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USE OF NEUTRON FILTERS FOR FAST REACTOR FUEL IRRADIATIONS IN A THERMAL REACTOR CORE

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USE OF NEUTRON FILTERS FOR FAST REACTOR FUEL IRRADIATIONS IN A THERMAL REACTOR CORE ‡

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R. P. Morissette *
J. H. Field +

ABSTRACT

The use of filters is discussed for cases in which it is desirable to harden the spectrum of the incident neutrons on specimens of high cross section. It is shown that significant improvements can be made in the surface-to-center (and peak-to-average) power production ratios. This technique results in an improved temperature distribution in the fuel specimen that is more prototypical of the temperature profiles expected in the fast reactor fuels.

A demonstration of this technique is discussed in which an 0.875-inch diameter mixed oxide fuel containing 17% PuO_2 produced 18 kW/ft in a thermal reactor core after elimination of essentially all thermal neutrons.

INTRODUCTION

The Southwest Experimental Fast Oxide Reactor (SEFOR) is a 20-MW(t) fast spectrum reactor fueled with $\text{PuO}_2\text{-UO}_2$ and cooled with sodium. SEFOR will have characteristics similar to the large, soft spectrum, fast breeder reactors fueled with mixed $\text{PuO}_2\text{-UO}_2$. Economic studies of these large power reactors indicate the potential for producing low cost power. SEFOR will be used to obtain physics and engineering data at fuel compositions, temperatures, and crystalline state characteristic of power reactor operating conditions. SEFOR is particularly designed for the systematic determination of the Doppler coefficient of reactivity at temperatures up to the vicinity of fuel melting.

The SEFOR Project consists of two major parts: the design and construction of the reactor and a related research and development program. Funds for the design and construction of the facility are being provided by the Southwest Atomic Energy Associates (a group of seventeen investor-owned utility companies located in the South and Southwest part of the United States), and the Karlsruhe Laboratory of West Germany, EURATOM, and the General Electric Company.

The United States Atomic Energy Commission is supporting the research and development program. The Research and Development Program consists of two phases:

- Phase I - Pre-Operational Research and Development
- Phase II - Post-Construction Research and Development
(the program)

* Irradiation Processing Operation

+ Advanced Products Operation

‡ Presented at the International Symposium on Developments in Irradiation Capsule Technology Castlewood Country Club, Pleasanton, California, May 3-5, 1966.

The work described in this report was performed during Phase I of the Research and Development Program under Task 3.0, Fuel Development.

The purpose of this task was to gain experimental information, through transient and non-transient fuel testing, to guide the design of the fuel and to establish operation limits for SEFOR. Large diameter (0.875-inch) mixed oxide fuel rods approaching 20% PuO_2 were planned for SEFOR and it was very desirable to use similar fuel pins in the fuel testing program.

At the time this program was carried out, most irradiation testing (including all transient testing) was restricted to thermal reactors because of the lack of fast reactor irradiation facilities. This fact, coupled with the need for tests at prototypical SEFOR size and enrichment, gave rise to an investigation of thermal neutron flux filters as a means to reduce the severe self-shielding and achieve a more nearly typical radial power and temperature profile.

Two capsules with cadmium flux filters which have been used in the SEFOR program to remove the thermal neutron component from the flux environment in a thermal test reactor core are described.* By removing the thermal flux component, the self-shielding in a 17% enriched specimen was estimated to be equivalent to a 5% enriched specimen in an unfiltered flux. Even though 5% fuel enrichment in a thermal spectrum does cause more self-shielding than prototypical fuel in a fast reactor, the steady-state temperature profile in the fuel was judged to be an adequate likeness for worthwhile testing

FILTER TECHNIQUES

The use of neutron filters per se is not new, especially in the field of reactor physics. Cadmium ratios have been used for many years to define a ratio of thermal-to-fast neutrons. This is done simply by taking the ratio of activation of two dosimeter wires or foils (one cadmium coated and one uncoated) exposed to a normal thermal flux spectrum. Filters have also been used in process flow channels to harden the neutron spectrum to decrease depression factors in large experimental assemblies.

In the SEFOR program, the use of filters in fuel irradiation capsules was desired for both steady-state experiments in a thermal test reactor (such as GETR) and for transient irradiations in TREAT. For the steady-state capsule (4A), a simple cadmium sleeve was used to simplify calculation and fabrication techniques. The calculated decrease in the self-shielding is shown in Figure 1.

* A description of the fuel irradiation experiments conducted under the SEFOR project will be included in a forthcoming report.

FIGURE 1 CALCULATED RADIAL FISSION POWER DISTRIBUTION IN
SEFOR SPECIMEN 4A CONTAINING 17% PuO_2 -83% UO_2

In the transient capsule (4B) several alternatives were considered, including (a) an external cadmium layer and an aluminum heat sink (to avoid rethermalizing the flux with the normal beryllium heat sink) and (b) replacement of the beryllium heat sink with nickel. The cadmium filter was again selected based on the comparison with a 5% enriched unfiltered case (Figure 2). The 5% enrichment was used as a base case since this enrichment had been used on other SEFOR experiments in TREAT.

DESCRIPTION OF CAPSULE

The steady-state irradiation capsule, 4A, (Figure 3) is 1-3/4 inches in diameter and contained a stack of UO_2 -17% PuO_2 pellets of 0.875-inch diameter. The fuel was clad in Type-316 stainless steel and contained natural UO_2 insulators at both ends. A telescoping extensometer was placed at the top of the fuel column to record the differential expansion of the fuel during full power conditions. Since the fuel column was expected to expand up to 1 2 inch, the cadmium sleeve surrounding the fuel extended 1-1 2 inches beyond the top of the fuel (at room temperature) and 1 inch below the bottom of the fuel. Three nickel and iron dosimeter wires were clipped inside the flux filter to record the neutron flux.

The cadmium sleeve for Capsule 4A was clad with Type-304 stainless steel and served as a primary container outside the fuel specimen. Sodium was used for bonding inside the primary container and NaK in the secondary container. The fuel specimen was instrumented both internally and externally with tungsten-rhenium and Chromel-Alumel thermocouples, respectively. Chromel-Alumel thermocouples were also used inside and outside the cadmium sleeve. The highest temperature Chromel-Alumel thermocouple was used for control to assure that the cadmium was operated in-pile below its melting point (610 F).

For the transient irradiations in TREAT, capsule 4B was designed with an interchangeable cadmium filter to provide flexibility at the time of irradiation. This change was in recognition of the inherent uncertainties in the TREAT flux spectrum, and provided for the use of some thermal flux if such become necessary. As assembled, the capsule incorporated a 0.025-inch thick cadmium layer, but a 0.007-inch filter was also fabricated. The capsule utilized an aluminum heat sink, was sodium filled and was equipped with a tungsten-rhenium in-fuel thermocouple. (1, 2, 3)

FILTER FABRICATION DEVELOPMENT

The initial criteria required in the cadmium filter sleeve for SEFOR Capsule 4A were no voids and complete bonding. Several surface preparations and melting techniques were used before a satisfactory product was obtained. The process described below is the final effort and resulted in generally good bonding on both the inner and outer surfaces of the cadmium with no unbonded areas greater than 1/8 inch diameter. The 1/8-inch small voids were judged satisfactory in view of the thickness of the cadmium (0.035 inch). The extent of bonding achieved indicated that the cadmium

FIGURE 2 RELATIVE FISSION DISTRIBUTION FOR SEFOR 4B SPECIMEN IN TREAT

FIGURE 2 RELATIVE FISSION DISTRIBUTION FOR SEFOR 4B SPECIMEN IN TREAT

would be in intimate contact with the cladding at operating temperature and, therefore, satisfactory at the heat fluxes considered ($\sim 250,000 \text{ Btu/h-ft}^2$).

Before assembly, all surfaces in which cadmium bonding was desired were electroplated with 3 to 4 mils of cadmium. The machined and plated parts were then cleaned and assembled in a flux filter fixture (Figure 4). Among the machined parts was a sheet of cadmium that was rolled to fit into the annulus provided in the stainless steel concentric tubes.

The assembled fixture was placed into a tube furnace and evacuated until the furnace reached 600°F . Above the cadmium melting point, an argon atmosphere was used to suppress the toxic cadmium vapors. The fixture was then heated to a minimum of 800°F and held for 3 to 4 hours. Vacuum and vibration were used intermittently to clear the annulus of any gaseous impurities. The resultant products were x-rayed and examined metallographically (on control specimens) to evaluate voids and bonding. Following inspection approval, the fixture was dissected by removing the filter portion for its inclusion in the capsule container.

POWER CALCULATIONS FOR CAPSULE 4A

With the thermal neutron flux component removed from the fuel, other sources of power become predominant. (1) fission from epithermal and fast neutrons, (2) gamma heating, and (3) reaction heating (in the cadmium). The fission cross sections of plutonium for epithermal and fast neutrons are difficult to deal with at best and contributed to the decision to use pure cadmium in the filter instead of a more ideal metallurgical alloy, such as silver-indium-cadmium. Epithermal resonance cross sections in both silver and indium would have lead to greater uncertainties in the power calculations.

Since in the steady-state capsule, core positions were needed to obtain a high epithermal and fast neutron flux, the gamma heating was high also. In the outer core position of GETR selected for the experiment, the gamma heating effect was calculated to be nearly one-half the fission heating. An estimate of the average power generation rates in the Capsule 4A fuel specimen and the flux filter appear below.

INSIDE SPECIMEN

Heat Source	Specific Power (W/gm)	Linear Rate (kW/ft)
Fission - thermal neutrons ($<0.17 \text{ eV}$)	< 0.01	< 0.1
Fission - epithermal neutrons ($0.17 \text{ eV to } 0.18 \text{ MeV}$)	9.9	11.8
Fission - fast neutrons ($> 0.18 \text{ MeV}$)	1.8	2.2
Gamma - in fuel	5	6
Total Specimen Power	16.7	20.

OUTSIDE SPECIMEN

Gamma - in filter	5
Reaction - in filter	5

FIGURE 4 FLUX FILTER MOLTING FIXTURE

Fission heating was calculated for the SEFOR Capsule 4A in the GETR core by using a one-dimensional transport theory determination of flux depression, and PDQ,⁽⁴⁾ a two-dimensional diffusion theory flux calculation to determine interaction of the capsule with the reactor.

POWER CALCULATIONS FOR CAPSULE 4B

To calculate the epithermal power depression in the Capsule 4B, a computer code, REAX,⁽⁵⁾ was written. This code subdivides the energy range immediately above thermal into as many as 2000 energy groups and calculates in each energy group, the source, flux, and Doppler-broadened cross sections as a function of radial position in a fuel rod. These calculation have been described in detail by Protsik.⁽⁵⁾

The specimen power generation was calculated using PDQ with thermal and epithermal cross sections obtained from THERMOS⁽⁶⁾ and REAX. The results are shown below and compared to the 5% enriched, unfiltered case:

	UO ₂ 5% Enriched Without Filter	UO ₂ -17% PuO ₂ 25 mil Cadmium Filter
<u>Fuel Pin (fissions/cc) =</u>	2.663×10^{-5}	1.058×10^{-5}
TREAT Fissions		
<u>Insulator (fissions/cc) =</u>	4.015×10^{-6}	0.574×10^{-6}
TREAT Fissions		
Power Spectrum, %		
Fast (> 9.1 keV)	2.77	11.75
High Epithermal (55.6 ev to 9.1 keV)	4.96	28.91
Low Epithermal (0.625 to 55.6 ev)	9.24	43.49
Thermal (< 0.625 eV)	83.03	15.85

STEADY-STATE OPERATION OF CAPSULE 4A

Capsule 4A was irradiated in the GETR during Cycles 72 and 73. The capsule completed 55 days of operation corresponding to a burnup of ~ 600 MWd/MT. Peak fission power at the lower end of the fuel averaged over the irradiation period, was 13.3 kW/ft. The corresponding total power (fission + gamma) was 17.9 kW/ft which compared well with the desired power of 20 kW/ft. Calculated average fuel temperature at the peak position was 4000 °F. Both the central fuel thermocouple (at the low power end of the pin) and the mid-radius thermocouple (at the high power end of the pin) indicated temperatures in excess of 3000 °F early in the irradiation, but became erratic with continued exposure.

TRANSIENT OPERATION OF CAPSULE 4B

Capsule 4B was subjected to four filtered flux transients in TREAT. Test data showed that insufficient fast flux was available in TREAT at maximum power to attain the desired central temperatures. Both thicknesses of cadmium discussed under "Description of Capsule" were used in the tests. Extrapolated data from a low power transient with the 0.025 inch thickness of cadmium predicted a peak temperature of less than 3500 °F (versus the 4800 °F desired) at maximum TREAT power. The 0.007-inch filter was installed, and at maximum TREAT power, a temperature of 3800 °F was reached, but with a calculated flux depression substantially greater than the base case (5% enriched UO_2) and atypical of SEFOR conditions.

CONCLUSIONS

Based on the experience with these SEFOR capsules it can be concluded that

1. Power calculations on mixed oxide in a thermal reactor with cadmium as a thermal neutron filter can be performed with reasonable accuracy, where the spectrum is well characterized
2. A thermal neutron filter with cadmium can be cast in stainless steel without large voids and with some metallurgical bonding
3. Flux filters can be used to improve the testing of fast reactor fuel compositions in thermal test reactors, where there is a substantial fast and epithermal flux component.

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