The insertion of (9a, b) into (8) gives at once

$$J_{1R}^{+} = J_{2L}^{-}$$

With the normalization of Eqs. (9a, b), however, the last expression is just the identity

$$T_L \equiv T_R$$

proving that no distribution of effective diffusion constants and absorption cross sections within the slab is capable of representing directional transmissions in monoenergetic diffusion theory.

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Apparent Boiling of Uranium Oxide in the Center of a Fuel Pin During Transient Power Generation

Ceramic fuels, and particularly mixed uranium–plutonium oxide, are of considerable interest for use in a new concept of fast reactor termed the FCR[1] and extensive development work on fabrication and irradiation performance of these fuels is now in progress. This work, in common with that for many nuclear reactor concepts, includes a study of the performance of the fuels under severe transient power generation conditions such as may occur during an accidental nuclear excursion. During one of the more violent of these power excursion tests it appears that the UO_2 in a substantial portion of the test fuel pin reaches its boiling point. The mode of this boiling, and some of the occurrences preceding it, may have considerable significance to many reactor accident studies.

[1] Fast Ceramic Reactor, presently under development by General Electric in a program sponsored by the USAEC.

This series of tests of oxide fuels was undertaken with the assistance of ANL—the operators of the TREAT (Transient Reactor Test) facility, and had the following objectives:

Investigate the performance characteristics of this class of fuel when subjected to transients of varying severity; observations to include such aspects as thermal expansion of fuel, thermal stress effects on clad, materials interaction during transient high temperatures, damage or redistribution of fuel material, etc.

Determine the performance limit of this class of fuel when clad with stainless steel and employed in a sodium-cooled system; two cases of particular interest being the performance limit of the fuel for the reference power reactor, and of the fuel for the specially designed EFCR (Experimental Fast Ceramic Reactor), in which it is intended to carry out severe power excursions for analytical and demonstration purposes.

The plan of the experiments called for a sodium-filled capsule, designed as a calorimeter to permit computation of maximum fuel temperature and integrated power, and suitable for insertion in the TREAT facility in place of a standard fuel assembly. The capsules have instruments to

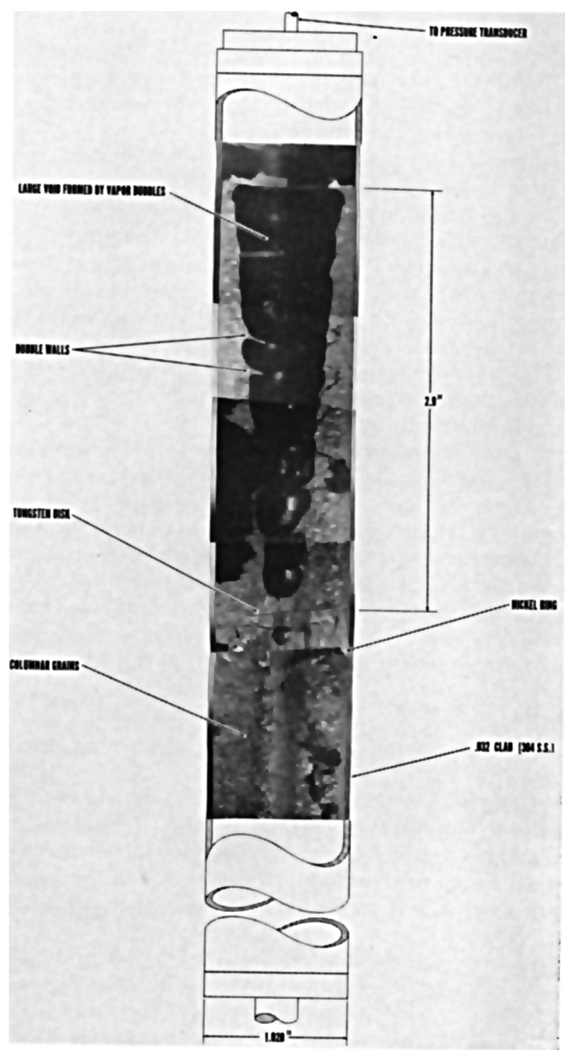

Fig. 1. Upper section APED-TREAT sample #10

give capsule and fuel temperatures, fuel expansion, and pressure generation within the fuel rod. Also included within the test fuel rod were tungsten spacer disks, between stacks of pellets, and support rings welded to the clad to permit special tests regarding fuel expansion effects to be conducted.

Many transients of gradually increasing severity, up to the point of incipient failure of the fuel have been run.

From these tests, the most severe of which is illustrated in Fig. 1, the following observations have been made.

1. Under conditions of adequate cooling, stainless steel clad UO_2 fuel, similar to that proposed for the EFCR, can withstand a transient power output of several thousand times full power, taking the fuel to a maximum temperature of approximately 7000°F, and resulting in the generation of a significant internal pressure, believed due to boiling of some of the UO_2 fuel. A significant pressure surge was detected in the fuel at the time of this transient.

2. The apparent boiling phenomenon is evidenced both by large bubbles, apparently separated by menisci (the remains of which are evident in the figure), and by more finely dispersed bubbles throughout the high temperature portion of the fuel cross section. (As these bubbles are limited to the high temperature region and do not extend to the limits of the molten section of the fuel, they are considered to be due to boiling rather than to possible outgassing.)

3. Very substantial grain growth of the UO_2 is evident to within 10–50 mils of the fuel clad even though the fuel was estimated to be at temperatures above 3000°F for less than 30 sec. This is considered confirmatory evidence that the fuel melted nearly out to the clad and recrystallized from the melt into the larger columnar grains evident in the section. Thus, the fuel containment appears similar in form to that which occurs in skull casting; namely, a well-cooled metal container, in this case the sodium-cooled cladding, maintains a frozen layer of material against itself, thereby preventing direct contact with the liquid material.

4. Polished specimens indicate areas in which liquid UO_2 appears to have been forced through cracks in the unmelted envelope, thereby contacting the stainless steel directly. There is, however, no evidence of interaction at these joints as apparently rapid quenching of the UO_2 occurred.

5. Post-transient dimensions of both fuel material and cladding in the most severe transient indicate that gross radial expansion occurred to a degree greater than can be accounted for by differential fuel-clad expansion (assuming UO_2 expands up to its melting point) and that the fuel material has swelled excessively in the axial direction. Both of these effects are thought to be due to internal vapor generation.

It is concluded that for this fuel, which is of interest for this new class of fast reactors now under active development, the transient maximum fuel temperature threshold, beyond which the fuel clad may rupture, is in excess of 7000°F. This threshold temperature may be approximately 7300°F—the temperature at which the vapor pressure of UO_2 may exceed the short-time burst pressure of type 304 SS tubing ($t/d = 0.03$) at the 1600°F mean wall temperature estimated for such transients in a sodium-cooled fast reactor. Over-all thermal expansion of the fuel appears to be a function of internal spaces present in the ceramic fuel prior to the transient; gross swelling due to vapor formation, although evident, is suspected to occur following a time delay which may preclude it as an effective shutdown mechanism for prompt excursions of fast reactors.

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