FULL SCALE EXPERIMENT TO DETERMINE THE THERMAL RESPONSE FOLLOWING LOSS OF COOLANT WATER FROM A FLASK CONTAINING IRRADIATED LWR FUEL

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Abstract

FULL SCALE EXPERIMENT TO DETERMINE THE THERMAL RESPONSE FOLLOWING LOSS OF COOLANT WATER FROM A FLASK CONTAINING IRRADIATED LWR FUEL.

Water filled flasks, with a steel body, lead liner and internal fuel containment bottle, are used extensively to transport irradiated light water reactor fuel. If all the water was lost from the flask, then there would be a considerable increase in the thermal resistance between the fuel and the flask body, with a consequent rise in fuel temperatures. Full scale experiments have been conducted on an Excellox flask to determine thermal performance in the dry state. The experimental rig consisted of the flask fitted with electrical heaters to simulate fuel elements and instrumented to investigate temperature changes. Because of temperature limitations on the rig, a computer model has been developed to extend the temperature transients to equilibrium. Temperatures have proven to be appreciably lower than previously predicted and can be significantly reduced by partial replacement of water to fill the flask–bottle interspace or by increasing the air pressure surrounding the fuel. The model is being further developed to investigate the performance of flasks of similar design for different fuel arrays and loadings.

1. INTRODUCTION

British Nuclear Fuels plc and its subsidiary company Pacific Nuclear Transport Ltd, are major transporters of irradiated fuel. Strong steel containers (flasks) are used for this purpose. During normal operation of a flask containing irradiated fuel the fission product decay heat is dissipated through the flask body to the surrounding air. LWR fuel may be transported in water-filled flasks with the water providing good convection heat transfer between the fuel and the flask body. Conduction through the flask body and convection and radiation from it to the surroundings completes the heat transfer system and the fuel is kept cool (typically 50-100°C).

If all the water was lost there would be an increase in the thermal resistance between the fuel and the flask body, with a consequent rise in the fuel and flask temperatures. To check the satisfactory operation of a flask after such an event, BNFL have conducted a series of experiments on a 'wet' flask operated in the dry state. For a better understanding of the heat-transfer process, tests have also been conducted for a range of air pressures (sub-atmospheric and pressurised), with air replaced by helium and with water filling of the annuli between the fuel container bottle and flask body. The work was carried out by AEE Winfrith, an establishment of the United Kingdom Atomic Energy Authority, under contract to BNFL.

This paper describes the experimental rig, presents test results and explains how this information has been used to develop a computer model to extend the range of results to thermal equilibrium.

2. FLASK DESIGN AND THERMAL BEHAVIOUR

The flask investigated is the "Excellox" design, as shown in Fig 1. It consists of a massive carbon steel welded fabrication, with an approximately 10 cm thick cylindrical body, a 35 cm thick base and a solid 30 cm thick lid, bolted and sealed to the body. The outer surface is finned to dissipate heat. The ends of the flask and penetrations are protected against impact by shock absorbers consisting of balsa wood encased in stainless steel. An external neutron shield cover may be fitted over the top of the finned area. Additional gamma shielding is fitted in the form of a lead liner approximately 15 cm thick extending over the length of the flask cavity. The liner has water-circulation holes through its thickness to permit convective flow to the flask body, (Fig 3). Typical overall dimensions are 2 m diameter by 6 m long.

Fuel is carried in a special container known as a 'Multi-element Bottle' (MEB) which may be designed to accommodate different arrays and types of LWR fuel. Boral plates form part of the channels in which the fuel is located. The fuel is cooled and heat transfer achieved in normal operation by water which occupies much of the free space in the flask and MEB. A gas space (ullage) is necessary in both the flask and the MEB to allow for water expansion with temperature and to collect any radiolytic and fission-product gases. Any of the fuel designs at present in use in light water reactors may be carried, with fuel pin arrays

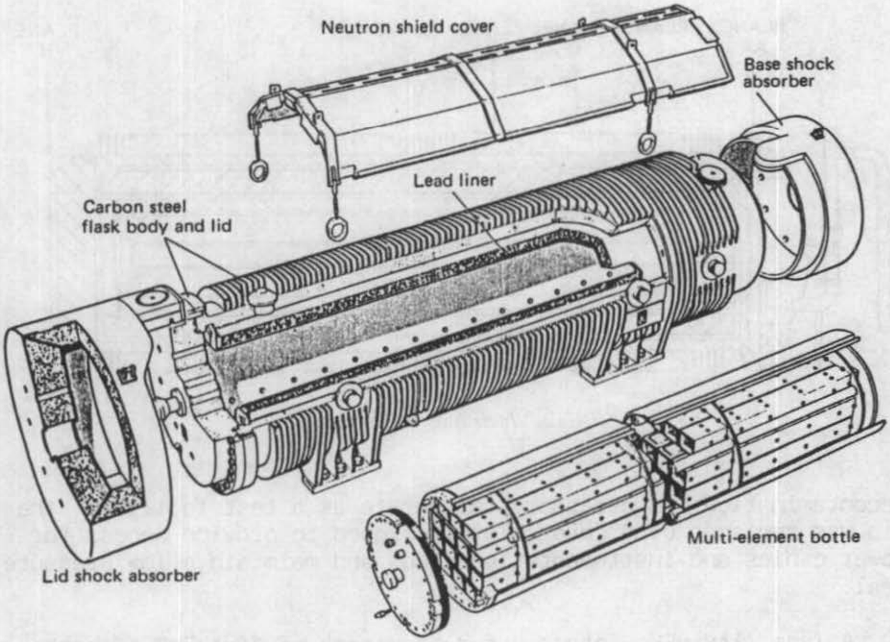

FIG. 1. Excellox 3A irradiated fuel transport flask.

ranging from 7x7 or 8x8 (BWR) to 15x15 or 17x17 (PWR). The capacities of flasks currently in use are 5 PWR or 12 BWR elements (Excellox 3, 3A or 3B) and 7 PWR or 15 BWR elements (Excellox 4).

In the normal operating condition with water present in the flask and MEB, good conduction and convection heat transfer occur between the fuel pins and the flask body. Temperature gradients are small and fuel and flask internal components remain cool (within about 50°C of the flask body temperature). With the loss of water, the spaces between the fuel, the MEB, the lead liner and the flask body become filled with air, through which heat is transferred mainly by radiation, with some contribution by convection. The increased thermal resistance requires larger thermal gradients to dissipate the same heat load resulting in higher fuel and flask component temperatures.

3. EXPERIMENTAL RIG

3.1 The Flask Simulation

The flask incorporated into the test rig was of the Excellox 3A type, which is typical of those in general use. Previous use had been for transport of irradiated LWR fuel from Japan to the UK, and

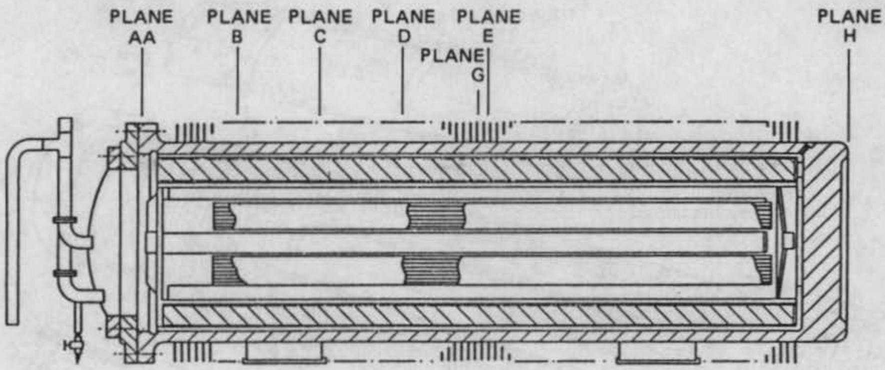

FIG. 2. Instrumentation planes.

decontamination was necessary to operate as a test facility. The lid was replaced by a cover plate designed to provide access for power cables and instrumentation leads and maintain a low pressure seal.

A Type 1149 MEB, intended for transport of five PWR elements was fitted into the flask. The MEB lid was modified and fitted with electrical seal adaptors for heater cables and instrumentation. Existing screwed connections were used as access for internal atmosphere monitoring and control instrumentation. The flask was mounted horizontally and the lid and base were lagged to simulate the thermal insulation normally provided by the shock absorbers.

3.2 The Simulated Fuel

The five PWR fuel elements were simulated by electrical heater rods assembled into bundles and inserted into the fuel channels in the MEB. Each bundle was a 17x17 array of 9.5 mm diameter heater rods and dummy control rod guide tubes on a 12.6 mm pitch, giving a total of 264 heaters and 25 guide tubes per bundle. The heaters were 4100 mm long 'Incaloy' tubes with a 3600 mm long heated zone. They were assembled into dummy grid plates to give an accurate simulation of the PWR element geometry.

The number of power connections through the seal adaptors in the MEB lid was reduced by connecting heaters in banks of twelve. The total rating of the five heater bundles was 52.8 kW. This gave a reserve of 50% over the 30 kW maximum design heat load of the flask.

3.3 Instrumentation

Chromel-Alumel, Type K, thermocouples were used to measure component temperatures. Those inside the flask were stainless

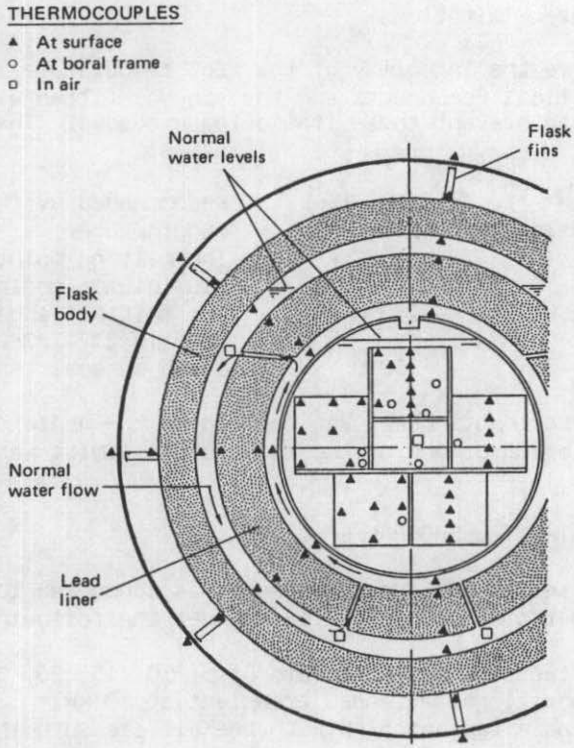

FIG. 3. Thermocouple position on the test rig at centre plane E of flask.

steel sheathed and peaned or clipped into position. Those on the outside were plastic covered and attached using an epoxy resin adhesive.

Thermocouples were located on all the major flask components, including the heater, the MEB, the boral plates, the lead liner and the flask body. The axial location of the instrumentation planes is shown in Fig 2. Most of the thermocouples were located at the centre plane of the flask (plane E), as shown in Fig 3. The top heater bundle was extensively instrumented since this region was expected to reach the highest temperature. The remaining four bundles were sufficiently instrumented to indicate temperature contours within the MEB. Centreline air temperature was measured using a thermocouple fitted with a Thermo-radiation shield. Thermocouple signals, power supply and pressure measurements were recorded on a floppy disc through a programmable data logger and micro-computer.

3.4 Temperature Limitations

To preserve the integrity of the rig, temperature limits were placed on critical components and the rig was fitted with automatic trip devices to prevent these from being exceeded. The limits were as follows:

Heater surface	800°C)	Recommended by the
Heater terminals	250°C)	manufacturer.
Boral plates	550°C	The melting point of the aluminium cladding is 650°C
Lead liner	250°C	The melting range for 4% Sb lead is 277-292°C.
Flask seals	150°C	Based on seal tests.

During the experiments power was applied to the heaters until either equilibrium or one of the temperature limits was reached.

4. THE EXPERIMENTAL PROGRAMME

An extensive series of transient tests was conducted to demonstrate the thermal performance of the flask under the following conditions:

(1) Six tests at heater powers of 5, 10, 15, 20, 30 and 40 kW. An additional extended transient at 30 kW.

(2) A single test at 5 kW with the air pressure in the MEB reduced to 0.15 bar.

(3) A single test at 5 kW with a helium atmosphere in the MEB.

(4) Three tests at 10, 20 and 30 kW with the MEB filled with air and the annuli between the MEB and the flask body (ie each side of the lead liner) filled with water.

(5) Eight tests at 5, 10, 20 and 30 kW with the pressure in the MEB increased to 2.72 bar and 4.44 bar.

For the ambient pressure air-filled tests the MEB was vented to atmosphere. The reduced pressure and helium tests were carried out to determine the significance of convection and gas conduction heat transfer in the MEB. The water-filled annuli tests were to show the effect of partial refill of the flask with water, (ie the MEB remaining air-filled). The pressurised air tests were to investigate the reduction in equilibrium temperatures which might be obtained by resealing and pressurising the flasks.

5. EXPERIMENTAL RESULTS

5.1 Air Atmosphere Tests

Measured transient temperatures of the hottest heater in the top bundle at the centre plane E are presented in Fig 4. The 5 and 10 kW tests were allowed to proceed to thermal equilibrium.

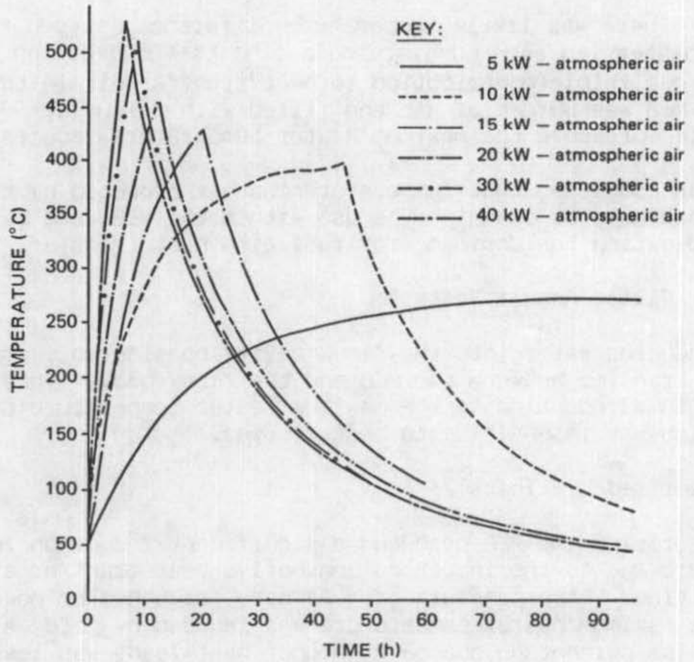

FIG. 4. Temperature transients for hottest heater pin in top bundle at centre plane E.

Because of the limiting temperature of the heater terminals the power was switched off for the remaining tests when the terminals reached 250°C. It was found that the results could be fitted to an exponential relationship:

$$\frac{T - Ta}{Tmax - Ta} = 1 - e^{\emptyset t}$$

where T is the component temperature at time t, Tmax is the equilibrium temperature, Ta is the ambient air temperature and Ø is a transient coefficient. At 30 kW heat load the maximum heater temperature was calculated to be 665°C.

An additional, potentially rig damaging, test at 30 kW heat load was conducted at the end of the programme, when the temperature transient was allowed to continue for 24 hours. Some of the heater terminals exceeded 250°C and at the end of the test 28% of the heaters had failed. The total heater power reduced from 30kW to 21.7 kW and the maximum heater temperature reached an equilibrium value of 580°C.

5.2 Reduced Air Pressure and Helium Tests

With the air pressure reduced to 0.15 bar in the MEB the maximum heater temperature increased from 272°C to 304°C at a power of 5 kW. There was little temperature difference between the hottest heaters in each bundle, indicating that convection was making a negligible contribution to heat transfer within the MEB. When the MEB was purged of air and filled with helium at atmospheric pressure the maximum heater temperature reduced by 15°C.

It was concluded that temperature changes produced by reducing the air pressure or changing the gas within the MEB were relatively small indicating the dominance of radiation heat transfer.

5.3 Water-Filled Annuli Tests

Introducing water into the flask cavity considerably improves the heat transfer between the MEB and the flask body. This resulted in a reduction in the maximum heater temperature of about 110°C which was insensitive to heater power.

5.4 Pressurised MEB Tests

Pressurising the MEB produced a significant reduction in heater temperature due to the increased convective heat transfer at higher air densities. At a pressure of 4.44 bar, for a heater power of 5 kW, the maximum heater temperature was reduced by 75°C, a change of 28%. The percentage change at higher heat loads was less due to the increasing importance of radiation heat transfer.

6. THE COMPUTER MODEL

Because of temperature limitations on the rig, some of the higher power tests could not be continued to thermal equilibrium and it was necessary to develop a computer model to extend the test results. The test rig was represented by a two-dimensional finite element model of the cross-section at the mid-point of the flask where the majority of the heater thermocouples were situated (ie plane E). The finite-element general heat-transfer code TAU [1] of the UNCLE suite [2] was used for the modelling. The code solves the heat-diffusion equation over a two or three-dimensional region under equilibrium or transient conditions. A wide range of boundary conditions can be applied and there is a particularly powerful treatment of surface to surface radiation.

The finite element mesh is shown in Fig 5. Because of flask symmetry, only a half cross-section is represented. Heater regions were given averaged values of density and specific heat derived from the heater materials. The heat transfer across the heater assemblies is dependent on pin-to-pin radiation and gas conduction. To simplify the model a temperature-dependent conductivity was derived using the pin bundle heat-transfer code RIGG [3]. This conductivity, as a function of the local temperature was then input into the finite-element model. Other

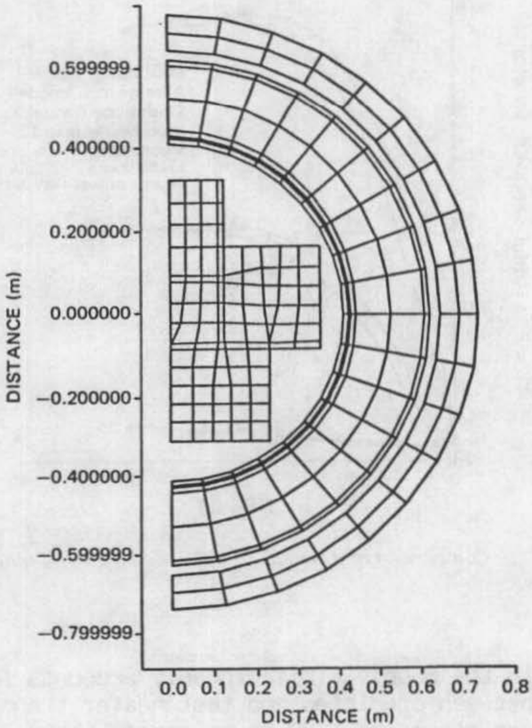

FIG. 5. Finite element mesh used in computer model of test rig.

material properties and radiation and convection-boundary conditions within the flask were modelled.

Because of the dominance of radiation heat transfer, it was found that, by making an adjustment to the MEB and lead-shield emissivities used in the model, good agreement was obtained between model and test transients at 5 kW heater power. At heater powers up to 40 kW with physical properties kept constant, similar good agreement between model and test data was obtained (within about 3%).

The computer model was used to extend the higher power test results (Fig 4) to predict heater equilibrium temperatures. These proved to be in good agreement with those derived using the exponential relationship given in Sec 5.1 above.

The 30 kW extended transient test provided a further check of the accuracy of the model at higher powers. A comparison of model and test temperature transients for the hottest heater, average MEB and flask body is given in Fig 6. Since the test data did not indicate which heaters failed, the power was shared equally amongst

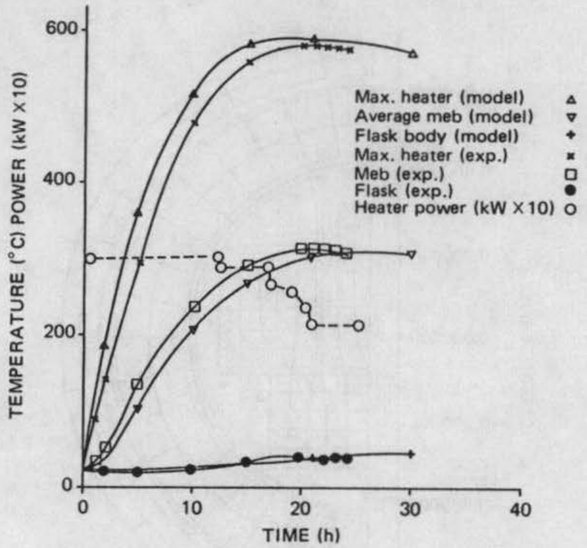

FIG. 6. Comparison of nominal 30 kW experiment and model results.

the heaters in the model. This probably accounts for the discrepancy between predicted and test heater transients. Even so, the peak values after about 20 hours agree within 7°C.

The fuel simulation and experimental conditions differ from those which apply to a flask carrying irradiated fuel. In particular, the thermal properties of the heater pins (conductivity, specific heat, etc) were similar, but not identical, to those of the fuel. Also, each heater produced a constant axial power distribution which did not simulate the radiation-induced axial form factor, typically 1.2 for PWR fuel. A further computer model is under development to correct for these differences.

7. CONCLUSIONS

1 Following complete loss of water from an Excellox 3A flask containing five simulated PWR elements, the maximum equilibrium fuel pin temperature for a total heat load of 30 kW is 665°C. Fuel and flask component temperatures are significantly lower, some 200°C than previously determined by theoretical analysis.

2 Good agreement has been achieved between test results and finite element model predictions (Fig 6). Further work is in progress to extend the results to simulate actual irradiated fuel.

3 Replacement of water in the annuli between the MEB and flask body and/or pressurisation of the air in the MEB produces an appreciable reduction in the maximum equilibrium temperatures.

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