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Chief, Declassification Branch

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URANIUM INVESTMENT IN A CIRCULATING FLUORIDE
POWER-PRODUCING REACTOR

A B S T R A C T

A bare reactor having UF_4 dissolved in NaZrF_5 has the following combinations of critical radius R , and critical concentration c (in grams $\text{U}^{235}/\text{cm}^2$).

Minimum radius	$R = 105 \pm 10 \text{ cm}$	$c = \infty$
Minimum concentration	$R = \infty$	$c = 0.0035 \pm 0.00016$
Minimum investment	$R = 136 \text{ cm}$	$c = 0.0208$, Investment 218 kg U^{235}

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URANIUM INVESTMENT IN A CIRCULATING FLUORIDE
POWER-PRODUCING REACTOR

In the course of preliminary discussions of a circulating fluoride power-producing reactor, it is of interest to determine the relation between size and critical concentration of an unreflected reactor consisting of UF_4 dissolved in a fluoride mixture. Though the uranium investment can obviously be reduced by the use of a reflector and by the insertion of moderator into the core, the unreflected homogeneous reactor would have the advantage of low power density at the interface between fluoride and container material and the absence of any other fluoride-solid interfaces.

The bare homogeneous fluoride reactor can, with adequate accuracy, be described by the criticality equation:

$$1 = \epsilon p f \eta \frac{e^{-B^2\tau}}{1 + L^2 B^2} \dots \quad (1)$$

In this equation, ϵ is the fast fission factor; p is the resonance escape probability, both of which can be set equal to one; f is the thermal utilization, which, for m , mole % of UF_4 has the value

$$f = \frac{m \sigma_U}{m \sigma_U + (1-m) \sigma_O} \dots \quad (2)$$

where

σ_U = the absorption (capture plus fission) cross section of uranium

σ_O = the absorption cross section of the other constituents of the mixture.

(The absorption cross section of the fluorine in the UF_4 is negligible).

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Specializing to $U^{235}F_4$ in $NaZrF_5$, we have, according to BNL 325

$$\sigma_U = 687 \pm 7 \text{ barns}$$

$$\begin{aligned}\sigma_o &= 0.505 \pm 0.01 + 0.18 \pm 0.004 + 5 \times (0.005 \pm 0.005) \text{ barns} \\ &= 0.710 \pm 0.027 \text{ barns}\end{aligned}$$

$$f = \frac{687 \text{ m}}{686.29 \text{ m} + 0.710} \dots \quad (2a)$$

η , the number of fission neutrons per neutron absorbed for U^{235} is 2.08 ± 0.02 , according to BNL 325.

B is the buckling, which for a spherical reactor of radius R is given by

$$B = \frac{\pi}{R} \dots \quad (3)$$

τ is the age which can be obtained for $NaZrF_5$ from ORNL CF-54-8-97 by J. E. Faulkner. (This relatively old computation should be checked against the latest cross section data). In this memo, the age in $NaZrF_5$ from fission to indium resonance is given as $433 (1 \pm 0.25) \text{ cm}^2$, assuming a density of 4 g/cm^3 .

Actually the density at 600°C is 3.23, according to ORNL CF-54-6-188, p. 8. Thus the age to indium resonance is to be multiplied by $(4/3.23)^2$, and the result is $664 \pm 166 \text{ cm}^2$. To this we have to add the age from indium resonance (1.44 eV) to 600°C (0.0754 eV), that is over a lethargy range of 2.95. Using the scattering cross sections for the transport cross section we get the following transport cross section for a $NaZrF_5$ molecule, according to BNL 325:

$$3.4 \pm 0.2 + 6.3 \pm 0.3 + 5 \times (4.0 \pm 0.1) = 29.7 \pm 0.6 \text{ barns} = 29.7 (1 \pm 0.02) \text{ barns}.$$

Using from H. R. Kroeger's "Table of Neutron Cross Sections and Related Data" the following values for ξ : Na, 0.0852; Zr, 0.0220; F, 0.1025 and also using the above scattering cross sections, one gets for the slowing down power of a $NaZrF_5$ molecule $2.48 \pm 0.05 = 2.48 (1 \pm 0.02) \text{ barns}$. The

molecular weight of NaZrF_5 is 209.22, so that there are $3.23 \times 0.602 \times 10^{24} / 209.22 = 0.00929 \times 10^{24}$ molecules NaZrF_5/cc . Thus the age from indium resonance to thermal is:

$$(2.95/3 \times 0.00929^2 \times 29.7 \times 2.48) (1 \pm 0.03) = 155 \pm 5 \text{ cm}^2.$$

The total age, from fission to 600°C , is thus $819 \pm 166 \text{ cm}^2 = 819(1 \pm 0.20) \text{ cm}^2$. L is the diffusion length, $L^2 B^2 \ll 1$.

With the above substitutions, Eq. (1) yields the following relationship between m and R :

$$1 = \frac{\eta m \sigma_U}{m \sigma_U + (1-m) \sigma_O} e^{-\tau \frac{\pi^2}{R^2}} \dots \quad (4)$$

If the UF_4 solution is very concentrated so that $m \sigma_U \gg (1-m) \sigma_O$, then Eq. (4) degenerates to

$$R = \pi \sqrt{\frac{\tau}{\log \eta}} \dots \quad (5)$$

or with the numerical values given above

$$R = 105 (1 \pm 10) \text{ cm} . \quad (5a)$$

This would be the minimum radius that would go critical.

The other limiting case would be an infinite reactor which would go critical with the minimum concentration. For this reactor

$$m = \frac{1}{1 + \frac{\sigma_U}{\sigma_O} (\eta - 1)} \quad (6)$$

or with the numerical values used above

$$\begin{aligned} m &= \frac{1}{1 + \frac{687}{0.710} \times 1.08} \\ &= 0.0956 (1 \pm 0.046) \text{ mole } \% = 0.142 (1 \pm 0.046) \text{ wt } \% \text{ U}^{235} \text{ F}_4 \\ &= 0.0035 (1 \pm 0.046) \text{ g U}^{235} / \text{cm}^3. \end{aligned}$$

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Of further interest is the reactor which embodies a minimum uranium investment in the core. (This is not exactly the reactor with the minimum total uranium investment, since the total uranium investment also contains the uranium in the heat exchanger, pumps, etc. In order to reduce these parts of the investment it may pay to reduce the uranium concentration, even if this increases the reactor size).

The uranium investment in the reactor is

$$I = \frac{4\pi}{3} R^3 \rho \frac{m \cdot M}{\bar{M}} \dots \quad (7)$$

where

M = the molecular weight of the compound containing the fissionable atom

$\bar{M}$ = the molecular weight of the solvent

ρ = the density of the solvent.

The slight displacement of solvent by the fissionable material is neglected. With the numerical values appropriate to the problem

$$I = \frac{4\pi}{3} \times 3.23 \times \frac{311}{209.22} mR^3 = 20.11 mR^3 \dots, \quad (7a)$$

whereas Eq. (4) yields

$$m = \frac{0.001033}{e^{-8083/R^2} - 0.4803} \quad (4a)$$

Hence, the problem reduces itself to minimizing

$$I = \frac{0.02077 R^3}{e^{-8083/R^2} - 0.4803}$$

by suitable choice of R . The minimum occurs at 140 cm radius, $m = 0.568\%$, $I = 313.5 \text{ kg } U^{235} F_4$.

At this concentration the absorption cross section connected with each molecule NaZrF_5 , including the absorption cross section of U^{235} associated with this molecule, is $0.710 + 0.00568 \times 687 = 4.61$ barns. The transport cross section is 29.7 barns/ NaZrF_5 molecule and there are 0.00929×10^{24} such molecules/cc. Hence the diffusion length is

$$L = 1/0.00929 \sqrt{3 \times 4.61 \times 29.7} = 5.31 \text{ cm}$$

so that L^2/B^2 is indeed small compared to one, as previously claimed.

The extrapolation length $0.71L \sim 4$ cm, so that the radius of the actual reactor would be 136 cm. Since the extrapolation length is 2.7% of the radius, the investment would be 8.1% smaller than computed above without credit for the extrapolation length. This yields an investment of 288 kg U^{235} F_4 , or 218 kg U^{235} .