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ABSTRACT

A two-dimensional theoretical heat transfer model of a HIFAR Mark IV/Va fuel element has been developed and validated by comparing predicted thermal performances with experimental temperature responses obtained from irradiated fuel elements during simulated accident conditions. Full details of the model's development and its verification have been reported elsewhere. In this report, the model has been further used to ascertain acceptable limits of fuel element decay power for the start of two specific LOCAs which have been identified by the Regulatory Bureau of the AAEC.

For a single fuel element which is positioned within a fuel load/unload flask and is not subjected to any forced convective air cooling, the model indicates that fission product decay powers must not exceed 1.86 kW if fuel surface temperatures are not to exceed 450°C.

In the case of a HIFAR core LOCA in which the complete inventory of heavy water is lost, it is calculated that the maximum fission product decay power of a central element must not exceed 1.1 kW if fuel surface temperatures are not to exceed 450°C anywhere in the core.

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FISSION PRODUCTS; FORECASTING; FUEL ELEMENTS; HEAT TRANSFER; HEAVY WATER; HIFAR REACTOR; LOSS OF COOLANT; MATHEMATICAL MODELS; REACTOR CORES; SIMULATION; TEMPERATURE DEPENDENCE; TWO-DIMENSIONAL CALCULATIONS

EDITORIAL NOTE

From 27 April 1987, the Australian Atomic Energy Commission (AAEC) is replaced by Australian Nuclear Science and Technology Organisation (ANSTO). Serial numbers for reports with an issue date after April 1987 have the prefix ANSTO with no change of the symbol (E, M, S or C) or numbering sequence.

CONTENTS

1. INTRODUCTION

In late 1984, staff from the Commission's Regulatory Bureau (hereafter called the Bureau) and Nuclear Technology Division (NTD) met to discuss the possibility of predicting HIFAR fuel element temperatures for particular postulated loss-of-coolant accidents (LOCAs). On the basis of these discussions it was agreed that the following program of theoretical work should be pursued:

(a) Development of a theoretical heat transfer model of the current HIFAR fuel element.

(b) Validation of this model and any assumptions it makes against known experimental results for controlled simulated accidents.

(c) Extension of the analysis to multiple arrays of fuel elements in order that transient and steady-state temperatures can be estimated for 25 fuel elements situated in a HIFAR core devoid of any liquid coolant.

As background information for this work the Bureau provided the following information on temperature limits:

1. 260°C - limit on rewetting.
2. 400-450°C - limit on clad strength, danger of thermal shock if cold water injection takes place and onset of fuel plate blistering leading to onset of release of gaseous fission products.
3. 620-650°C - melting of the cladding.

There would be a gradual increase in fission product release in the temperature range 450-620°C up to a maximum at melting [Carlson 1984]. Bureau staff also indicated that the mission time of the emergency core cooling system (ECCS) should be such that if failure occurred "the temperature of the fuel, with no other action, would not exceed 400-450°C, thus providing a margin to melting of the cladding" [Carlson 1984].

On the basis of these criteria, it was considered that when assessing relationships between equilibrium temperature and fuel element power output, a maximum temperature level of 450°C should be taken.

A second requirement itemised by the Bureau was that it "wished to confirm that the current limit for unloading fuel from the reactor (below 2 kW fission decay power) does mean that such an element can be suspended in air without forced cooling indefinitely, with no danger of the temperature reaching the melting point of the cladding. The Bureau would prefer to see this limit being the onset of fuel plate blistering."

The objective of this report is to describe the work that has been performed towards achieving the goals of the agreed program of theoretical work and to provide estimates of the HIFAR fuel element fission product decay powers at which the maximum fuel surface temperature will not exceed 450°C when

(a) a current design HIFAR fuel element is suspended in air and is not cooled by forced convection, and

(b) the fuel element is situated among an array of 25 fuel elements contained within the HIFAR core but uncooled by any liquid or forced convection of gas, *i.e.* 25 fuel elements in stagnant air.

2. DEVELOPMENT OF THEORETICAL MODEL AND ITS VERIFICATION

Figure 1 shows a cross-sectional view of a HIFAR Mark IV/Va fuel element. A comprehensive description of the development and validation of a simple theoretical model which can be used to represent such a fuel element has already been reported [Green 1987a]. As a consequence, it is only necessary here to provide a brief resumé of this earlier work.

The model developed was based upon a two-dimensional finite element transient heat transfer code HEATRAN [Collier 1969]. Green [1987] provides complete descriptions of

(a) the manner in which asymmetrical physical features were considered,

(b) the physical properties and heat sources that were used, and

(c) the thermal boundary conditions that were assumed.

The same parameters were used to formulate not only a simple model of a HIFAR Mark IV/Va fuel element but also a model of an Oak Ridge Reactor (ORR) box-type fuel element.

To examine the validity of these two fuel element models, they were used to calculate temperature responses at fission product decay powers corresponding to various non-forced convective conditions and comparisons made between measured temperature responses and calculated values.

Comparison of calculated and measured thermal responses obtained by Parsons [1971] for a HIFAR Mark IV/Va fuel element showed the following:

(i) The end effects of the fuel element need to be incorporated in the model since they account for approximately 25 per cent of the power dissipated; however, detailed modelling of the fuel element ends is not important.

(ii) Agreement between calculated and extrapolated steady-state temperatures is excellent when the surface thermal emissivity is assumed to be 0.35.

(iii) Calculated rates of temperature rise in the initial phase of a transient are greater than those observed in experiments - this discrepancy may be attributable to the experimental procedure used in determining the transient data.

(iv) Notwithstanding the difference between the calculated and measured rates of temperature rise in the initial phase of a transient, the maximum discrepancy between calculated and measured temperatures is ~ 70°C, with the calculated values being the greater.

(v) Axial power distribution did not significantly affect thermal responses.

Using the same surface thermal emissivity as that ascertained from examining the thermal responses of a HIFAR fuel element, the thermal responses of a theoretical model of the ORR fuel element were calculated and compared with experimental data obtained by Wett [1960]. This comparison demonstrated two points:

(i) Calculated and experimental responses are in excellent agreement, the maximum difference between calculated and measured temperatures being less than 15°C.

(ii) Axial temperature distributions measured near equilibrium conditions were also in close agreement with calculated values. The calculated temperatures were approximately 20-30°C greater than measured values.

Furthermore, the theoretical principles relating to heat removal mechanisms, geometry, decay heat generation and physical properties for these analytical models are such that the thermal response of any geometrical configuration can be calculated without the need for arbitrary, and perhaps unjustifiable, assumptions relating to heat transfer mechanisms or thermal properties.

Since the results of this earlier work, further validation of the HIFAR Mark IV/Va fuel element model has been obtained by comparing theoretical temperature responses with experimental data that have been reported by Wolters [1976]. In Wolters' experiments, an FRJ-2 fuel element (very similar to the HIFAR MarkIV/Va fuel element) was used. One objective was to obtain a relationship between fission product decay power and thermal power by using forced convective air cooling. This involved shrouding the fuel element in two concentric stainless steel cylinders and using the internal 'thimble' space of the fuel element for instrumentation. Apart from performing steady-state heat balance experiments, Wolters also conducted tests in which the forced convective air cooling was absent, and external heat losses from the shroud of the fuel element were severely restricted because of the presence of ancillary stainless steel tubes, thus simulating a transient accident condition. Such a configuration provided suitable data for another stringent test of the model. However, before the HIFAR fuel element model could be used to determine temperature transients which could be compared with experimental data obtained by Wolters, both the external stainless steel tubes and the internal instrumentation tube within the fuel element thimble had to be included in the theoretical model. With this done, comparisons of theoretical and experimental temperature responses were performed, and excellent agreement demonstrated. A full report on this work is in preparation [Green 1987b].

In summary, for a variety of geometrical arrangements, it has been shown that relatively simple heat transfer models of the DIDO* class reactor fuel elements have been developed and can be used to predict temperature

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* HIFAR and FRJ-2 are experimental reactors whose designs were based on the DIDO reactor built by the UKAEA at Harwell. As a consequence they are known as DIDO class reactors.

responses to a reasonably good degree of accuracy. Arising from this work, it therefore becomes feasible to use the model for (a) predicting temperature responses during postulated accident conditions which cannot easily be experimentally simulated, and (b) stipulating safe operating guidelines.

3. FISSION PRODUCT DECAY POWER LIMIT FOR A FUEL ELEMENT WHEN BEING UNLOADED

Specification of the decay time (and the corresponding fission product decay power) beyond which fuel plate temperatures of a HIFAR Mark IV/Va fuel element will not exceed 450°C, requires a knowledge of the relationship between fission product decay power and maximum equilibrium fuel plate temperature for the appropriate thermal boundary conditions.

Experimental investigations designed to gain such information for the case of a fuel element suspended in a transport flask, with the forced convective air cooling system inoperative, were performed by [Parsons 1971]. The work, although valuable, suffered from three drawbacks. First, because the prospect of any fuel element damage was unacceptable, measured transient fuel surface temperatures were not permitted to exceed 450°C, thereby resulting in the non-attainment of steady-state conditions for some experiments. Second, since fission product decay powers could not be easily manipulated, extrapolation of data was necessary. Third, the fuel surface temperatures were not measured at the mid axial height of the fuel element, *i.e.* the position of the most likely maximum temperature.

Development of the theoretical model discussed in **section 2** overcomes these problems. The fuel element model which has been formulated, is capable of predicting both the transient temperatures and the low power steady state values measured by Parsons. **Table 3** in Green [1987a] indicates a comparison between calculated equilibrium temperatures and those extrapolated from experimental response data. Bearing in mind that at the higher thermal power outputs, extrapolation to steady state conditions was somewhat subjective since recorded temperatures were still changing quite perceptibly with time, the agreement between calculated and experimental equilibrium values is very good and, in the case of fuel temperatures, less than 450°C may be considered as excellent. As already mentioned, however, the temperatures given in **table 3** of Green [1987a] relate to fuel surface temperatures at the plane of the measuring thermocouple and are not the maximum values. The following table indicates the corresponding relationship between the thermal power output and calculated *maximum* fuel surface temperatures:

Thermal Power Output (kW)	Maximum Fuel Plate Temperature (°C)
1.09	488
0.73	383
0.49	297
0.39	255

These data are shown graphically on **figure 2** where, from interpolation, it can be seen that if a temperature limit of 450°C is imposed upon the fuel surface temperature, the thermal power output from the fuel element should not exceed 0.95 kW. Assuming, as in earlier work [Green 1987a], that the thermal power output is 0.51 times the fission product decay power*, the limiting fission product decay power becomes 1.86 kW.

4. FISSION PRODUCT DECAY POWER LIMIT FOR FUEL ELEMENTS IN A DRY CORE

Although it is possible, because of the availability of relevant experimental data, to develop a heat transfer model of a single fuel element which will predict the thermal performance of such an element when it is in isolation, the prediction of thermal performance when the HIFAR fuel element is surrounded by an array of similar fuel elements poses a more difficult problem.

* Wolters [1976] has shown experimentally that this assumption is reasonable. He has determined ratio values which range between 0.52 and 0.46 for irradiated FRJ-2 fuel elements that have been in a shutdown mode for between 0.01 and 11.5 days.

For this situation, although the internal heat transport mechanisms within each fuel element (*i.e.* thermal radiation and conduction through the gas between the fuel tubes and natural convection within the thimble space) are the same as those for a single fuel element suspended in stagnant air, the external radiant transfer of heat to neighbouring fuel elements and external natural convection heat loss mechanisms may be different and possibly more complex. The question arises, therefore, as to whether the single HIFAR fuel element model which has been developed and shown to be capable of accurately reproducing experimental data can be adapted to a multi-fuel element problem.

4.1 Suitability of a Single Fuel Element Model

Determination of the thermal performance of any heated surface in an array of heated rods or fuel elements which are enclosed within a cylinder, and are cooled by natural convection, conduction and thermal radiation through a gas, is a complex problem which is receiving an increasing amount of theoretical and experimental attention. On the theoretical front, there have been attempts to use (a) finite element methods to ascertain the performance of 7-rod and 91-rod bundles subjected to fully developed natural convection cooling [Magallon 1981], and (b) a Monte Carlo analytic technique to calculate the transient thermal performance of fuel rod arrays, assuming that thermal radiation is the sole heat transfer mechanism [Reilly *et al.* 1978].

Experimentally, the most appropriate work has been that of Keyhani and Kulacki [1985] who have studied natural convection in enclosures containing tube bundles. As part of their work, they studied natural convection phenomena in a 5 x 5 array of heated rods contained within a cylindrical enclosure - a configuration which is relevant to the dry HIFAR core accident postulated in **section 1**.

It would seem therefore that a closer examination of the findings of these various theoretical and experimental studies could provide assistance in determining the thermal performance of a HIFAR core should it be accidentally drained of water.

Reilly *et al.* [1978], in their theoretical calculations of radiative effects, examined fuel pin arrays in which the pitch to rod diameter ranged between 1.25 and 1.38*. They found that "the effects of thermal radiative heat transfer to the duct wall (*i.e.* the containment cylinder) are significant only on the outside row of the array". The second and third rows from the containment wall were only marginally influenced by the duct wall temperature. Their work would seem to indicate that for the innermost heated rods, thermal radiation does not play a major role in removing heat from the rod surfaces but acts only in the role of redistributing thermal energy between surfaces.

For the drained HIFAR core situation, in which an array of 25 fuel elements is involved, it would appear that the innermost fuel elements may be unaffected by thermal radiative cooling. Hence it would seem pertinent to assume that thermal radiation should be discounted as a heat removal mechanism when assessing maximum temperature levels. This will possibly render the calculated limiting fuel element decay powers as being conservative. If thermal radiation is assumed as ineffective and conduction between fuel elements, and the reactor containment vessel may be assumed as being negligibly small because of the relatively large interstitial distances and the low thermal conductivity of air, the only heat removal mechanism that could significantly affect the inner fuel element temperatures is that of natural convection.

On this point, the work of Keyhani and Kulacki [1985] is most useful since they have analysed their experimental data from a 5 x 5 array in terms of each heated rod and have developed correlations for each rod in terms of (i) the external diameter of the rod, (ii) the temperature difference between the rod surface and the cylinder enclosing the rod array, and (iii) coolant properties based on mean containment temperature. Furthermore, the local rod correlations that have been formulated indicate that in the central region of the array the correlations for each rod are almost identical.

The pitch-to-rod-diameter ratio which Keyhani and Kulacki used in their 5 x 5 experimental bundle was 2.25. This is larger than the pitch-to-fuel-element-external-diameter ratio of fuel elements in the HIFAR core. However extensive work which has been performed to assess the effect of pitch-to-rod-diameter ratio on the heat transfer characteristics of rod bundles which are forced convective cooled, has shown that heat transfer from the rod surfaces is little affected by the pitch-to-rod-diameter ratio provided that this ratio is greater than

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* In HIFAR the pitch-to-fuel-shroud-diameter ratio is approximately 1.5.

approximately 1.2 [Sutherland 1968]. Consequently, it would seem reasonable to hypothesise that Keyhani and Kulacki's findings for a 5 x 5 rod array may be applied with some confidence to the HIFAR 25 fuel element array problem.

In summary therefore, when considering the thermal performance of 25 HIFAR Mark IV/V fuel elements in a drained core configuration, the following assumptions are made:

(a) The most central fuel element will be the hottest.

(b) According to the theoretical work of Reilly *et al.* [1978] the innermost fuel elements will be unable to dissipate any significant amount of fission product decay heat by thermal radiaticn. Hence thermal radiation heat losses from the external surface of the shroud of a central fuel element can be neglected.

(c) Effects of conduction through a gas between the most central fuel element and the reactor containment vessel are negligible.

(d) Suitable natural convection correlations based upon

 (i) local fuel element conditions, and

 (ii) the difference between the local fuel element surface temperature and the overall containment temperature (*i.e.* of the reactor aluminium tank (RAT)),

may be inferred from the work of Keyhani and Kulacki [1985].

Arising from these assumptions it is possible to use the single HIFAR fuel element model already developed to ascertain the fission product decay power at which the maximum fuel surface temperature will not exceed 450°C when the HIFAR core is completely devoid of liquid coolant. The only requirement is that the appropriate natural convection heat transfer coefficients are input to the shroud surface of the fuel element model.

4.2 External Boundary Heat Transfer Coefficients

The experimental correlations and data obtained by Keyhani and Kulacki [1985] for the inner rods of a 5 x 5 array (see **figure 3** for the rod numbering system) are shown on **figure 4**.

To a very good approximation, these data can be correlated by the single expression

$$Nu_d = 0.055\, Ra_d^{1/3} \quad . \tag{1}$$

For a vertical cylinder whose characteristic dimension is diameter, Fishenden and Saunders [1950] found that in the turbulent flow range, natural convection processes are described by the equation

$$Nu = 0.10\, Ra^{1/3} \quad . \tag{2}$$

Similarly, for a vertical cylinder of large diameter whose characteristic linear dimension is height, they found that a suitable correlation is

$$Nu = 0.12\, Ra^{1/3} \quad . \tag{3}$$

Fishenden and Saunders further showed that for air at atmospheric pressure, these two expressions could be simplified respectively to

$$h = 0.25\, [T_w - T_a]^{0.25^*} \quad , \tag{4}$$

and

$$h = 0.30\, [T_w - T_a]^{0.25^*} \quad , \tag{5}$$

where h is the heat transfer coefficient expressed in British Imperial Units, T_w is the temperature of the wall in °F and T_a is the ambient temperature in °F. Using Fishenden and Saunders' approach, **equation 1** can be

* In his earlier work, Green [1985] used an average of **equations 4** and **5** when calculating the thermal performance characteristics of a single isolated HIFAR fuel element.

expressed, for dry atmospheric air, in the form

$$h = 0.135\,[T_w - T_a]^{0.25} \quad . \tag{6}$$

Thus in specifying boundary conditions applicable to the single HIFAR MarkIV/Va fuel element model, **equation 6** has been used, and has been assumed as being operative both on the external surface of the fuel element shroud and on the internal surface of the thimble space. This latter assumption may, in fact, be conservative since in previous calculations for a single isolated fuel element, it has been assumed that natural convection within the thimble volume can be described by the heat transfer coefficient given by the mean heat transfer coefficient derived from **equations 4** and **5**.

With respect to the specification of the sink temperature of the natural convection process, the correlations developed by Keyhani and Kulacki to describe their 5 x 5 array experimental natural convection data are based on the temperature difference between the heated rod surface and the wall temperature of the containing cylinder. In analysing the HIFAR core, therefore, the temperature of the RAT has been taken as the sink temperature. In all these analyses it has been assumed that the RAT is effectively cooled and kept at a constant temperature of ~ 25°C.

4.3 Predicted Fission Product Decay Powers

The relationship between thermal power output and maximum fuel plate temperature for steady state conditions is given in **figure 5**. From this figure it can be seen that if a limiting temperature criterion of 450°C is chosen, fuel element thermal decay powers in a dry HIFAR core should not exceed 0.56 kW. Using a ratio of thermal decay power to fission product decay power of 0.51, this means that fission product decay power of a fuel element should not exceed 1.1 kW.

Ancillary information on the transient temperatures of a fuel element during the first hour of the dry core condition is shown in **figure 6**. This figure depicts the fuel element temperature responses for thermal power outputs of 0.25, 0.5, 0.75 and 1 kW. From these data it can be seen that after one hour, the maximum fuel plate temperature levels above ambient have reached approximately three quarters of the steady-state values.

5. DISCUSSION AND CONCLUSIONS

A relatively simple two-dimensional thermal model of a HIFAR Mark IV/Va fuel element has been developed and used to calculate the transient and equilibrium thermal performances for conditions in which the fuel element is not subjected to forced convective cooling. The applicability and accuracy of the model has been validated by comparing predicted performances with experimental data that have been obtained during simulated accident conditions.

Arising from the confidence gained from making these comparisons, the model has been further used to predict fuel element decay power limits for two accident conditions specified by the AAEC's Regulatory Bureau.

For the postulated accident involving a fuel element contained within a fuel load/unload flask in which the forced convective air cooling system has completely failed, the model indicates that if the maximum fuel surface temperature is not to exceed 450°C at any time, the fission product decay power of the element must be below 1.86 kW.

In the case of a postulated LOCA which involves the loss of the total coolant inventory of the HIFAR core, before the single fuel element model could be used, further investigations were necessary to ascertain the influence of neighbouring fuel elements, since such fuel elements would also be experiencing a temperature transient. From data in the published literature, it was feasible to deduce appropriate boundary conditions for the single fuel element model to account for neighbouring fuel elements, and hence to determine a fuel element decay power below which the maximum fuel surface temperature would not exceed 450°C. This decay power is 1.1 kW.

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7. NOTATION

d   Diameter of heated rod

h   Heat transfer coefficient

Nu   Nusselt number

Ra   Rayleigh number

T   Temperature

Subscripts

a   ambient

d   rod

w   wall

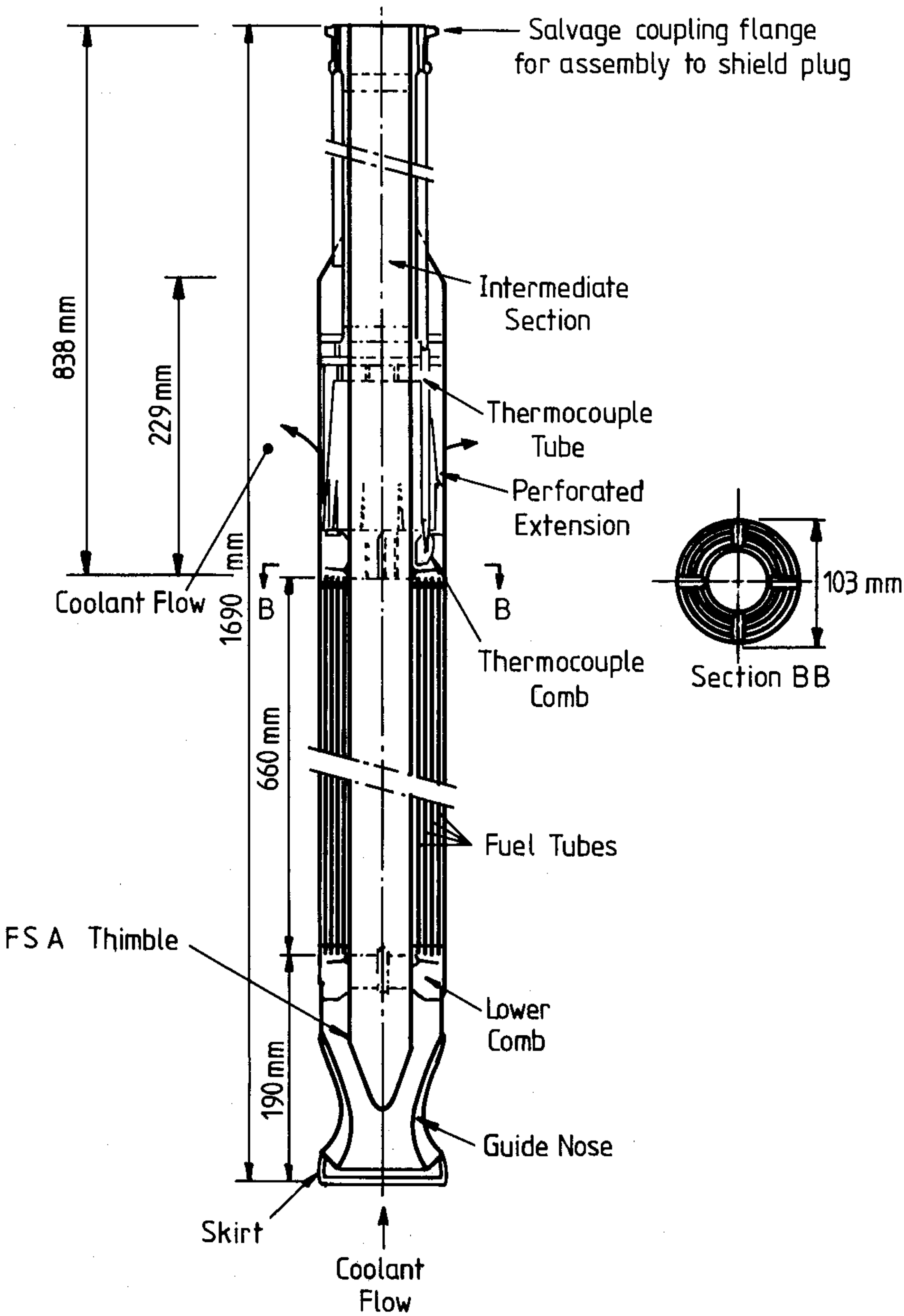

Figure 1 HIFAR fuel element
Mark IV/VA

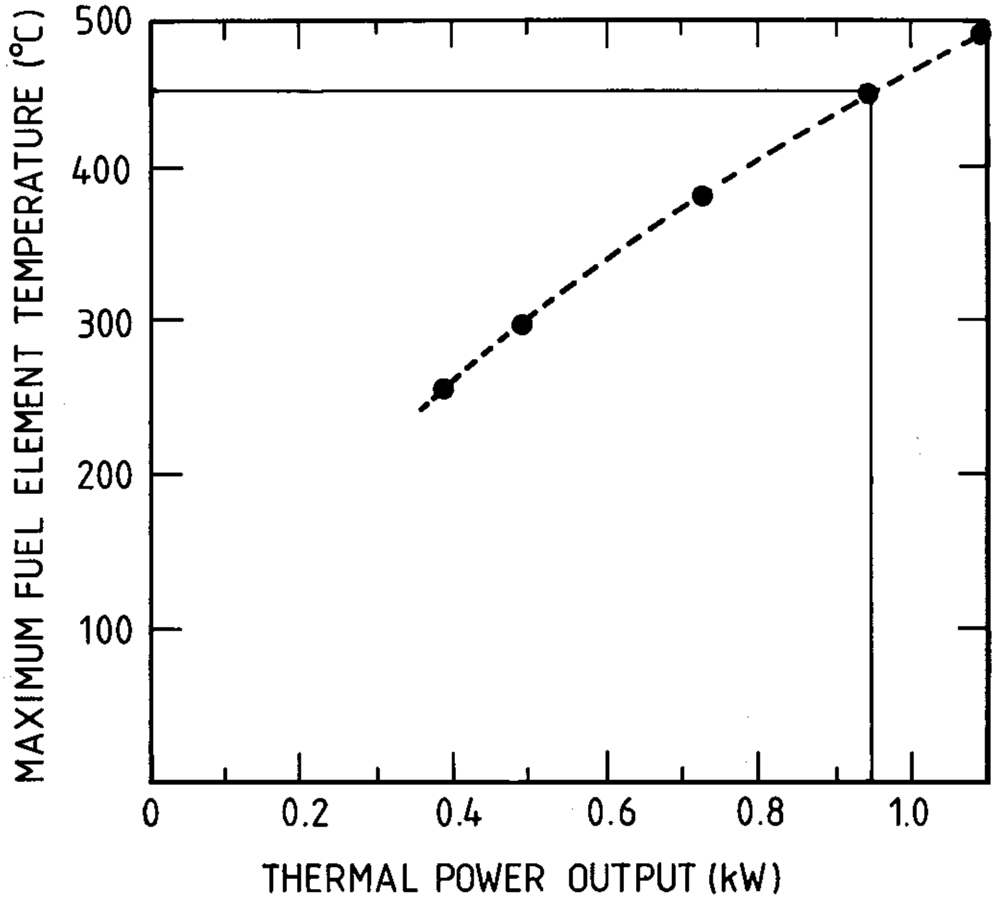

Figure 2 Relationship between maximum equilibrium temperature and thermal power output for a fuel element in a transport flask

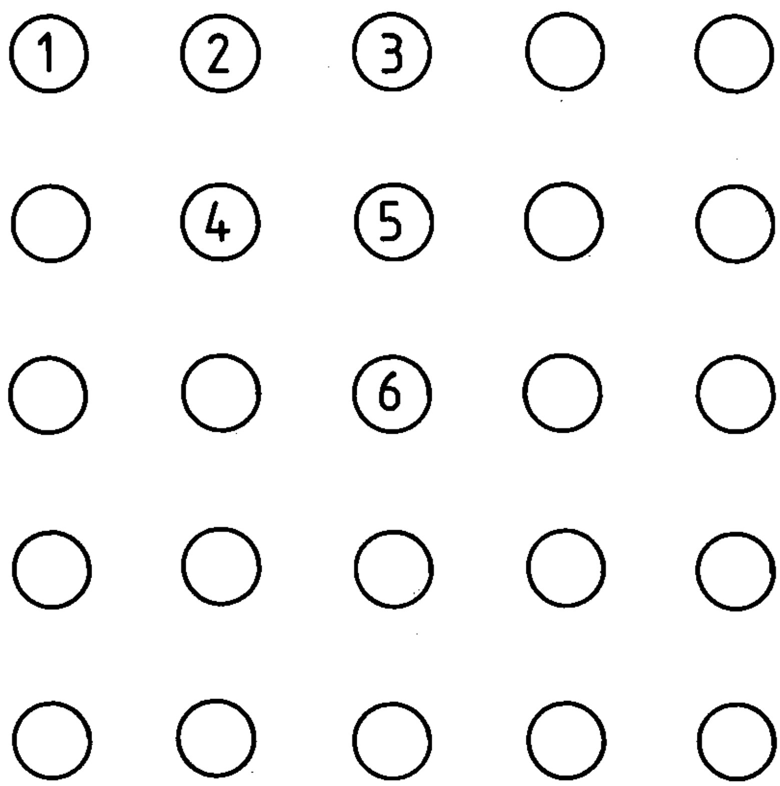

Figure 3 5 × 5 rod array and numbering system used by Keyhani and Kulacki

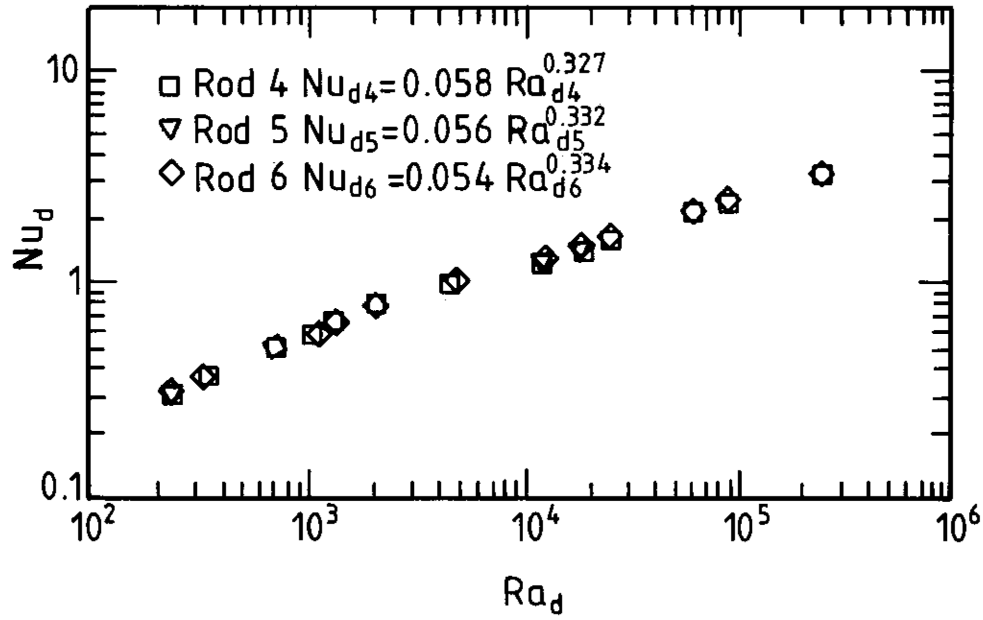

Figure 4 Convective Nusselt numbers for individual rods in 5 × 5 rod bundle

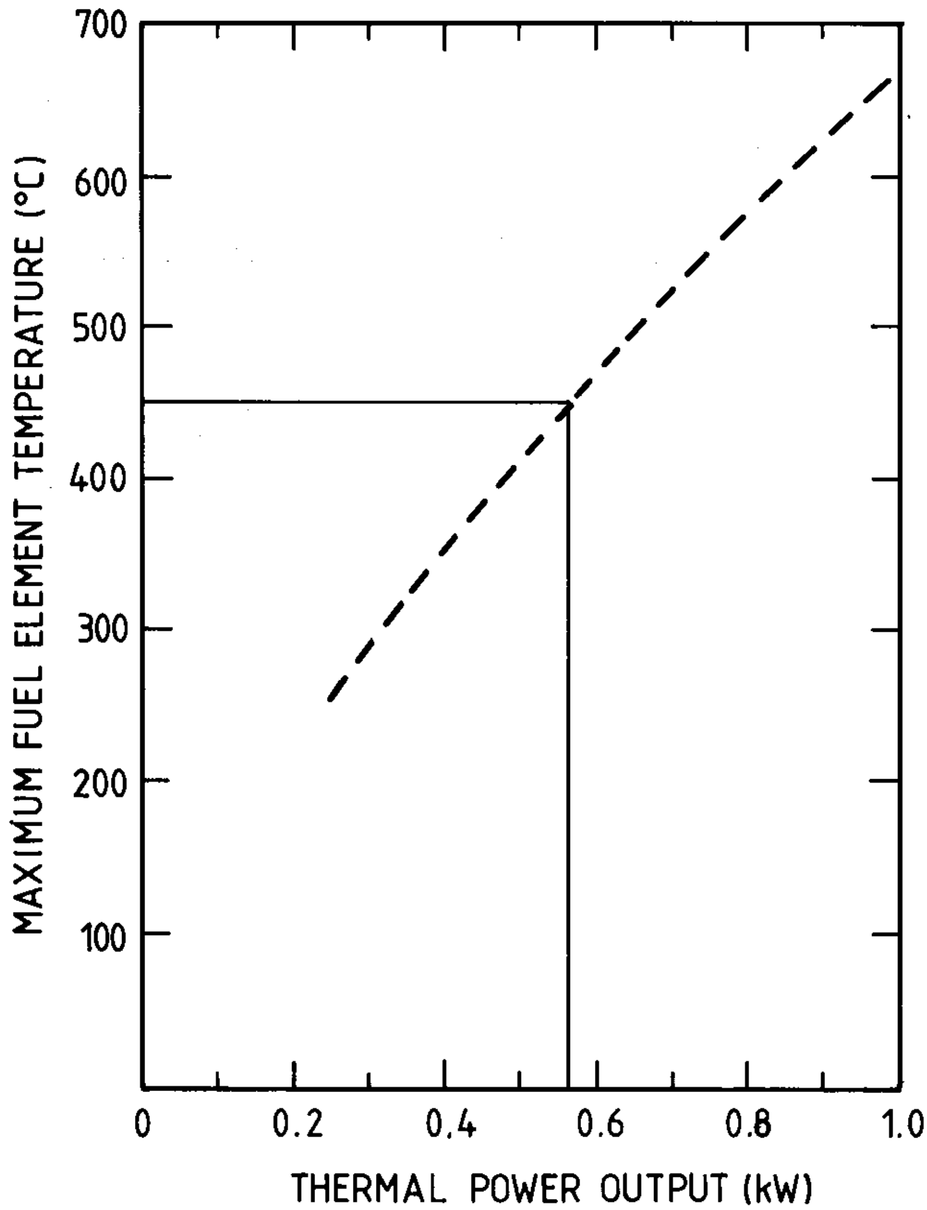

Figure 5 Relationship between maximum equilibrium fuel element temperature and thermal power output for a fuel element in a dry core

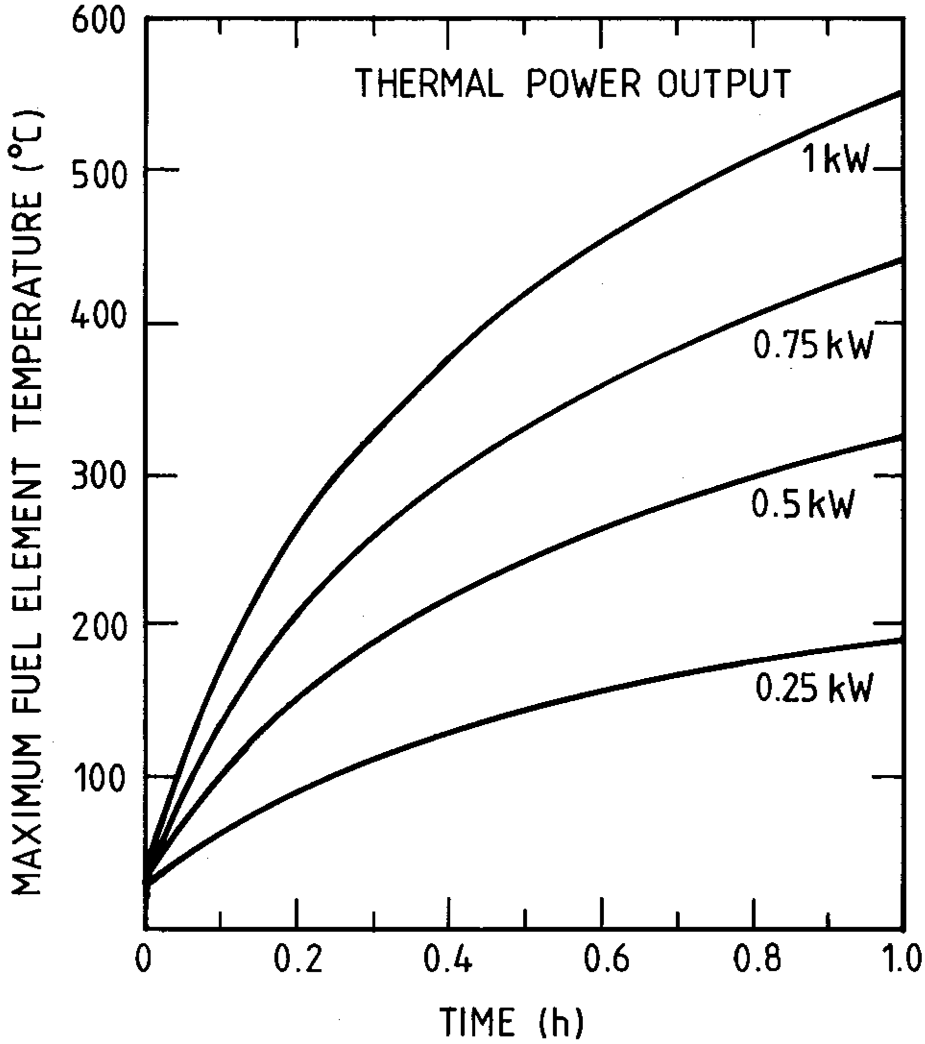

Figure 6 Transient response for various thermal power outputs of a fuel element in a dry core