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UNMITIGATED BORON DILUTION EVENTS IN A PWR*

by

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Los Alamos, New Mexico

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ABSTRACT

Dissolved boron is required for control of reactivity in a pressurized water reactor that is shut down. TRAC-PF1 calculations for a typical PWR for vessel-closed and vessel-open configurations show that a high-power excursion (approaching 20% of nominal operating power) is possible if dilution of the boron solution occurs. The calculations also show that sufficient heat capacity exists in the primary system to prevent a large temperature increase and that natural circulation flow of high concentration boron solution from the primary system into the core region will terminate the excursion.

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*Work performed under the auspices of the US Nuclear Regulatory Commission.

I. INTRODUCTION AND SUMMARY

Control of reactivity in a pressurized water reactor (PWR) is accomplished by control rods and by boron dissolved in the reactor coolant. Inadvertent addition of unborated water to the reactor coolant system decreases the boron concentration and increases reactivity. In the event that the boron solution is diluted during power operation, the reactivity insertion will cause the power to increase and automatic safety systems (reactor scram) will act to shut down the reactor. When a plant is shut down and control rods are inserted, boron still is required to maintain the necessary shutdown margin. A dilution event during shutdown is not stopped by any automatic safety system and will result in reactor criticality if the operator does not take the proper corrective action. In this paper, TRAC-PF1 (Ref. 1) analyses of unmitigated boron-dilution events in a PWR when it is shut down are presented and discussed.

The discussion of boron dilution events in a Final Safety Analysis Report (FSAR)[2] points out the difficulty of initiating a dilution event. The FSAR notes that for unborated water to enter the reactor coolant system, three independent events must occur. These events are:

1) opening the primary water makeup control valve,

2) starting the primary water supply pump(s), and

3) starting the charging pump(s).

It is argued that it is unlikely for these events to occur simultaneously. Licensee Event Reports, however, indicate that boron-concentration-change events have occurred with sufficient frequency that they must be considered an anticipated operational occurrence. A simple dilution model is used in the FSAR to estimate the time available between initiation and incipient criticality. The maximum addition rate of unborated water is 10 kg/s (175 gpm) with both primary supply pumps running. The initial boron concentration is 2000 ppm boric acid by weight and the initial reactivity of the system is -.08 Δk. The volume of water to be diluted is assumed to be 135 m^3 (4780 ft^3). This corresponds to the liquid volume of the primary system filled to the level of the vessel head flange. The time to reduce the boron concentration in this volume to 1200 ppm (the concentration required for criticality) is estimated to be 91 min. In this period, the operator has a prompt and definite indication of the boron dilution from the audible count-rate instrumentation. High count rate, which occurs as power increases, results in an alarm in both the containment and control room. The FSAR states that 91 min is ample time for the operator to respond to the alarm by closing the misaligned valves and stopping the primary water supply and charging pumps. In the analysis presented here, it was assumed that the operator does not respond.

Two configurations of the shutdown reactor system were calculated with TRAC-PF1. In the closed-vessel configuration the system was filled to the normal operating level and was at atmospheric pressure. In the open-vessel configuration the system was filled to the level of the head flange. Availability of a boron-concentration tracker in TRAC-PF1 that was coupled to the reactor kinetics allowed a direct calculation of the effect of unborated water entering the system at the maximum possible rate (10 kg/s). In the closed-vessel case a critical system was obtained in 80 min, in reasonable agreement with the simple model used in the FSAR. In fact, if it is assumed in the simple model that the volume being diluted is that of the vessel filled to the head flange (118 m^3 or 4167 ft^3), then the time to criticality is reduced to 75 min. For approximately 150 s after the system was critical, the power increased. Feedback from increasing fuel and coolant temperatures limited the power excursion to 516 MW. Heating of the liquid in the core region resulted in natural circulation flow in the primary loop. This, in turn, resulted in undiluted boron solution entering the core region and terminating the excursion. The dilution process was allowed to continue, and this produced a second excursion. Once again this excursion was limited by temperature feedback and was terminated by inflow of higher-concentration boron solution. The peak power for the second excursion was 400 MW. Continued dilution produced a third excursion. The fluid motions induced by the first two excursions left the entire primary system at a more uniform concentration that was below the level required to maintain the reactor subcritical. Higher-concentration boron solution was therefore no longer available to terminate the third excursion. The power approached 5000 MW before temperature feedback started reducing the power at 233 min. This high power increased the system pressure to the safety valve setpoint. This represents a serious temperature and pressure excursion; boiling in the core region and its associated negative feedback would be required to terminate this excursion. It must be pointed out that almost 4 h have elapsed since the accident was initiated, affording the operator ample time to stop the source of unborated water. It is thus extremely unlikely that the accident would proceed to this serious stage.

In the open-vessel case, the first (and only excursion calculated) occurred at 125 min. The peak power was limited by negative temperature feedback to 650 MW. Increased liquid temperatures in the core region did not produce the coolant flows in the primary system that were observed in the closed-vessel case. The reason for this is that the loops, in particular the tops of the steam generator U-tubes, were not filled with liquid, and the incomplete flow path interrupted the flow. The power therefore remained high until boiling occurred in the core region. The agitation of the primary system liquid caused by the boiling was sufficient to bring higher concentration boron solution into the core region and terminate the excursion. Thus the outcome of the first excursion for the open-vessel case was similar to that of the closed-vessel case.

Although high power (approaching 20% of nominal operating power) was attained in the first excursion for both cases, sufficient heat capacity existed in the primary system to prevent a large temperature increase and a passive shutdown mechanism was available to terminate the first excursion. In view of the alarms that would be induced by this excursion, it would appear unlikely that the accident would proceed beyond the first excursion.

II. ASSUMPTIONS AND MODEL DESCRIPTION

TRAC-PF1 (Ref. 1) was used for the analysis of boron dilution events in a four-loop Westinghouse PWR. The calculations were made for the system shortly after refueling; the reactor was at a beginning-of-equilibrium-cycle (BOEC) state and all of the control rods were inserted. The noding diagram of the TRAC model is shown in Fig. 1. Information for this model was obtained from the FSAR.[2]

Three of the four loops (Loops A, C, and D) were combined for computational efficiency. The remaining loop (Loop B) contained the pressurizer. Included in the model were the hot and cold legs, loop seals, vessel, pressurizer, U-tubes of the steam generator, inlets and outlet for the residual heat removal (RHR) system and the main coolant pumps (although the pumps were never operating). Two configurations of the system were considered.

In the closed vessel configuration the system was filled to the normal operating level, but the system was still at atmospheric pressure. In the open-vessel configuration (Fig. 1) the vessel was filled to the level of the head flange. Additionally, it was assumed that:

1) Unborated water entered the system at the maximum rate for both primary water supply pumps (175 gpm, 10.2 kg/s).
2) The boron worth was -10^{-4} Δk per change in boron concentration [measured as weight of boric acid per weight of solution in units of parts per million (ppm)].
3) Reactivity coefficients for the point kinetics model for fuel and coolant temperature and void formation were those of a BOEC core. Note that for the boron concentrations of interest, the moderator coefficient is always negative.
4) The boron concentration was initially 2000 ppm throughout the system.
5) The reactor was critical when the average concentration in the core region was reduced to 1200 ppm.
6) The power-operated-relief-valve (PORV) setpoint was 3.0 MPa (the setpoint when the RHR system is in operation).

These assumptions were taken directly from the FSAR. If the unborated water entering the system is uniformly mixed with fixed mass M of boric acid solution and the mass flow out of the system equals the mass flow in, the resulting reactivity ρ is given by

$$\rho(t) = .12 - .2 \exp(-10.2\, t/M) \qquad (1)$$

where t is the time since dilution began. In the FSAR, it was assumed that the volume being diluted was that of the primary system filled to the vessel head flange (135 m^3, 4780 ft^3). This results in criticality in 91 min. Because the inlets for unborated water are in the cold legs and the outlet is in the Loop A hot leg, the flow path for the undiluted water is mainly through the vessel. If mixing occurs only below the head flange (118 m^3) in the vessel, criticality is attained in 75 min. Thus, the time available to the operator to act is reduced by 17% as compared to the FSAR estimate. If the remainder of the system does not participate in the mixing then the boron concentration in all other components will be at its original value (2000 ppm).

TRAC-PF1 currently tracks the movement of a solute such as boric acid. Code modifications specific to this problem were made to determine the reactivity effects of varying core-average boric acid concentration. Ten kg/s of unborated water entered the cold legs and 10 kg/s of water at the local concentration are removed from the combined Loops A, C, and D hot leg. This induced a flow from the cold legs through the vessel and out the hot legs. A problem seen in the closed-vessel model, in which the primary system is full of liquid, was that flows close to 10 kg/s (~4 kg/s) were induced by gravity. In other words, flows of this size were produced by small elevation errors in the model. This additional flow could reduce the time for unborated water to reach the core region as it could be swept along slightly faster by the artificial flow. This was less of a problem in the open-vessel case where the flow path was interrupted by a vapor bubble in the steam generator U-tubes (recall that the system was drained to the level of the head flange in the open-vessel case). The conditions for the calculations are summarized in Table I.

III. RESULTS FOR CLOSED-VESSEL CASE

The sequence of events for the closed-vessel case was determined by TRAC-PF1. The important system parameters are given in Figs. 2-7. As unborated water entered the system, reactivity increased and criticality occurred at 80 min (4785 s, see Figs. 2 and 3). The time to criticality agrees reasonably well with that determined by Eq.(1) (75 min). The dilution reactivity given by Eq.(1) and also plotted on Fig. 2 is quite different, however. In particular, the upturn in reactivity that is seen in the TRAC calculation is not present. This upturn was a result of lower-concentration boron solution entering the core region as the power began to increase. The density difference when the core water heated was sufficient to induce flow into the core region (Figs. 4 and 5). The boron concentration decreased as one proceeded from the core to the source of unborated water. The first water to enter the core was therefore less borated than that present in the core region and the rate of reactivity addition therefore increased when motion was induced. The power peaked at 516 MW (Fig. 6) following the introduction of approximately -.009 Δk of fuel temperature (Doppler) reactivity. Coolant reactivity also contributed to the power turnover. In an auxiliary calculation with no coolant temperature feedback, the power was 20% higher. The limiting reactivity was thus largely Doppler feedback. The induced flow eventually swept higher-concentration boron solution upstream of the source of unborated water into the core. This higher concentration solution terminated the first excursion. The average boron concentration in the core region and the resulting reactivity was similar to that present at the start of the dilution event (1920 ppm and -0.074 Δk, respectively). In the course of the first excursion the core average pressure went from 0.26 MPa to 0.75 MPa briefly and then back to 0.34 MPa as cooler liquid from the rest of the system entered the core region. The exact time of the first excursion depends upon the flow to the vessel from the unborated water source. Figure 5 shows that the primary flow increased at 2000 s because of small elevation changes in the geometric model that were described in Section II. This artificial flow may have reduced the time to criticality by moving unborated water into the core. A better estimate of the time to criticality would require more analysis and a more refined geometric model.

As dilution continued, a second excursion was induced at approximately 10000 s. As with the first excursion, the peak power was limited by Doppler and coolant temperature feedback and terminated by inflow of higher concentration boron solution. The peak power in this excursion was 400 MW. The boron concentration reactivity following the second excursion was higher (-0.02 Δk). The core-average temperature increased to 354 K as a result of the second excursion. The expansion associated with this temperature increase filled the pressurizer and briefly opened the PORV.

Continued dilution resulted in a third excursion. When this excursion began, the boron concentration in the primary system was at or below the level at which the core was critical. Doppler and coolant temperature feedback and core voiding were thus required to limit the power of this excursion. The peak power reached in this excursion was 5000 MW. Rapid pressurization of the system prevented boiling in the core during the excursion. Fuel heating resulted in a net negative reactivity, leading to decreasing power (Fig. 3). High-pressure voiding of the core would be required to permanently terminate the power burst. In view of the time elapsed and the number of indications received by the operator, it is unlikely that the event would proceed to this serious third excursion.

IV. RESULTS FOR OPEN-VESSEL CASE

The sequence of events for the open-vessel case was determined by two methods. The first method failed shortly after peak power was reached because of numerical difficulties encountered in the TRAC calculation. The second method provides an indication, albeit not quantitively consistent with the first calculation, of how the accident proceeds. This description includes the first calculation until it breaks down numerically. This is followed by a brief description of the second method and its results.

The addition of unborated water resulted in reactor criticality at approximately 7500 s in this case. Criticality occurred 2500 s later than in the closed-vessel case because vapor in the steam generator prevented the artificial flow seen in the closed-vessel case. Because the flow of unborated water into the system was the same for a longer period of time, the boron concentration upstream of the core was lower. This resulted in a slightly more severe excursion than in the closed-vessel case (Figs. 8 and 9). As with the closed-vessel case, the power excursion was limited by fuel and coolant temperature feedback. The peak power calculated was 650 MW. With the vessel open the saturation temperature was reached and violent boiling began in the core region. Resulting numerical difficulties prevented completion of the calculation.

For the second method, the positive reactivity associated with dilution of the coolant was computed using Eq.(1) and input in tabular form. At the start of the calculation the reactor was critical, and the boron concentration was 1200 ppm in the core and 2000 ppm in the remainder of the system. Figs. 10-14 give the results for the transient. As was pointed out in Section III, the reactivity is underestimated by Eq.(1); the peak power was therefore lower (120 MW). The power (Fig. 11) was turned over by Doppler and coolant temperature feedback (Fig. 10) and then reduced by inflow of higher concentration boron solution (Fig. 12). Continued dilution resulted in a second power peak that caused some boiling and additional heating in the core region (Fig. 13). The agitation by the boiling and the decreased density induced a large flow at 1000 s (Fig. 12) that brought in enough boron to terminate the excursion. Qualitatively these results should not differ from those obtained by fixing the method that failed. The energy generated in this first excursion is determined only by the dilution rate and the temperature feedback. A comparison of Fig. 7 with Fig. 14, graphs of the energy generated in the course of the respective transients, shows that the use of Eq.(1) for the dilution reactivity results in a halving of the energy generated in the first excursion. This gives an indication of the magnitude of the error introduced by using Eq.(1).

V. CONCLUSIONS AND RECOMMENDATIONS

TRAC-PF1 calculations for a typical PWR for a vessel-closed and vessel-open configuration have shown that a high-power (approaching 20% of nominal operating power) excursion is possible. Sufficient heat capacity exists in the primary system to prevent a large temperature increase. A passive shutdown mechanism (flow into the core region of high-concentration boron solution) is available to terminate this excursion. Further excursions are possible, but not likely, in view of information that will be received by the operator who probably will take actions to terminate the dilution process.

Further analysis of these transients will require more accuracy in the geometric modeling to eliminate the artificial motions induced by gravity. The vessel-open case failed because of difficulties with low-pressure boiling models. These models are currently being updated. To follow the boiling process better, additional nodes should be added to the core region. Incorporation of these changes should not change the qualitative results obtained in this report.

REFERENCES

1. Safety Code Development Group, "TRAC-PF1, An Advanced Best-Estimate Computer Program for Pressurized Water Reactor Analysis" Los Alamos National Laboratory report (to be published).

2. "Zion Station Final Safety Analysis Report," Commonwealth Edison Company (1973).

TABLE I

CONDITIONS FOR BORON DILUTION ACCIDENT CALCULATIONS

Reactor Configuration	
Closed-Vessel Case	System filled to normal operating level and closed
Open-Vessel Case	System filled to hot legs and opened to atmosphere
Initial Conditions	
Reactivity	$-.08\ \Delta k$
Coolant Temperature	320 K
System Pressure	0.1 MPa
Boron Concentration	2000 ppm in entire system
Boron Dilution Reactivity	Determined by model
Delayed Neutron Precursor Concentrations	0. atoms/m^3*
Power	10 kW
Reactivity Feedback Coefficients	
Fuel Temperature	$-0.42 \times 10^{-4}\ \Delta k/K$
Coolant Temperature	$-0.36 \times 10^{-4}\ \Delta k/K$
Void Reactivity	$\frac{dk}{d\alpha} = 0.005 - 0.20 \quad (\Delta k/\Delta\alpha)$**

*This will result in an initial power decrease.

**$\Delta\alpha$ is the change in core-average void fraction.

List of Figures

Fig. 5. Flow in Loop B-hot leg in closed-vessel case followed heating of core liquid. (Compare with Fig. 4.) The low peak at 1000 s, caused by artificial gravity imbalances, probably reduced the time to achieve criticality.

Fig. 6. Three power excursions resulted from boron dilution in closed-vessel case. Each excursion was turned over by fuel and coolant temperature feedback. The first and second excursions were terminated by inflow of higher concentration boron solution. The initial decrease in power was caused by starting with zero delayed neutron precursor concentrations.

Fig. 7. Energy generated in closed-vessel case increased step-wise as three excursions occurred.

Fig. 8. Boron dilution resulted in an increase in reactivity in open vessel case. Doppler feedback turned the power over.

Fig. 9. Power increased rapidly following dilution reactivity increase in open-vessel case. This calculation failed shortly after power peaked at 650 MW.

Fig. 10. Reactivity components for open-vessel case. Dilution resulted in an increase in power that was turned over by temperature feedback. Agitation by boiling at 1000 s resulted in an inflow of higher concentration boron solution. This calculation began with the reactor critical.

Fig. 11. Power in open-vessel case was reduced by temperature feedback. Further dilution then increased the power, which resulted in boiling and inflow of higher concentration solution. This terminated the excursion. This calculation began with the reactor critical.

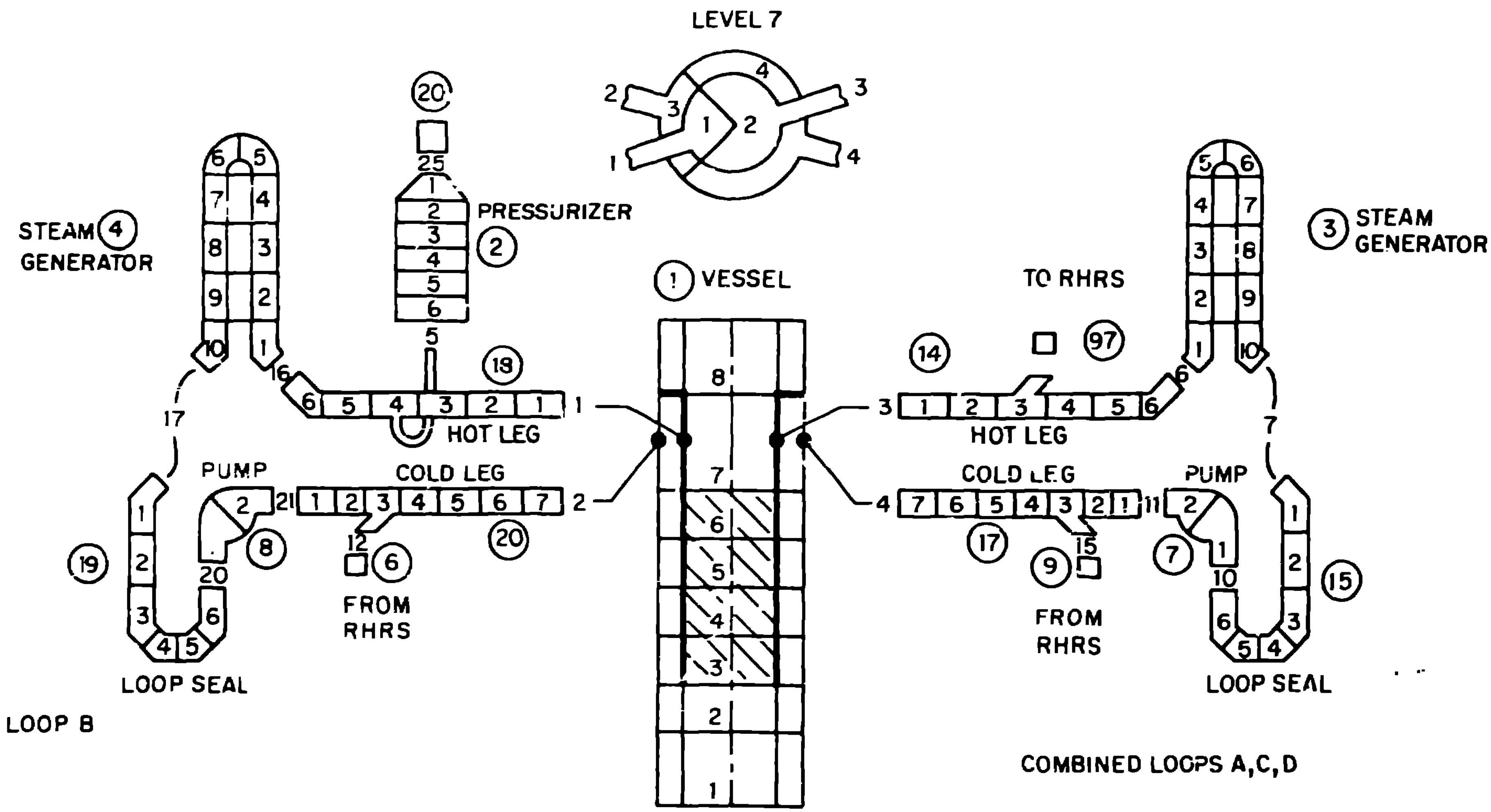
Fig. 12. Flow in open-vessel case was induced by heating and boiling in the core region.

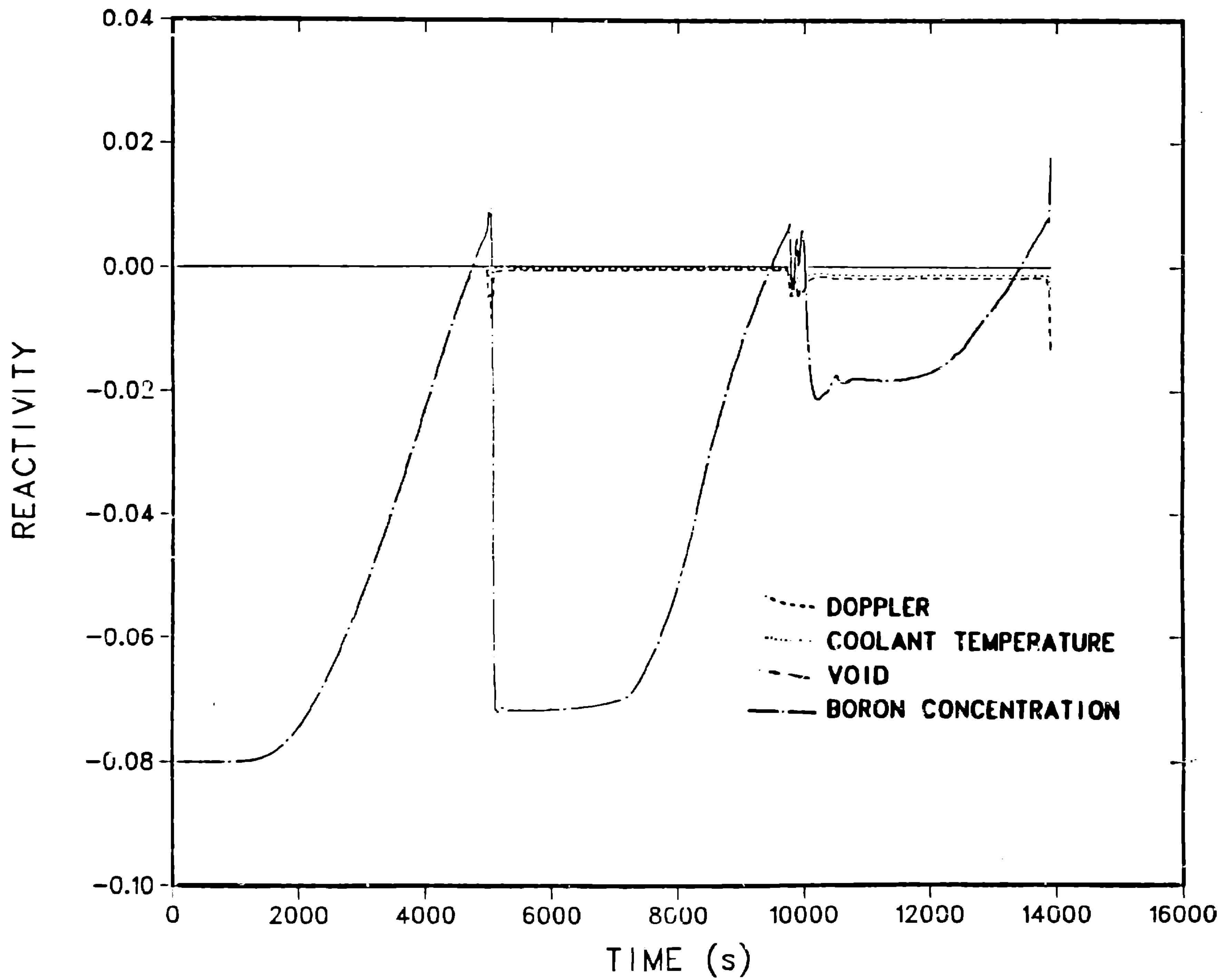
Fig. 13. Temperature in open-vessel case increased during the excursion then decreased as cooler liquid flowed into the core region.

Fig. 14. Energy produced in first excursion in open vessel case was half that seen in Fig. 7 giving an indication of the error caused by using Eq. (1) to determine dilution reactivity.

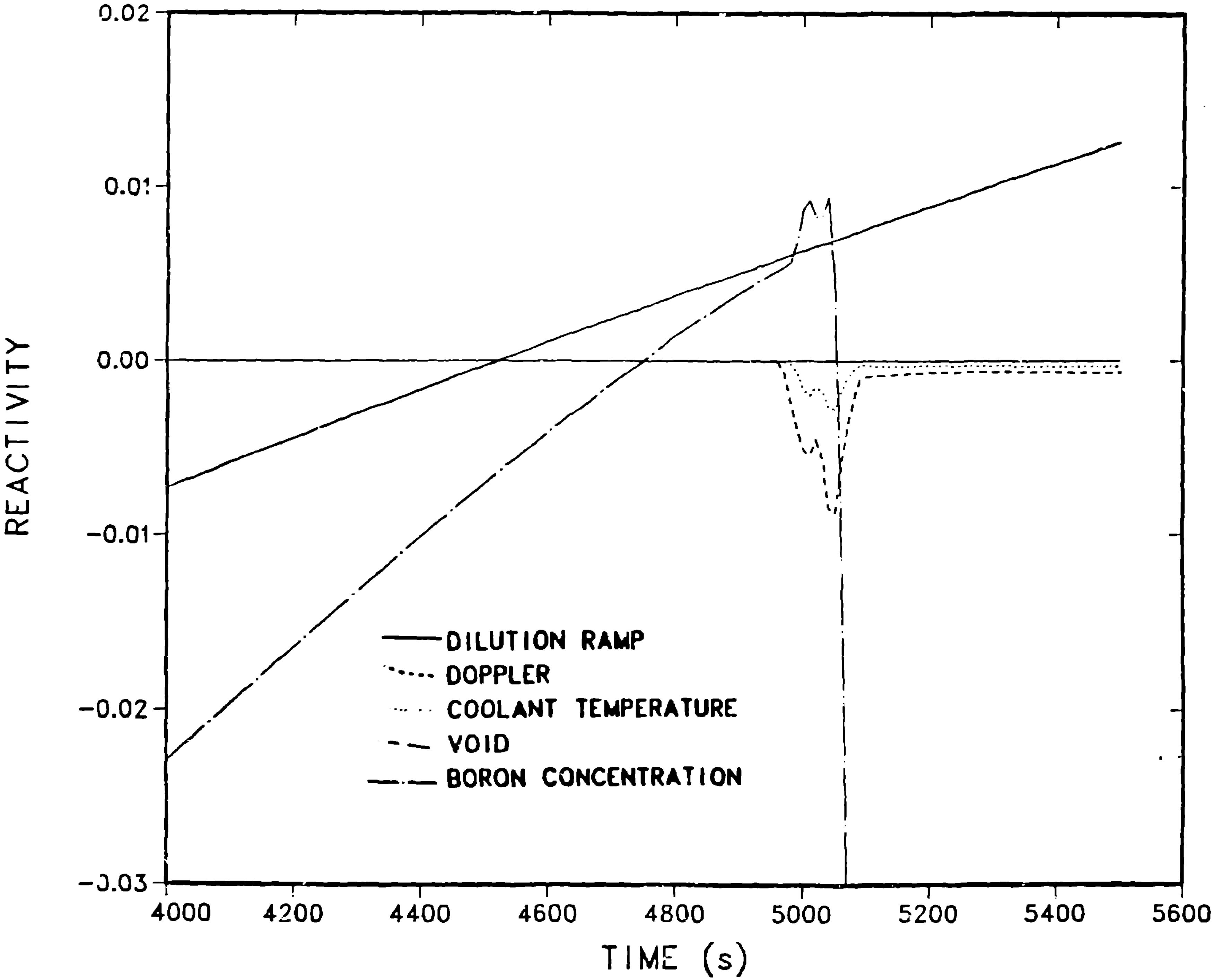
Fig. 1.

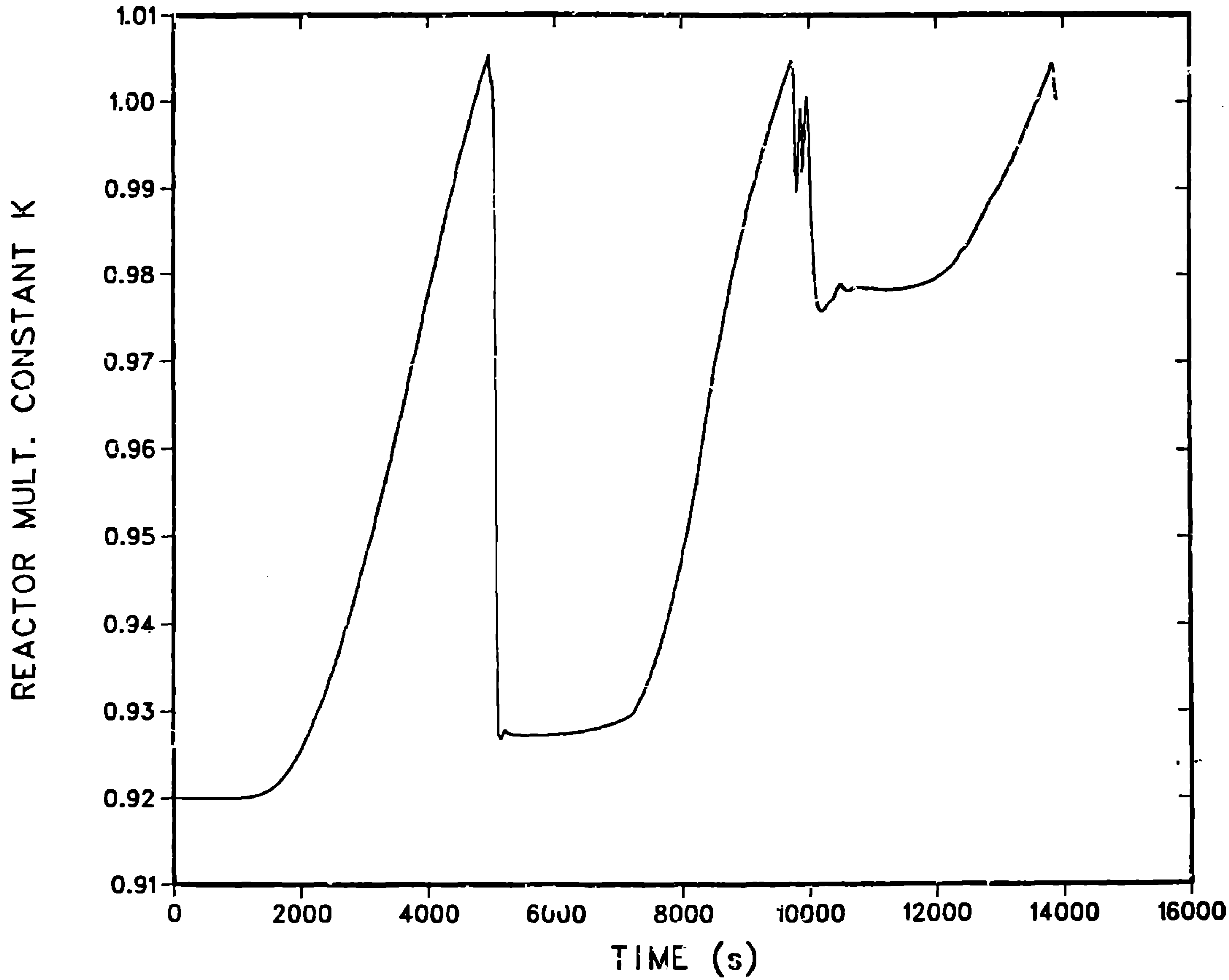
TRAC NODING DIAGRAM





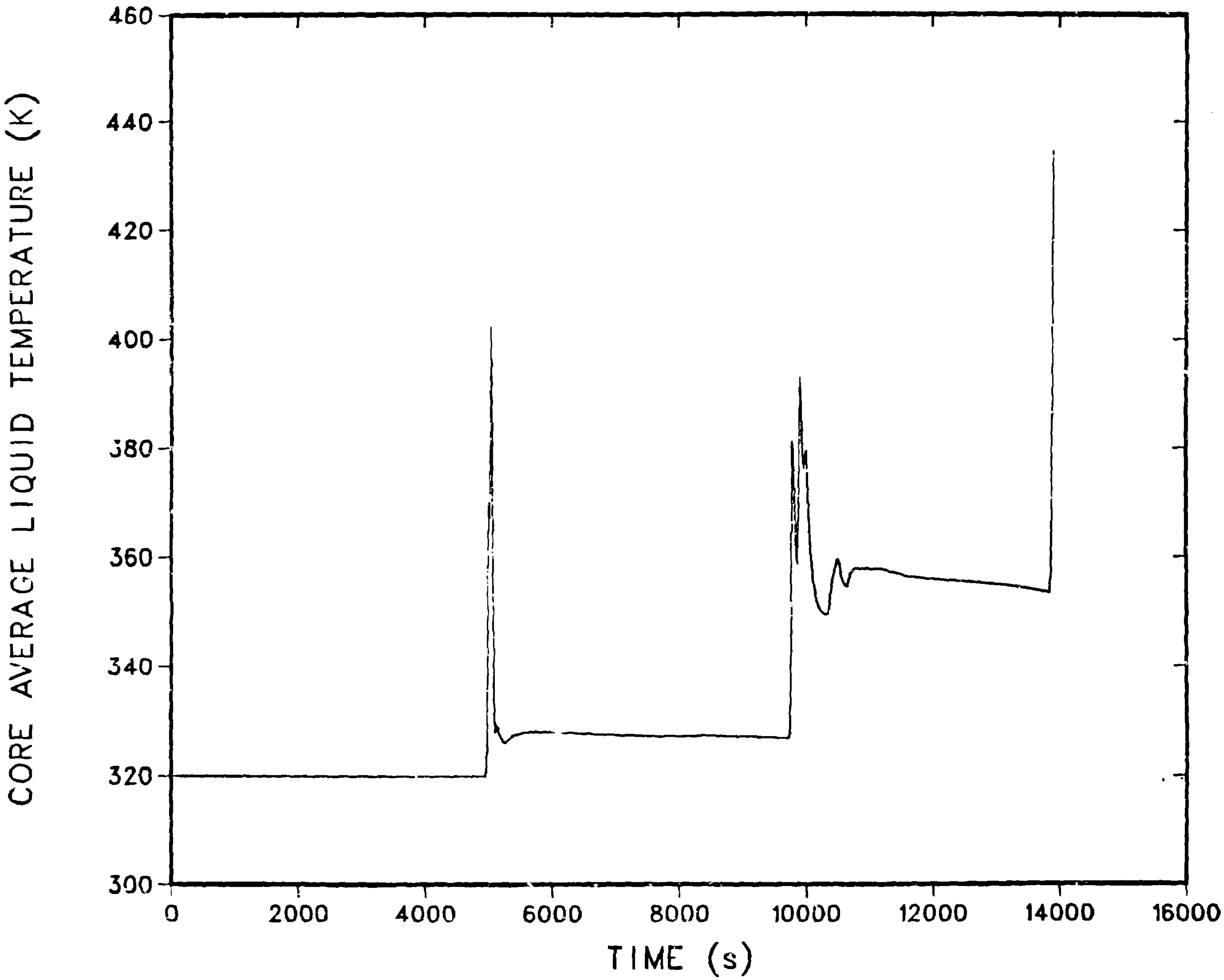
REACTIVITY
TIME (s)
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
0
2000
4000
6000
8000
10000
12000
14000
16000
DOPPLER
COOLANT TEMPERATURE
VOID
BORON CONCENTRATION


0.02
0.01
0.00
−0.01
−0.02
−0.03
REACTIVITY
4000
4200
4400
4600
4800
5000
5200
5400
5600
TIME (s)
DILUTION RAMP
DOPPLER
COOLANT TEMPERATURE
VOID
BORON CONCENTRATION



REACTOR MULT. CONSTANT K
1.01
1.00
0.99
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0.91
0
2000
4000
6000
8000
10000
12000
14000
16000
TIME (s)

Fig. 4



CORE AVERAGE LIQUID TEMPERATURE (K)
460
440
420
400
380
360
340
320
300
0
2000
4000
6000
8000
10000
12000
14000
16000
TIME (s)

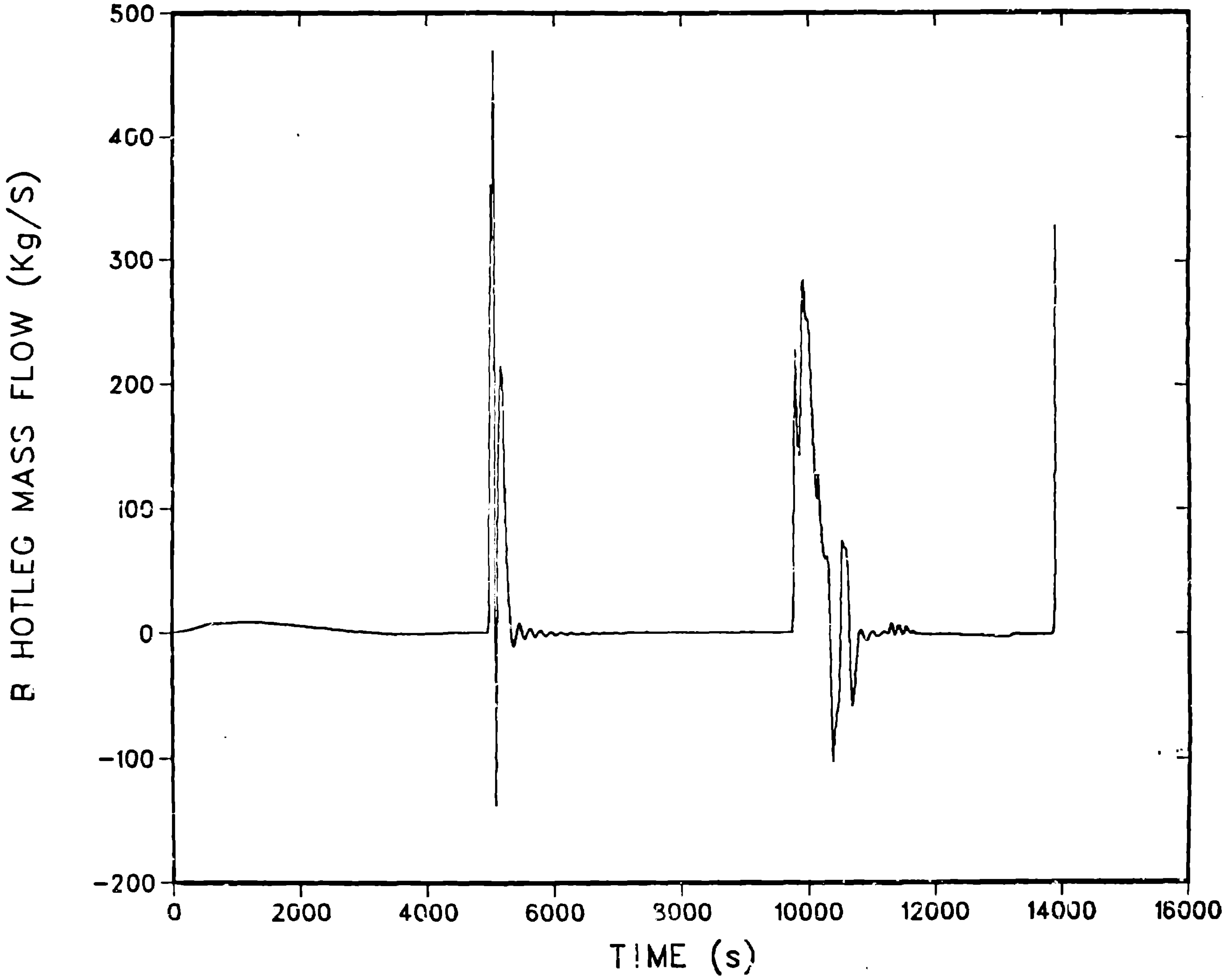
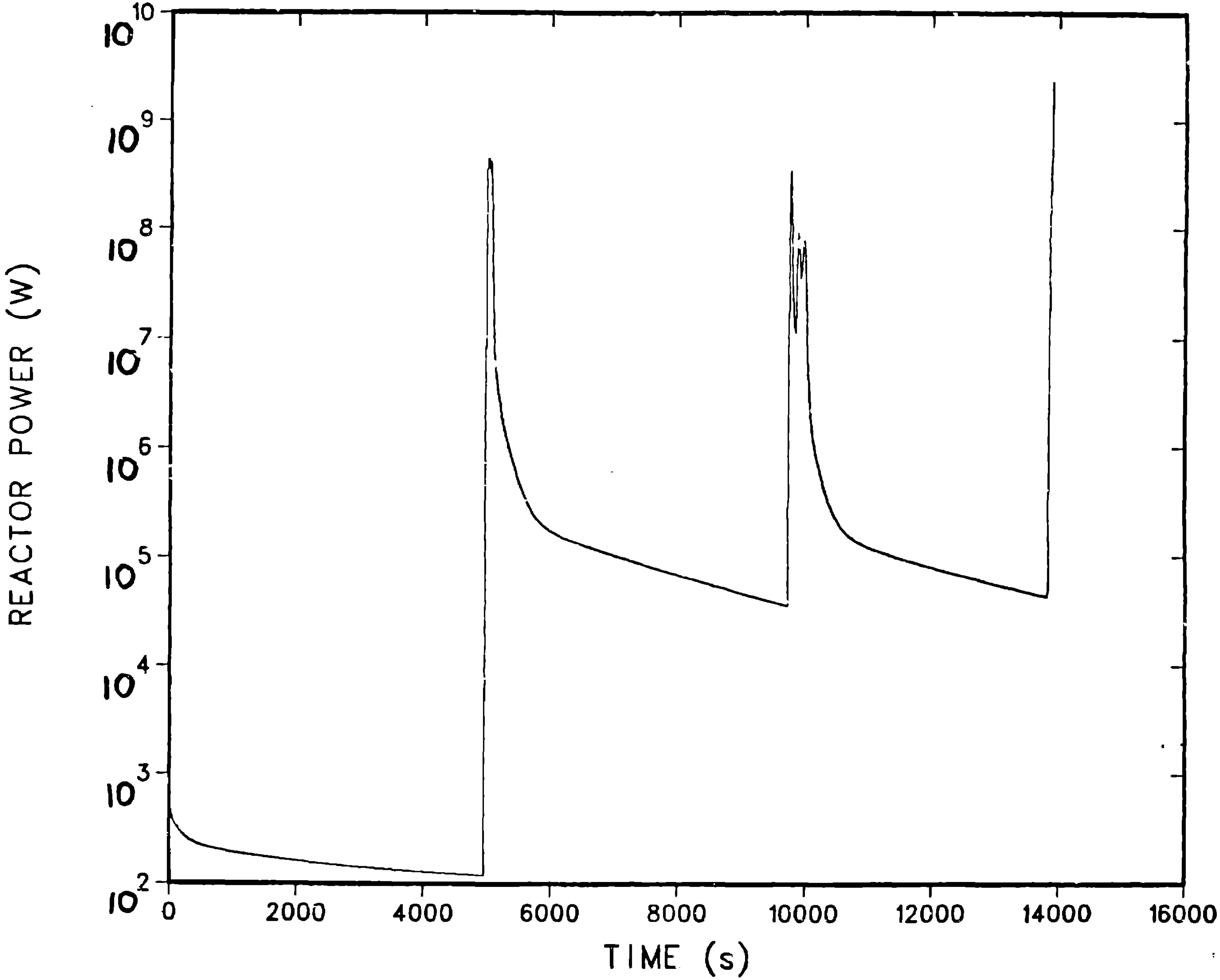
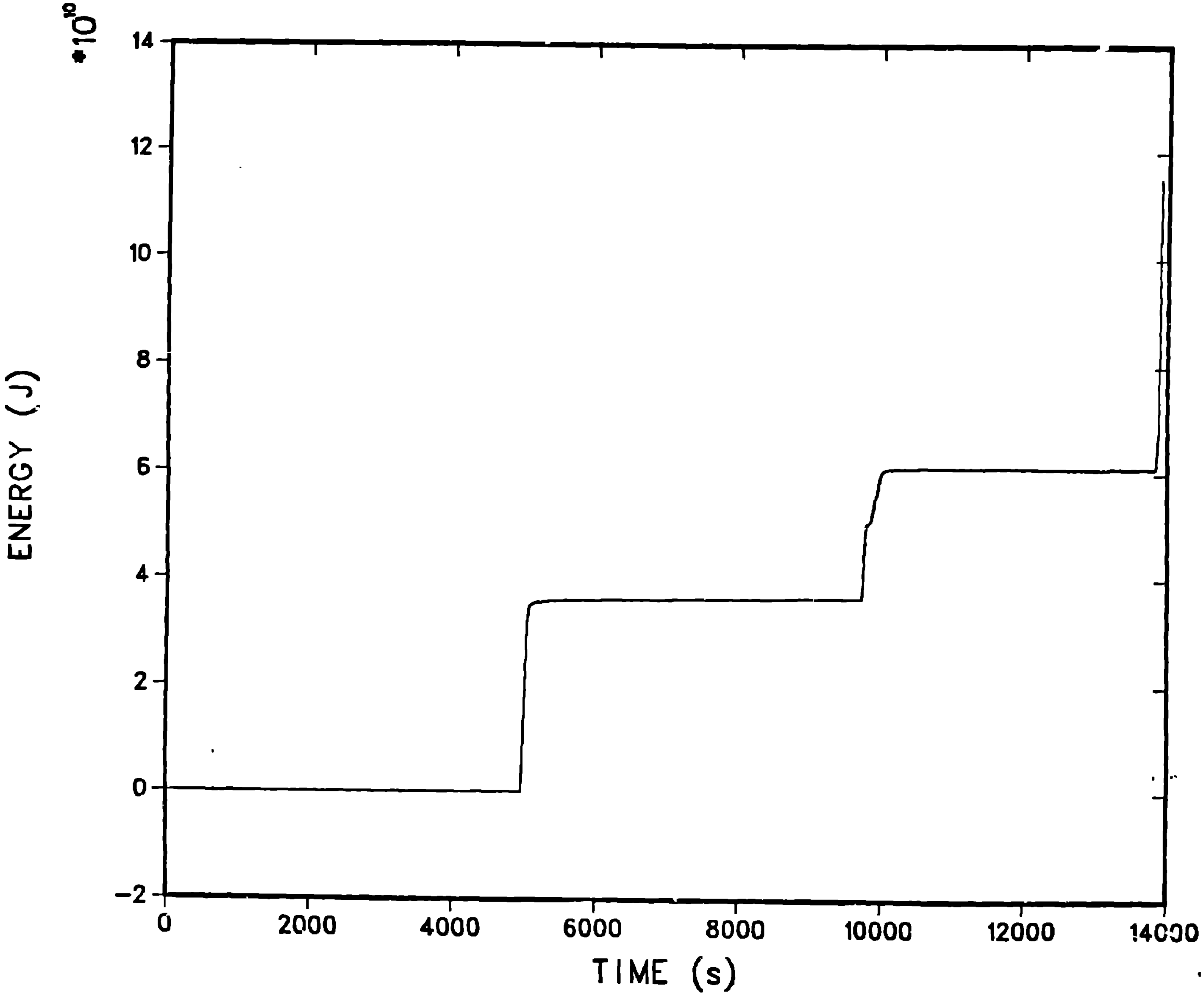

B HOTLEG MASS FLOW (Kg/S)
500
400
300
200
100
0
−100
−200
0
2000
4000
6000
8000
10000
12000
14000
16000
TIME (s)

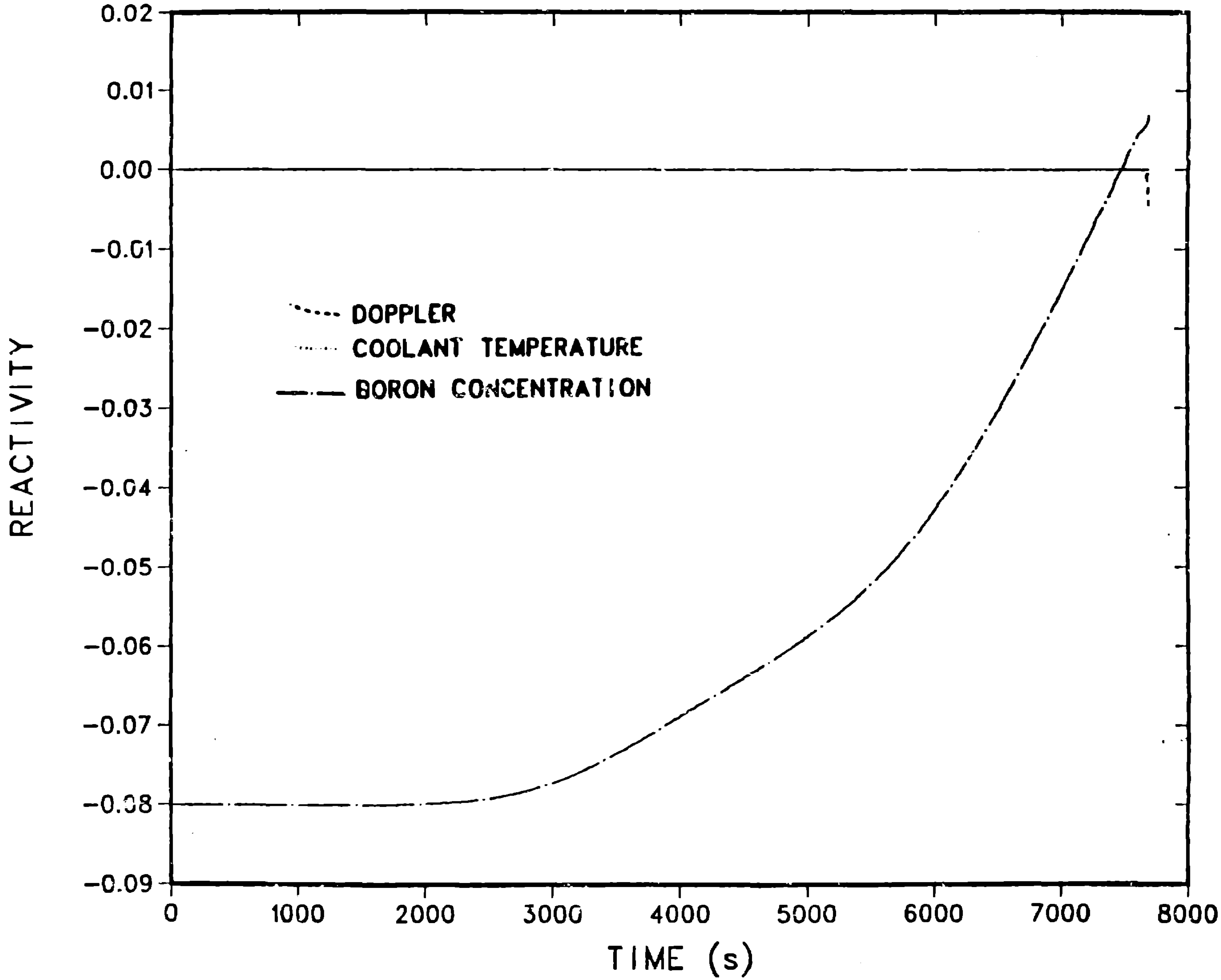
Fig. 6.



REACTOR POWER (W)
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
0
2000
4000
6000
8000
10000
12000
14000
16000
TIME (s)

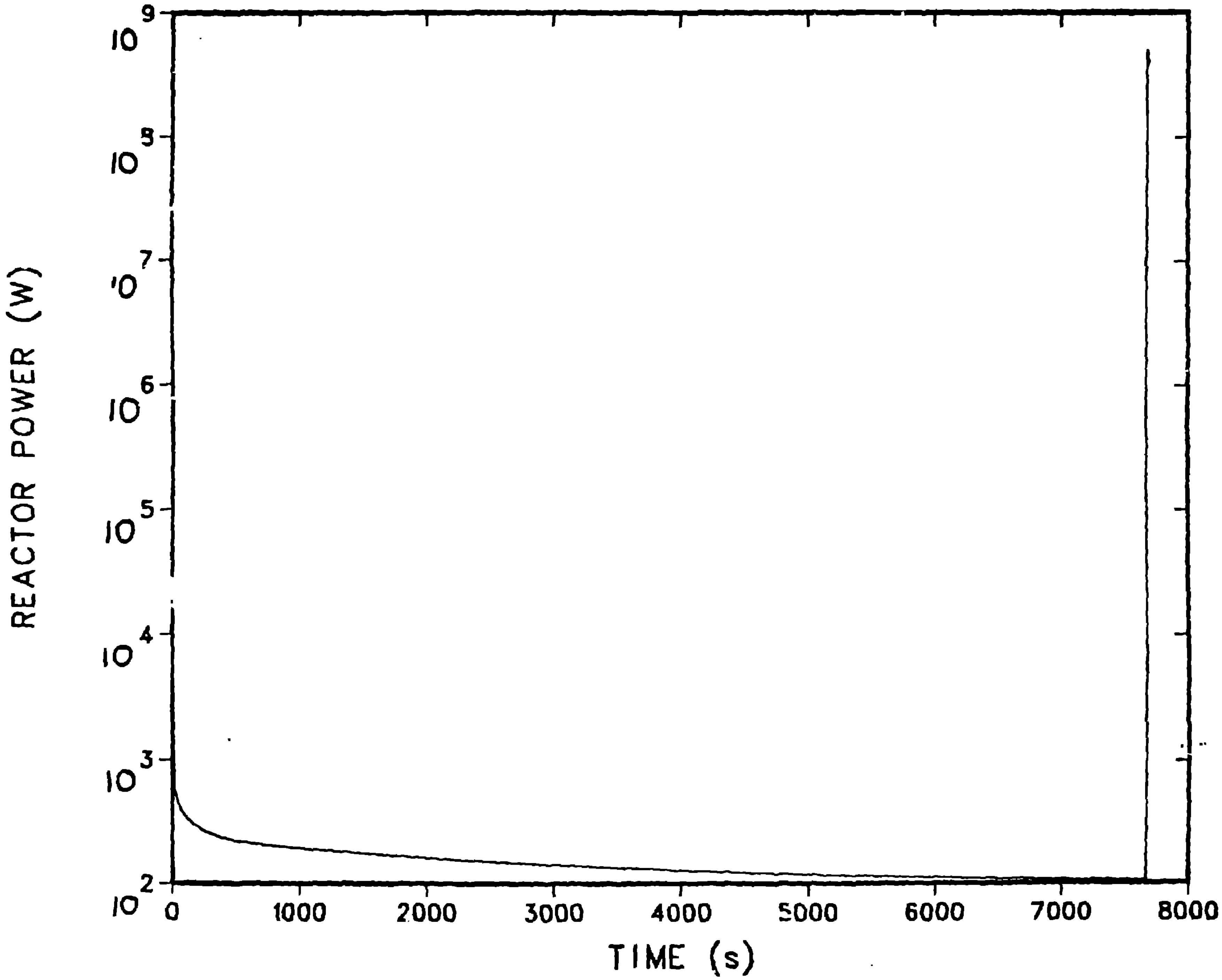


*10^10
14
12
10
8
6
4
2
0
−2
ENERGY (J)
0
2000
4000
6000
8000
10000
12000
14000
TIME (s)

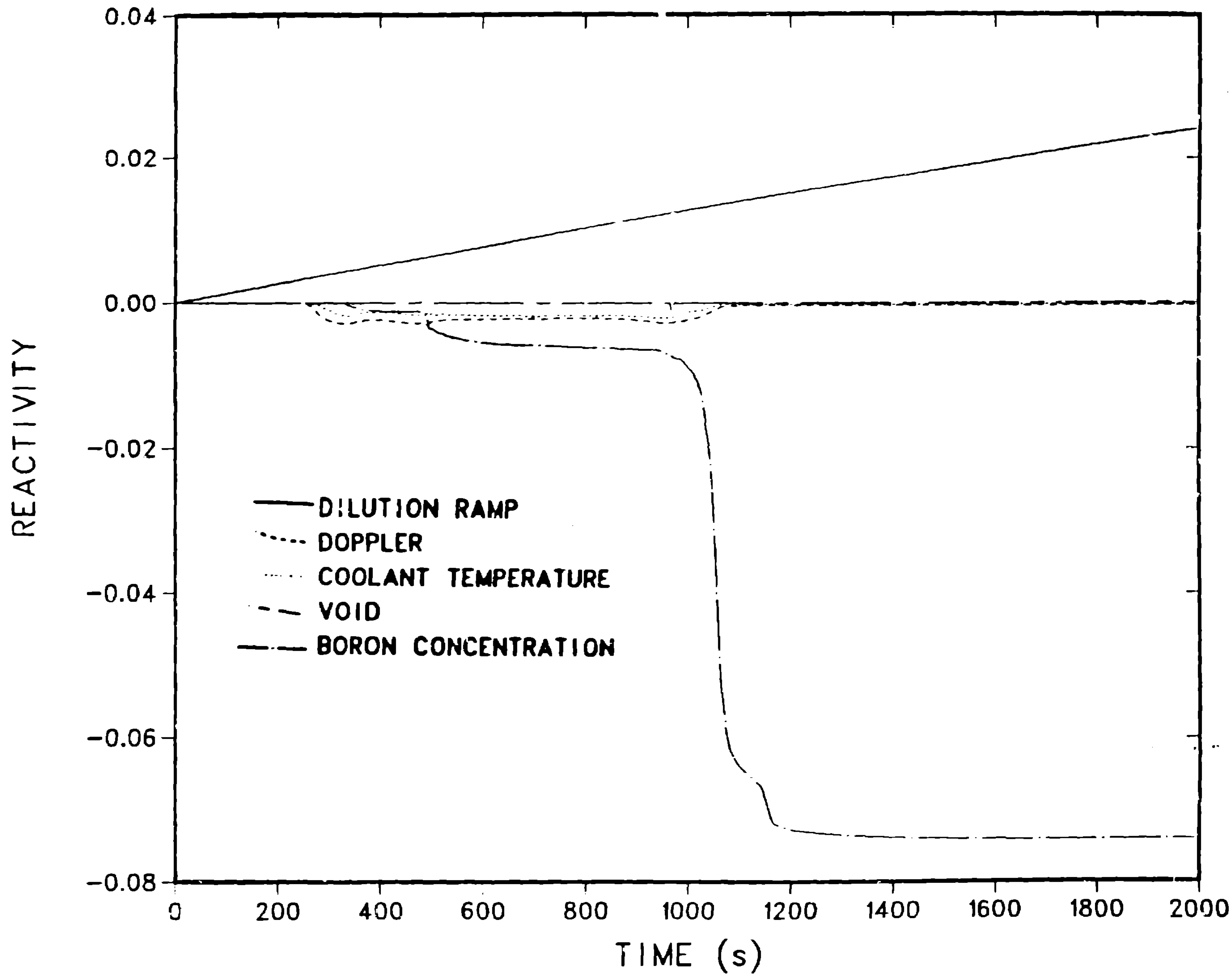


DOPPLER
COOLANT TEMPERATURE
BORON CONCENTRATION
REACTIVITY
TIME (s)
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
-0.08
-0.09
0
1000
2000
3000
4000
5000
6000
7000
8000

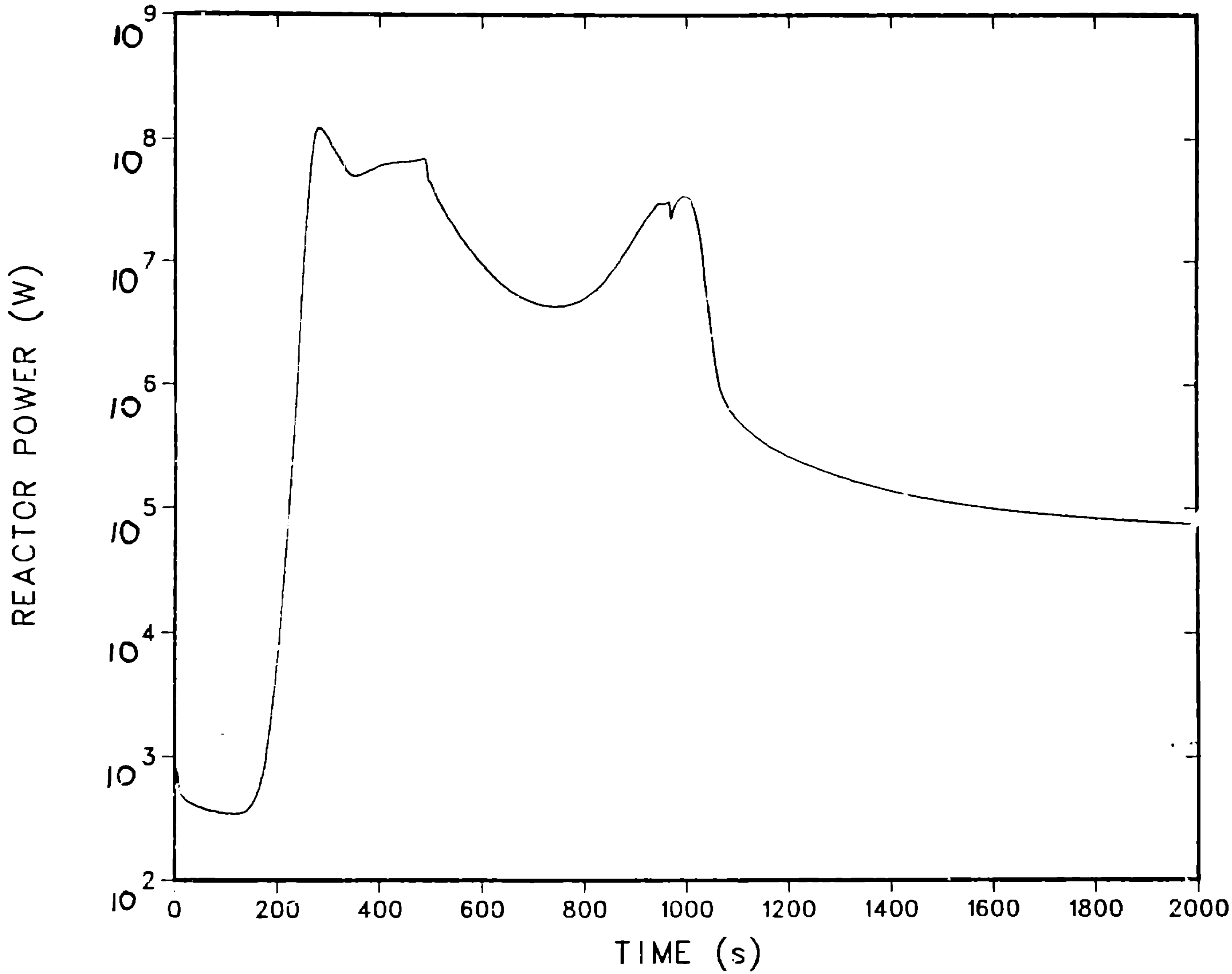
Fig. 9.



10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
REACTOR POWER (W)
0
1000
2000
3000
4000
5000
6000
7000
8000
TIME (s)

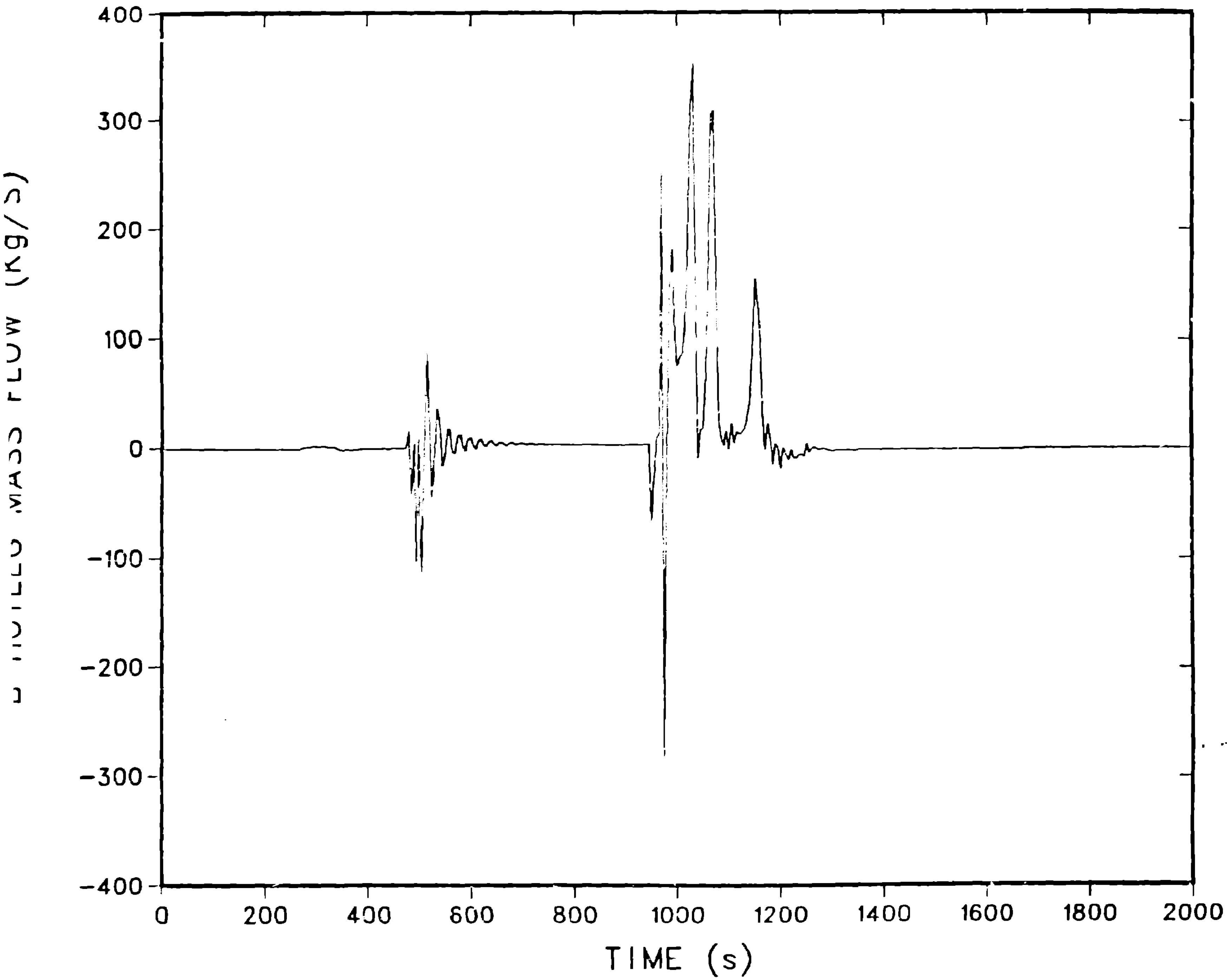


0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
REACTIVITY
0
200
400
600
800
1000
1200
1400
1600
1800
2000
TIME (s)
DILUTION RAMP
DOPPLER
COOLANT TEMPERATURE
VOID
BORON CONCENTRATION



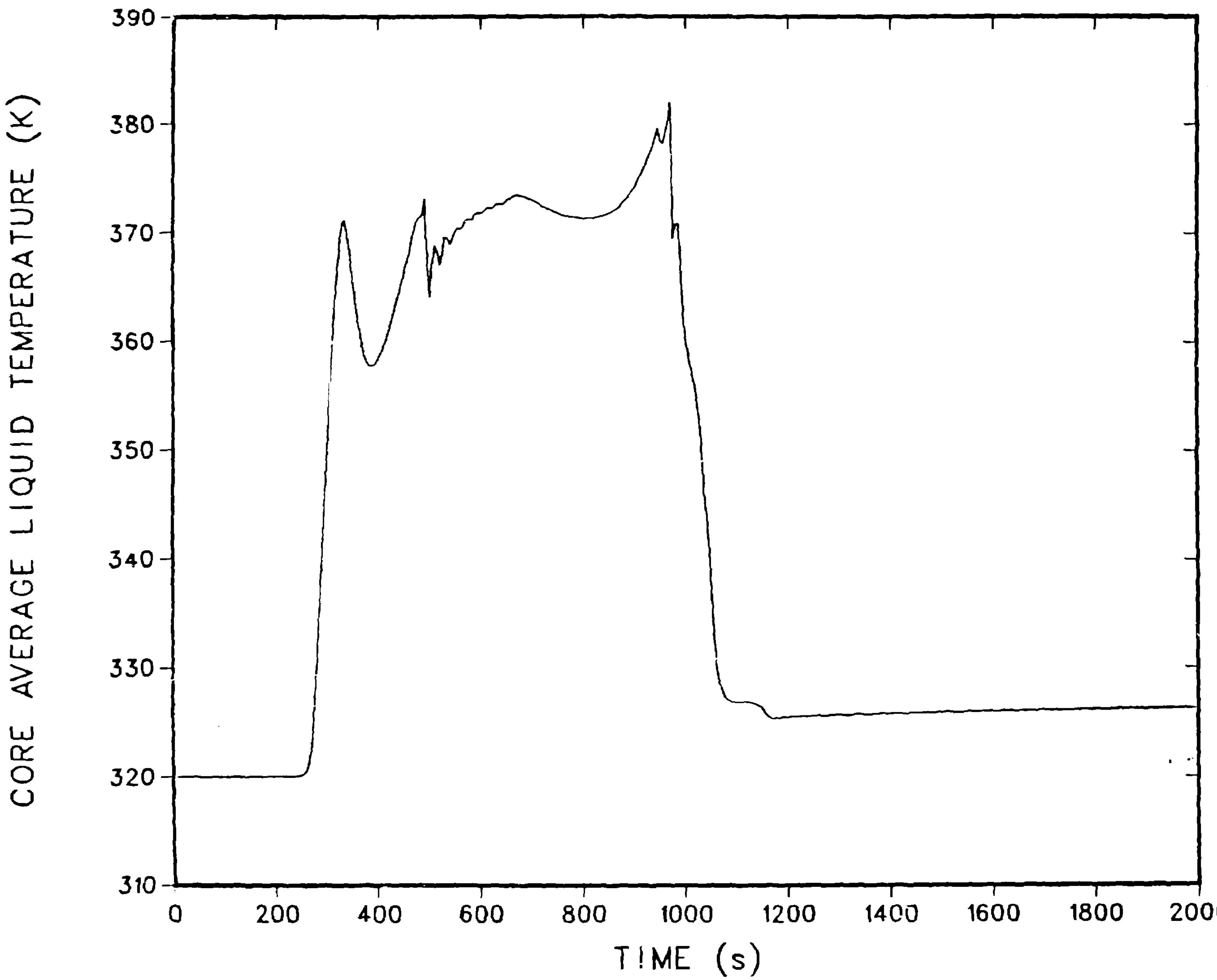
REACTOR POWER (W)
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
0
200
400
600
800
1000
1200
1400
1600
1800
2000
TIME (s)

Fig. 12.



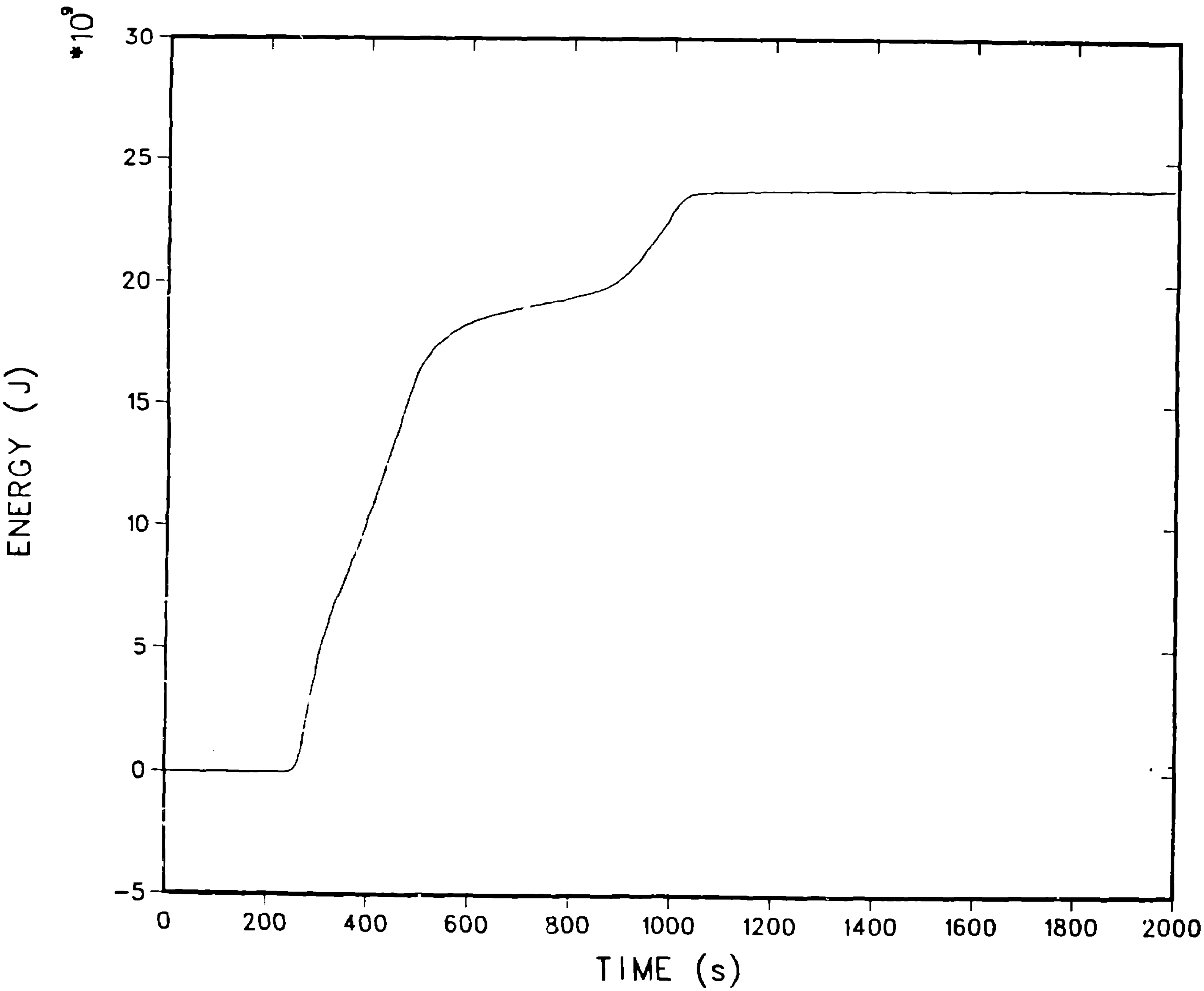
400
300
200
100
0
-100
-200
-300
-400
0
200
400
600
800
1000
1200
1400
1600
1800
2000
TIME (s)

Fig. 13.



CORE AVERAGE LIQUID TEMPERATURE (K)
390
380
370
360
350
340
330
320
310
0
200
400
600
800
1000
1200
1400
1600
1800
2000
TIME (s)

Fig. 14.



*10^9
30
25
20
15
10
5
0
−5
ENERGY (J)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
TIME (s)