PRELIMINARY EVALUATION OF THE 20% ENRICHED URANIUM
CORE FOR THE MATERIALS TESTING REACTOR

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June 3, 1958

AEC RESEARCH AND DEVELOPMENT REPORT

PHILLIPS PETROLEUM CO.
ATOMIC ENERGY DIVISION
(UNDER CONTRACT NO. AT (10-1)-205)
IDAHO OPERATIONS OFFICE
U.S. ATOMIC ENERGY COMMISSION

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by

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SUMMARY

In November, 1957 the MTR was successfully operated on 20% enriched fuel for 646 megawatt days, of which 550 were at the original MTR design power of 30 megawatts. This power level was selected before the experiment on the basis of heat transfer limitations imposed by the use of a uniform fuel distribution.

The plate spacing of the fuel elements deviated from specifications and it was necessary to select fuel elements and their placement in the core. One fuel element developed a pinhole in the cladding and released gaseous fission products soon after the start of operation at high power. Although the level of the fission products did not necessitate shutting down the reactor, the defective fuel element was replaced as a precaution. No further difficulties occurred which could be attributed to the core.

A number of reactor physics measurements preceded the operation at power. The results of some of these measurements and other important items are listed below:

Smallest Critical Loading - Grams U-235	2060
Full Core Loading - Grams U-235	5130
Megawatt Days	646
Metal-Water Ratio	.770
Excess Reactivity	13.2%
(Resonance Escape Probability)	.96 - .98
x (Fast Fission Factor)	
Temperature Coefficient	$-2.1 \times 10^{-4} \frac{\Delta K}{K} / ^\circ F$
Megawatt Days From Plutonium Fissions	< 13

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I. INTRODUCTION

At the request of the Atomic Energy Commission an experimental study has been made of the operating characteristics of the MTR with a 20% enriched uranium core. The tests were carried out in November, 1957, and included physics measurements as well as full scale operation at 30 thermal megawatts. The core was fabricated by the Babcock and Wilcox Company after a considerable amount of development work incidental to solving the various problems involved. The MTR operated satisfactorily, with only minor difficulties, for a total of 646 megawatt days of which approximately 550 were at 30 megawatts. The present report is a factual summary of the physics and operational information obtained from the tests in the reactor of the 20% enriched uranium core.

II. DESCRIPTION OF CORE

The full core loading, Figure 1, consisted of 23 fuel elements each containing a nominal content of 200 grams of U-235 in 20% enriched uranium and 4 shim rods each containing 132 grams of U-235 in 90% enriched uranium. At the start of the cycle the shims were new and, therefore, contained no fission products.

	1	2	3	4	5	6	7	8	9
1	F	F	F	F	F	F	F	F	F
2	F	SF # 4	F	SF # 3	F	SF # 2	F	SF # 1	F
3	F	F	F	F	F	F	F	F	F
4	Be	Be (# 5)	Be	SBe # 6	Be	SBe # 7	Be	SBe # 8	Be
5	Be	Be	Be	Be	Be	Be	Be	Be	Be

MTR LATTICE

Be - BERYLLIUM PIECE

F - FUEL ELEMENT

SF - SHIM SAFETY ROD WITH FUEL

SBe - SHIM SAFETY ROD WITH BERYLLIUM

FIG. 1

20% ENRICHED FUEL - FULL CORE LOADING

The fuel elements had 19 plates each .060" thick as compared to the usual MTR elements which have two outside plates .065" thick and 17 plates .050" thick. This change was necessary to accommodate the large total amount of uranium. It resulted in raising the metal water ratio from .648 for the 93% enriched core to .770 for the 20% enriched core.

At the start of the test 36 fuel elements were available. Most of these had deviations from specifications in the plate spacing considerably beyond the permissible tolerance. To minimize the effects of these deviations the best 23 fuel elements were selected for use in the core. In addition, it was necessary to specify the elements to be used in critical locations in the core.

Radiographs of fuel plates indicated that there was some non-uniformity in the dispersion of the uranium in the fuel meat.

Prior to the loading of the core hydraulic and static deflection tests were made and 4 elements tested at 40 megawatts to demonstrate that the 20% enriched elements were acceptable for a full core loading of the MTR.

A number of the core parameters are listed in Table I. The cross sections are in cm^2 for the entire core volume and assume a homogeneous core with a Maxwell-Boltzman distribution of neutrons at 100°F. The uranium cross sections are also corrected for the deviation from a $1/v$ dependence of the cross sections with energy.

III. ESTIMATE OF THE RESONANCE ESCAPE PROBABILITY

An initial estimate of the resonance escape probability was made by comparing the critical masses of a 20% enriched core with that of a 93% core of similar geometry. Time limitations on the experiment made it necessary to load the 93% core first so that after obtaining a 20% critical core the loading could continue from that point to the full slab core. When it was found that the 20% core required one more element than the 93% core to go critical, it was not considered feasible to go back and load a 93% core of the same geometry. Figure 2 shows the two cores. The reactor was brought critical each time with all rods withdrawn except the #2 fuel shim. The critical positions of the #2 rod are as follows:

#2 Rod Position

<u>Fuel</u>	<u>Inches</u>	<u>Grams U-235</u>
20%	28.122	2063
93%	23.318	1848

TABLE I
MTR 20% ENRICHED CORE
CORE PARAMETERS

Vol. Metal	44,899	cm ³
	2,740	in ³
Vol. Aluminum	43,639	cm ³
	2,663	in ³
Vol. Water	58,309	cm ³
	3,558	in ³
Vol. Core	103,208	cm ³
	6,298	in ³
Core Dimensions	28.699" x 9.144" x 24.000"	
	72.867 cm. x 23.217 cm. x 60.936 cm.	
Metal-Water Ratio	.770	
Σa - U-235	7919	cm ²
Σf - U-235	6655	cm ²
Σa - U-238	113	cm ²
Σa - H ₂ O	1139	cm ²
Σa - Total	9712	cm ²
Thermal Utilization*	.815	
Number of Fuel Elements	23	
Grams U-235 in Fuel Elements	4600	
Grams U-238 in Fuel Elements	18400	
Grams U-235 in Shim Rods	530	
Grams U-238 in Shim Rods	40	
Total Grams U-235	5130	
Total Grams U-238	18440	
Total Grams Uranium	23570	

* Considers only U-235 as fuel.

	1	2	3	4	5	6	7	8	9
1	Be	OUT	OUT	OUT	Be	Be	F	F	F
2	OUT	SF #4	OUT	SF #3	Be	SF #2	F	SF #1	F
3	OUT	OUT	OUT	OUT	Be	Be	F	F	F
4	OUT	Be (#5)	Be	SBe #6	Be	SBe #7	Be	SBe #8	Be
5	Be	Be	Be	Be	Be	Be	Be	Be	Be

SMALL CRITICAL LOADING 93% ENRICHED FUEL

	1	2	3	4	5	6	7	8	9
1	Be	OUT	OUT	OUT	Be	Be	F	F	F
2	OUT	SF #4	OUT	SF #3	Be	SF #2	F	SF #1	F
3	OUT	OUT	OUT	Be	Be	F	F	F	F
4	OUT	Be (#5)	Be	SBe #6	Be	SBe #7	Be	SBe #8	Be
5	Be	Be	Be	Be	Be	Be	Be	Be	Be

SMALL CRITICAL LOADING 20% ENRICHED FUEL

Be - BERYLLIUM PIECE
 F - FUEL ELEMENT
 SF - SHIM SAFETY ROD WITH FUEL
 SBe - SHIM SAFETY ROD WITH
 BERYLLIUM
 OUT - POSITION EMPTY, i.e. FILLED
 WITH WATER

FIG. 2

SMALLEST CRITICAL CORES

From considerations of the statistical weight of the added element and the rod worth the product of the fast fission factor and the resonance escape probability, (ϵp), of the 20% enriched core is estimated to be between 0.96 and 0.98 of that for the 93% enriched core. If the usual assumption that (ϵp) for the 93% enriched core is unity is correct then the above values are the estimate of this parameter for the 20% enriched core.

The number of megawatt days produced by a core provides another means of determining (ϵp). A measurement of the effect of the lattice experiments on reactivity indicated that without these experiments approximately 850 megawatt days would have been obtained. No full core of 93% fuel containing an equivalent amount of U-235 has ever been loaded in the MTR. However, it is estimated that such a core would produce 1,000 to 1,100 megawatt days. This estimate is based upon measurements on a loading of 168 gram elements. A perturbation study of the effect of (ϵp) on megawatt days also yields a value of .96 to .98 for the product of the fast fission factor and the resonance escape probability, (ϵp).

When the fuel elements have cooled sufficiently an analysis will be made of the uranium and plutonium isotopes to provide another estimate of the resonance escape probability.

The predicted range of values for the resonance escape probability was 0.89 to 0.93 (1). In the calculations of available megawatt days, the fast fission factor was assumed to be unity. Thus, after the initial experimental measurement, described above, of the product of the fast fission factor and resonance escape probability (ϵp) it was possible to calculate that the megawatt days available from the core would be sufficient to give a satisfactory cycle time.

IV. MEASUREMENT OF EXCESS K AND SHIM ROD CALIBRATION BY DISTRIBUTED POISON

The excess reactivity of the full 9 by 3 slab core, Figure 1, was measured by insertion of boron-polyethylene tapes in the fuel elements and shims. The poison was inserted in steps so that a calibration of the shim rods could be obtained. A plot of the average fuel shim position versus the equivalent reactivity of the poison required to keep the reactor just critical is given in Figure 3.

The beryllium shims were completely withdrawn for all measurements. The effect of the poison on the reactivity was computed from the approximate formula:

$$\frac{\Delta K}{K} = \frac{\Sigma \text{poison}}{\Sigma \text{poison} + \Sigma \text{pile}}$$

Σ pile is the thermal absorption cross section of the homogenized core without any added poison.

(1) McMurry, H. L., Haldin, R., and Marsden, L. L., Nuclear Calculations for the MTR with Geneva Fuel, IDO-16357.

FIG. 3

MTR 20% ENRICHED CORE
SHIM ROD CALIBRATION
BY DISTRIBUTED POISON

V. TEMPERATURE COEFFICIENT

The temperature coefficient of reactivity was measured at low power by heating the cooling water with steam. Figure 4 shows a plot of reactivity versus temperature. This was derived from a plot of critical rod position versus temperature. The temperature coefficient was negative with a value of $2.1 \times 10^{-4} \Delta K/K$ per degree fahrenheit. This was somewhat over twice that for the usual core. The larger value for the 20% enriched core can be attributed in a large measure to the decrease in resonance escape probability produced by temperature broadening of the U-238 resonances.

VI. POISON STATISTICAL WEIGHT MAP

The relative effect of poison in a number of selected lattice locations was determined by measuring the effect on the critical rod position of the insertion of a known amount of boron into these locations. The measured locations were selected so that the effect of poison in the other core locations could be estimated from symmetry considerations. The results are shown in Figure 5. The equivalent measurements for an early MTR core are shown in Figure 6. The most significant difference is lower relative values of the edge locations as compared to the central locations for the 20% enriched core. The relative weight should be essentially independent of the type of fuel. Part of this difference may have arisen from an increase in the thermal cross section of the beryllium reflector. This occurs because of the buildup of Li^6 and He^3 following the fast neutron n, α reaction with beryllium. The increased number of experiments in the beryllium reflector since the early measurements also contributes to the decrease in importance of the edge locations.

VII. FLUX MEASUREMENTS

The flux was measured by irradiation at a power of 200 kilowatts of cobalt wires in each of the core lattice locations, except for two of the shims, and in a number of locations in the beryllium reflector and experimental facilities. Figure 7 is a contour map of the maximum flux for the core and beryllium reflector. Figure 8 gives a similar map for a 93% enriched core. As the fuel loadings differ only the distributions should be compared. Changes in the experimental loading may account for the differences in this distribution.

VII. VOID COEFFICIENT

The void coefficient was measured by observing the change in reactivity produced by the displacement of water by magnesium in selected lattice locations. The void coefficient was expressed in change of reactivity per cubic centimeter of void in the fuel element. The void

	1	2	3	4	5	6	7	8	9
1	.21				.85		.58	.35	.19
2					1.00		.67		.17
3	.27				1.06				.19

VALUES ARE RATIO OF CHANGE IN REACTIVITY IN A LATTICE LOCATION TO THAT PRODUCED BY THE INSERTION OF THE SAME AMOUNT OF POISON IN 25.

FIG. 5
RELATIVE POISON STATISTICAL
WEIGHT MAP 20% ENRICHED CORE

.37				.80				
				1.00		.75		.30
.51				.96				.32

FIG. 6
RELATIVE POISON STATISTICAL
WEIGHT MAP STARTUP
93% ENRICHED CORE

VALUES OF CONTOURS ARE $n_v \times 10^{-14}$
neutrons/cm²/sec BASED UPON A REACTOR
POWER OF 30 MW

FIG. 7

20% ENRICHED CORE FLUX MAP
MAXIMUM FLUX VALUES

VALUES OF CONTOURS ARE $\text{nv} \times 10^{-14}$
neutrons/cm²/sec BASED UPON FLUX
VALUES FROM CHARGE 36 AND A
REACTOR POWER OF 30 MW

FIG. 8

93% ENRICHED CORE FLUX MAP
MAXIMUM FLUX VALUES

was considered to be approximately 90% of the volume of the magnesium. This is based on the effect of the magnesium on the moderating ratio. The reactivity changes, after correction for the absorption cross section, and the void coefficients are listed in Table II. It should be noted that in all measured lattice locations the coefficient is negative.

TABLE II
VOID COEFFICIENTS

<u>Lattice Location</u>	<u>% Change in Reactivity</u>	<u>Void Coefficient $\Delta K/K$ per c.c. of Void</u>
L-25	-0.64	-2.9×10^{-6}
L-27	-0.44	-2.0×10^{-6}
L-17	-0.30	-1.4×10^{-6}
L-31	-0.11	-0.5×10^{-6}
L-11	-0.06	-0.3×10^{-6}
L-39	-0.06	-0.3×10^{-6}
L-19	-0.04	-0.2×10^{-6}

IX. POWER FROM PLUTONIUM

An estimate of the power resulting from plutonium fissions was made on the basis of assumptions that the amount of U-238 remained constant and that an effective average flux over the core volume and operating cycle could be used. First the amount of plutonium present as a function of the megawatt days of operation was computed. From this the fraction of the total fissions produced by plutonium and thus the percentage of the known reactor power arising from plutonium fissions was found. The power produced by plutonium fissions as a function of megawatt days of reactor operation is shown in Figure 9. Of the total energy of 646 MWD less than 2% arises from plutonium fissions.

X. OPERATION AT 5 MEGAWATTS

After completion of the low power experiments the reactor was operated at a power of 5 megawatts for 49 hours. This time extended sufficiently beyond the attainment of xenon equilibrium to provide the basis for an estimate of the megawatt days available from the core, in case a failure occurred soon after the start of operation at high power. The successful operation at 30 megawatts made it unnecessary to rely on this estimate.

At the completion of the operation at 5 megawatts the power was dropped to 50 kilowatts and the critical rod positions recorded at 15 minute intervals to obtain a measurement of the xenon transient as shown in Figure 10. The peak reactivity loss was 7.6% for the 20% enriched core as compared to 8.6% for an initial 93% enriched core.

FIG. 9

POWER PRODUCED BY PLUTONIUM FISSIONS
MTR 20 % ENRICHED CORE

PERCENT OF TOTAL POWER

3.0
2.0
1.0

0 60 120 180 240 300 360 420 480 540 600

MEGAWATT DAYS

PPCo. - 1-13-58 MA

XI. OPERATION AT FULL POWER

After the measurement of the xenon transient was completed the reactor power was raised in steps to 30 megawatts on a schedule determined by heat transfer limitations. The operating history in terms of power versus megawatt days of operation is shown in Figure 11.

A short time after the power had been raised to 20 megawatts gaseous fission products were detected from one element. The level of activity was such as to indicate a pinhole in the cladding of the element and did not interfere with operation of the reactor or its facilities. As a precaution the element was replaced before raising the power. The reactor was then operated at powers up to 30 megawatts until all of the excess reactivity was burned out. No further difficulties in operation occurred that could be attributed to the core.

Figure 12 plots the average fuel shim rod position as a function of megawatt days for the 20% enriched core. Figure 13 gives the excess reactivity consumed versus megawatt days.

XII. CONCLUSIONS

The operation of the MTR for 646 megawatt days, of which 550 were at a power of 30 megawatts, on the 20% enriched core has demonstrated that from nuclear and engineering points of view this composition is a very satisfactory fuel for a high flux testing reactor. This report does not consider the problem of fuel costs which will certainly weigh heavily in the final evaluation of this fuel.

The significant information gained from this test is that it is possible to load enough fuel per element to produce a satisfactory operating cycle time and still be able to manufacture an element which can withstand the conditions in a high flux reactor. The fact that the resonance escape probability is somewhat higher than calculated produced a charge life which was actually greater than would be needed in usual MTR practice.

The quality of the flux spectrum for testing reactor purposes is slightly better than for a 93% enriched core since the fast to thermal flux ratio is about 3 to 4% higher for the 20% enriched core. Therefore, although the thermal flux per megawatt would be about 4% lower the fast flux per megawatt would be about the same. In test reactor technology, it is the fast flux that is usually the important parameter.

On first glance at the performance of the fuel elements in this test it would seem that the present method of fabrication leaves something to be desired. This, however, is not an entirely fair appraisal

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REMAINING EXCESS REACTIVITY - PERCENT

FIG. 13

EXCESS REACTIVITY VERSUS MEGAWATT DAYS
MTR 20% ENRICHED CORE

PPCo. -1-13-58-MA

of the problem since it was several years before the technology of the standard MTR elements was completely worked out. What one should say rather is that at present the rejection rate of production 20% enriched elements would be considerably higher than with standard elements. The fact that several test elements have been subjected to the full rigors of 40 megawatt operation in the MTR demonstrates that 20% enriched elements which have passed inspection seem to be as satisfactory from the point of view of radiation damage as standard MTR elements. It seems reasonable that if the demand warrants, a 20% enriched element can be produced with a rejection rate essentially as low as for the usual elements. In such a case, it is the opinion of the MTR staff that from an operational standpoint the two fuels would be interchangeable.

Results of the tests on the core are summarized in Table III.

TABLE III

SUMMARY OF TEST RESULTS

Smallest Critical Loading - Grams U-235	2060
Estimated Critical Mass - Grams U-235	2010
Full Core Loading - Grams U-235	5130
Megawatt Days from Core	646
(Resonance Escape Probability)	.96 - .98
x (Fast Fission Factor)	
Excess Reactivity of Full Core	13.2%
Temperature Coefficient $\frac{\Delta K}{K} / ^\circ F$	-2.1×10^{-4}
Megawatt Days from Plutonium Fissions	413

XIII. ACKNOWLEDGEMENTS

Many persons made essential contributions to the evaluation of the 20% enriched core. It is not possible to give proper individual credit to all of them. Special acknowledgement must be made of the enthusiastic cooperation and assistance of Operations personnel.