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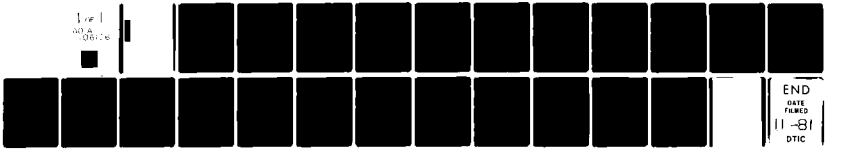

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(6) THE POSSIBLE USE OF CERMET FUEL IN THE DIDO AND PLUTO HEAVY-WATER RESEARCH REACTORS

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ABSTRACT

International restrictions on the supply of highly enriched uranium have resulted in the requirement to fuel research reactors with a lower-enrichment uranium fuel.

A study has been made of the feasibility of using low-enrichment fuels of a new type in the DIDO and PLUTO reactors. This work has been done as a contribution to the studies currently being carried out internationally on the implications of using lower-enrichment fuels in heavy-water-moderated research reactors.

The uranium content of the U/Al alloy at present used cannot be increased sufficiently to maintain the requisite U^{235}_{1} content without undesirable effects on the physical properties of the alloy. A different type of fuel will therefore be required to maintain the desired nuclear characteristics. A possible solution to the problem is the use of a cermet (U_3O_8/Al) fuel material.

This paper describes a preliminary study of the feasibility of this concept from the heat-transfer and safety viewpoints.

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1. Introduction

The DIDO/PLUTO fuel elements currently used are of two main types. Both consist of a central cylindrical aluminium thimble surrounded by a number of concentric cylindrical fuel plates and, on the outside, an aluminium cylinder. The layout of a Mk 5/7 fuel element is shown in Fig. 1. The inner (Al) tube/experiment thimble has a diameter of 5.08 cm, and is used for housing in-core experiments. The other type of element, known as the S2 fuel element, is similar, but has more fuel tubes and a 2.54 cm central thimble. This paper investigates the thermal problems involved in replacing the U/Al-alloy (75% w/w U^{235}) fuel plates with U/Al-cermet (20% w/w U^{235}) plates, having the same outside dimensions to retain the same hydraulic characteristics. The investigation is limited to the Mk 5/7 fuel-element configuration. Cermet fuel plates have already been used in the Puerto Rico Nuclear Centre pool reactor (PRNC), and assumptions on cermet composition are based on information given by Kucera et al[1] for this reactor, which is a 5 MW(th) pool reactor. The interface conductance between cermet and cladding is an unknown quantity, since this type of fuel plate has not been manufactured in production quantities in the U.K. Experimental measurements will be required if this fuel is to be used; a poor contact at the interface could lead to high temperature differences and possible melting of the aluminium in the cermet.

2. Fuel-Plate Dimensions

From Ref. (1), each PRNC fuel plate contains 10.67 g of U^{235}, and measures 23⅝ in. × 2½ in. × 0.024 in. Hence the volume of cermet is 1.4175 in^3 (23.229 cm^3). Each DIDO Mk 5/7 fuel element contains 205 g U^{235}. Thus, assuming that the DIDO cermet fuel will have the same composition as the PRNC fuel, the required volume of cermet is easily found:

$$V_c = 23.229 \times \frac{205}{10.67} = 446.2 \text{ cm}^3.$$

The fuel loading in the four plates of a Mk 5/7 element has been optimised by Hopper[2], and the resulting dimensions are given in Table 1 below.

TABLE 1

Dimensions of Mk 5/7 Fuel Tubes and U^{235} Loading

Tube	U^{235} (g)	r_i (cm)	r_o (cm)	$\bar{r}$ (cm)
Thimble	-	2.540	2.699	2.620
'A'	43.8	3.010	3.178	3.094
'B'	49.3	3.487	3.655	3.571
'C'	55.8	3.965	4.133	4.049
'D'	56.1	4.442	4.610	4.526
Outer	-	4.837	4.992	4.915

The fuel loading in Table 1 results in the inner fuel tube 'A' having the highest fuel density, so calculations will be restricted to this tube as the worst case. In fact, the variation in fuel density from 'A' to 'C' is very small (≈ 2½%), while tube 'D' requires ≈ 10% less fuel density.

The Mk 5/7 fuel is 'tapered' at top and bottom, so that the effective length is 18.5 in. (46.99 cm) instead of 24 in. (60.96 cm).

Let the thickness of the cermet fuel in the tube be t cm. For fuel tube 'A', $V_c = 23.229 \times \frac{43.8}{10.67} = 95.354\ cm^3$.

$$V_c = 2\pi \bar{r}_A\, lt, \text{ so } t = V_c/2\pi \bar{r}_A\, l = \frac{95.354}{2\pi \times 3.094 \times 46.99}$$

$$= 0.1044 \text{ cm.}$$

To retain the existing 'A'-tube dimensions, this would allow 0.0318 cm (0.0125 in.) for the Al cladding. For tubes 'B' and 'C' the difference is very small, while for tube 'D' the fuel-core thickness required reduces to 0.091 cm (0.036 in.), allowing 0.038 cm (0.015 in.) for the cladding. Table 2 shows the radial dimensions of the cermet fuel.

TABLE 2

Dimensions of Cermet in Fuel Tubes

Tube	r_1 (cm)	r_2 (cm)
'A'	3.042	3.146
'B'	3.520	3.622
'C'	3.998	4.100
'D'	4.480	4.572

r_1 is the inner radius and r_2 the outer radius of the cermet in each tube

3. Steady Conditions for the Highest-Rated Fuel Element at 1.3 × Nominal Power (1.63 MW)

Approximately 10% of the fission heat from a DIDO/PLUTO MTR fuel element is deposited outside the fuel tubes, so the heat generation in the fuel tubes is ≈ 1.5 MW for a total heat output of 1.63 MW[2]. Fig. 2 shows the heat-generation rate in fuel tube 'A' of a typical fuel element (D3 in DIDO) as a function of axial position. The maximum power density is seen to be 3020 W/cm^3. The fuel tubes are sufficiently thin that they may be treated as flat plates without significant loss of accuracy when calculating temperature distribution.

Temperature difference from fuel-centre plane to fuel/cladding interface

$$\Delta T_c = \frac{I(t/2)^2}{2k_c}, \qquad (1)$$

where t = fuel-plate thickness

k_c = cermet thermal conductivity (Fig. 3; Appendix 1) (36.6% v/v U_3O_8)

$t = 0.104$ cm, $k_c = 0.32$ W/cmK ;

$$\therefore \Delta T_c = \frac{3020 \times 0.052^2}{2 \times 0.32} = 12 \text{ K.}$$

3.1 Temperature Difference Across Fuel/Cladding Interface (ΔT_{int})

The interface conductance (h_{int}) has been calculated (Appendix 2) as 1.42 W/cm^{2}K.

$$A_s = 2\pi (r_1 + r_2) = 2\pi (3.042 + 3.146) = 38.88 \text{ cm}^2/\text{cm},$$

where A_s = interface surface area/unit length.

Maximum linear power rating,

$$Q_{max} = I_{max} (\pi (r_2^2 - r_1^2)) \qquad (2)$$

$$= 3020\pi (3.146^2 - 3.042^2) = 6105.8 \text{ W/cm}$$

$$\Delta T_{int} = \frac{Q_{max}}{A_s . h_{int}} = \frac{6105.8}{38.88 \times 1.42} = 110.6 \text{ K.}$$

3.2 Temperature Difference Across Cladding (ΔT_{cl})

$$\Delta T_{cl} = \frac{\phi . t_{cl}}{K_{cl}} \qquad (3)$$

$$\phi = \frac{Q}{A} = \frac{6106.0}{38.88} = 157.0 \text{ W/cm}^2 = 1.57 \text{ MW/m}^2$$

$$t_{cl} = 0.032 \text{ cm}$$

$$K_{cl} = 2.4 \text{ W/cm K.}$$

$$\therefore \Delta T_{cl} = \frac{157 \times 0.032}{2.4} = 2.1 \text{ K.}$$

3.3 Temperature Difference Across D_2O Coolant Film (ΔT_f)

From the subcooled boiling correlation of Thom[3]:

$$(T_w - T_{sat}) = 22.65\, \phi^{0.5} \exp(-P/87), \qquad (4)$$

where T_w = wall temperature (^oC)

T_{sat} = saturation temperature of fluid (104^oC)

ϕ = surface heat flux (1.57 MW/m^2)

P = fluid pressure (1.1 bar).

$$\therefore T_w = 104 + 22.65 \sqrt{1.57} . \exp(-0.01264) = 132.0^oC.$$

The D_2O temperature will be 50^oC at inlet and up to 74^oC at outlet, so equation (4) gives a max. heat-transfer coefficient (h_f) for the D_2O at 74^oC.

$$h_f = \phi/\Delta T_f = 1.57/(132-74) = 0.0271 \text{ MW/m}^2\text{K} = 2.71 \text{ W/cm}^2\text{K.}$$

As this coefficient is of the same order as a single-phase coefficient to D_2O at high mass flux, the latter will be calculated from the Dittus-Boelter correlation:

$$(Nu) = 0.023\, (Re)^{0.8} (Pr)^{0.4} \qquad (5)$$

Total flow through fuel element, $\dot{m}_T$ = 17,300 g/s

D_2O flow area, $A_T = \pi[(13.01^2 - 2.699^2) + (3.487^2 - 3.178^2) + (3.965^2 - 3.655^2)$
$+ (4.442^2 - 4.133^2) + (4.837^2 - 4.61^2)]$
$= 34.53\ cm^2$

Mass flux, $G_T = \dot{m}_T/A_T = 17,300/34.53 = 501.0\ g/cm^2\ s$

$$(Re) = \frac{G_T.d_e}{\mu}\ ;\ d_e = \frac{4A_T}{s} = \frac{4 \times 34.53}{2\pi(\Sigma(r_i+r_o))} = 0.5782\ cm$$

$\mu = 5.5 \times 10^{-3}$ g/cm s (viscosity of D_2O at 60°C)

k = 0.0063 W/cm K (thermal conductivity of D_2O at 60°C)

$$\therefore (Re) = \frac{501 \times 0.5782}{5.5 \times 10^{-3}} = 52,669$$

$$(Pr) = 3.6; \quad \therefore (Nu) = 0.023 \times 52,669^{0.8} \times 3.6^{0.4} = 229.9$$

$$h'_f = \frac{(Nu).k}{d_e} = \frac{229.9 \times 0.0063}{0.5782} = 2.505\ W/cm^2K.$$

The boiling coefficient (Thom), h_f = 2.71 W/cm^2K, is slightly higher than the single-phase coefficient for D_2O at the maximum temperature of 74°C, and the maximum wall temperature of 132°C is therefore selected.

3.4 Overall Temperature Difference, Fuel Centre to D_2O (ΔT_T)

$$\Delta T_T = \Delta T_c + \Delta T_{int} + \Delta T_{cl} + \Delta T_f = 12.0 + 110.6 + 2.1 + 58.0 = 182.7\ K$$

Max. fuel-centre temp., $\hat{T}_{UO} = T_f + \Delta T_T = 74 + 182.7 = 256.7°C.$

3.5 Fuel Mean Temperature (at max. fuel-temp. level)

$$\bar{T}_{UO} = \frac{\int_0^{t/2} \left(\hat{T}_{UO} - \frac{Ix^2}{2k_{UO}}\right) . dx}{t/2} = \hat{T}_{UO} - \frac{I.(t/2)^2}{6k_{UO}}$$

$$= 256.7 - (3020 \times 0.052^2)/(6 \times 0.34) = 252.7°C.$$

4. Effect of 25 MJ Transient in Whole Reactor Core

4.1

In this transient, which is required to be withstood by the Harwell MTRs, it is assumed that 25 MJ of heat is added to the fuel plates instantaneously, i.e. with no heat transfer to the coolant. The initial conditions are for normal full-power operation. Thus, the conditions may be taken from the previous section for the inner fuel tube 'A' of a fuel element operating at 1.63 MW (1.3 × nominal full power

in the highest-rated fuel element). A 25 MJ whole-core transient would add 1.2 MJ to the highest-rated fuel element and (from the power distribution with the element given by Hopper[2]) 247.4 kJ to fuel tube 'A'.

Fuel Tube 'A'

Volume of cermet, V_c = 95.354 cm^3

Mass of U^{235} = 43.8 g (Hopper[2])

Mass of U^{238} = 43.8 × 4 = 175.2 g

Total mass of U = 43.8 + 175.2 = 219.0 g

Total mass of U_3O_8 = 219 × (3 × 237.4 + 8 × 16)/(3 × 237.4)

= 258.4 g

Total mass of U_3O_8/Al cermet (64% w/w U_3O_8) = 403.7 g

Density of cermet, ρ_c = 403.7/95.35 = 4.23 g/cm^3

Specific heat of U_3O_8, $C_{p_{UO}}$ = 0.316 J/g K

Mass of Al in cermet, m_{Al} = 403.7 - 258.4 = 145.3 g

Specific heat of Al, $C_{p_{Al}}$ = 0.985 J/g K

Heat capacity of cermet, $(mC_p)_c = (mC_p)_{UO} + (mC_p)_{Al}$ = 224.8 J/K

Volume of tube 'A', $V_T = \pi(3.178^2 - 3.01^2) \times 60.96$ = 199.09 cm^3

Volume of Al cladding, $V_{cl} = V_T - V_c$ = 199.09 - 95.35 = 103.74 cm^3

Density of Al cladding, ρ_{Al} = 2.71 g/cm^3

Mass of Al cladding, $m_{cl} = \rho_{Al} V_{cl}$ = 103.74 × 2.71 = 281.1 g

Heat capacity of Al cladding, $(mC_p)_{cl} = m_{cl}C_{p_{Al}}$ = 276.9 J/K

Heat capacity of fuel tube, $(mC_p)_T = (mC_p)_c + (mC_p)_{cl}$ = 501.7 J/K.

Assume that heat is uniformly distributed through the plate and cladding:

$$\text{Temperature rise, } \Delta T = Q/(mC_p)_T = \frac{247.4 \times 10^3}{501.7} = 493.0 \text{ K.}$$

However, 10% of the fission heat is deposited outside the fuel plates, reducing the temperature rise to 0.9 × 493.0 = 443.7 K.

The maximum fuel temperature at the start of the transient was previously calculated as 256.7°C, and the mean fuel temperature at the maximum-temperature axial level was calculated as 252.7°C. Thus the maximum fuel temperature after the transient is calculated to be (256.7 + 443.7) = 700.4°C. However, this is 40°C above the melting point of Al (660.1°C), so the Al would reach 660.1°C and start to melt.

Latent heat of fusion of Al, λ_{Al} = 401.3 J/g

Heat to melt Al in cermet, $Q_{fus} = m_{Al} \lambda_{Al}$ = 145.3 × 401.3 = 5.83 × 10^4 J

Heat available to melt Al (Q_{avl}) is found from the apparent temperature excess

above the melting point multiplied by the heat capacity of the cermet.

$$Q_{avl} = (700.4 - 660.1) \times 224.8 = 9059 \text{ J}$$

$$\text{Proportion of Al in cermet melted} = \frac{Q_{avl}}{Q_{fus}} = \frac{9059}{58310} = 0.155.$$

Thus, on the assumption of an instantaneous 25 MJ transient in the core, with all the extra heat uniformly distributed in the fuel tubes (both cermet and cladding), 15.5% of the aluminium in the fuel would melt. While this limited melting of the aluminium in the cermet would not constitute any safety hazard, the model on which it is based is unrealistic though generally pessimistic.

4.2

A more realistic transient calculation takes account of heat transfer to the coolant during a ramped power increase, and of the distribution of heat within the fuel tube. To investigate this, a two-dimensional (r-z geometry) model of a fuel element was set up, using the finite-difference transient heat-transfer code, 2DT[7].

The model used is shown in Fig. 4. It consists of six concentric annular tubes, the innermost and outermost tubes being of aluminium and the remainder being fuel tubes (Al/cermet/Al sandwich) . D_2O coolant flows upwards between the tubes. Heat transfer from the outside boundaries of the model is ignored; it will have a negligible effect, and any error in the model from this cause must be pessimistic. Steady conditions were computed for the model with 1.5 MW total heat generation from the fuel tubes and 17.3 kg/s total D_2O-coolant flow. The distribution of power among the fuel tubes[2] was 309.2 kW from 'A', 348.2 kW from 'B', 406.7 kW from 'C', and 436.0 kW from 'D'. The flow distribution up the coolant channels was taken from Lorenz[8]. The axial distribution of power in the fuel element is taken from a typical axial thermal-neutron flux profile in DIDO D3 fuel-element position[10] - as shown in Fig. 2.

The maximum fuel temperature (nominal steady state) in the inner fuel tube 'A' was computed to be 247°C at 3 cm above the core-centre plane. Corresponding cladding and D_2O temperatures were 129°C and 65°C (in the coolant channel on the outer side of the inner fuel tube 'A'). The model steady-state temperature distribution was then used for initial conditions for a one-second transient in which the power was increased exponentially so that an additional 1.2 MJ of heat was generated in the whole element, this corresponding to an additional 25 MJ in the whole core and to 247.4 kJ in the inner fuel tube 'A'. The computer program accepts heat-generation rates in the form:

$I(r,z) = I_o(r,z)e^{m\tau}$, where $I_o(r,z)$ is the heat-generation rate at position (r,z) at time $\tau = 0$.

Assume that the heat-generation rates of all regions increase at the same rate. To find the value of m to give the required total heat production, Q_T, over the 1s transient,

$$Q_T = \int_{\tau=0}^{1} W \, d\tau = W_o \int_{o}^{1} e^{m\tau} \, d\tau = W_o \frac{1}{m} \left[e^{m\tau} \right]_o^1 ,$$

where W is the total power produced by the fuel element. (I(r,z) will vary with time in the same way as W.) In this case, W_o = 1.5 MW, Q_T = (1.5 + 1.2) = 2.7 MJ (τ = 1.0 s).

$$2.7 = \frac{1.5}{m} [e^m - 1]; \quad 2.7m = 1.5 [e^m - 1]; \quad e^m = 1.8 m + 1;$$

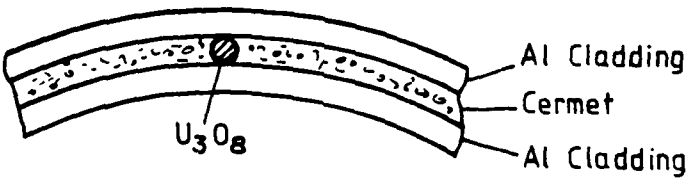
$$m = 1.045868. \quad \therefore I(r,z) = I_o(r,z) \exp(1.045868 \tau).$$

This transient has a doubling time of 0.663 s, giving a power of 4.27 MW from the fuel element at the end of the one second. Fig. 5 shows the transient power increase and the consequent response of the highest fuel temperature in fuel tube 'A'. This is seen to reach 527°C at the end of the transient, which is 133°C below the melting point of aluminium. A doubling time of 0.663 s would be caused by a step addition of 0.6% δk/k. During the one-second transient postulated above, D_2O mean temperature would increase by 15°C, which, from the negative coefficient of reactivity, would give -0.6% δk/k; thus, to sustain the transient, an additional 0.6% δk/k would have to be added over the one-second transient. The model assumed single-phase liquid heat-transfer coefficients to the D_2O of 2.3 to 2.45 W/cm^{2}K throughout the transient. In fact, the coefficients would increase at first as subcooled nucleate boiling increased (with increasing power), but might reduce drastically after about 0.5 s as the burn-out heat flux was exceeded. No bulk boiling would occur, and the short time and changing conditions would probably exclude film burn-out. This transient could not occur with the safety and control systems operated with the Harwell MTRs.

The maximum credible addition of reactivity to the Harwell MTRs is taken to be 1.2% δk/k at a maximum rate of 0.75% δk/k, controlled by the vertical control rods to give the power transient shown in Fig. 6 (worst case). The resulting maximum fuel-table-'A' temperature is also shown. The fuel temperature peaks at 283°C, a rise of only 36°C, insufficient to give any safety problems.

5. Heat Transfer Within U_3O_8 Particles

The accompanying sketch shows the maximum-sized U_3O_8 particle which can be accommodated in the fuel plate. This is assumed to be a sphere having a diameter of 0.104 cm (i.e. the full width of the fuel plate.



Volume of sphere, $V_{UO} = \frac{4}{3}\pi r^3 = 5.89 \times 10^{-4}$ cm^3

Density of U_3O_8, $\rho_{UO} = 8.34$ g/cm^3

Mass of U_3O_8 sphere, $m_{UO} = (V.\rho)_{UO} = 4.91 \times 10^{-3}$ g

U_3O_8 contains 84.8% w/w U, so mass of U in sphere, $m_U = 0.848 \times 4.91 \times 10^{-3}$

$= 4.16 \times 10^{-3}$ g

U contains 20% w/w U^{235}, so mass of U^{235} in sphere, $m_{235} = 0.20 \times 4.16 \times 10^{-3}$

$= 8.33 \times 10^{-4}$ g

Mass of U^{235} in fuel tube 'A' is 43.8 g

Power produced in fuel tube 'A' is 309.2 kW

Power produced from sphere at mean tube-'A' rating is

$$309.2 \times 10^3 \times 8.33 \times 10^{-4}/43.8 = 5.88 \text{ W}$$

Max./mean axial rating is 1.20

Power from sphere at max. tube-'A' rating $= 5.88 \times 1.20 = 7.08$ W

Heat-generation rate in sphere, $I_{UO} = \frac{7.08}{5.89 \times 10^{-4}} = 1.20 \times 10^4$ W/cm^3

Temperature difference from centre to surface of sphere,

$$\Delta T_{UO} = \frac{I_{UO} \cdot r^2}{6k_{UO}} = \frac{(1.20 \times 10^4) \times 0.052^2}{6 \times 0.018} = 300.4 \text{ K.}$$

The local heat flux through the cladding to the D_2O from the U_3O_8 sphere will be higher than the average flux. Assuming half the heat passes radially inwards and half radially outwards, the flux, $\phi_{max} = (7.08/2)/(\pi \times 0.052^2) = 416.7$ W/cm^2.

Temperature difference across fuel/cladding interface,

$$\Delta T_{int} = \phi/h_{int} = \frac{416.7}{1.42} = 293.5 \text{ K}$$

Temperature difference across cladding

$$\Delta T_{cl} = \phi\, t_{cl}/k_{cl} = \frac{416.7 \times 0.032}{2.4} = 5.6 \text{ K}$$

Temperature difference across D_2O film (Thom[3]),

$$(T_w - T_{sat}) = 22.65\, \phi^{0.5} \exp(-P/87)$$

$$= 22.65 \times \sqrt{4.167} \exp(-0.01264) = 45.7 \text{ K}$$

$T_{sat} = 104^oC$; $\therefore T_w = 149.7^oC$

Max. U_3O_8 temperature, $\hat{T}_{UO} = T_w + \Delta T_{cl} + \Delta T_{int} + \Delta T_{UO}$

$= 149.7 + 5.6 + 293.5 + 300.4 = \underline{749.2^oC}$.

Such a particle size (1040 μm) is much larger than the upper limit (149 μm) of the range of particle sizes reported by Kucera et al[1]. Although this large size does not lead to unacceptable temperatures, a more likely maximum size is 200 μm (≡ 0.02 cm).

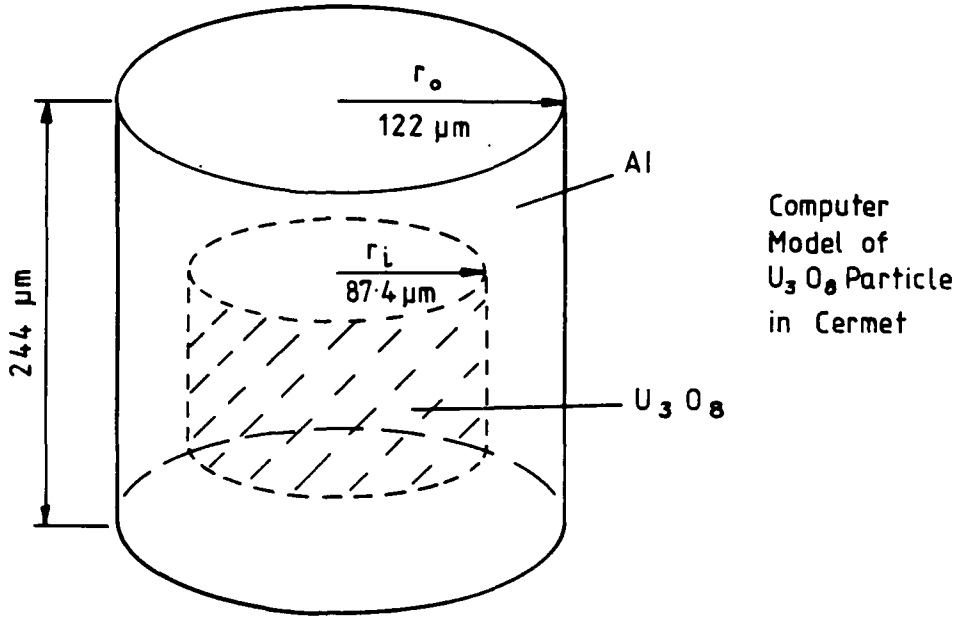
This leads to:

$$\Delta T_{UO} = \frac{1.20 \times 10^{4} \times 0.01^{2}}{6 \times 0.018} = 11.1 \text{ K.}$$

Such a particle would not significantly perturb the average heat flux from the cermet, so the maximum U_3O_8 temperature may be calculated from the maximum cermet temperature, T_c, computed (Section 3).

$$T_{UO} = \hat{T}_c + \Delta T_{UO} = 247 + 11 = 258^{\circ}C.$$

To assess the effect of the maximum transient power excursion, illustrated in Fig. 6, on a U_3O_8 particle of the size of a 200 μm diameter sphere, a simple model was set up, consisting of a right cylinder of U_3O_8 (174.8 μm diameter) surrounded by a hollow right cylinder of aluminium (244 μm diameter). The model therefore contained the same proportion of U_3O_8 (36.6% v/v) to aluminium (63.4%) as the cermet. The U_3O_8 cylinder was of the same volume (4.19×10^{-6} cm^3) as a 200 μm diameter sphere. The model was set up with an all-round boundary temperature of 247°C, representing the general cermet temperature computed in Section 3. The U_3O_8 was assigned a heat-generation rate of 12,000 W/cm^3, corresponding to a fuel-element power of 1.5 MW.



This model was then run to steady state, which showed a maximum U_3O_8 temperature of 258°C. From this initial condition, a transient of the form shown in Fig. 6 was applied to the model; the temperature history at the centre of the U_3O_8 particle is also shown

in Fig. 6. The resulting maximum U_3O_8 temperature was 297°C at 0.37 s after the start of the transient. The exponential transient ($I = I_o \exp(1.045868\ \tau)$) was also applied to the model for one second, with the results shown in Fig. 5. The maximum U_3O_8 temperature was then 582°C at the end of the one-second transient.

6. Conclusions

Provided that good bonding can be obtained between the cermet and the aluminium cladding, there appear to be no problems from a heat-transfer viewpoint to the use of U_3O_8/Al-cermet fuel. Where information has been lacking, pessimistic assumptions have been made in the calculations, which nevertheless lead to maximum cermet temperatures below any which should cause problems. Experimental measurements of thermal conductivity should be made when the cermet is selected. Local temperatures in the U_3O_8 particles within the cermet have been predicted, and present no problems in normal operation, nor for the maximum credible transient power excursion for the Harwell MTRs.

APPENDIX 1

Thermal Conductivity of U_3O_8-Al Cermet

Fig. 3 from Ref. (4) shows the thermal conductivities of U_3O_8-Al dispersions at ambient temperature (20^oC).

The cermet considered has 64% w/w U_3O_8 and 36% Al. Density of U_3O_8 is 8.34 g/cm^3 and that of Al 2.71 g/cm^3.

$$\frac{\rho_{Al} \cdot V_{Al}}{\rho_{UO} \cdot V_{UO}} = \frac{36}{64} = \frac{2.71\ V_{Al}}{8.34\ V_{UO}}$$

$$\therefore \quad V_{Al} = 1.731\ V_{UO}.$$

The cermet has 63.4% v/v Al and 36.6% U_3O_8.

Touloukian[5] gives thermal conductivities for a number of UO_2-metal cermets; three of these are shown in Table A1.1 below, together with the conductivities of UO_2 and the component metals. These cermets contain higher proportions of uranium oxide than the U_3O_8-Al cermet considered here. However, in each case the thermal conductivity increases with rising temperature, although the UO_2 conductivity on its own reduces, as do the conductivities of two of the component metals. U_3O_8 conductivity is low at ambient temperature, and would not be expected to vary significantly with temperature. Al conductivity falls fairly slowly from 120^oC to 650^oC. On this evidence, it seems likely that the conductivity of the Al-U_3O_8 cermet would increase with temperature, so an assumption of conductivity invariant with temperature is probably pessimistic.

TABLE A1.1

Material	k_1 (W/cm K)	T_1 (^oC)	k_2 (W/cm K)	T_2 (^oC)
UO_2	0.0774	50	0.0304	900
Mb	1.371	50	1.147	650
UO_2-Mb cermet (70% v/v UO_2)	0.201 (0.183)*	50	0.204 (0.104)*	650
St.Steel	0.148	50	0.269	900
UO_2-St.St. cermet (70% v/v UO_2)	0.079 (0.094)*	50	0.142 (0.058)*	900
Cr	0.980	50	0.714	900
UO_2-Cr cermet (80% v/v UO_2)	0.146 (0.129)*	50	0.205 (0.057)*	900
U_3O_8	0.018	20	0.018?	600
Al	2.36	20	2.13	600
U_3O_8-Al cermet (37% v/v U_3O_8)	0.34 (0.388)*	20	0.34 (0.364)*	600

* Values in brackets are from equation (A1.1).

k_{UO_2} is calculated from $k_{UO_2} = 1/(11.75 + 0.0235T)$, where k is the thermal conductivity in W/cmK and T is the temperature in ^oC from Ref. (6).

A simple method of estimating cermet conductivity from its component materials is to take a logarithmic mean value:

$$\ln k_c = \alpha \ln k_a + \beta \ln k_b \,, \qquad \text{(A1.1)}$$

where subscripts a, b and c refer to the metal, the oxide and the cermet respectively and α and β are the volume fractions of metal and oxide respectively; *e.g.* for the UO_2-Mb cermets at 50°C

$$\ln k_c = 0.3 \ln (1.371) + 0.7 \ln (0.0774) = -1.6965$$

$$\therefore \quad k_c = 0.183 \text{ W/cm K} \,.$$

This value is close (-9%) to the value of 0.201 W/cm K from Ref. (5). Using this method for the UO_2-Mb cermet at 650°C gives k_c = 0.104 W/cm K. Thus, while the method provides a good estimate of cermet thermal conductivity at low temperature, it underestimates the measured value by $\approx$ 50% at the higher temperatures. A similar, but even more pronounced effect occurs with the other two cermets. The values calculated from equation (A1.1) are given in brackets below the values from Ref. (5).

APPENDIX 2

Interface Conductance, U_3O_8-Al Cermet to Al

The conditions at this interface are not known, but because of the very high heat flux through it, contact must be good to prevent melting of the aluminium in the cermet. Main[9] gives methods of calculating interface conductance. The starting point is to assume three separate conductance paths in parallel:

$$h_T = h_f + h_s + h_r , \qquad (A2.1)$$

where subscripts T, f, s and r refer to total, fluid, solid and radiation respectively; h is the conductance (or heat-transfer coefficient in the case of h_T). In this case, h_r may be ignored, since any temperature above 600°C at the interface will result in melting of the aluminium.

(a) Fluid Conductance, h_f

$$h_f = \frac{k_f}{d} , \qquad (A2.2)$$

where k_f is fluid conductivity, k_f (air) = 0.0004 W/cm K, and d is the effective gap thickness.

$$d = C(R_1 + R_2) + g_1 + g_2 , \qquad (A2.3)$$

where R_1, R_2 are surface roughnesses, C is the roughness-height factor (C = 1.5 for heavy contact), and g_1 and g_2 are temperature-jump distances.

Here assume $R_1 = R_2 = 25 \times 10^{-6}$ cm.

From Ref. (9),

$$g_1 = g_2 = \frac{(2 - \alpha)P_a}{\alpha P} Z , \qquad (A2.4)$$

and $Z \approx 3 \times 10^{-5}$ cm, $\alpha \approx 0.45$, $P = P_a = 1$ bar.

$$g_1 = g_2 = \frac{1.55 \times 3 \times 10^{-5}}{0.45} = 1.03 \times 10^{-4} \text{ cm}$$

$$d = 1.5 (2.5 \times 10^{-6} + 2.5 \times 10^{-5}) + 2 (1.03 \times 10^{-4})$$

$$= 2.81 \times 10^{-4} \text{ cm}$$

$$h_f = \frac{k_f}{d} = \frac{4 \times 10^{-4}}{2.81 \times 10^{-4}} = 1.42 \text{ W/cm}^2 \text{ K} .$$

(b) Solid Conductance h_s

This is very difficult to quantify, and since the value of h_f found above is adequate to prevent an excessive ΔT across the interface no attempt will be made to do so. For the U-Al-alloy fuel, the assumption is normally made that contact is complete, and hence $h_s = \infty$; in this case, the pessimistic assumption of no solid contact is made, so that $h_s = 0$.

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Nomenclature

A_s	-	Surface area
A_T	-	Total flow area through fuel element
C	-	Roughness height factor
C_p	-	Specific heat
d	-	Effective gap thickness
d_e	-	Equivalent diameter of coolant channels
g	-	Temperature-jump distance
G	-	Mass flux of coolant
h	-	Heat-transfer coefficient
I	-	Heat-generation rate
k	-	Thermal conductivity
l	-	Fuelled length
m	-	Mass
P	-	Pressure
Q	-	Heat
r	-	Radius
R	-	Roughness height of surface
S	-	Wetted perimeter
t	-	Thickness
T	-	Temperature
V	-	Volume
W	-	Power from fuel element
Z	-	Temperature-jump parameter

Greek

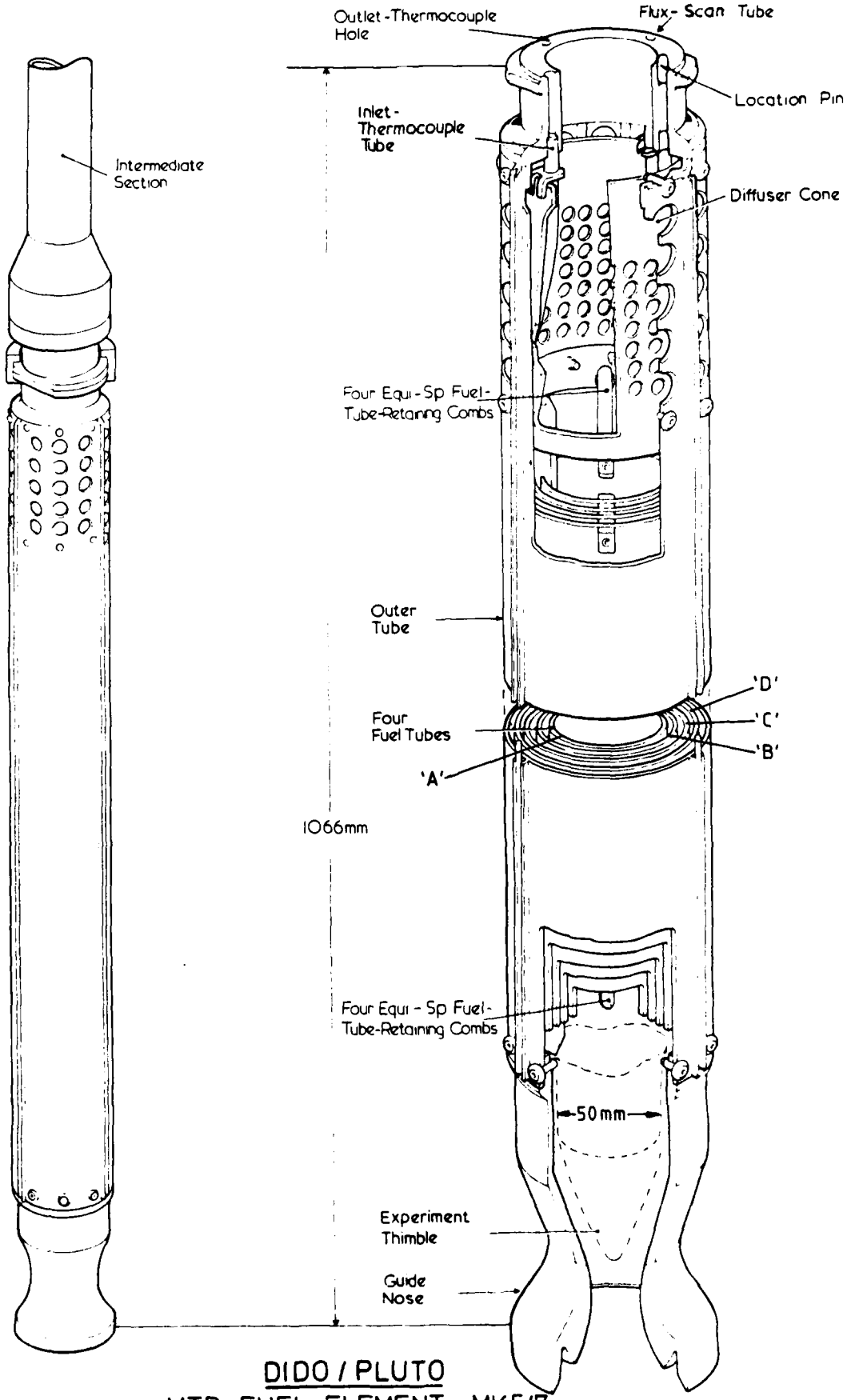
α	-	Accommodation coefficient
ΔT	-	Temperature difference
λ	-	Latent heat of fusion
μ	-	Dynamic viscosity
ϕ	-	Heat flux
τ	-	Time

Dimensionless Groups

(Nu)	-	Nusselt No. ($= hd_e/k$)
(Pr)	-	Prandtl No. ($= C_p.\mu/k$)
(Re)	-	Reynolds No. ($= G.d_e/\mu$)

Subscripts

Al	-	Aluminium	int	-	Interface
avl	-	Total available	max	-	Maximum
c	-	Cermet	o	-	Outer
cl	-	Cladding	s	-	Surface
e	-	Equivalent	sat	-	Saturation
f	-	Fluid or film	T	-	Total
fus	-	Available for fusion	UO	-	UO_3O_8
i	-	Inner	W	-	Wall



DIDO / PLUTO
MTR FUEL ELEMENT - MK5/7
FIG. 1

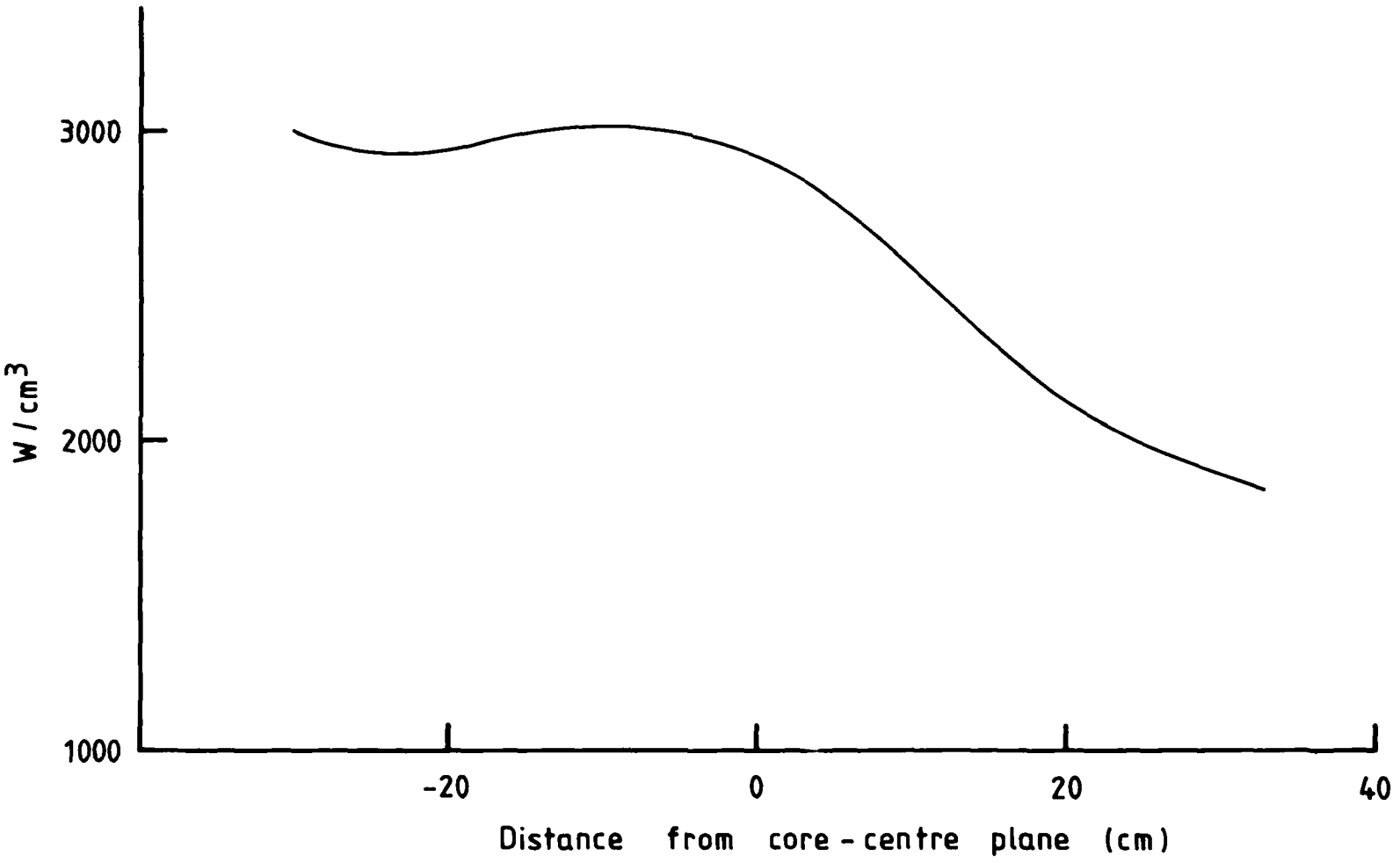


FIG.2 POWER DENSITY IN FUEL TUBE 'A' FOR 1·5MW FROM F.E.

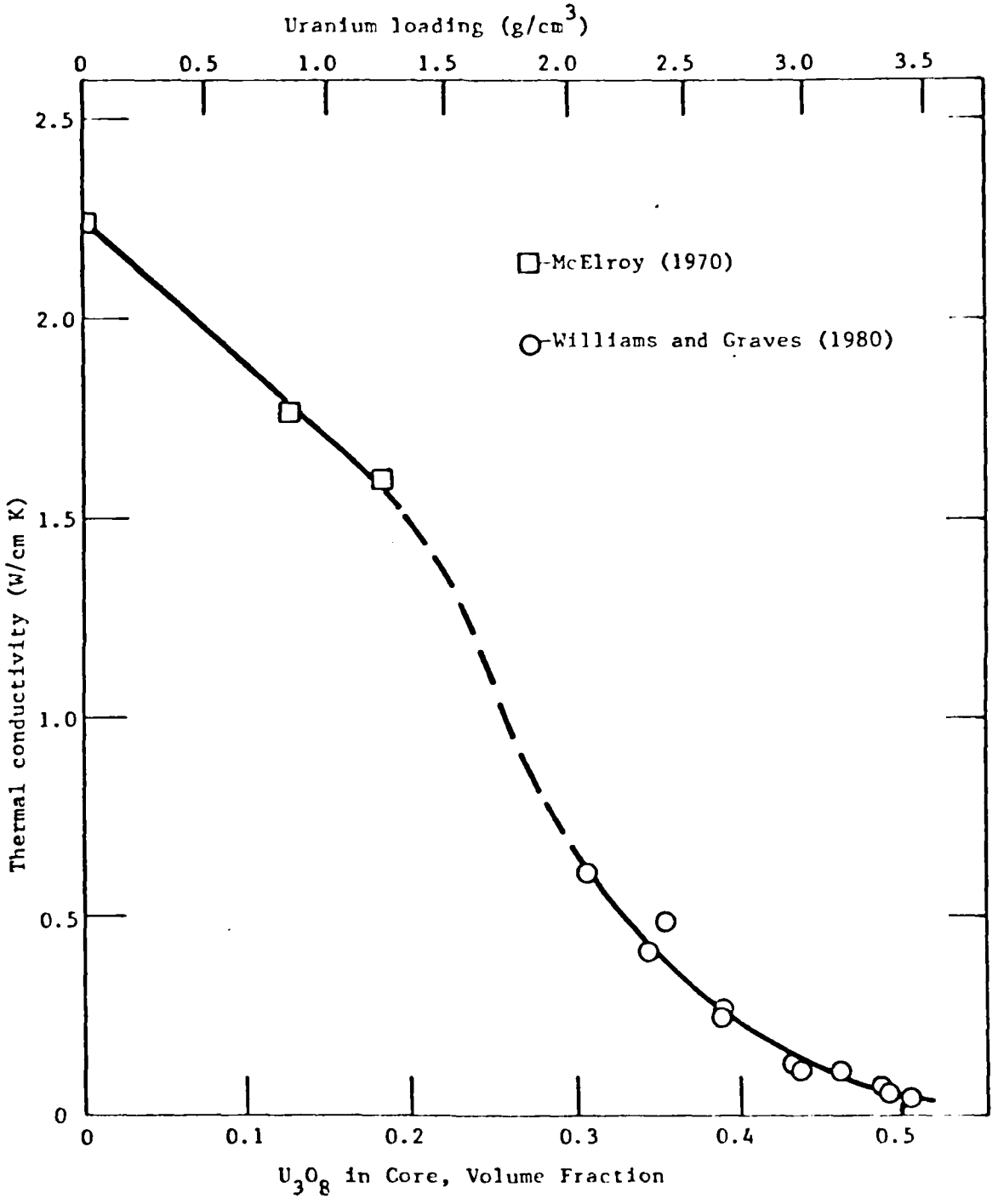
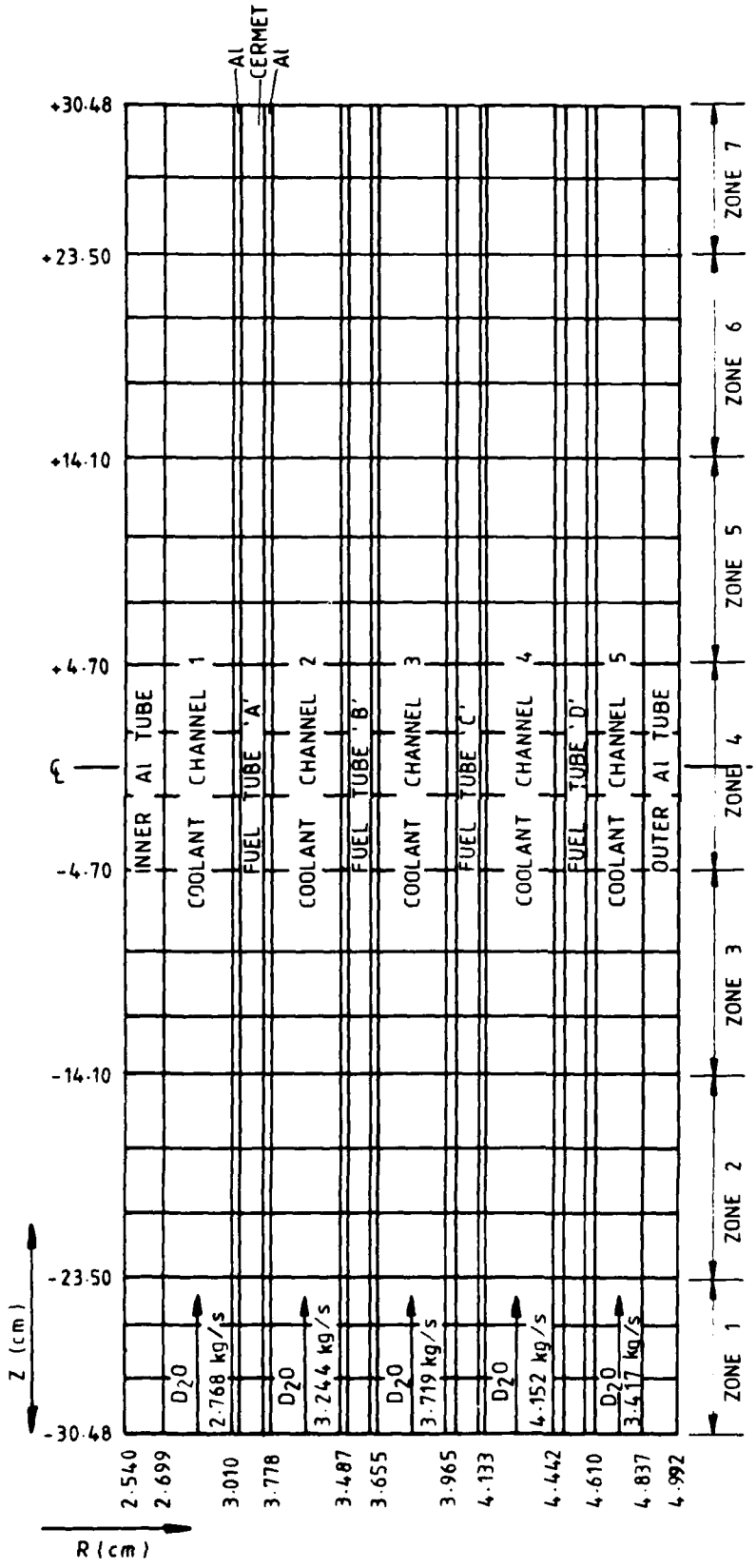


Fig. 3 Thermal Conductivity of U_3O_8-Al Dispersions



HEAT - GENERATION RATES IN FUEL TUBES (kW) STEADY CONDITIONS

ZONE	'A'	'B'	'C'	'D'
1	30·7	34·6	40·3	43·5
2	52·9	59·6	69·6	74·5
3	55·8	63·0	73·4	78·7
4	55·6	62·5	73·0	78·2
5	50·1	56·4	65·8	70 5
6	41·2	46·4	54·2	58·6
7	21·6	24·4	28·4	30·4
TOTAL	307·9	346·9	404·7	434·4

FISSILE HEAT - 1493·9 kW

GAMMA HEAT (Al) - 6·1 kW

TOTAL HEAT - 1500 kW

COOLANT CONDITIONS (STEADY STATE , 1500 kW)

No.	FLOW (kg/s)	H.T.Coeff (W/cm²K)	T_{IN} (°C)	T_{OUT}* (°C)
1.	2·768	2·30	50	63·4
2	3·244	2·34	50	74·0
3	3·719	2·38	50	74·2
4	4·152	2·42	50	74·1
5	3·417	2·45	50	65·9

*THE D_2O - COOLANT OUTLET TEMPERATURES (T_{OUT}) ARE COMPUTED BY THE PROGRAM FOR THE CONDITIONS OBTAINING . OTHER PARAMETERS ARE INPUT INFORMATION .

EXTERNAL BOUNDARIES ARE ALL ADIABATIC .

FIG . 4 COMPUTER MODEL OF FUEL ELEMENT

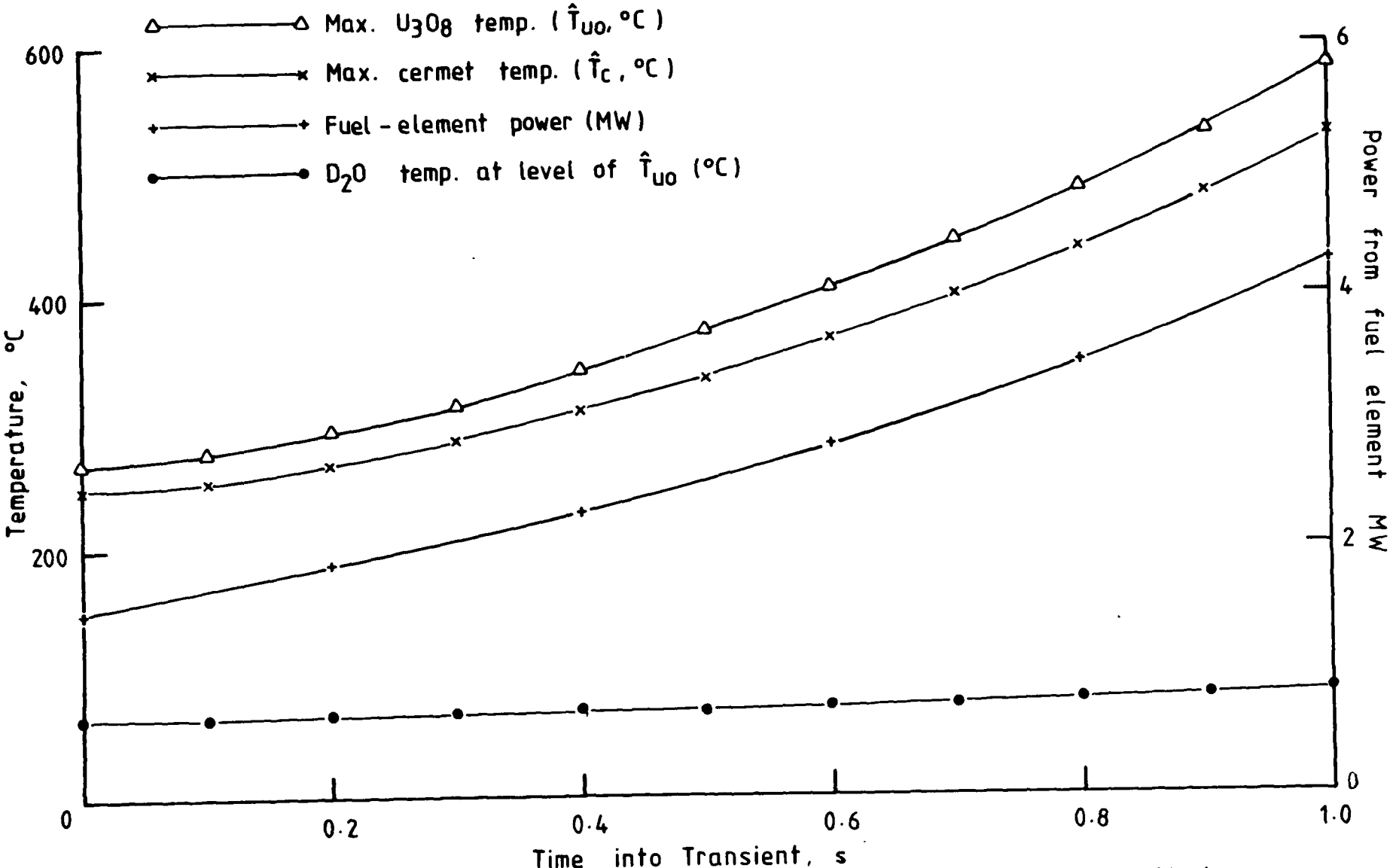


FIG. 5 TEMPERATURE RESPONSES TO CORE POWER TRANSIENT ($I = I_0 e^{1.045868\tau}$), WHERE τ = TIME IN s - FUEL TUBE 'A'

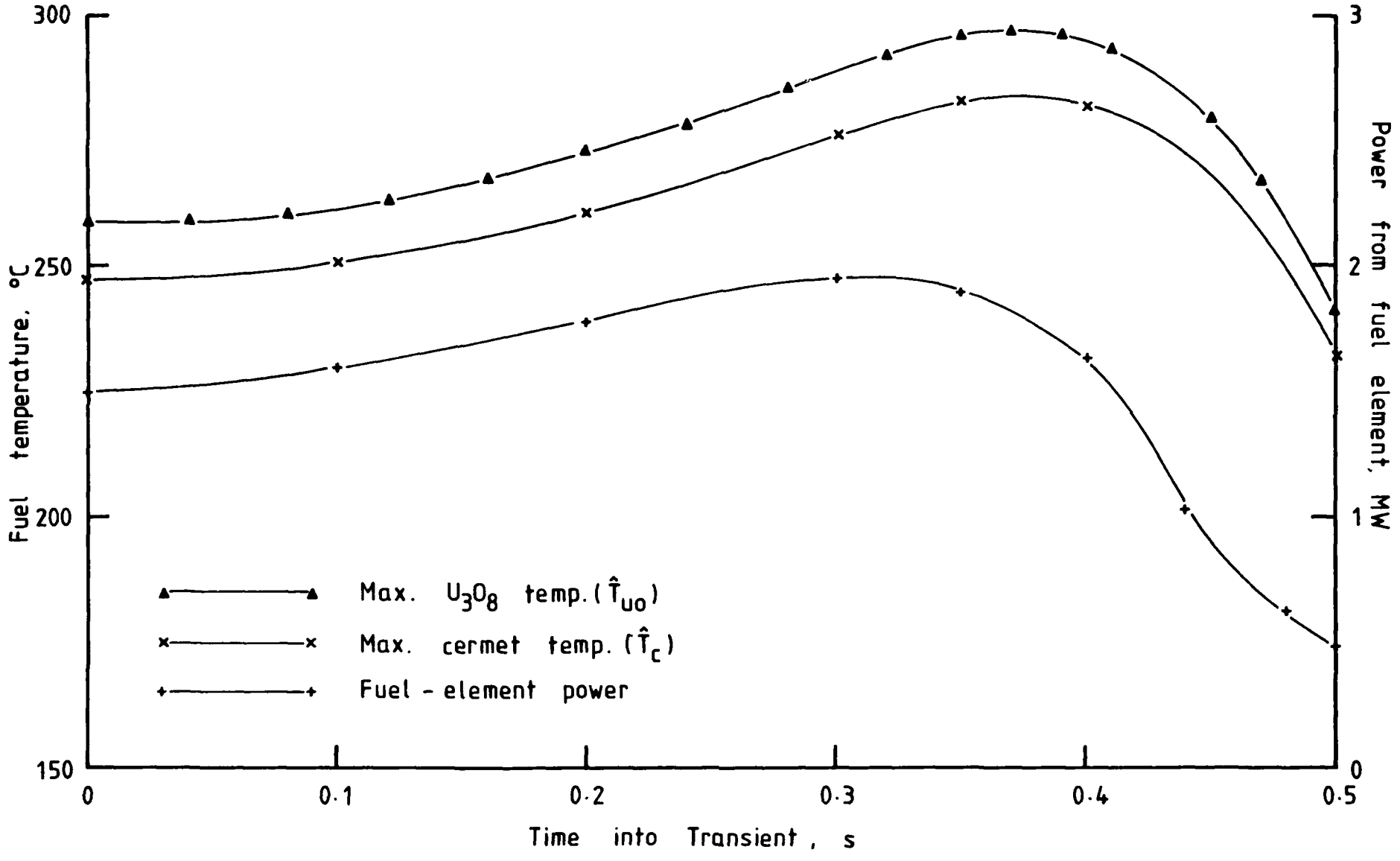


FIG. 6 FUEL - TEMPERATURE RESPONSE TO CORE - POWER TRANSIENT (+0·75 % $\delta k/k\ s^{-1}$, REACTOR TRIP AT 1·65 MW)