

**AUSTRALIAN ATOMIC ENERGY COMMISSION
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**MEASUREMENT OF THE DYNAMIC RESPONSE OF
THE MATERIALS TESTING REACTOR HIFAR**

by

**J.R. HARRIES
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ABSTRACT

Power transients were initiated in the HIFAR Materials Testing Reactor by altering both the temperature of the primary coolant circuit and the flow rate of the primary coolant. Analysis of the time variation of the reactor power and the D₂O temperature provided information about the flow of D₂O in the reactor aluminium tank and the time response of the negative power coefficient. The experimental power transients were compared with calculations carried out with the HIDYN code, which combines the neutron kinetics with the primary coolant characteristics.

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TRANSIENTS; HIFAR REACTOR; REACTOR KINETICS; REACTOR COOLING SYSTEMS;
REACTIVITY; POISONING; TEMPERATURE COEFFICIENT

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1. INTRODUCTION

A knowledge of the temperature coefficient of reactivity for the materials testing reactor HIFAR is necessary for the evaluation of its intrinsic safety. Previously, the temperature coefficient has been measured by determining the reactivity needed to compensate for a change in the reactor D₂O temperature after thermal equilibrium had been established [Wilson 1972; Duerden 1973]. This static coefficient is important for reactor control, but it might not include the time-dependent effects that are essential for the analysis of reactivity or temperature transients. A realistic model of the HIFAR dynamics, including the negative temperature coefficient, decreases the need to rely on the safety instrumentation and allows less stringent operational procedures.

The present experiments were designed to provide data about the dynamic temperature coefficient. In the first set of experiments, with the reactor at 10 MW, temperature transients were induced in the primary coolant by turning off the secondary coolant flow to the heat exchangers. The resulting increase in the D₂O temperature reduced the reactivity and consequently the power. The power was allowed to fall to 0.7 MW; then the secondary flow was restored and the power increased.

In the second set of experiments, flow transients were produced in the primary circuit by switching the third D₂O circulation pump on and off. The resulting D₂O temperature changes again caused a power transient. The analysis of these transients provides information about the dynamic temperature coefficient and enables the reactivity to be expressed as an empirical function of the reactor power, inlet D₂O temperature and D₂O flow rate.

2. HIFAR

2.1 Primary Coolant Circuit

The HIFAR primary circuit (Figure 1) contains 10 tonnes of D₂O of which 6 tonnes is in the reactor aluminium tank (RAT). The D₂O in the RAT (Figure 2) can be divided into three functional components: the coolant D₂O flowing in the fuel elements; the moderator D₂O lying outside the fuel elements but within the core region (*i.e.* a cylinder enclosing the fuel sections of the elements); and the reflector D₂O lying outside the core region. Within the core region 25 per cent of the D₂O is coolant and 75 per cent is moderator. With the two D₂O pumps operating, the mean residence time of the D₂O in the RAT is 15 s.

Four downcomers of 180 mm bore take the D_2O from the outer regions of the RAT into a 254 mm bore suction header, and thence to the three circulation pumps. In normal operation at 10 MW, two D_2O pumps produce a flow rate of 400 kg s^{-1} . With only one pump operating, the the D_2O flow rate is 270 kg s^{-1} and with three pumps operating the flow rate is 475 kg s^{-1} . The pumps deliver the D_2O to a discharge header connected to the tube side of three heat exchangers which are all normally in use. The heat exchangers are cooled on the shell side by light water in the secondary coolant circuit.

After cooling, the D_2O passes up three 230 mm bore pipes into the plenum chamber in the base of the RAT where it is distributed to the 25 fuel elements. The D_2O flows through the coolant channels in the fuel elements at a velocity of about 4 m s^{-1} , and is discharged horizontally from each fuel element through a diffuser outlet consisting of 60 circular apertures of 19 mm diameter. With two pumps operating, the mean velocity of the D_2O leaving the diffuser outlets is 0.85 m s^{-1} . The diffuser outlets are located 1094 mm above the plenum chamber, 80 mm above the downcomer inlets, and 616 mm below the D_2O surface (Figure 2).

2.2 Secondary Coolant Circuit

A simple outline of this circuit is shown in Figure 1. The eight cooling towers have individual fans which may be switched off, or run at low or high speed to allow a variable H_2O cooling rate. The inlet and outlet header valves and the by-pass valve control the H_2O flow through the heat exchangers. Adjustment of these controls allows the operator to keep the D_2O temperature close to 50°C at the inlet to the heat exchanger during normal operation.

2.3 Time Response of the Temperature Coefficient of Reactivity

Changes in the temperature of the coolant D_2O within the fuel elements will produce immediate reactivity changes due to neutron spectrum and leakage effects. At the standard D_2O flow rate the D_2O takes 0.15 s to traverse the coolant channel and, consequently, an instantaneous change in D_2O temperature at the fuel element inlet would result in a reactivity change which would be complete in less than 0.2 s.

The temperature of the moderator D_2O also affects the reactivity, but the lack of knowledge of the flow patterns in the RAT precludes any definite statements about the time response. Changes in the D_2O flow rate or temperature could also produce changes in the mixing patterns.

In normal operation, there does not appear to be any change in reactivity which could be attributed to rapid changes in flow patterns. If such changes occur, the effects are small enough to be masked by random noise or coarse control arm (CCA) oscillations.

Three models of the flow in the RAT can be considered, each predicting different time responses for the moderator D₂O temperature, and hence a possibility of measurable differences in the reactor power transients.

2.3.1 Uniform mixing model

The uniform mixing model assumes that rapid mixing will occur producing a uniform temperature throughout the RAT. For a constant volume reservoir, such as the RAT, the mean D₂O temperature $T_m(t)$ is related to the inlet temperature by

$$T_m(t) = \frac{1}{\tau} \int_0^{\infty} T_f(t-s) \exp(-s/\tau) ds, \quad (1)$$

where $T_f(t-s)$ is the temperature of D₂O entering the RAT from the fuel elements at the earlier time $t-s$ and τ is the mean residence time in the RAT which is given by

$$\tau = \frac{\text{RAT capacity (6169 kg)}}{\text{flow rate } F}.$$

If $T_f(t)$ changes instantaneously from 40 to 50°C, with a flow of 400 kg s⁻¹, it will take 10 s for T_m to rise from 40 to 45°C. Hence uniform mixing throughout the RAT will lead to a significantly delayed component of the temperature coefficient.

2.3.2 Strong flow model

Instead of mixing throughout the RAT, it is more likely that most of the D₂O from the diffuser outlets will be deflected up or down by flows from adjacent fuel elements, and by the obstruction caused by the vertical rigs and the CCAs. This would give a strong flow from the fuel element outlets to the core region.

If half of the flow is directed downwards through the core area of 0.44 m², then the velocity would be 0.41 m s⁻¹ for a total D₂O flow of 400 kg s⁻¹. The velocity must decrease to zero at the plenum surface which is 1.094 m below the outlets. If the velocity decreases linearly, then the time taken for D₂O to flow a distance d below the outlets is:

$$t = (1.094/0.41) \log_e [1.094/(1.094-d)] \quad (2)$$

The delay to reach the mean core height ($d = 0.44$ m) will be 1.4 s. On the other hand, if the downwards flow continues undiminished, at least through the core region, then the delay would be 1.1 s.

Hence this strong flow model implies that the moderator D_2O will respond to a temperature change in the coolant D_2O in 1 to 1.5 s.

2.3.3 Stagnation model

At the other extreme, the D_2O in the core region might not be directly affected by the flow from the fuel element outlets. At 10 MW, the plenum chamber and the top of the fuel element surfaces have a temperature difference of $6^\circ C$ which would tend to establish a stable stratification of the D_2O . It can be shown, by equating the potential and kinetic energy, that a stream of $50^\circ C$ D_2O with downwards velocity of only 0.2 m s^{-1} will penetrate one metre into D_2O at $44^\circ C$. Since the mean velocity of the D_2O emerging from the fuel element diffuser outlets is 0.85 m s^{-1} , some of this D_2O will be deflected downwards with sufficient velocity to destroy any stratification.

Furthermore, at 10 MW, gamma heating of the D_2O at the core centre produces a temperature rise of about $1^\circ C \text{ s}^{-1}$ [Wilson 1970] which will cause convection currents away from this region. Hence, even if the flow from the diffusers does not destroy the stratification, the convection currents caused by gamma heating will ensure movement of the D_2O and the temperature of the core and moderator will be delayed, at most, by some tens of seconds with respect to the D_2O leaving the fuel elements. A delay of this magnitude should be easily recognisable in the transient experiments.

3. TEMPERATURE TRANSIENT EXPERIMENT

This experiment was carried out at the end of a normal operation of 23 days at 10 MW. Five hours before the start of the experiment, the D_2O outlet temperature was reduced from the standard operating temperature of $50^\circ C$ to $40^\circ C$ by running all cooling tower fans at high speed. This allowed a reasonable variation in the D_2O temperature during the experiment without causing the reactor to shut down because of a high fuel element temperature trip.

To produce a temperature transient, the three header valves that control the flow of H_2O to the heat exchangers (Figure 1) were closed as simultaneously as possible. With no secondary coolant flow through the heat exchangers, the primary D_2O temperature increased. The CCA angle was held constant and the rise in D_2O temperature resulted in an immediate

negative power transient which was allowed to continue until the power had fallen to about 0.7 MW. The header valves were then opened to reduce the D₂O temperature, produce a positive reactivity input, and raise the power. The power returned to a value somewhat less than the original 10 MW owing to the buildup of xenon poisoning during the experiment. The CCAs were then raised to restore the reactor power to 10 MW where it remained for about 20 minutes before repeating the sequence.

The basic parameters measured during the transient were the D₂O temperature and reactor power. A fuel element fitted with several thermocouples was loaded into lattice position B3. This fuel element has 24 thermocouples but, for this experiment, data were taken from the thermocouples C1 and C2 which project into the D₂O inlet region (Figure 3), and thermocouples A1 and A4 which are located in the coolant channels above the fuel region. The steady state output voltages from three of the thermocouples were biased off, and the residual signals amplified by a factor of 2000 before being recorded on magnetic tape. The output from one thermocouple was measured using a millivolt potentiometer at regular intervals during each experiment.

A reactor power signal was taken from the installed multiranged linear power channel which consists of a gamma-shielded RC2 ion chamber feeding a signal to a Keithley picoammeter type 409.

The temperature and power signals were recorded on four tracks of an AMPEX FR-1300 tape recorder. Data were recorded for about one minute before the header valves closed and, for the first two experiments, data were only recorded during the power decrease. In the last three experiments, the data were recorded until the power stabilised. Recording finished when the CCAs were moved.

Tape recorded data were subsequently digitised using a 12-bit analogue-to-digital converter (ADC) attached to a PDP9 computer. Samples were taken every 0.5 s, the four channels being sampled successively at intervals of 200 μ s. The digitisation was checked for two of the signals by re-digitising using a 10-bit Digital Electronics Corporation ADC with a PDP10/11 computer.

The gain of the Keithley picoammeter was increased by a factor of ten when the power fell below 1.5 MW, and switched back when it again reached 1.5 MW. Power data were normalised so that the initial power for experiment 5 was 10 MW. The power signal exceeded the linear range

of the tape recorder after switching to the higher sensitivity range (below 1.5 MW), and corrections were made to remove the non-linearity from the data. The signal on the higher sensitivity range was normalised to the low sensitivity range by assuming that the power was continuous and the signal changed by exactly a factor of ten. This meant that a small zero correction was introduced. The resulting power trace for experiment 5 is shown in Figure 4. In this experiment, the power stabilised at about 8.7 MW after the transient and the record ended just before the operator moved the CCAs to raise the power back to 10 MW.

Temperature signals were normalised by using a linear regression to fit the digitised data to the millivoltmeter readings. Figure 5 shows the normalised temperatures above ambient for thermocouples C1 and A4 during experiment 5. When the header valves were closing, the initial effect on the D₂O temperature was small, but the final closure caused a sharp increase in temperature. The total temperature rise corresponded to the normal temperature difference across the heat exchanger of 6°C. As the power decreased, the temperature difference between the A4 and the C1 positions decreased. Reopening the H₂O header valves caused the D₂O temperature to fall rapidly and, as the power rose, the C1 and A4 temperatures again separated.

The mean temperature of the D₂O in the coolant channels of all the fuel elements can be calculated from the inlet temperature and the thermal power. Figure 6 shows the mean coolant temperature as well as the mean temperature of the D₂O at the diffuser outlets of the fuel elements.

3.1 Inverse Kinetics

The reactivity of the system was obtained from the power data by using the inverse kinetics equation:

$$\rho(t) = \beta + \frac{\Lambda}{n(t)} \frac{dn(t)}{dt} - \Lambda \frac{S(t)}{n(t)} - \frac{1}{n(t)} \sum_{i=1}^N \beta_i \{n(0)e^{-\lambda_i t} + \int_0^t n(\tau)\lambda_i e^{-\lambda_i(t-\tau)} d\tau\}, \quad (3)$$

where $\rho(t)$ is the instantaneous reactivity, $n(t)$ is the neutron density, $S(t)$ is the external neutron source, Λ is the prompt neutron generation time, and β_i and λ_i are the yield and decay constant for the delayed neutron group i . The power was assumed to change exponentially between

successive 0.5 second sampling points. Six delayed neutron groups and nine photoneutron groups (Table 1) were used in the calculation. For most of the calculations, the source was assumed negligible and a photoneutron effectiveness of 0.54 was used. The total delayed neutron fraction, β , including photoneutrons, was 0.00704 [Connolly *et al.* 1968]. The inverse kinetics code was checked against the standard HIFAR reactivity table for doubling times of 1, 10, 100 and 1000 s.

The inverse kinetics calculation was carried continuously through the series of five experiments even though the cumulative effect on the long lived groups was very small. The calculated reactivity for experiment 5 is shown in Figure 7. The general shape of the reactivity curve shows a strong resemblance to the temperature curve.

3.2 Xenon Poisoning

During each experiment the reduction of power caused a buildup of xenon and this significantly changed the reactivity of the system. Samarium poisoning can be neglected because it is less than one per cent of the xenon poisoning for the time scales characteristic of the present experiments.

The xenon buildup has been calculated using the equations given by Argonne National Laboratory [1963]. The amount of xenon present depends on the neutron flux during the previous operation. The simplest flux to use is the mean flux obtained from the reactor power and the mass of uranium-235 in the core. This flux certainly gives the correct production rate of xenon in the whole reactor, but it does not make any allowance for the greater reactivity worth of xenon in the higher flux regions at the core centre. Calculations were carried out to determine the effect of increasing and decreasing the flux-to-power ratio by 30 per cent. This was found to have less than one per cent effect on the poisoning curve.

A greater difficulty is the uncertainty in the relationship between xenon concentration and its reactivity worth. Duerden [1973] derived a xenon poison table for HIFAR from various shutdown data and gave a value of 0.01192 $\Delta k/k$ for 30 minutes after shutdown from 10 MW. This was used to normalise the poisoning calculation. However, the poisoning probably varies from core to core and an uncertainty of ± 20 per cent would not be unreasonable.

The xenon poisoning was calculated continuously for the whole

experimental period. Between experiments, the xenon and iodine concentrations were calculated every 30 seconds and, where the necessary power variation had not been recorded on the magnetic tape, it was interpolated with information from the HIFAR operator's log book. At the beginning of each experiment, the CCAs were assumed to have been moved to balance the poisoning. In the calculation a constant component, corresponding to some of the reactivity held in the CCAs, was subtracted from the calculated poisoning reactivity so that the poisoning reactivity was zero at the beginning of each experiment.

The calculated poisoning reactivity for experiment 5 is shown in Figure 7. The positive effect before the transient was due to the burning out of the excess xenon remaining from the previous experiments. At the end of the experiment, the xenon poisoning was worth about $-0.001 \Delta k/k$.

3.3 Temperature Coefficient of Reactivity

The change in reactivity during the transient is due to two effects, the xenon poisoning and the temperature change. After subtracting the poison reactivity, the remaining reactivity is that due to the temperature of the D_2O in the core.

If there are no significant time delays, as in the strong flow model, the reactivity feedback can be related directly to an effective D_2O temperature in the core. The effective temperature is taken to have the form

$$T_e(t) = T_{in}(t) + \gamma D(t) \quad , \quad (4)$$

where $T_{in}(t)$ is the temperature at the fuel element inlet (at thermocouple C1), $D(t)$ is the mean D_2O temperature rise across the core, and γ is the effective temperature parameter which depends on the relative importance of coolant and moderator D_2O . The effective temperature would be expected to be between the mean coolant temperature and the fuel element outlet temperature, i.e. $0.5 < \gamma < 1.0$.

The mean D_2O temperature rise across the core can be expressed as

$$D(t) = P(t) / [F(t) \times C_p] \quad , \quad (5)$$

where $P(t)$ is the reactor power in watts, $F(t)$ is the D_2O flow rate in $kg \ s^{-1}$, and C_p is the specific heat of D_2O in $J \ kg^{-1} \ K^{-1}$.

The reactivity, ρ , has been fitted using the least-squares method to the function

$$\rho(t) = \alpha[T_{in}(t) + \gamma D(t)] + C + \rho_{xe} \quad , \quad (6)$$

where α is the temperature coefficient of reactivity acting on the effective temperature, ρ_{xe} is the xenon poisoning reactivity, and C is a constant that includes the CCA worth. The values of α , γ , and C were varied in the least-squares analysis. The fits to the three experiments for which power increase as well as power decrease data were recorded are shown in Figures 8, 9 and 10. The mean values of the parameters give a reactivity relationship of

$$\rho(t) = 30.9 \times 10^{-5} [T_{in}(t) + 0.78 D(t)] + C + \rho_{xe} \quad . \quad (7)$$

3.3.1 Errors in the temperature coefficient of reactivity

Several sources of error in the analysis were investigated. The reproducibility for the three experiments for which records were taken, during power decrease and increase, gives standard deviations of

$$\sigma_{\alpha} = 0.3 \times 10^{-5} \quad \sigma_{\gamma} = 0.02 \quad . \quad (8)$$

The reactivity worth of a given amount of xenon was obtained by calculating the xenon present 30 minutes after shutdown and normalising to a poisoning reactivity worth of $0.01192 \Delta k/k$ (see Section 3.2). However, this value could be in error by up to $\pm 0.002 \Delta k/k$. When variation of the xenon poisoning of this magnitude is incorporated in the least-squares fit, the parameters are changed by

$$\Delta_{\alpha} = 1.5 \times 10^{-5} \quad \Delta_{\gamma} = 0.08 \quad . \quad (9)$$

The xenon poisoning might need to be referenced to an effective flux that is greater than the mean flux in the core. If the effective flux for the xenon production and removal is varied by 40 per cent from the mean flux, the effect is only

$$\Delta_{\alpha} = 0.05 \times 10^{-5} \quad \Delta_{\gamma} = 0.004 \quad . \quad (10)$$

A variation in the effectiveness of the photoneutron contribution to the chain reaction causes differences in the reactivity calculated by the inverse kinetics calculation. The photoneutrons are less effective than the delayed neutrons produced by fission products, mainly because many are produced further from the core. The calculations assumed a photoneutron effectiveness factor of 0.54, but this is a difficult parameter to determine. If the photoneutron effectiveness factor is changed by 0.20, the fit between the reactivity and temperature is still

satisfactory, and variation in the parameters is

$$\Delta_{\alpha} = 1.2 \times 10^{-5} \quad \Delta_{\gamma} = 0.12 \quad . \quad (11)$$

In the reactor there are many materials being irradiated; some of these materials contribute neutrons by emitting energetic gammas which cause photoneutron emission from the D_2O . The source strength 80 h after shutdown and following the fuel change is about 5 W [Wilson 1972], but this source is derived mainly from the fission photoneutron groups and not from irradiated rigs and other materials. When the reactor is at power, the background source could be greater than the shutdown source. A source of 100 W actually improves the least-squares fit, whereas a source of more than 200 W worsens the fit. With a source of 200 W the parameters change by

$$\Delta_{\alpha} = +0.4 \times 10^{-5} \quad \Delta_{\gamma} = -0.11 \quad . \quad (12)$$

There are two other major sources of error, the measurements of temperature and power. The thermocouples were chromel-alumel junctions used over a small temperature range. In the experiments only the change in temperature was recorded. The output from the recording equipment was checked against the measurements using a bridge type, zero current millivoltmeter and were found to agree within about 1 mV. Further, the thermocouples C1 and C2 measured temperature changes of 16.3 and 16.7°C as the coolant temperature changed from 47 to 33-32°C, i.e. a change of 14-15°C, as measured by installed instrumentation. If the differences are real, which is doubtful, it suggests a potential error of perhaps 11 per cent, and this error produces variations in the parameters of

$$\Delta_{\alpha} = 3.4 \times 10^{-5} \quad \Delta_{\gamma} = 0.08 \quad . \quad (13)$$

Finally the power measurement could be in error. The results depend only on the relative power, and measurements on the equipment after the experiments showed that the picoammeter and the tape recorder were working properly. Some difficulty was experienced because of the non-linearity caused by the overloading of the tape recorder amplifier and the normalisation of the power data taken on the high sensitivity range. To derive an understanding of the likely effects, a least-squares fit was carried out using only the data for powers greater than 3 MW. This caused a change in the parameters of

$$\Delta_{\alpha} = +1.2 \times 10^{-5} \quad \Delta_{\gamma} = -0.07 \quad . \quad (14)$$

All of the errors have been calculated by making pessimistic assumptions about the possible range of uncertainties in the input parameters. An overall error can be obtained by combining the individual errors in quadrature to give

$$\alpha = (30.9 \pm 4.1) \times 10^{-5} \quad \gamma = 0.78 \pm 0.21 \quad . \quad (15)$$

3.4 Discussion

Calculations of the temperature feedback in HIFAR have shown that about 75 per cent of it comes from the temperature of the D₂O in the coolant channels [Connolly, AAEC private communication]. HIFAR is difficult to model because of the large excess reactivity held down by the CCAs and various rigs. The calculated temperature coefficient depends on the method used to achieve criticality in the calculational model. When criticality was obtained by varying the core axial buckling, the temperature coefficient at 40°C was $38.0 \times 10^{-5} \Delta k/k \text{ K}^{-1}$, whereas when all the D₂O in the RAT was poisoned to obtain criticality, the temperature coefficient was $45.6 \times 10^{-5} \Delta k/k \text{ K}^{-1}$.

Although the initial reactivity decrease for experiment 5 lags the temperature by about 2 s (Figure 10), the temperature and reactivity decrease together in experiments 3 and 4 (Figures 8 and 9). Possibly, the difference between the different experiments could be due to the different order of closing the three H₂O valves which have individual switches and motors. The fuel element input temperature was measured at one fuel element and, because only partial mixing occurs in the plenum chamber, the measured temperature was probably weighted towards the temperature change of one of the heat exchangers. Hence a variation in the closing order of the H₂O valves could result in the observed reactivity decrease (a whole reactor effect) being slightly ahead of or behind the measured temperature decrease at the single fuel element.

If there are any delays, they should be apparent as peaks in the residual curves of the fitting procedure at the time of the maximum rate of change of reactivity. There were peaks on the residual curves at these times, but there was no consistency between experiments to indicate whether they were positive or negative. Hence it was concluded that any delays were less than a few seconds. This implies that the D₂O in the RAT follows a flow pattern similar to the flow proposed in the strong flow model (Section 2.3.2).

Attempts were made to fit the data using a uniform mixing in the RAT with 15 s and longer mixing times. However, there was no significant improvement in the fit even with the addition of the extra variable.

For mixing times greater than 200 s, any moderator effects would be indistinguishable from the effect of errors in the xenon poisoning data. To check for the possibility of long delay or mixing time components, the temperature of the D₂O was changed and the CCA angle was recorded every ten minutes for two hours. The temperatures were measured by the thermocouple on the central fuel element and by the thermocouple on the D₂O outlet. In Figure 11, the mean of these two readings is averaged and plotted against the CCA angle. The curve suggests that there are no components of the temperature coefficients with lag times greater than 200 s. The mean temperature coefficient from these data is $(38 \pm 3) \times 10^{-5} \Delta k/k \text{ K}^{-1}$, where the error comes from the uncertainty in the CCA calibration.

4. FLOW TRANSIENT EXPERIMENT

The effective temperature of the D₂O in the core region depends on the temperature of the D₂O at the inlet to the fuel elements and the D₂O flow rate. Flow transients were produced by switching on the third D₂O circulation pump which is off during normal operation. This caused the flow rate to increase from 400 to 475 kg s⁻¹ and produced the small positive power transient shown in Figure 12.

The immediate effect of the increased flow is to reduce the temperature rise in the fuel elements and hence reduce the effective core temperature. This produces a sharp but small increase in power. At the same time, the increased flow through the heat exchanger causes an increase in the temperature of the D₂O leaving the heat exchanger. After about two seconds delay, this warmer D₂O begins to enter the fuel element, increasing the effective core temperature again and causing a decrease in the reactor power. This temperature increase only partially compensates for the initial decrease and so the temperature of D₂O entering the RAT remains less than the temperature before the transient. After about 10 s, this cooler D₂O from the RAT has time to circulate around the primary circuit and the power again rises. Eventually, the whole primary circuit temperature rises owing to the increased power, and the negative temperature coefficient causes the power to stabilise.

During the experiment, the temperatures of all the fuel elements,

except the most highly rated element, were recorded at 10 s intervals, using standard thermocouples and the HIFAR data acquisition system. The inlet D₂O temperature could not be measured because the multi-thermocoupled fuel element was not in the core for this experiment.

The sequence of events in the flow transients is complex, involving the characteristics of the primary coolant circuit. The experiment can only be adequately analysed by comparison with the dynamic model of HIFAR that will be developed in the next section.

5. DYNAMIC MODEL OF HIFAR

5.1 The Primary Coolant Circuit

The model divides the primary coolant circuit into five components:

- . The heat exchangers, including the temperature and flow characteristics, but excluding the mixing and time delays in the pipework.
- . The riser pipework to the fuel elements including half of the heat exchanger.
- . The fuel elements.
- . The reactor aluminium tank.
- . The downcomer pipework, including the D₂O circulation pumps and the other half of the heat exchanger.

This simplified primary coolant circuit is shown in Figure 13.

5.1.1 Heat exchangers

The first component comprises the heat exchanger temperature and flow characteristics. The heat exchangers are a conventional shell and tube type with tubes set on a triangular 14.3 mm pitch. The heavy water flows through the tubes and the light water flows through the shells in four passes.

The overall heat conductance coefficient, U , of a heat exchanger is given [after Glasstone & Sesonke 1967] by:

$$\frac{1}{U} = \frac{d_e}{h_t d_i} + \frac{d_e \log_e (d_e/d_i)}{2k} + \frac{1}{h_s} \quad , \quad (16)$$

where h_t is the tube side heat transfer coefficient, h_s is the shell side heat transfer coefficient, k is the thermal conductivity of the tube wall ($24.2 \text{ W m}^{-1} \text{ K}^{-1}$), d_i is the internal diameter of the tube (7.035 mm) and d_e is the external diameter of the tube (9.525 mm).

The rate of heat transfer, q , is

$$q = UA \Delta T_m \quad , \quad (17)$$

where A is the heat transfer area on the shell side and ΔT_m is the mean temperature difference given by

$$\Delta T_m = [TI(D_2O) - TO(H_2O) + TO(D_2O) - TI(H_2O)]/2, \quad (18)$$

where TI is the inlet temperature and TO is the outlet temperature.

Now the outlet temperatures from the heat exchanger can be related to the rate of heat transfer, q, by

$$\begin{aligned} TO(D_2O) &= TI(D_2O) - q/[F(D_2O)C_p(D_2O)] \\ TO(H_2O) &= TI(H_2O) + q/[F(H_2O)C_p(H_2O)] \end{aligned}, \quad (19)$$

where F is the flow rate and C_p the specific heat at constant pressure. The outlet temperatures from equation 19 can be substituted into equations 17 and 18 to obtain the rate of heat transfer in a form independent of the outlet temperatures.

$$q = \frac{UA[TI(D_2O) - TI(H_2O)]}{1 + \frac{UA}{2} \left[1/[F(D_2O)C_p(D_2O)] + 1/[F(H_2O)C_p(H_2O)] \right]}. \quad (20)$$

The shell side heat transfer coefficient, h_s , is determined from the following correlation:

$$j = \frac{h_s}{C_p G_{\max}} Pr_b^{2/3} \left(\frac{\mu_s}{\mu_b} \right)^{0.14}, \quad (21)$$

where j is the Colburn j factor, $G_{\max}$ is the mass flow per unit area (= H_2O flow in $kg\ s^{-1}/0.7113\ m^2$), μ is the viscosity, C_p is the specific heat at constant pressure, Pr is the Prandtl number ($C_p \mu/k$), k is the thermal conductivity, s refers to the wall surface and b refers to the bulk property.

Kreith [1973] gives values of j as a function of $(G_{\max} d_e / \mu_b)$ for the lattice size and geometry of the HIFAR heat exchangers. The bulk temperature was taken to be the mean of the inlet and outlet temperatures. The temperature difference between the wall surface and the bulk coolant will be less than $15^\circ C$ and so the factor $(\mu_s / \mu_b)^{0.14}$ could be taken as unity. Knowledge of j enables h_s to be calculated for any set of temperatures and flow rates.

The tube side heat transfer coefficient is determined from another correlation given by Kreith [1973] for straight tubes:

$$h_t = 0.023 C_p G Re_d^{-0.2} Pr^{-2/3}, \quad (22)$$

where G is the mass flow per unit area (= D_2O flow in $kg\ s^{-1}/0.2146\ m^2$),

Re_d is the diameter Reynolds number (Gd_i/μ) and all properties are evaluated at the film temperature. The film temperature is derived as follows:

$$T_{\text{film}} = (T_{\text{bulk}} + T_{\text{surface}})/2 \quad , \quad (23)$$

$$\text{where } T_{\text{bulk}} = (T_{\text{in}} + T_{\text{out}})/2 \quad , \quad (24)$$

$$\text{and } T_{\text{bulk}} - T_{\text{surface}} = q/(h_t A_i) \quad , \quad (25)$$

where A_i is the internal heat transfer area of the tubes.

The material properties of D_2O and H_2O used in the calculations are listed in Table 2 with linear interpolation being used within the $10^\circ C$ intervals. A preliminary heat exchanger calculation was carried out with the material properties at the inlet temperatures. The heat transfer coefficients were calculated with equations 21 and 22, the overall heat conduction by equation 16 and the rate of heat transfer by equation 20. The preliminary calculation provided an estimate of the outlet temperatures by equation 19 which could be used to determine the bulk and film temperatures by equations 23, 24 and 25. The calculation was then repeated with the material properties at these more realistic temperatures.

The calculated D_2O outlet temperature is shown as a function of H_2O flow rate and D_2O inlet temperature in Figures 14 and 15 respectively.

Before the heat exchanger characteristics can be used in the dynamics program, an allowance must be made for the heat capacity of H_2O on the shell side. The mass of H_2O is 2454 kg and this acts as an additional mixing mass in the primary circuit. The specific heat of D_2O and H_2O are almost equal so a mixing volume of 2454 kg is used with the sum of the D_2O and H_2O flow rates. The temperature of D_2O leaving the heat exchanger, $T_1(t)$, is given by

$$T_1(t) = TO(D_2O, t) + [T_1(t-\Delta t) - TO(D_2O, t)] \exp(-(F_d + F_h)\Delta t/2454), \quad (26)$$

where $TO(D_2O, t)$ is the instantaneously determined D_2O outlet temperature from equation 19, F_d is the D_2O flow rate in $kg\ s^{-1}$, F_h is the H_2O flow rate in $kg\ s^{-1}$, and Δt is the time step used in the calculation.

5.1.2 Risers

The D_2O from the heat exchangers passes up the risers, through the inlet plenum to the fuel element inlets. For the model, the risers are taken to include all the pipework in the latter half of the heat exchangers, the risers and the plenum. This contains 919 kg of D_2O and

causes a time delay between the heat exchangers and the fuel elements. In addition, the turbulence and the varying flow profile across the pipes causes longitudinal mixing in the pipework. Davies [1972] gives a correlation for the calculation of the effective longitudinal diffusivity for straight pipes. For a flow of 400 kg s^{-1} , the mean time delay from the heat exchanger to the inlet of the fuel element is 1.625 s and the longitudinal mixing, assuming only straight pipes of the same diameter as the risers, would introduce a standard deviation of 0.22 s about the mean. The branching, bends, and changes in cross section in the actual pipework could increase the mixing considerably. For the model, it was assumed that 25 per cent of the pipework mass, i.e. 230 kg, was taken as a mixing reservoir, leaving 75 per cent, i.e. 689 kg, as a delay. Hence the inlet temperature to the fuel elements, $T_2(t)$, was calculated as

$$T_2(t) = T_1(t - \delta_1) + [T_2(t - \Delta t) - T_1(t - \delta_1)] \exp(-F_d \Delta t / 230) \quad , \quad (27)$$

where the time delay δ_1 is

$$\delta_1 = 689 / F_d \quad .$$

5.1.3 Fuel elements

The D_2O flows through the fuelled region of the fuel elements in 0.15 s during normal operation. The mean temperature across the core at the outlet of the fuel elements, $T_3(t)$, is given by

$$T_3(t) = T_2(t) + P(t) / (F_d C_p) \quad , \quad (28)$$

where $P(t)$ is the instantaneous power in watts, F_d is the flow in kg s^{-1} and C_p is the heat capacity in $\text{J kg}^{-1} \text{K}^{-1}$. The transit time of the D_2O through the fuel elements is not included.

5.1.4 Reactor aluminium tank

The D_2O leaving the fuel elements is mixed with the 6168 kg of D_2O already in the RAT. Although the strong flow discussed in Section 2.3.2 probably does exist within the core region, the volume of the core is less than 10 per cent of the RAT volume. Mixing in the RAT volume is the more important process, and the RAT outlet temperature is assumed to be equal to the mean temperature of all the D_2O in the RAT. Hence the RAT outlet temperature, $T_4(t)$, is given by

$$T_4(t) = T_3(t) + [T_4(t - \Delta t) - T_3(t)] \exp(-F_d \Delta t / 6168) \quad . \quad (29)$$

5.1.5 Downcomers

The D_2O flows down the downcomers, through the pumps and the

headers into the heat exchangers. The downcomers are taken to include all the pipework from the downcomer inlets to halfway through the heat exchangers. The temperature relation of the downcomers is calculated in the same way as the risers. Twenty-five per cent of the D₂O is taken to be a mixing reservoir and the other 75 per cent is taken to cause a time delay.

The power dissipated by the circulation pumps (45 kW/pump) will appear as heating in the primary circuit and is added in the downcomer component.

As well as the D₂O in the circuit, there is a thermal capacity associated with the pipework in the whole primary circuit. A water equivalent for the pipework of 3000 kg was assumed and this was added in the downcomer section.

Combining all these effects, the temperature at the input to the heat exchanger was given by

$$T_5(t) = T_4(t - \delta_4) + T_p + [T_5(t - \Delta t) - T_4(t - \delta_4) - T_p] \times \exp[-F_d \Delta t / (576 + W_e)] \quad , \quad (30)$$

where the time delay δ_4 is

$$\delta_4 = 1727 / F_d \quad ,$$

the temperature rise T_p due to N pumps is

$$T_p = 45000N / (F_d C_p) \quad ,$$

and W_e is the water equivalent of the pipework.

5.2 The HIDYN Code

The description of the HIFAR primary coolant circuit (Section 5.1) is combined with a neutron kinetics calculation in the HIDYN code.

The neutron kinetics is calculated using the point reactor kinetics code AIREK III [Blue & Hoffman 1963]. This code calculates the reactor power from a given reactivity function and in the original form varies the time step to provide constant accuracy. The HIDYN model uses fixed time steps, usually 0.5 s, to simplify the interface between the neutronics and the coolant circuit calculations.

The reactivity is calculated using the formula derived in the temperature transient experiment (equation 7) which relates the reactivity to the D₂O temperature at the fuel element input, the reactor power, the D₂O flow rate and the xenon concentration. The xenon calculation is

essentially as described in Section 3.2 for the temperature transient experiment.

HIDYN accepts a set of initial equilibrium conditions, and transients are produced by varying the parameters of the primary or secondary coolant circuit. The type of transient is determined by an input parameter, and complex changes in flow rates or input temperatures can be set up in the subroutines. The code initially adjusts the H₂O inlet temperature so that the heat transferred through the heat exchanger is equal to the power produced in the reactor.

A range of input parameters can be specified; these include the individual circulation pump power, the water equivalent of the pipework, the thermal capacity of the H₂O in the heat exchanger, the temperature coefficient of reactivity, and also neutron kinetic parameters such as prompt neutron lifetime and the delayed neutron groups. The code determines the equilibrium xenon and iodine concentrations but it will accept non-equilibrium values as input if required. This feature was necessary to enable the code to reproduce the conditions of the temperature transient experiment.

5.3 Comparison with Experiment

The code has been used to calculate the power profiles corresponding to the measured temperature and flow transients. Temperature transients were initiated by decreasing the flow rate of the secondary coolant at a rate corresponding to the closing of the H₂O inlet valves. The valves take 50 s to close, the flow being reduced by 17 per cent in the first 40 s, and essentially stopping 4 s before the valve closure is complete.

The calculated power profiles for temperature coefficients of $30.9 \times 10^{-5} \Delta k/k \text{ K}^{-1}$, as stated in Section 3, and $43.4 \times 10^{-5} \Delta k/k \text{ K}^{-1}$, as obtained from static measurements [Wilson 1972, Duerden 1973] are shown in Figure 4. The calculated temperatures around the primary circuit for $\alpha = 43.4 \times 10^{-5} \Delta k/k \text{ K}^{-1}$ are shown in Figure 16. The initial xenon and iodine values and the closing and opening times of the H₂O valves have been taken from experiment 5.

Similar calculations were carried out for the D₂O flow rate transient experiment. The transient was initiated by increasing the D₂O flow rate linearly from 400 to 475 kg s⁻¹ over 1.5 s and adding the 45 kW power from the third pump. The calculated power for the flow transients is compared with the observed power trace in Figure 12. Because the

temperature at the inlet of the fuel elements is initially constant, the first peak, 3 s after the third pump is switched on, is proportional to the product of the temperature coefficient, α , and the effective temperature parameter, γ , of equation 6. Comparison of the calculated peak power for various values of α and γ with the observed relative peak power shows that the product, $\alpha\gamma$, is

$$\alpha\gamma = 35.7 \times 10^{-5} \Delta k/k \text{ K}^{-1} \quad . \quad (31)$$

This initial peak is an immediate temperature effect and depends on the change in the D₂O flow rate, but it is relatively insensitive to the other primary coolant circuit parameters. Since γ cannot be greater than 1.0, and is more likely to be about 0.78 as found in the temperature transient experiment, this implies that $\alpha \sim 46 \Delta k/k \text{ K}^{-1}$.

6. CONCLUSIONS

Small experimental power transients have shown that the time delay between the change in the temperature of coolant entering the HIFAR core and the resulting reactivity change was less than two seconds. The lack of any significant feedback contribution delayed by more than this implies that the D₂O from the fuel element outlets flows into the region between the fuelled sections of the fuel elements within two seconds.

The dynamic temperature coefficient of $(30.9 \pm 2) \times 10^{-5} \Delta k/k \text{ K}^{-1}$ deduced from the temperature transient experiment is less than the observed static coefficient of $43.4 \times 10^{-5} \Delta k/k \text{ K}^{-1}$ which is consistent with the flow transient experiment. It is suspected that the temperature measurements of the temperature transient experiment could be in error. Most likely the coefficient of $43.4 \times 10^{-5} \Delta k/k \text{ K}^{-1}$ is the correct value but, for safety studies where it is important to be conservative, the value of $30 \times 10^{-5} \Delta k/k \text{ K}^{-1}$ would be advisable unless the discrepancy is reduced by further experiment.

The HIDYN code that was developed to aid the analysis of these experiments has been able to calculate power profiles in reasonable agreement with the experimental transients.

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TABLE 1
DELAYED AND PHOTONEUTRON DATA

Delayed Neutrons, $\beta = 0.0065$

Group	Half-life	Decay Constant (s^{-1})	β_i
1	55.72 s	0.0124	0.000215
2	22.72 s	0.0305	0.001424
3	6.22 s	0.111	0.001274
4	2.30 s	0.301	0.002568
5	0.61 s	1.14	0.000748
6	0.23 s	3.01	<u>0.000273</u>
			0.0065

Photoneutrons, $\beta_\gamma = 0.0010$, photoneutron
effectiveness $\gamma_p = 0.54$

Group	Half-life	Decay Constant (s^{-1})	$\gamma_p \beta_i$
7	12.8 d	6.26×10^{-7}	2.65×10^{-7}
8	53 h	3.63×10^{-6}	5.51×10^{-7}
9	4.4 h	4.37×10^{-5}	1.72×10^{-6}
10	1.65 h	1.17×10^{-4}	1.25×10^{-5}
11	27 m	4.28×10^{-4}	1.11×10^{-5}
12	7.7 m	1.50×10^{-3}	1.80×10^{-5}
13	2.4 m	4.81×10^{-3}	3.76×10^{-5}
14	41 s	1.69×10^{-2}	1.09×10^{-4}
15	2.5 s	2.77×10^{-1}	<u>3.49×10^{-4}</u>
			5.40×10^{-4}

TABLE 2(a)
PROPERTIES OF H₂O USED IN THE MODEL

Temp. (°C)	Specific Heat, C_p (J kg ⁻¹ K ⁻¹)	Absolute Viscosity, μ (N s m ⁻²)	Prandtl No. Pr
0.01	4218	1.786×10^{-3}	13.2
10	4194	1.304×10^{-3}	9.32
20	4182	1.002×10^{-3}	6.95
30	4179	0.7983×10^{-3}	5.40
40	4179	0.6539×10^{-3}	4.33
50	4181	0.5478×10^{-3}	3.56
60	4185	0.4673×10^{-3}	2.99
70	4191	0.4048×10^{-3}	2.56
80	4198	0.3554×10^{-3}	2.23
90	4207	0.3156×10^{-3}	1.96
100	4218	0.2831×10^{-3}	1.75

Data from the UK Committee on the Properties of Steam [1970]

TABLE 2(b)
PROPERTIES OF D₂O

Temp. (°C)	Specific Heat, C_p (J kg ⁻¹ K ⁻¹)	Absolute Viscosity, μ (N s m ⁻²)	Prandtl No. Pr
0	(4248)	$(2.356) \times 10^{-3}$	(17.81)
10	4224	1.684×10^{-3}	12.31
20	4212	1.260×10^{-3}	8.98
30	4208	0.972×10^{-3}	6.77
40	(4208)	0.788×10^{-3}	(5.39)
50	(4210)	$(0.659) \times 10^{-3}$	(4.47)
60	(4214)	0.552×10^{-3}	3.68
70	(4220)	$(0.481) \times 10^{-3}$	(3.18)
80	(4227)	$(0.418) \times 10^{-3}$	(2.74)
90	(4236)	0.365×10^{-3}	2.39
100	(4247)	0.323×10^{-3}	2.11

Data from Lottes [1960] with interpolated values in parenthesis.

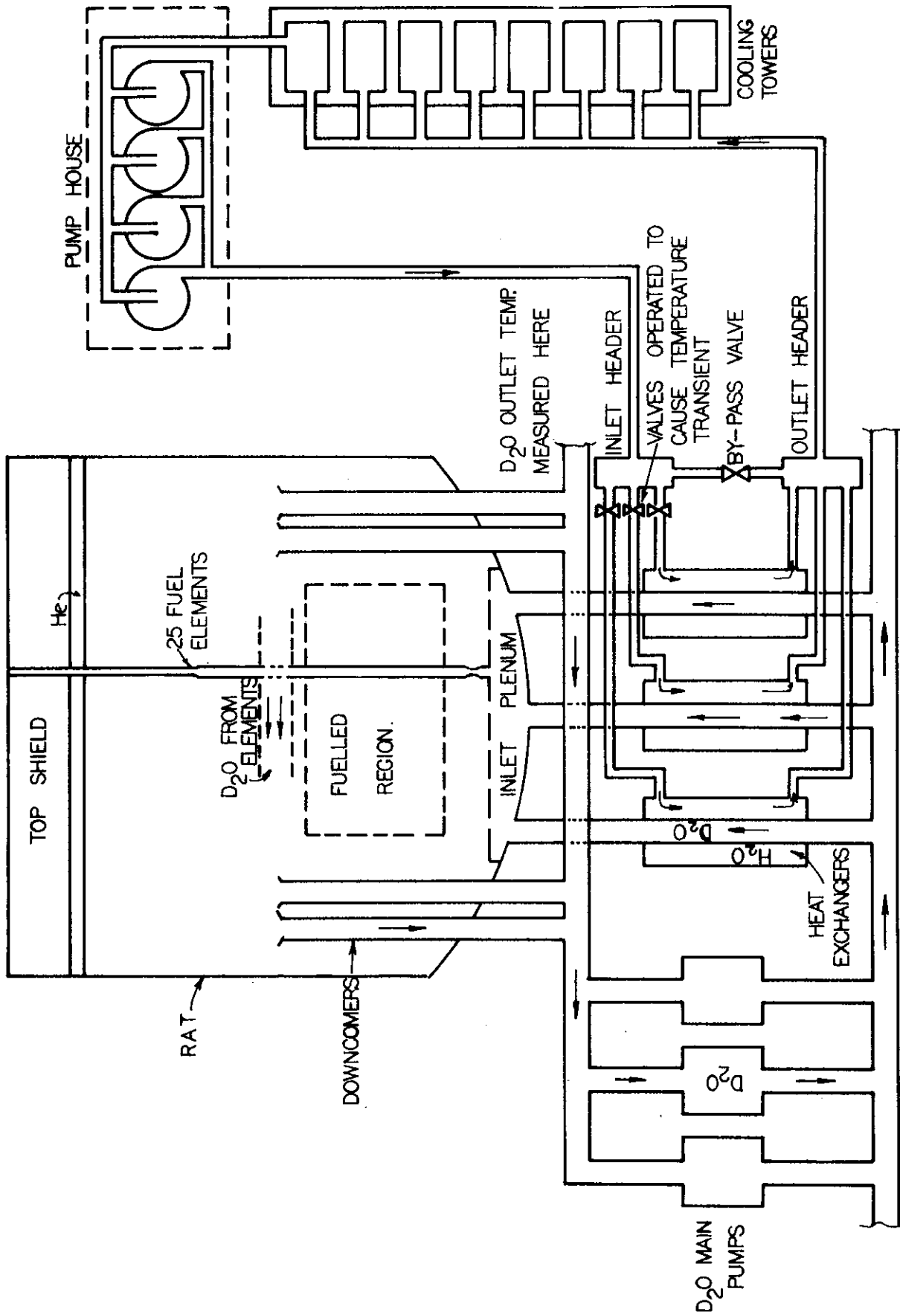


FIGURE 1. HIFAR PRIMARY COOLANT CIRCUIT

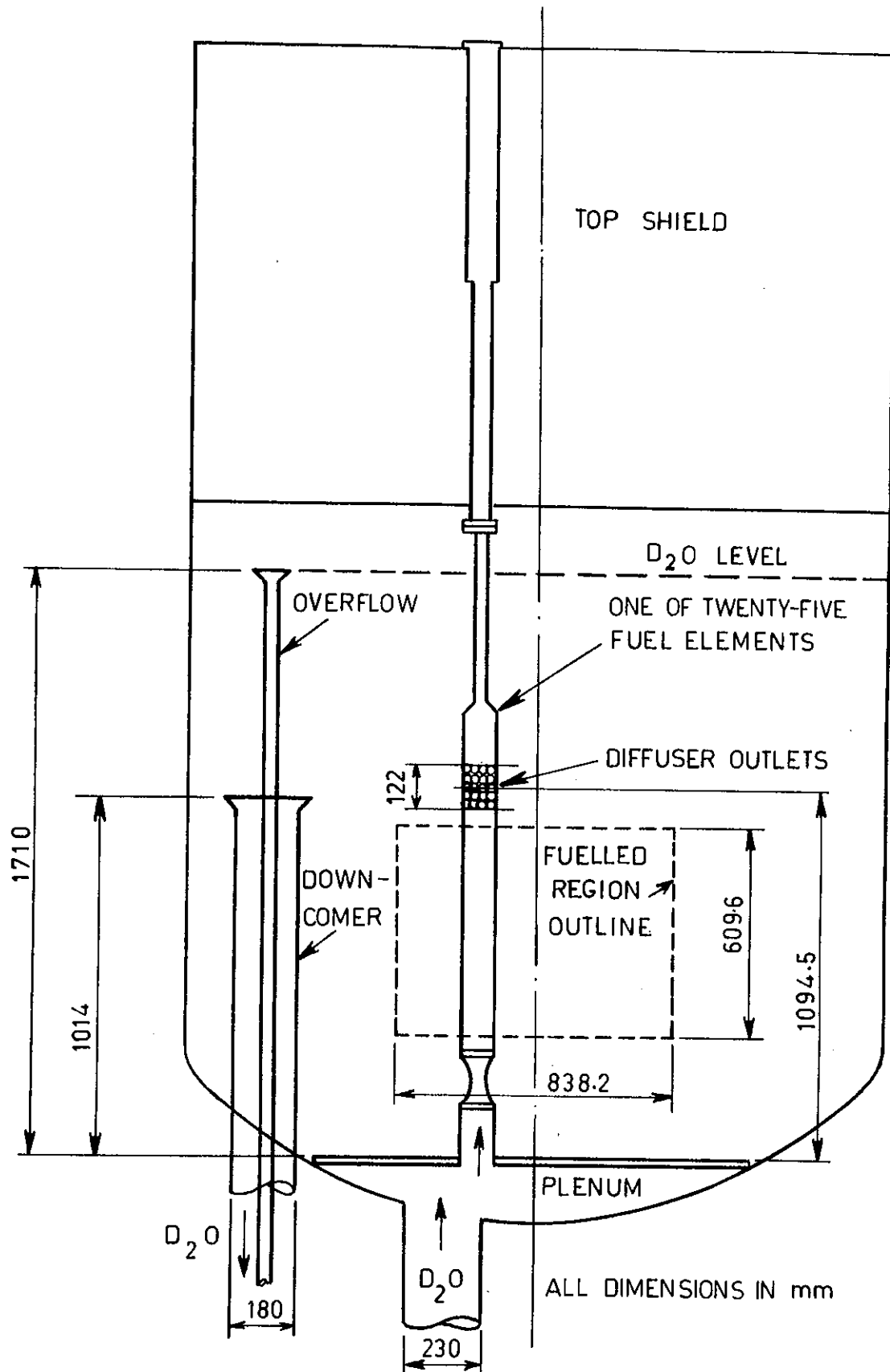


FIGURE 2. INTERNAL LAYOUT AND DIMENSION OF THE REACTOR ALUMINIUM TANK AND CONTENTS

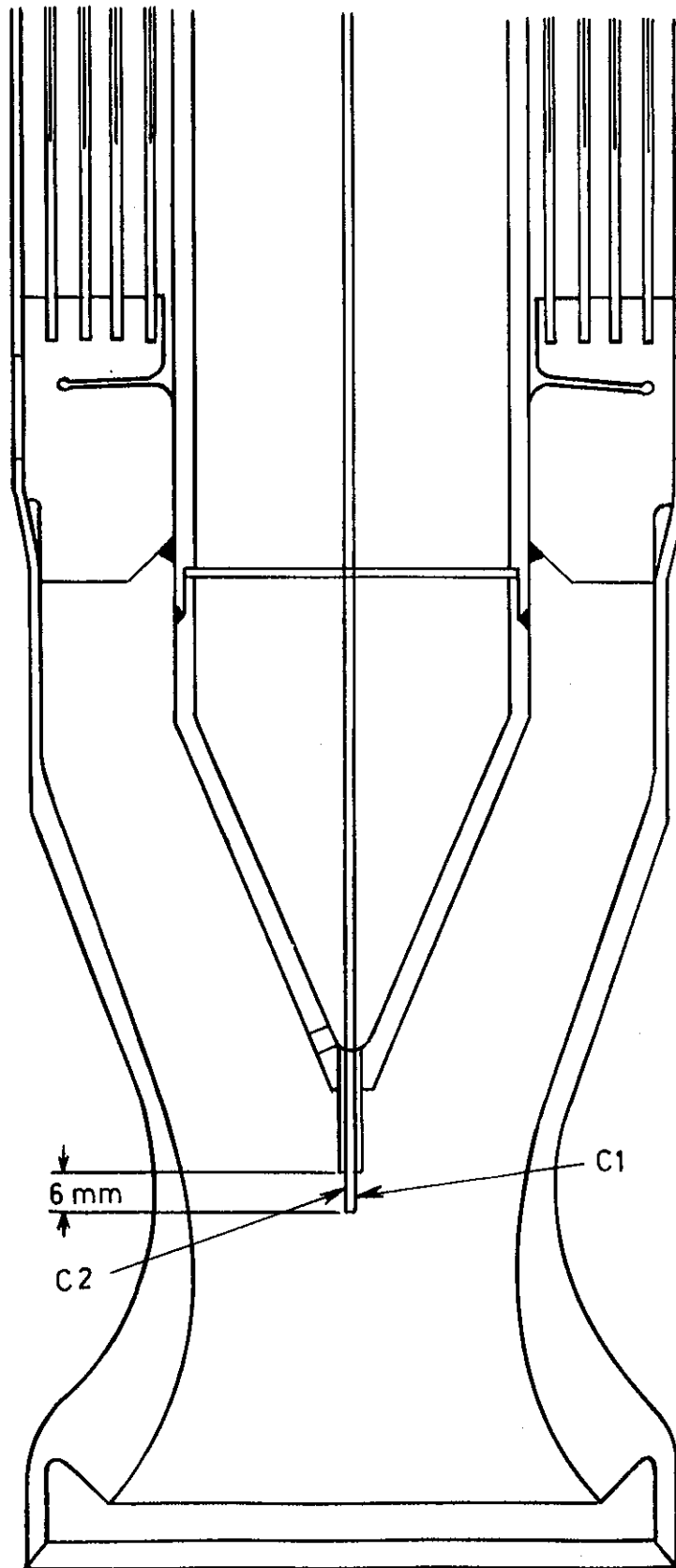


FIGURE 3. THE POSITION OF THERMOCOUPLES C1 AND C2 AT THE COOLANT INLET TO THE FUEL ELEMENT.

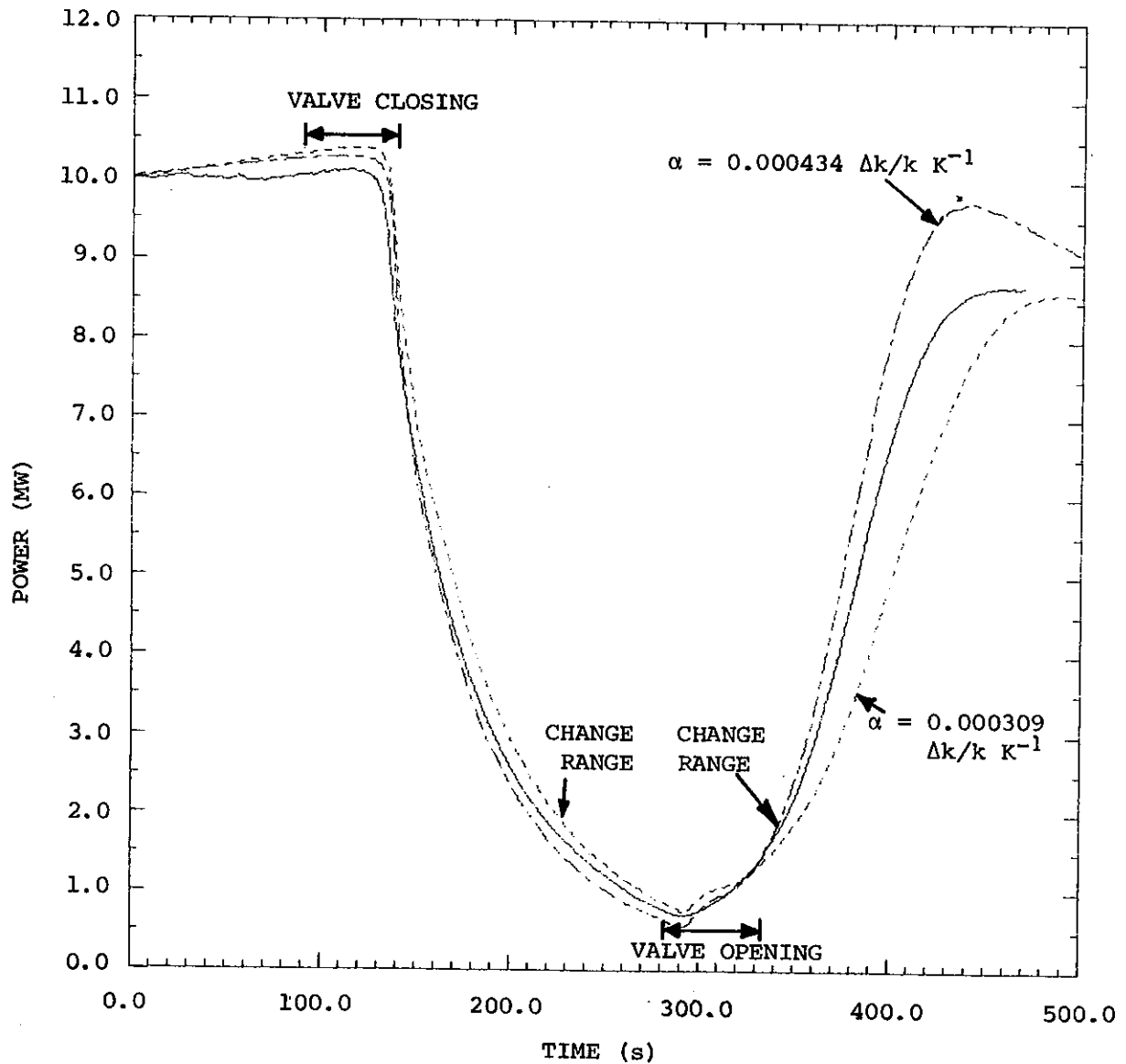


FIGURE 4. THE POWER TRANSIENT (FULL LINE) PRODUCED BY STOPPING AND STARTING THE SECONDARY COOLANT FLOW IN EXPERIMENT 5 COMPARED WITH THE POWER CALCULATED USING HIDYN (DOTTED LINES)

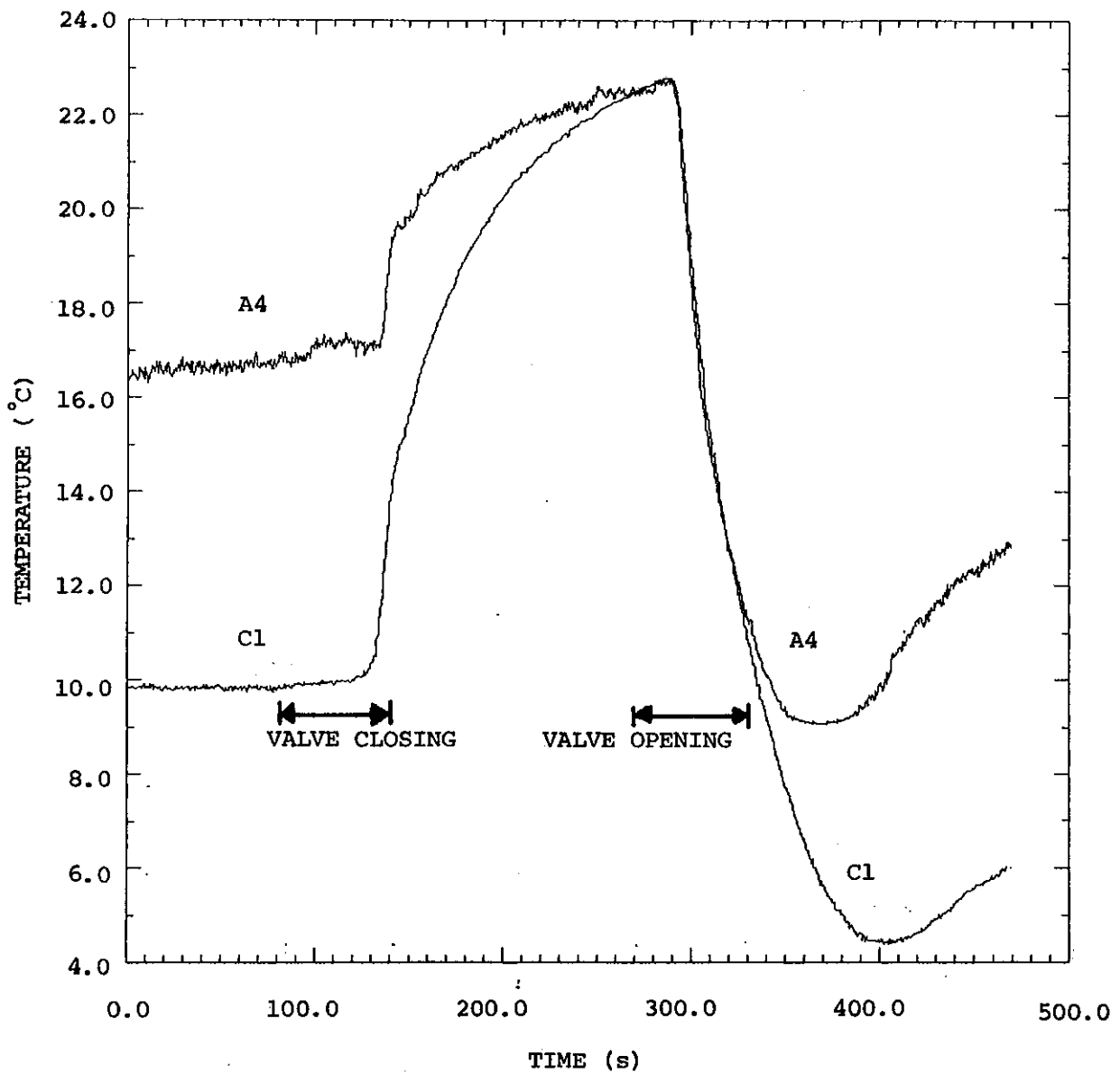


FIGURE 5. THE TEMPERATURES ABOVE AMBIENT MEASURED BY THERMOCOUPLES A4 AND C1 FOR EXPERIMENT 5.

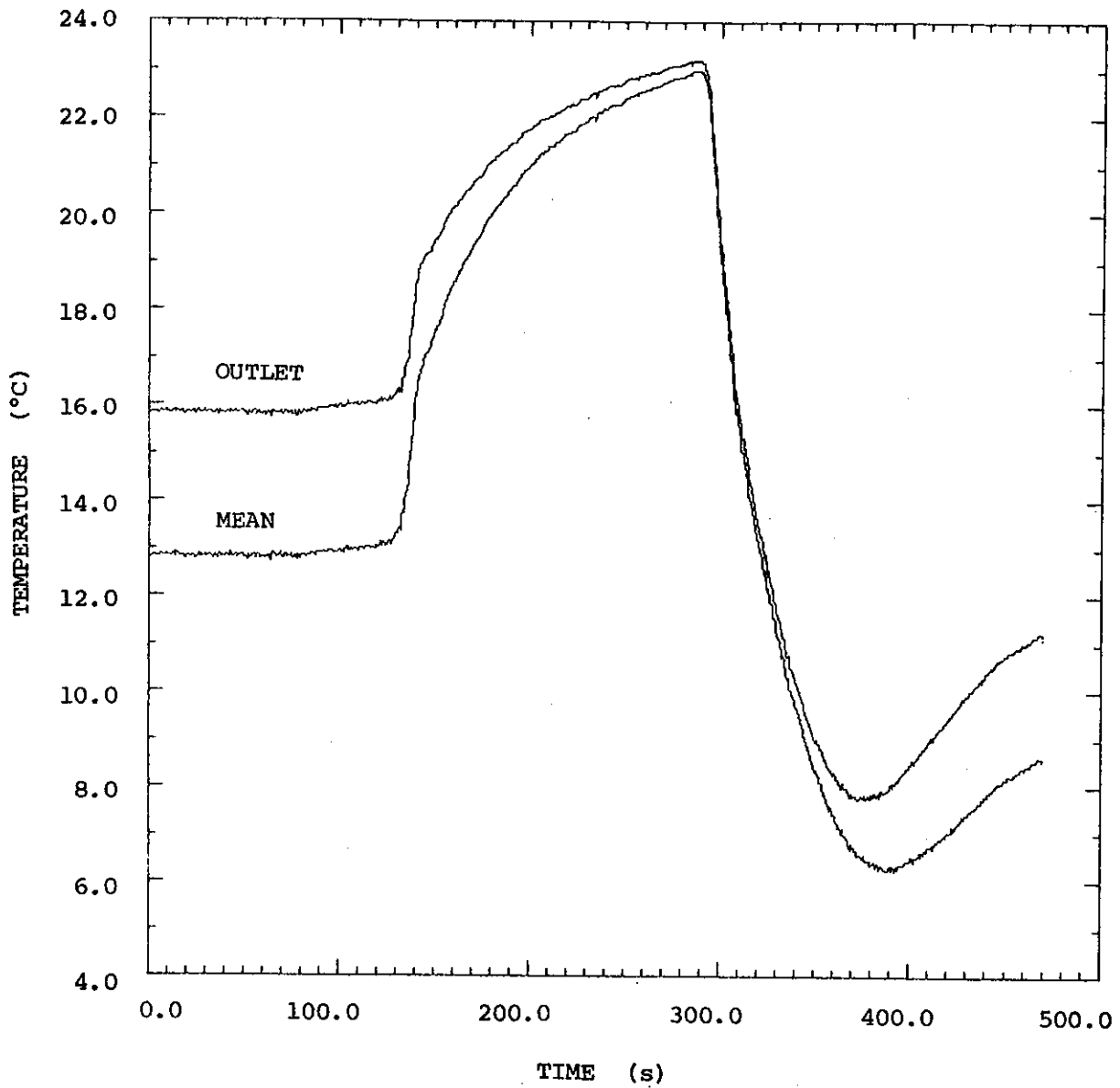


FIGURE 6. THE MEAN D₂O TEMPERATURE IN ALL THE FUEL ELEMENTS AND MEAN TEMPERATURE AT THE FUEL ELEMENT DIFFUSER OUTLETS

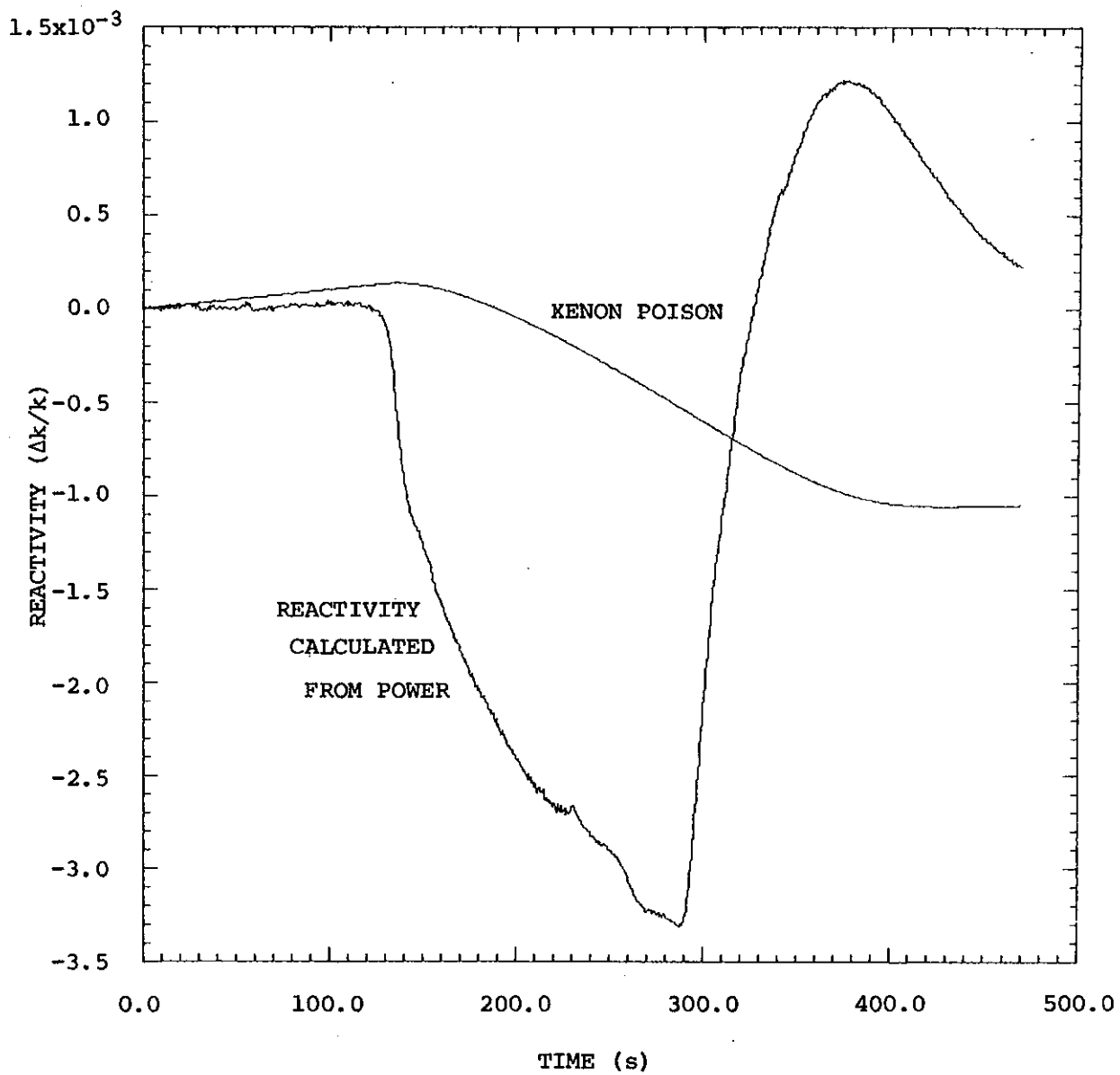


FIGURE 7. THE CALCULATED REACTIVITY AND XENON POISONING FOR EXPERIMENT 5

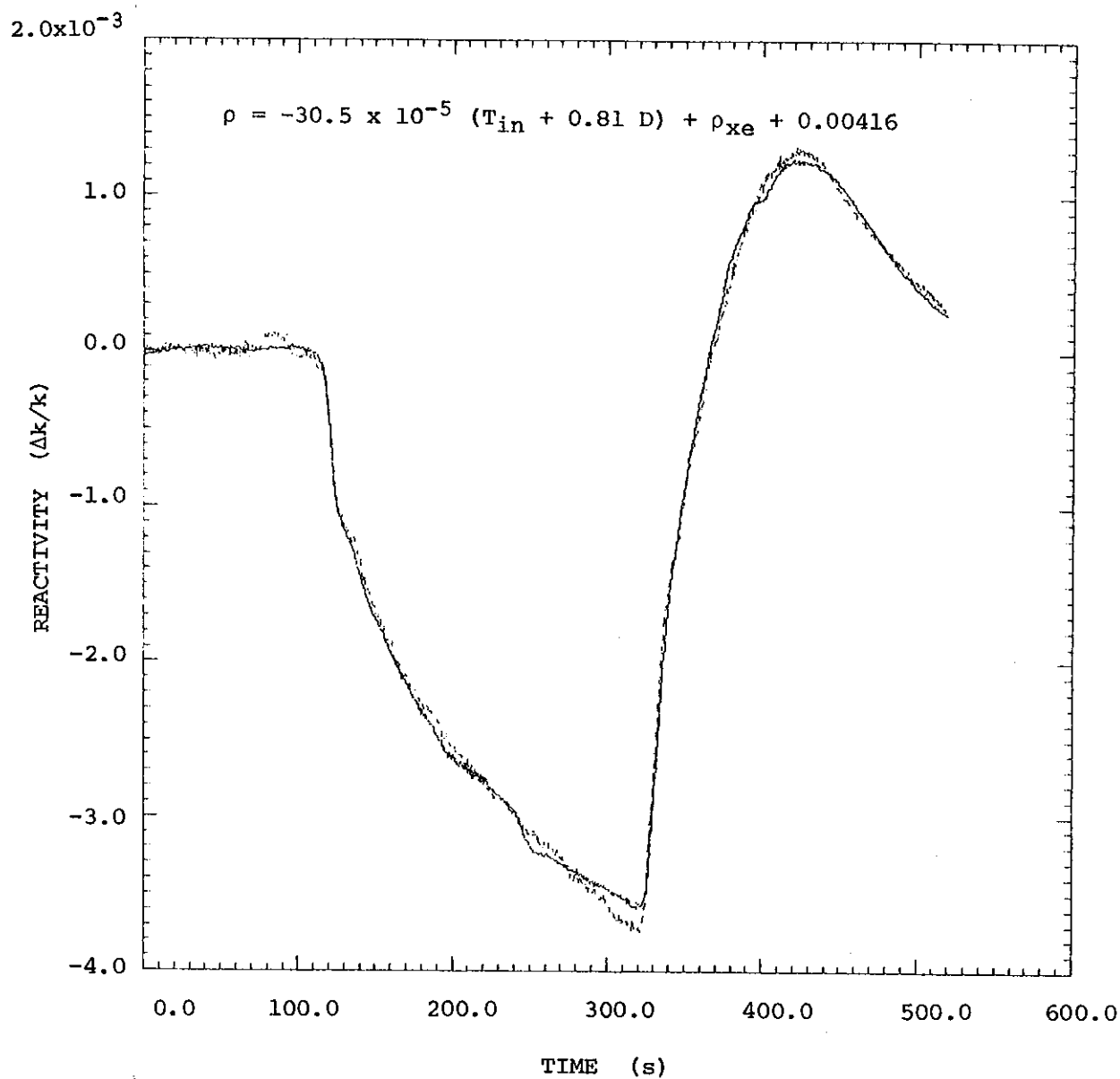


FIGURE 8. THE FIT OF THE EFFECTIVE D₂O TEMPERATURE
 FEEDBACK TO THE REACTIVITY DATA OF
 EXPERIMENT 3. THE REACTIVITY DATA ARE
 SHOWN AS A SOLID LINE AND THE FIT
 AS A DASHED LINE

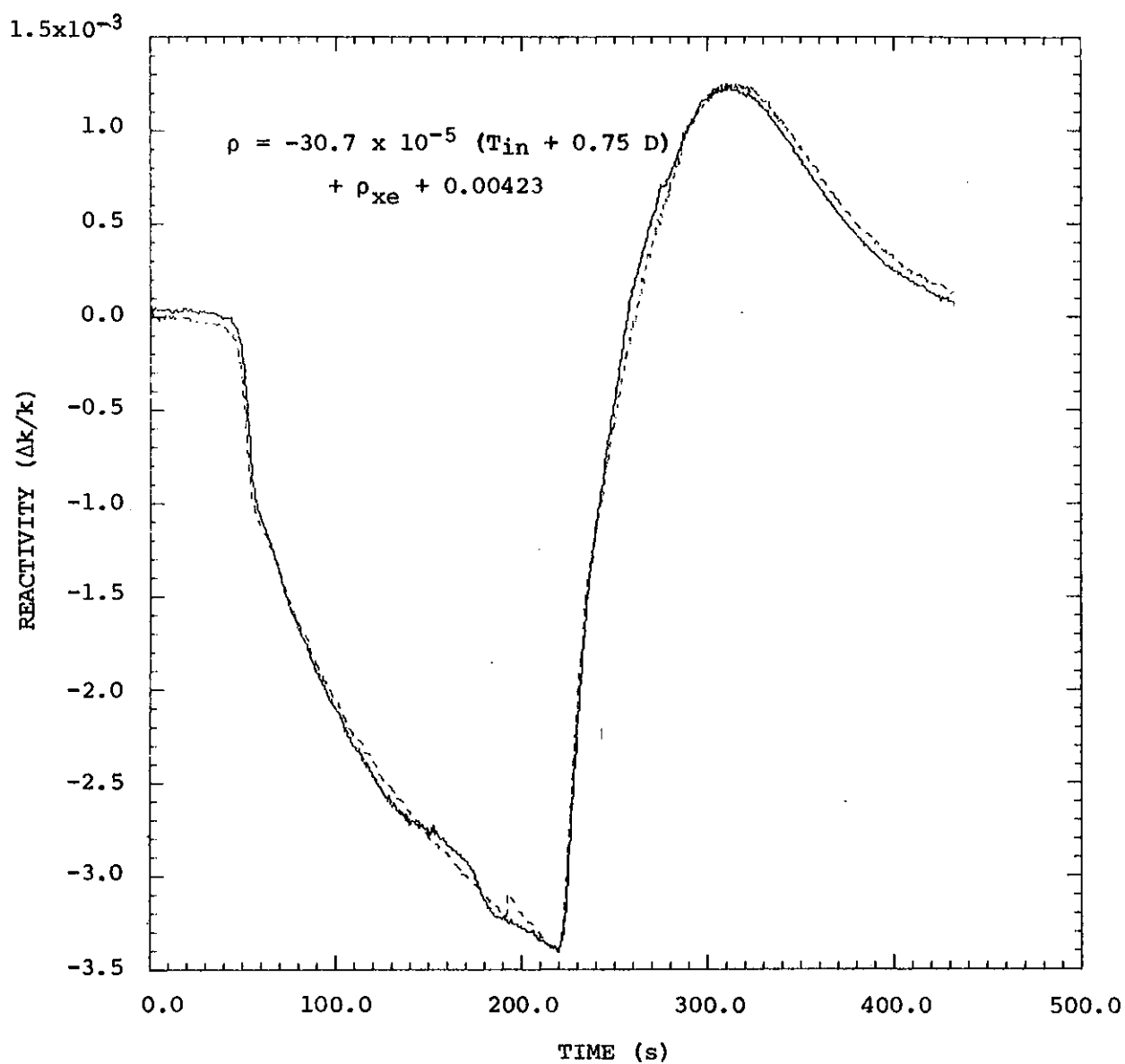


FIGURE 9. THE FIT OF THE EFFECTIVE D₂O TEMPERATURE FEEDBACK TO THE REACTIVITY DATA OF EXPERIMENT 4

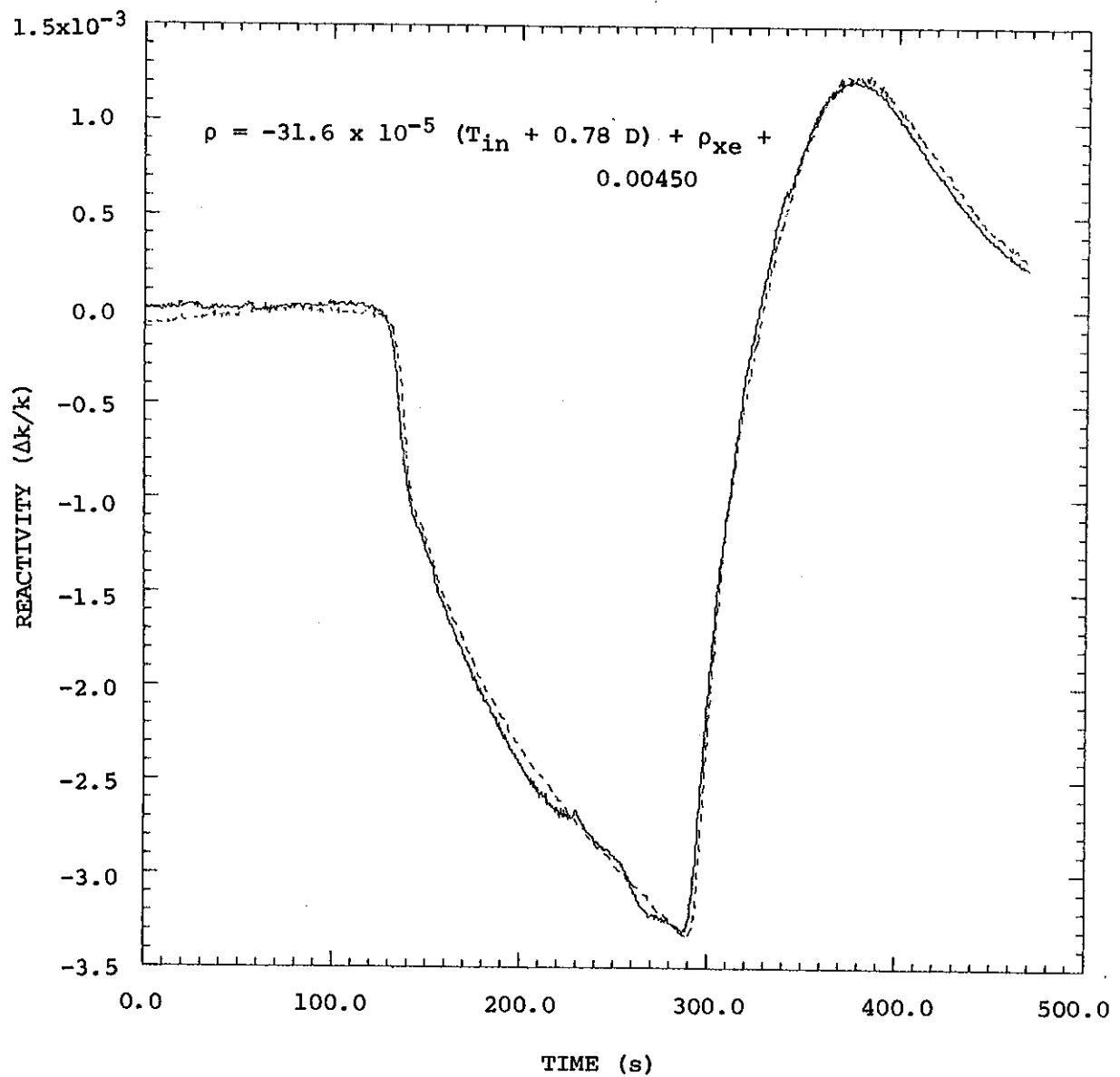
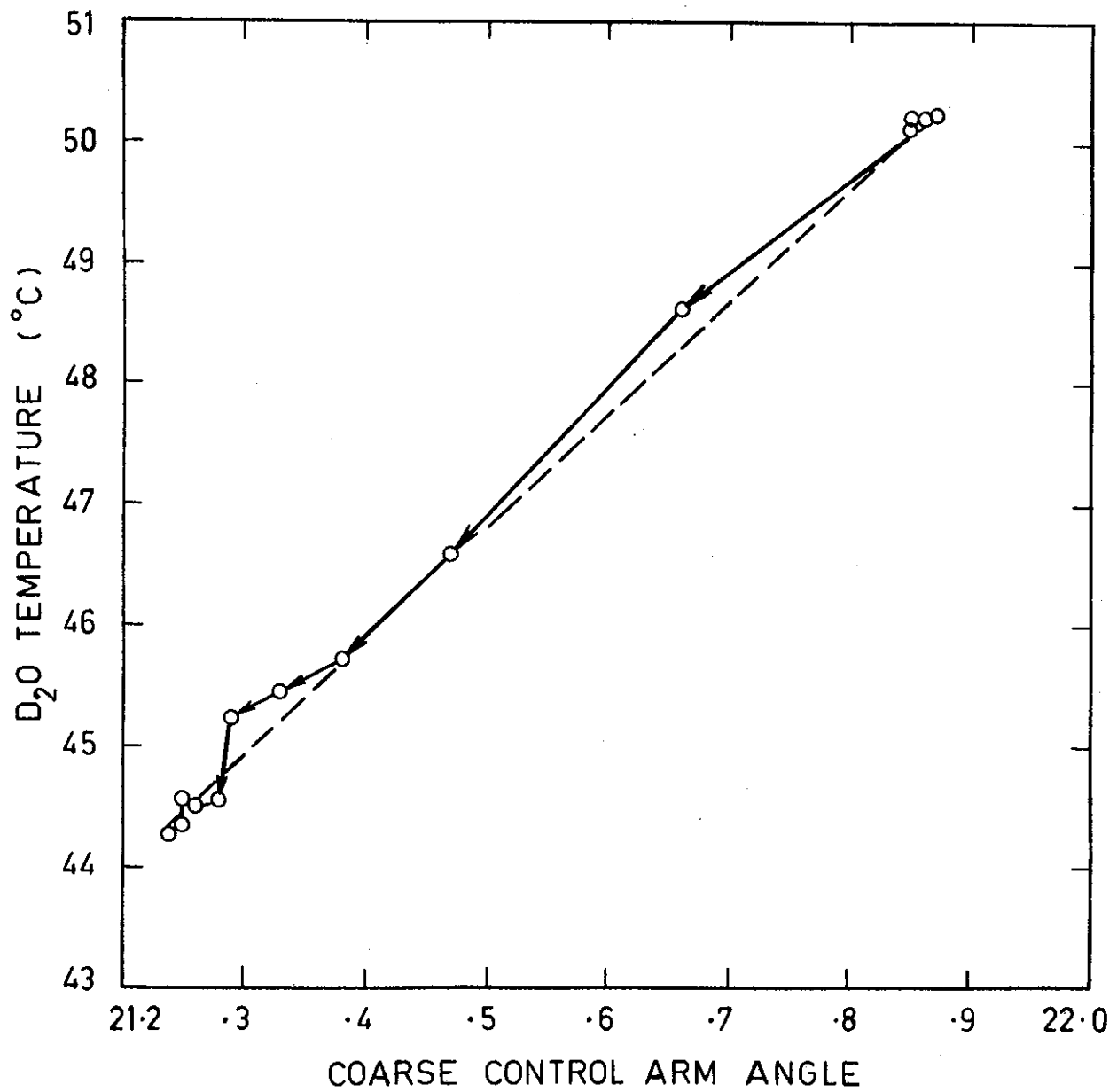


FIGURE 10. THE FIT OF THE EFFECTIVE D₂O TEMPERATURE FEEDBACK TO THE REACTIVITY DATA OF EXPERIMENT 5



**FIGURE 11. THE COARSE CONTROL ARM (CCA) MOVEMENT
FOR A CHANGE IN D₂O TEMPERATURE**

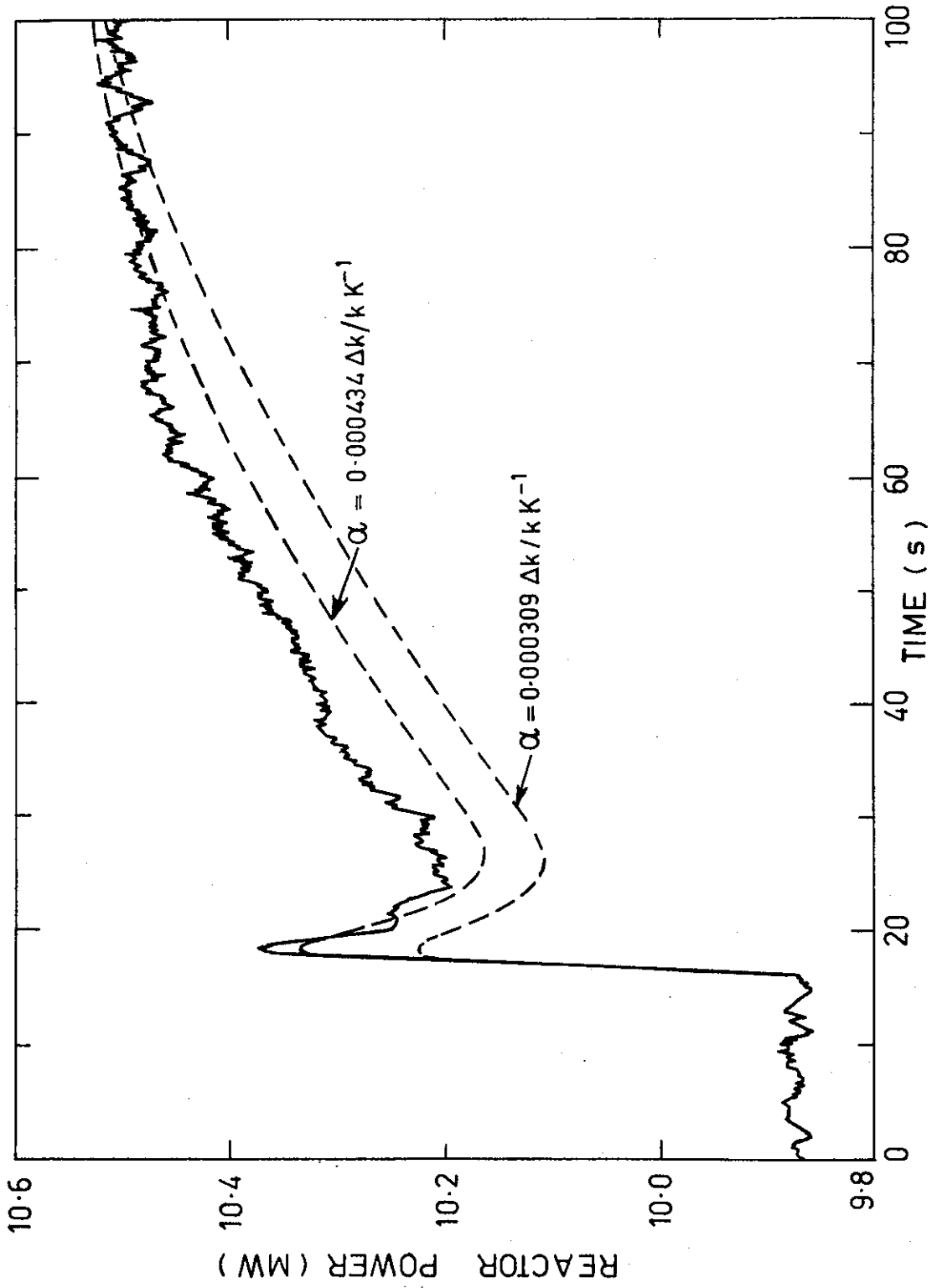


FIGURE 12. THE POWER TRANSIENT (FULL LINE) PRODUCED BY SWITCHING ON THE THIRD D2O CIRCULATION PUMP COMPARED WITH THE POWER CALCULATED USING HIDYN (DOTTED LINES).

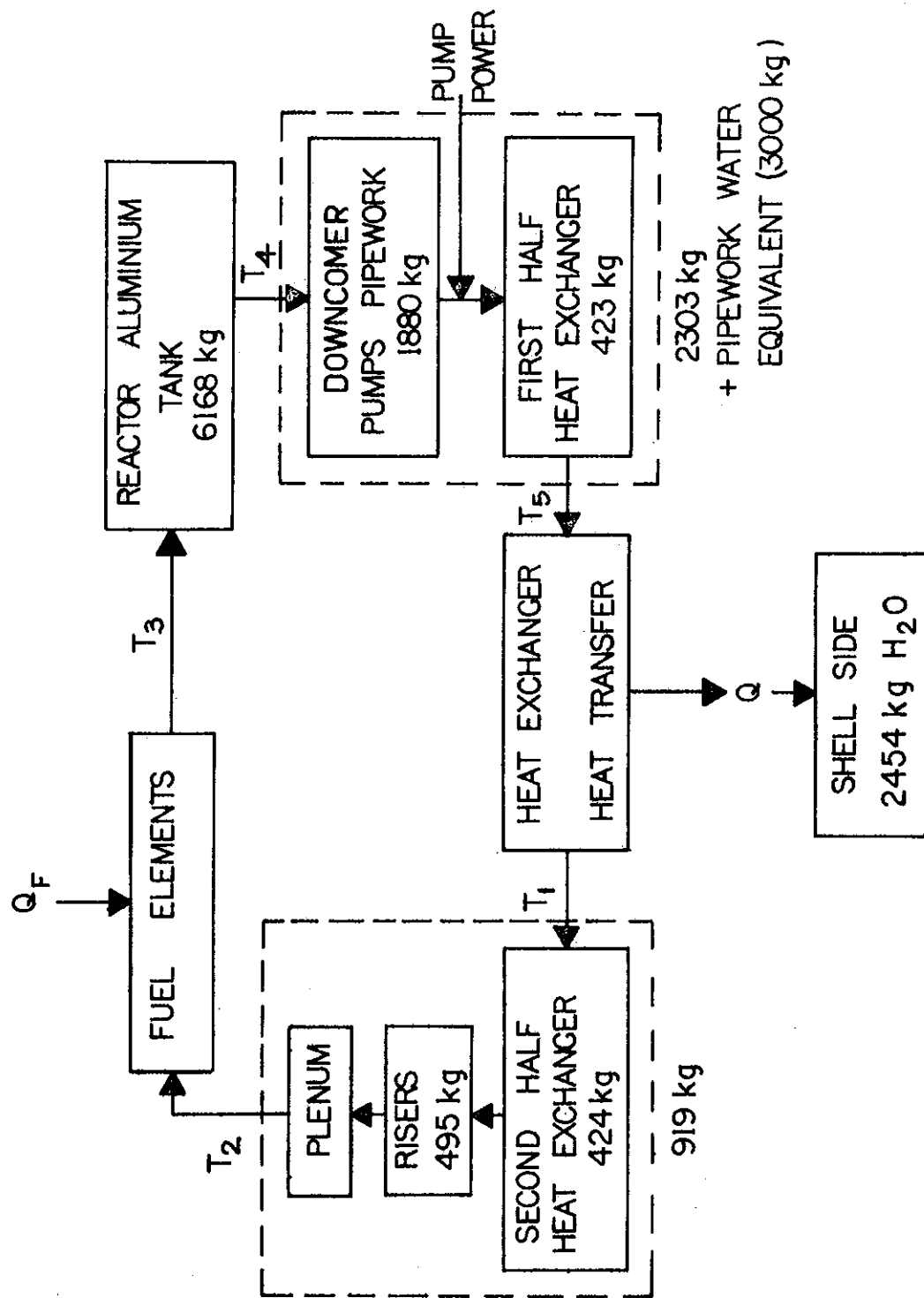
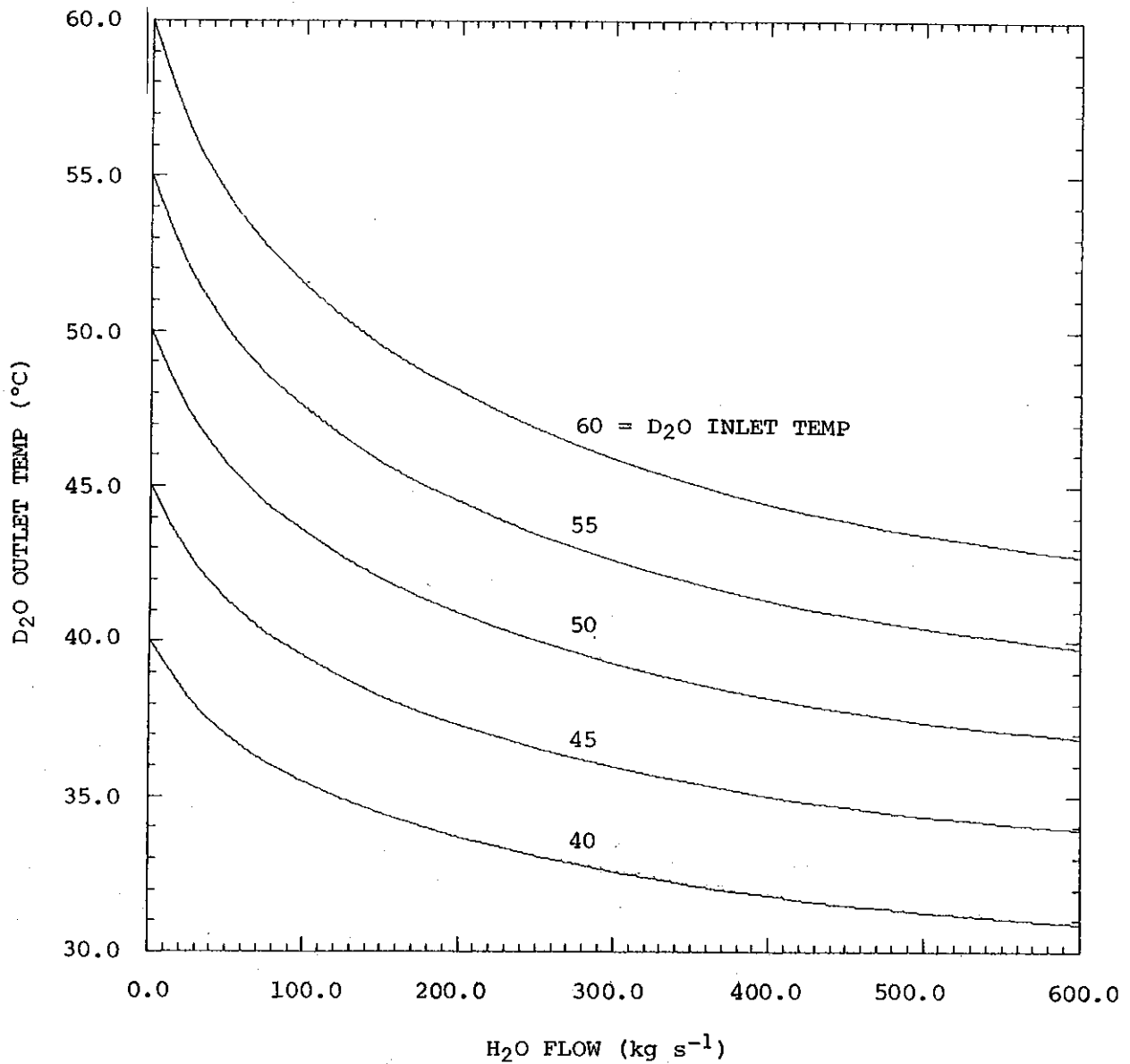
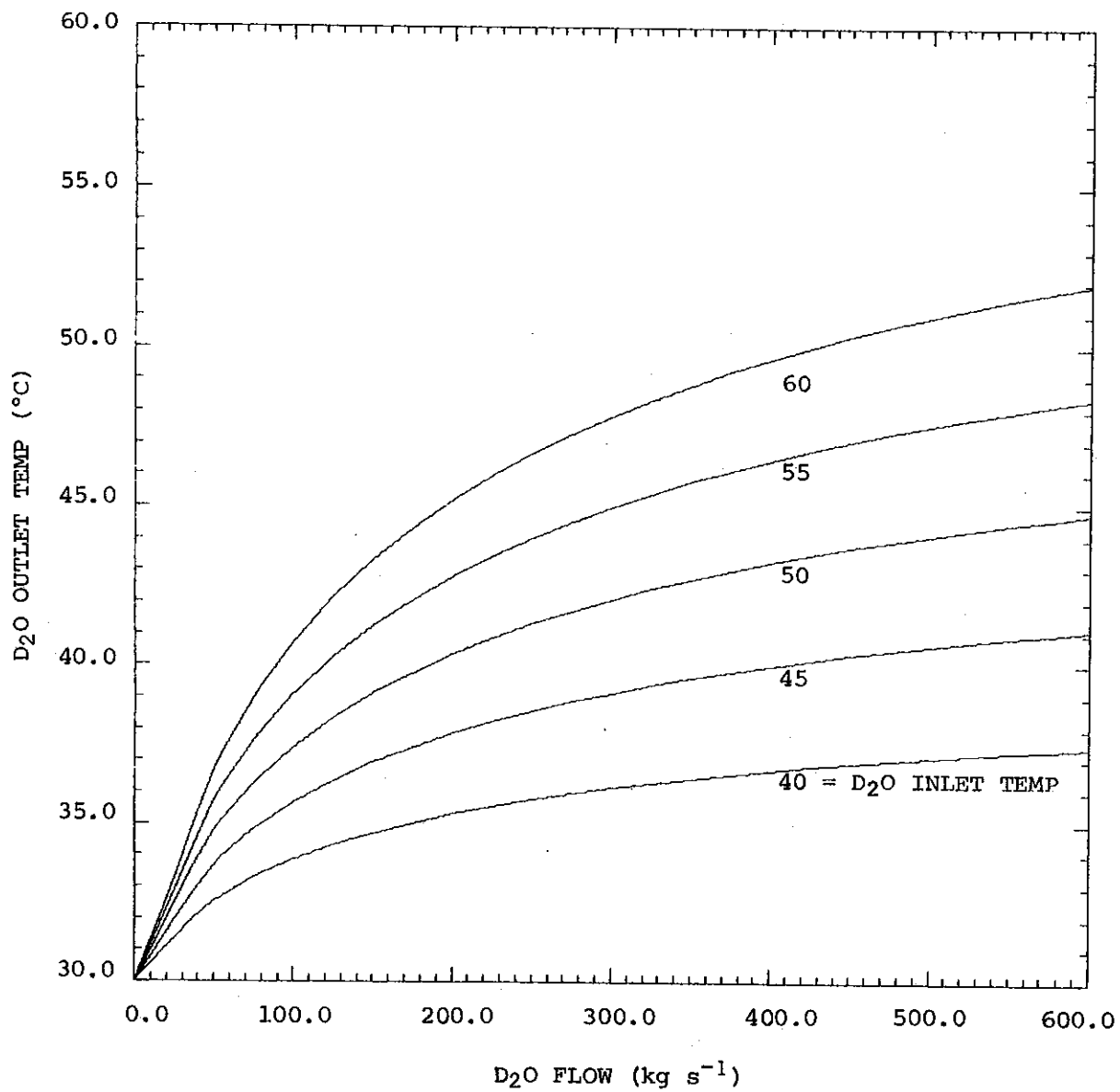


FIGURE 13. SCHEMATIC OF THE HIFAR PRIMARY COOLANT CIRCUIT USED IN THE MODEL



**FIGURE 14. THE CALCULATED HEAT EXCHANGER CHARACTERISTICS
AS A FUNCTION OF H₂O FLOW RATES**



**FIGURE 15. THE CALCULATED HEAT EXCHANGER CHARACTERISTICS
AS A FUNCTION OF D₂O FLOW RATES**

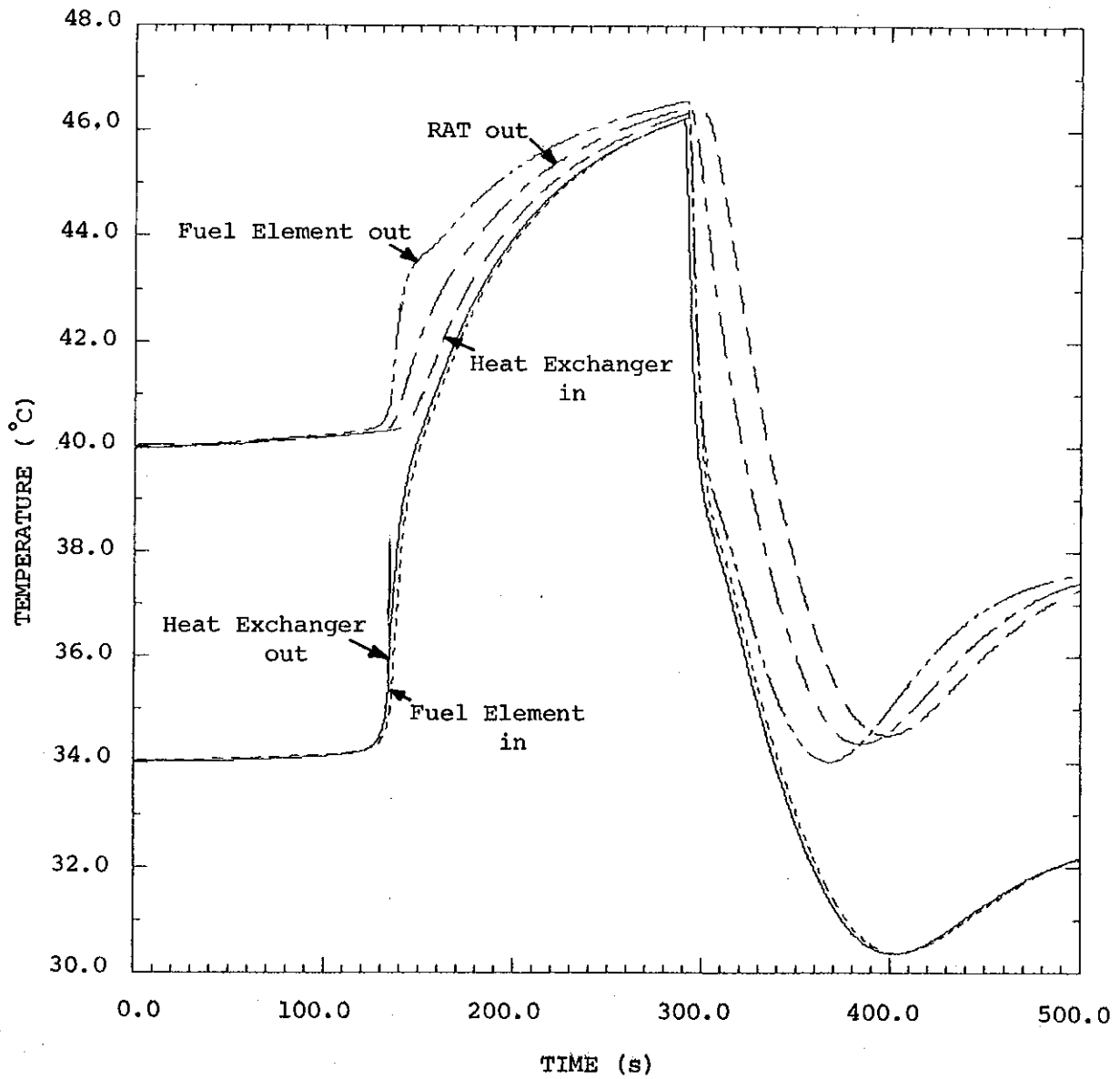


FIGURE 16. THE TEMPERATURES CALCULATED BY HIDYN FOR THE TRANSIENT PRODUCED BY CLOSING THE H₂O VALVES AT 88s AND OPENING THEM AT 286s