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CALCULATION OF THE EFFECT OF FUEL PARTICLE SIZE ON REACTOR DYNAMICS

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ABSTRACT

The effect of fuel particle size on the dynamic behaviour of a 500 MW beryllia moderated reactor fuelled with oxide particles of diameter 2 to 500 microns dispersed in beryllia is discussed. Negative feedback of reactivity proportional to the reactor power occurs because of the very small thermal time constant of the fuel particles. For large fuel particles, the feedback considerably reduces the peak power and the energy release following a reactivity accident.

CONTENTS

1. INTRODUCTION

In this report an analogue study of the effect of fuel particle size on the kinetic behaviour of a 500 MW. beryllia moderated, pebble bed reactor is discussed. The fuel oxides are assumed to be contained in particles of diameter 2 to 500 microns dispersed in BeO in the atom ratio Pu:Th:BeO = 1:20:2000.

Initially calculations were confined to a core in which the PuO_2 fuel was contained in particles 200 microns in diameter. The variation of power, fuel temperature, moderator temperature, and total reactivity were calculated for a reactivity increase of 0.01 $\Delta k/k$ at rates of 0.01, 0.005, 0.001 $\Delta k/k$ per second. Initial powers of 10, 50, and 500 MW were considered.

These calculations confirmed that fuel particle size is important in dynamic calculations and the effect was further investigated by adding 0.01 $\Delta k/k$, linearly over one second, to reactors with different fuel particle sizes and compositions operating at a steady power of 10 kW.

The fuel distributions considered were:

(a) 50, 200, and 500 micron diameter spheres containing ThO_2 and PuO_2, and

(b) 50 and 200 micron diameter spheres containing PuO_2.

In Case (b), the ThO_2 is dispersed in the BeO. The actual size of the ThO_2 particles is unimportant as it has little effect on the kinetics of the core apart from effects on the temperature coefficient. Larger fuel particles were not considered because particle density would be too low. The results of this work show that smaller fuel particle cores would behave in the same way as Case (b) of 50μ particles; thus the full range of possible behaviour is covered.

2. THE MODEL

The reactor was described by the space independent reactor kinetics equations using two groups of delayed neutrons for the first set of calculations and one group of delayed neutrons for the second set. Fuel and moderator temperature coefficients of reactivity were as given in Table 1. The fuel temperature coefficient was entirely a Doppler effect. The moderator coefficient included the effects of changes in thermal neutron spectrum and expansion of the core.

2.1 Heat Generation

Most of the γ-ray and neutron kinetic energy from fission is converted into heat in the moderator. A very small percentage of the total fission product particle kinetic energy is transferred to the moderator by fission product migration. The (n,γ) and $(n,2n)$ reactions generate heat in the moderator. It has been estimated that 10 per cent. of the total power is liberated in the moderator for particles of the sizes considered in this work. It is assumed that this 10 per cent. of the power is uniformly distributed in the moderator and the remaining 90 per cent. is uniformly distributed in the fuel.

2.2 Coolant

The heat flow from the moderator to the carbon dioxide coolant was assumed to be zero. The results of the calculations show that during the excursion only a small proportion of the heat produced would flow into the coolant. Therefore this assumption, which of course greatly under-estimates the heat flow, only produces small inaccuracies in the moderator temperature and the power level. Also, removal of heat from the core during a power excursion would only increase the magnitude of the excursion because the inhibiting effect of the negative temperature coefficient is reduced. Therefore the effect of the assumption is a slight reduction in the magnitude of the power excursion.

2.3 Fuel to Moderator Heat Transfer Coefficient

We assume that the heat transfer from fuel to moderator is directly proportional to the mean fuel to moderator temperature difference. Then the heat balance equation for the fuel is:

$$\frac{dT_f}{dt} = A_f P - B\,(T_f - T_m)$$

where B and A_f are constants and T_f and T_m are the mean fuel and moderator temperatures respectively. To find an appropriate value for B the steady state value of $(T_f - T_m)$ must be calculated. This is done by associating with each fuel particle a volume of moderator given by the total moderator volume divided by the total number of fuel particles. The moderator is assumed to be a sphere surrounding the particle as shown in Figure 1, and the temperature distribution is assumed to be spherically symmetric. The temperature distribution corresponding to a steady power of 500 MW is also shown in Figure 1. The mean moderator temperature is assumed to be given by:

$$T_m = 0.5\,(T_{fs} + T_{ms}) \quad ,$$

where T_{fs} and T_{ms} are the temperatures of the outer surface of the fuel and moderator regions respectively.

Therefore:

$$B = A_f \left(\frac{P}{T_f - T_m}\right)_{\text{steady state}}$$

$$= H/a^2 \quad , \tag{1}$$

where H depends on the fuel particle composition and a is the fuel particle radius.

$$H = 0.13 \text{ cm}^2 \text{ sec}^{-1} \text{ for } PuO_2 \text{ particles}$$

$$= 0.16 \text{ cm}^2 \text{ sec}^{-1} \text{ for } PuO_2 - ThO_2 \text{ particles.}$$

The term $B\,(T_f - T_m)$ does not in fact accurately represent the heat flow from the fuel to the moderator at all times. The results given later in this report show that the heat capacity of the fuel is so small that the temperature distribution in the fuel particle is the steady state distribution corresponding to the instantaneous power. This is not so for the moderator and therefore $T_{fs} - T_m$ will depend on the past history of the reactor. In fact when the power is rising it will be smaller than the steady state value corresponding to the instantaneous power and when the power is falling it will be larger. Therefore when the power is rising the term $B(T_f - T_m)$ is too small; when the power is falling it is too large. However, as:

$$T_f - T_{fs} >> T_{fs} - T_m,$$

this only leads to small inaccuracies. These inaccuracies can only be overcome by calculating the temperature distribution in the moderator during the transient.

The results can be applied to a system fuelled with non-spherical or coated particles once the fuel to moderator heat transfer coefficient is known. The particle size is only used in the calculation of this heat transfer coefficient and thus the results can be taken as applying to any system with the appropriate heat transfer coefficient. The actual heat transfer coefficients are given in Table 2 in units of megawatts thermal core output per degree Centigrade difference between the mean fuel and moderator temperatures. For long cylindrical particles the heat transfer coefficients are obtained by taking a in Equation 1 equal to two thirds of the cylinder diameter.

2.4 Equations

The following equations describe the system under the above assumptions:

$$\frac{dP}{dt} = \frac{(\Delta k - \beta)\,P}{\ell} + \sum_i \lambda_i C_i \tag{2}$$

$$\frac{dC_i}{dt} = \frac{\beta_i P}{\ell} - \lambda_i C_i \tag{3}$$

$$\frac{dT_f}{dt} = A_f\,P - B\,(T_f - T_m) \tag{4}$$

$$\frac{dT_m}{dt} = A_m P + C\,(T_f - T_m) \tag{5}$$

$$\Delta k = -\gamma_f \, \Delta T_f - \gamma_m \, \Delta T_m + \Delta k_{in} \tag{6}$$

$$\begin{aligned} \Delta k_{in} &= Gt \text{ for } t \leqslant 0.01/G \\ &= 0.01 \text{ for } t > 0.01/G \; . \end{aligned} \tag{7}$$

Equations 4 and 5 are the heat balance equations for the fuel and moderator respectively; (6) expresses the reactivity feedback and (7) gives the reactivity forcing function. The kinetic equations (2) and (3) are recast as follows using:

$$\alpha = \frac{\dot{P}}{P}$$

$$D_i = \frac{C_i}{P}$$

$$\alpha = \frac{(\Delta k - \beta)}{\ell} + \Sigma D_i \lambda_i \tag{8}$$

$$\frac{dD_i}{dt} = -\lambda_i D_i + \frac{\beta_i}{\ell} - D_i \alpha \tag{9}$$

The quantity α is the reciprocal of the reactor period. The equations were solved by analogue computation.

3. RESULTS FOR HIGH INITIAL POWER

The effects of adding 0.01 $\Delta k/k$ at rates of 0.01, 0.005, 0.001 $\Delta k/k$ per second to the 200 micron PuO_2 core with total temperature coefficient -1.68×10^{-4} $\Delta k/k$ per degC (Figures 2, 3 and 4) are very similar. If the ramp is continued for long enough as in Figure 4 the power tends to a constant level at which the resulting linear rise in both fuel and moderator temperature is just sufficient to counteract the reactivity being introduced by the ramp. As the heat flow is constant, all temperature differences will be constant. In Figures 2 and 3 the ramp terminates before this state is reached. This behaviour is in marked contrast to that experienced in homogeneous cores. The behaviour of such a reactor after addition of 0.01 $\Delta k/k$ as a 1 second ramp, can easily be shown to consist of large oscillations of decreasing amplitude, the peak power of the first oscillation being 2.2×10^4 MW, about four times greater than that for the inhomogeneous core considered here. This is because the surface to volume ratio of the fuel is very much smaller for a 200 micron particle than for a 2 micron or smaller particle, and thus at higher power a much larger temperature difference between fuel and moderator is required to maintain the required heat flow from the fuel to the moderator. Also a greater proportion of the heat is liberated in the moderator in the small particle core. Because of the small thermal capacity of the fuel, the difference between the rate of heat generation in the fuel and the heat flow from fuel to moderator is very small for the rates of change of power considered in this report. In fact, the time lag ($\frac{1}{B} \bumpeq 10^{-3}$ sec) between these two is of the order of the prompt neutron lifetime for a 200 micron particle and thus the fuel temperature responds very rapidly to changes in power. As all changes in power considered are small in times of order $1/B$ the temperature distribution in the fuel particle is quasi-static and the fuel temperature is given by:

$$T_f(t) = \frac{A_f P}{B} + T_m \tag{10}$$

Putting Equation 10 into Equations 5 and 6 we get:

$$\Delta k = -\left(\frac{\gamma_f A_f}{B}\right) P - (\gamma_f + \gamma_m) \Delta T_m + \Delta k_{in} \tag{11}$$

$$\dot{T}_m = \left(A_m + \frac{A_f C}{B}\right) P \tag{12}$$

Thus we may treat the inhomogeneous core as having two negative reactivity feedback mechanisms, one proportional to the reactor power and the other to the moderator temperature. The remaining two calculations in the first series indicate the effect of adopting lower initial powers (Figures 5 and 6).

Similar behaviour is found except that a definite power peak appears. This led to the detailed investigation of a start-up accident which is now discussed.

4. RESULTS FOR LOW INITIAL POWER

Figures 7 to 10 show the variation of power, mean fuel temperature, mean moderator temperature, and reactivity with time for the five cores considered. The more important quantities are shown in Table 2. The size and composition of the fuel particle has an effect on both power and temperature transients. Large fuel particles reduce both the peak power and the integrated power of the excursion. The peak power is reduced by an order of magnitude in some cases. However, the peak power is only important because it determines the local stresses in the moderator surrounding the fuel particle. As the fuel to moderator temperature difference is larger for the large particles these stresses may be larger and thus the lower peak power may be no real advantage. This depends on the expansion room available to the fuel particles. If there is a small gap or a low density layer between fuel and moderator, then the lower peak power is a distinct advantage. The reduced integrated power is an advantage, because the fuel ball stresses, other than those produced by fuel particle expansion, depend on it.

However, there is a definite limit to the improvement possible and this limit is reached in both of the large particle cores; the 200 micron PuO_2 and the 500 micron PuO_2-ThO_2 cores. The 50 micron mixed core gives the largest integrated power and this is the worst case. That this integrated power is much more than that required to terminate the excursion is shown by the fact that the reactor is 0.51 per cent. subcritical after the excursion. In fact, the reactor is subprompt critical ($\Delta k < \beta$) when the power is at its maximum. Any energy released after the peak power must insert negative reactivity as the fuel and moderator temperatures are equal and both will rise. This is not true for the inhomogeneous case. The release of energy after the peak power does not add negative reactivity as the large addition of energy to the moderator raises the moderator temperature and has a negative reactivity effect. This is offset by a fall in fuel temperature which only involves a small energy transfer. Thus Δk does not change much after the peak power is reached and is in fact in the range $0 < \Delta k < \beta$. At this stage the reactor power is falling slowly even though $\Delta k > 0$. This is because the concentration of delayed neutron precursors is well below equilibrium level. Increasing the particle size only reduces the integrated power by a factor of two, and therefore the overall temperature rise by a factor of two. This lower integrated power is liberated over a longer period in the large particle cores and this allows more time for corrective action.

It is of interest to discuss the effect of varying the distribution of the temperature coefficient between the fuel and the moderator, keeping the total temperature coefficient constant at -1.4×10^{-4} $\Delta k/k$ per degC. For all particle sizes the case of a zero moderator coefficient, that is:

$$\gamma_f = 1.4 \times 10^{-4}, \quad \gamma_m = 0 ,$$

is almost the same as for the 500 micron PuO_2-ThO_2 cores, as the moderator coefficient plays only a small part in terminating this excursion. The case of a zero fuel coefficient is more interesting.

When $\gamma_f = 0$ and $\gamma_m = -1.4 \times 10^{-4}$, it is obvious that the variation of power, moderator temperature, and reactivity will be the same as for the 50 micron PuO_2-ThO_2 core. However, the fuel temperature will depend on the particle size and is given by $T_f - T_m = \frac{A_f P}{B}$. For a 200 micron PuO_2 core, the fuel to moderator temperature difference would rise to 800°C. This strengthens the point that it is desirable to have as much of the temperature coefficient as possible associated with the fuel temperature. This is also shown by comparing the 200 micron PuO_2 and the 500 micron PuO_2-ThO_2 cores. These cores both have about the same heat transfer coefficients. The power, moderator temperature, and reactivity curves are very similar. The difference in the fuel temperature curves is due almost entirely to the different distribution of the temperature coefficient.

TABLE 1

REACTOR KINETIC PARAMETERS AND TEMPERATURE COEFFICIENTS

Delayed Neutron Parameters

1 Group	$\beta = 0.00187$	$\lambda = 0.0685\ \text{sec}^{-1}$
2 Group	$\beta_1 = 0.000935$	$\lambda_1 = 0.036\ \text{sec}^{-1}$
	$\beta_2 = 0.000935$	$\lambda_2 = 0.74\ \text{sec}^{-1}$

Prompt Neutron Lifetime = 2×10^{-4} seconds

Temperature Coefficients $\Delta k/k$ per deg C

		Fuel	Moderator	Total
Initial Calculations Figures 2-6		-11.0×10^{-5}	-5.8×10^{-5}	-1.68×10^{-4}
PuO_2-ThO_2 Particles	Figures 7-10	-11.25×10^{-5}	-2.75×10^{-5}	-1.4×10^{-4}
PuO_2 Particles		-4.5×10^{-5}	-9.5×10^{-5}	-1.4×10^{-4}

TABLE 2

ENERGY RELEASE RESULTING FROM A LINEAR ADDITION OF 1 PER CENT. REACTIVITY OVER 1 SECOND AT 10 kW

Particle Composition	$PuO_2 - ThO_2$			PuO_2	
Diameter (microns)	500	200	50	50	200
Heat Transfer Coefficient MW/deg C per total mass	300	1,900	30,000	2,400	150
Energy released MW sec	7,400	9,200	12,500	11,500	7,900

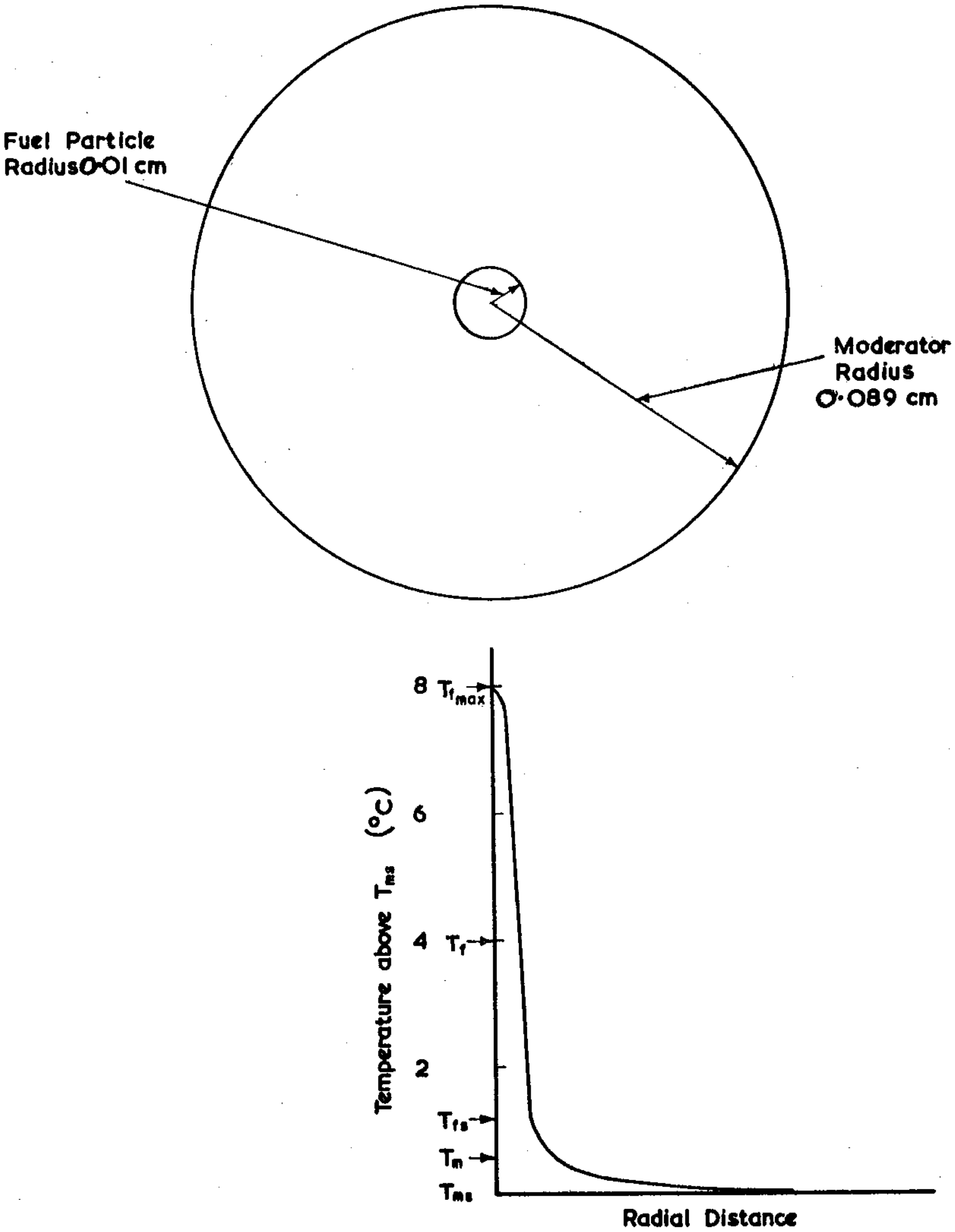

FIGURE 1. TEMPERATURE DISTRIBUTION THROUGH 200 MICRON PuO_2 PARTICLE AND ASSOCIATED BERYLLIA

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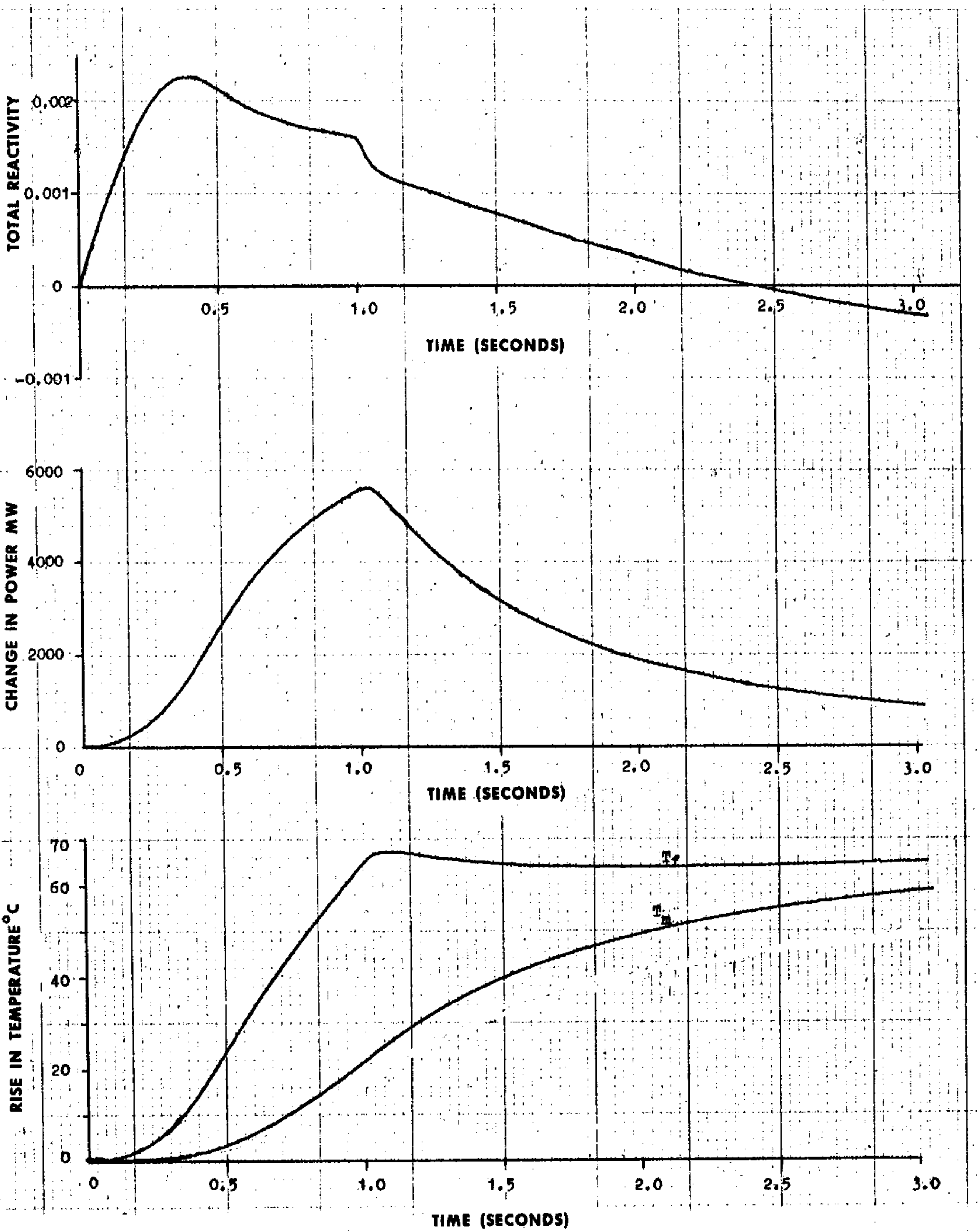

FIGURE 2. BEHAVIOUR OF A PuO_2 PARTICLE FUELLED REACTOR RESULTING FROM A LINEAR ADDITION OF 0.01 $\Delta k/k$ OVER 1 SECOND AT 500 MW

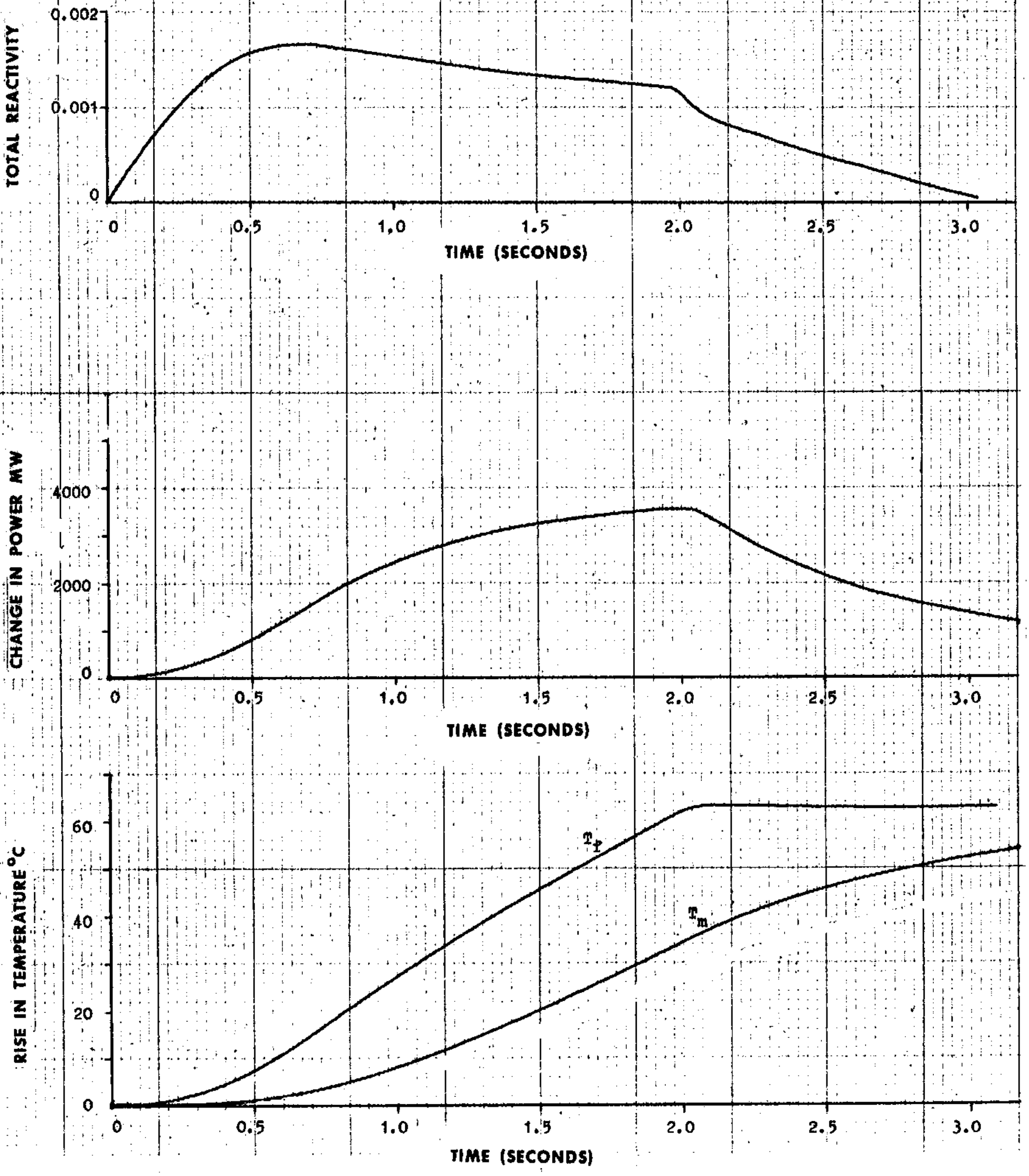

FIGURE 3. BEHAVIOUR OF A PuO_2 PARTICLE FUELLED REACTOR RESULTING FROM A LINEAR ADDITION OF 0.01 $\Delta k/k$ OVER 2 SECONDS AT 500MW

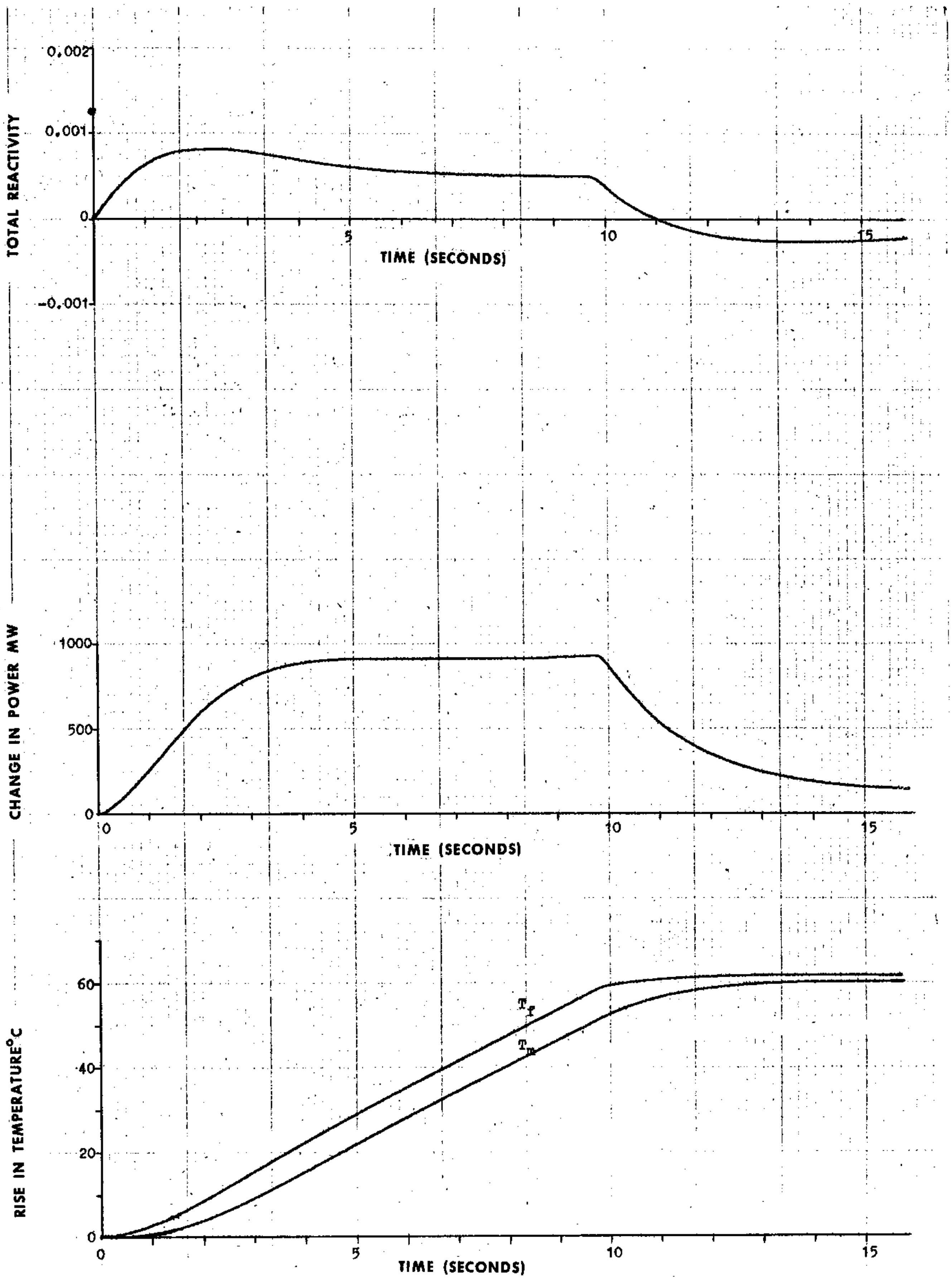

FIGURE 4. BEHAVIOUR OF A PuO_2 PARTICLE FUELLED REACTOR RESULTING FROM A LINEAR ADDITION OF $0.01\Delta k/k$ OVER 10 SECONDS AT 500 MW

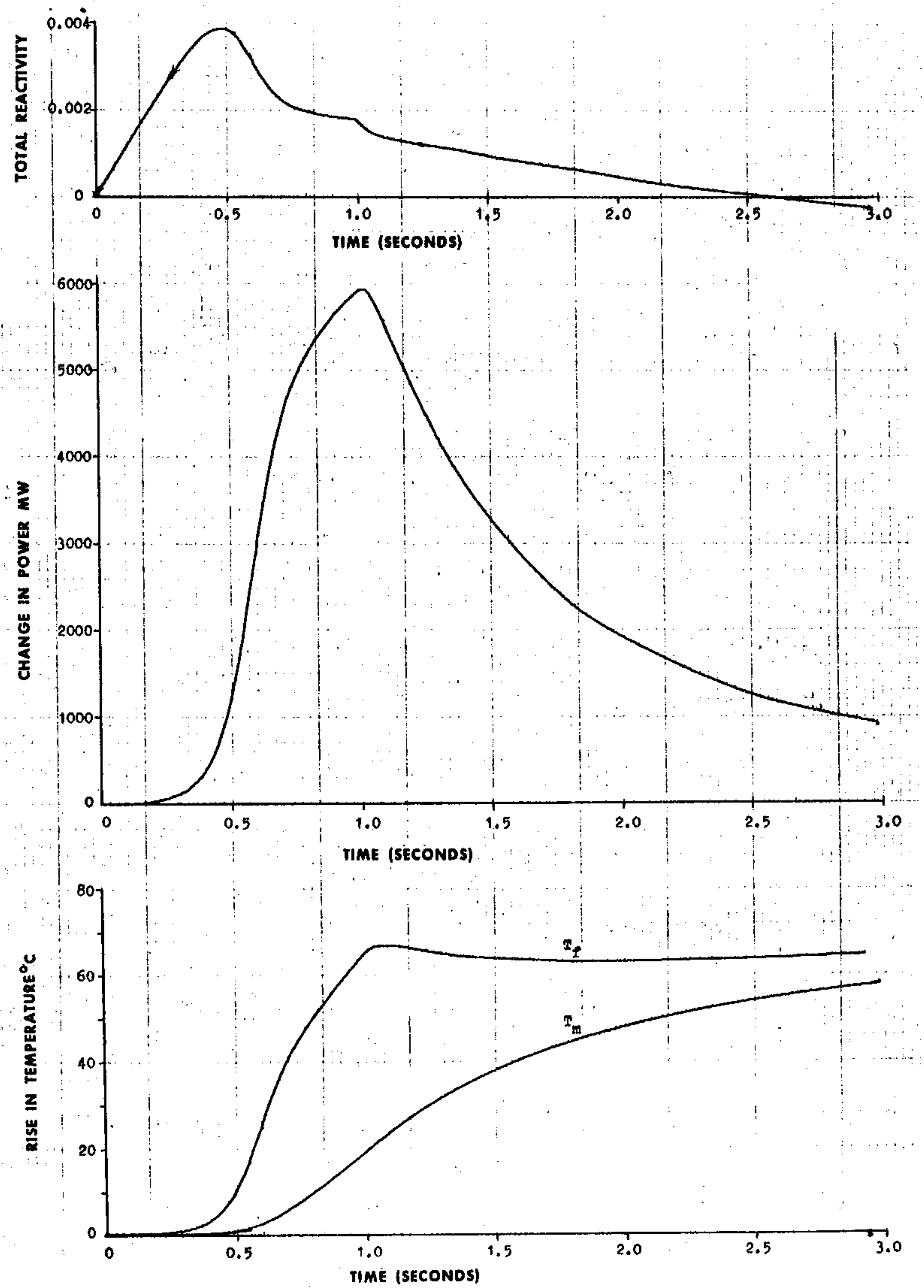

FIGURE 5. BEHAVIOUR OF A PuO_2 PARTICLE FUELLED REACTOR RESULTING FROM A LINEAR ADDITION OF 0.01 $\Delta k/k$ OVER 1 SECOND AT 50MW

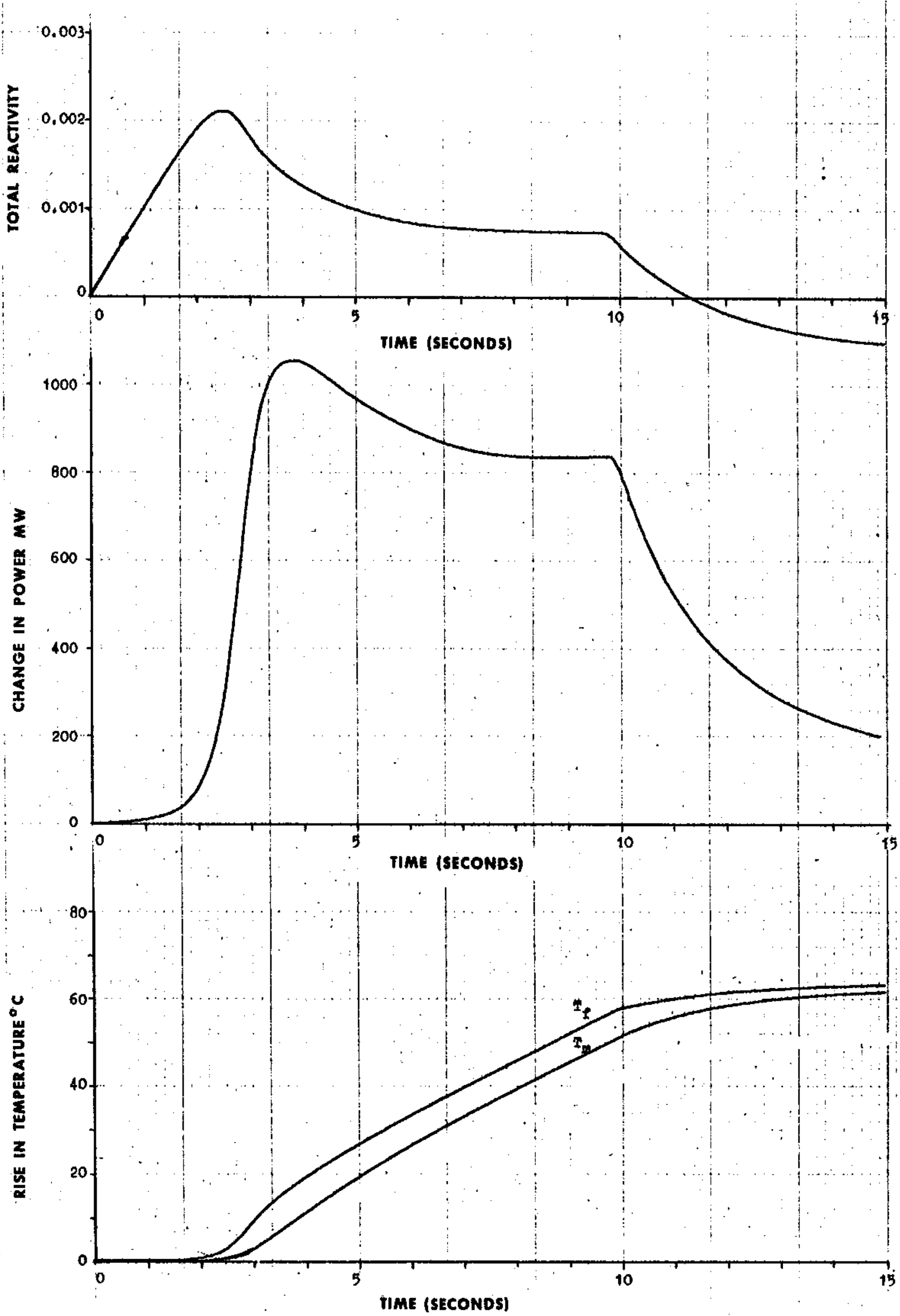

FIGURE 6. BEHAVIOUR OF A PuO_2 PARTICLE FUELLED REACTOR RESULTING FROM A LINEAR ADDITION OF 0.01 $\Delta k/k$ OVER 10 SECONDS AT 10MW

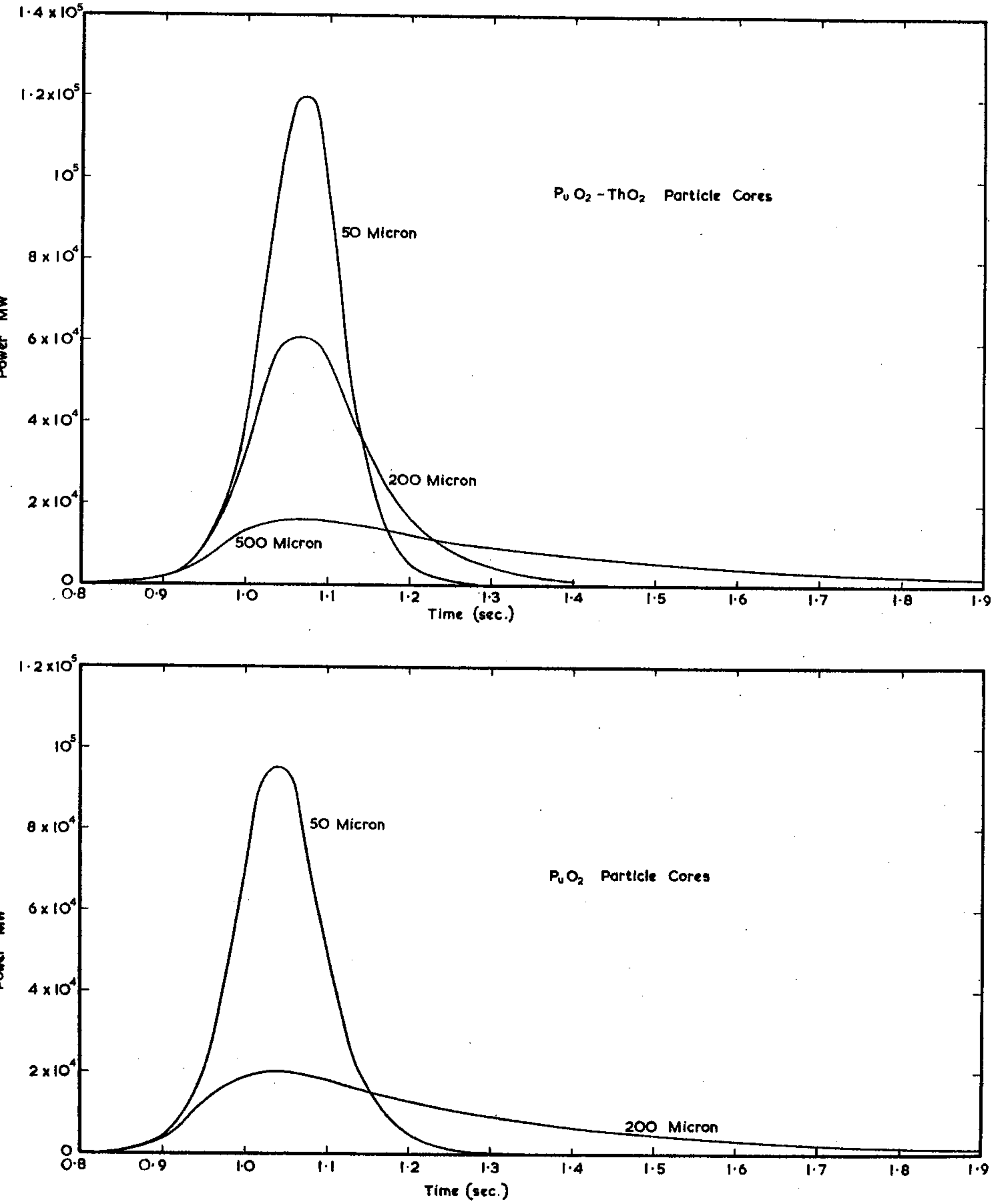

FIGURE 7. POWER TRANSIENTS RESULTING FROM A LINEAR ADDITION OF 0.01 △ k/k OVER 1 SECOND AT 10 kW

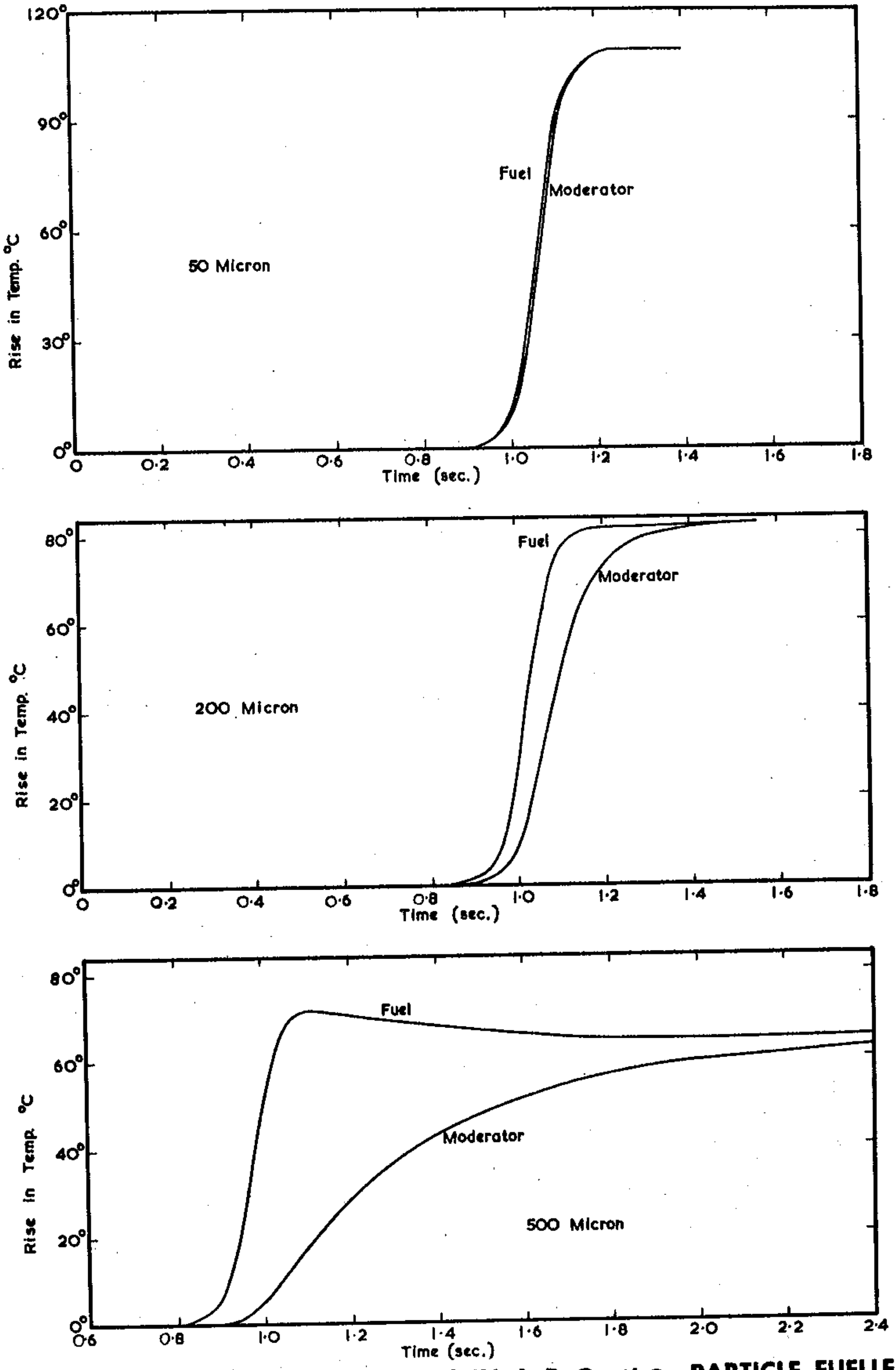

FIGURE 8. TEMPERATURE CHANGES IN A PuO_2-ThO_2 PARTICLE FUELLED REACTOR RESULTING FROM A LINEAR ADDITION OF 0.01 $\Delta k/k$ OVER 1 SECOND AT 10 kW

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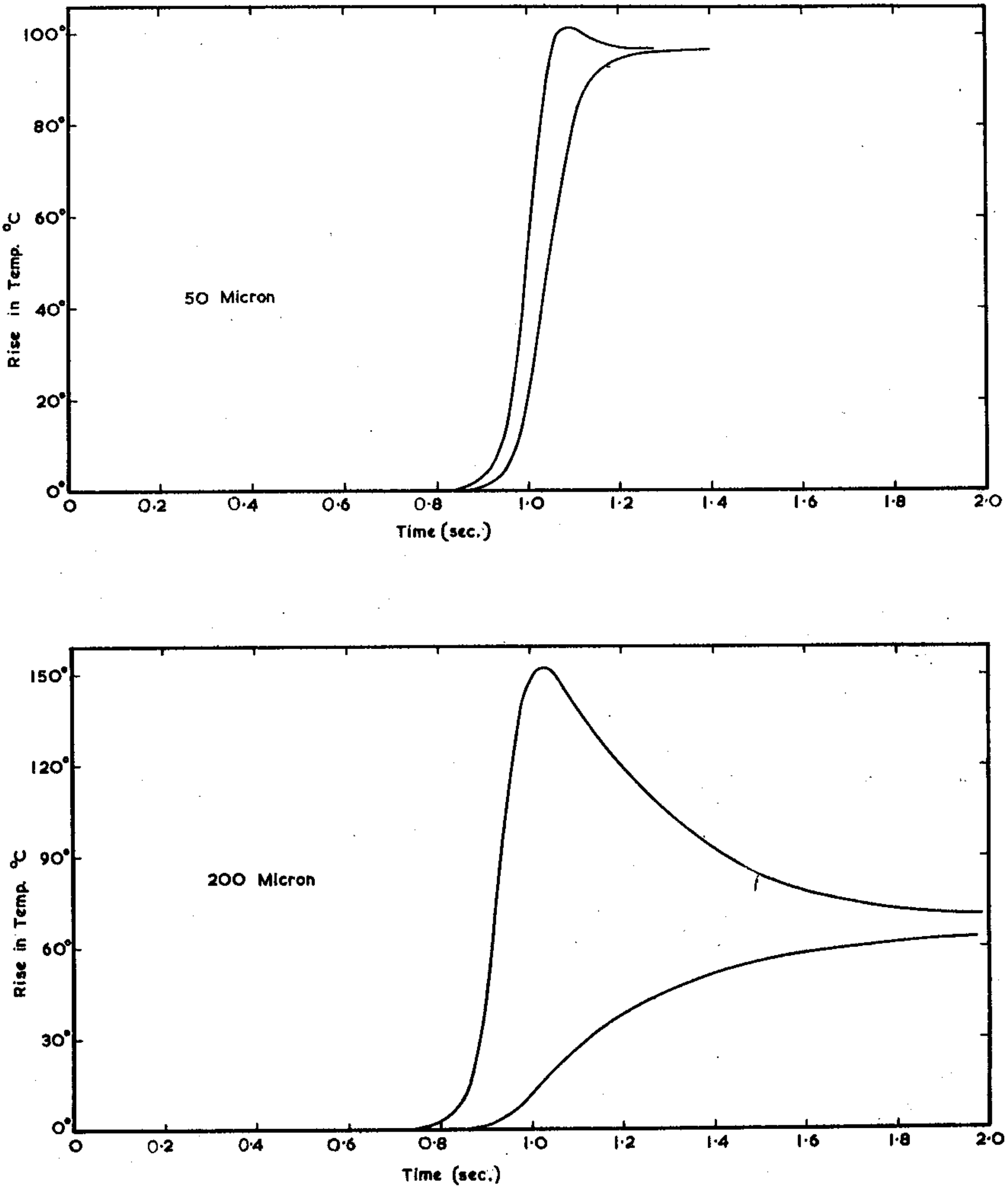

FIGURE 9. TEMPERATURE CHANGES IN A PuO_2 PARTICLE FUELLED REACTOR RESULTING FROM A LINEAR ADDITION OF 0.01 Δ k/k OVER 1 SECOND AT 10 kW

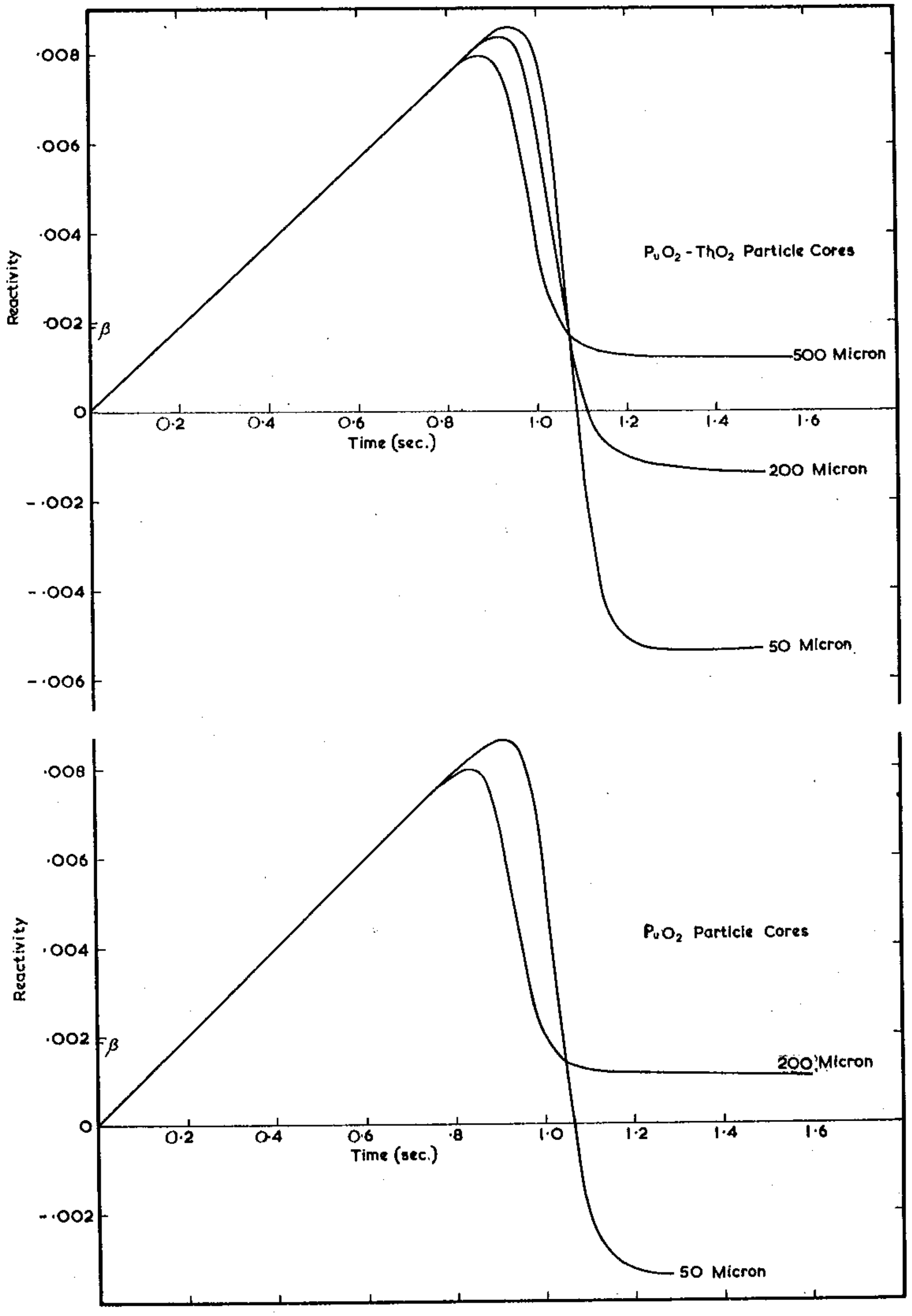

FIGURE 10. CHANGES IN TOTAL REACTIVITY RESULTING FROM A LINEAR ADDITION OF 0.01 $\Delta k/k$ OVER 1 SECOND AT 10 kW