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ATOMIC ENERGY OF CANADA LIMITED

ÉNERGIE ATOMIQUE DU CANADA LIMITÉE

THE ANALYSIS WITH THE CODE TANK OF A POSTULATED REACTIVITY-INSERTION TRANSIENT IN A 10-MW MAPLE RESEARCH REACTOR

ANALYSE AVEC LE PROGRAMME DE CALCUL TANK D'UNE TRANSITOIRE POSTULÉE D'INSERTION DE RÉACTIVITÉ DANS UN RÉACTEUR DE RECHERCHES MAPLE DE 10 MW

R. J. Ellis

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Whiteshell Nuclear Research Establishment

Établissement de recherches nucléaires de Whiteshell

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RÉSUMÉ

Dans ce rapport, on examine l'analyse d'un accident postulé de perte de réglage (LOR) dans un réacteur de recherches à combustible métallique MAPLE. Le scénario de transitoire choisi comporte une perte de réglage lente à partir d'une faible puissance de réacteur: on suppose que les barres de commande sont retirées lentement jusqu'à ce qu'un arrêt brusque à 12 MW interrompt le retrait.

On a exécuté la simulation à l'aide du programme de calcul à cinétique de réacteurs espace-temps et de la modélisation en détail en deux dimensions du réacteur et en deux groupes d'énergie neutronique. Dans ce même rapport, on met l'accent sur les techniques de modélisation employées dans TANK ainsi que sur le facteur "physique" de l'analyse.

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ABSTRACT

This report discusses the analysis of a postulated loss-of-regulation (LOR) accident in a metal-fuelled MAPLE Research Reactor. The selected transient scenario involves a slow LOR from low reactor power: the control rods are assumed to withdraw slowly until a trip at 12 MW halts the withrawal.

The simulation was performed using the space-time reactor kinetics computer code TANK, and modelling the reactor in detail in two dimensions and in two neutron-energy groups. Emphasis in this report is placed on the modelling techniques used in TANK and the physics considerations of the analysis.

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CONTENTS

1. INTRODUCTION

To properly describe transient behaviour in a reactor, the time-dependent behaviour of the reactor power level, inverse reactor period, reactivity, and fuel, cladding and coolant temperature distributions are required. The space-time reactor kinetics computer code TANK (Transient Analysis with Neutron Kinetics) is used to calculate this information during simulations of transients in the Atomic Energy of Canada Limited (AECL) MAPLE class of research reactors. Details are calculated on a site-by-site basis, giving a two-dimensional description of the transient behaviour.

2. THE REACTOR KINETICS COMPUTER CODE TANK

TANK has been described in detail elsewhere [1,2,3] and only the main features will be mentioned here. TANK is being developed as a space-time reactor kinetics computer code for simulating reactivity transients in MAPLE Research Reactors. It is used for modelling reactor behaviour in a two-neutron-energy-group representation, in two dimensions. The two designated neutron-energy groups are fast neutrons with kinetic energy ≥ 0.625 eV and thermal neutrons with kinetic energy <0.625 eV. Some neutronics considerations are included for effects in the third (axial) direction, e.g., coolant void distributions along a fuel channel and control and shutdown rod positions.

For TANK simulations, nuclear reactors are modelled in two dimensions on a hexagonal mesh of up to 900 cells. The actual number of cells depends on the size and complexity of the reactor. Each cell in the hexagonal mesh representation of the reactor is characterized by a set of nine kinetics parameters: fast and thermal neutron macroscopic absorption and fission cross sections, fast-to-thermal macroscopic removal cross sections, fast and thermal axial diffusion coefficients, and the cell-averaged fast and thermal neutron velocities. These parameters are obtained from computations with the multigroup transport code WIMS [4,5], which uses the ENDF/B-V [6] cross-section library.

The kinetics parameters for the cells corresponding to fuelled sites in the reactor core are continuously updated via parameterized equations during the simulations. The updating of the kinetics parameters accounts for the reactivity feedback effects of fuel-element temperature change, coolant density change, and void formation.

TANK uses numerical methods to solve the neutron kinetics equations for the two energy groups. A flux factorization approach [7] is used in TANK to separate the space and time dependence of the total neutron flux level,

$$\phi(r,t) = \psi(r,t)N(t)$$

where ϕ is the space-time neutron flux, ψ is the primarily space-dependent shape function and N is the time-dependent amplitude function. The

Improved Quasistatic Approximation [7,8] is used in TANK to account for a weak time dependence of the shape function.

The kinetics calculations in TANK account for delayed neutrons in addition to the prompt fission neutrons. TANK has the capability to handle up to 15 delayed-neutron precursor or photoneutron groups. The two-neutron-energy-group reactor kinetics equations are coupled with the delayed precursor concentration equations to form a set of differential equations [1] that describes the fast- and thermal-neutron flux levels during reactivity insertion transients.

Subroutines in TANK account for reactivity feedback mechanisms in the simulation of transients in MAPLE Research Reactors. The effects of coolant temperature and density and fuel temperature on the total reactivity are simulated.

Reactivity feedback effects are simulated in TANK analyses by updating the temperature- and void-dependent cross sections as conditions in the reactor change. The cross sections are recalculated in TANK subroutines, as mentioned above, at each time step during the transient simulation. The new values are fed back into the kinetics algorithm of TANK.

Temperature distributions in the fuel, cladding and coolant are continuously updated for each individual fuelled site. This process [2] involves numerous thermalhydraulic considerations, such as the geometry and composition of the fuel pins, coolant flow rates, density and pressure, helium gap effects (not applicable for the MAPLE-X10 Research Reactor), and cladding-coolant heat transfer coefficients. Axial form factors are used in TANK to calculate the peak linear power ratings for each fuel channel. The fuel-element temperatures for the hottest axial plane are then determined. Heat transfer coefficients between the cladding wall and the coolant are determined in TANK for each fuel assembly using the heat transfer package of the thermalhydraulics code SPORTS-M [9,10] for subcooled and saturated boiling.

The possible production of coolant void near the cladding surface of hot fuel elements is modelled in TANK using the heat transfer package of SPORTS-M. Voiding occurs initially when the fin-base (i.e., the cladding surface between fins) temperature is sufficiently high at the hottest axial position for the hottest fuel channel. An importance-weighting technique is used in TANK to account for bubbles carried downstream by the coolant. The axial flux-squared distribution is used in determining the "worth" of the void bubbles as a function of position. This approach allows for the presence of both detached bubbles and bubbles that adhere to the hot cladding surface.

Once the simulation of the transient is under way, the behaviour of the reactor is detailed for small time increments. The size of the time step is determined in TANK and depends on the rates of change of reactor conditions. For rapid changes in conditions, the size of the time step can be as small as ~0.1 ms. The lower limit in time-step size is the neutron

generation time, Λ, which is nominally 8×10^{-5} s for a metal-fuelled MAPLE Research Reactor.

3. THE MAPLE CLASS OF RESEARCH REACTORS

MAPLE Research Reactors can be either metal- or UO_2-fuelled, depending on the application. The MAPLE-X10 Research Reactor calls for the use of two types of metal fuel materials in its 19-site core [2]: U_3Si-Al and U-Al. The MAPLE-X10 initial power core configuration consists of (a) twelve 36-element driver fuel assemblies with aluminum-clad U_3Si-Al fuel elements; (b) three 12-element fuel assemblies with aluminum-clad U-Al fuel elements; and (c) four aluminum "dummy" assemblies in the shutdown and central sites. Annular hafnium shrouds, which provide a control and shutdown capability, move axially along the control rod and shutdown sites; the shrouds are located outside a circular flow tube.

Figure 1 represents the 19 hexagonal cells in the TANK model for the MAPLE-X10 initial power core. The twelve 36-element driver assemblies are denoted by DR, the three 12-element assemblies (in the control rod sites) by CR, and the three shutdown sites and the central site are DUMMY sites. The numbers indicated at each site correspond to the hexagonal cell in the TANK model; this particular core is modelled with 649 hexagonal cells.

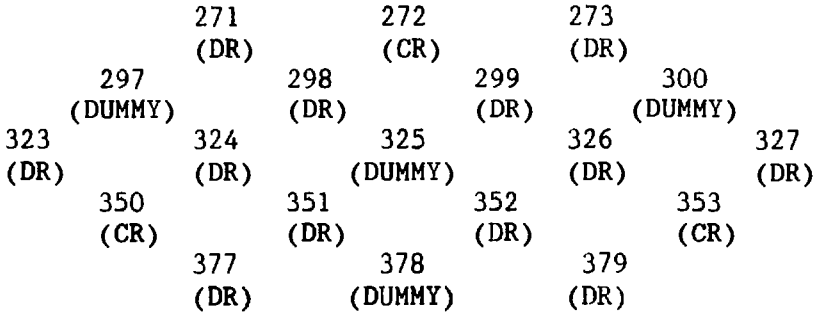

FIGURE 1: The Initial Power Core of a Metal-Fuelled Maple Research Reactor, as Represented in the Model Used in the Code TANK

Some of the thermalhydraulic and geometric information about this reactor that is used in TANK is presented in Table 1. Note that the fuel elements are all finned to increase the effectiveness of heat transfer to the coolant. The coolant flow is quite high, resulting in a high degree of subcooling for steady-state operation at full power.

TABLE 1

SOME MAPLE-X10 FUEL-ELEMENT DATA USED IN TANK

	DRIVER ASSEMBLY	CONTROL ROD ASSEMBLY
Fuel Material	U_3Si-Al	U-Al
Clad Material	Aluminum	Aluminum
Number of Fins	8	10
Coolant Velocity	5.18 m/s	6.68 m/s
Mean Pressure	198.2 kPa	244.2 kPa

Table 2 presents information on the delayed-neutron precursor groups considered in the MAPLE-X10 Research Reactor simulations with TANK. The yields of the delayed-neutron groups accounts for the presence of both ^{235}U and ^{238}U in the fuel. The column 4 entries are reciprocals of the decay constants λ_i listed in column 3.

TABLE 2

DELAYED-NEUTRON PRECURSOR GROUP INFORMATION

DELAYED GROUP	YIELD (%)	DECAY CONSTANT (s^{-1})	LIFETIME (s)
1	0.0260	0.01270	78.74
2	0.1467	0.03171	31.54
3	0.1302	0.1154	8.666
4	0.2824	0.3119	3.206
5	0.0905	1.400	0.714
6	0.0189	3.880	0.258

4. A POSTULATED ACCIDENT SCENARIO FOR SIMULATION WITH THE CODE TANK

The loss-of-regulation (LOR) accident scenario analyzed below is unlikely to happen in reality. The MAPLE-X10 Research Reactor is assumed to be operating at 100 W (10^{-5} full power) with full coolant flow (see Table 1). The three control rods (#272, #350, and #353; see Figure 1) begin withdrawal at a slow constant velocity of approximately 0.2 mm/s. As a result, reactivity is added to the reactor, initially at approximately

0.05 mk/s. The accident is allowed to continue until the total reactor power level reaches 12 MW, at which point the trip of a shutdown system is assumed to freeze the control rods in place.

TANK is used to simulate the transient behaviour for a duration of 15 min into the accident, by which time operator intervention is assumed likely.

5. TANK SIMULATION RESULTS

In this section, the results of the transient analysis of the postulated LOR accident are presented.

Figure 2 presents the behaviour of the dynamic reactivity as a function of time. Note the initial ramp insertion of reactivity caused by the slow constant withdrawal of the three control rods. At 76.3 s, the reactivity peaks at 4.27 mk; fuel temperature feedback then causes the reduction of the reactivity. A shutdown system has the control rods freeze in place at 86.6 s because the total reactor power (see Figure 3) exceeded 12 MW, a trip set point, 0.2 s (trip delay time) earlier. Further temperature feedback effects are seen as periodic oscillations in reactivity, occurring because of the variation in coolant inlet temperature. There is an 18-s circuit time so the effects are delayed. As seen in the figure, the reactivity becomes zero by ~750 s.

Figure 3 shows a plot of the total reactor power as a function of time. Before 70 s, the total reactor power level is almost imperceptible since the initial power was only 100 W. Over a relatively short time, the power climbs to 20.8 MW by 99 s; the channel temperatures rise accordingly (seen in later figures). As the reactivity drops, the inverse reactor period, α, becomes negative resulting in a power level reduction. Note that the small oscillations in the power level also occur every 18 s and they are caused by the variation in the inlet coolant temperature, as mentioned above.

The inverse reactor period, α, is a function of the dynamic reactivity, ρ, the total delayed fraction, β, the prompt-neutron generation time, Λ, the relative amplitude, N, the delayed group decay constants, λ_i, the normalized concentrations of the delayed precursor groups, η_i, as seen in the following α equation:

$$\alpha = \frac{\rho - \beta}{\Lambda} + \frac{\Sigma \lambda_i \eta_i}{N} .$$

In Figure 4, the relative concentrations, η_i, of the six delayed-neutron precursor groups (see Table 2) are plotted. Note the effect of the decay constant: when λ is small as in Group 1, the concentration changes slowly and smoothly; when λ is large, as in Group 6, the concentration varies as quickly as the power level. A more important quantity is the product of the decay constant and the precursor concentration, as shown in Figure 5. This variable is seen in the second term of the α equation.

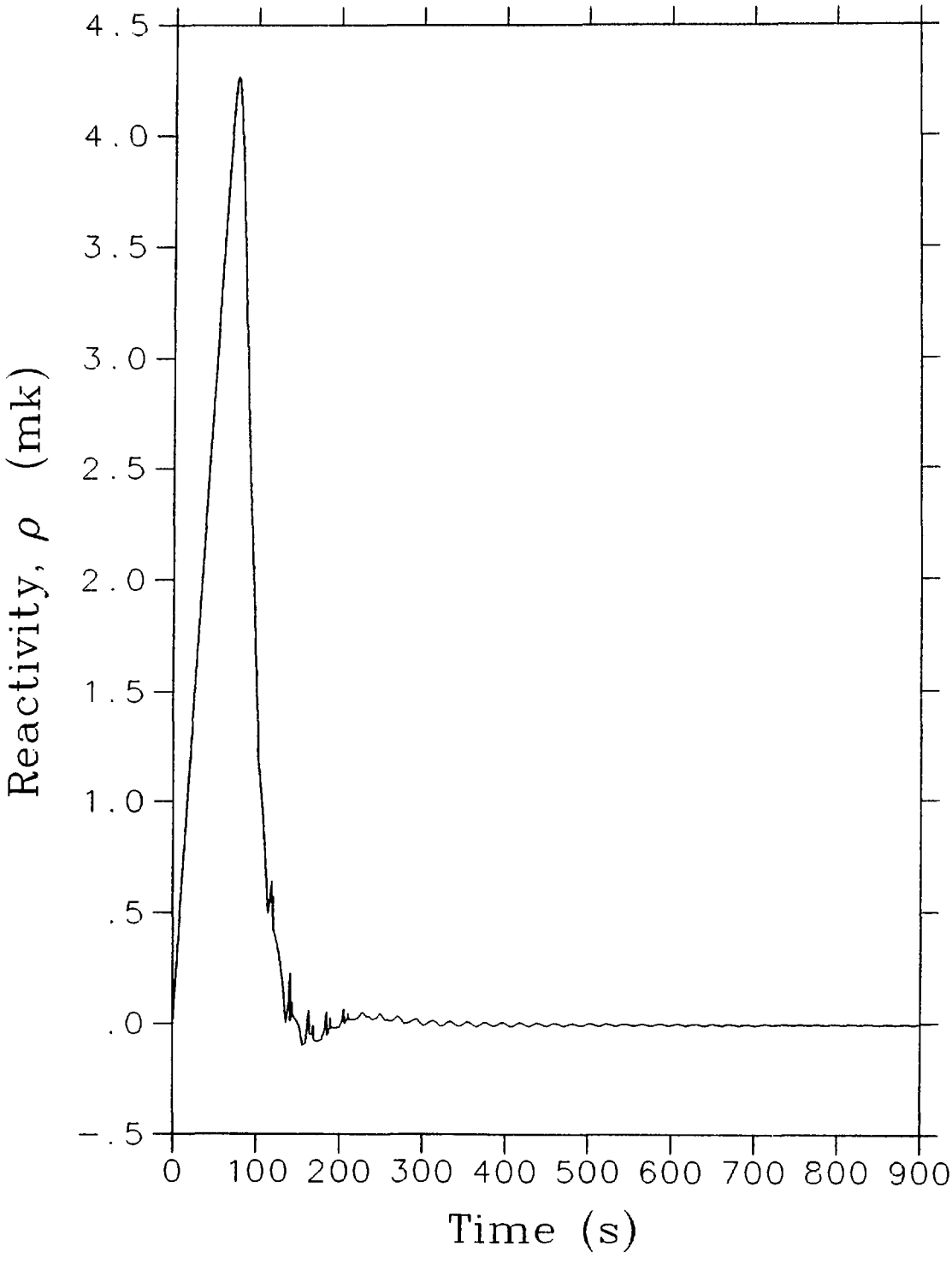

FIGURE 2: Dynamic Reactivity as a Function of Time: A Simulation Using TANK

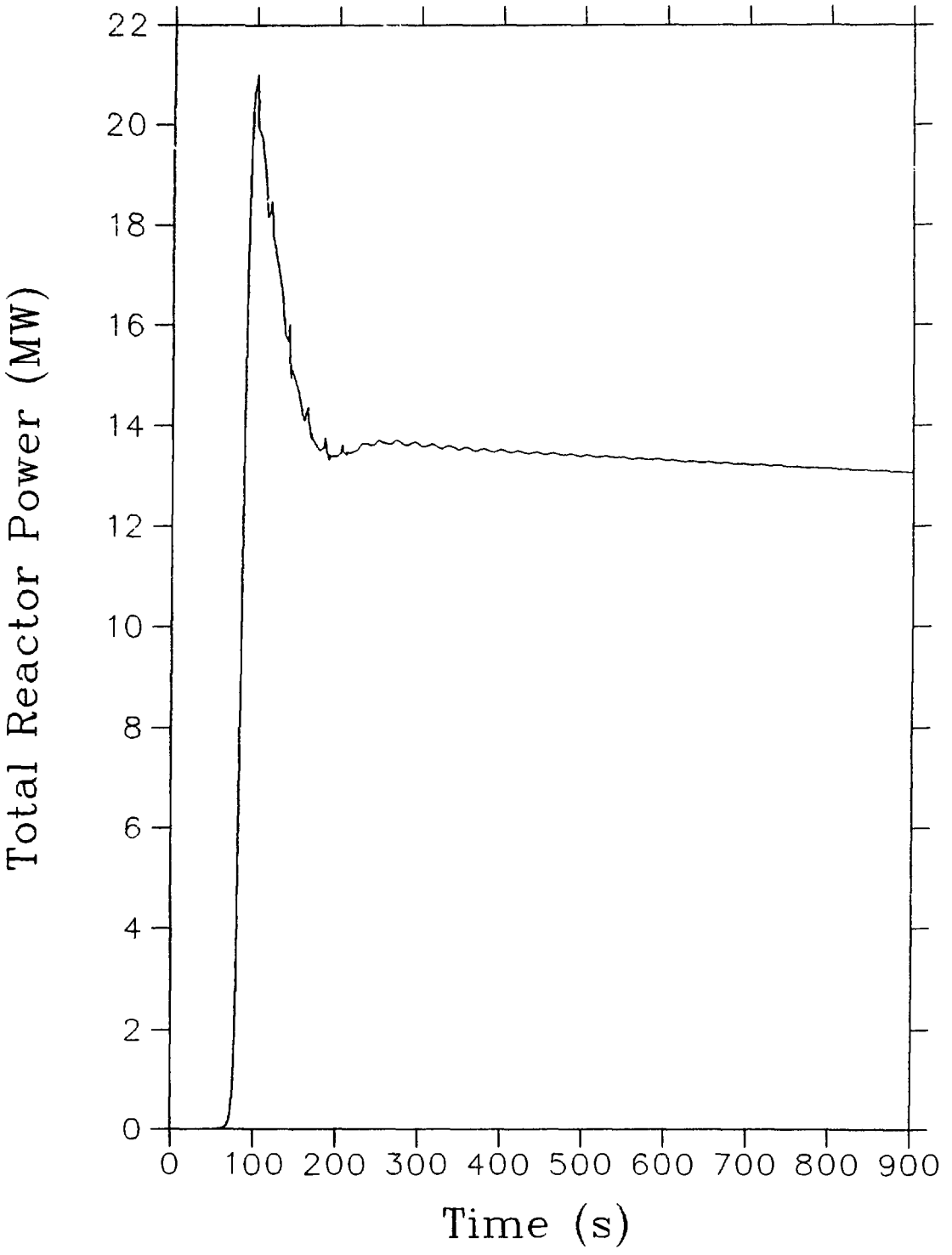

FIGURE 3: Total Reactor Power as Simulated with TANK

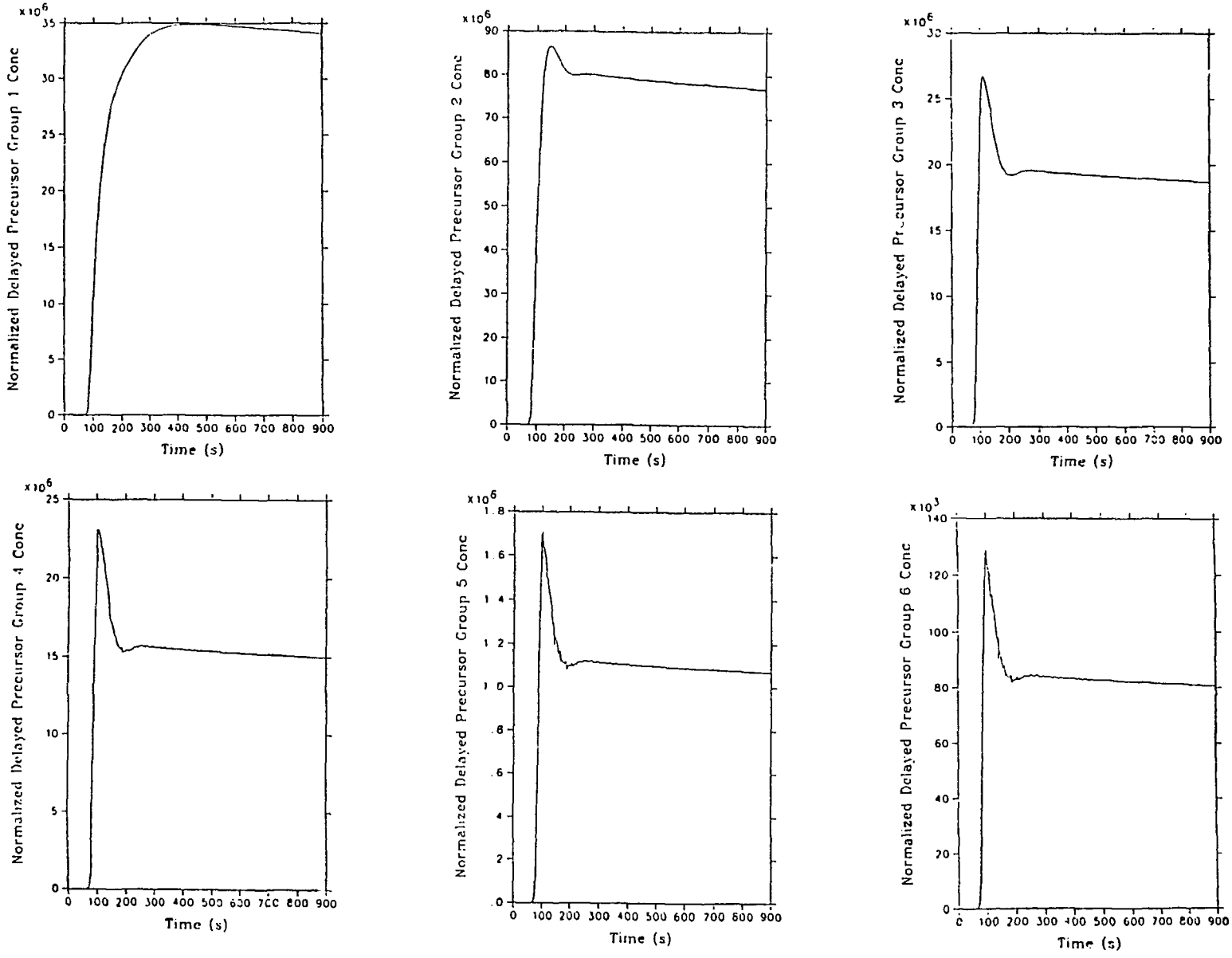

FIGURE 4: The Time Behaviour of the Concentrations of the Six Delayed Precursor Groups, as Calculated in Tank

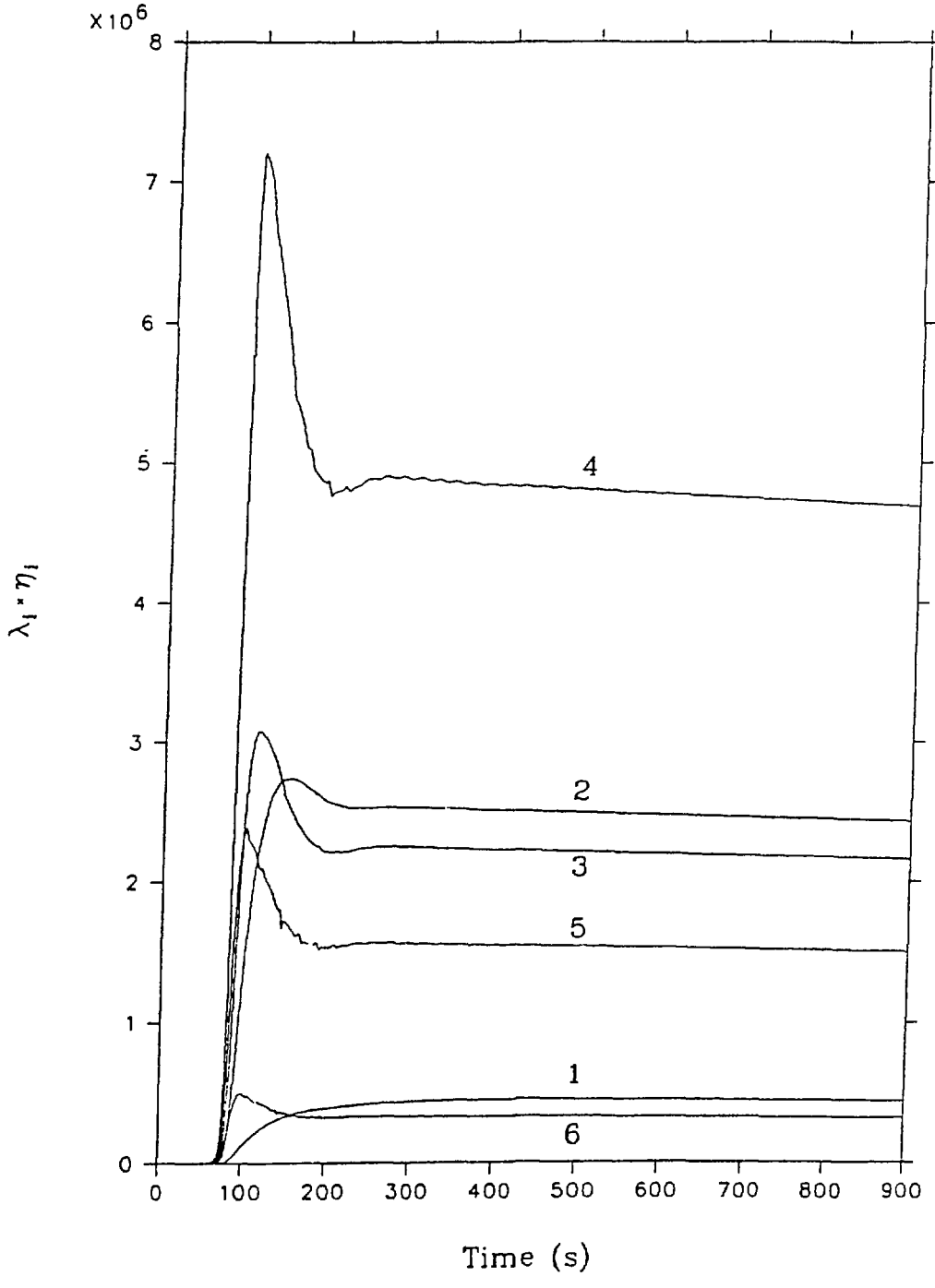

FIGURE 5: The Product of Decay Constant and Concentration for the Six Delayed Precursor Groups

The inverse reactor period is also known as rate log of the reactor power. Figure 6 shows the behaviour of the inverse period during the transient. The inverse period rises during the control rod withdrawal to a maximum of nearly 0.4 s^{-1}, which corresponds to a positive reactor period of 2.5 s. Fuel temperature feedback causes the inverse period to drop, but the reactor power rises until it becomes zero or negative. Note that between 100 and 170 s, the average inverse period is substantially negative. This is visualized in Figure 3 where the power level is seen to drop from 21 MW to about 14 MW over this time duration. The spikes in the inverse period curve occur as a result of the changes in reactivity caused by coolant inlet temperature. After 250 s, there is a slight tendency for α to be negative. This is seen as the slow drop in the power level to 13 MW at 900 s.

Since this transient is the result of the equal withdrawal of all three control rods (sites #272, #350, and #353, in Figure 1), symmetry of fuel channel power levels occurs. The power levels of one of each of the control rods (#272), the inner drivers (#299), and the outer drivers (#273) are plotted in Figure 7. Not surprisingly, the inner driver site develops more power than the outer driver site. Also, by virtue of its smaller fuel loading, the twelve-element control rod assemblies generate far less channel power than the drivers. For each of the sites, the channel power peaks and then decreases (by 200 s) to a level that slowly drops.

In Figures 8, 9 and 10, the variations in channel temperatures are shown. What is referred to as "peak centreline" temperature is the temperature of the centreline of a fuel pin in the hottest axial plane. The "peak fin-base" temperature is the temperature of the cladding surface of the fuel pin in the hottest axial plane midway between two fins. The "bulk coolant" temperature is the average temperature of the coolant in the specified fuel channel. "Inlet coolant" temperature is the temperature of the coolant in the inlet plenum. The "pool temperature" is the average temperature of the light water in the reactor pool.

Figure 8 (outer driver channel, site #273) shows that under the accident scenario, the peak centreline temperature reaches 175°C, well below the failure temperature of 660°C. The peak fin-base temperature rises to 114°C while the bulk coolant temperature seems to stabilize at 53°C. The inlet coolant temperature is the same for all the fuel channels. It is seen to rise from the initial reactor coolant temperature of 20°C to 35°C by 106 s. The heat exchanger then maintains the coolant temperature at this temperature until the capacity of the secondary side is exceeded; the coolant temperature then rises in response to the increased heat deposition in the core. As mentioned earlier, a circuit time of 18 s delays the effects of hot coolant travelling from the core to the inlet plenum. The pool temperature (also shown in Figures 9 and 10) rises very slowly from 20°C to 28.5°C in 900 s. This is the result of the large volume of water in the pool.

Figure 9 shows the behaviour of the fuel-element temperatures for an inner driver (#299) channel. The centreline temperature peaks at

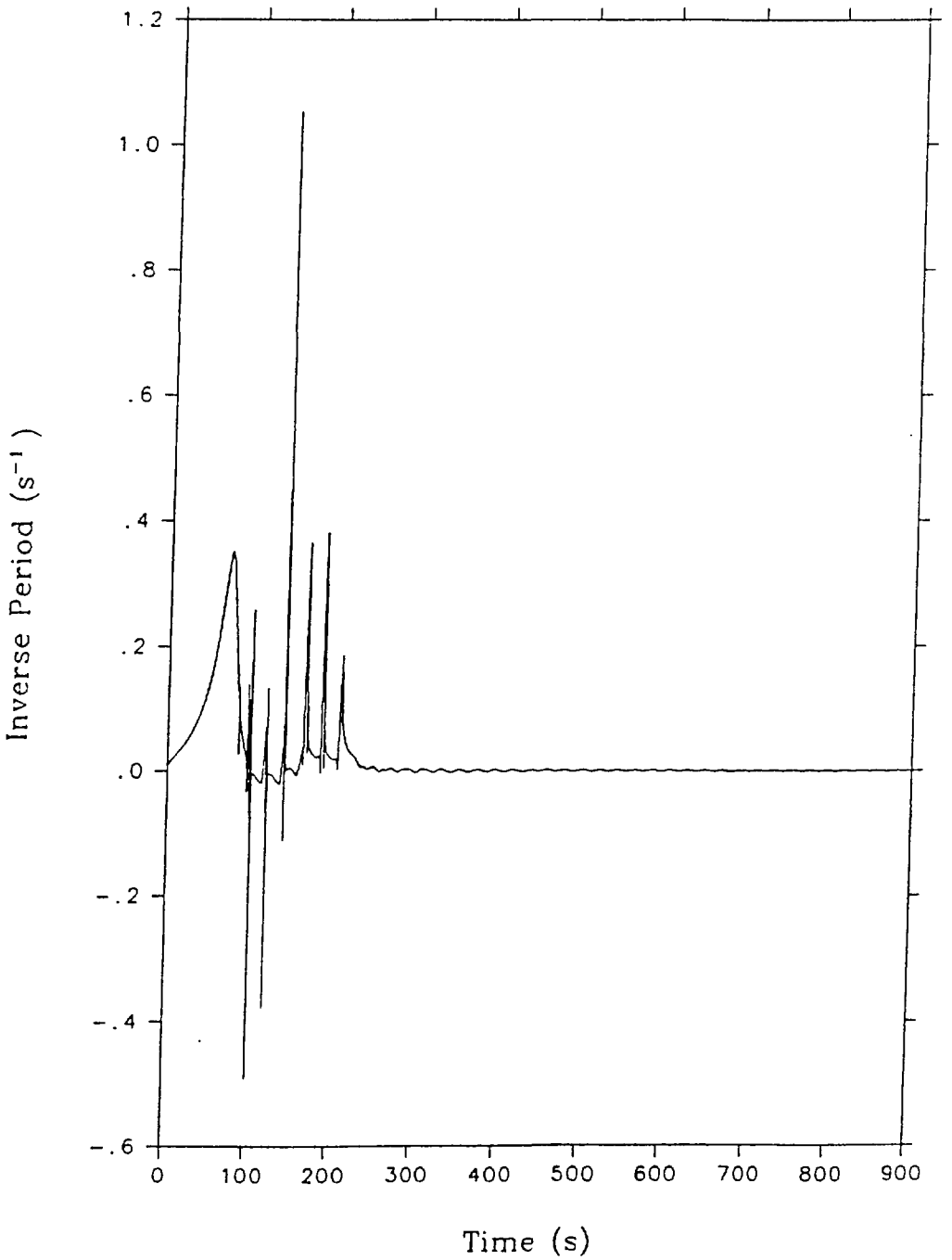

FIGURE 6: Inverse Reactor Period as a Function of Time

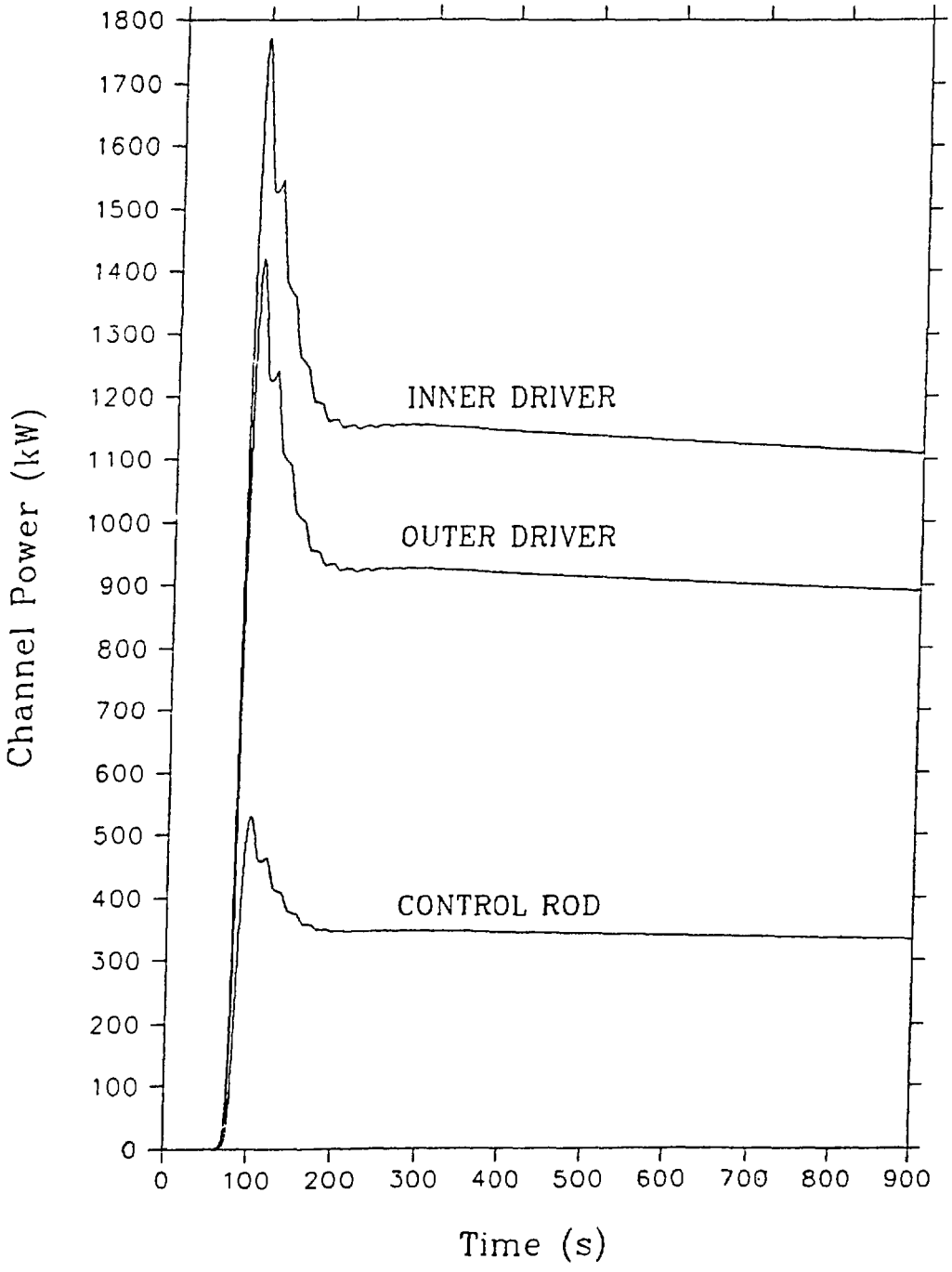

FIGURE 7: TANK Simulation of Channel Power for Representative Inner Driver, Outer Driver, and Control Rod Sites

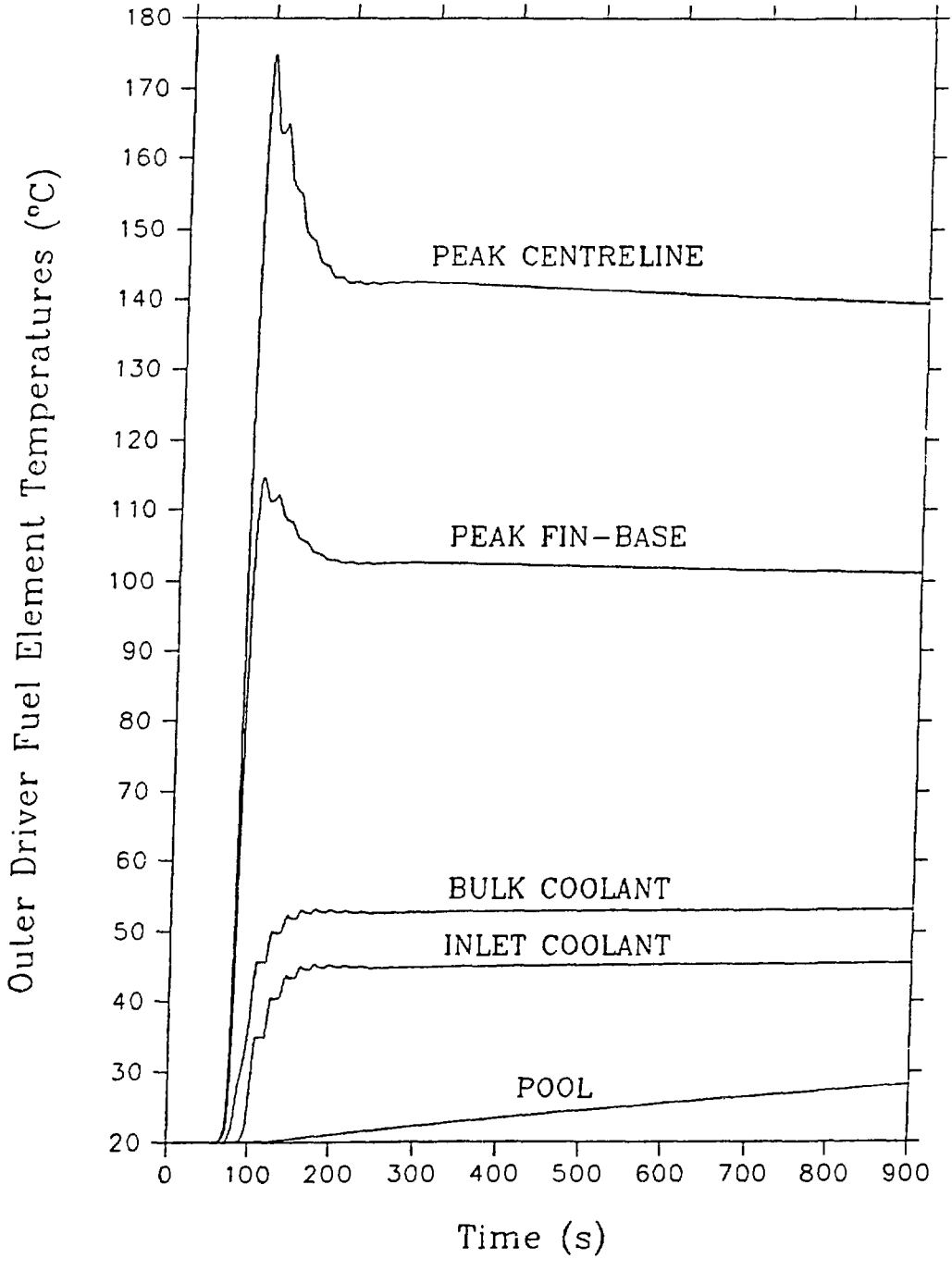

FIGURE 8: **Time Behaviour of Important Fuel Pin Temperatures for an Outer Driver Site**

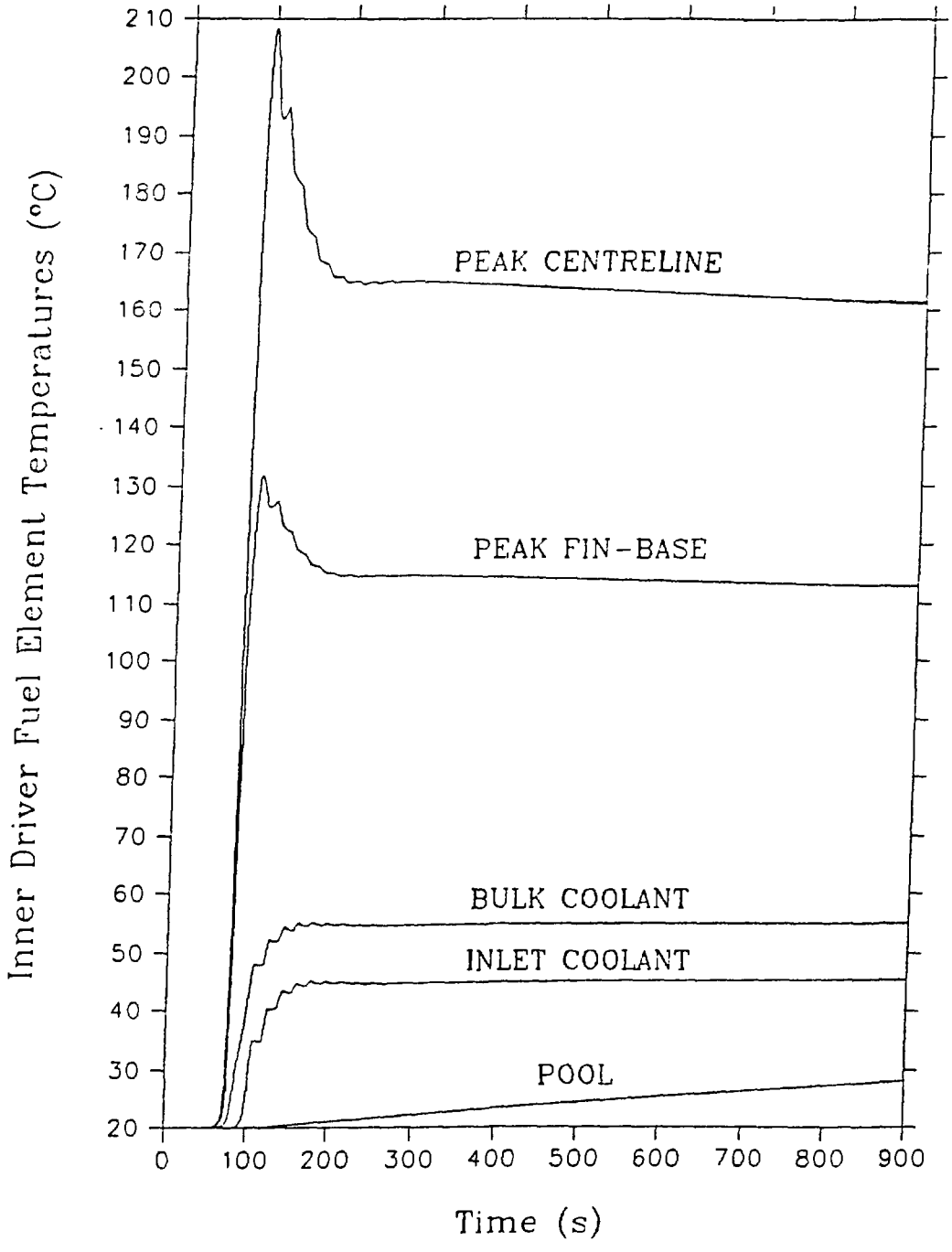

FIGURE 9: Time Behaviour of Important Fuel Pin Temperatures for an Inner Driver Site

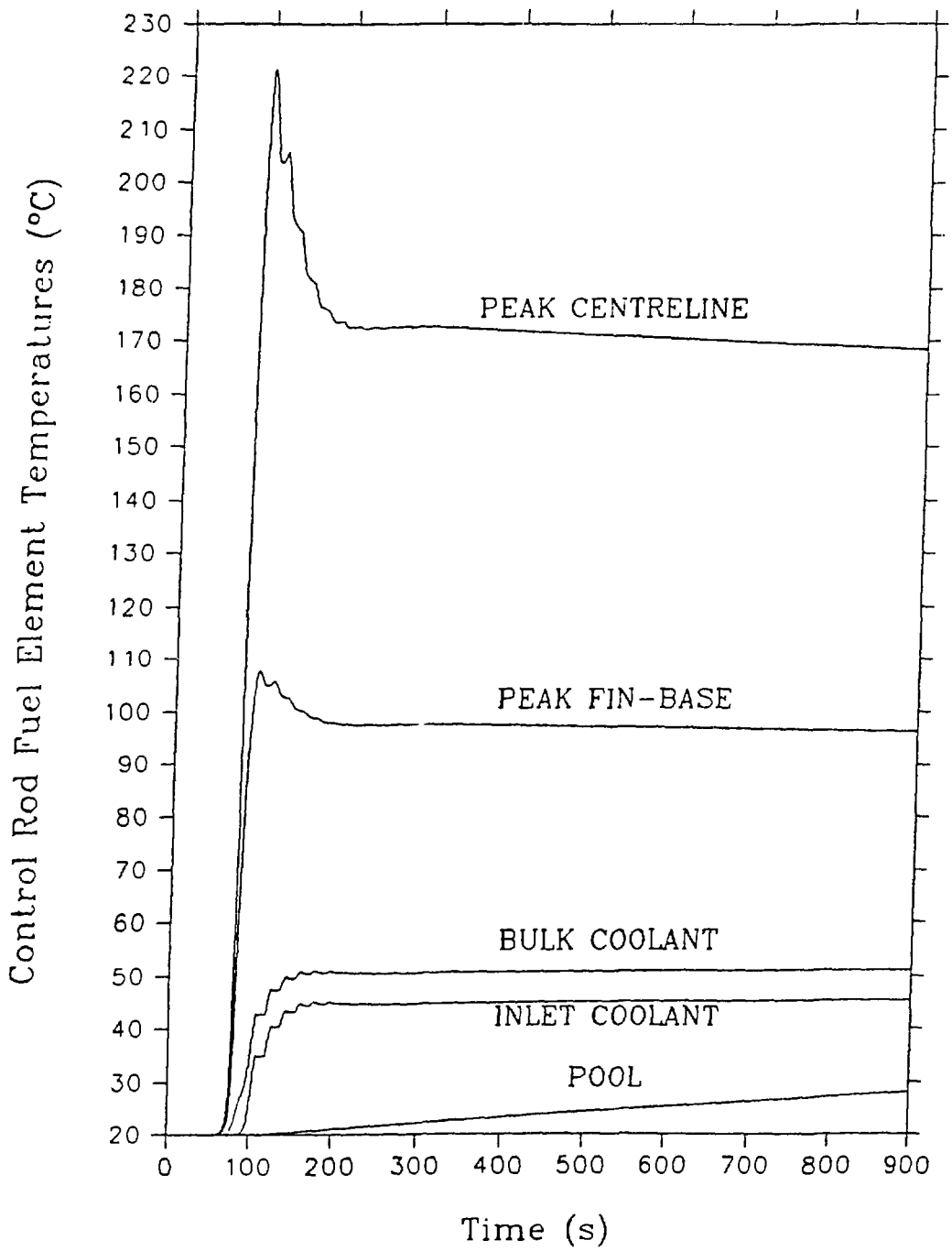

FIGURE 10: **Time Behaviour of Important Fuel Pin Temperatures for a Control Rod Site**

210°C and the fin-base temperature at 132°C. The bulk coolant temperature reaches 55°C.

Figure 10 presents the temperature variations of a fuel element from control rod #272. Although the channel power level is lower than any driver site, the temperatures are greater. This is the result of the smaller size of the twelve-element assembly. The centreline temperature reaches 221°C, which is the hottest fuel temperature anywhere in the core. The fin-base peak temperature reaches 109°C and the bulk coolant temperature is 51°C.

6. CONCLUSIONS

The TANK simulation of the postulated LOR accident scenario shows that the reactor will survive the transient excursion with no damage. All peak temperatures are well below any failure thresholds. By 15 min, the reactor conditions stabilized; in fact, there was a slight drop in power and temperature levels.

Negative temperature reactivity feedback effects play a major role in limiting the transient. Large-scale void formation is not a factor in the arrest of this accident situation, but coolant density decrease (as its temperature rises) does help.

One very interesting observation is that the first 70 s of the transient may go unnoticed. If the inverse period is not monitored, nothing would indicate the accident was under way. There would be a noise associated with the withdrawal of the control rods, but, if that could not be correlated to any other evidence of transient behaviour, the problem could be overlooked. The reactor, though, is seen to be able to bring itself under control, within a relatively short time of about five minutes.

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