This plate failed during irradiation.

NOTE: Pre- and post-irradiation measurements were not taken on the same plate. The pre-irradiation measurements were taken on specimens mounted from non-irradiated plates. Other plates of the same composition were irradiated to the desired amount after which time specimens were mounted and post-irradiation measurements taken.

TABLE XII (CON'T)

EXPERIMENTAL DATA FOR IRRADIATED PLATE HAVING COMPLETED POST-IRRADIATION EXAMINATION

DIMENSIONS

Composition No.	Plate No.	Length		Width		Thickness		percent volume change
		before irradiation	after irradiation	before irradiation	after irradiation	before irradiation	after irradiation	
3	4	2.87	2.87	2.31	2.32	.052	.052	+0.29
3	6	2.87	2.88	2.31	2.31	.053	.052	-1.42
4	15	2.87	2.87	2.31	2.31	.050	.049	-1.81
4	18	2.87	2.87	2.31	2.31	.052	.051	-1.74
5	10	2.87	2.87	2.31	2.31	.045	.045	0.00
6	24	2.81	2.87	2.31	2.31	.041	.040	-2.20
6	22	2.81	2.87	2.31	2.31	.041	.040	-2.20
11	5	2.81	2.87	2.31	2.32	.053	.052	-1.42
11	2	2.81	2.88	2.31	2.31	.053	.052	-1.42
12	4	2.81	2.88	2.31	2.31	.054	.052	-0.56
12	5	2.81	2.88	2.31	2.31	.053	.053	+0.29
13	3	2.89	2.88	2.31	2.31	.050	.050	-0.30
13	7	2.88	2.88	2.31	2.31	.050	.050	0.00
14	4	2.88	2.88	2.31	2.31	.051	.051	0.00
14	5	2.87	2.88	2.31	2.31	.051	.051	+0.30
15	2	2.87	2.88	2.31	2.32	.053	.053	+0.85
15	4	2.88	2.88	2.32	2.32	.053	.052	-1.71
16	*3	2.87	2.87	2.31	2.31	.053		** +14
16	4	2.87	2.88	2.31	2.32	.053	.053	+0.86
17	5	2.87	2.87	2.31	2.31	.051	.049	-0.04
18	3	2.88	2.88	2.31	2.31	.050	.050	0.00
19	31	2.87	2.87	2.31	2.31	.051	.050	-0.21
19	33	2.87	2.88	2.31	2.31	.051	.051	-0.17

* This plate blistered during irradiation.

** Volume change estimated from photographs.

TABLE XII (CON'T)

EXPERIMENTAL DATA FOR IRRADIATED PLATE HAVING COMPLETED POST-IRRADIATION EXAMINATION

WEIGHTS

Compos- ition No.	Plate No.	Weights (grams)			% weight change	
		before irradiation	after irradiation but before cleaning	after irradiation and after cleaning	before cleaning	after cleaning
3	4	16.1488	16.1510	15.5679	+ .01	-3.60
3	6	16.1718	16.1645	15.4061	- .05	-4.74
4	15	15.3391	15.2631	14.5861	- .05	-4.91
4	18	15.7850	15.6107	15.2040	-1.1	-3.68
5	10	14.0614	14.1018	13.9396	+ .287	- .858
6	24	12.7490	12.7312	12.2770	- .14	-3.70
6	22	12.7945	12.7442	12.1685	- .39	-4.89
11	5	16.4383	16.4512	15.7722	+ .08	-4.05
11	2	16.3048	16.3146	15.8575	+ .06	-2.74
12	4	16.5932	16.6384	15.7708	+ .27	-4.95
12	5	16.3031	16.3465	15.8163	+ .27	-2.99
13	3	15.5102	15.5296	15.1091	+ .13	-2.58
13	7	15.4832	15.5055	15.0481	+ .14	-2.81
14	4	15.6176	15.6516	15.4745	+ .218	- .914
14	5	15.6006	15.6319	15.2251	+ .20	-2.41
15	2	16.3768	16.3941	15.9178	+ .11	-2.80
15	4	16.3323	16.3404	15.7657	+ .11	-3.47
16	3	16.1534	16.4403	15.6921	+1.8	-2.85
16	4	16.2210	16.2343	15.8861	+ .06	-2.06
17	5	15.4558	15.4923	15.3370	+ .236	- .77
18	3	15.4393	15.4467	15.2973	+ .048	- .92
19	31	15.5704	15.5382	14.8901	- .21	-4.37
19	33	15.7007	15.6265	15.1164	- .47	-3.72

TABLE XIII

EXPERIMENTAL DATA FOR IRRADIATED PLATES
HAVING INCOMPLETE POST-IRRADIATION EXAMINATIONS

Plate Composition	Composition No.	Plate No.	Total Nvt	% Burnup	No. of Cycles in MTR	Average Flux	Results of Visual Inspection
54 wt% UO_2 , 20% Enriched in Al	1	18	1.72×10^{20}	8	1	$.98 \times 10^{14}$	Good
	1	28	4.88	22	3	$.91 \times 10^{14}$	Good
	1	25	7.28	31	4	1.12×10^{14}	Surface marks and discoloration
	1	20	7.86	33	4	1.23×10^{14}	Good
	1	22	14.18	51	7	1.22×10^{14}	Surface marks and discoloration
	1	21	16.07	56	7	1.07×10^{14}	Surface marks and discoloration
25 wt% U, 20% Enriched in Al Alloy	2	5	1.93	9	1	1.22×10^{14}	Surface roughness and discoloration
	2	6	4.20	22	2	1.30×10^{14}	Good
	2	11	5.33	24	3	1.21×10^{14}	Surface marks and discoloration
	2	9	13.45	50	7	1.14×10^{14}	Surface marks and discoloration

TABLE XIII (CON'T)

EXPERIMENTAL DATA FOR IRRADIATED PLATES
HAVING INCOMPLETE POST-IRRADIATION EXAMINATIONS

Plate Composition	Composition No.	Plate No.	Total Nvt	% Burnup	No. of Cycles in MTR	Average Flux	Results of Visual Inspection
(Con't) 25 wt% U, 20% Enriched in Al Alloy	2	10	14.06×10^{20}	51	6	$.99 \times 10^{14}$	Surface marks and discoloration
	2	7	15.34	54	7	1.01×10^{14}	Surface marks and discoloration
18 wt% U, 93.5% Enriched in Al Alloy	3	2	1.92	9	1	1.27×10^{14}	Good
	3	7	4.07	19	2	1.25×10^{14}	Good
	3	1	11.58	45	6	1.22×10^{14}	Surface roughness and discoloration
	3	5	14.33	52	8	1.17×10^{14}	Surface roughness and discoloration
22.7 wt% UO_2 , 93.5% Enriched in Al	4	22	1.72	8	1	$.98 \times 10^{14}$	Good
	4	17	7.28	31	4	1.12×10^{14}	Surface marks and discoloration
	4	21	8.98	37	6	1.14×10^{14}	Surface roughness and discoloration
	4	20	14.18	51	7	1.22×10^{14}	Surface marks and discoloration

TABLE XIII (CON'T)

EXPERIMENTAL DATA FOR IRRADIATED PLATES
HAVING INCOMPLETE POST-IRRADIATION EXAMINATIONS

Plate Composition	Composition No.	Plate No.	Total Nvt	% Burnup	No. of Cycles in MTR	Average Flux	Results of Visual Inspection
30 wt% UO ₂ , 93.5% Enriched in Al	5	11	1.16 x 10 ²⁰	6	1	.76 x 10 ¹⁴	Plate bent after one cycle. Not suitable for further reactor use.
	5	12	1.16	6	1	.76 x 10 ¹⁴	
	5	14	2.57	12	2	.76 x 10 ¹⁴	Good
	5	7	3.60	17	3	.79 x 10 ¹⁴	Surface roughness and discoloration
	5	8	9.99	30	7	.79 x 10 ¹⁴	Surface roughness and discoloration
	5	15	10.31	41	7	.79 x 10 ¹⁴	Surface roughness and discoloration
	5	17	13.67	50	9	.92 x 10 ¹⁴	Surface roughness and discoloration
45 wt% UO ₂ , 93.5% Enriched in Al	6	20	1.12	6	1	.67 x 10 ¹⁴	Good
	6	23	5.52	24	4	.89 x 10 ¹⁴	Surface marks and discoloration
	6	21	6.32	27	4	.99 x 10 ¹⁴	Good
	6	15	11.54	44	8	1.03 x 10 ¹⁴	Surface marks and discoloration

TABLE XIII (CON'T)

EXPERIMENTAL DATA FOR IRRADIATED PLATES
HAVING INCOMPLETE POST-IRRADIATION EXAMINATIONS

Composition	Composition No.	Plate No.	Total Nvt	% Burnup	No. of Cycles in MTR	Average Flux	Results of Visual Inspection
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 in Al Alloy	7	2	1.08×10^{20}	5	1	$.77 \times 10^{14}$	Good
	7	4	1.08	5	1	$.77 \times 10^{14}$	Plate bent after one cycle. Un-suitable for further reactor use.
	7	5	1.08	5	1	$.77 \times 10^{14}$	
	7	6	1.08	5	1	$.77 \times 10^{14}$	
	7	7	1.08	5	1	$.77 \times 10^{14}$	
	7	8	1.08	5	1	$.77 \times 10^{14}$	
	7	9	4.01	18	3	$.82 \times 10^{14}$	Surface roughness and discoloration
	7	10	7.85	33	5	1.07×10^{14}	
	7	12	7.85	33	5	1.07×10^{14}	
	7	13	7.85	33	5	1.07×10^{14}	
	7	11	11.25	44	6	1.12×10^{14}	

TABLE XIII (CON'T)

EXPERIMENTAL DATA FOR IRRADIATED PLATES
HAVING INCOMPLETE POST-IRRADIATION EXAMINATIONS

Composition	Composition No.	Plate No.	Total Nvt	% Burnup	No. of Cycles in MTR	Average Flux	Results of Visual Inspection
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 in Al	8	26	1.12×10^{20}	6	1	$.67 \times 10^{14}$	Good
	8	15	3.26	15	3	$.67 \times 10^{14}$	Good
	8	18	5.52	24	4	$.89 \times 10^{14}$	Surface marks and discoloration
	8	22	6.32	27	4	$.99 \times 10^{14}$	Good
	8	20	11.54	44	7	1.03×10^{14}	Surface marks and discoloration
	8	19	14.94	53	9	1.07×10^{14}	
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 0.07 wt% B in Al Alloy	9	7	1.08	5	1	$.77 \times 10^{14}$	Bent after one cycle. Plate was not returned to reactor.
	9	1	1.08	5	1	$.77 \times 10^{14}$	Plate bent after one cycle. Un-suitable for further reactor use.
	9	2	1.08	5	1	$.77 \times 10^{14}$	
	9	3	1.08	5	1	$.77 \times 10^{14}$	

TABLE XIII (CON'T)

EXPERIMENTAL DATA FOR IRRADIATED PLATES
HAVING INCOMPLETE POST-IRRADIATION EXAMINATIONS

Composition	Compo- sition No.	Plate No.	Total Nvt	% Burnup	No. of Cycles in MTR	Average Flux	Results of Visual Inspection
(Con't) 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 0.07 wt% B in Al Alloy	9	4	1.08×10^{20}	5	1	$.77 \times 10^{14}$	Plate bent after one cycle. Un- suitable for further reactor use.
	9	5	1.08	5	1	$.77 \times 10^{14}$	
	9	9	4.01	18	3	$.82 \times 10^{14}$	Surface roughness and discoloration
	9	11	7.85	33	5	1.07×10^{14}	
	9	12	11.25	33	7	1.12×10^{14}	
	9	13	7.85	33	5	1.07×10^{14}	
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 0.08 wt% B in Al	10	14	1.16	6	1	$.74 \times 10^{14}$	Good
	10	13	4.23	19	3	$.84 \times 10^{14}$	Surface roughness and discoloration
	10	16	6.86	29	4	1.08×10^{14}	
	10	17	6.86	29	4	1.08×10^{14}	
	10	1	10.33	41	7	$.88 \times 10^{14}$	

TABLE XIII (CON'T)

EXPERIMENTAL DATA FOR IRRADIATED PLATES
HAVING INCOMPLETE POST-IRRADIATION EXAMINATIONS

Composition	Composition No.	Plate No.	Total Nvt	% Burnup	No. of Cycles in MTR	Average Flux	Results of Visual Inspection
18 wt% U, 93.5% Enriched Plus .057 wt% B in Al Alloy	11	1	1.87×10^{20}	9	1	1.10×10^{14}	Surface roughness
	11	6	7.32	31	4	1.09×10^{14}	Surface roughness and discoloration
	11	4	8.53	35	5	1.02×10^{14}	
	11	7	13.08	48	8	1.06×10^{14}	
18 wt% U, 93.5% Enriched Plus .115 wt% B in Al Alloy	12	7	1.92	9	1	1.27×10^{14}	Good
	12	1	4.07	19	2	1.24×10^{14}	Surface roughness and discoloration
	12	3	11.58	45	6	1.22×10^{14}	
	12	6	14.98	53	8	1.24×10^{14}	
22.7 wt% UO_2 , 93.5% Enriched Plus .062 wt% B in Al	13	16	1.53	7	1	$.98 \times 10^{14}$	Slight surface roughness and discoloration
	13	2	1.87	9	1	1.27×10^{14}	Good

TABLE XIII (CON'T)

EXPERIMENTAL DATA FOR IRRADIATED PLATES
HAVING INCOMPLETE POST-IRRADIATION EXAMINATIONS

Composition	Composition No.	Plate No.	Total Nvt	% Burnup	No. of Cycles in MTR	Average Flux	Results of Visual Inspection
(Con't) 22.7 wt% UO ₂ , 93.5% Enriched Plus .062 wt% B in Al	13	17	5.19×10^{20}	23	3	1.14×10^{14}	Surface roughness and discoloration
	13	5	12.46	47	7	1.15×10^{14}	Surface roughness and discoloration
22.7 wt% UO ₂ , 93.5% Enriched Plus .123 wt% B in Al	14	1	1.87	9	1	1.27×10^{14}	Good
	14	7	4.29	20	2	1.36×10^{14}	Surface marks and discoloration
	14	6	12.84	48	7	1.14×10^{14}	
	14	22	3.89	18	2	1.07×10^{14}	Surface roughness and discoloration
18 wt% U, 93.5% Enriched Plus .0123 wt% Gd ₂ O ₃ in Al Alloy	15	3	1.24	6	1	$.63 \times 10^{14}$	Surface roughness and discoloration Plate was also slightly bent.
	15	5	10.51	41	5	1.16×10^{14}	Surface roughness and discoloration
	15	6	15.23	54	8	1.16×10^{14}	
	15	7	15.23	54	8	1.17×10^{14}	

TABLE XIII (CON'T)

EXPERIMENTAL DATA FOR IRRADIATED PLATES
HAVING INCOMPLETE POST-IRRADIATION EXAMINATIONS

Composition	Composition No.	Plate No.	Total Nvt	% Burnup	No. of Cycles in MTR	Average Flux	Results of Visual Inspection
18 wt% U, 93.5% Enriched Plus .057 wt% B plus .013 wt% Gd ₂ O ₃ in Al Alloy	16	7	1.24×10^{20}	6	1	$.63 \times 10^{14}$	Some surface roughness
	16	5	10.51	41	5	1.16×10^{14}	Surface marks and discoloration
	16	2	11.99	46	6	1.14×10^{14}	
	16	6	14.83	53	8	1.14×10^{14}	
22.7 wt% UO ₂ , 93.5% Enriched Plus .013 wt% Gd ₂ O ₃ in Al	17	7	1.42	7	1	$.98 \times 10^{14}$	Plate bent during first cycle. Un-suitable for further reactor use.
	17	8	1.42	7	1	$.98 \times 10^{14}$	
	17	10	3.33	16	2	1.02×10^{14}	Surface roughness and discoloration. Plate was slightly bent after one cycle but was replaced in the reactor for one more cycle.
	17	14	3.33	16	2	1.02×10^{14}	
	17	5	4.82	22	3		Surface roughness and discoloration. Plate was slightly bent after 2 cycle It was not re-turned to the reactor.

TABLE XIII (CON'T)

EXPERIMENTAL DATA FOR IRRADIATED PLATES
HAVING INCOMPLETE POST-IRRADIATION EXAMINATIONS

Composition	Composition No.	Plate No.	Total Nvt	% Burnup	No. of Cycles in MTR	Average Flux	Results of Visual Inspection
(Con't) 22.7 wt% UO ₂ , 93.5% Enriched Plus .013 wt% Gd ₂ O ₃ in Al	17	18	9.04×10^{20}	37	5	1.09×10^{14}	Surface roughness and discoloration
	17	6	12.71	48	7	1.08×10^{14}	
	17	16	15.27	54	9	1.03×10^{14}	
22.7 wt% UO ₂ , 93.5% Enriched Plus .062 wt% B plus .013 wt% Gd ₂ O ₃ in Al	18	11	1.42	7	1	$.98 \times 10^{14}$	Good
	18	2	1.42	7	2	1.02×10^{14}	Surface roughness and discoloration
	18	10	4.82	22	3	$.96 \times 10^{14}$	
	18	9	13.56	50	6	1.02×10^{14}	
	18	14	13.59	50	7	1.15×10^{14}	Surface marks and discoloration
18 wt% U, 93.5% Enriched in Al Alloy	19	35	1.93	9	1	1.22×10^{14}	Good
	19	34	4.20	19	2	1.30×10^{14}	
	19	30	13.45	50	7	1.14×10^{14}	Surface marks and discoloration
	19	32	14.67	53	8	1.06×10^{14}	

TABLE XIII (CON'T)

EXPERIMENTAL DATA FOR IRRADIATED PLATES
HAVING INCOMPLETE POST-IRRADIATION EXAMINATIONS

Composition	Composition No.	Plate No.	Total Nvt	% Burnup	No. of Cycles in MTR	Average Flux	Results of Visual Inspection
100% ThO ₂	20	1	1.82×10^{20}		approx $1\frac{1}{4}$	$.73 \times 10^{14}$	Discoloration and distinct lines showing boundaries of ThO ₂
	20	4	1.82		approx $1\frac{1}{4}$	$.73 \times 10^{14}$	Distortion and boundary lines of ThO ₂
	20	5	1.82		approx $1\frac{1}{4}$	$.73 \times 10^{14}$	Discoloration and boundary lines of ThO ₂
	20	6	1.82		approx $1\frac{1}{4}$	$.73 \times 10^{14}$	Discoloration and boundary lines of ThO ₂
	20	7	1.82		approx $1\frac{1}{4}$	$.73 \times 10^{14}$	Discoloration and boundary line of ThO ₂ . Cladding separated from picture frame.
	20	9	1.82		approx $1\frac{1}{4}$	$.73 \times 10^{14}$	Blister, discoloration and boundary lines, ThO ₂ . Cladding separation from core and picture frame.

TABLE XIII (CON'T)

EXPERIMENTAL DATA FOR IRRADIATED PLATES
HAVING INCOMPLETE POST-IRRADIATION EXAMINATIONS

Composition	Composition No.	Plate No.	Total Nvt	% Burnup	No. of Cycles in MTR	Average Flux	Results of Visual Inspection
(Con't) 100% ThO ₂	20	15	1.82×10^{20}		approx $1\frac{1}{4}$	$.73 \times 10^{14}$	Discoloration and boundary lines of ThO ₂
	20	16	1.82		approx $1\frac{1}{4}$	$.73 \times 10^{14}$	Blister, discoloration and boundary lines of ThO ₂ . No rupture in cladding.
98.5% ThO ₂ Plus 1.5 wt% UO ₂	21	3	1.02		1	$.48 \times 10^{14}$	Good
	21	4	1.02		1	$.48 \times 10^{14}$	
	21	5	1.02		1	$.48 \times 10^{14}$	
	21	8	1.02		1	$.48 \times 10^{14}$	
	21	9	1.06		1	$.48 \times 10^{14}$	
	21	10	1.02		1	$.48 \times 10^{14}$	Pin holes developed in cladding
	21	11	1.02		1	$.48 \times 10^{14}$	
	21	12	1.02		1	$.48 \times 10^{14}$	

TABLE XIV

PHASE II 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
24	18 wt% U, 93.5% Enriched in Al Alloy	1100 Al plus .5% Ni	15	20			X		X	X	X			X	X
25	18 wt% U, 93.5% Enriched in Al Alloy	1100 Al plus 1% Ni	15	20			X		X	X	X			X	X
26	45 wt% U, 30% Enriched in Al Alloy	1100 Al	15	20	X		X							ordered	
27	45 wt% U, 40% Enriched in Al Alloy	1100 Al	15	20	X		X							ordered	
28	52 wt% UO ₂ , 30% Enriched in Al	1100 Al	15	20	X									X	X
29	42 wt% UO ₂ , 40% Enriched in Al	1100 Al	15	20	X									X	X

PHASE II FUEL PLATES

[illegible]

TABLE XIV (CON'T)

PHASE II 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
36	18 wt% UO_2 , 93.5% Enriched in Al plus 0.036 wt% B	1100 Al	15	20	X	X	X							X	X
37	18.7 wt% UO_2 , 93.5% Enriched Plus 0.951 wt% Dy_2O_3 in Al	1100 Al	15	20	X	X	X							X	X
40	18.7 wt% UO_2 , 93.5% Enriched Plus .037 wt% B Plus .505 wt% Dy_2O_3 in Al	1100 Al	15	20	X	X	X							X	X
41	18.7 wt% UO_2 , 93.5% Enriched Plus .036 wt% B Plus 1.275 wt% Ir in Al*	1100 Al	15	20	X	X	X							X	X

TABLE XIV (CON'T)

PHASE II 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
42	18.7 wt% UO_2 , 93.5% Enriched Plus .0115 wt% Gd_2O_3 plus .0363 wt% B in Al	1100 Al	15	20	X	X	X							X	X
43	100 wt% Th	1100 Al	15	70			X					X		ordered	
44	98 wt% Th plus 2 wt% U, 93.5% Enriched	1100 Al	15	70			X					X		ordered	
45	100 wt% Th	Zr	15	70			X			X		X		ordered	
46	98 wt% Th Plus 2 wt% U, 93.5% Enriched	Zr	15	70			X			X		X		ordered	
47	22.3 wt% U_3O_8 , 93.5% Enriched Plus .0018 wt% B-nat in Al	1100 Al	15	20	X	X	X							X	X

TABLE XIV (CON'T)

PHASE II 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
48	22.3 wt% U_3O_8 , 93.5% Enriched Plus .0018 wt% B-nat in Al	1100 Al	15	20	X	X	X							X	X
49	22.3 wt% U_3O_8 , 93.5% Enriched Plus .0023 wt% B_4C -nat in Al	1100 Al	15	20	X	X	X							X	X
50	6.1 wt% UO_2 , 93.5% Enriched in Al	1100 Al	15	20									X	X	X
51	11.6 wt% UO_2 , 93.5% Enriched in Al	1100 Al	15	20									X	X	X
52	16.8 wt% UO_2 , 93.5% Enriched in Al	1100 Al	15	20									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.

NOTE: Post-irradiation inspection has not been performed on any of these sample fuel plates.

TABLE XV

PHASE III SAMPLE FUEL PLATES

Composition No.	Plate Composition	Clad Material	Clad Thickness (mils)	Core Thickness (mils)	Purposes							Status
					Fuel Stability	Fabrication Techniques	High Strength	Corrosion Resistance	Clad Materials	Clad Thickness	Calibration Standard	Fabricated
53	18 wt% U, 93.5% Enriched in Al Alloy	6061 Al	15	20		X	X		X			
54	35 wt% U, 93.5% Enriched Plus 1 wt% Si in Al Alloy	6061 Al	10	15	X	X	X		X	X		
55	45 wt% U, 20% Enriched Plus 3 wt% Si in Al Alloy	6061 Al	15	20	X	X	X		X			
56	18 wt% U, 93.5% Enriched in Al Alloy	APM-M257	15	20		X			X			
57	35 wt% U, 93.5% Enriched Plus 1% Si in Al	APM-M257	10	15	X	X	X		X	X		
58	30 wt% U, 93.5% Enriched in Al Alloy	APM-M257	8	16	X	X	X		X	X		

TABLE XV (CON'T)

PHASE III SAMPLE FUEL PLATES

Composition No.	Plate Composition	Clad Material	Clad Thickness (mils)	Core Thickness (mils)	Purposes							Status
					Fuel Stability	Fabrication Techniques	High Strength	Corrosion Resistance	Clad Materials	Clad Thickness	Calibration Standard	Fabricated
59	45 wt% U, 20% Enriched Plus 3% Si in Al Alloy	APM-M257	15	20	X	X	X		X			
60	30 wt% U, 93.5% Enriched in Al Alloy	X8001 Al	8	16	X	X		X	X	X		
61	18 wt% U, 93.5% Enriched in Al Alloy	X8002 Al	15	20		X		X	X			
62	18 wt% U, 93.5% Enriched in Al Alloy	X8003 Al	15	20		X		X	X			
63	18 wt% U, 93.5% Enriched in Al Alloy	5052 Al	15	20		X	X		X			
64	18 wt% U, 93.5% Enriched in Al Alloy	1100 Al	6	20		X				X		

TABLE XV (CON'T)
PHASE III SAMPLE FUEL PLATES

Composition No.	Plate Composition	Clad Material	Clad Thickness (mils)	Core Thickness (mils)	Purposes							Status
					Fuel Stability	Fabrication Techniques	High Strength	Corrosion Resistance	Clad Materials	Clad Thickness	Calibration Standard	Fabri- cated
65	0.3 gram U ²³⁵ Plus 4.0 mg B	1100 Al	15	20							X	
66	0.5 gram U ²³⁵ Plus 4.0 mg B	1100 Al	15	20							X	
67	0.7 gram U ²³⁵ Plus 4.0 mg B	1100 Al	15	20							X	
68	0.9 gram U ²³⁵ Plus 4.0 mg B	1100 Al	15	20							X	
69	1.1 gram U ²³⁵ Plus 4.0 mg B	1100 Al	15	20							X	
70	0.7 gram U ²³⁵ Plus 8.0 mg B	1100 Al	15	20							X	
71	0.7 gram U ²³⁵ Plus 12.0 mg B	1100 Al	15	20							X	
72	1.1 gram U ²³⁵ Plus 12.0 mg B	1100 Al	15	20							X	

NOTE: None of these sample fuel plates have been irradiated.