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Author(s): Cheng-Chih Tsai

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EG&G Idaho, Inc.
Idaho Falls, Idaho 83415

Prepared for the
U.S. Nuclear Regulatory Commission
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INTERIM REPORT

EGG-CDAP-5149

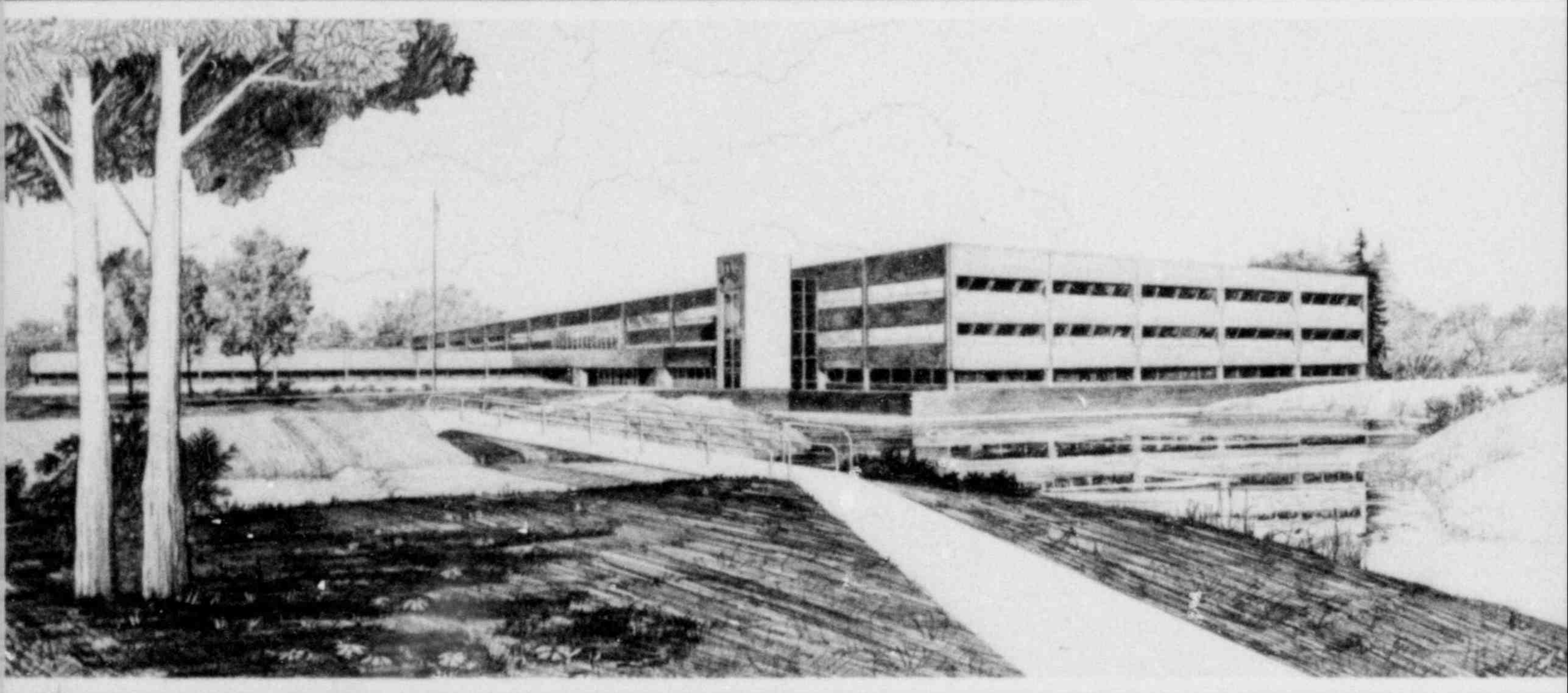
APRIL 1980

CODE DEVELOPMENT AND ANALYSIS PROGRAM

PARAMETRIC STUDY ON CLADDING SURFACE REWET

Cheng-Chih Tsai

U.S. Department of Energy
Idaho Operations Office • Idaho National Engineering Laboratory



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ABSTRACT

The TRAC-P1A computer program with the Iloeje minimum film boiling temperature correlation was used to study the influence of the thermal hydraulic parameters void gap heat conductance, fuel rod power, fluid velocity, and void fraction on cladding surface rewet behavior. The results of this study indicate that the high minimum stable film boiling temperature given by the Iloeje correlation, relative to that used in TRAC-P1A, is the decisive factor in predicting early cladding surface rewet after reactor blowdown, and that void fraction and liquid flow rate have the dominant effects on rewetting behavior.

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SUMMARY

The implementation of the Iloeje minimum stable film boiling temperature correlation enables the TRAC computer code to predict the early rewetting of the hottest cladding surface and more accurately predict the peak cladding temperatures in the LOFT L2-2 and L2-3 tests. Since the surface rewet is influenced by other local thermal hydraulic parameters, in addition to the minimum film boiling temperature, there is the possibility that the close agreement between predicted and measured temperature is the result of incorrectly calculated thermal hydraulic parameters compounded with the surface rewet predicted with the Iloeje correlation. A study on the influence of the local thermal hydraulic parameters like void gap heat conductance, fuel rod power, cladding surface properties, fluid velocity, and void fraction, on cladding surface rewetting behavior was carried out to provide added insight into the rewetting phenomenon.

A simple TRAC model simulating a fuel rod segment and its surrounding coolant channel was used to carry out the study. The TRAC-P1A computer program was modified to add the Iloeje correlation as an option for the minimum film boiling correlation, and to have more input control over the thermal hydraulic conditions around the fuel rod. The transient calculations were carried out and the results were compared with their base case counterparts. The results indicated that the high minimum film boiling temperature given by the Iloeje correlation was the decisive factor in predicting cladding surface rewet. The coolant void fraction and liquid flow rate have strong influences on surface rewetting behavior. The other parameters influence the surface rewet to lesser extents.

PARAMETRIC STUDY ON CLADDING SURFACE REWET

1. INTRODUCTION

Recent implementation of the Iloeje minimum film boiling correlation[1] in the TRAC computer program[2] has substantially improved its prediction on the LOFT L2-2 and L2-3 tests.[3,4] In contrast to other computer code predictions, the TRAC code with the Iloeje correlation was able to predict early rewettings of the hottest clad surface in those nuclear tests, and as a result, more accurately predicted peak cladding temperatures.

Besides the minimum film boiling temperature correlation, the cladding temperature is also influenced by other thermal hydraulic parameters; e.g., local fluid conditions, gap heat conductance and power generation rate in the fuel rod. Since the complete set of data on these thermal and hydraulic parameters is not available, a complete comparison between computer code prediction and experimental data is not possible. The agreement between TRAC predicted cladding temperatures and measured temperatures does not necessarily imply the validity of the Iloeje correlation. There is the possibility that the agreement is a result of incorrectly calculated thermal hydraulic parameters in addition to surface rewet predicted by the Iloeje correlation. It is therefore desirable to study the effect of each important parameter on surface rewet and peak cladding temperature. A study on the sensitivity of predicted clad surface temperature to important thermal hydraulic parameters was therefore carried out. This document describes the results of this study. The remainder of this report is organized into the following sections: Section 2 - Analysis Approach; Section 3 - The Results of Base Case Calculation and Discussion; Section 4 - Results of Parametric Study, and Section 5 - Conclusions.

2. ANALYSIS APPROACH

To carry out this study, efforts were made to: (a) modify the TRAC-P1A computer program, (b) set up a TRAC calculation model, and (c) carry out transient calculations under varying thermal hydraulic conditions. These efforts are described in the following subsections.

2.1 Code Modification

The modification of the TRAC-P1A computer program for this study includes: (a) the Iloeje correlation was added as an option for the minimum film boiling temperature correlation, (b) the "FILL" type option of the "FILL" component in the TRAC code was expanded such that coolant mixture velocity, temperature, and void fraction can be input as functions of time, and (c) adjusting multipliers were included such that several thermal hydraulic parameters can be easily adjusted.

The update deck for implementating the Iloeje correlation as a minimum film boiling option was provided by Los Alamos Scientific Laboratory (LASL). The Iloeje correlation as implemented in TRAC is subjected to constraints for high mass flux and for low pressure. When the mass flux G is larger than 135.6 Kg/m^2-sec (100000 lbm/ft^2-hr), the minimum film boiling temperature T_{min} is taken to be the value calculated at G = 135.6 Kg/m^2-sec. At low pressure the Iloeje correlation gives unrealistically low values for T_{min}. Except at low pressure, the T_{min} given by the Iloeje correlation is higher than the T_{min} given by the original TRAC-P1A correlation. The T_{min} used in TRAC is therefore taken as the larger of the T_{min} values given by the Iloeje correlation and the standard TRAC-P1A correlation, which is the Henry modification to Berenson's formula (see Reference 2). These constraints were imposed so that the Iloeje correlation will not be extrapolated beyond its data base, and were recommended in the Denver Workshop on Rewet Phenomena (April 11-12, 1979). Refer to the Appendix for the implemented Iloeje correlation.

The "FILL" type option was expanded so that there is more control of the fluid properties entering "FILL" component and, consequently, the fluid properties surrounding the hot clad surface. The adjusting multiplier introduced in the modified TRAC code includes:

1. RPOWRX: The power used in the TRAC calculation is the input power times RPOWRX
2. VELX: The velocity set by the "FILL" component used in the TRAC calculation is input velocity times VELX

3. ALPX: The void fractions set by the "FILL" and "BREAK" components used in the TRAC calculation are the input void fractions times ALPX.

2.2 The Calculation Model

To carry out the calculations efficiently, a simple TRAC model was used. This model, shown schematically in Figure 1, is to simulate a portion of the fuel rod and its surrounding coolant in a reactor. The "VESSEL" component contains a rod segment and its coolant channel. The "FILL" and "BREAK" components are for imposing inlet and outlet flow boundary conditions, respectively. Since they cannot be connected to the "VESSEL" component directly, as restricted by TRAC, they are connected through pipes to the "VESSEL" component. The dimensions of the TRAC model are listed in Table 1.

Proper time-dependent boundary conditions at the "FILL" and "BREAK" must be specified such that the fluid conditions in the "VESSEL" modeled surrounding the rod segment are properly simulated. The fluid conditions for the base case calculations at the "FILL" and the "BREAK" were taken from the results RELAP pretest calculation for the LOFT L2-3 test. Since the main interest here is the sensitivity of clad surface rewet on local thermal hydraulic conditions, rather than the local thermal hydraulic conditions themselves, exact simulation of the thermal hydraulic conditions was not emphasized. Figures 2, 3, and 4 show the entrant mixture temperature, velocity, and void fraction, respectively. The exit pressure, mixture void fraction, and temperature are shown in Figures 5, 6, and 7, respectively. Figure 8 shows the base case rod power history which at t = 0 (steady state) corresponds to a linear heating rate of 40 kW/m. The gap conductance may vary with time after the transient due to the time-dependent temperature distribution in the fuel rod. For the base case, the gap conductance h_{gap} at steady state (t = 0) was taken to be 4345 W/m^2-K and during the transient (t > 0) an average value of h_{gap} = 3630 W/m^2-K was used. These values correspond to the steady state value and the average value within ten seconds after transient initiation, used by LASL in the LOFT L2-2 posttest analysis.[3]

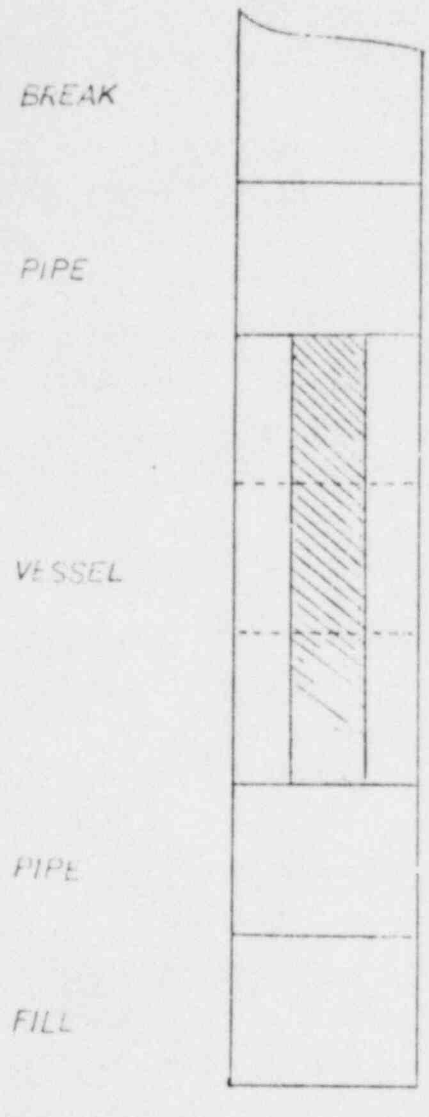

Figure 1. Schematic of TRAC model for rewet parametric study.

TABLE 1. DIMENSIONS OF TRAC MODEL

Vessel	
Fuel pellet O.D.	9.3 mm
Gap width	0.095 mm
Clad O.D.	10.72 mm
Clad thickness	0.617 mm
Flow area	1.14 cm^2
Hydraulic diameter	13.5 mm
Axial length	13.97 cm
Number of cells	3
Pipe	
Inner radius	6.03 mm
Flow area	1.14 cm^2
Axial length	4.65 cm
Fill	
Cell length	4.65 cm
Cell volume	5.32 cm^3
Break	
Cell length	4.65 cm
Cell volume	5.32 cm^3

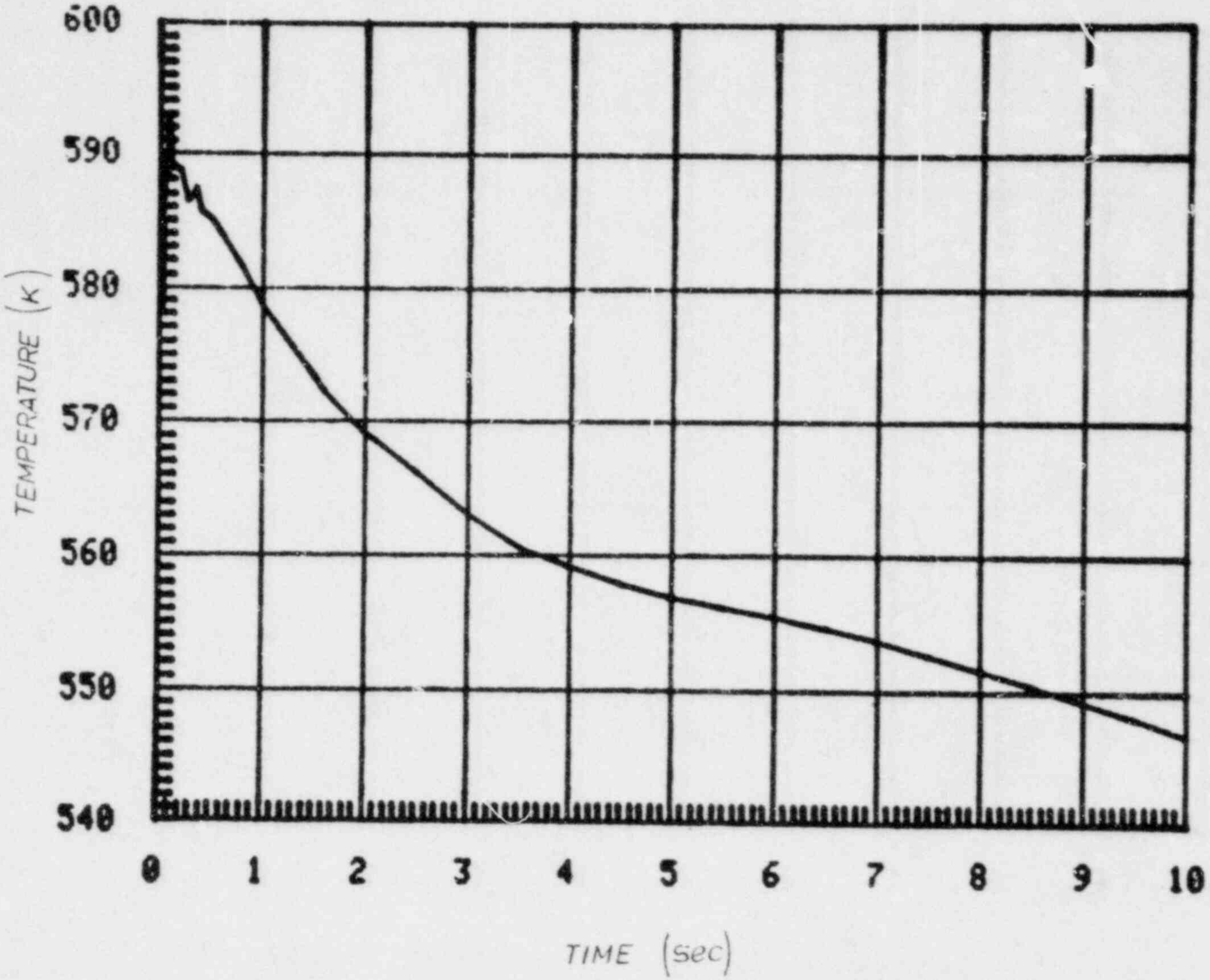

Figure 2. Entrant mixture temperature.

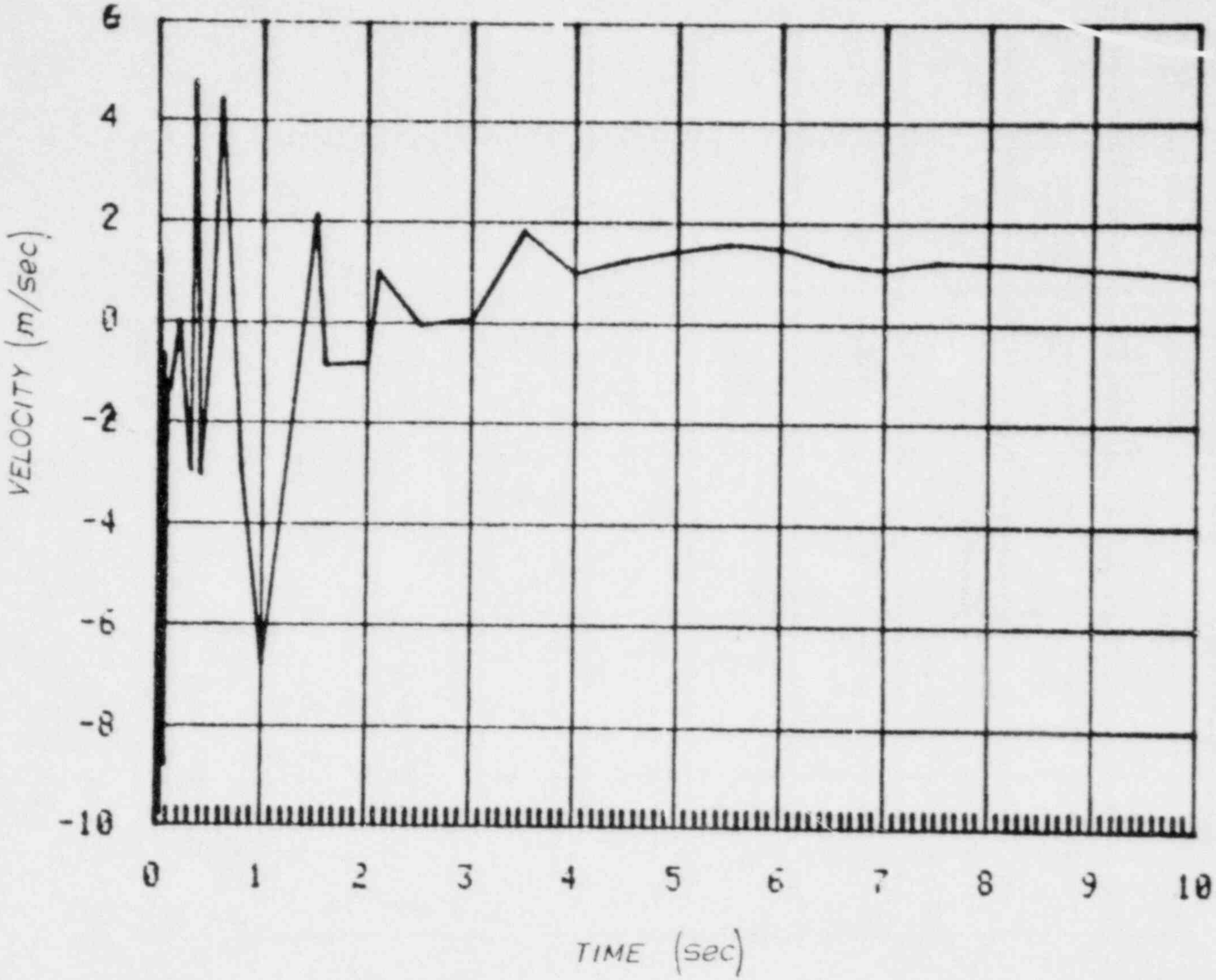

Figure 3. Entrant mixture velocity.

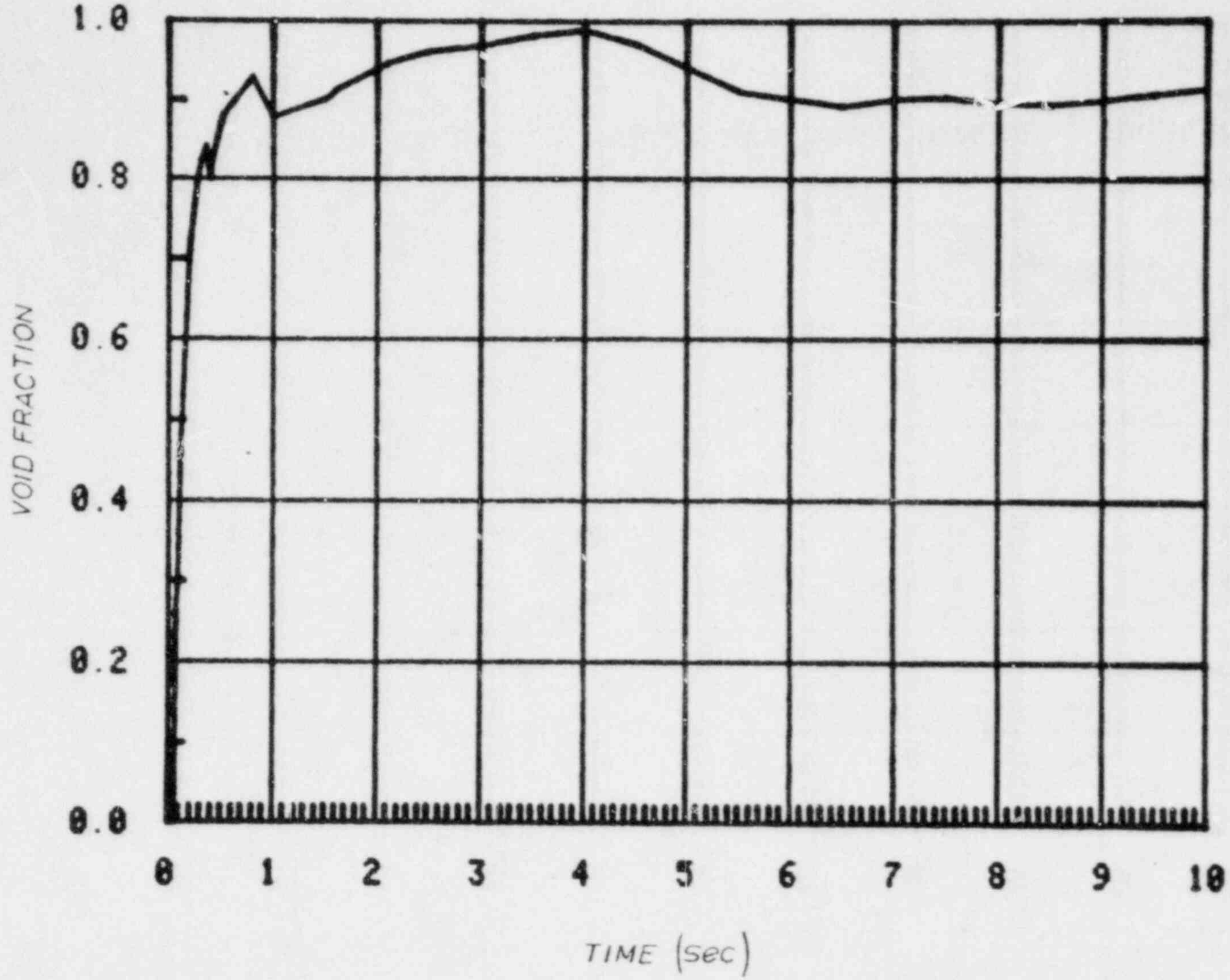

Figure 4. Entrant mixture void fraction.

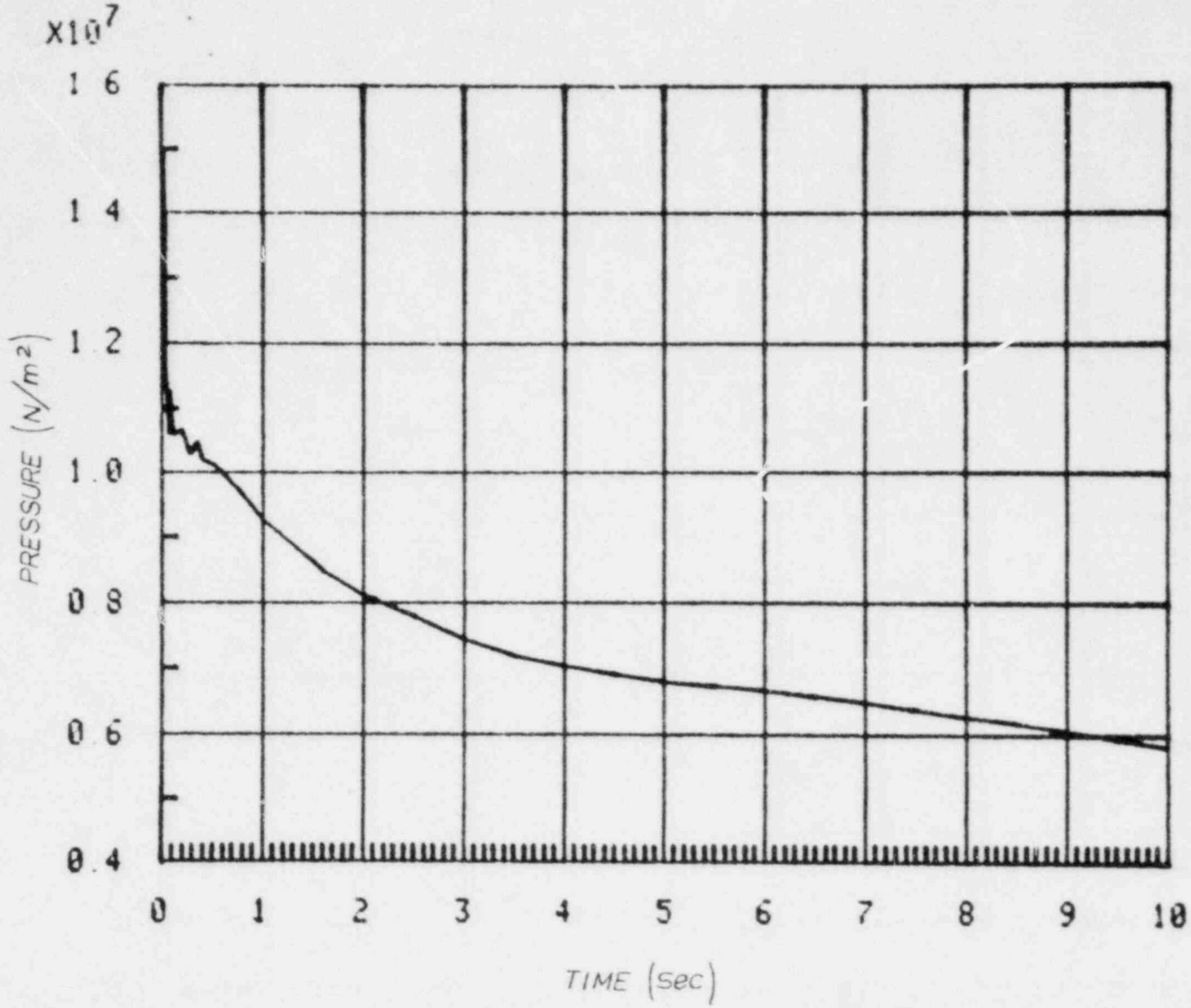

Figure 5. Exit pressure.

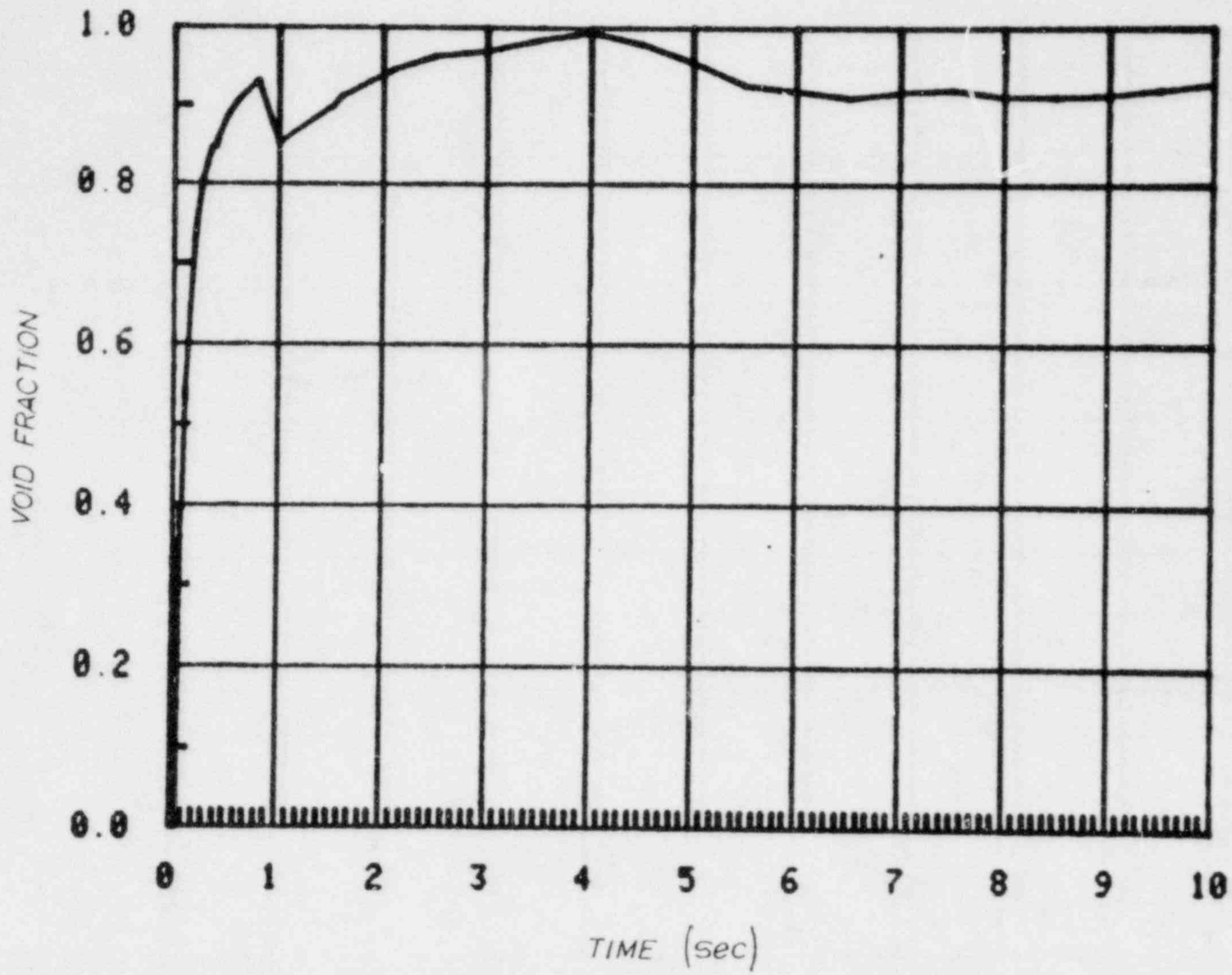

Figure 6. Exit void fraction.

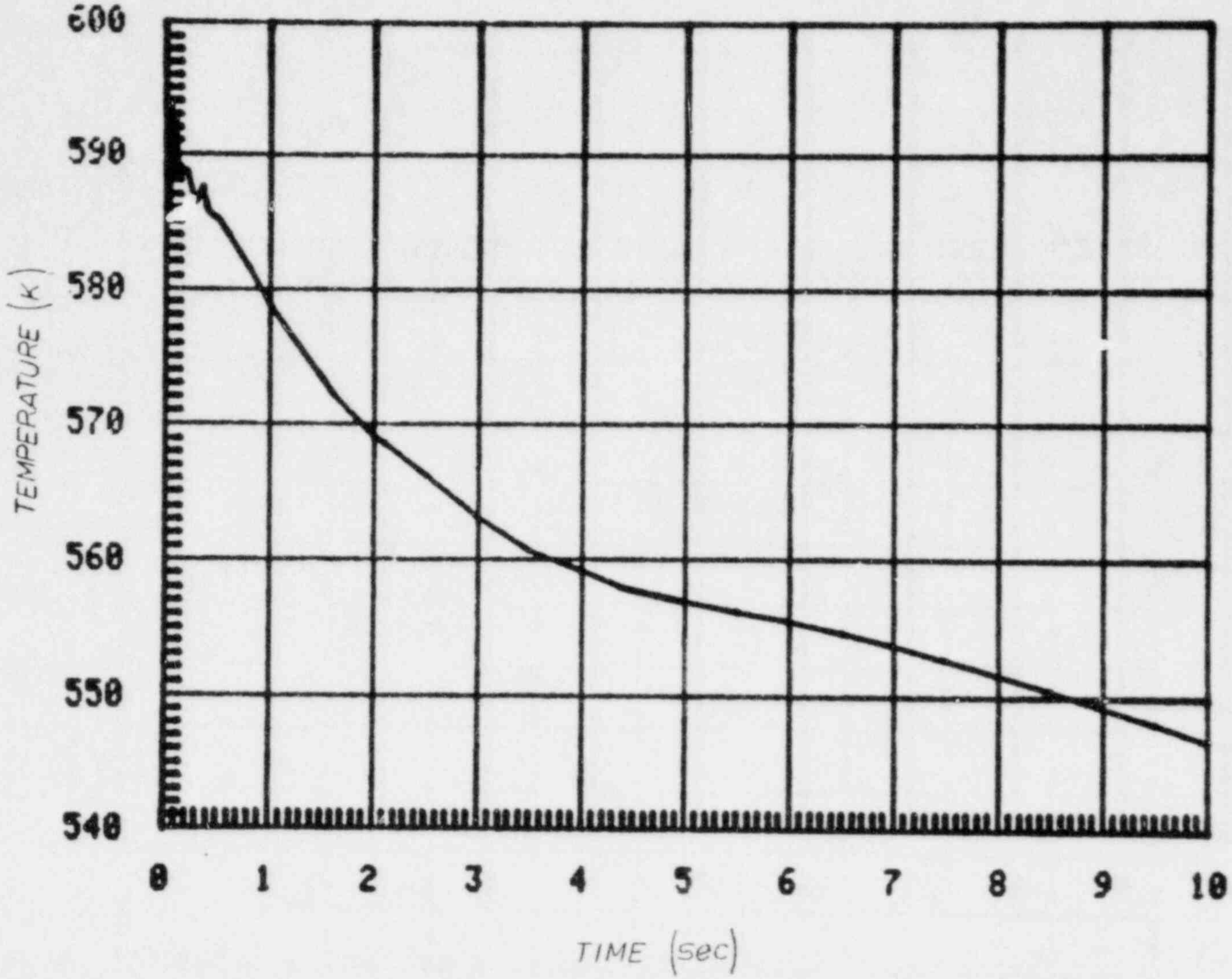

Figure 7. Exit mixture temperature.

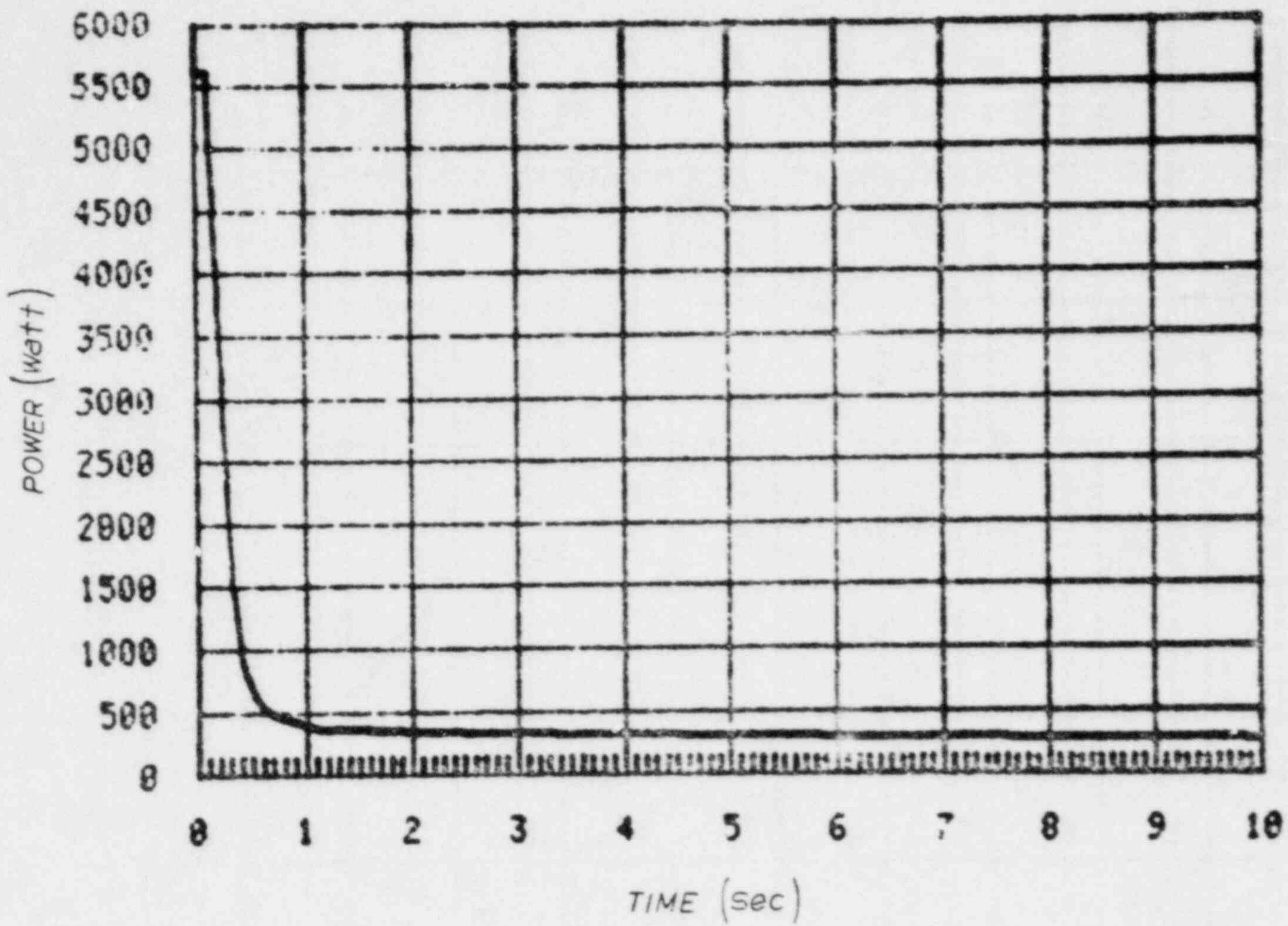

Figure 8. Base case rod power.

2.3 Calculation Procedure

This sensitivity study was started by choosing a base case, which has been described in the previous subsection. Since the interest here is the early rewet of the clad surface, the transient calculation was carried out to only ten seconds after blowdown. The calculation was repeated with the important parameters like rod power, gap conductance, fluid velocity, and void fraction adjusted individually. The results calculated by TRAC were plotted by the interactive graphic processor, MAGNUM[5] at the Idaho National Engineering Laboratory (INEL).

2.4 Heat Transfer Logic in TRAC

To facilitate the discussion of the calculated results, the TRAC surface heat transfer logic is briefly described here. TRAC constructs, from a set of surface heat transfer correlations, a generalized boiling curve based on local surface temperature, surface properties, and fluid conditions. The wall temperature at critical heat flux, the minimum film boiling temperature, the heat transfer mode, and the heat transfer coefficients to liquid and vapor are computed on the basis of this curve. Figure 9 illustrates schematically the resulting piecewise smooth boiling curve. This curve changes as local conditions change.

The correlations used are listed in Table 2. Of particular importance in determining the boiling curve are the determinations of critical heat flux q''_{CHF} and minimum film boiling temperature T_{min}. The critical heat flux is determined from a combination of the Zuber and Biasi correlations. Refer to the Appendix for the critical heat flux correlations and the minimum film boiling temperature correlation. The important characteristics of the critical heat flux correlations are the strong dependence on void fraction or flow quality. The Iloeje minimum film boiling correlation also has strong dependence on mass flux and equilibrium quality. The wall temperature at q''_{CHF} is given by

$$T_{CHF} = T_s + q''_{CHF}/h_{NB} \qquad (1)$$

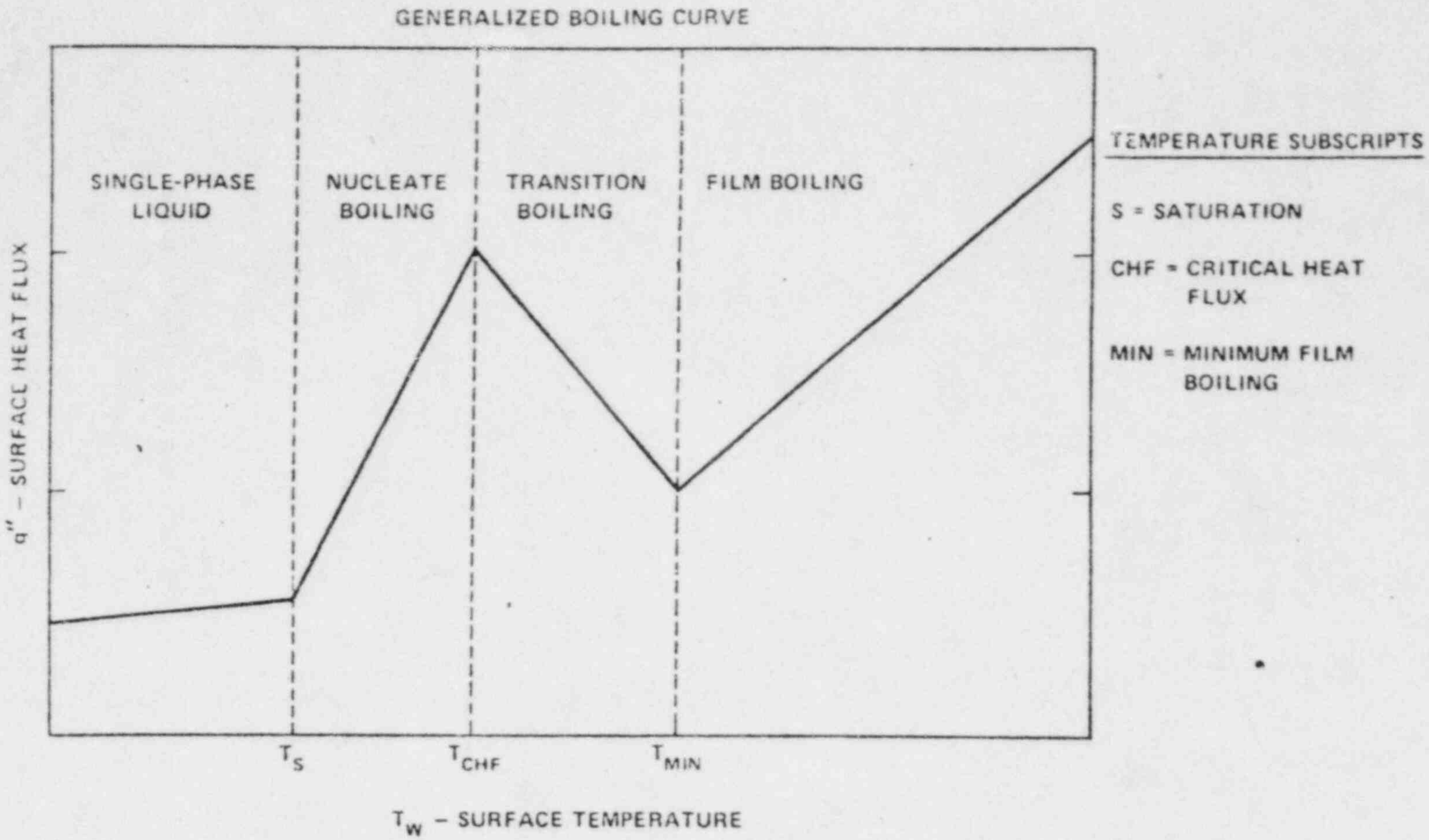

Figure 9. TRAC boiling curve.

TABLE 2. TRAC HEAT TRANSFER CORRELATIONS

Regime	Mode No.	Correlation
Forced convection to single-phase liquid	1	Laminar flow: constant Nusselt number Turbulent flow: Dittus-Boelter
Nucleate boiling and forced convection vaporization	2	Chen
Transition boiling	3	Log-log interpolation
Film boiling	4	Modified Bromley Dougall-Rohsenow
Forced convection to single-phase vapor	6	Free convection: McAdams Turbulent flow: Dittus-Boelter
Forced convection to two-phase mixture	7	Laminar flow: constant Nusselt number Turbulent flow: Dittus-Boelter
Horizontal film condensation	11	Chato
Vertical film condensation	12	Nusselt theory
Turbulent film condensation	13	Carpenter and Colburn
Critical heat flux	--	Low flow: Zuber pool boiling High flow: Biasi
Minimum stable film boiling	--	Los pressure: Henry-Berenson High pressure: Iloeje, et al.

where

T_s = the saturation temperature

h_{NB} = the nucleate boiling heat transfer coefficient.

The heat flux at T_{min} is given by

$$q''_{min} = (1 - \alpha)\, h_{FB}\, (T_{min} - T_s) \tag{2}$$

where

h_{FB} = the film boiling heat transfer coefficient.

The heat transfer regime (or heat transfer mode) is determined by comparing the surface temperature T_w to T_s, T_{CHF} and T_{min}. After the heat transfer regime is determined, as seen in Figure 9, the appropriate correlation is chosen according to Table 2 to find heat transfer coefficients to liquid and vapor. In the transition boiling regime, the heat transfer coefficient h_{TB} is determined by log-log interpolation between the q''_{CHF} and T_{min} points of the boiling curve.

$$h_{TB} = [\delta\, q''_{CHF} + (1 - \delta)\, q''_{min}]\, (T_w - T_s)^{-1}, \tag{3}$$

where

$$\delta = \left(\frac{T_s - T_{min}}{T_{CHF} - T_{min}}\right)^2$$

Since q''_{CHF}, T_{CHF}, and T_{min} are functions of hydrodynamic parameters as well as thermodynamic parameters, the boiling curve for cladding surface heat transfer is rapidly varying during a reactor blowdown analysis. At the beginning of the blowdown, a rapid pressure decrease causes a decrease in T_s. Bulk boiling causes T_w to decrease. The flow rate decrease (increased void or quality) causes q''_{CHF}, T_{CHF}, and T_{min} to decrease. When T_w is above T_{CHF}, but below T_{min}, the surface goes into transition boiling, the heat transfer rate decreases, and the cladding surface begins to heat up. The coolant flow rate does not decrease continuously, but rather fluctuates. At an early stage of the heatup, the surface temperature is relatively low. A small increase in liquid flow rate will cause T_{CHF} to increase above T_w and the surface returns to nucleate boiling (RNB), which cools the surface rapidly. If the flow decrease is sustained the surface heatup continues. When T_w reaches T_{min} due to increasing T_w or decreasing T_{min}, or both, the surface heat transfer rate reaches a minimum. The surface heat transfer then goes into film boiling and later may be cooled only by vapor. The surface heat transfer rate increases with increasing T_w until the surface heat transfer balances the heat transfer from fuel pellet to cladding surface, at which time the peak cladding temperature occurs.

After surface dryout, if the liquid flow rate past the cladding surface is high enough, surface rewet can occur. When T_w is not too high, the liquid flow rate can cause T_{min} to increase to a value equal to T_w. The surface then goes into transition boiling. T_{min} and T_{CHF} continue to increase with further liquid flow rate increase. At the same time, the surface is cooled because of better surface heat transfer. Since q''_{CHF} is usually larger than q''_{min} and the surface heat transfer is given by Equation (3), when T_w is further below T_{min} better surface heat transfer is obtained. If the liquid flow continues to increase before RNB, the surface cooling is an accelerating process until RNB is reached. If the liquid flow decreases before RNB, the surface cooling processes are slowed down. Depending on the flow rate, the surface may even begin to heat up and go into film boiling again.

3. RESULTS OF BASE CASE CALCULATION AND DISCUSSION

Although the results for all three levels of the vessel component were calculated by TRAC, only the level one results will be presented and discussed. The results for the base case are presented in Figures 10 to 17. Figures 10 and 11 show the cladding temperature and heat transfer mode, respectively. Other thermal hydraulic properties are in Figures 12 to 17. Figures 10 and 11 show that the cladding surface has gone through dryout and rewet. The maximum cladding temperature reached was about 1015 K. Return to nucleate boiling (RNB) occurred at about 5.9 seconds after transient initiation.

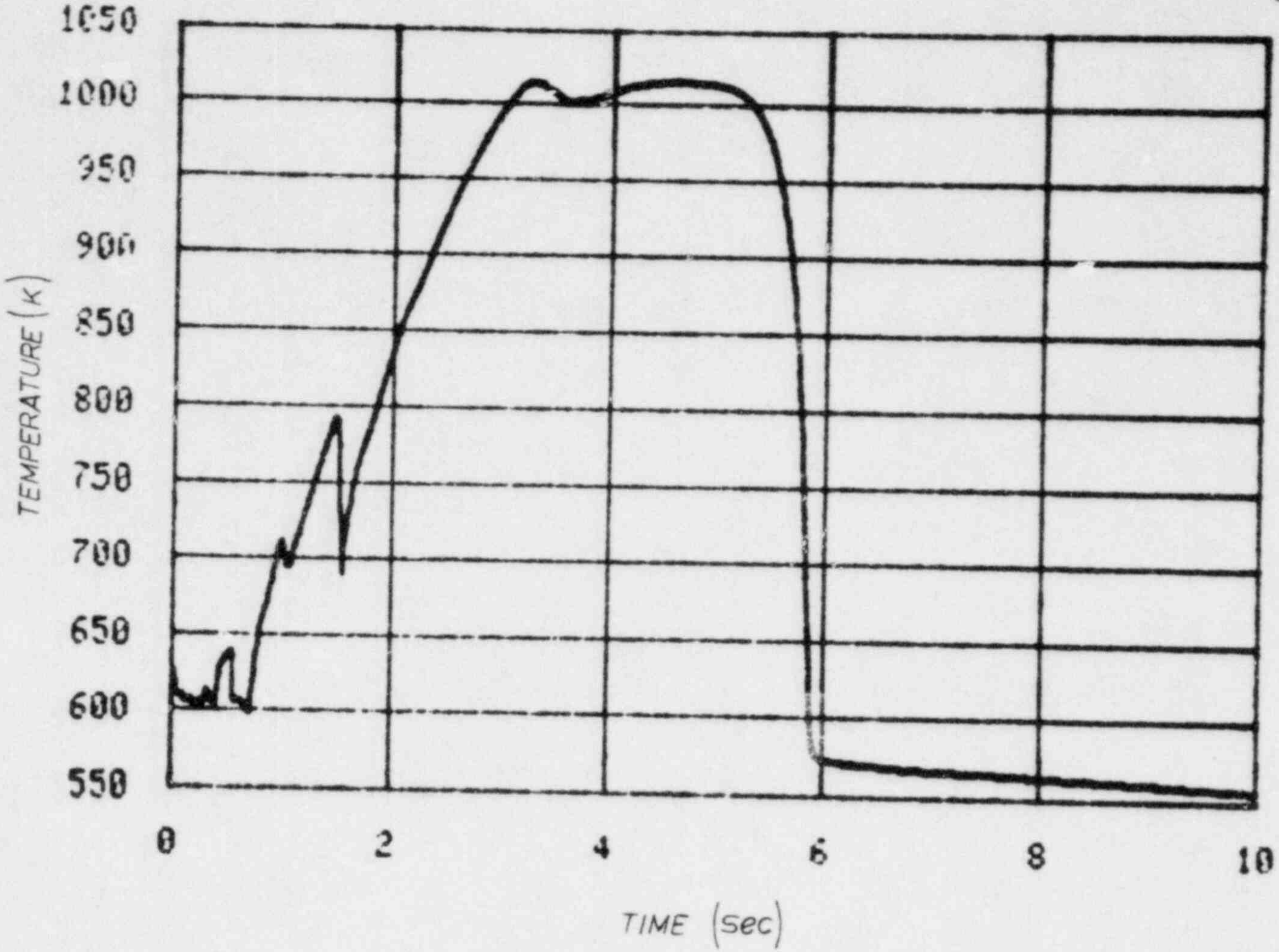

Figure 10. Base case cladding temperature.

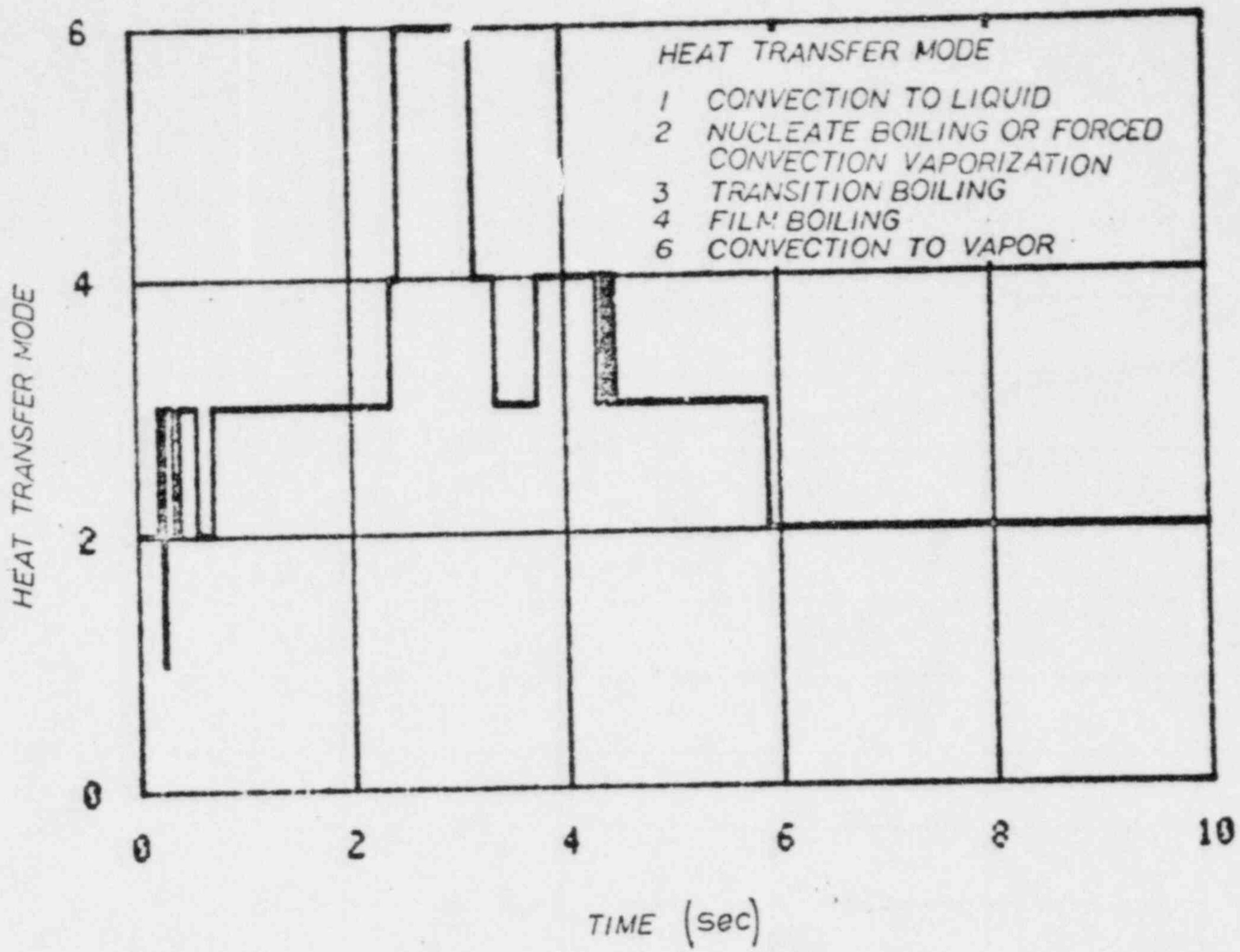

Figure 11. Base case heat transfer mode.

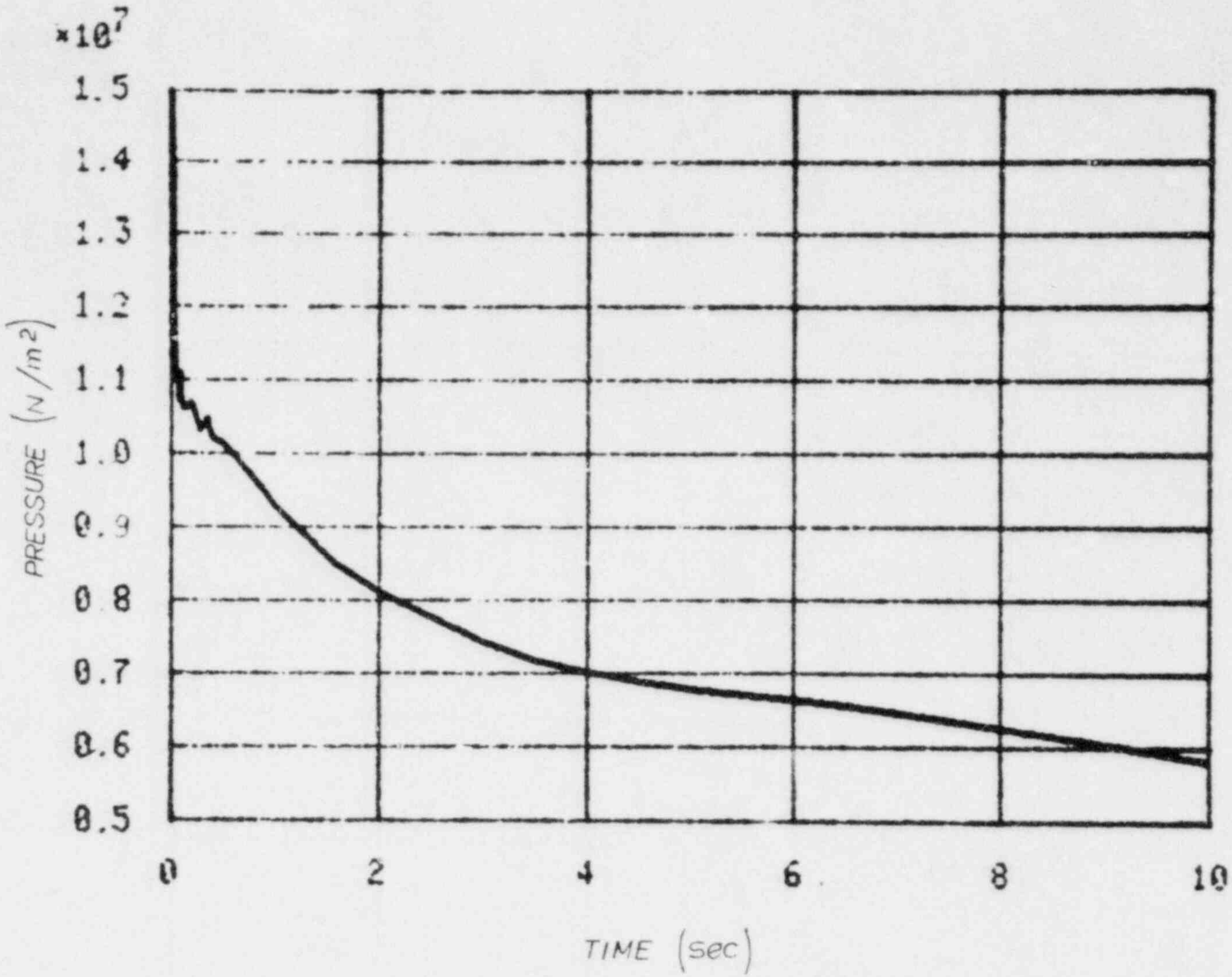

Figure 12. Base case pressure.

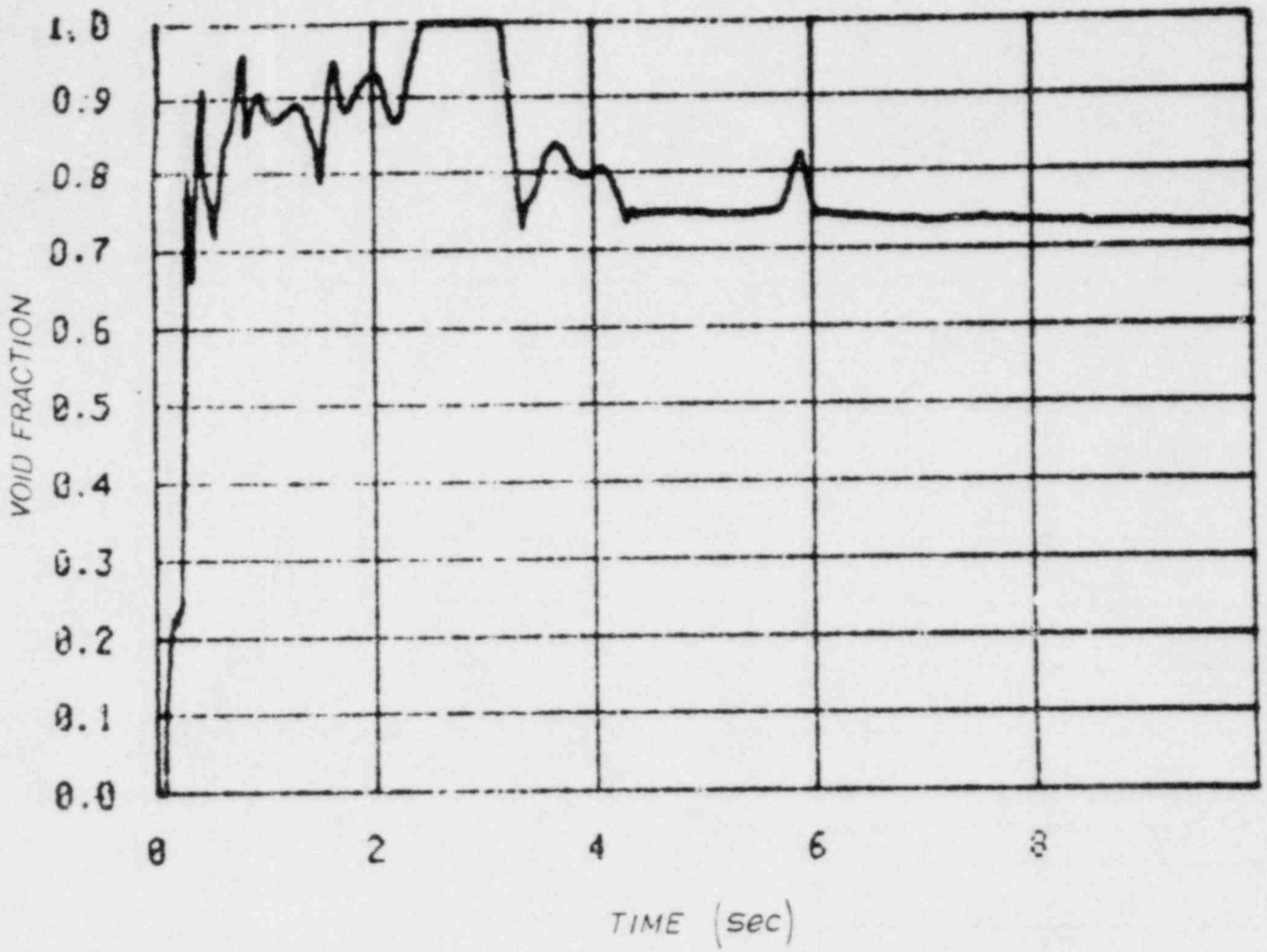

Figure 13. Base case void fraction.

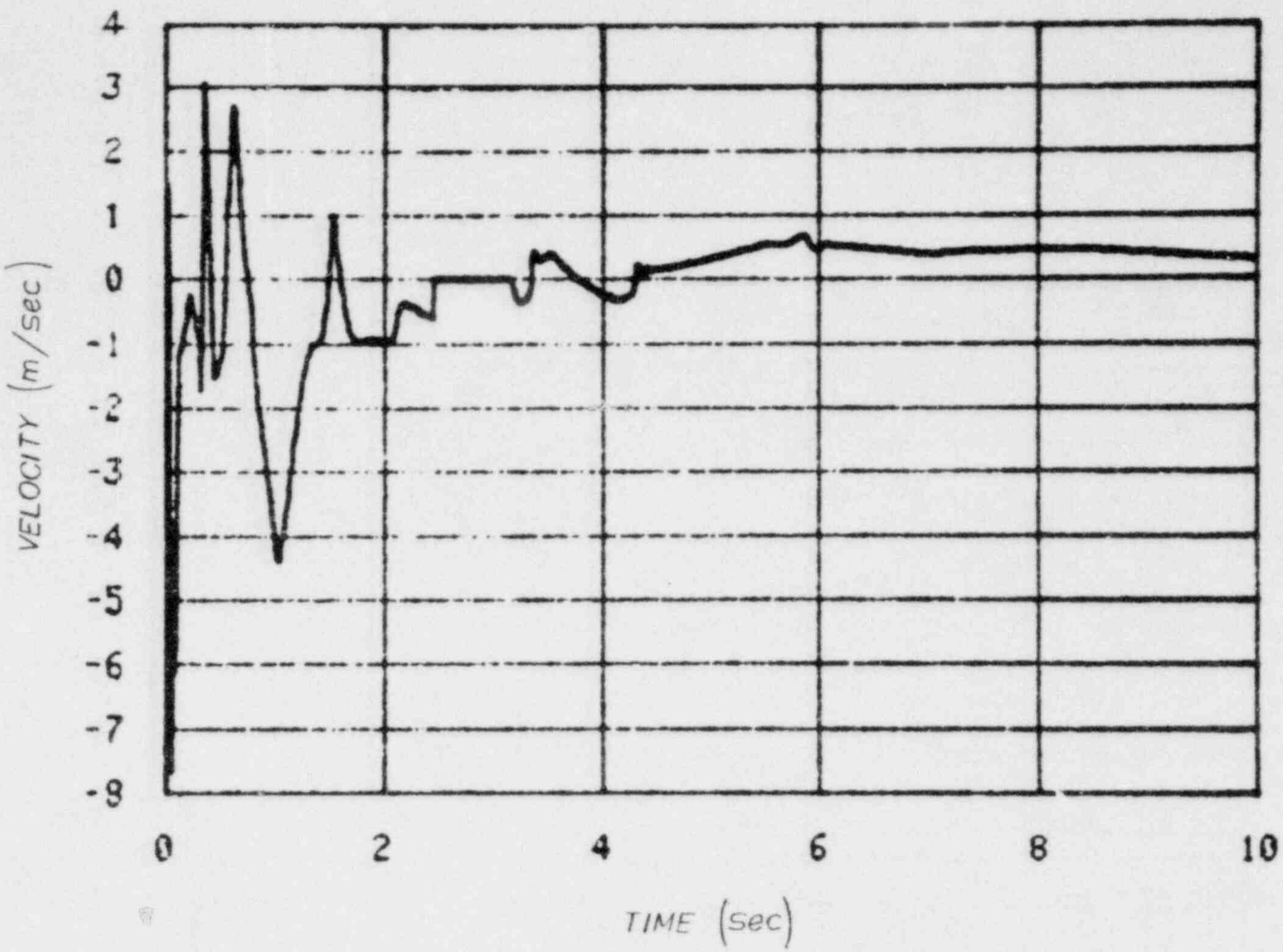

Figure 14. Base case liquid velocity.

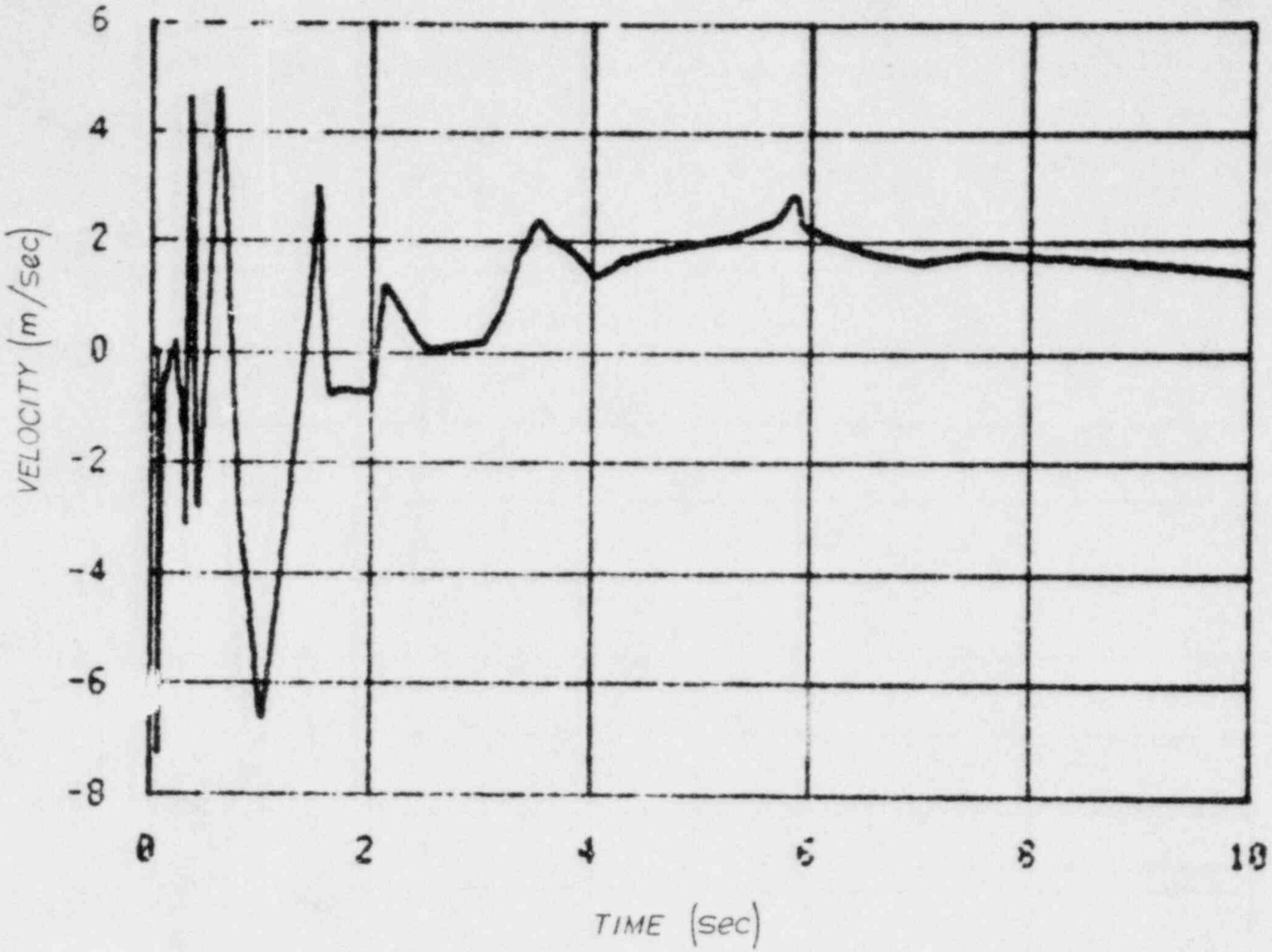

Figure 15. Base case vapor velocity.

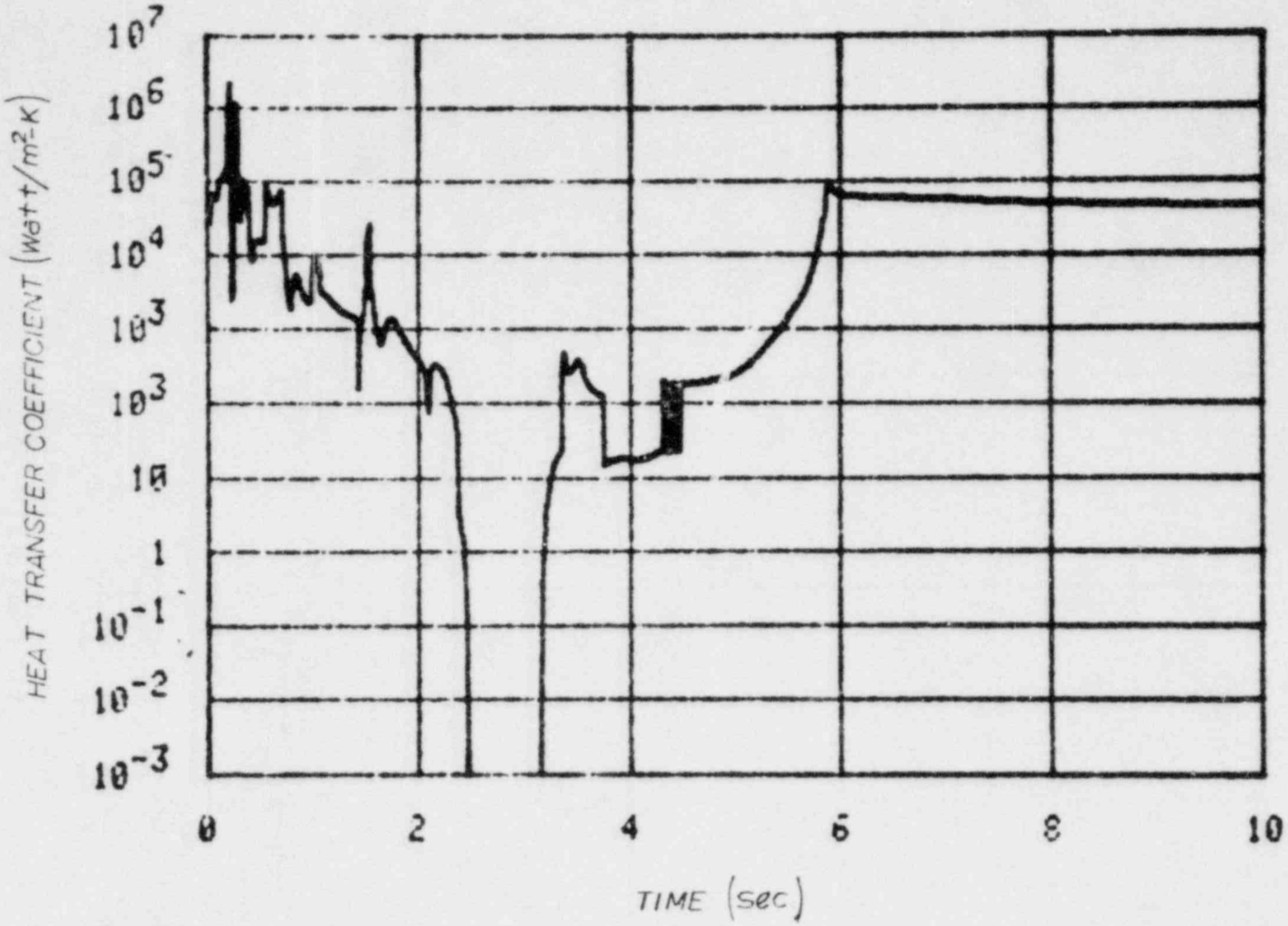

Figure 16. Base case heat transfer coefficient to liquid.

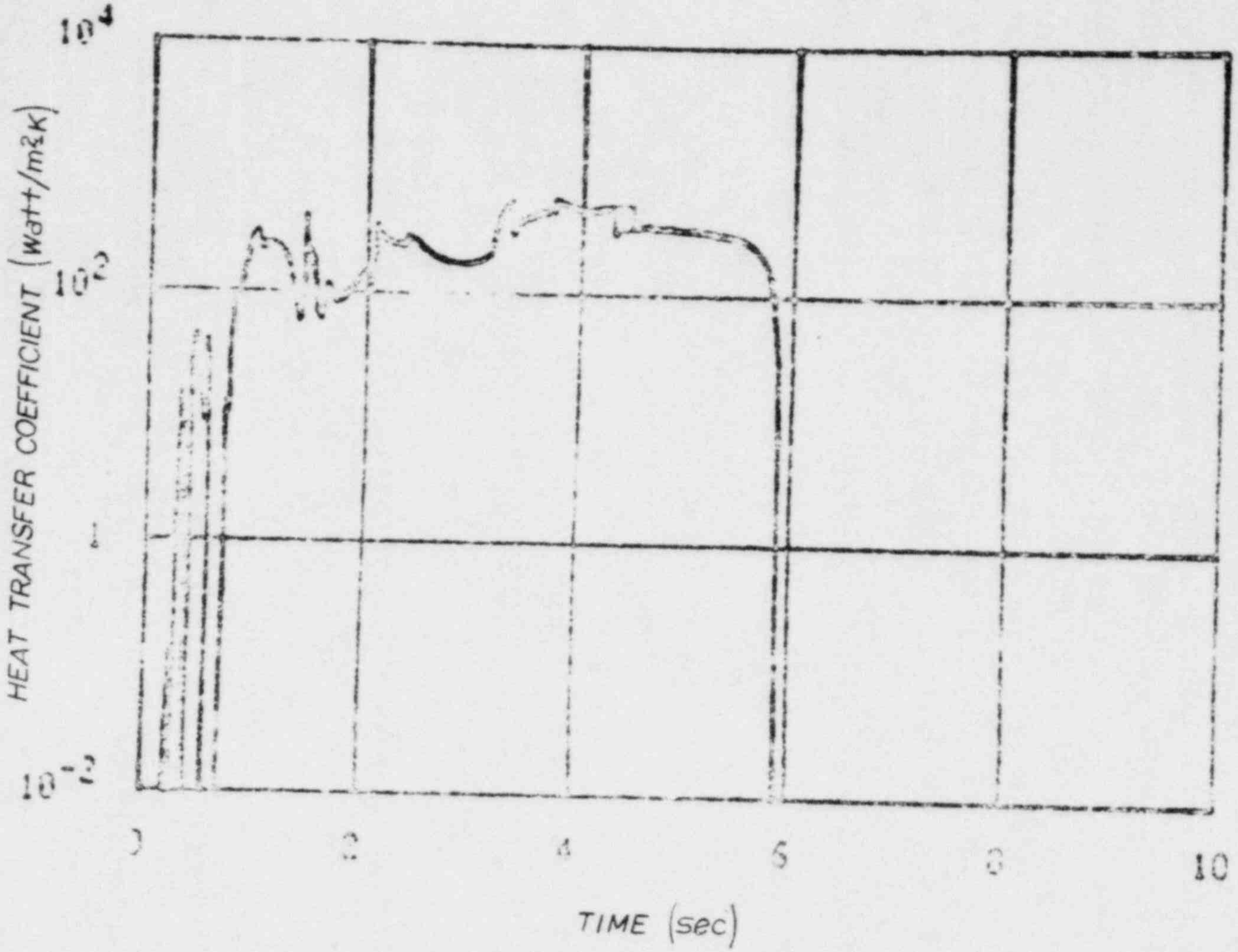

Figure 17. Base case heat transfer coefficient to vapor.

Within 3.2 seconds after transient initiation, the rapid flow decrease causes rapid decreases in q''_{CHF}, T_{CHF}, T_{min}, and heat transfer rates. Except within 0.5 seconds after transient initiation, the rod power decreases relatively slowly. The cladding surface heats up when the surface heat transfer goes through transition boiling, film boiling, and heat transfer to vapor. As shown in Figure 13, at 3.2 seconds after transient initiation, after dryout, liquid is again present. From about 4.3 to about 6 seconds after transient initiation, the liquid flow rate steadily increases, as shown in Figures 13 and 14. As a result, the cladding surface quickly goes into transition boiling. As discussed in Section 2.4, the increasing T_{CHF} and T_{min}, due to continuously increasing liquid flow rate together with lower surface temperature T_w, causes increasing heat transfer rates. The surface cooling process is then an acclerating process until the surface returns to nucleate boiling at 5.9 seconds.

For comparison, the TRAC calculation was repeated using the standard TRAC-P1A T_{min} correlation instead of the Iloeje correlation. The histories of cladding temperature and surface heat transfer modes are shown in Figures 18 and 19, respectively. There was no surface rewet and the predicted peak cladding temperature was about 80 K higher. The TRAC-P1A T_{min} does not depend on hydrodynamic parameters of the flow, and the transition between transition boiling and film boiling tends to be surface temperature controlled. The effects of hydrodynamic parameters on the transition from film boiling to transition boiling are through surface cooling and are therefore much less effective. As shown in Figures 17 and 18, the increasing liquid flow cools off the cladding surface slowly, and the surface stays in film boiling from 3.2 seconds after transient. Under the fluid conditions present, the Iloeje T_{min} is much higher than the TRAC-P1A T_{min}. Thus, the Iloeje correlation permits establishment of transition boiling after the initial dryout, while the TRAC-P1A correlation does not.

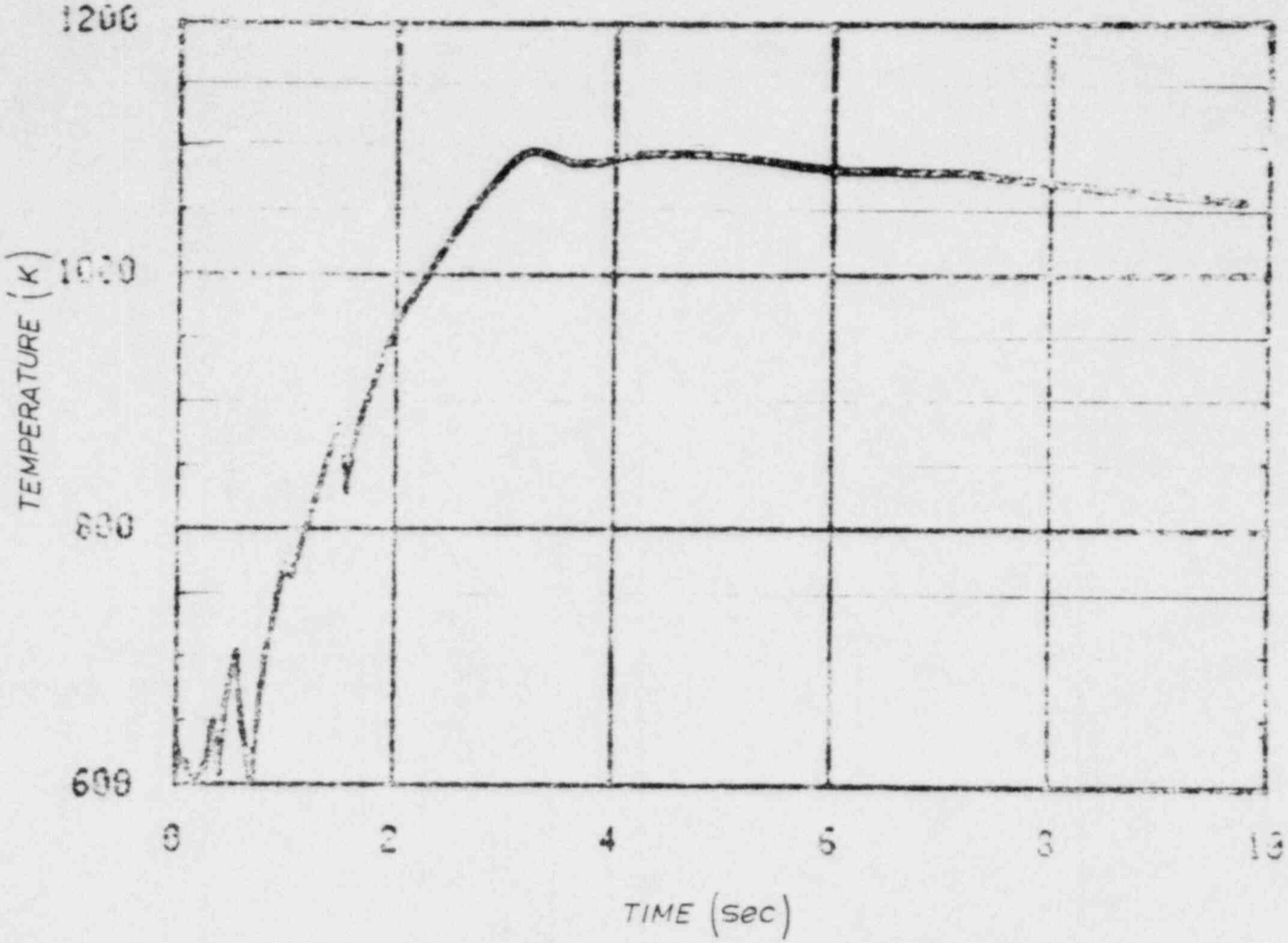

Figure 18. Cladding temperature calculated with TRAC-P1A T_{min} correlation for base case.

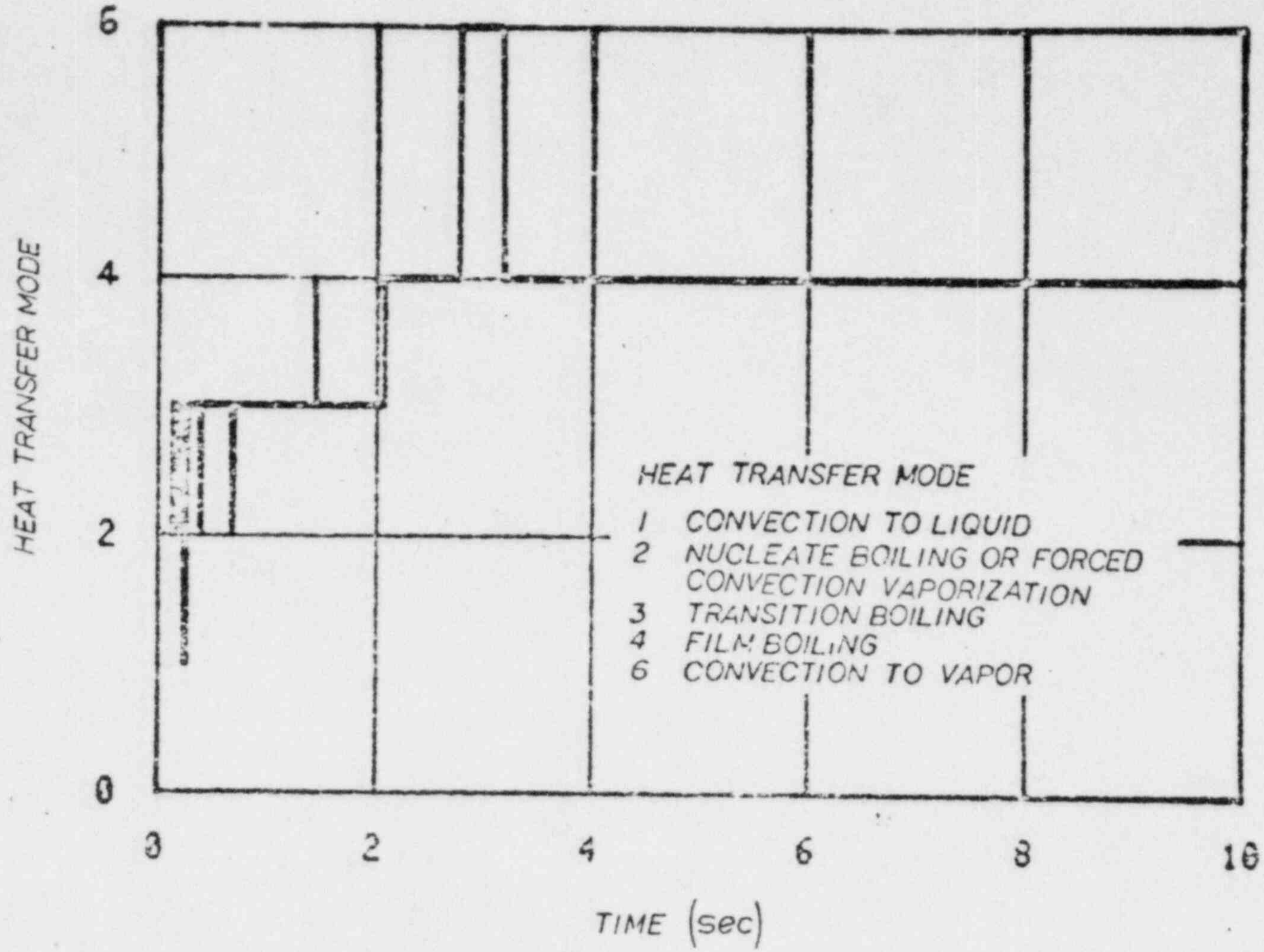

Figure 19. Heat transfer mode calculated with TRAC-P1A T_{min} correlation for base case.

4. THE RESULTS OF THE PARAMETRIC STUDY

The parameters of interest are cladding surface properties, rod power, gap heat conductance, fluid velocity, and void fraction. Their influences on predicted clad surface rewet will be discussed in the following subsections.

4.1 The Influence of Clad Surface Properties

Of particular interest is the effect of the oxide layer on the clad surface. No significant effect of the surface properties occurs in the Berenson correlation which contains all of the property variations of the Iloeje correlation; the Iloeje correlation also shows no significant property variations. The critical heat flux is determined from a combination of the Zuber and the Biasi correlations, neither has surface property variation. As a result, surface heat transfer has no significant surface property variation. This was confirmed by a TRAC calculation for a case with zirconium oxide cladding. The plotted clad temperature history is almost indistinguishable from that for the base case. It is worthwhile to observe that surface properties could be expected to play a role in the thermal response of fuel. Thus, in using correlations that do not include a surface property effect, the implicit assumption is made that this effect is negligible.

4.2 The Influence of Rod Power

An increased rod power is expected to increase cladding heatup and delay surface rewet. Figures 20 and 21 show the cladding temperature and heat transfer mode, respectively, calculated with 5% increased rod power. The peak cladding temperature is about 35 K higher than for the base case. As shown in the Appendix, when void fraction is less than 85%, the Iloeje T_{min} is almost independent of void fraction. Therefore, mixture mass flux, which at a pressure far below critical is mainly determined by liquid mass flux, has a dominant effect on T_{min}.

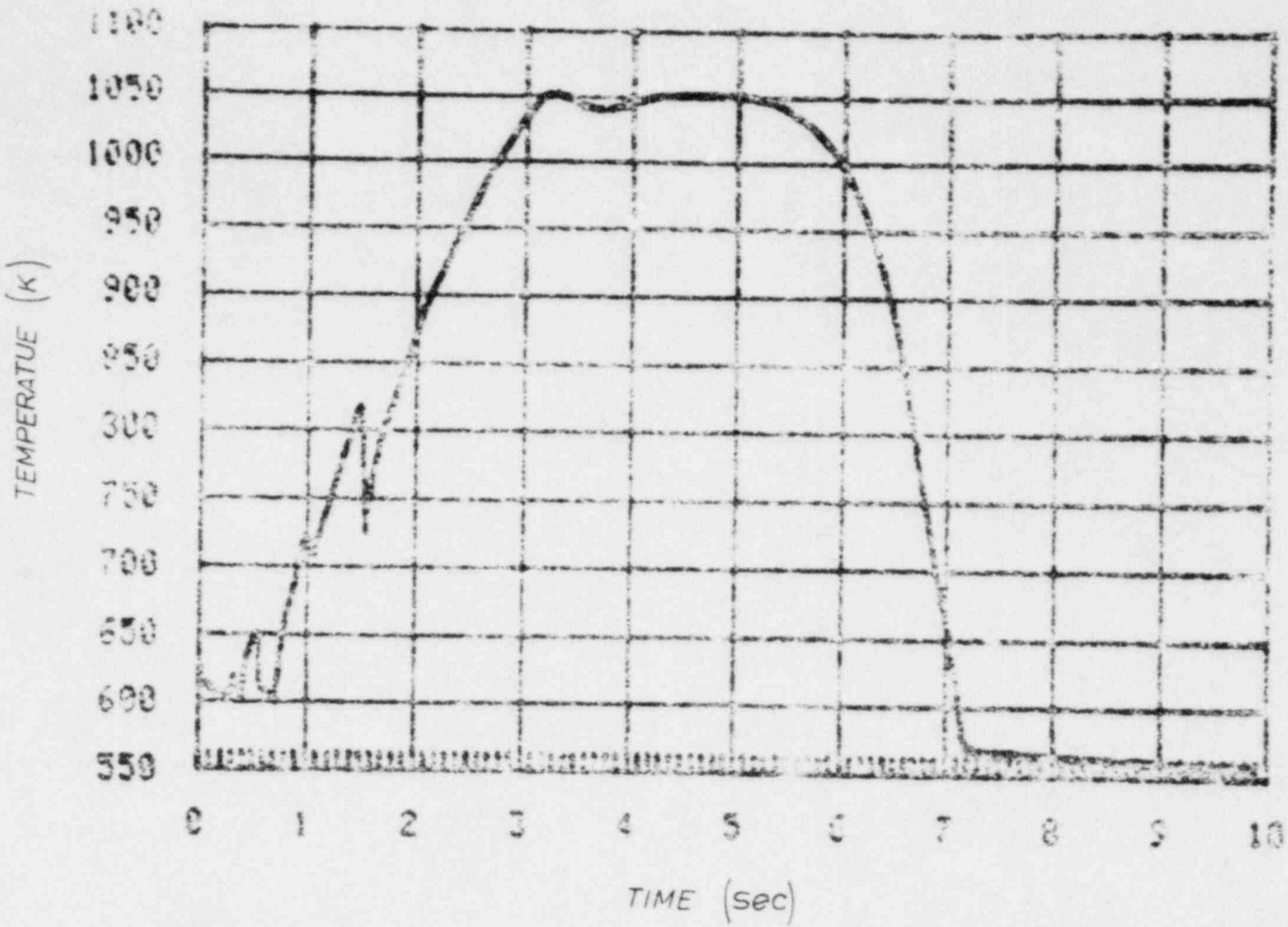

Figure 20. Cladding temperature calculated with 5% increased rod power.

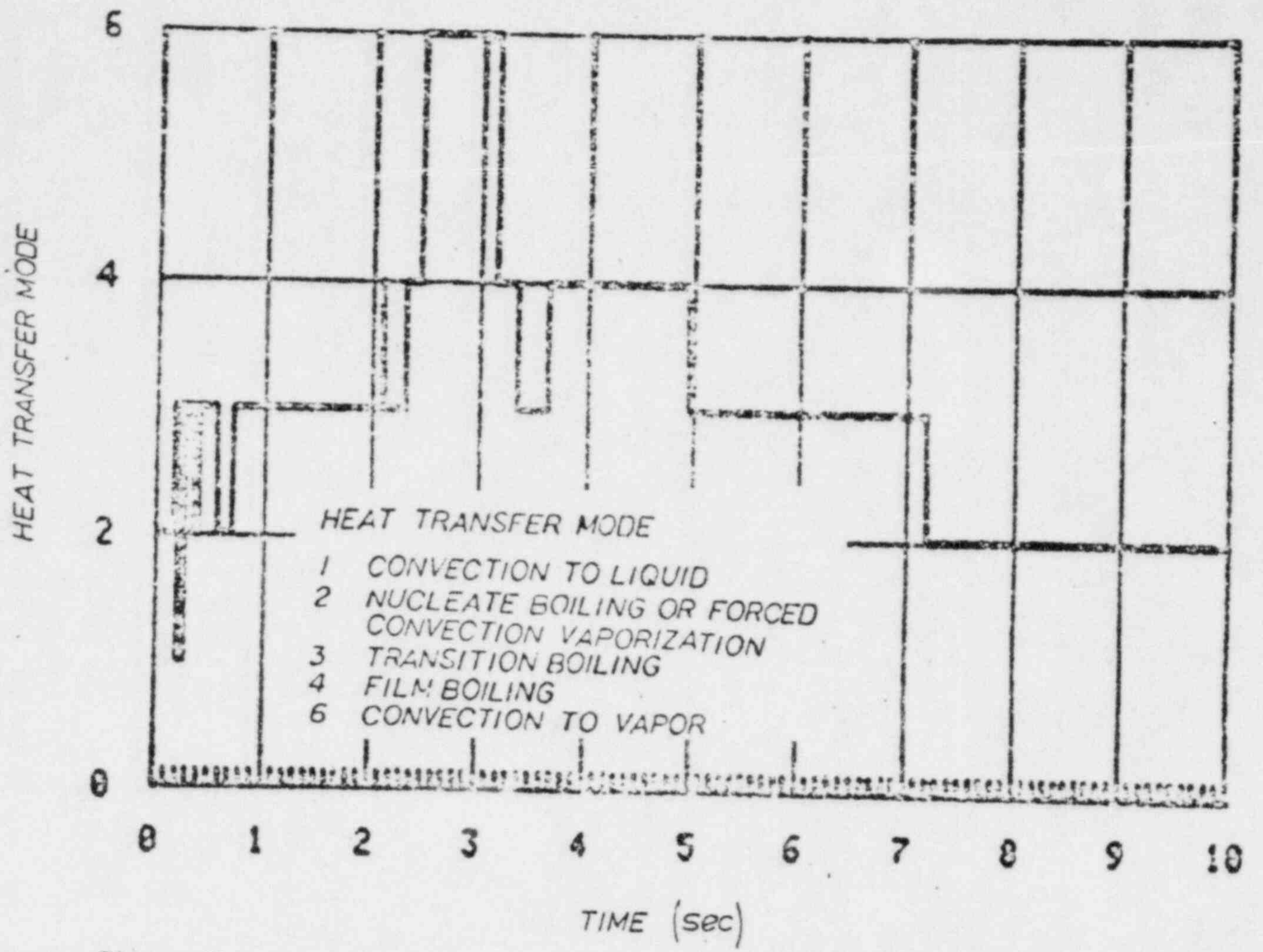

Figure 21. Heat transfer mode calculated with 5% increased rod power.

Starting with higher peak cladding temperature after dryout, a correspondingly higher liquid flow must be reached to have the surface return to transition boiling; therefore, rewet is delayed. The delay time is dominantly influenced by the peak cladding temperature reached and by the rate of increase of the liquid flow rate. Note also that in Figure 20 the rate of clad surface cooling immediately prior to RNB is somewhat lower than that of the base case. As can be seen from Figures 22 and 23, for liquid velocity and void fraction, respectively, the liquid flow rate decreases during the period from about 6 to 7 seconds after transient initiation; therefore, T_{min} decreases in this period. The decrease in T_{min} reduces heat transfer and results in a slower RNB process. In comparison with the base case, the RNB time is delayed from 5.9 to 7.2 seconds after transient initiation.

Another calculation has been done with a 5% decrease in rod power. The RNB process occurs before liquid flow decreases, about 6 seconds after transient initiation. The RNB time is only about 0.2 second earlier than for the base case. This can be seen from comparison of Figures 20 and 24. Thus, it is seen that the effect of rod power on predicted surface rewet time is not symmetrical.

4.3 The Influence of Gap Heat Conductance

The gap heat conductance affects transient energy transport and stored energy at steady state. The gap heat conductance is therefore expected to have an effect on clad surface rewet. The calculated cladding temperature with gap heat conductance reduced by 5% at steady state and unchanged from the base case during the transient is shown in Figure 25. The delay in RNB time due to increased stored energy is less than 0.2 seconds.

A larger gap heat conductance during the transient will increase clad heatup rate during the early transient and affect the peak cladding temperature reached, therefore, the rewet time. Figure 26 shows the cladding temperature calculated with constant transient gap heat conductance increased 20% from the base case. The RNB time is delayed by about 0.1 second.

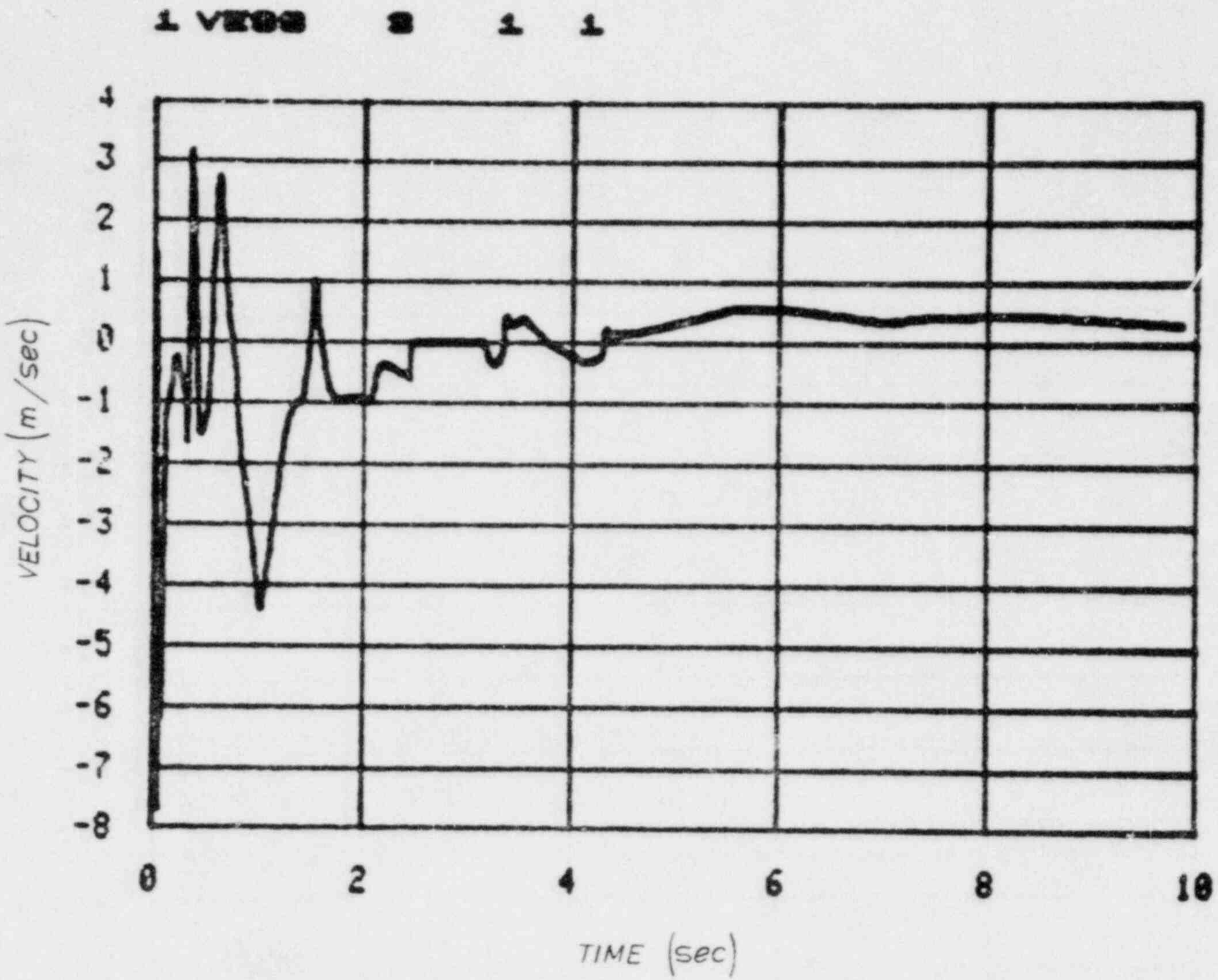

Figure 22. Liquid velocity calculated with 5% increased rod power.

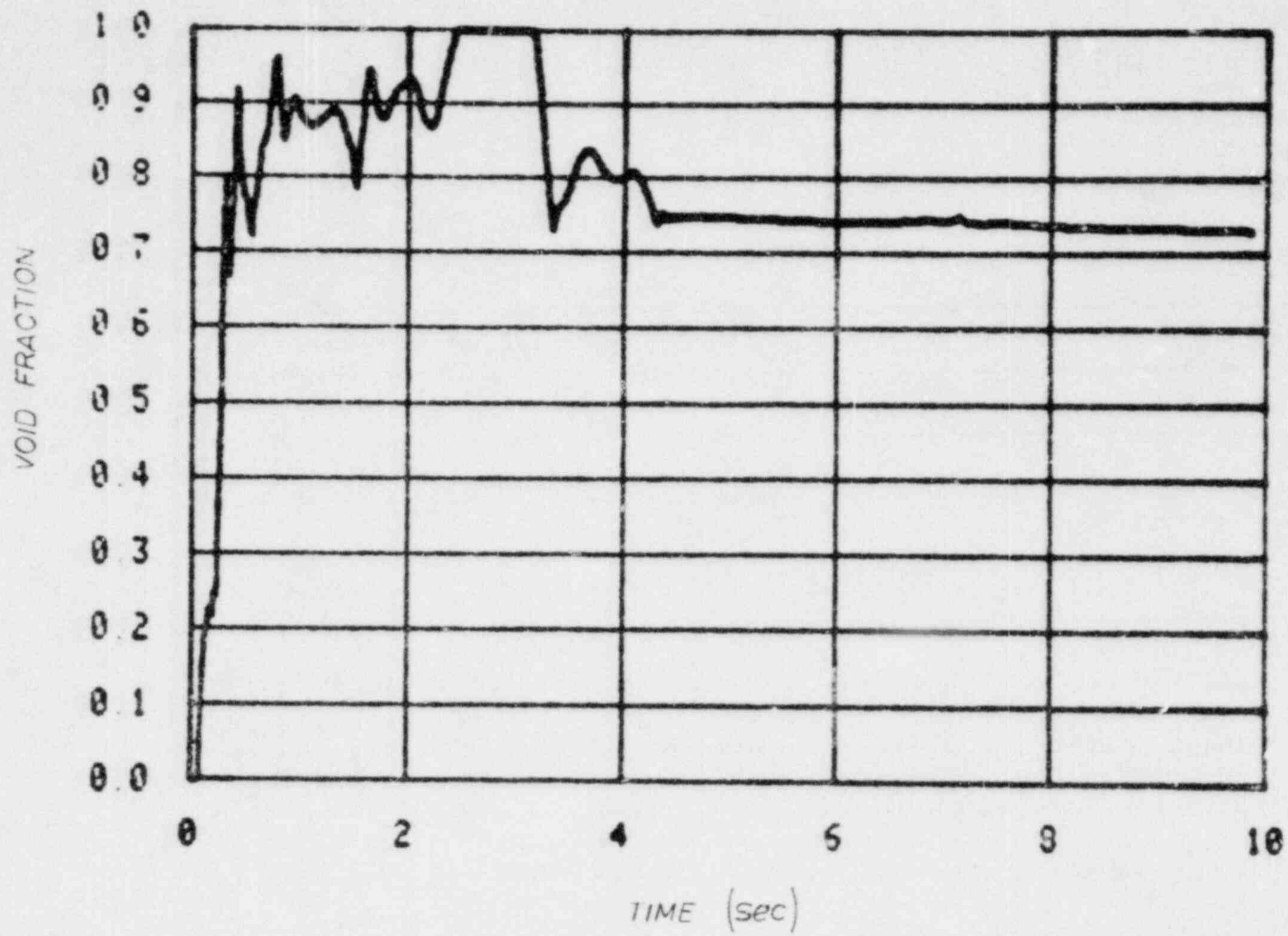

Figure 23. Void fraction calculated with 5% increased rod power.

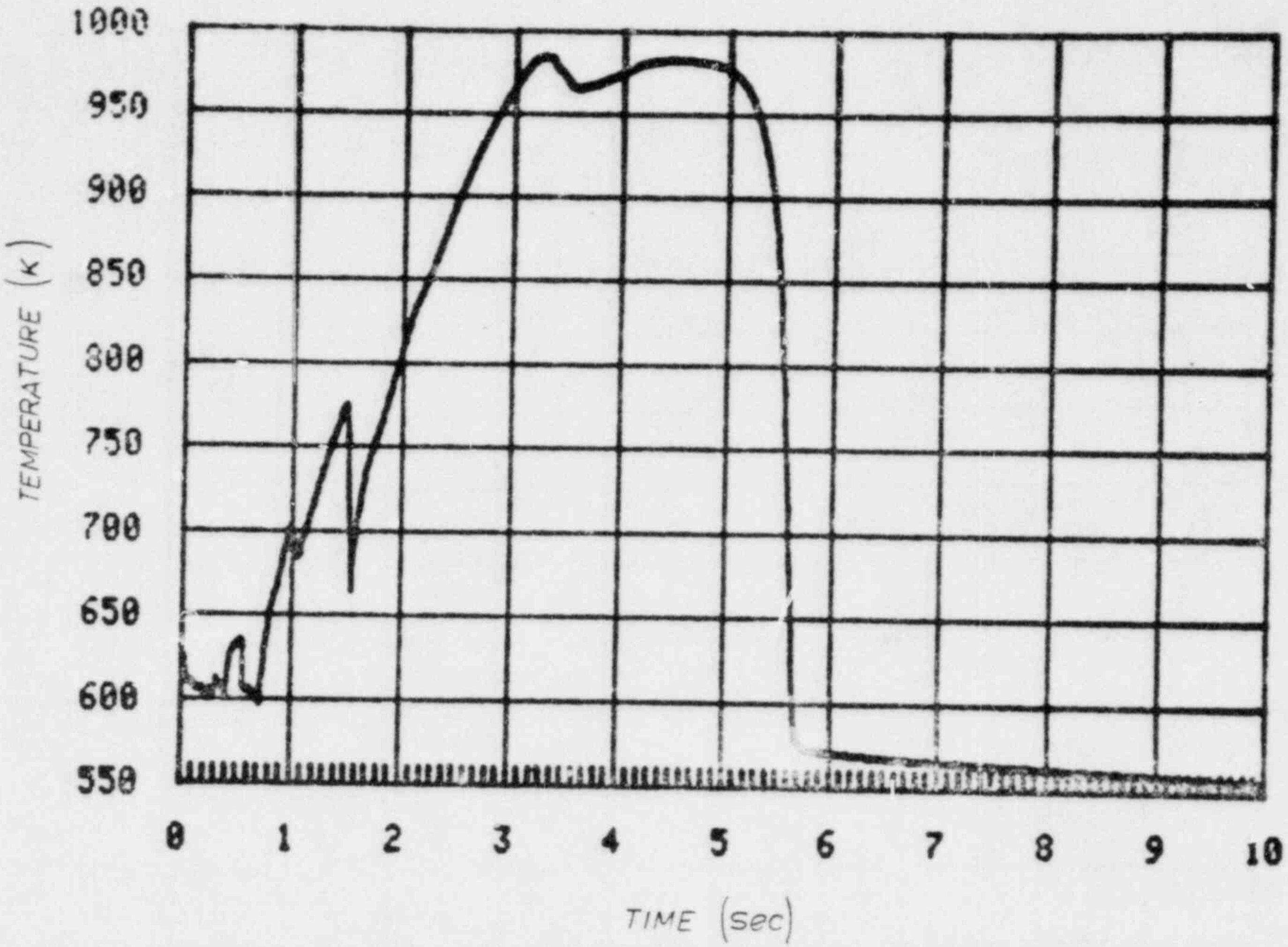

Figure 24. Cladding temperature calculated with 5% reduced rod power.

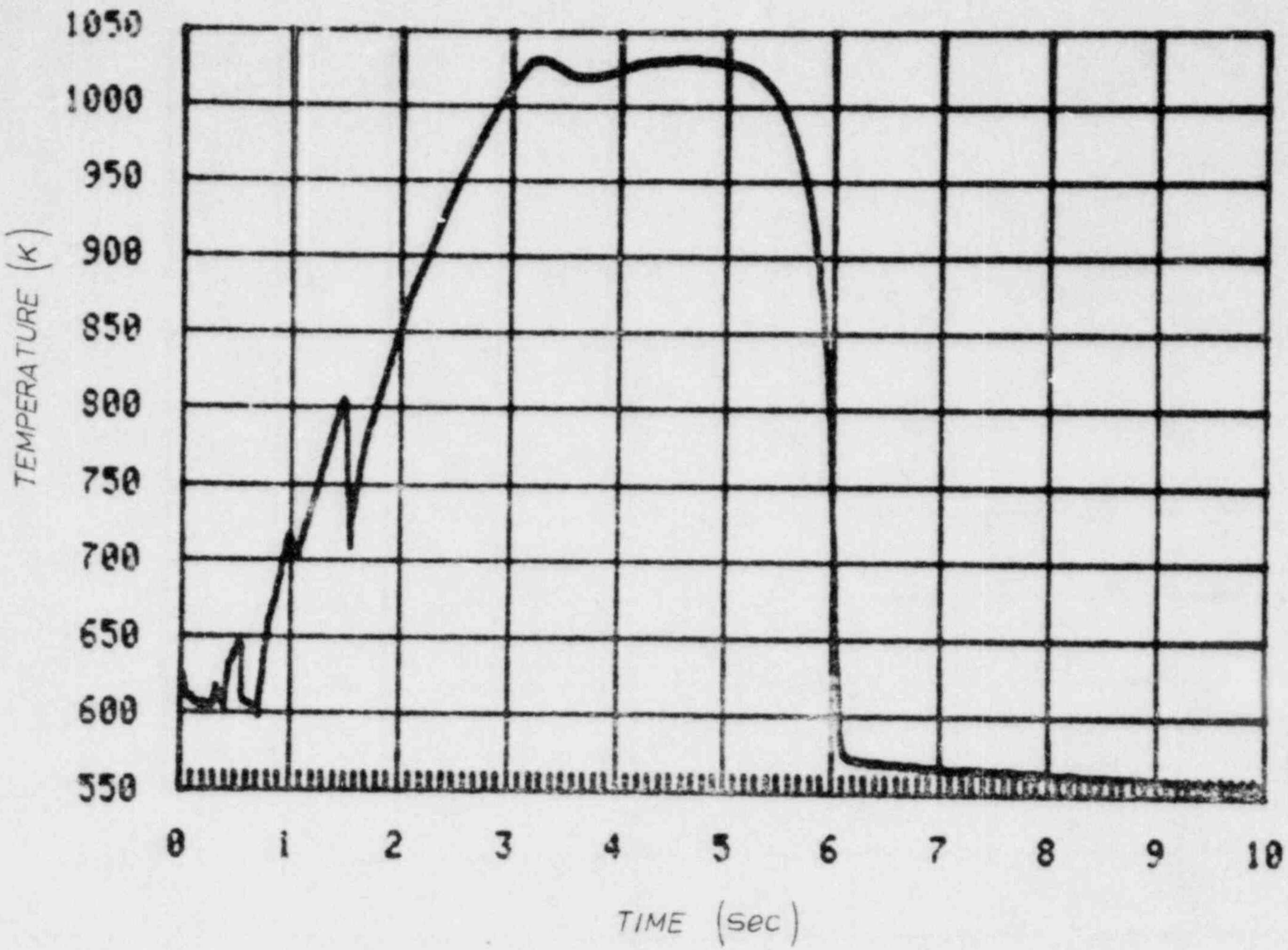

Figure 25. Cladding temperature calculated with 5% reduced steady state gap heat conductance.

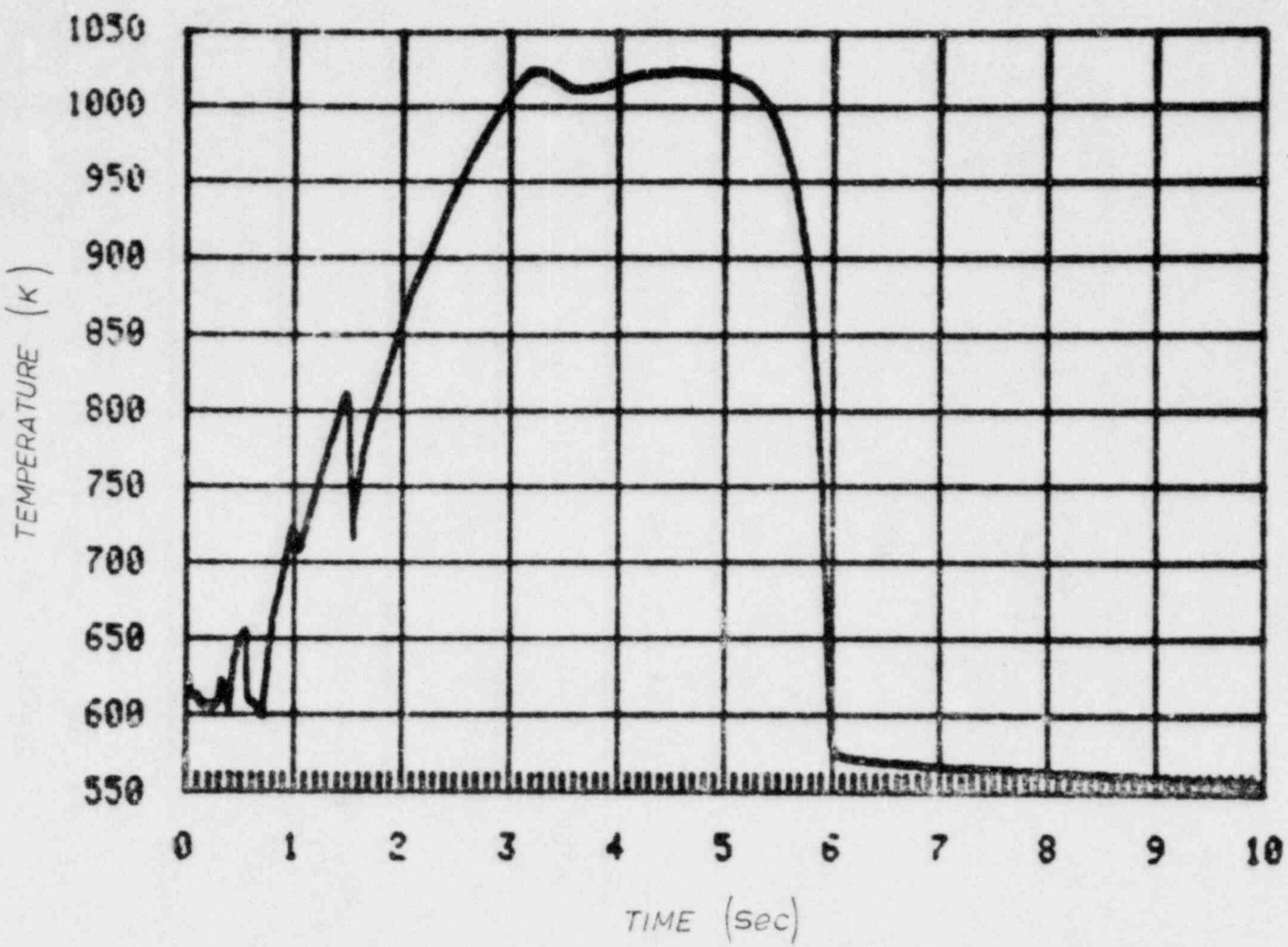

Figure 26. Cladding temperature calculated with 20% increased gap heat conductance.

The effect of gap heat conductance on predicted surface rewet time is not significant for changes of the magnitude studies; however, the uncertainty associated with gap conductance is usually large, so gap heat conductance is likely to be of significance in RNB.

4.4 The Influence of Fluid Velocity

The Iloeje T_{min} has strong dependence on mass flux and therefore fluid velocity. The dependence of the Iloeje T_{min} with imposed constraints on mass flux G is shown in the Appendix. As stated in Section 2, there is a constraint on Iloeje T_{min} correlation at high mass flux G. For $G > 135.6$ Kg/m^2-sec, T_{min} is independent of G, and for $G < 135.6$ Kg/m^2-sec, T_{min} is a strong function of mass flux, except at low pressures. At $G < 135.6$ Kg/m^2-sec, an increase in G increases T_{min} and the transition boiling heat transfer coefficient. A higher T_{min} also implies that surface rewet occurs at higher surface temperature. The better heat transfer before dryout results in lower peak cladding temperature which also influences surface rewet.

When entrant fluid velocity is increased by 5%, the predicted clad cladding temperature is shown in Figure 27. The RNB time is about 0.2 seconds earlier and peak cladding temperature is about 10 K lower in comparison with the base case. Figure 28 shows the cladding temperature calculated with 5% reduced fluid velocity. The RNB time is 0.3 seconds later and the peak cladding temperature is 10 K higher in comparison with the base case. Therefore, the effect of fluid velocity is decisively asymmetrical in terms of RNB time.

4.5 The Influence of Void Fraction

At high void fraction, both mass flux and quality are strong functions of void fraction and strongly influence the Iloeje T_{min}. The clad surface rewet behavior is expected to be strongly influenced by void fraction, particularly at high void fraction. Figures 29 and 30 show the cladding temperature and heat transfer mode, respectively, calculated with fluid void fraction 98% of that for base case. The peak

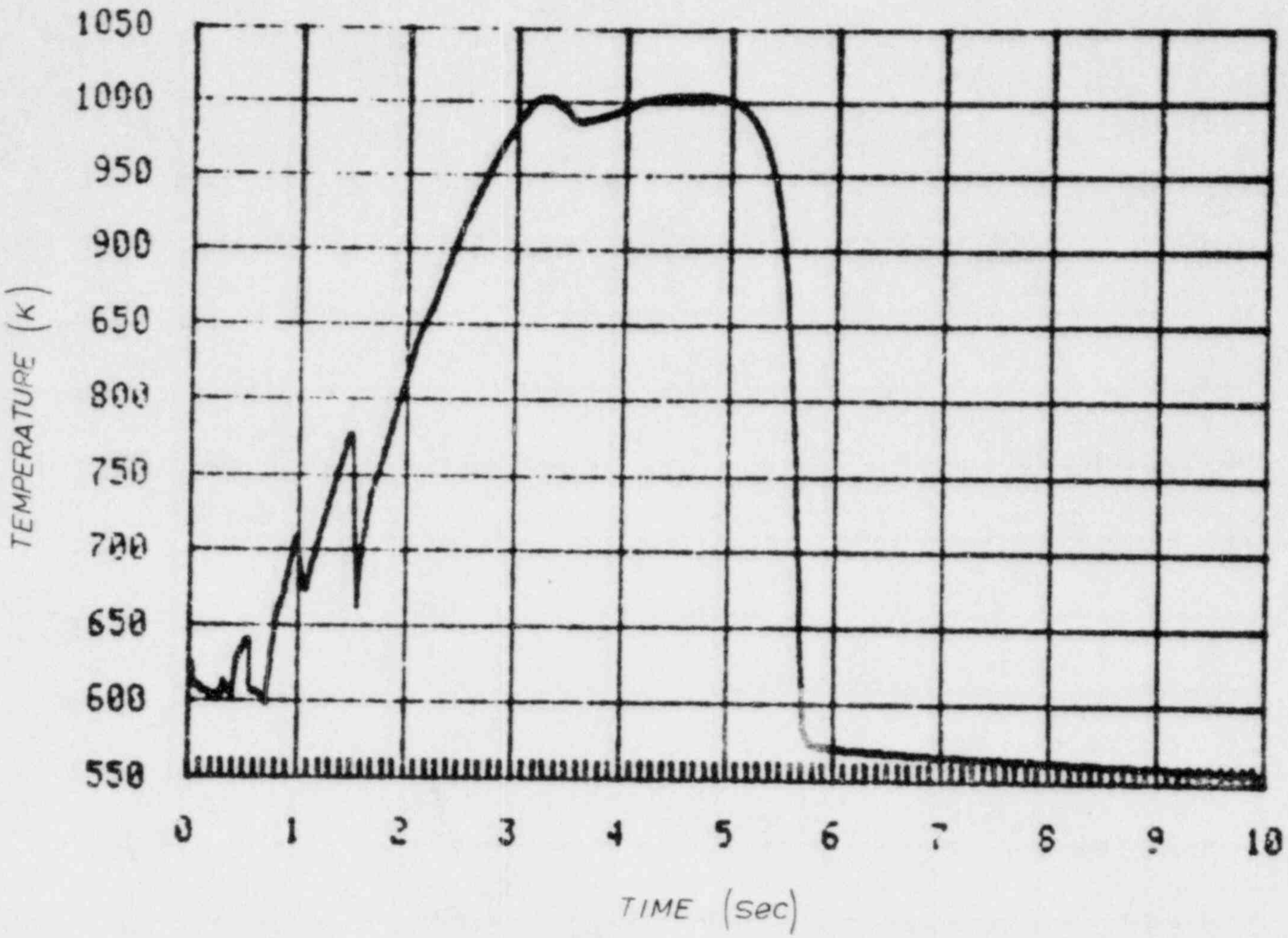

Figure 27. Cladding temperature calculated with 5% increased fluid velocity.

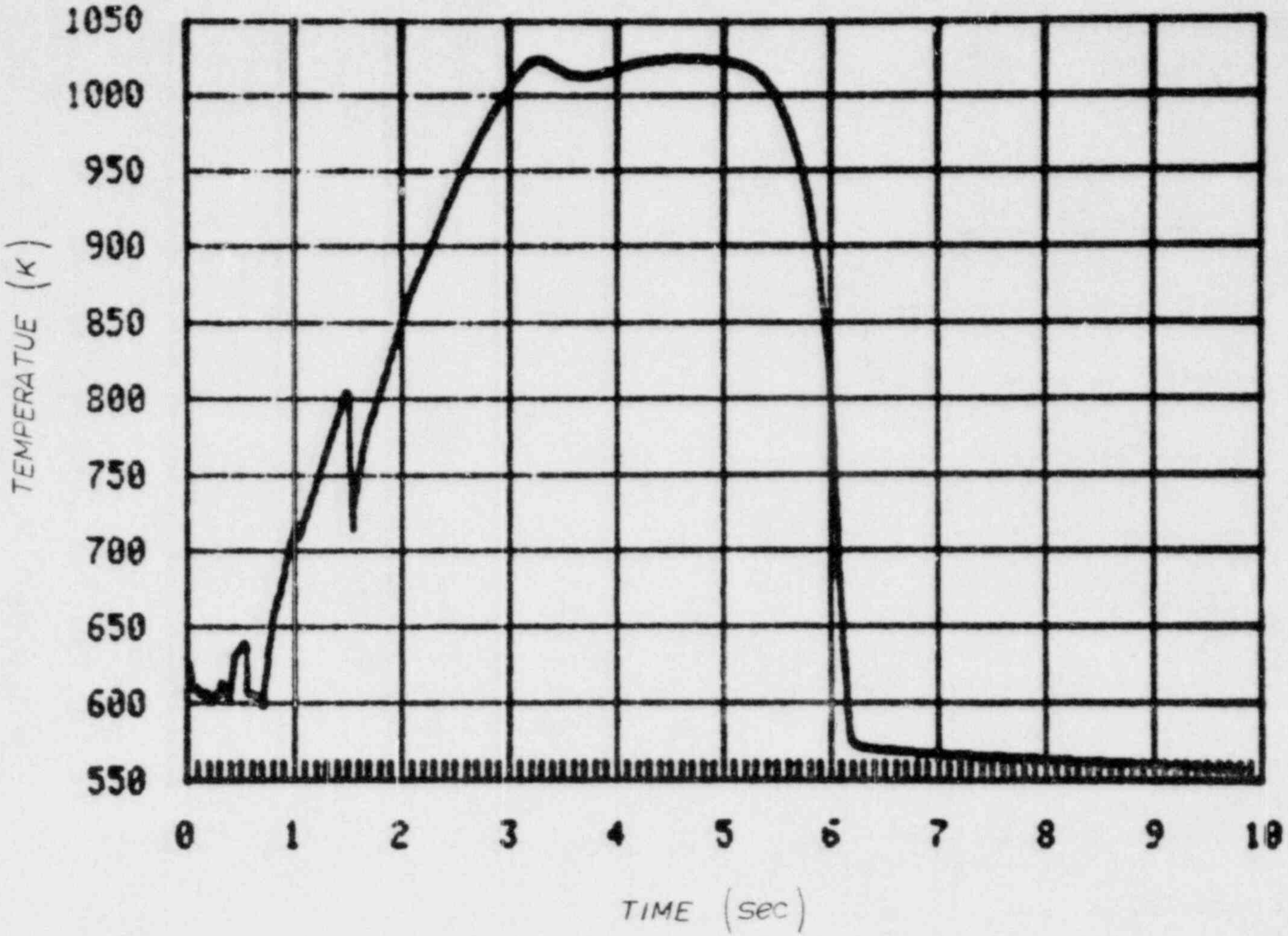

Figure 28. Cladding temperature calculated with 5% reduced fluid velocity.

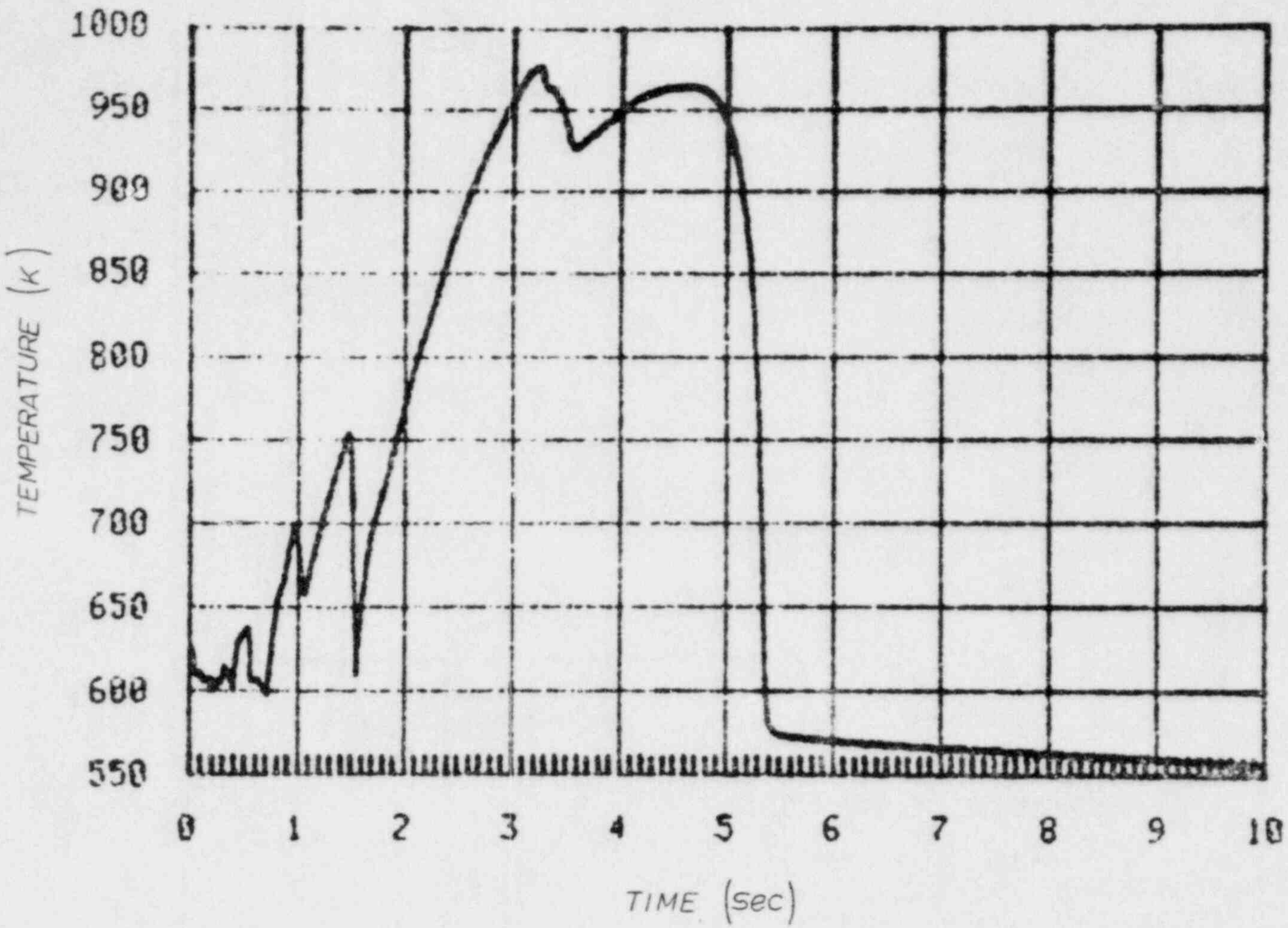

Figure 29. Cladding temperature calculated with the void fraction 98% of the base case.

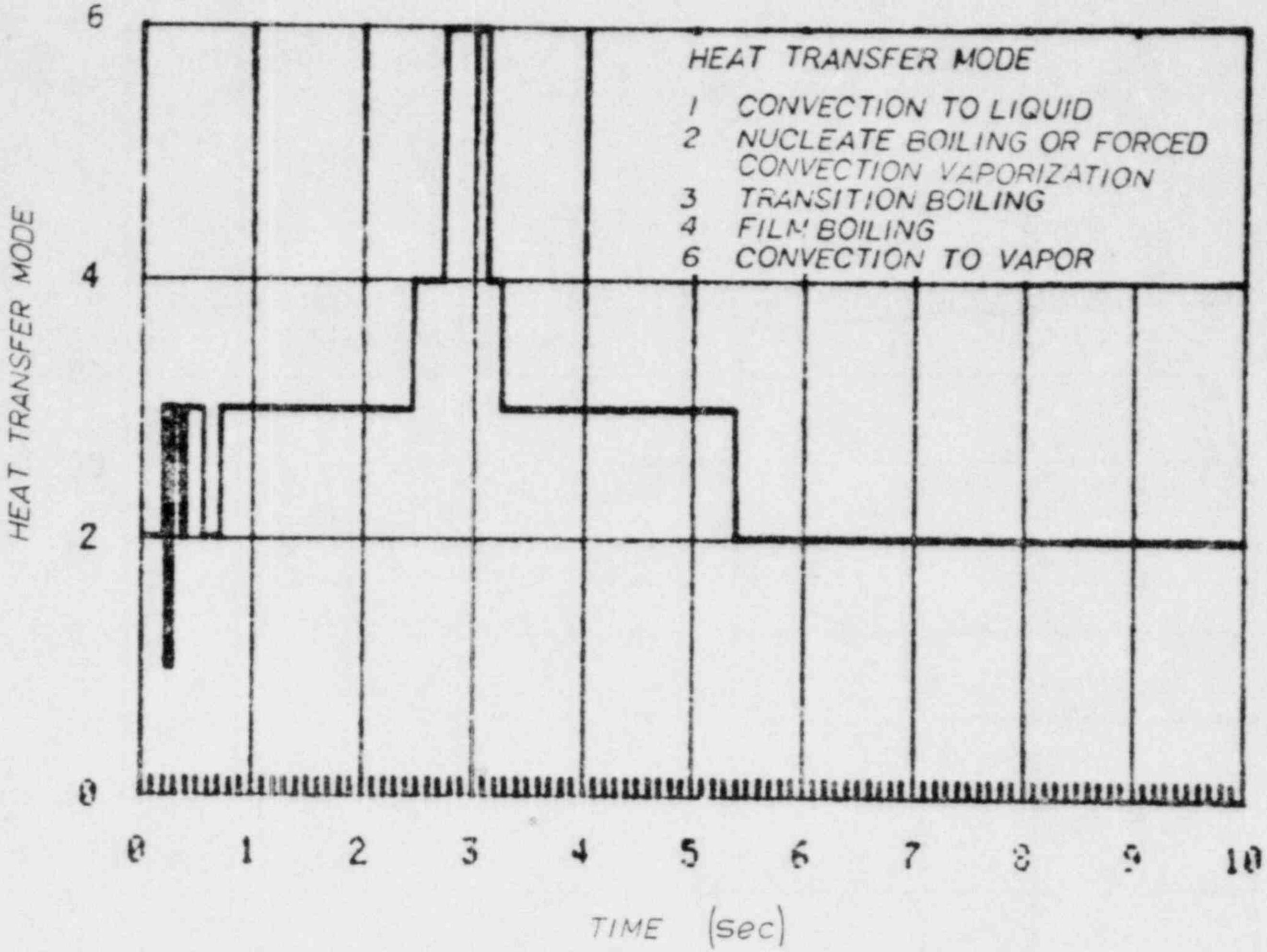

Figure 30. Heat transfer mode calculated with the void fraction 98% of base case.

cladding temperature is 40 K lower and RNB time is 0.5 second early in comparison with the base case. Also evident are significantly larger decreases in temperature associated with velocity fluctuations at 0.5, 1, 1.5 and 3.2 seconds. The final rewet at 5.4 seconds is shaper. The increased heat transfer coefficients due to lower void fraction are particularly evident at these times.

5. CONCLUSIONS

The results of this study can be summarized as follows:

1. The Iloeje minimum film boiling temperature correlation, in contrast to other correlations, is strongly dependent on hydrodynamic parameters. Selection of the Iloeje correlation decisively influences the prediction of clad surface rewet. The rewet tends to be flow rate controlled according to the Iloeje correlation
2. If the Iloeje correlation is correct, coolant void fraction, particularly at high void, strongly influences the surface reset behavior. A relatively small change in void fraction can cause substantial changes in predicted cladding temperature.
3. Rod power and gap heat conductance influence clad surface rewet through their effects on the cladding temperature. They do not appear to strongly influence clad rewet through hydrodynamics.
4. The fluid velocity directly affects the Iloeje T_{min}. However, its effect on surface rewet is not as strong as void fraction. In fact, its effect on surface rewet may be as much due to its effect on cladding surface temperature as to its effect on T_{min}.

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APPENDIX

CRITICAL HEAT FLUX AND MINIMUM FILM BOILING CORRELATION

The critical heat flux q''_{CHF} with its corresponding wall temperature T_{CHF} and the minimum film boiling temperature T_{min} are essential in constructing the TRAC boiling curve which strongly influences the surface rewet predictions. The determination of q''_{CHF} and the Iloeje minimum film boiling correlation used in TRAC are briefly described here.

The critical heat flux is determined from a combination of Zuber's pool boiling correlation and the Biasi correlation. At low flow rates, the Zuber pool boiling correlation is used:

$$q''_{CHF} = (1 - \alpha)\, 0.131\, \rho_g\, h_{\ell g} \left[\frac{\sigma g\, (\rho_\ell - \rho_g)}{\rho_g^2}\right]^{1/4} \qquad \text{(A-1)}$$

where the factor $(1 - \alpha)$ was recommended for low flow and countercurrent flow conditions. For high flow rate, the Biasi correlation is used:

$$q''_{CHF} = \frac{1.883 \times 10^7}{D^n\, |G|^{1/6}} \left[\frac{f_p}{|G|^{1/6}} - x\right] \qquad \text{(A-2)}$$

and

$$q''_{CHF} = \frac{3.78 \times 10^7}{D^n\, |G|^{0.6}}\, h_p\, (1 - x) \qquad \text{(A-3)}$$

where

α = void fraction

ρ = liquid or vapor density depending on subscripts ℓ and g (Kg/m^3)

$h_{\ell g}$ = heat of vaporization (J/Kg)

σ = surface tension (N/m)

g = gravitational constant (9.8 m/sec^2)

G = mass flux (g/cm^2-sec)

x = flow quality

n = 0.4 for $D \geq 1$ cm

n = 0.6 for $D \leq 1$ cm

f_p = $0.7249 + 0.099\, p \exp(-0.032\, p)$

h_p = $-1.159 + 0.149\, p \exp(-0.01\, p) + \frac{8.99\, p}{10 + p^2}$

D = hydraulic diameter (cm)

p = pressure (bar).

The Zuber correlation is used for mass fluxes less than 100 Kg/m^2-sec in upflow and less than 600 Kg/m^2-sec in downflow. The Biasi correlation is used for other ranges. When the mass flux is less than 200 Kg/cm^2-sec and greater than 100 Kg/cm^2-sec for upflow, the mass flux is set 200 Kg/m^2-sec. When the mass flux is less than 700 Kg/m^2-sec and greater than 600 Kg/m^2-sec for downflow, the mass flux is set to 700 Kg/m^2-sec. Equation (A-3) is used for mass flux less than 300 Kg/m^2-sec; otherwise the larger of the q''_{CHF} values given by Equations (A-2) and (A-3) is used.

In contrast to other minimum film boiling correlations, the Iloeje correlation is dependent on the hydrodynamic parameters, mass flux and equilibrium quality. To help understand the TRAC prediction on clad surface rewet, the dependence of the Iloeje minimum film boiling temperature, T_{min}, is plotted and presented here.

The Iloeje T_{min} is given by

$$T_{min} = T_{sat} + 0.29\, \Delta T_{Ber} (1 - 0.295\, x_e^{2.45}) \left[1 + (G \times 10^{-4})^{0.49} \right]$$

where

T_{sat} = saturation temperature

x_e = equilibrium quality

G = mass flux in lbm/ft^2-hr.

ΔT_{Ber} is Berenson's minimum film boilin temperature and is given by

$$\Delta T_{Ber} = 0.127 \frac{\rho_f}{K_f} h_{fg} \left(\frac{g\, \Delta\rho}{\rho_\ell + \rho_v}\right)^{2/3} \left(\frac{g_c \sigma}{g \Delta\rho}\right)^{1/2} \left(\frac{\mu_f}{g \Delta\rho}\right)^{1/3}$$

ρ_ℓ, ρ_v, ρ_f = densities of liquid, vapor and vapor film, respectively (lbm/ft^3)

$\Delta\rho$ = $\rho_\ell - \rho_v$

K_f = vapor film thermal conductivity (Btu/hr/ft-°F)

h_{fg} = enthalpy of evaporation (Btu/lbm)

g = acceleration of gravity ($ft\text{-}sec^2$)

g_c = conversion factor (32.2 $lbm\text{-}ft/lbf\text{-}sec^2$)

σ = surface tension (lbf/ft)

μ_f = dynamic viscosity of vapor film (lbf/hr-ft).

Figure A-1 shows the variation of Iloeje T_{min} with mass flux. The constraints at high mass flux (> 135.6 $Kg/m^2\text{-}sec$) and low pressure have been imposed in Figure A-1 and the rest of the figures in this section. Figure A-2 shows the pressure dependence of Iloeje T_{min}. Figures A-3 and A-4 show the dependency of the Iloeje T_{min} on quality and void fraction, respectively.

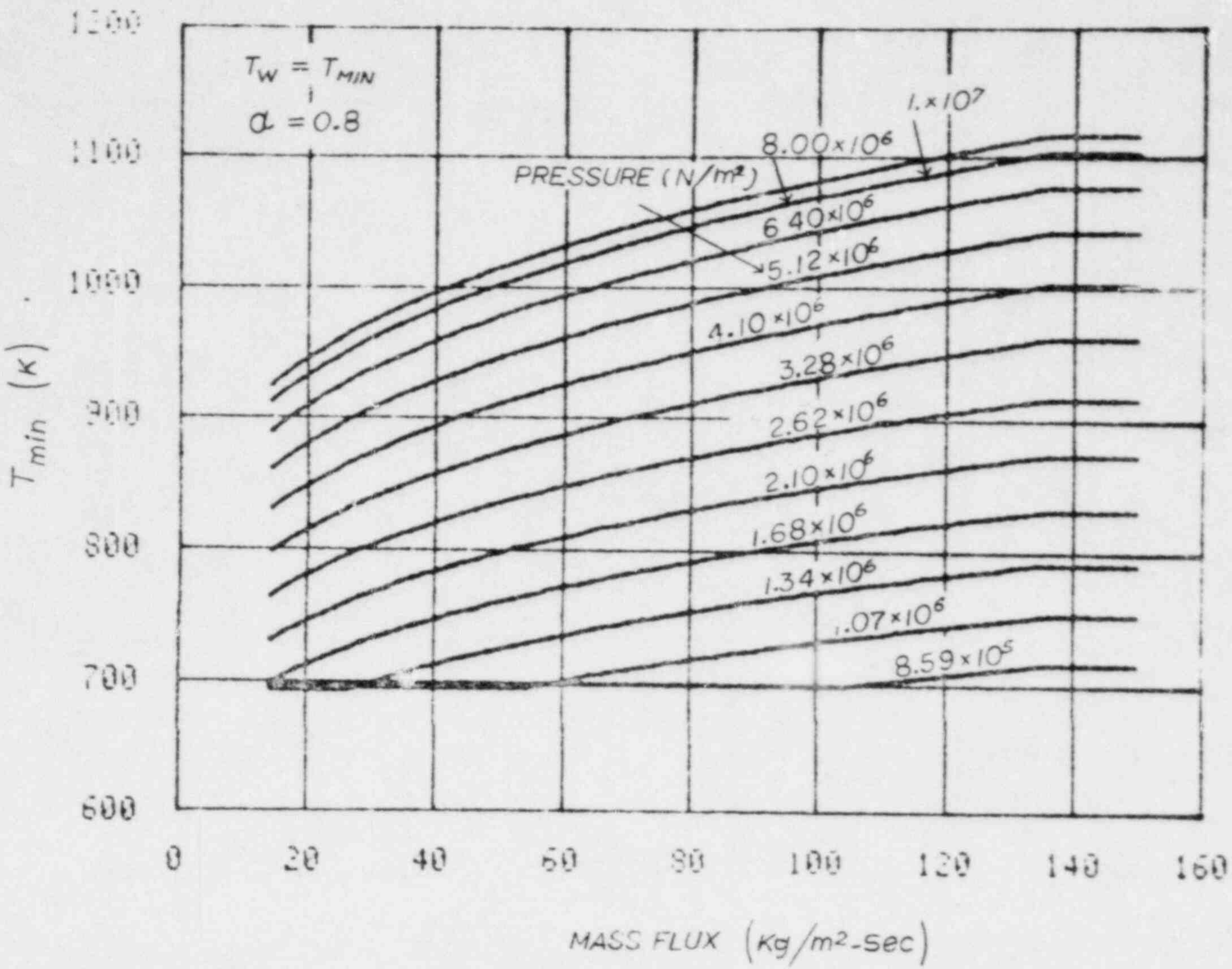

Figure A-1. Dependence of Iloeje T_{min} on mass flux.

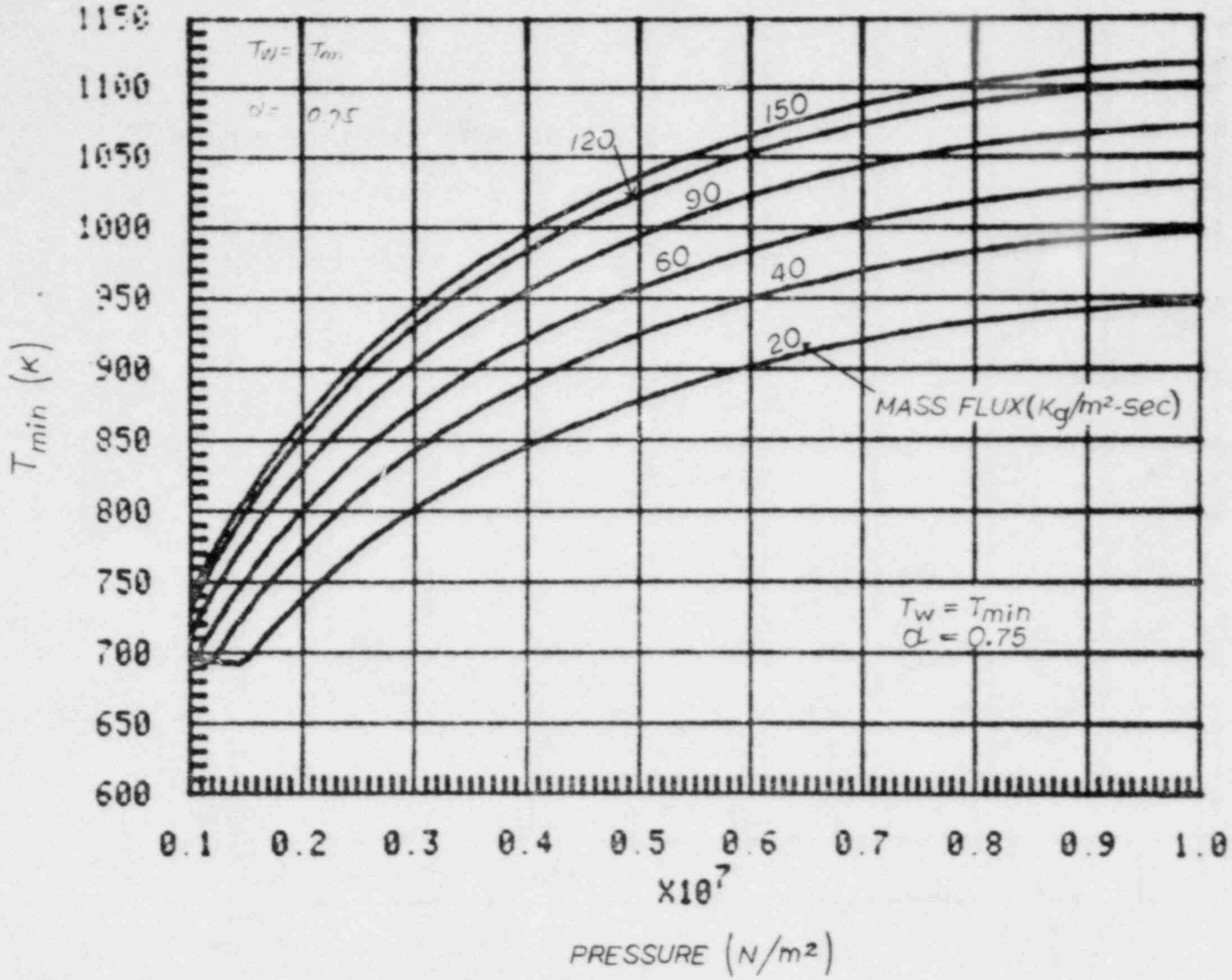

Figure A-2. Dependence of Iloeje T_{min} on pressure.

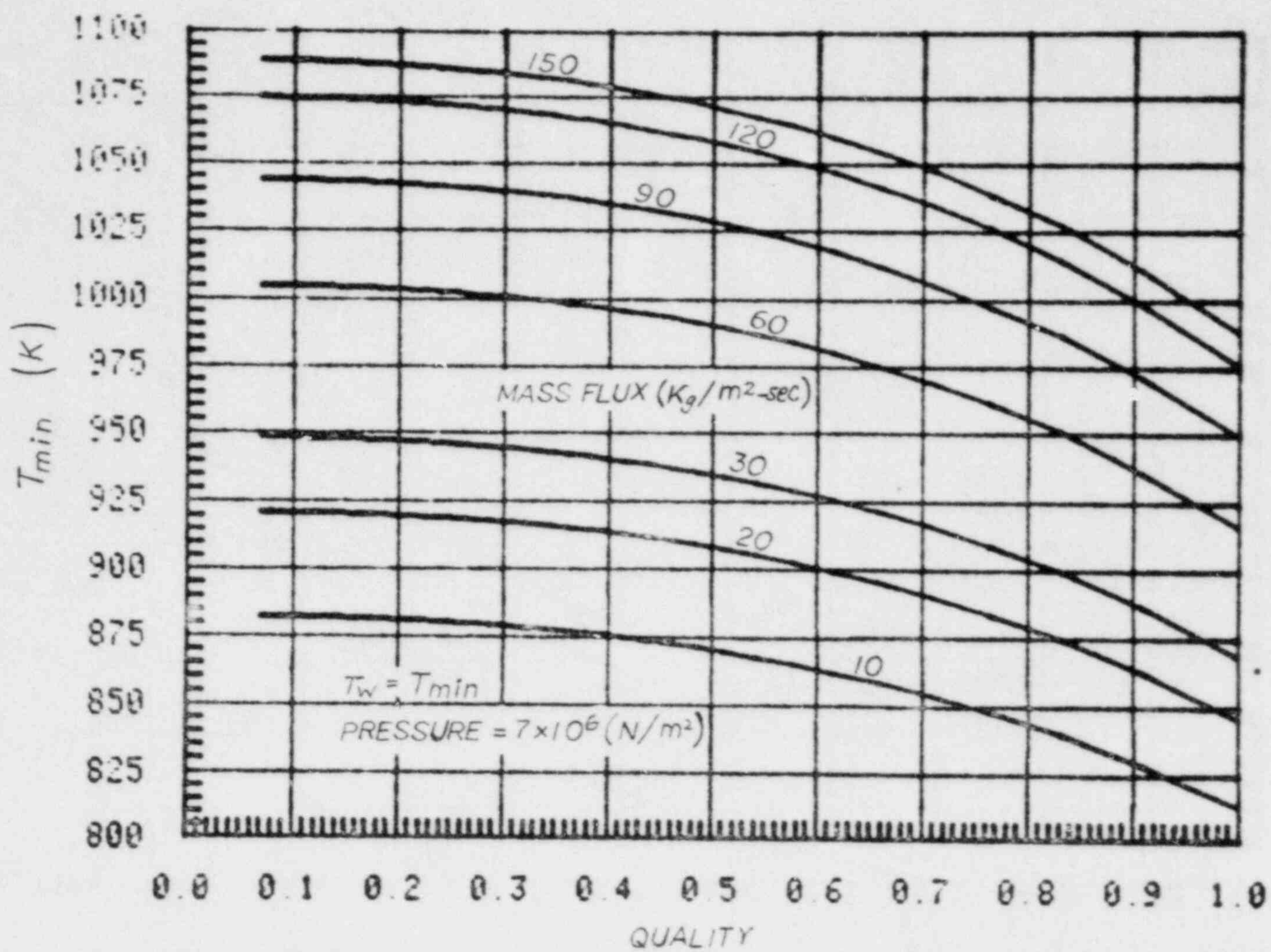

Figure A-3 Dependence of Iloeje T_{min} on equilibrium quantity.

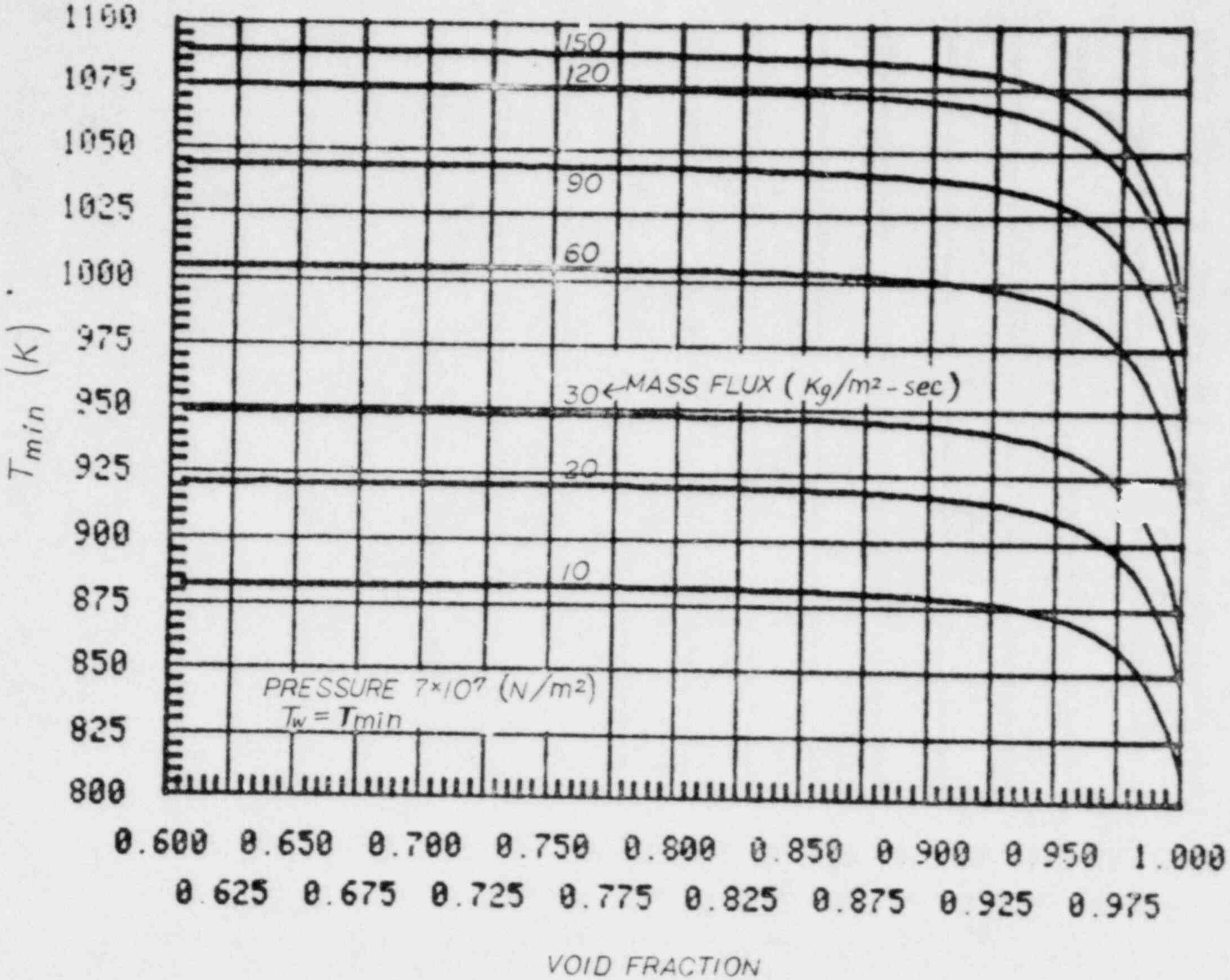

Figure A-4. Dependence of Iloeje T_{min} on void fraction.