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RESULTS OF A PRELIMINARY EXPERIMENTAL INVESTIGATION OF A VAPOR TRANSPORT FUEL PIN

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SUMMARY

In-pile experimental tests were conducted on a vapor transport fuel pin in the NASA Plum Brook reactor. Two fuel pins were mounted side-by-side in a holder assembly. Sheathed chromel alumel thermocouples with their leads contained in a 3/4 inch diameter protective flux tube were used for clad temperature measurements.

The fuel pins consisted of stacked fully enriched UO_2 pellets enclosed in a type 316 stainless steel clad 1/2 inch outside diameter and 3 inches in length. Each fuel pin contained four pellets for a total of 22 grams of fuel weight.

The experiment was operated to maintain the maximum clad temperature at 395° K corresponding to a fuel temperature at the central void surface of 2350° K.

Total primary coolant water flow past the pin holder was calculated to be 110 gallons per minute. Forty-four gallons per minute at a velocity of 36.5 feet per second flowed around each fuel pin.

Calculations indicated the maximum heat flux was at the point of the highest temperature, $q''\ max = 0.24\ kW/cm^2$ or $7.62\ Btu/hr\ ft^2$.

A series of high resolution neutron radiographs of the nuclear fueled vapor transport capsule was taken. The thermal neutrons emitted from the core of the 60 megawatt Plum Brook reactor facility were used.

INTRODUCTION

A high performance fuel pin has been proposed (ref. 1) for use in compact high power long life mobile reactors. Fuel redistribution is purposefully utilized in this concept to relieve the adverse effects of nonuniform fuel pin-power distribution, and the effect of nonuniform fuel burnup. The vapor transport pin is essentially a thick-walled pressure vessel with a lining of nuclear fuel on the inside surface. The "vapor transport fuel pin" is proposed for use in gas, liquid metal or water cooled reactors.

Tests were conducted at the NASA Plum Brook 60 megawatt reactor located at Sandusky, Ohio to establish the feasibility of utilizing vapor transport to increase the average power level and operating temperature of a fuel pin.

The prime consideration in the design of the vapor transport fuel pin is that the fuel should operate at an inside temperature high enough to permit the nuclear fuel to vaporize and thereby produce a flow of fuel in the vapor state within the fuel pin cavity (ref. 2).

A central void is included in the design to provide space for vapor transport and fuel movement to occur. Fuel is thus allowed to redistribute by the vapor transport process within these void regions to reduce local "hot spots." With the reduction in "hot spots" on the fuel pin outer surface, a higher average surface temperature operation is allowable thereby providing higher power outputs per pin surface area.

The vapor transport fuel pin data taken during and after five irradiation cycles totaling 1700 hours is described in this report. Migration of the fuel is shown by neutron radiographs taken after each reactor cycle.

EXPERIMENTAL EQUIPMENT

Figure 1 shows the vapor transport fuel pin in a schematic drawing. Pins of this type were used in the experimental investigation. Figure 1(a) depicts the fuel in the pin as it was assembled and before irradiation in the reactor. Figure 1(b) depicts a schematic drawing of the vapor transport pin of the fuel after redistribution due to vapor transport. The fuel assumes a shape and thickness in this ideal case to produce a constant heat flux at the outside clad surface.

Figure 2 shows an assembled set of vapor transport fuel pins before insertion into the reactor for irradiation. Three surface temperature measuring thermocouples 0.020 inch in diameter are embedded into the outside clad of each pin. Spirally wound thermal flux wires are shown on the outside of each pin. The bottom two thermocouples embedded in the clad were used for control and were held at constant temperature.

Figure 3 is a photograph of the back of the same two fuel pins. One-sixteenth inch diameter thermocouple leads are shown extending from the end wells and are used to measure end cap temperatures. The vertical adjustable facility tube used to position the pins in the reactor core is shown at the top of the photograph. The pins are numbered 009 and 010 for identification purposes.

The UO_2 fuel pellets were fabricated by pressing and sintering annular UO_2 cylinders to approximately 95 percent of theoretical density and then machining to size, permitting a tight slip fit into the stainless steel clad. The UO_2 cylinders were stacked to obtain the desired capsule loading of 22 grams UO_2. The fuel loaded capsules were closed by electron beam welding in a vacuum furnace and then tested for leaks.

Five ceramic grade UO_2 lots were received from Oak Ridge for fuel pellet fabrication. All material contained U-235 isotopic enrichment of 93.14 percent. Type 316 stainless steel 1/2 inch O.D. with a 0.095 inch wall was used for the capsule wall. Type 316 stainless steel rod 1/2 inch in diameter was used for machining the end plugs.

The pellets were uniaxially pressed in an annular three-segment steel die at a pressure of 20 ksi. Pellets were sintered in dry hydrogen using a heat-up time of 30 hours followed by a four hour hold at 1700° C and then cooled in 12 hours.

Machined specimens were ultrasonically cleaned in successive baths of acetone and 200 proof ethyl alcohol followed by vacuum drying. The pellets were then outgassed in a vacuum of 10^{-5} torr at 1200° C. Inspection showed spherical porosity indicating the material would not sinter during initial irradiation. The oxygen to uranium ratios taken on the fuel pellets varied from 2.010 to 2.005.

Figure 4 is a preirradiation thermal neutron radiograph of the same pins shown in figures 2 and 3. The hollow centers of the fuel pellets are not shown in the thermal exposures, however they do appear in the epithermal exposures.

The preirradiation thermal neutron radiograph measurements indicated the following conditions in the fuel pin arrangement:

1. A gap of 0.05 inch existed between the bottom pellets and the bottom cap of the fuel pin cavity in both pins.

2. Fuel pin 009 had a separation between the upper and lower pellet. The space was measured to be 0.915 inch.

EXPERIMENTAL PROCEDURE AND RESULTS

The vapor transport fuel pin was inserted into the reactor to maintain a operating clad temperature of 395° K corresponding to a calculated central void fuel surface temperature of 2350° K for a total of 104 hours operating time.

The average nominal thermal flux at the pin surface was 4.9×10^{13} N/cm^2 seconds.

Some fuel redistribution occurred during the first two hours or irradiation. This fuel position change showed up in thermocouple temperature changes along the clad.

When the experimental pins were withdrawn from the reactor core, the bottom well thermocouples did not follow the temperature indicated during the initial insertion. In the full out position, the bottom well end cap thermocouple (see fig. 1) read 70° K higher than they did at preinsertion.

The temperature changes were due to the fuel vaporizing from the inside of the lower fuel pellet and moving to a cooler area. For instance the closest cooler area upon which the vapor could condense was the bottom end cap. This new fuel position caused the increased temperature reading of the bottom end well.

Figure 5 is a thermal neutron radiograph made of the fuel pins after 104 hours operation at a power level of 5.6 kilowatts. When compared to figure 4, changes in fuel position especially near the bottom can be seen.

Figure 6 is an epithermal neutron radiograph of the same fuel pins. Notice how the central fuel voids appear and how clearly the redistributed fuel outline is displayed compared to the thermal neutron radiograph in figure 5.

Figure 7(a) shows a plot of middle clad outside temperature against accumulated megawatt days with the fuel pin operating at a fixed bottom clad ref. temperature of about 347° K. The increase in middle clad temperature with time is shown, and is due to the redistribution of the UO_2 by vapor transport. As the fuel was redistributed, the pin position was changed to compensate for the decrease in the bottom clad reference temperature. This is shown in figure 7(b). An increasing number in vaft position means the capsule is being inserted further into the reactor core to a higher neutron flux level.

Figure 7(a) shows that as the bottom clad reference temperature was being held constant to within the required tolerances, the remaining clad temperature increased with irradiation time.

Figure 8 is a thermal neutron radiograph of the same two vapor transport fuel pins after 500 hours of irradiation time in the reactor. Redistribution of the fuel is still occurring but not at as great a rate as the initial insertion. Figure 9 is an epithermal neutron radiograph taken at the same time as figure 8 of the same pins. The detail of the central voids are more clearly shown than the previous thermal radiograph.

Figure 10 is a thermal neutron radiograph taken at the same time but with the fuel pins rotated 45^{o} clockwise to give a better view of the cone shaped fuel on the left.

Figure 11 is an epithermal neutron radiograph taken after 740 hours of irradiation time. The fuel is still being redistributed in the cavity but some cracking and displacement of the fuel due to mechanical shocks in handling may be seen.

Figures 12 and 13 are thermal and epithermal neutron radiographs taken after 1700 hours of irradiation time. During this irradiation the outside clad temperature was raised 5^{o} K above the previous setpoints. As can be seen in the epithermal radiograph, figure 13, the fuel has now completely filled the pin cavity on the left, while the pin on the right is still in the process of complete redistribution.

This is due to the original difference in fuel position. That is the pin on the left had more of the fuel placed near the top of the pin before irradiation than the pin on the right.

The clear area shown between the fueled portion of the pin on the left located about halfway up the pin is probably due to breakage. This breakage could have been caused by mechanical shock when the fuel pins were removed from the reactor for neutron radiography. The same mechanical breakage may be seen in figures 10 and 11 where a portion of the fuel has been broken away from the walls.

SUMMARY OF RESULTS

In-pile experimental tests were conducted on a vapor transport fuel pin in the NASA Plum Brook reactor. Two fuel pins are mounted side-by-side in a holder assembly. Sheathed C/A thermocouples with their leads contained in a 3/4 inch diameter protective flux tube were used for clad temperature measurements.

The fuel pins consisted of stacked fully enriched UO_2 pellets enclosed in a 316 stainless steel clad, 1/2 inch outside diameter and 3 inches long.

The fuel pins contained four pellets for a total of 22 grams of fuel weight.

The experiment was operated to maintain the maximum clad temperature below 395° K (252° F), corresponding to a fuel temperature of 2350° K.

For the two pin configuration, total primary coolant water flow past the holder configuration pins was calculated to be 110 gpm and 44 gpm at 36.5 fps around the fuel pin.

Calculations indicated the maximum heat flux at the point of the highest temperature q'' max = 0.24 kW/cm^2 or 7.62 Btu/hr ft^2.

For these pins, irradiated with successive insertions into the reactor for a total irradiation time of 1700 hours, the following results were obtained.

1. Indicated wall temperatures of the clad dropped from the initial insertion value of 373° K when exposed to constant neutron flux level.

2. Continued insertion to higher neutron flux levels was required to hold the hot end clad temperature constant.

3. Neutron radiographs taken after the first irradiation cycle showed observable vapor transport had occurred during the first 104 hours of irradiation.

4. Reinsertions into the reactor plus additional radiographs showed that vapor transport occurred after each irradiation, up to a total exposure time of 1700 hours.

5. The hot end well clad temperature was initially colder than the side wall temperature, but after 1700 hours of irradiation the end well was the highest temperature, and finally reached the predetermined maximum inside clad operating temperature.

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2. F. A. Nichols, "Behavior of Gaseous Fission Products in Oxide Fuel Elements," WAPD-TM-570, Bettis Atomic Power Lab. (1966).

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4. J. P. Barton and J. P. Reeves, Brit. J. Non-Destruct. Testing, 8, 79 (Dec. 1966).

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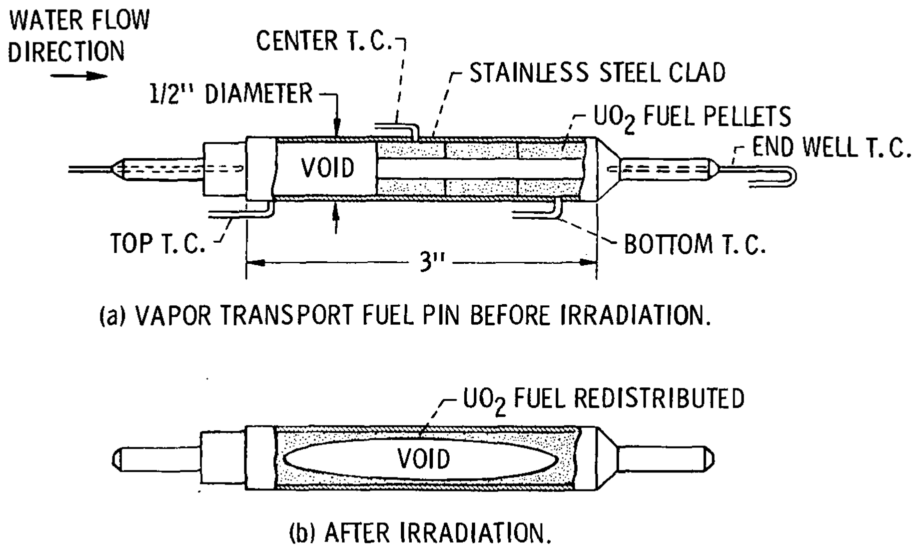

Figure 1. - Schematic drawings of vapor transport fuel pin showing fuel conditions before and after irradiation.

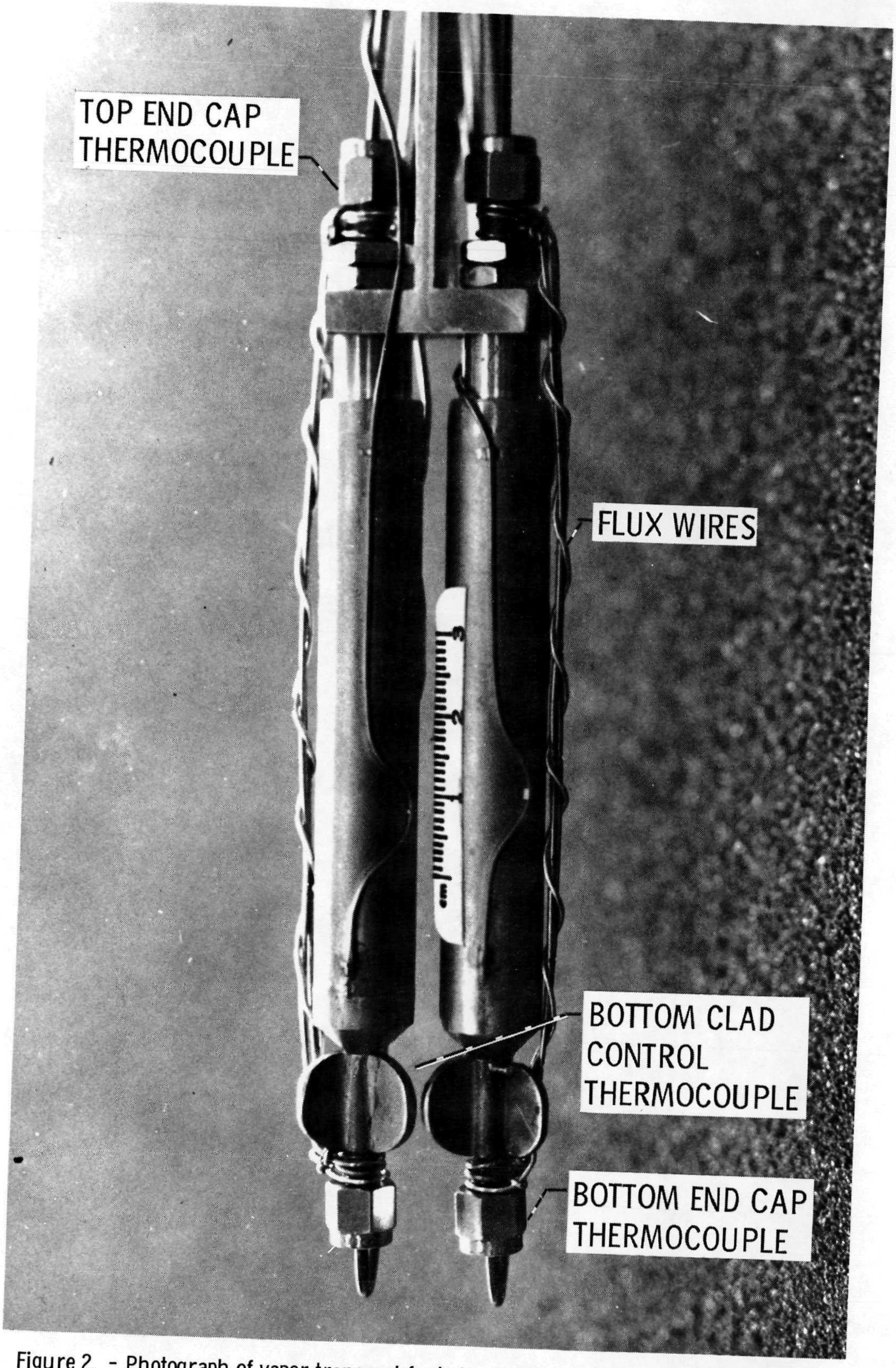

Figure 2. - Photograph of vapor transport fuel pins before irradiation. Pin number 010 on left of photograph, pin number 009 on right of photograph.

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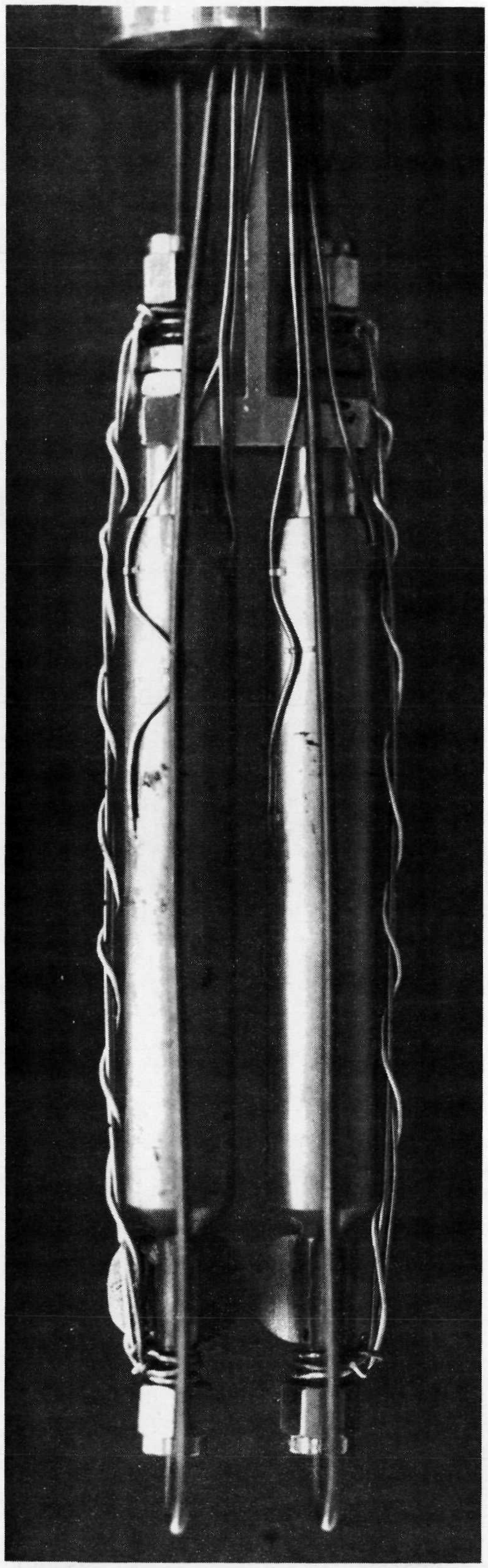

Figure 3. - Photograph of vapor transport fuel pins before irradiation, backview of figure 2. Pin number 009 on left of photograph, pin number 010 on right of photograph.

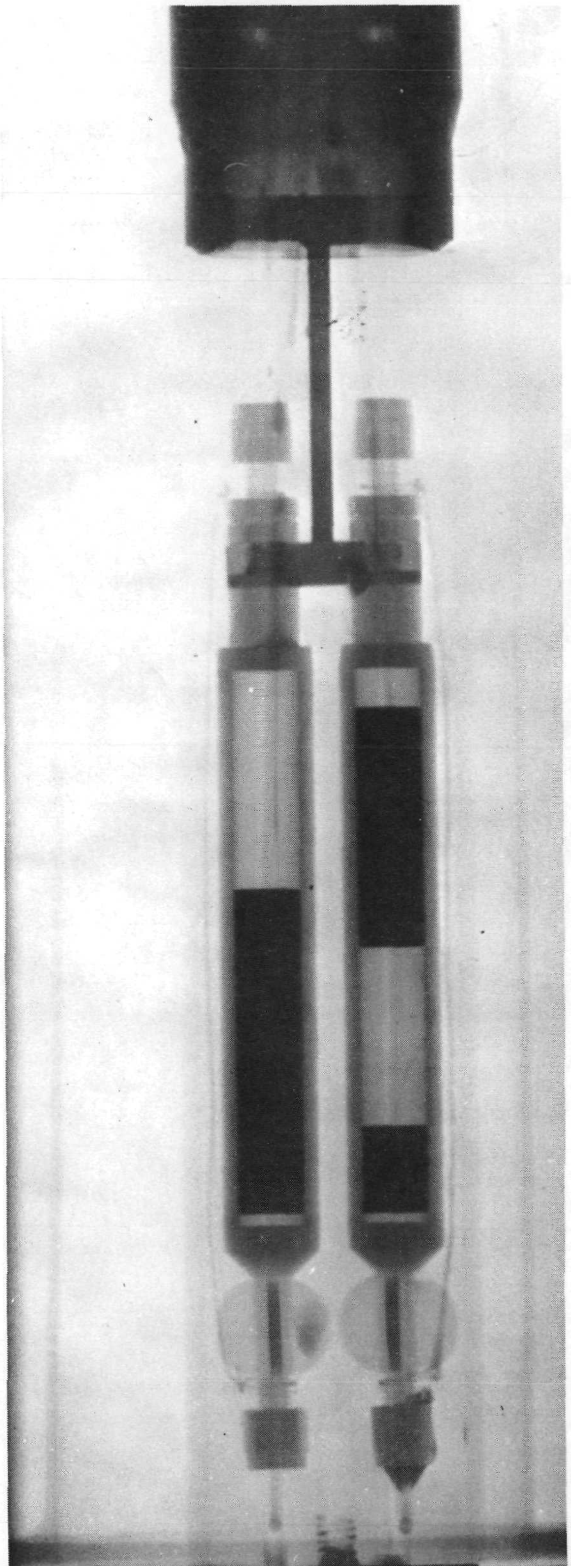

Figure 4. - Pre-irradiation thermal neutron radiograph of vapor transport fuel pins. Pin number 009 on right, number 010 on left.

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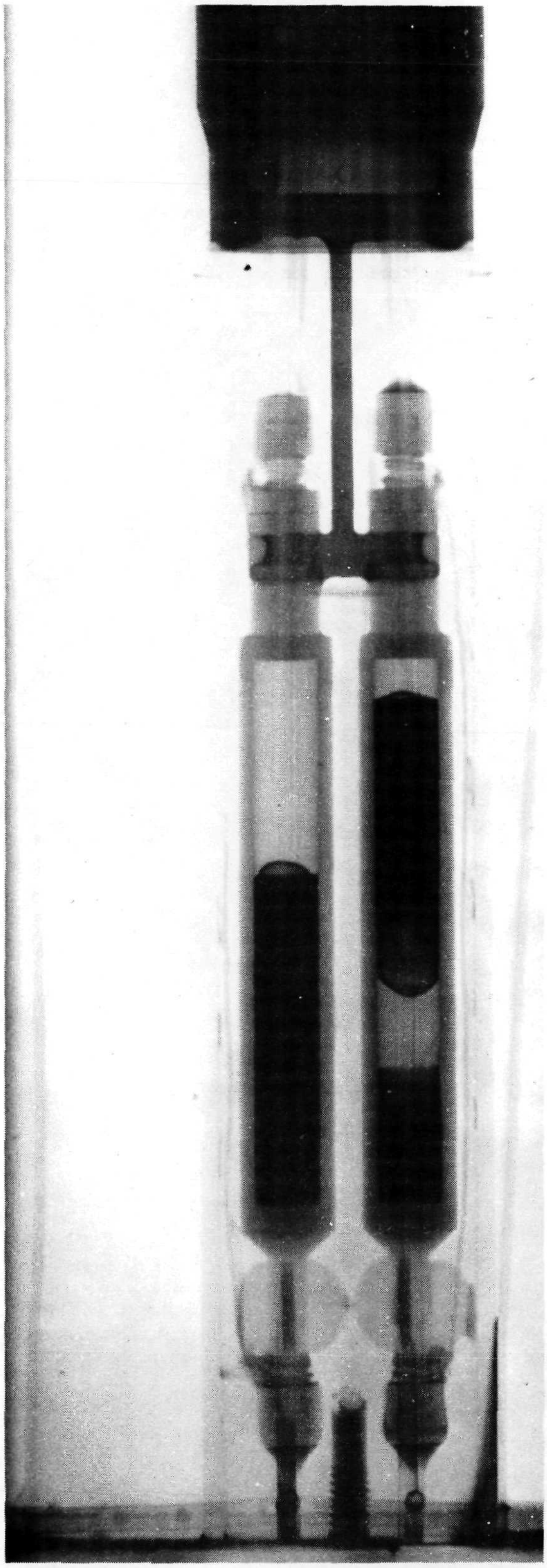

Figure 5. - Thermal neutron radiograph of vapor transport fuel pins taken after 104 hours of irradiation. Pin number 009 on right, number 010 on left.

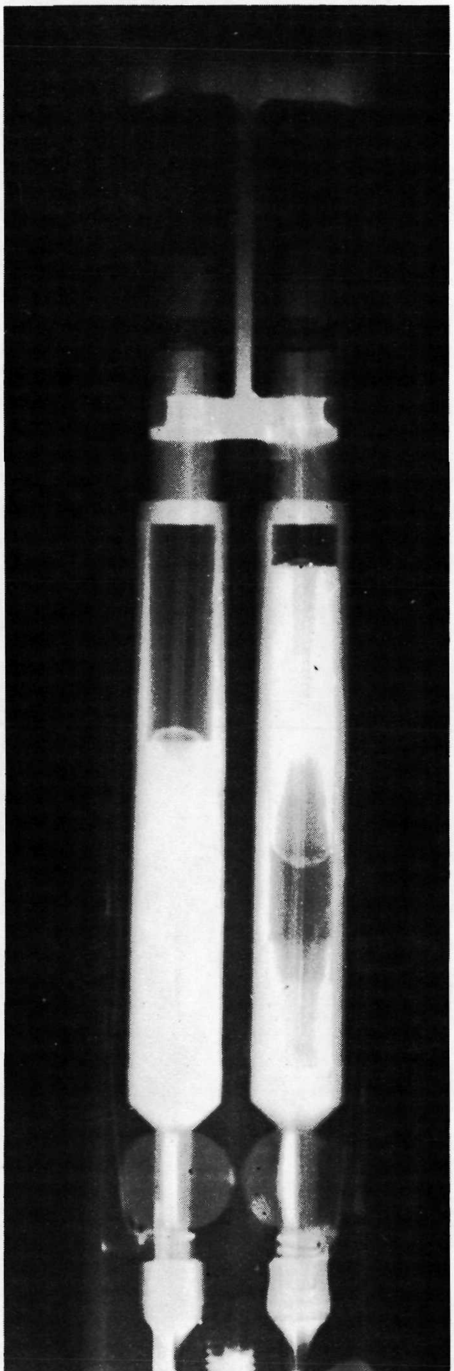

Figure 6. - Epithermal neutron radiograph of vapor transport fuel pins taken after 104 hours irradiation. Pin number 009 on right, number 010 on left.

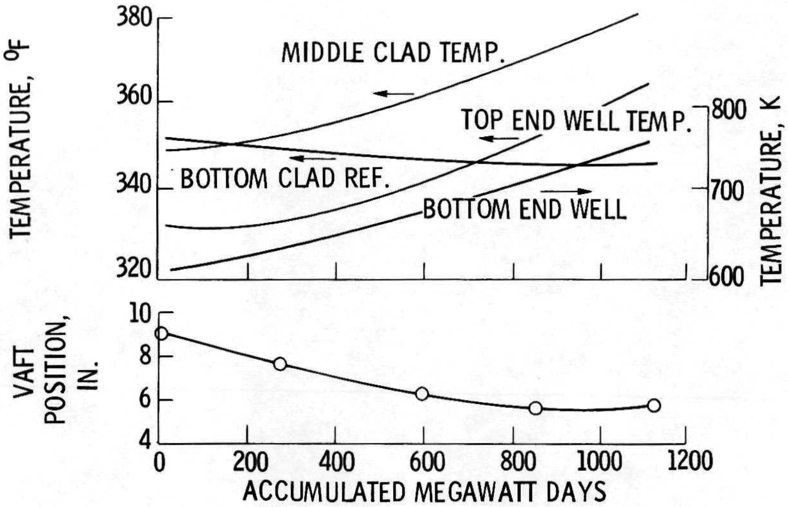

Figure 7. - End well and clad outside temperature changes as a function of time and vaft position.

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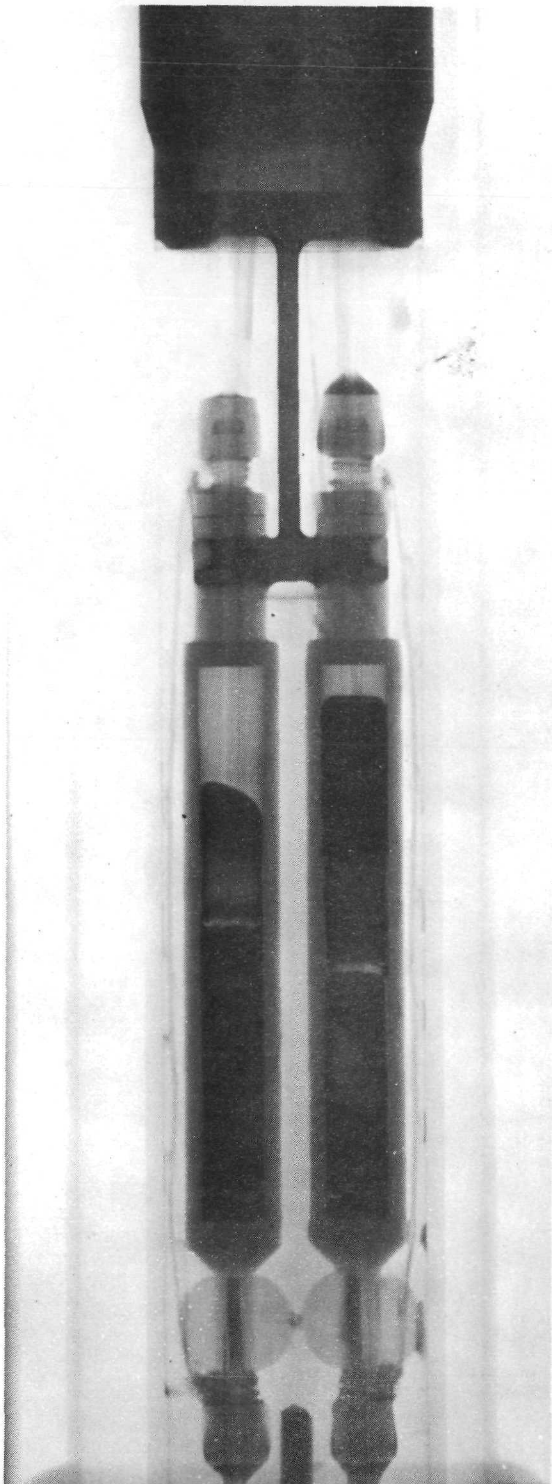

Figure 8. - Thermal neutron radiograph of vapor transport fuel pins taken after 500 hour irradiation. Pin number 009 on right, number 010 on left.

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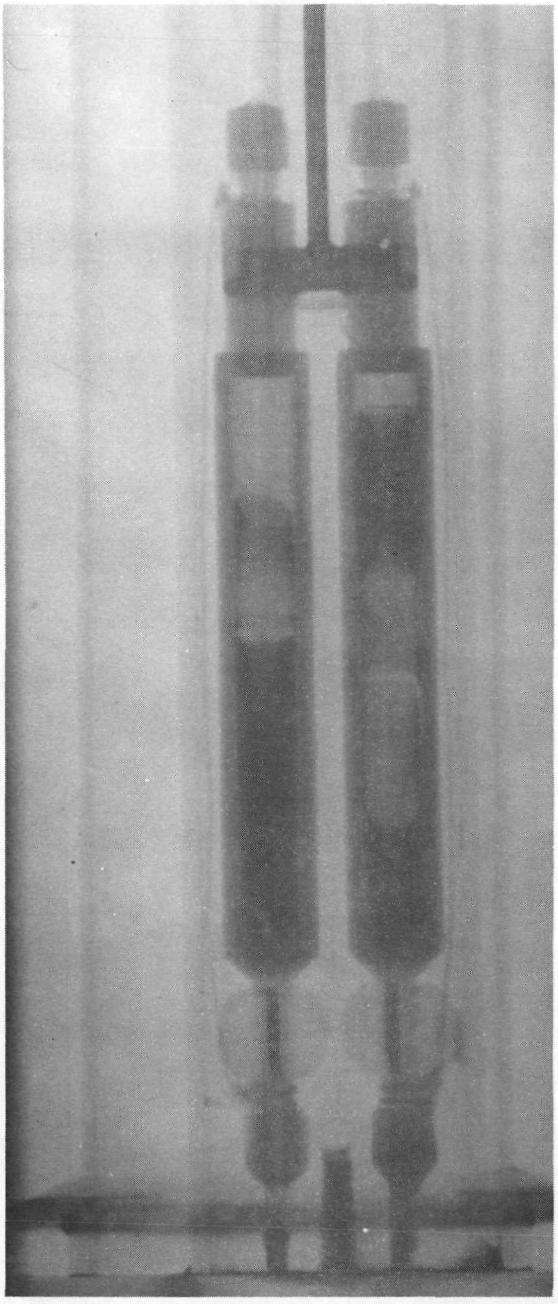

Figure 9. - Epithermal neutron radiograph of vapor transport fuel pin after 500 hours irradiation. Pin number 009 on right, number 010 on left.

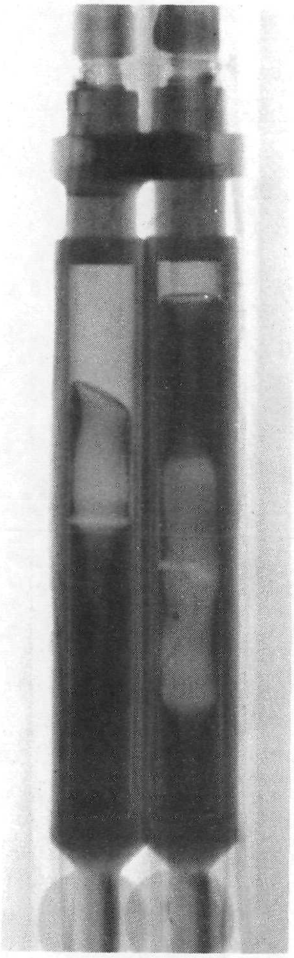

Figure 10. - Epithermal neutron radiograph taken at same time as figure 9, but rotated 45° clockwise.

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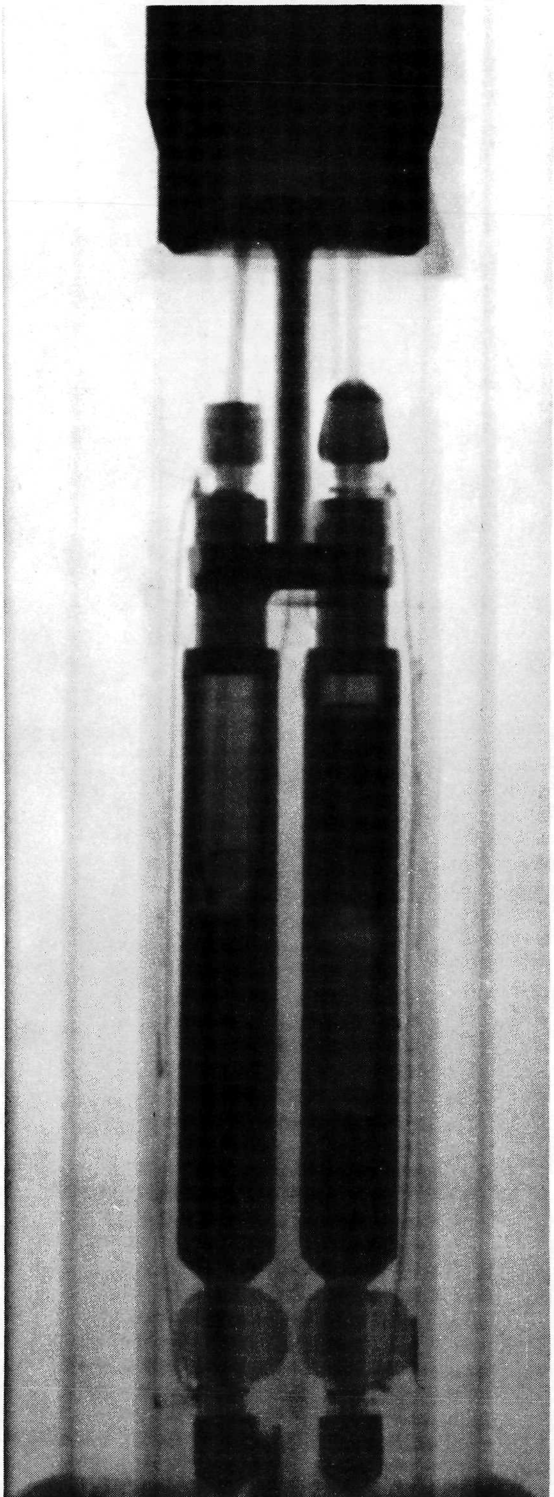

Figure 11. - Epithermal neutron radiograph of vapor transport fuel pin taken after 740 hour irradiation. Pin number 009 on right, number 010 on left.

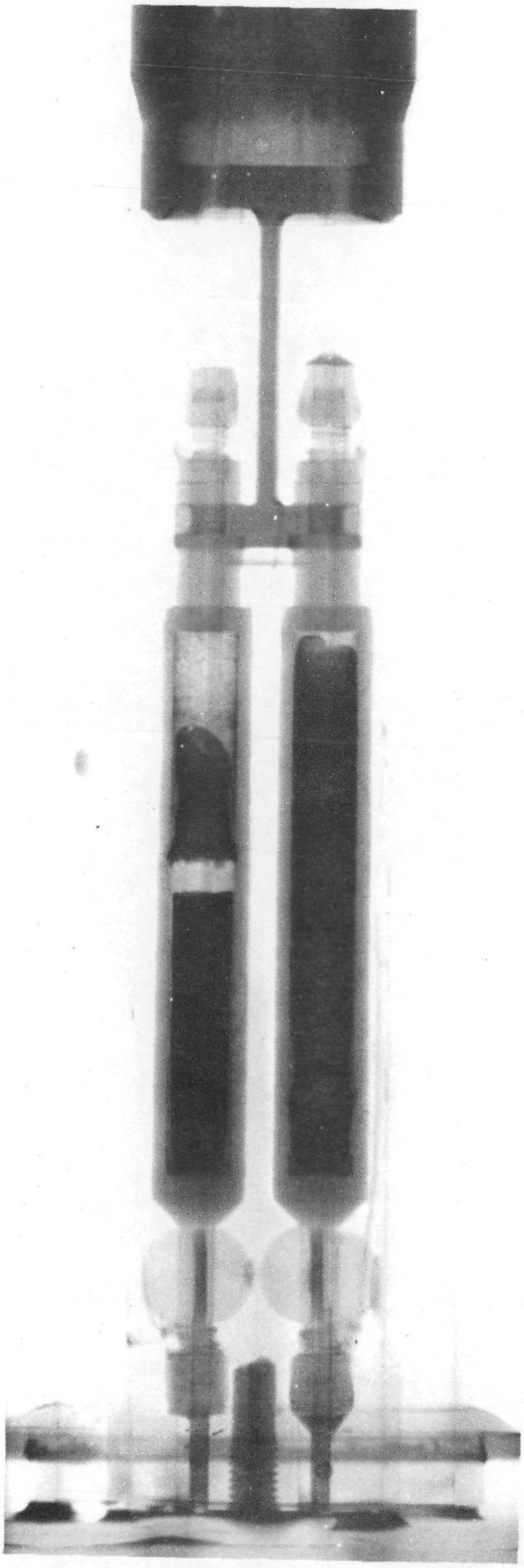

Figure 12. - Thermal neutron radiograph of vapor transport fuel pin after 1700 hours irradiation. Pin number 009 on right, number 010 on left.

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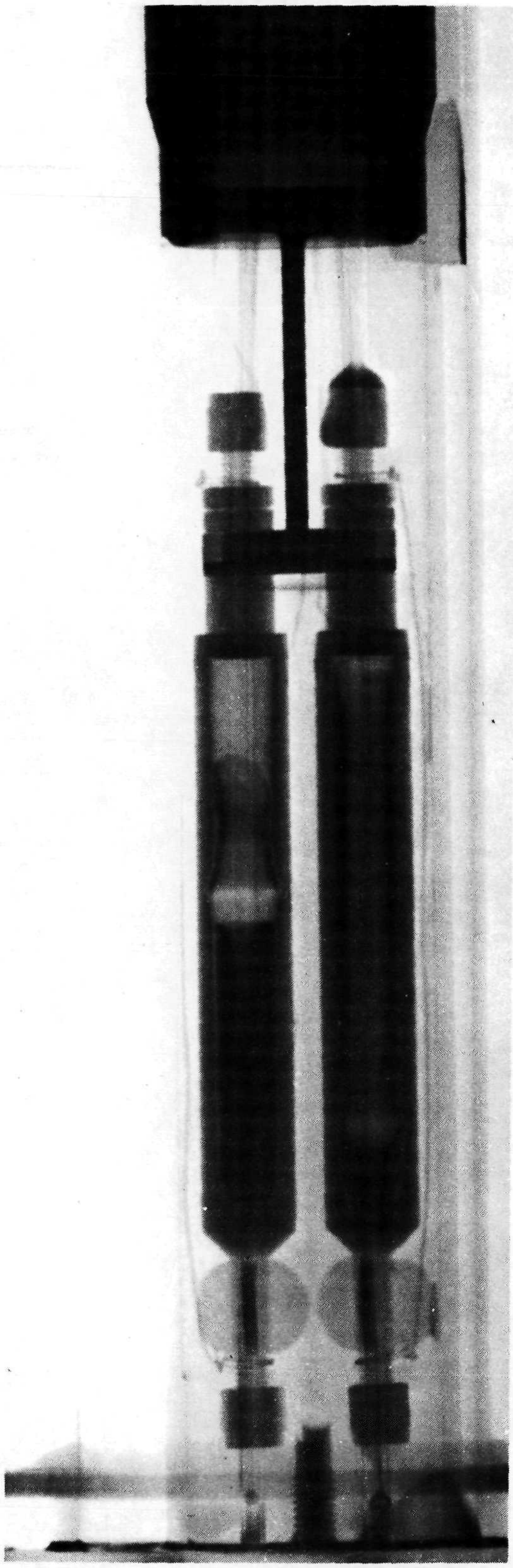

Figure 13. - Epithermal neutron radiograph of vapor transport fuel pin after 1700 hours irradiation. Pin number 009 on right, number 010 on left.