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Author(s): P. N. Demmie

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U.S. Nuclear Regulatory Commission
and the U.S. Department of Energy
Idaho Operations Office
Under contract No. EY-76-C-07-1570
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For U. S. Nuclear Regulatory Commission

CODE ASSESSMENT AND APPLICATIONS PROGRAM

AN INVESTIGATION OF THE STEAM VOID COLLAPSE WATERHAMMER INITIATING MECHANISM

by

P. N. Demmie

February 1979

EG&G Idaho, Inc.

IDAHO NATIONAL ENGINEERING LABORATORY

DEPARTMENT OF ENERGY

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ABSTRACT

An investigation of the steam void collapse waterhammer initiating mechanism was made. The results and conclusions of this investigation are presented and discussed in this report.

SUMMARY

An investigation of the steam void collapse waterhammer initiating mechanism was performed. The investigation was constrained to the use of existing state-of-the-art techniques. A steam void collapse simulation using the computer program K-FIX/MOD1 established that K-FIX/MOD1 was operable for this type of problem. Some of the results of this simulation are in qualitative agreement with phenomena observed in spherical · ble collapse in highly subcooled water and are explainable in terms of the . fluid model used in K-FIX/MOD1. However, several aspects of the results are controversial and unexplained. An examination of K-FIX/MOD1 to resolve these controversial results revealed an inadequacy in the treatment of interphase heat transfer and mass transfer in K-FIX/MOD1 for steam void collapse simulations. An alternate treatment is proposed which couples the mass transfer to the interphase heat transfer and includes latent heat effects. Because no assurance can be given that any state-of-the-art computer program - K-FIX, TRAC, or THERMIT - can perform a satisfactory steam void collapse analysis, the most promising approach to analytical modeling of the steam void collapse phenomenon involves the analysis of experimental data with one of the newest computer programs, TRAC or THERMIT.

CONTENTS

FIGURES

AN INVESTIGATION OF THE STEAM VOID COLLAPSE WATERHAMMER INITIATING MECHANISM

I. INTRODUCTION

An investigation of the steam void collapse waterhammer initiating mechanism using existing state-of-the-art techniques was completed. This report is a summary of this investigation.

Severe waterhammer incidents have occurred in commercial pressurized water reactor piping systems[1]. The relatively frequent occurrence and severity of these incidents, sometimes resulting in significant damage, has become a matter of concern since a potential safety issue may be involved.

It is generally believed that the pertinent initiating mechanisms for waterhammer include steam void collapse, discharge of water into a voided line, and check valve closure associated with a pipe break in the vicinity of the valve. The basic approach of the present program at EG&G Idaho is the modeling of these initiating mechanisms and integrating these models with the hydraulic and structural response codes presently available to assess reactor system damages.

An initial evaluation of the analytic requirements for simulating steam void collapse showed that the capability to model multi-dimensional, non-equilibrium effects was necessary. Since K-FIX/MOD1[2] was the only computer program with these capabilities available at INEL at the inception of this investigation, the initial phase of this investigation involved a preliminary evaluation of the operability of K-FIX/MOD1 on a steam void collapse simulation. It was found that, in terms of operability, K-FIX/MOD1 could be utilized in this investigation[3].

An analysis of a steam void collapse simulation based on the K-FIX/MOD1 two-fluid model is given in Section II. Although some of the results of this simulation are in qualitative agreement with phenomena observed in spherical bubble collapse in highly subcooled water and are explainable in terms of K-FIX/MOD1 two fluid model, some aspects of the results are controversial. An examination of K-FIX/MOD1 to resolve these controversial results revealed an inadequacy in the treatment of interphase heat transfer and mass transfer in K-FIX/MOD1. A critique of this treatment is given in Section III. An alternate treatment is proposed in Section IV which couples the mass transfer to the interphase heat transfer and includes latent heat effects. Alternate computer programs for steam void collapse analysis are discussed in Section V. The conclusions of this investigation are given in Section VI. An appendix is included which shows the effects on time step reductions of the results of the simulation discussed in Section II.

II. ANALYSIS OF A STEAM VOID SIMULATION BASED ON THE K-FIX/MOD1 TWO-FLUID MODEL

Modeling as a two-dimensional Cartesian grid the vertical cross section of a 10 inch diameter pipe 48 inches long and using K-FIX/MOD1, the collapse of a 6 inch by 4 inch steam void entrapped in a pipe containing a highly subcooled liquid was simulated for 200 ms using values of a condensation rate multiplier ranging from 0.01 to 1.0[3]. In these simulations, the fluid was initially at rest, the initial pressure of the fluid in the pipe was 7.483 MPa, the initial temperature in the steam void was 563.5 K (the saturation temperature corresponding to 7.483 MPa), and the initial temperature of the remaining fluid in the pipe was 505.2 K. Pure water at a pressure of 7.483 MPa and temperature of 505.2 K entered the pipe as the steam condensed. As is evident from the different pressure histories shown in Figures 1 and 2 for the 0.01 and 1.0 condensation rate multipliers, the value of the condensation rate multiplier is important for the subsequent behavior of the steam void. The 0.01 multiplier leads to pressure oscillations that increase in amplitude to a maximum pressure before damping out, while the 1.0 multiplier leads to a large depressurization followed by a maximum over-pressurization and pressure oscillations that damp out. Since the pressure behavior with the 1.0 multiplier is more consistent with some experimental data than the pressure behavior with the 0.01 multiplier[4,5,6], this analysis will proceed for the simulation using the 1.0 multiplier.

Initially, the temperature in the steam void is greater than the temperature of the adjacent fluid. The ensuing cooling in the steam void initiates condensation of the steam, since the condensation rate is proportional to the difference between the saturation temperature and the steam temperature.

The condensation of steam leads to a decrease in pressure in the steam void. This sequence of events implies that there is an initial time lag between changes in the temperature and resulting changes in the pressure. That this is the case is clear from Figures 3 and 4 which show the temperature and saturation temperature in cell (13,5) as a function of time from t = 0.0 s to t = 0.02 s. Cell (13,5) is one of the six cells - (12,5), (13,5), (14,5), (12,6), (13,6), and (14,6) - comprising the initial steam void in a computing mesh and boundary cell perimeter consisting of 24 cells in the x-direction and 7 cells in the y-direction. The depressurization resulting from condensation drives the steam void temperature lower. However, since a highly non-equilibrium situation exists when the steam void temperature is lower than the saturation temperature in the void and the temperature of the adjacent fluid, the temperature in the steam void quickly attains a relative minimum and increases. After a time lag, the pressure (and therefore the saturation temperature) in the steam void attains a relative minimum and then increases. The temperature in the steam void continues to increase, reaches the saturation temperature in the steam void (at which time condensation ceases), and is driven to higher temperatures by the compression of the steam resulting from the inertial effects of the fluid in the steam void. A highly non-equilibrium situation exists with the steam void temperature above the saturation temperature in the void and the adjacent fluid. Therefore, the temperature in the steam void attains a relative maximum and decreases. After a time lag the pressure in the steam void also attains a relative maximum and decreases. At this stage another cycle of temperature and pressure oscillation has begun. To see how this oscillation behavior ceases, consider Figures 3 and 4 and let d be the time difference between the i^{th} relative

minimum in the temperature and saturation temperatures shown in these figures. It is seen from these figures that as i increases the d_i becomes smaller and the curves nearly coincide at t = 0.02 s. This behavior is attributed to the damping effects of viscosity, turbulence, and interphase friction and the increasing transfer of energy to the liquid present in the region of the original steam void as more liquid is produced by condensation. From Figures 5 and 6, which show the respective temperature and saturation temperature in cell (13,5) as a function of time from t = 0.0 s to t = 0.2 s, it is seen that from approximately t = 0.02 s to approximately t = 0.068 s, the temperature in cell (13,5) is nearly the saturation temperature. From Figure 7 cell (13,5) contains nearly all liquid at t - 0.068 s. Thus the temperature in the steam void remains near the saturation temperature until nearly all the steam in it has condensed. Then, as shown in Figure 5 for cell (13,5), the fluid in the region of the original steam void cools.

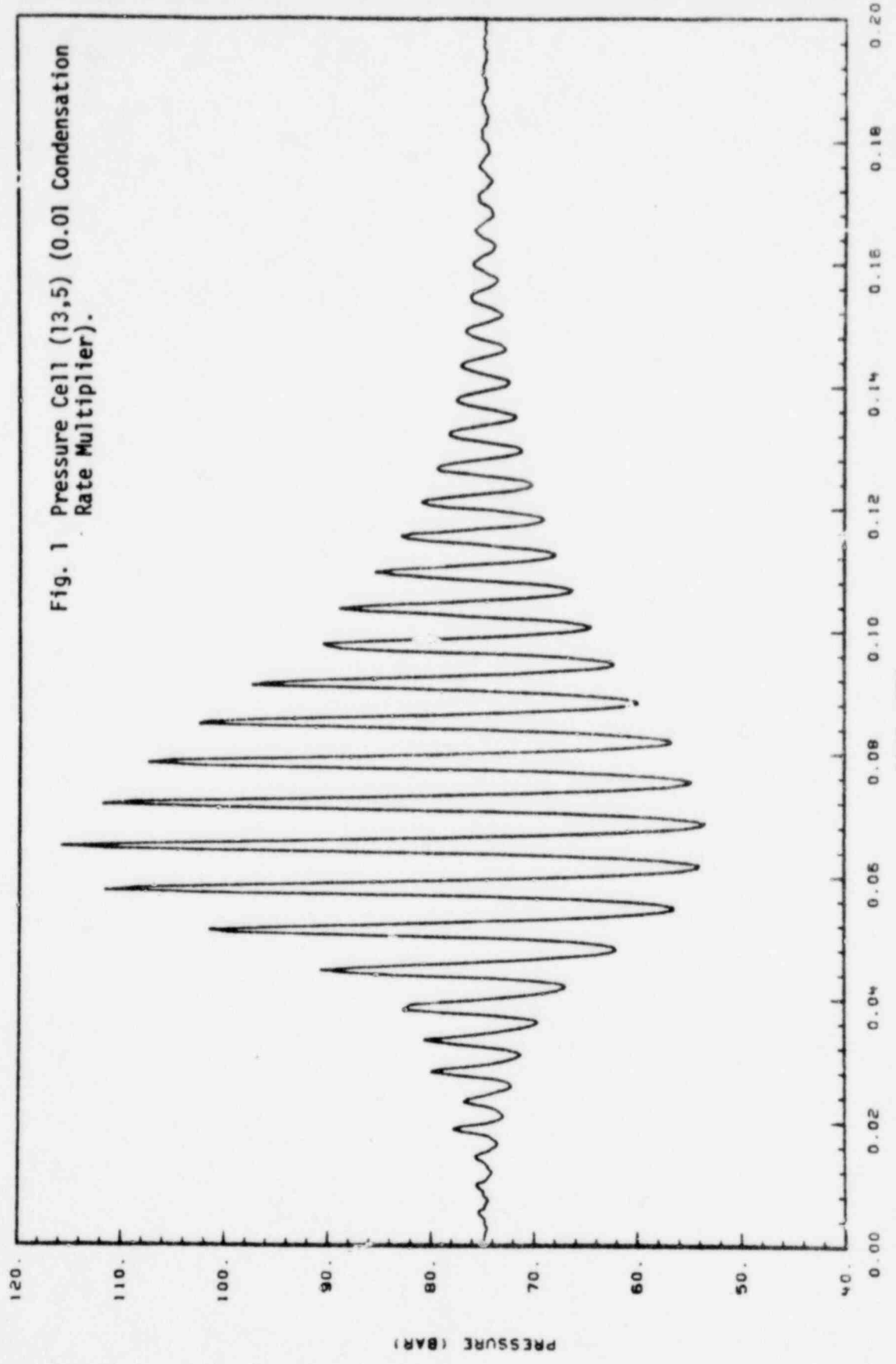

Fig. 1 Pressure Cell (13,5) (0.01 Condensation Rate Multiplier).

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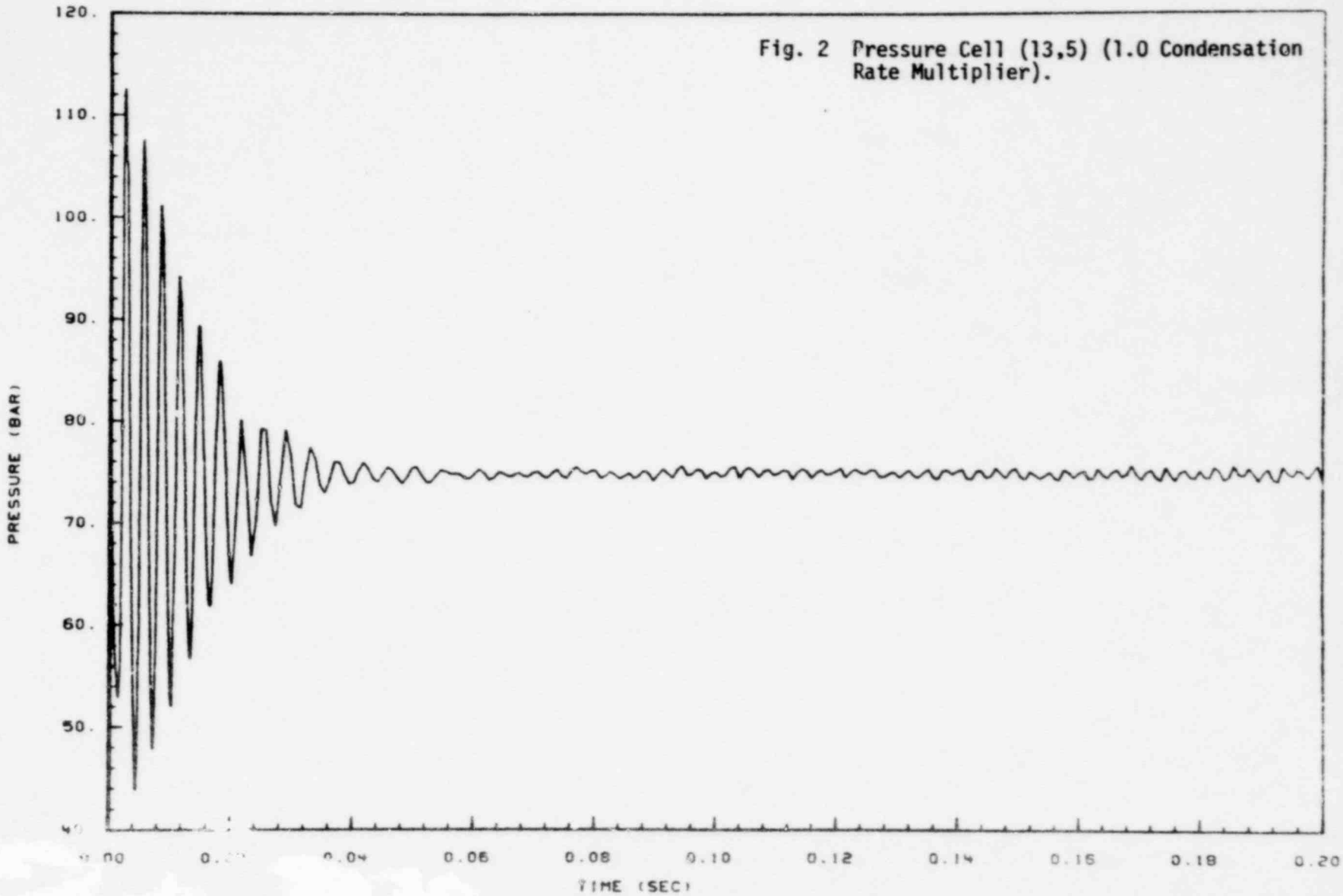

Fig. 2 Pressure Cell (13,5) (1.0 Condensation Rate Multiplier).

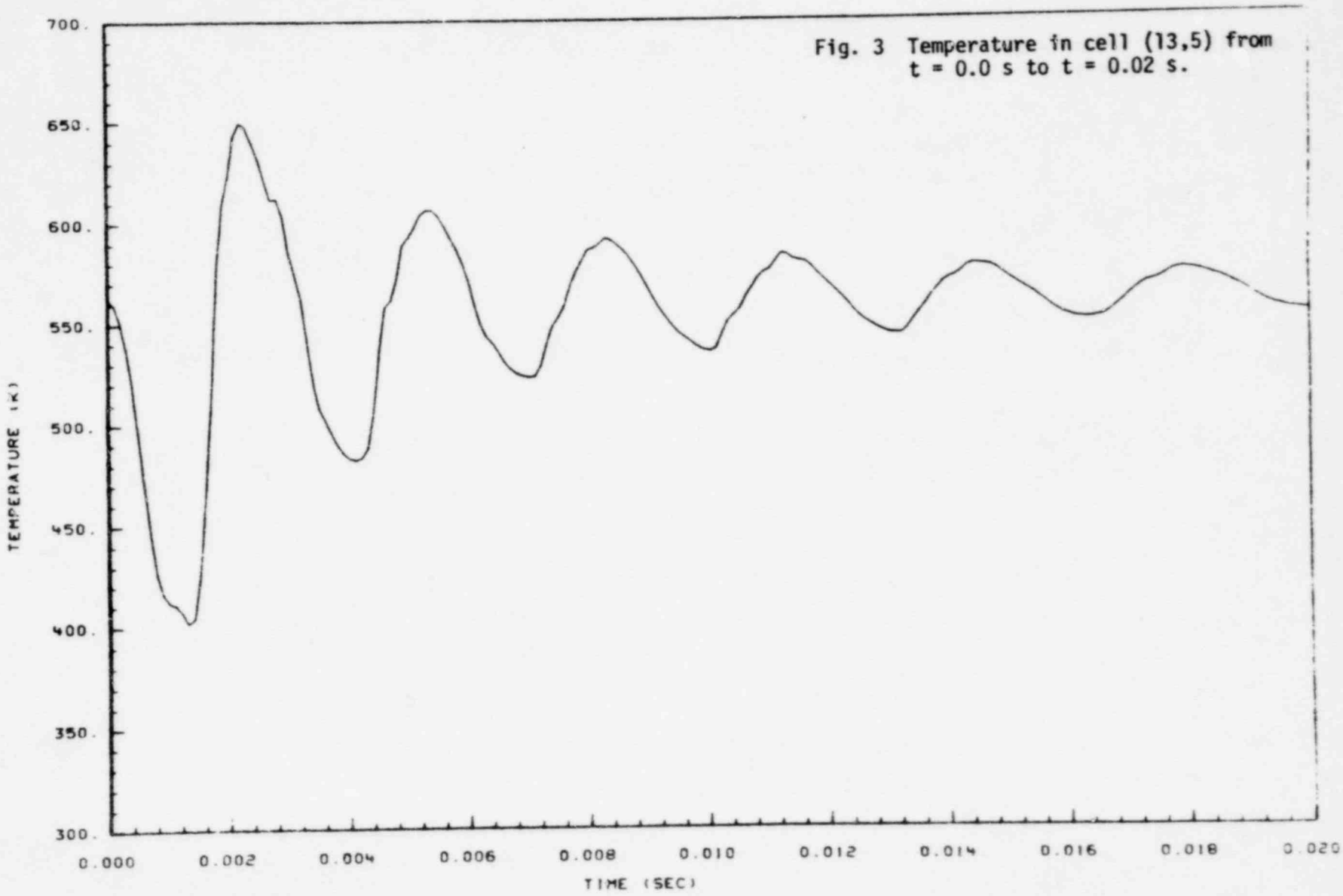

Fig. 3 Temperature in cell (13,5) from t = 0.0 s to t = 0.02 s.

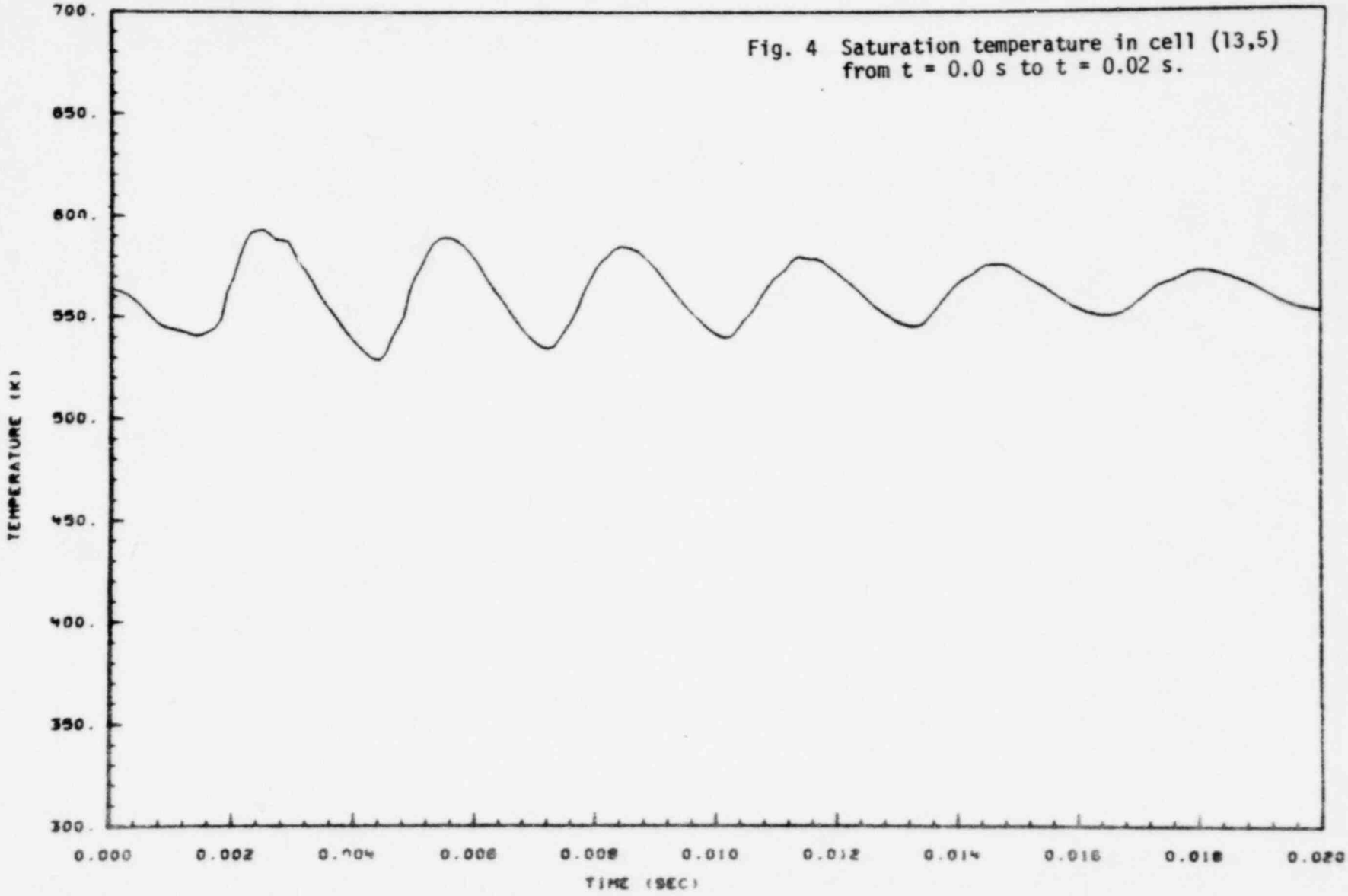

Fig. 4 Saturation temperature in cell (13,5) from t = 0.0 s to t = 0.02 s.

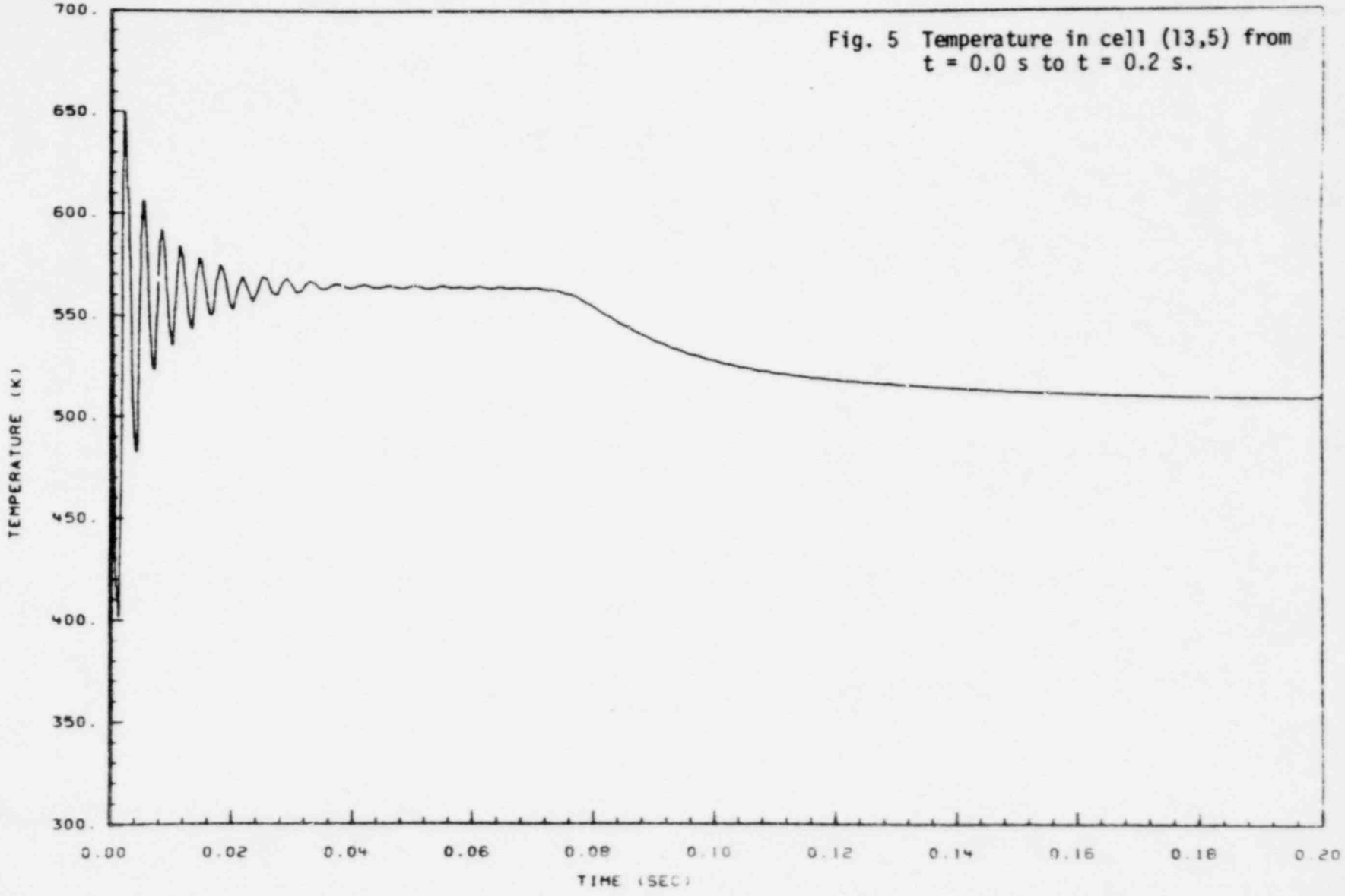

Fig. 5 Temperature in cell (13,5) from t = 0.0 s to t = 0.2 s.

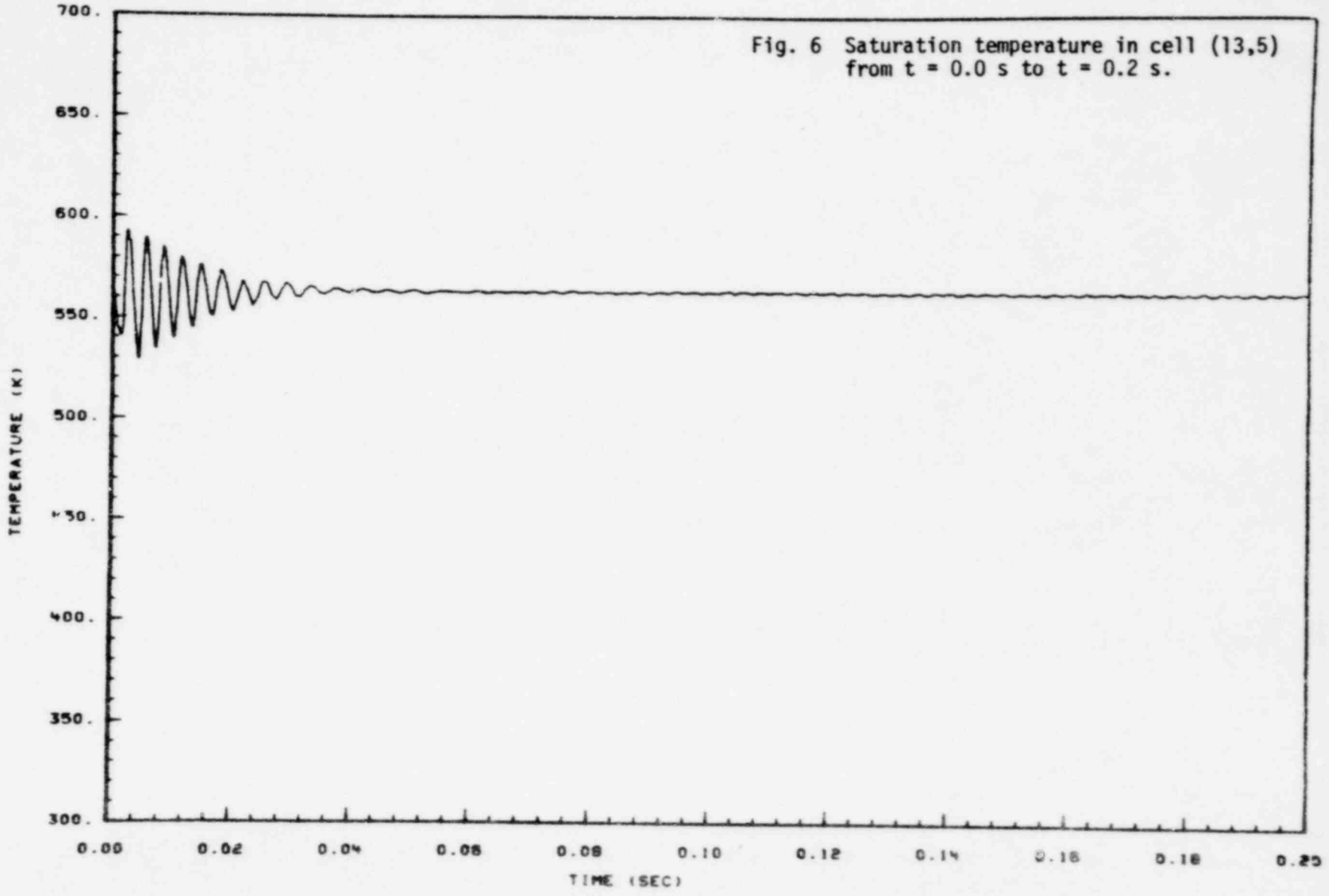

Fig. 6 Saturation temperature in cell (13,5) from t = 0.0 s to t = 0.2 s.

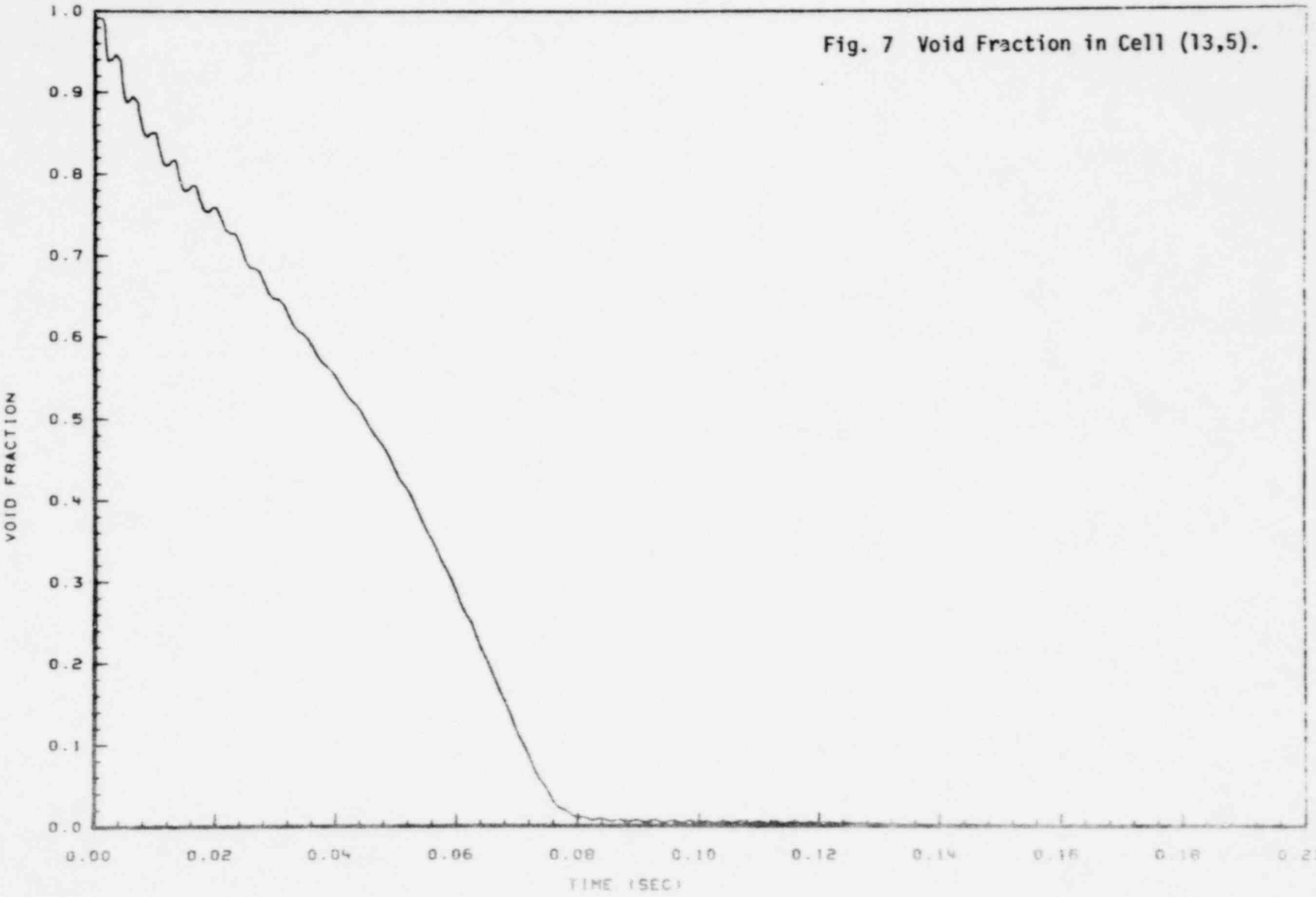

Fig. 7 Void Fraction in Cell (13,5).

III. CRITIQUE OF THE TREATMENT OF INTERPHASE HEAT TRANSFER AND MASS TRANSFER IN K-FIX/MOD1

The analysis given in Section II shows that the results of the simulation of steam void collapse with condensation rate 1.0 are physically explainable in terms of the condensation rate. These results exhibited a thermo-mechanical behavior characterized by nonequilibrium phenomena as the system is driven towards a stable thermodynamic equilibrium state characterized by complete condensation of the steam. They are qualitatively consistent with both the theoretical predicted and experimentally observed oscillations in bubble size inherent in bubble collapse in highly subcooled liquids[4,5,6]. The "rebound effect", where the pressure of the collapsing steam void decreases and then increases to a relative maximum, is present in this simulation and is supported in the literature[4,5,6]. Multiple rebounds, which are also present in this simulation, have actually been observed[7].

In spite of the qualitative agreement of these results with observations and their being physically explainable, there are at least two controversial aspects of these results:

(1) The amplitudes of the temperature oscillations are large and in particular, the temperature in the steam void drops significantly below the temperature of the adjacent fluid during the first oscillation.

(2) The void fraction in the steam void is high during the time of the oscillations and is very high at the time of the first rebound.

(1) is controversial since no reasonable physical explanation can be advanced for the phenomenon, while (2) is controversial since the bubble collapse observations cited show rebounding when the bubble is quite small and hence has a low void fraction.

An examination of K-FIX/MOD1 was made to attempt to resolve these controversial results. This examination revealed inadequacies in the treatment of interphase heat transfer and mass transfer in K-FIX/MOD1 for steam void collapse simulations. These inadequacies are

(1) The terms modeling interphase heat transfer and energy exchange resulting from mass transfer in the gas and liquid specific internal energy equation,

(2) The constitutive relations used in these terms,

(3) The method in which these terms are computed in the numerical solution algorithm used by K-FIX/MOD1 (and hence by K-FIX[8]).

It is believed that the elimination of these inadequacies would result in a computer program that would more realistically simulate steam void collapse.

The terms in the gas and liquid specific internal energy equations of the K-FIX/MOD1 two-fluid model that represent interphase heat transfer and energy exchange resulting from mass transfer are

$$R\,(T_\ell - T_g) + (\Gamma_e - \Gamma_c)H_g \qquad (1)$$

in the gas specific internal energy equation and

$$R\,(T_g - T_\ell) - (\Gamma_e - \Gamma_c)\,H_g \qquad (2)$$

in the liquid specific internal energy equation, where

R = the interphase heat transfer function,

T_ℓ = the temperature of the liquid,

T_g = the temperature of the gas,

Γ_e = the evaporation rate,

Γ_c = the condensation rate, and

H_g = the specific enthalpy of the gas.

Since the effects of interphase heat transfer and energy exchange associated with mass transfer must be absent in the total specific internal energy equation, the sum of the terms representing these effects in the gas and liquid specific internal energy equations must be zero. Since the sum of Expressions (1) and (2) is trivially zero, the choice of the functions R, Γ_e and Γ_c is arbitrary. This lack of coupling between the mass transfer rate, $\Gamma_e - \Gamma_c$, and the interphase heat transfer is physically incorrect. The mass transfer rate cannot be independent of the interphase heat transfer as is permitted in the K-FIX/MOD1 two-fluid model.

Constitutive relations for R, Γ_e, and Γ_c are required for the interphase heat transfer and mass transfer terms in Expressions (1) and (2). In K-FIX/MOD1, R must be a large constant, Γ_e is proportional to $T_\ell - T_s$ if $T_\ell > T_s$ and 0 otherwise, and Γ_c is proportional to $T_s - T_g$ if $T_g < T_s$ and 0 otherwise, where T_s is the saturation temperature. A large constant R implies that $T_\ell = T_g$. This is an undesirable restriction but one that experience demonstrates is required to avoid temperature instabilities. The expressions in K-FIX/MOD1 for Γ_e and Γ_c do not account for latent heat effects. This is highly inadequate for steam void collapse simulations, since as energy is transferred to or from the steam void to the adjacent subcooled fluid the effects of changing phase at the saturation temperature must be included. Thus the failure to include latent heat effects would contribute to abnormally large amplitudes in temperature oscillations such as those observed in the simulation discussed in Section II. Therefore, the mass transfer model must account for latent heat effects.

In the numerical solution of the specific internal energy equations at the $(n + 1)$ time level, the numerical solution algorithm used by K-FIX/MOD1 computes R at the n^{th} time level, T_ℓ and T_g in the R $(T_\ell - T_g)$ terms at the $(n + 1)^{st}$ time level, and Γ_e, Γ_c, and Hg at a time level intermediate to the

n^{th} and $(n + 1)^{st}$ time levels. This is considered inadequate, since the T_ℓ present in Γ_e and the T_g present in Γ_c should also be computed at the $(n + 1)^{st}$ time level. It is hoped that computing all the temperatures at the same time level will remove the need to use large values for R to avoid temperature instabilities.

IV. AN ALTERNATE TREATMENT OF INTERPHASE HEAT TRANSFER AND MASS TRANSFER

In this section an alternate treatment of interphase heat transfer and mass transfer is proposed. This treatment couples the mass transfer rate to the interphase heat transfer rate and includes latent heat effects. Thus, inadequacies (1) and (2) discussed in Section III are removed by this treatment. The form of the interphase heat transfer rates permits an implicit treatment of the gas and liquid temperatures in the numerical solution algorithm used in K-FIX/MOD1. Thus inadequacy (3) discussed in Section III can also be removed by this treatment.

In this model the terms representing interphase heat transfer and energy equations are

$$q_{ig} + \Gamma H_{sg} \tag{3}$$

in the gas specific internal energy equation and

$$q_{i\ell} + \Gamma H_{s\ell} \tag{4}$$

in the liquid specific internal energy equation, where

q_{ig} = the heat transfer rate between the interface and the gas,

$q_{i\ell}$ = the heat transfer rate between the interface and the liquid,

Γ = the mass transfer rate,

H_{sg} = the gas saturation specific enthalpy, and

$H_{s\ell}$ = the liquid saturation specific enthalpy.

Thus in this model it is proposed that Expressions (3) and (4) replace Expressions (1) and (2) in the K-FIX/MOD1 two-fluid model. The requirement that the sum of Expressions (3) and (4) be zero yields the mass transfer rate

$$\Gamma = - (q_{ig} + q_{i\ell})/(H_{sg} - H_{s\ell}) \quad . \tag{5}$$

This mass transfer rate is a function of the interphase heat transfer rate $(q_{ig} + q_{i\ell})$ and the latent heat $(H_{sg} - H_{s\ell})$. With the gas at temperature T_g, the liquid at temperature T_ℓ, and the interface bounding the gas and liquid regions at temperature T_s, q_{ig} and $q_{i\ell}$ may be expressed in the form

$$q_{ig} = h_{ig} A (T_s - T_g) \text{ and} \tag{6}$$

$$q_{i\ell} = h_{i\ell} A (T_s - T_\ell), \tag{7}$$

where

h_{ig} and $h_{i\ell}$ are interphase heat transfer coefficients and

A = the interphase surface area per unit volume.

By using Expressions (3) and (4) with Γ, q_{ig}, and $q_{i\ell}$ given by Equations (5), (6), and (7), respectively, all temperatures can be computed at the $(n + 1)^{st}$ time level in the K-FIX/MOD1 numerical solution algorithm.

V. USE OF ALTERNATE COMPUTER PROGRAMS FOR STEAM VOID COLLAPSE ANALYSIS

At the inception of the study described in this report, K-FIX was the only computer program with non-equilibrium capabilities that was operable at INEL. Section IV suggests improvements to K-FIX to eliminate known inadequacies. It should be emphasized that these changes will not guarantee a satisfactory steam void collapse analysis tool; however, they must be made for K-FIX to be used at all.

Since initiating the steam void collapse study, two additional computer programs with non-equilibrium capabilities have become operational at INEL - TRAC and THERMIT. Experience accumulated outside the scope of this study indicates that these computer programs have numerical schemes that are more stable than that of K-FIX. Therefore, the newer programs are more operable and probably are faster running on comparable problems than K-FIX. However, they are known to lack adequate models for certain important phenomena, so significant model development is needed to perform a steam void collapse analysis.

The present study emphasizes that steam void collapse analysis is a challenging task for any computer program. As a result, no assurance can be given that any computer program can perform a satisfactory steam void collapse analysis. We believe that the most promising approach to analysis of steam void collapse would be to apply TRAC or THERMIT to the analysis of available experimental data. Necessary program modifications would be identified by the data comparisons.

Existing experiments may not have sufficient measurements or be in systems which are geometrically similar to PWR systems. It would be preferable to perform experiments on highly-instrumented scaled or full scale systems and correlate these experiments with an advanced code. No code can be relied upon for this type of problem in the absence of data comparisons.

VI. CONCLUSIONS

The conclusions advanced on the basis of this study are:

(1) K-FIX/MOD1 with appropriate modifications in the treatment of interphase heat transfer and mass transfer, may be useful for the analysis of steam void collapse.

(2) The most promising avenue for future work in the analysis of steam void collapse involves the use of TRAC or THERMIT to analyze appropriate experimental data on steam void collapse and then to use data comparisons for guiding program modifications.

(3) To insure greatest success in studying steam void collapse, the analysis program should be run in concert with a well-designed experimental program involving highly-instrumented scaled or full scale systems.

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APPENDIX A

EFFECTS OF TIME STEP REDUCTIONS ON THE RESULTS OF A STEAM VOID COLLAPSE SIMULATION USING K-FIX/MOD1

The steam void collapse simulation with condensation rate multiplier 1.0 discussed in Section II was run with a time step Dt = 0.05 ms from t = 0.0 s to t = 0.02 s and Dt = 0.2 ms from t = 0.2 s to t = 0.2 s. This simulation was rerun from t = 0.0 s to t = 0.02 s with Dt = 0.02 ms and Dt = 0.005 ms. The pressure histories for cell (13,5) from t = 0.0 sto t = 0.02 s are shown in Figures A-1, A-2, and A-3 for these three simulations. These figures show significantly different pressure as a function of time behaviors after the first rebound. At present no satisfactory explanation for this numerical phenomenon is available.

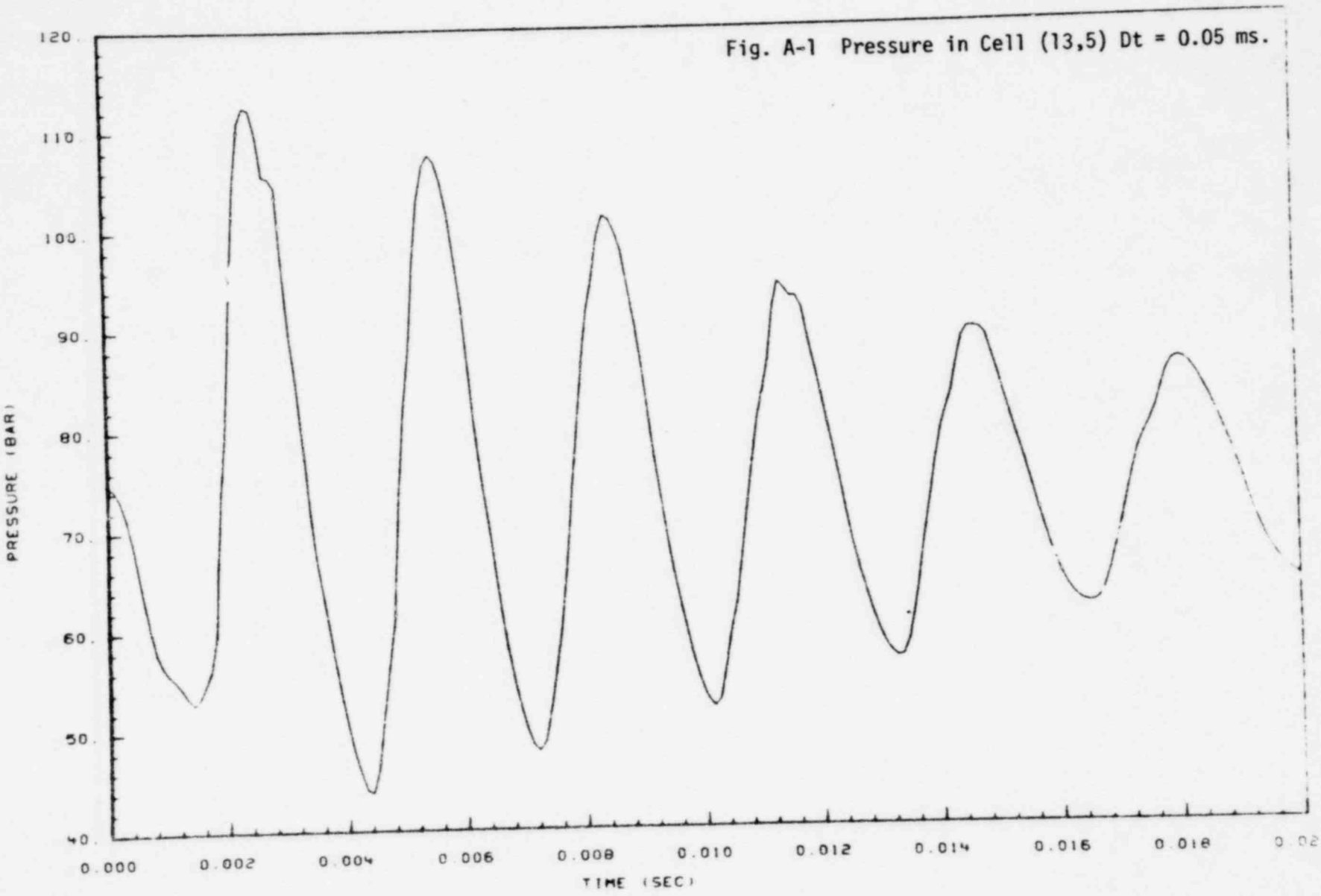

Fig. A-1 Pressure in Cell (13,5) Dt = 0.05 ms.

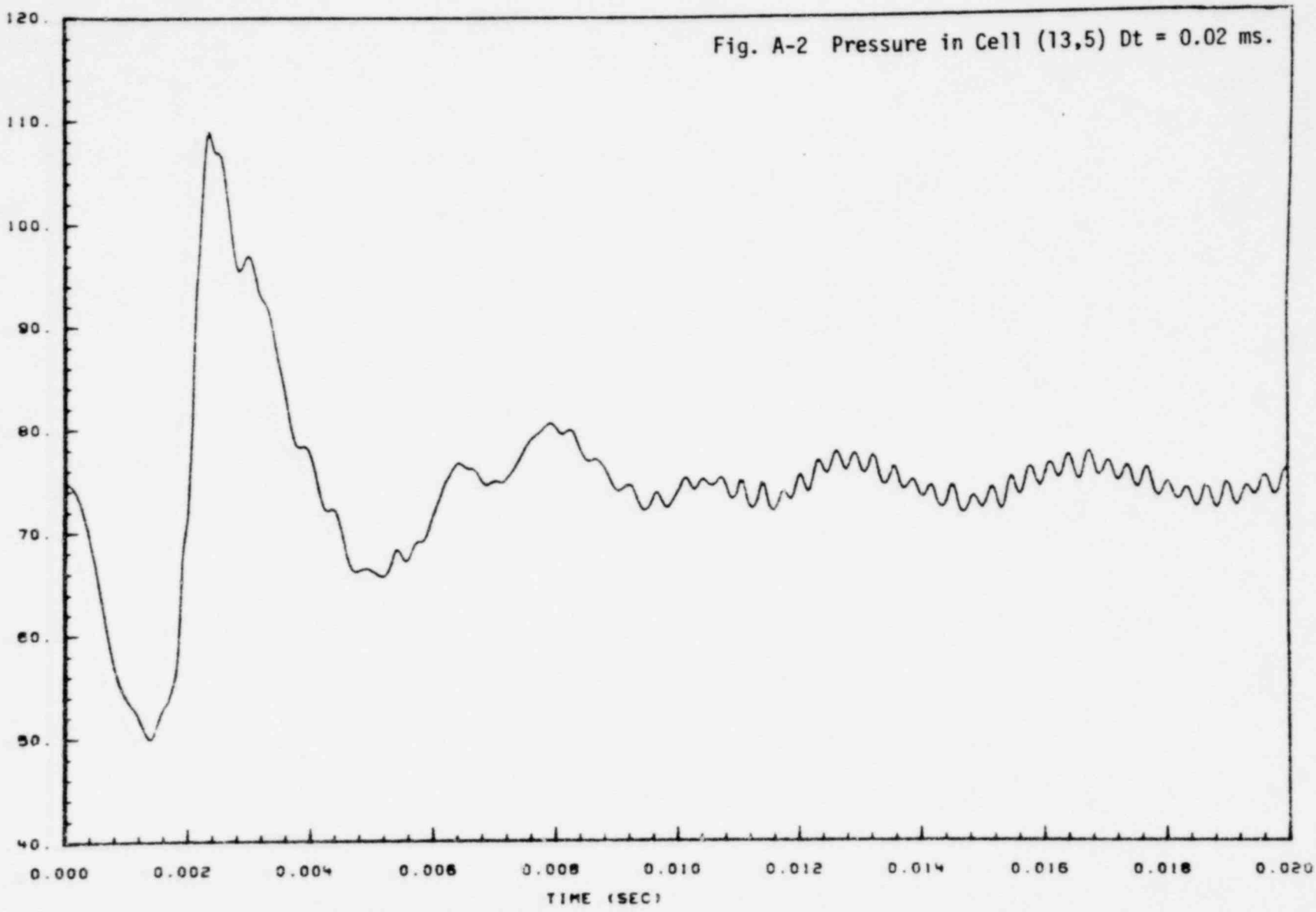

Fig. A-2 Pressure in Cell (13,5) Dt = 0.02 ms.

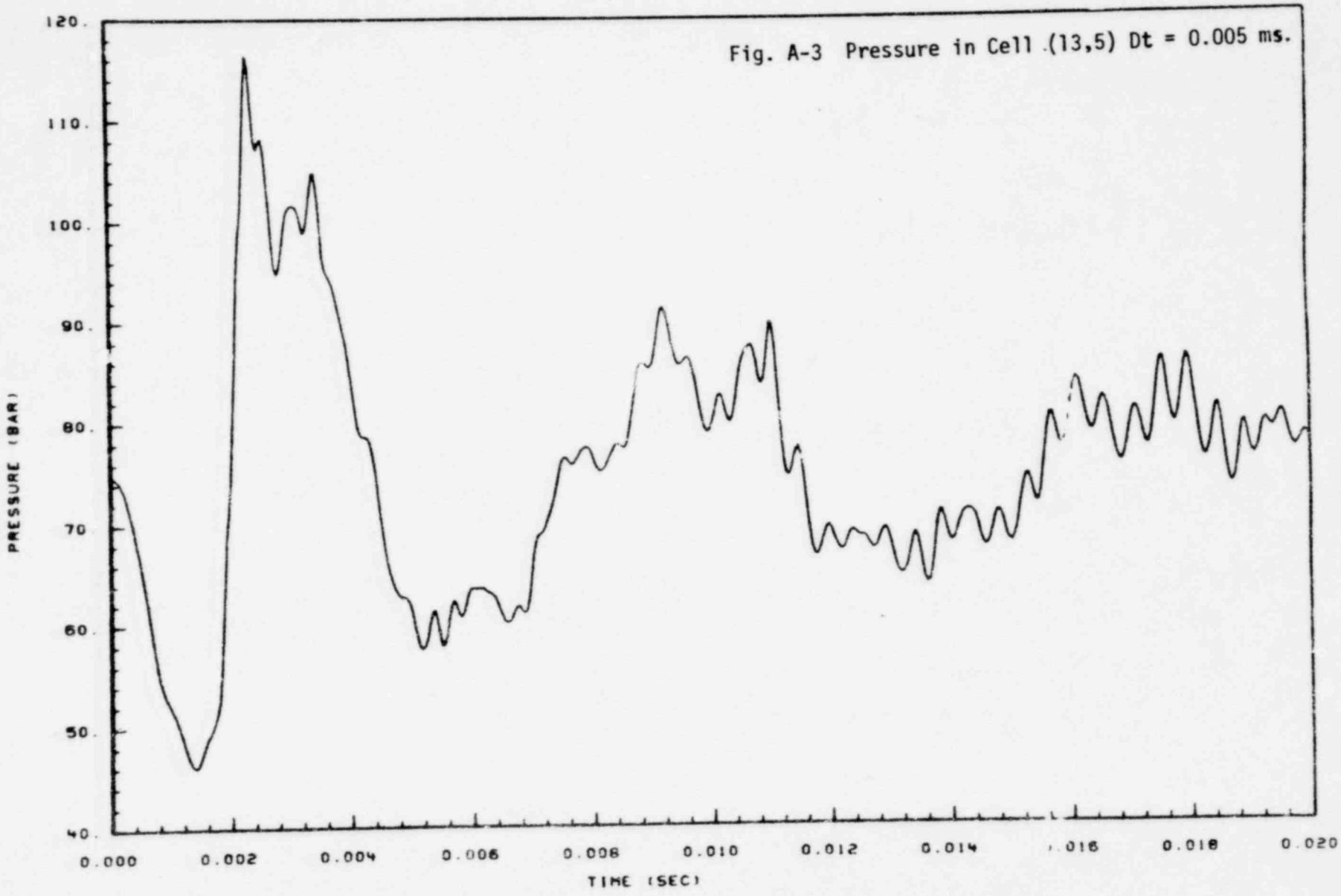

Fig. A-3 Pressure in Cell (13,5) Dt = 0.005 ms.