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SUBJECT: Reactivity--Lifetime Comparison of U²³⁵ and 10,000 MWD/Ton Pu as
Fuel for the APPR
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ABSTRACT

10,000 MWD/Ton Pu is compared on a reactivity-lifetime basis with U²³⁵ plus a boron burnable poison as fuel for the Army Package Power Reactor. The Pu fuel is found to have a flatter burnout curve requiring less initial excess reactivity to obtain a desired lifetime than a similar reactor fueled with U²³⁵ plus a burnable poison. However, a rather large Pu loading is required to obtain a multiplication greater than 1.

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Introduction

Aside from the possible economic value of nuclear fuels, the compactness of nuclear fuels has very definite strategic values from a military standpoint. Of particular importance is the long time intervals between refueling operations that is possible with a nuclear power plant, thus making the power plant relatively independent of supply lines and supply conditions. Methods of increasing reactor core life are, therefore, continually being investigated. One method employed in the Army Package Power Reactor (APPR, now referred to as the SM-1) is the addition of a burnable poison to the U^{235} fuel. For the same control rod restrictions, the burnable poison allows more nuclear fuel to be loaded into the core, which increases the life of the core if the burnable poison is consumed at the proper rate. Another possible method of increasing the core life is the use of a fuel, such as 10,000 MWD/Ton Pu, which produces fissionable atoms (Pu^{241}) while consuming other fissionable atoms (Pu^{239} and Pu^{241}). The possible advantages of 10,000 MWD/Ton Pu as fuel were studied by comparing the burnout behavior of this fuel relative to the burnout behavior of U^{235} in the APPR.

To make the comparison, an IBM 704, one dimensional, multigroup burnout code¹ was used. The core was broken into five radial regions allowing for non-uniform radial burnout but not for non-uniform axial burnout. In addition, the core was treated as a homogeneous mixture of materials even in the thermal energy group. Furthermore, cross sections consistent with those used in the economic value study² of Pu were used in this study; and no attempt was made to re-evaluate the results for other possible assumptions concerning the values for the Pu cross sections. However, the above limitations are not expected to invalidate a comparison study of this type.

Core Geometry and Composition

The geometry of the APPR was approximated by a right circular cylinder 56.0 cm in diameter, 68.2 cm in extrapolated height and reflected

¹Bookston, J. M., "Reactor Material Burnout Program," GMR-103, November 20, 1957.

²Kasten, P. R., et al., "Fuel Value of Plutonium," ORNL CF-58-12-24, December 5, 1958.

by 22.0 cm of water. The core volume fraction of water is 0.8019, and the remaining volume is composed of 304 stainless steel plus either UO_2 and boron or PuO_2 . 10,000 MWD/Ton Pu was taken to have the following composition:

Pu ²³⁹	55.1%
Pu ²⁴⁰	25.2%
Pu ²⁴¹	14.2%
Pu ²⁴²	5.5%

Group Structure and Cross Sections

The group structure inherent in the IBM code³ was utilized. Twenty fast groups extending from 10^7 ev down to 0.4 ev and one thermal group were used. Thermal cross sections were obtained by averaging the cross sections⁴ over a Maxwellian distribution characterized by the temperature of 440°F, which is the mean water temperature in the core. Fast absorption and fission cross sections were generated to yield the following resonance integrals while using the total and fission cross sections⁵ as a guide.

Isotope	Resonance Fission Integral (Barns)	Resonance Absorption Integral (Barns)	Neutrons Per Fission
U ²³⁵	270	405	2.46
Pu ²³⁹	510	789	2.90
Pu ²⁴⁰		8,700	
Pu ²⁴¹	923	1,228	3.06
Stainless Steel		2.2	

Absorptions in Pu²⁴² were neglected.

³Bookston, op. cit.

⁴Hughes, D. J., and Schwartz, R. W., "Neutron Cross Sections," BNL-325, Second Edition, July 1, 1958.

⁵Ibid.

Results and Discussion

Results from the APPR critical experiment⁶ were used to estimate a homogeneous loading of U^{235} and boron that would be equivalent in initial cold reactivity to the present APPR. On this basis, an equivalent homogeneous loading of 22.5 kg of U^{235} plus 23.7 grams of B^{10} was obtained. This compares to the actual heterogeneous loading of 22.5 kg of U^{235} and 21.0 grams of B^{10} . The calculated multiplication at operating temperature and without Xe was found to be $k_{eff} = 1.125$, which may be compared to the estimated value of 1.140 for the actual reactor. With the above uranium and boron loading, the reactor core was allowed to burn out at 10 Mw operating power in time intervals of 91 days. In each time interval the fluxes were assumed constant in space and energy. The resulting burnout curve is shown as the upper curve in Figure 1. With a Xe poisoning of about $2\% \Delta k/k^7$, the calculated core life would be 18.5 Mw years, which may be compared to an estimated life of 15 Mw years from the present operational history of the APPR. Allowing for non-uniform axial burnup would reduce the calculated lifetime and would, therefore, improve the agreement between the calculation and the present lifetime estimate.

An APPR loaded with 10,000 MWD/Ton PuO_2 as fuel was investigated by first obtaining the multiplication versus fuel loading characteristics. The results of these calculations are presented in Figure 2. Notice that rather large PuO_2 loadings are necessary to obtain multiplications greater than 1. The 45 kg PuO_2 loading, having about 2% excess k_{eff} hot, was then examined for core life with the burnout part of the reactor code. The burnout results are presented as the lower curve in Figure 1. With these results, together with the results of Figure 2, it was estimated that 60 kg of PuO_2 would have about the same reactivity lifetime as the previously investigated UO_2 fueled reactor. The burnout results for a 60 kg loading of PuO_2 are presented as the middle curve in Figure 1 and confirms the extrapolation from the 45 kg PuO_2 burnout results.

⁶Williams, D. V. P., et al., "Army Package Power Reactor Critical Experiment," ORNL-2128, August 8, 1956.

⁷MacKay, S. D., et al., "SM-1 (APPR-1) Research and Development Program Interim Report on Core Measurements," APAE-178, March 1, 1959.

As demonstrated by Figure 1, 10,000 MWD/Ton Pu fuel does indeed have a fairly flat reactivity burnout behavior. The use of such fuel would alleviate the control requirements since only 7.5% excess k_{eff}^{hot} is required to obtain about the same reactivity lifetime attained by U^{235} fuel with an initial loading to give 12.5% excess k_{eff}^{hot} .

The explanation of the slow burnout behavior of 10,000 MWD/Ton Pu may be found in the burnout behavior of the individual Pu isotopes which is presented in Figure 3. Although the Pu^{239} atom concentration decreases fairly rapidly, the atom concentration of Pu^{241} remains almost constant since it is continually being replenished by neutron absorptions in Pu^{240} . As time increases, Pu^{241} plays an increasingly important role in determining k_{eff} and thus tends to flatten the reactivity burnout curve.

The burnout behavior of 10,000 MWD/Ton Pu is certainly attractive from a control rod and lifetime viewpoint. However, the large loading required makes its use in the present APPR design rather doubtful. A 60 kg loading of PuO_2 would represent about 44% of the volume available to the fuel matrix in the present APPR design. This volume per cent is near the present day fabrication limit for UO_2 fuel.⁸ Furthermore, the matrix fuel material would be more susceptible to radiation damage since there will be less stainless steel "binding" atoms per fission recoil product. The reduction in volume per cent of the stainless steel "binder" will also result in a reduction in thermal conductivity of the fuel matrix.

Although 10,000 MWD/Ton Pu may not be suitable as fuel for the present APPR design, the attractive burnout characteristic of this fuel should not be overlooked for further reactor applications.

⁸ Beaver, R. J., Private Conversation.

FIGURE 1

FIGURE 2

FIGURE 3

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