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Heat Loss from Fuel Elements
Partially Immersed in Water

by

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ABSTRACT

Fuel-plate temperatures of inductively heated simulations of the aluminum MTR-type fuel elements used in the Omega West reactor have been measured as a function of power input and plate immersion depth in water. At immersions ≤ 5 in., the primary cooling mechanism is production and superheating of steam. A much more efficient cooling mechanism, percolation, becomes dominant at immersions > 5 in. Percolation carries liquid water directly up into the cooling channels and cools so effectively that increased input power decreases plate temperature, within the range of input power (≤ 5.1 kW) available.

I. INTRODUCTION

In the event of reactor coolant loss, a major hazard to be considered is melting of the fuel cladding due to fission afterheat, resulting in the release of large quantities of radioactive materials. Therefore, information about mechanisms which act to remove fission afterheat from reactor cores is important in safety evaluation. Of particular interest is the case of partial coolant loss from a water-cooled reactor, in which partial immersion of the fuel interferes with convective air cooling. For the MTR-type element (see Fig. 1), internal air convection would be completely blocked. Heat removal processes for this case were studied using a calibrated power input from an induction heater and a variable immersion depth in water. The power input distribution approximated that of the fission afterheat. From these studies it is possible to predict by extrapolation the maximum power dissipation at the melting point of aluminum for various immersion depths.

II. APPARATUS

The fission afterheat source is within the fuel-bearing regions of the element. Ideally, studies of afterheat removal mechanisms should utilize a heat source similarly located within the fuel plates. The most obvious source would be a real, activated element. However, the greater ease with which a nonradioactive element may be precisely and thoroughly instrumented, as well as the versatility of a controllable power input, led to the use of an induction heater and a dummy fuel element containing no fissionable material. The heat-source distribution was not confined to the simulated fuel plates; the nonfuel-bearing side plates were heated as well. In fact, because induction heating is greatest on the surface of a heated body, the outer fuel plates and side plates were heated at greater rates than the interior fuel plates. However, because of aluminum's high thermal conductivity, equilibrium temperature differences between the interior and exterior at any given height on the element were

Fig. 1. MTR-type fuel element as used at the Omega West reactor.

expected to be small. An induction heat source of low frequency was used, thereby further reducing the radial temperature gradients by increasing the heat deposition rate within the element. The maximum radial temperature difference observed was 10° C at equilibrium.

Because fission afterheat results from fission fragment decay, the heat source distribution is the product of the integrated thermal neutron flux within the element and the macroscopic cross section of the fuel, averaged and corrected for decay over the history of the element. In the Omega West reactor (OWR) the maximum fuel burnup is about 30%, and the vertical flux distribution has nearly the same shape throughout the core. Thus, the vertical profile of the afterheat source in any fuel element is approximated reasonably well by a typical vertical flux distribution. A coil for a 10-kHz induction heater was therefore made with a turn density proportional to such a distribution.¹ The coil was wound around a Pyrex tube of sufficient diameter to permit insertion of a fuel element. The Pyrex tube served four functions: (1) it provided electrical insulation between the element and the induction coil, (2) it contained the water, providing immersion levels above the bottom of coil, (3) it eliminated external air convection, and (4) it limited the surface area of the water at the immersion level, effectively preventing convection within the water.

The last two functions are important in pro-

viding an environment similar to that of an element among an array of elements, all generating after-heat. External air convection is limited by adjacent elements. The water near the center of the array is heated from above, making water convection negligible. Because the elements generating the higher afterheat rates are expected to be found near the center of the core, the experimental configuration for this work was designed to eliminate convection.

A dummy fuel element, similar in dimensions to those used in the OWR but containing no fissionable material, was instrumented with seven sheathed Chromel-Alumel thermocouples placed as shown in Fig. 2. The power input was calibrated by measuring the temperature change of water flowing through the element, which was fitted with water-tight end caps to restrict the water to the interior. The element was placed within the Pyrex tube in the heater coil as shown in Fig. 3. Water was passed through the element at a measured rate, and the temperature was recorded at the inlet and outlet. This process was repeated at several power levels to calibrate the induction heat input to $\pm 5\%$. The maximum input to the element was limited to 5.1 kW by the coil impedance.

The end caps were then removed, and a fitting with a "O" ring seal was placed on the lower end of the Pyrex tube, as shown in Fig. 4. This fitting supported the element at the proper height relative

Fig. 2. Instrumented dummy fuel element. Interior thermocouples are placed on the centerline and 4, 8, and 12 in. above the centerline.

Fig. 3. Calibration of power input. Water is confined to the interior of the element.

Fig. 4. Variable immersion level induction heating apparatus.

to the coil. An opening in the support equalized the water levels inside and outside the element. The constant-level device shown on the laboratory jack stand in Fig. 4 was connected by a flexible

tube to the water inlet in the bottom of the fitting. The element immersion level could thus be varied by means of the jack. Additional thermocouples were installed to monitor the water temperature near the lower end fitting and the steam outlet temperature within the upper end of the tube. The upper ends of the element and the Pyrex tube were open to the atmosphere.

III. PROCEDURE

Element and outlet steam temperatures were observed until they reached equilibrium for several values of input power and immersion depth. The internal temperatures obtained for each set of conditions were then plotted as a function of distance

from the end of the fuel plates, as shown in Figs. 5 through 8, and used to find the maximum fuel-plate temperature in each case.

An earlier test using electrical resistance strip heaters showed that metal temperatures as high as 630 °C could be obtained without loss of structural integrity in the element. However, when this temperature was reached during induction heating, localized melting began in the outer curved plates of the element. This melting is due to hot spots inherent in the induction heating method. For this reason the maximum observed temperature of a second dummy element was kept below 580 °C for these immersion tests.

Fig. 5. Fuel-plate temperatures at 2-in. plate immersion.

Fig. 7. Fuel-plate temperatures at 4-in. plate immersion.

Fig. 6. Fuel-plate temperatures at 3-in. plate immersion.

Fig. 8. Fuel-plate temperatures at 5-in. plate immersion.

Fig. 9. Maximum fuel-plate temperatures vs power input for inductively heated elements partially immersed in water.

IV. RESULTS

Figure 9 shows the maximum equilibrium plate temperature plotted against power input for each immersion depth. At depths of 2 and 3 in., the steam generated in the submerged section soon became superheated as it passed up through the element. At a 2-in. water depth and 2.3-kW input, for example, the exhaust steam was superheated 6 min after the application of power and reached a maximum temperature of about 525°C one hour later.

At a depth of 4 in., water began to percolate through the element at a power of 3 kW, as evidenced by occasional bursts of fine droplets in the exhaust. At 4 kW an almost steady stream of droplets was seen. This incipient percolation appears to have enhanced the cooling effect as indicated by the decreased slope of the 4-in. curve of Fig. 9, although the exhaust steam was still highly superheated (515°C at 4 kW).

At a depth of 5 in., vigorous percolation set in as is shown by the dramatic temperature drop in Fig. 9. Under this condition, the exhaust steam temperature fluctuated between the boiling point and the lowest plate temperature. The vapor was emitted in bursts. Even more effective percolation cooling occurred at 6-in. immersion depth; the maximum equilibrium plate temperature was below 140°C at 5.1 kW.

It appeared that the temperature distribution for each power and water level was the same whether starting from zero power or from other power and water level values; however, in some cases several hours were needed to establish equilibrium. During percolation, a temperature oscillation of about 10°C with a period of some tens of minutes was occasionally observed.

At the 6-in. immersion depth, a particularly marked initial fluctuation occurred when full power was applied to the cold element. The maximum plate temperature rose to about 300°C within 10 min, then dropped to 140°C 10 min later as percolation became effective. Such major initial oscillations are probably not pertinent, however. They arise from the sudden application of power to the dry region of the element above the water line which remains uncooled until the water within the element is raised to the boiling point. In a real element generating after-heat while draining, the thermal behavior would be somewhat different. The water that is found in the lower regions of the element when boiling begins arrived there from the upper cooling channels as draining progressed. It has thus been preheated and would boil earlier than the water used in this experiment. Also, vaporization of entrained water in the upper cooling channels would carry off additional heat before establishment of effective percolation. Large initial temperature fluctuations would occur during draining of the reactor tank only if the water level drop were very rapid.

Water consumption rates were measured at several powers. Table I shows these rates, together with those calculated taking into account the enthalpy increase in the outlet steam for the smaller immersion depths. Agreement is good except for the 6-in. case, where percolation may have carried off some unevaporated water. Because the input power was calibrated with the element at ambient temperature, the agreement between measured and calculated water consumption indicates a negligible heat loss due to radiation and external convection.

V. CONCLUSIONS

Water within a partially submerged fuel element is rapidly heated to the boiling point at any heat input rate which could conceivably result in melting.

Table I. WATER CONSUMPTION^{*} DURING HEATING TESTS

Input Power, kW	Depth, In.	Outlet Steam, °C	Water Loss Rate	
			Obs. liter/hr	Calc. liter/hr
1.8	3	460	2.1	2.0
2.3	2	527	2.3	2.4
5.1	5	~95*	7.5	7.2
5.1	6	~95*	7.9	7.2

* The boiling point of water at the elevation of Los Alamos is about 91°C.

At immersion levels up to about 3 in., the primary process of heat removal is the production and superheating of steam. The vapor pressure of the trapped water provides an efficient driving force which can remove up to 3.2 kW of afterheat at 3-in. immersion at the melting point.

At 4-in. plate immersion, some percolation cooling is evident, resulting in the removal of 5.0 kW at the melting point. At 5-in. immersion, perco-

lation becomes the dominant process of heat removal. The effectiveness of percolation as a cooling mechanism is clearly shown in Fig. 9. Concerning the decrease of temperature with increasing power input, it should be noted that a plate immersion depth of 5 in. places more than 20% of the heat source below the water level; during percolation the submerged plate temperature must be near the boiling point, so an increase in input power might be expected to force more water up the narrow coolant channels.

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REFERENCE

1. Omega West Reactor Operating Procedures, Revision 1, Section VI (November 26, 1968).