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THE BWR STEADY-STATE CAPABILITY OF THE WRAP-EM SYSTEM

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ABSTRACT

This report describes the computational procedure used in the WRAP-EM System to determine steady state operating conditions of a boiling water reactor (BWR). WRAP-EM is a modular computational system developed at the Savannah River Laboratory in support of the Nuclear Regulatory Commission program of light water reactor safety analysis. WRAP-EM is capable of performing, automatically, the full scope of calculations required to audit evaluation model analyses of a loss-of-coolant accident (LOCA).

This steady state computational procedure can be used to compute the equilibrium state of a BWR system corresponding to a particular system nodalization. With this procedure, BWR transient calculations can be performed without extensive manual calculations of the initial conditions.

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1. INTRODUCTION AND SUMMARY

A steady-state computational procedure for boiling water reactors (BWRs) has been developed as part of the WRAP-EM system. The WRAP-EM system is an integrated modular system of computer codes for complete analysis of the loss-of-coolant accident (LOCA) in light water reactors. The code system is being developed for the Nuclear Regulatory Commission for use in interpreting and evaluating reactor vendor evaluation model (EM) methods and results. Within the WRAP-EM system, a reprogrammed version[1,2] of the RELAP4/MOD5[3] code is used to calculate the blowdown phase of the accident. The RELAP4/MOD5 code provides no explicit procedure for initializing the transient thermal-hydraulic calculation. During the initial development of the WRAP-EM system, an automatic steady-state procedure for pressurized water reactors was developed[4] to eliminate this deficiency. A similar procedure has been developed for BWR systems and is described in this report.[a] Companion reports[5,6] present an overview of the WRAP-EM for BWR analysis and provide a detailed description of the input required.

To generate a steady-state, the computational module solves the time dependent mass, momentum and energy equations for a BWR under normal operating conditions. The solution procedure is similar to the WRAP-EM transient calculation, with the major exception being that no LOCA or other perturbation is allowed to occur. The procedure is started with an estimate of initial conditions provided by an initialization algorithm developed specifically for BWR systems. This algorithm computes self-consistent states, flows, and heat sources, starting from values of a few key system parameters that are supplied by the user. With these initial conditions, the time dependent equations are solved under conditions of invariant reactor power and system mass until a balance is obtained between system power input and output. The steady-state calculation terminates when instantaneous rates of change in mass, energy and flow throughout the system are less than user-defined convergence criteria. The majority of the subroutines composing the BWR steady-state module are identical to those in the WRAP-EM transient module (TWRAM). Because of this close structural correspondence, the steady-state module requires a minimal amount of independent long-term maintenance.

The steady-state module can be executed either as a stand-alone calculation or in-line with the transient calculation. To enable efficient and consistent in-line execution, automatic updates of key transient neutronic and hydraulic input records are made at the end of the steady-state calculation. Concise edits are performed at the end of the calculation to facilitate interpretation of results.

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[a] In the preparation of this document, a basic familiarity of the reader with the concepts presented in references 1 and 2 was assumed.

The module has been extensively tested using a typical BWR nodalization. These tests indicate that the solution procedure is unique, accurate, and reasonably efficient. Additionally, comparisons of the steady-state solution with a null transient calculation have demonstrated the solution techniques are consistent with those in TWRAM.

The remainder of this report contains:

- a description of the BWR system model,
- a description of the computational procedures employed in the steady-state module,
- a summary of user input requirements, and
- graphical results of application of the module to the Hope Creek test problem.

2. SYSTEM MODEL

A schematic of a typical BWR plant nodalization is shown in Figure 1. The nodalization shown in this figure consists of a central flow loop (containing the reactor core, upper plenum, steam separator, upper and lower downcomer and lower plenum) and recirculation loops. Steam passes out of the system from the steam dome by way of a steam line junction. Feedwater returns to the system in the lower downcomer by way of a feedwater junction.

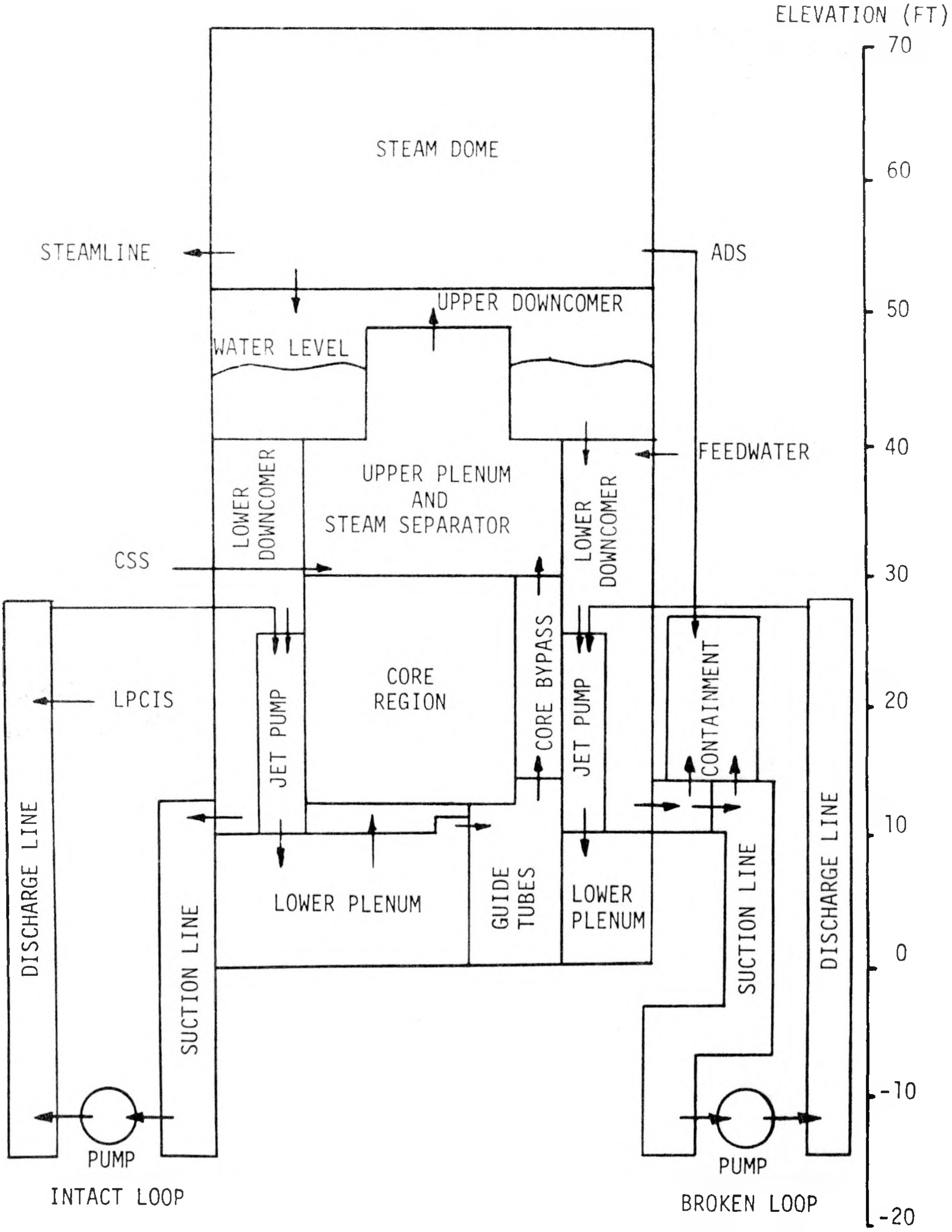
The steady-state procedure applies no restrictions to this typical nodalization. In the more general case, a few restrictions are placed on the nodalization for steady-state purposes. These restrictions relate in all cases to requirements imposed on the steam line and feedwater representations by the steady-state solution strategy. These restrictions are listed below.

1. Steam lines and feedwater lines are to be represented as fill junctions, with the steam line junctions having a negative flow.
2. Up to six steam line-feedwater junction pairs are permitted.
3. All of the steam line junctions must connect to a common volume, e.g., the steam dome.
4. All of the feedwater junctions must connect to a common volume, e.g., the lower downcomer.
5. A single connecting junction between the steam dome volume and the upstream volume (volume #2 in Figure 1) is permitted.

3. Input Requirements

One special input record is required for the BWR steady-state procedure. The WRAP.INPUT.BWRSS.$JOBNAME record specifies data pertaining to initial conditions, boundary conditions, and convergence criteria. These data are defined in Table 1.

FIGURE 1



HOPE CREEK SYSTEM MODEL

TABLE 1

DATA IN THE WRAP.INPUT.BWRSS.$JOB RECORD

Field No.	Data Definition	Default
1	Problem case name	
2	Problem step name	
3*	Specific volume of the steam dome	
4*	Total mass of water in the system	
5	Steam dome volume name	
6	Lower downcomer volume name	
7	An estimate of the steam dome pressure	1100 psi
8	An estimate of the total core flow rate	$3\text{x}10^4$ lbm/sec
9	Elapsed time before convergence tests begin	150 sec
10	Relative error in input vs output power	0.001
11	Minimum error in U/U	0.001
12	Minimum error in M/M	0.001
13	Minimum error in W/W	.001
14	The number (N) of steamline-feedwater junction pairs in this problem	
FOR EACH STEAM LINE FEEDWATER JUNCTION PAIR		
15+4(N-1)	Steam line junction name	
16+4(N-1)	Feedwater junction name	
17+4(N-1)	Steam line junction flow weight	1/N
18+4(N-1)*	Feedwater junction enthalpy	

In addition to this special record, the user is required to supply the full set of input data records[2] normally required by the WRAP transient calculation. In this regard, the user should take particular care to specify accurate representations of parameters in the momentum equations for each junction. Because of the nature of the initialization algorithm, inaccuracy in specification of junction form-loss coefficients is not compensated by residual junction friction factors.

In Table 1, quantities labeled with an asterisk are used in the steady-state solution as boundary conditions. These govern the stationary values of volume states and junction flows. Note that additional boundary conditions, the core power level and shape, must be defined by the user in other standard WRAP input records. Quantities 9 through 13 in Table 1 allow the user to control the convergence of the steady-state solution. Use of these quantities is discussed later in this report.

Note that the default values for these quantities, as well as for the user estimates of steam dome pressure and core flow, are subject to change as dictated by user experience with operation of the procedure. Specification of a flow weight for each steam line has the effect of maintaining each steam line flow at a constant fraction of the average flow in the steam dome. Steam lines whose weights are not specified by the user have, by default, equal flow rates.

4. COMPUTATIONAL PROCEDURE

The basis for the BWR steady-state procedure is a modified version of the WRAP-EM transient module, TWRAM, which performs a "pseudo-transient" calculation. This calculation is executed, under conditions of constant reactor power, system mass and boundary junction properties, until a stationary solution is obtained. After the results of this solution are stored, the calculation of the true transient can proceed.

The pseudo-transient calculation must be initialized with a complete representation of initial volume state variables and junction flows. For the convenience of the user, these initial conditions are calculated automatically by the steady-state procedure. This calculation is performed using an algorithm based on a modified version of the WRAP initialization module[1](WRIN). The purpose of this algorithm is to determine a full set of self-consistent volume state variables for the system, based both upon the input data supplied by the user and upon an estimate of the steady-state flow distribution within the system. Details of this algorithm are given in Appendix 1.

After the initialization is complete, the pseudo-transient calculation is performed. During this calculation, values of reactor power, feedwater junction enthalpy, feedwater flow and steam line flow are constrained. As indicated in Appendix 2, these constraints are sufficent to obtain closure of the system of conservation equations being solved at each time step.

The pseudo-transient calculation continues until convergence of state variables and flows is obtained. Convergence testing within the calculation is done in three stages, each of which may be controlled by the user. First, a real-time constant is imposed on the convergence test procedure. No tests will be made for elapsed times less than this constant. When this time is exceeded, a test of integral power convergence commences. This test, which is performed every 100 time steps, compares the instantaneous rates of energy generation and removal in the system. When the relative difference between these is less than a user-specified minimum, an integral energy balance is presumed and the third stage of convergence testing commences. This test, which is also performed every 100 time steps, is of the instantaneous relative values of the time rate of change of mass, energy and momentum for each volume and junction in the system. When the maximum value of each of these quantities is less than a user-specified minimum, differential convergence is achieved, and the steady-state calculation terminates.

Several types of edits are performed by the steady-state procedure. A print of system conditions both at the start and at the end of the calculation is performed. The WRAP intermediate data set (WIDS), containing all the data necessary for subsequent execution of the transient, is dumped to disk storage. Prior to dumping WIDS, several items in the data base are automatically updated to insure a successful execution of the transient calculation. Neutronics data are updated, to scale the reactivity consistent with the core temperatures computed by the steady-state procedure. This insures that the true transient starts with a zero initial reactivity. Additionally, fill junction data are updated to reflect the feedwater and steam line junction flow rates computed by the steady-state.

5. SAMPLE CALCULATIONS

Extensive computational testing of the procedures in the steady-state module has been performed, with the objectives of:

1. Uniqueness assessment
2. Convergence testing
3. Consistency checks

The steady-state procedure should, in principle, yield a stationary solution independent of the detailed thermodynamic states and flows supplied by the initialization algorithm. This solution "uniqueness" has been demonstrated with tests based on a particular nodalization of the Hope Creek reactor. These tests have also provided information on the convergence characteristics of the steady-state. The tests of consistency that have been performed confirm the accuracy and completeness of the data interface established between the steady-state and transient modules.

Results of calculations performed to confirm uniqueness and convergence of the procedure are presented in Appendix 3. These calculations were run with the same nodalization and boundary conditions; they exhibit effects of various assumptions made regarding initial conditions on the uniqueness and efficiency of the steady-state procedure. Several conclusions can be drawn from the results which are presented in Appendix 3 and summarized in Table 2, viz,

- The procedure is unique. Asymptotic values of state variables and flows are independent of initial steam dome pressure and core flow estimates.
- The procedure is acceptably efficient. Although the calculations in Appendix 3 were run to 500 reactor seconds to exhibit clearly the asymptotic nature of the results, inspection of these results reveals acceptable convergence in 200-250 secs. as is shown in Table 2. A mean CPU time to convergence of about 20 minutes on the IBM 360/195 is estimated.
- For a particular core flow, the procedure appears to converge most efficiently for initial steam dome pressure estimates substantially higher than the expected steady-state value. Estimates that are close to the expected value result in initial large pressure oscillations which delay convergence. Estimates that are low result in relatively slow, although quite smooth system pressure convergence. High estimates yield both rapid and relatively smooth convergence. These results have influenced the choice of the default steam dome pressure shown in Table 1.

A check for consistency between the steady-state and the transient modules was performed, with the Hope Creek Test Problem as a basis. This test confirmed both the convergence characteristics of the steady-state and the completeness of the data interface between the two modules. To perform the test, TWRAM was run for a "null transient" (no LOCA), with initial conditions computed with the steady-state procedure. Power feedback effects were included, and the steamline and feedwater boundary conditions used in the steady-state procedure were

TABLE 2

SUMMARY OF BWR STEADY-STATE TEST PROBLEMS

Case Number	Initial Steam Dome Pressure (psi)	Initial Core Flow *(lb/sec)	Time To Convergence (Reactor Seconds)	
			Steam Dome Pressure	Core Flow
1	950	2×10^4	275	150
2	1025	2×10^4	275	100
3	1100	2×10^4	225	75
4	950	3×10^4	250	150
5	1025	3×10^4	250	100
6	1100	3×10^4	200	100
7	950	4×10^4	250	150
8	1025	4×10^4	250	100
9	1100	4×10^4	200	75

*Asymptotic steady-state values for steam dome pressure and core flow are 1021.3 psi and 30050 lb/sec.

employed. Results of this calculation were examined to confirm both that initial reactivity for the transient was effectively zero and that volume states and junction flows remained constant.

Detailed edits of kinetics parameters from this calculation showed that the separate components of the initial reactivity were indeed effectively zero, both at the start of the transient and for the first time step. A slight reactivity drift occurred however, for several time steps immediately thereafter. Reasons for this drift are unknown. Examination of the time dependent behavior of state variables and flows indicated that the drift has no practical effect on the stability of the null transient. Examples of this stability, shown in Figures 2 through 6, confirm the consistency of the steady-state and transient modules.

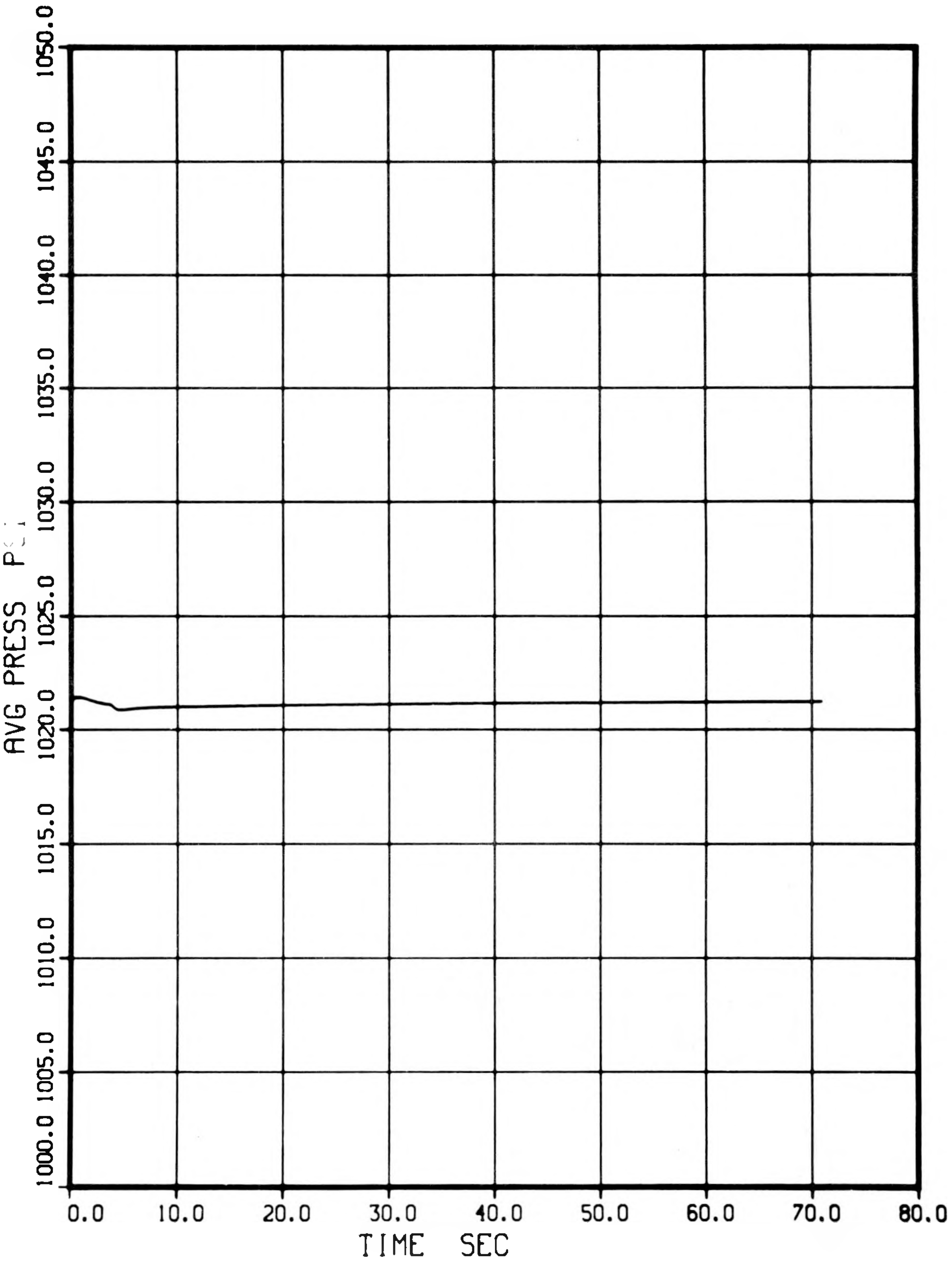


FIGURE 2. THE BWR STEADY-STATE CONSISTENCY TEST:
STEAM DOME PRESSURE vs TIME

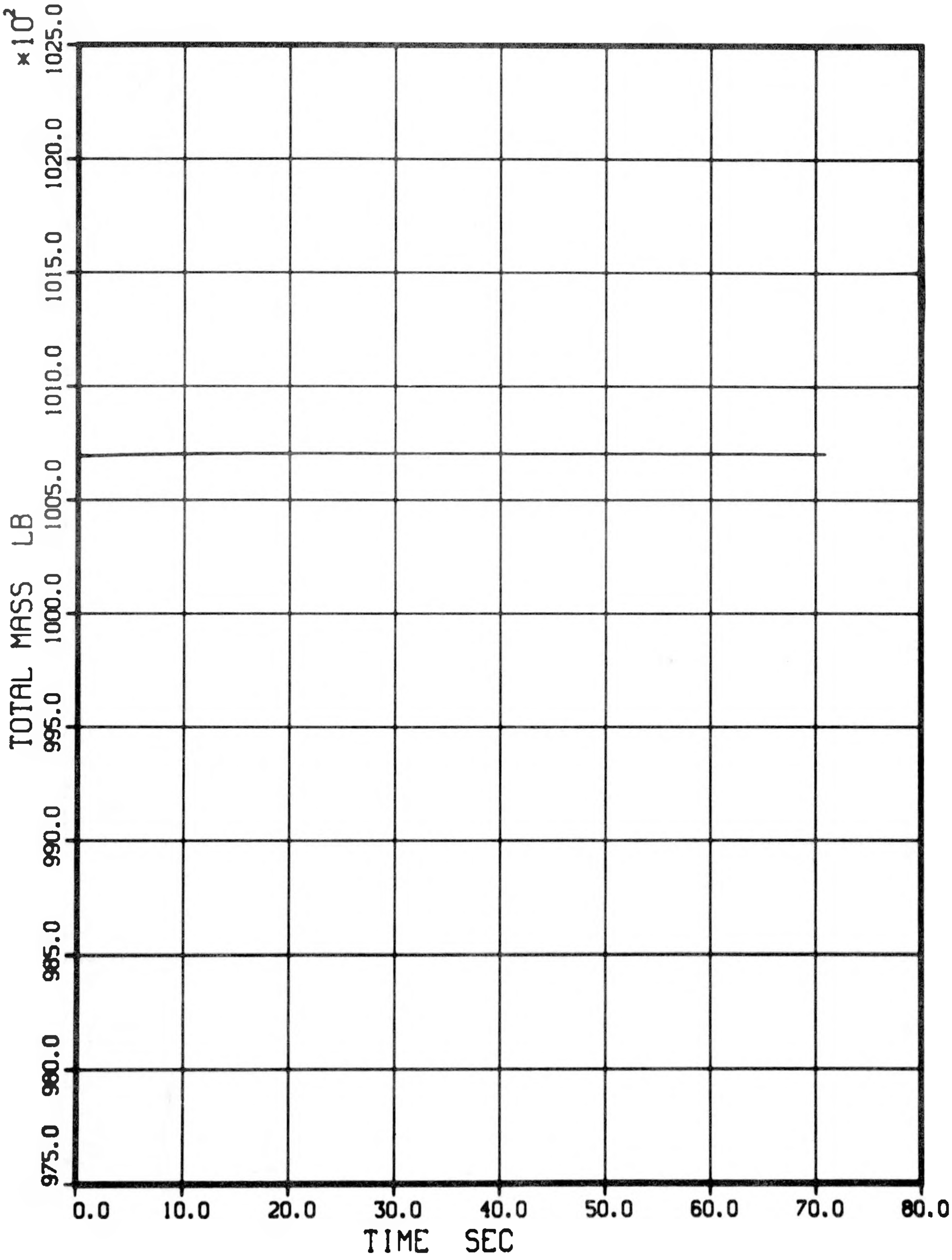


FIGURE 3. THE BWR STEADY-STATE CONSISTENCY TEST:
TOTAL MASS IN LOWER PLENUM vs TIME

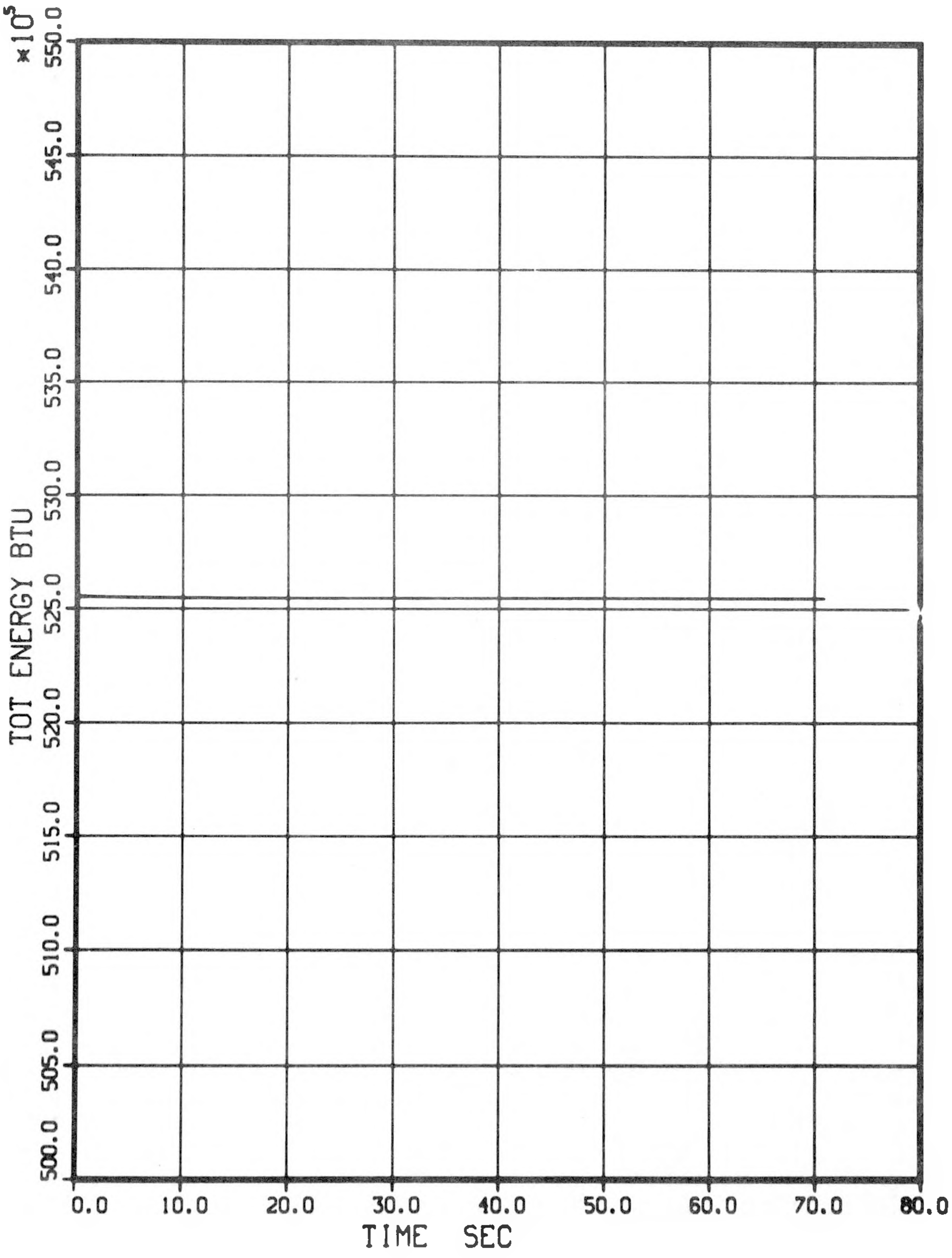


FIGURE 4. THE BWR STEADY-STATE CONSISTENCY TEST:
TOTAL ENERGY IN THE LOWER PLENUM vs TIME

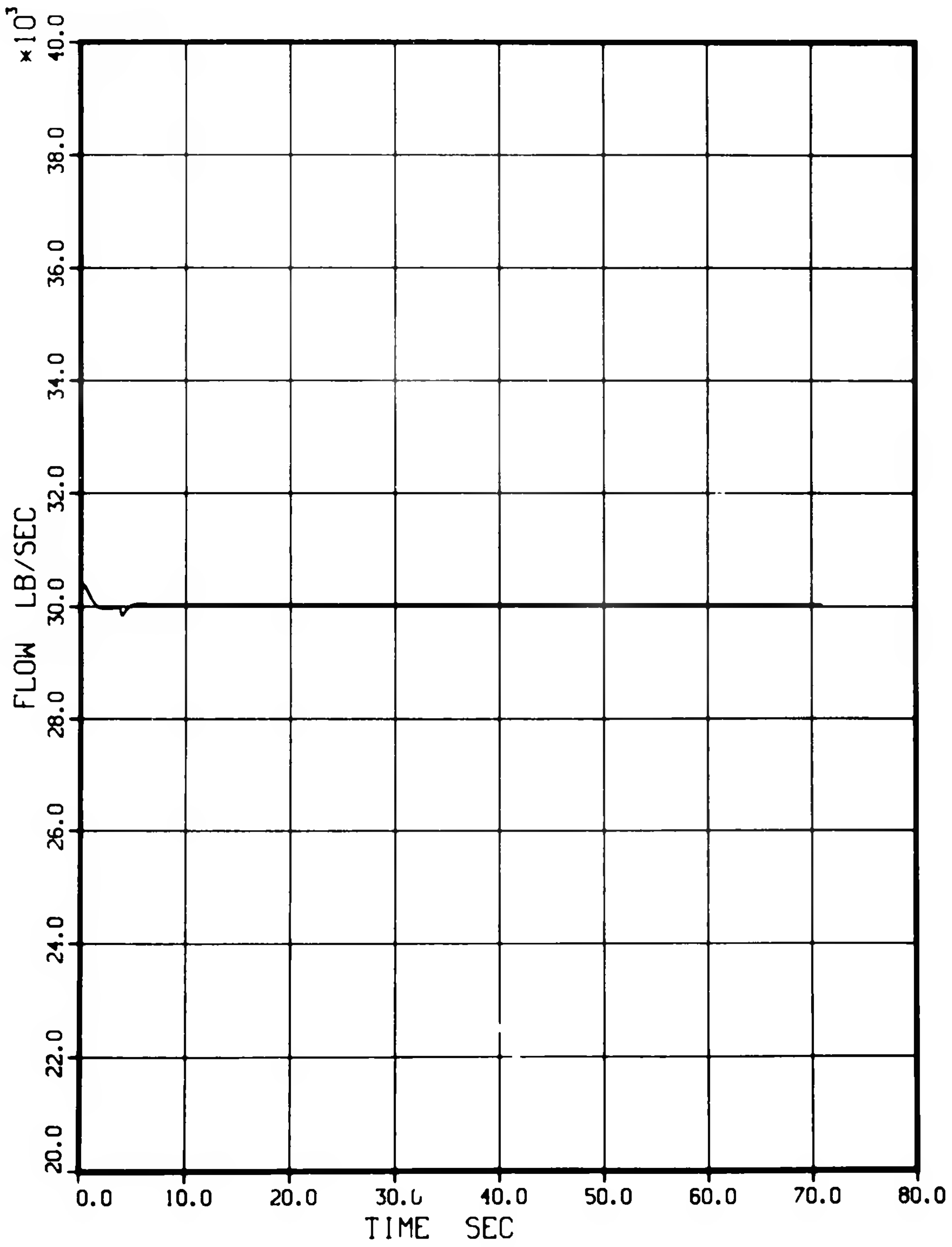


FIGURE 5. THE BWR STEADY-STATE CONSISTENCY TEST: TOTAL CORE FLOW vs TIME

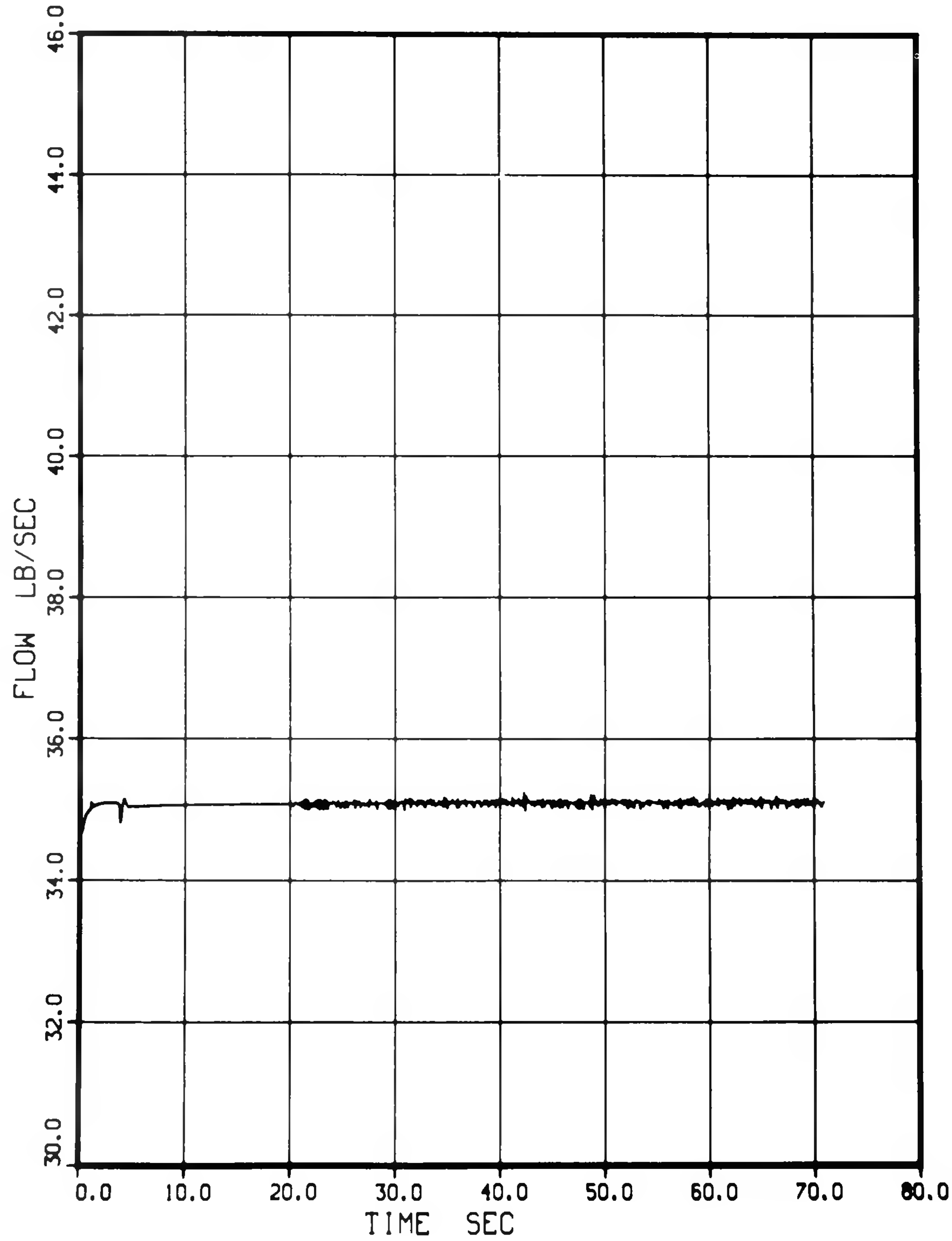


FIGURE 6. THE BWR STEADY-STATE CONSISTENCY TEST:
HOT CHANNEL FLOW RATE vs TIME

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APPENDICES

Appendix 1. Initialization of Volume States

Steps in the procedure for initialization of the BWR steady-state calculation are presented below:

1. First, the WRAP.INPUT.BWRSS record is read; default fields are defined where appropriate.
2. Energy sources in core volumes due to core slab heat generation are initialized.
3. Flows are initialized throughout the system. These flows are scaled to the total core flow defined by the user. The flow initialization algorithm is taken from the PWR steady-state procedure.[4]
4. Preliminary values of volume pressure and specific volume are established, via

   $P_i = P_{sd}; \quad \nu_i = \bar{\nu} \quad i\varepsilon(\text{NVOLX}-1),$

   where NVOLX = the total number of volumes in the system

   P_i, ν_i = pressure and specific volume for the i^{th} volume

   P_{sd} = the steam dome pressure guess supplied by the user

   $\bar{\nu}$ = the average specific volume for all volumes other than the steam dome, based on the specified values of steam dome specific volume and total system mass

5. Preliminary volume state descriptions are computed using the (P_i, ν_i) from (4).

6. Next an improved volume pressure distribution is computed by determining the incremental pressure drop between volumes due to gravity head; volume state descriptions are updated using this pressure distribution.

7. The distribution of specific volumes in the system is updated at constant pressure. This is done by solving a simplified form of the steady-state energy equation for the volume enthalpies, viz.,

$$\overline{W}_i \overline{h}_i = \sum_j w_j h_j + \overline{Q}_i/2 \tag{1}$$

where $\overline{W}_i$ and $\overline{h}_i$ = average flow and specific enthalpy in the i^{th} volume respectively

$\overline{Q}_i$ = the heat source to the i^{th} volume (from core slabs only)

and w_j, h_j = the flow and enthalpy, respectively, at the j^{th} junction to volume i, The enthalpy at the j^{th} junction, h_j, is computed as the outlet enthalpy for the upstream volume i.e.,

$$h_j = \bar{h}_{i'} + \bar{Q}_{i'}/2$$

where $\bar{h}_{i'}$ and $\bar{Q}_{i'}$ are the enthalpy and heat source for the upstream volume i'.

Equation (1) is solved by starting at volumes downstream of the lower downcomer and proceeding around this system for all volumes except the steam dome, whose state is fixed by input specifications. Each such solution is followed by an update of the equation of state for the volume in question, using volume pressure and enthalpy as independent variables.

After all volume states have been updated, the lower downstream mass is updated via the algorithm

$$M_{D1} = M_{D_o} + \alpha e_o \frac{V_D}{V_T} ; \qquad e_o = M_T - M_{T_o} , \qquad (2)$$

Where M_{D1} = new downcomer mass

M_{D_o} = previous downcomer mass

V_D = downcomer volume

V_T = total system volume

M_T = user-supplied total system mass

M_{T_o} = total system mass computed via the solution of (1) for all volumes

α = a built-in relaxation parameter.

8. Procedure (7) is iterated N+1 times, until e_N is arbitrarily small, whereupon the integral mass error represented by e_N is distributed uniformly over all the volumes except the steam dome, i.e., $M_{i_{N+1}} = M_{i_N} + e_N V_i/V_t$,

   $i \varepsilon (NVOLX-1)$, and the volume states are updated.

9. The distribution of volume pressures is updated, at constant specific volume. This is done by solving the steady-state momentum equation for each junction in the system, using a version of the WRIN pressure residual procedure that has been modified to solve explicitly for the junction ΔP rather than for the junction residual friction coefficient. Volume pressures are then updated using these junction pressure drops, and the volume states are recomputed as a function of pressure and specific volume.

10. Step (9) is iterated until the junction ΔP distribution converges.

11. Steps (7) through (10) are iterated until convergence in the volume pressure distribution is obtained.

12. Heat slab temperature distributions are initialized, via the standard SINITL procedure, and execution of the module is terminated.

Appendix 2. Solution of the Conservation Equations

The general BWR plant nodalization treated by the steady-state consists of a collection of

N_v	control volumes
N_j	junctions
N_{fw}	feedwater fill junctions
N_{sl}	steamline fill junctions, and
N_q	internal heat sources.

For this nodalization, the system of conservation equations solved at each time step consists of

$$\left.\begin{array}{ll} N_v & \text{energy balances} \\ N_v & \text{mass balances} \\ N_j-N_{sl}-N_{fw} & \text{momentum balances} \\ N_j-N_{fw} & \text{junction enthalpy relationships, and} \\ K(N_v) & \text{equations of state} \end{array}\right\} \qquad (3)$$

Solution of equations (3) must yield values of the following unknowns:

$$\left.\begin{array}{ll} N_j & \text{flows} \\ N_v & \text{energies} \\ N_v & \text{masses} \\ N_j & \text{junction enthalpies} \\ N_q & \text{heat fluxes} \\ K(N_v) & \text{volume state variables} \end{array}\right\} \qquad (4)$$

By comparison of the unknowns (4) with the system of equations (3), one observes that there is, in general, an excess of $2N_{fw} + N_{sl} + N_q$ variables, whose values must be fixed by the user to close the system. In the BWR steady-state procedure we have elected to fix

N_q	heat fluxes
N_{fw}	junction enthalpies
N_{sl}	steamline flows, and
N_{fw}	feedwater flows

Heat fluxes are fixed by user specification of the reactor power level and its spatial distribution within core heat slabs. Feedwater junction enthalpies are fixed by user specification of fill junction data. Steam line and feedwater flow rates are not defined explicitly by the user; instead they are defined by the steady-state procedure through specification at each time step of explicit relationships between certain of the flow equations, viz.,

$$W_{sl_i} = \alpha_i W_{SD}, \ i = 1,\ldots\ldots,N_{sl} \tag{5}$$

$$W_{fw_i} = W_{sl_i}, \ i=1,\ldots\ldots,N_{fw} \tag{6}$$

where W_{sl_i} = flow rate in the i^{th} steam line

W_{SD} = net flow into the steam dome

W_{fw_i} = flow rate from the i^{th} feedwater junction

α_i = a user-supplied flow weight for the i^{th} steamline junction

Equations (5) and (6) are solved in the steady-state procedure to determine values of steamline and feedwater flows at each time step. The effects of inclusion of equations (5) and (6) into the procedure are to conserve the mass of water in the steam dome and in the total system, respectively. Hence, the user must supply accurate initial values for these quantities to assure a physically reasonable final steady-state for his system.

Appendix 3. Results of BWR Steady-State Calculations

On the following pages, selected results of several BWR steady-state calculations are plotted. Results from nine different calculations are shown. Each of these calculations was based on the same nodalization of the Hope Creek reactor; each had the same boundary conditions. Each calculation was initiated with a different combination of volume state variables and junction flows. These initial conditions were computed based on the starting estimates of steam dome pressure and core flow shown in Table 3.1, below.

TABLE 3.1

INITIAL CONDITIONS SELECTED FOR BWR STEADY STATE TEST CALCULATIONS

Case Number	Initial Steam Dome Pressure (psi)	Initial Core Flow (lb/sec)
1	950	2×10^4
2	1025	2×10^4
3	1100	2×10^4
4	950	3×10^4
5	1025	3×10^4
6	1100	3×10^4
7	950	4×10^4
8	1025	4×10^4
9	1100	4×10^4

These estimates were selected to span a region of space symmetric about the asymptotic steady-state values of steam dome pressure and core flow.

The results presented are only a small part of the available data from the steady-state calculations, and are selected for display as being representative of the quality of convergence of the procedure. The results are taken directly from plots that were generated on microfiche by the WRAP output processor (WROP). In the plots, the following information is shown, as a function of elapsed time:

- o The instantaneous power balance, i.e., the difference between the input and output power (see Figures 3.1 through 3.9).
- o The steam dome pressure - volume 3 is the steam dome (see Figures 3.10 through 3.18).
- o The total mass and energy in the lower plenum - volume 10 is the lower plenum (see Figures 3.19 through 3.36).
- o The total core flow rates, as represented by the flow through Junction #1 (see Figures 3.37 through 3.45).
- o The flow rate in the hot channel, as represented by the flow in Junction #14 (see Figures 3.46 through 3.54).

From these results, several conclusions regarding the convergence characteristics of the procedure can be drawn, viz.,

- The procedure is unique, i.e., asymptotic values of state variables and flows are independent of initial steam dome pressure and core flow estimates as is demonstrated by the uniformity of the converged solution in all cases.
- The procedure is acceptably efficient. Although the calculations were run to 500 reactor seconds in all cases to exhibit clearly the asymptotic nature of the results, inspection of these results reveals acceptable convergence in 200-250 secs. A mean cpu time to convergence of about 20 minutes on the IBM 360/195 is estimated.
- For a particular core flow, the procedure appears to converge most efficiently for initial steam dome pressure estimates substantially higher than the expected steady-state value as is evident by comparing cases 1-3, 4-6, and 7-9. Estimates of the steam dome pressure that are close to the expected value (cases 2, 5, and 8) result in initial large pressure oscillations which delay convergence. Estimates that are low (cases 1, 4, and 7) result in relatively slow, although quite smooth system pressure convergence. High estimates (cases 3, 6, and 9) yield both rapid and relatively smooth convergence. These results have influenced the choice of the default steam dome pressure shown in Table 1.

FIGURE 3.1 POWER BALANCE FOR CASE 1

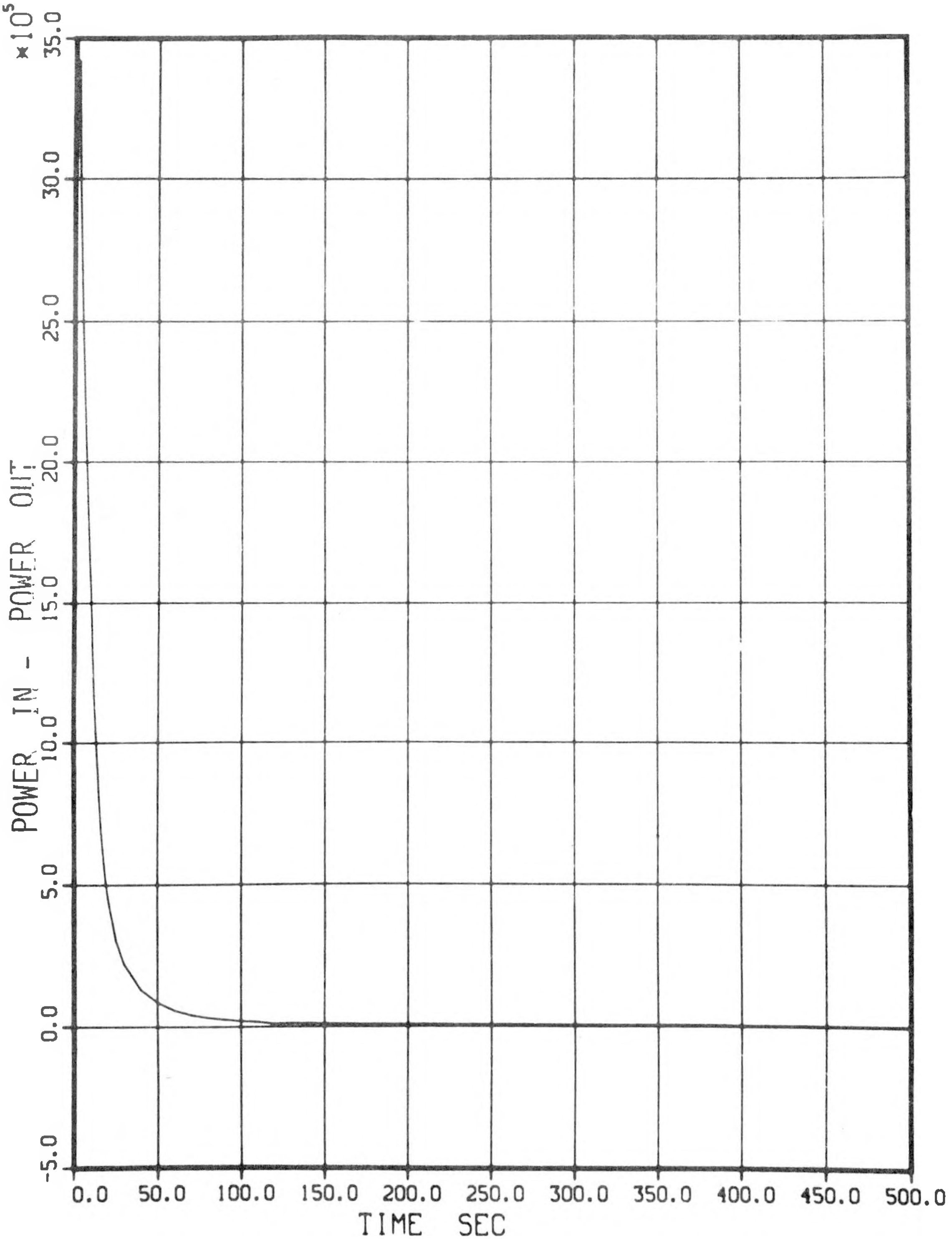


FIGURE 3.2 POWER BALANCE FOR CASE 2

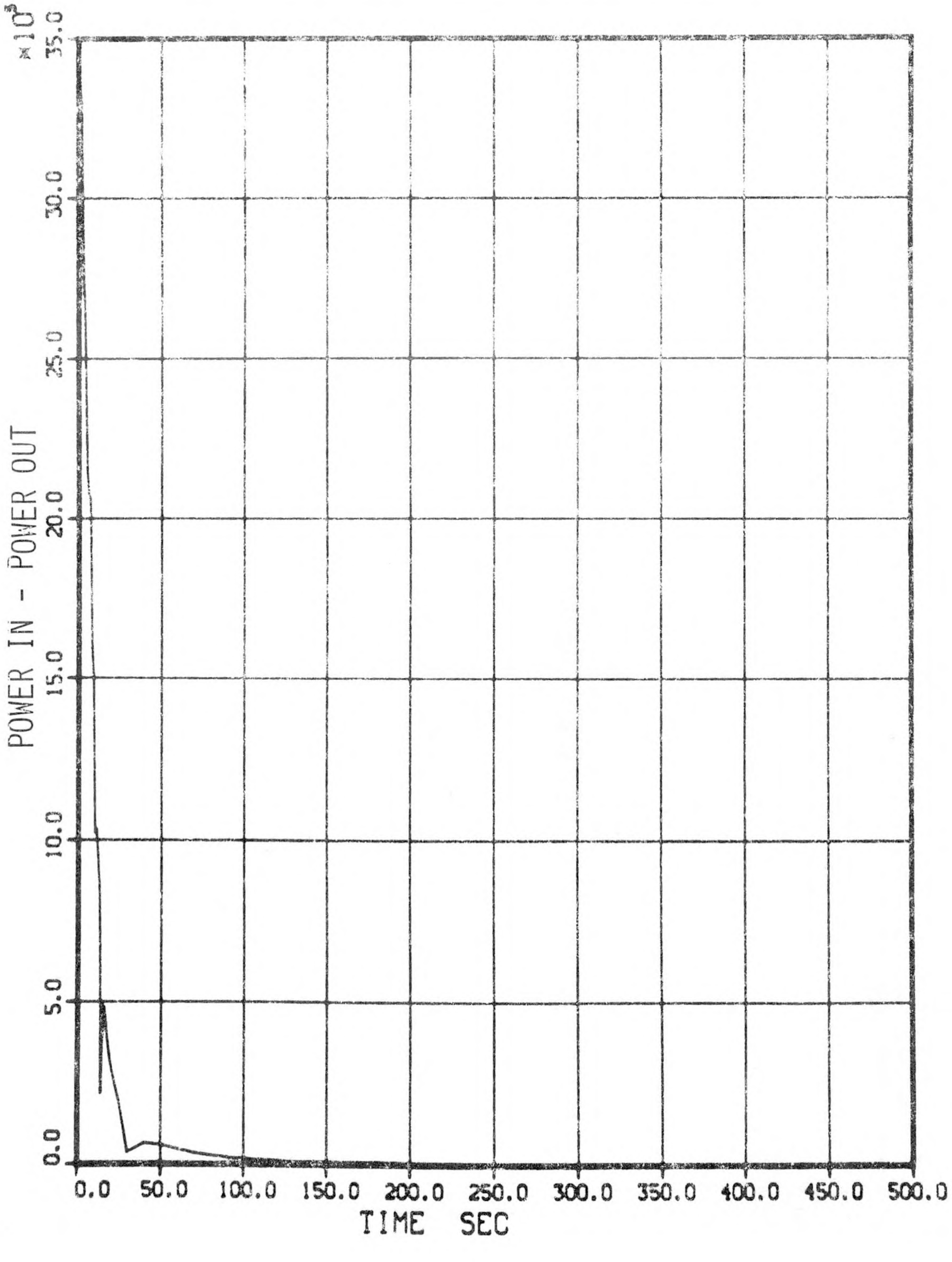


FIGURE 3.3 POWER BALANCE FOR CASE 3

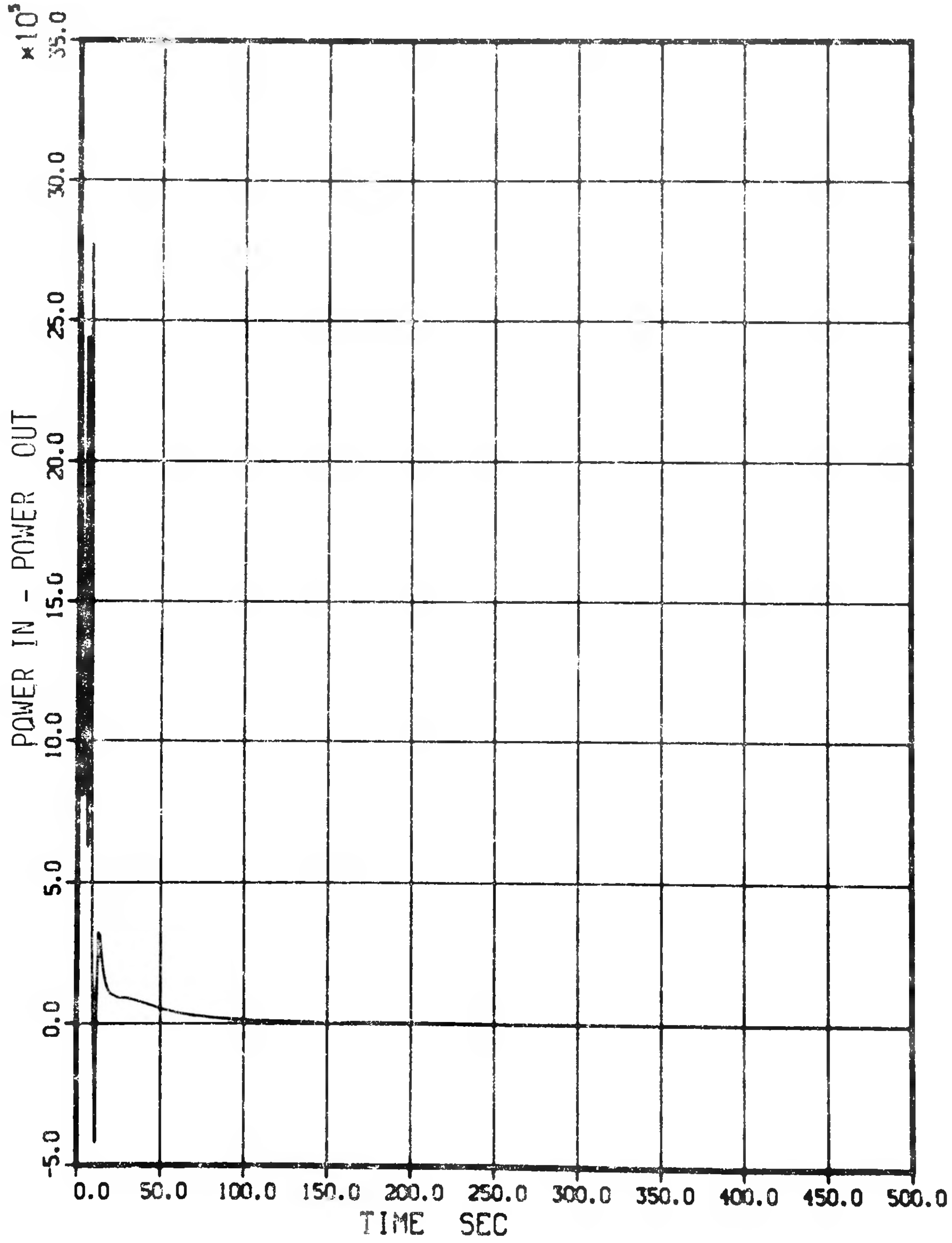


FIGURE 3.4 POWER BALANCE FOR CASE 4

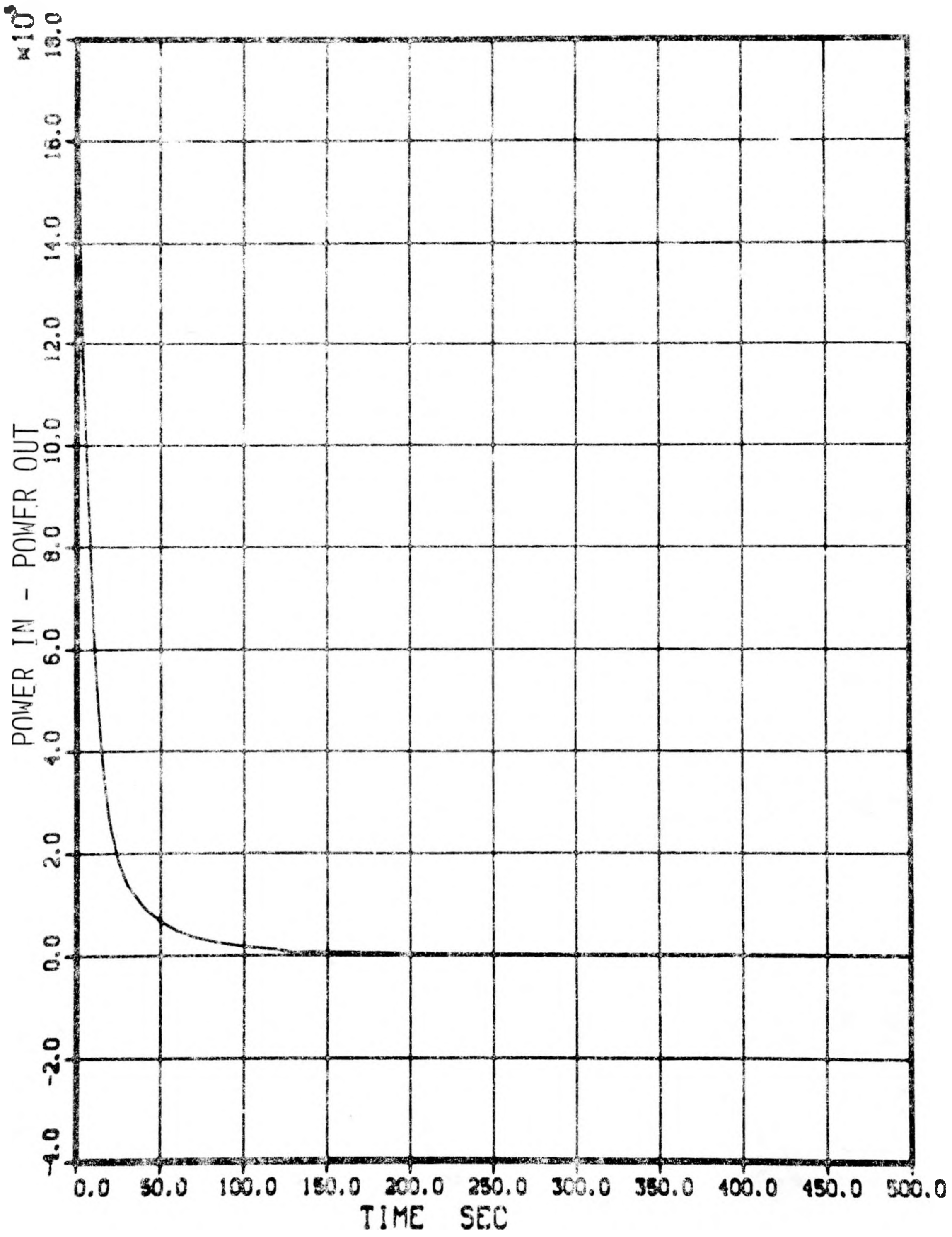


FIGURE 3.5 POWER BALANCE FOR CASE 5

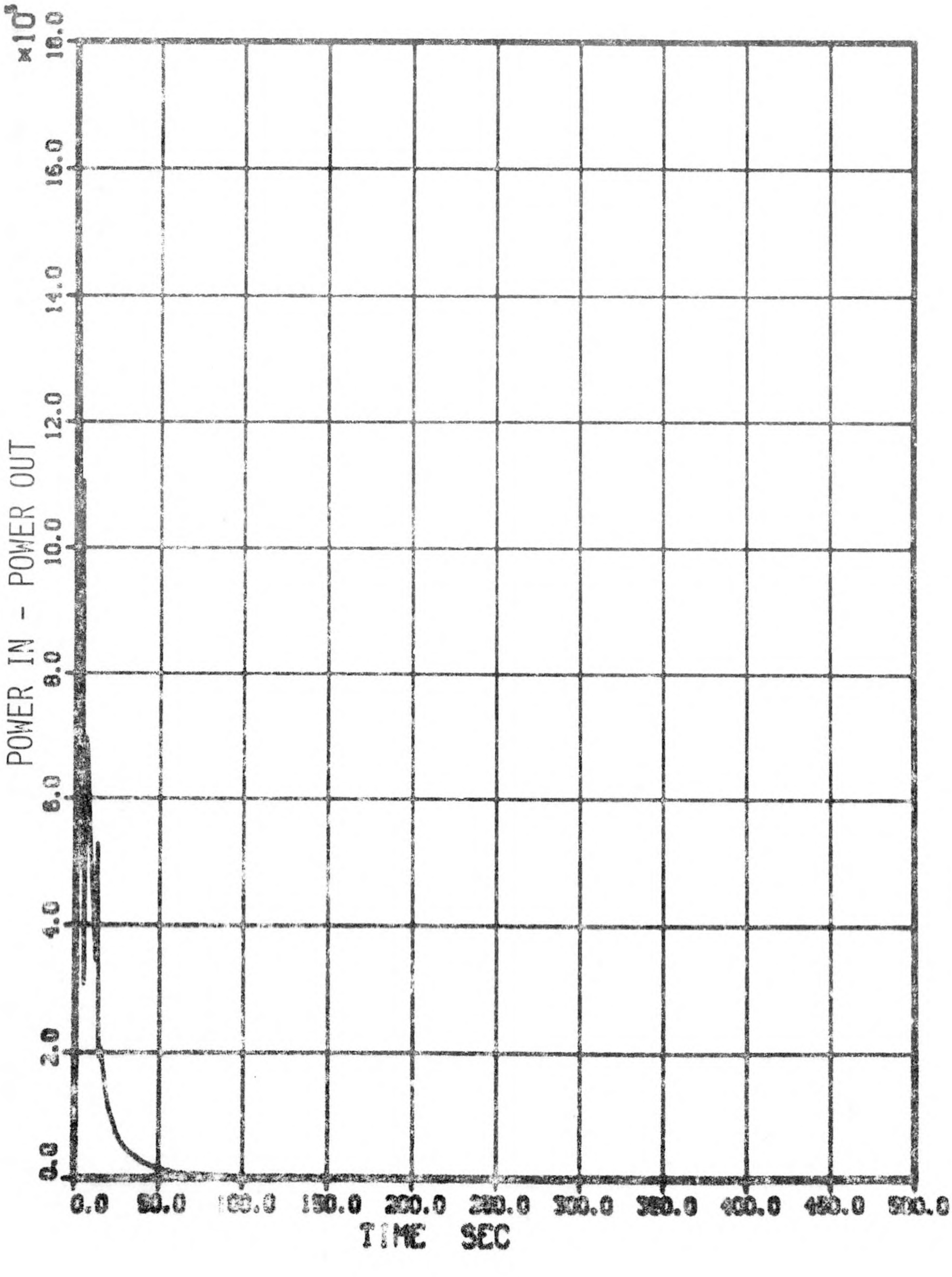


FIGURE 3.6 POWER BALANCE FOR CASE 6

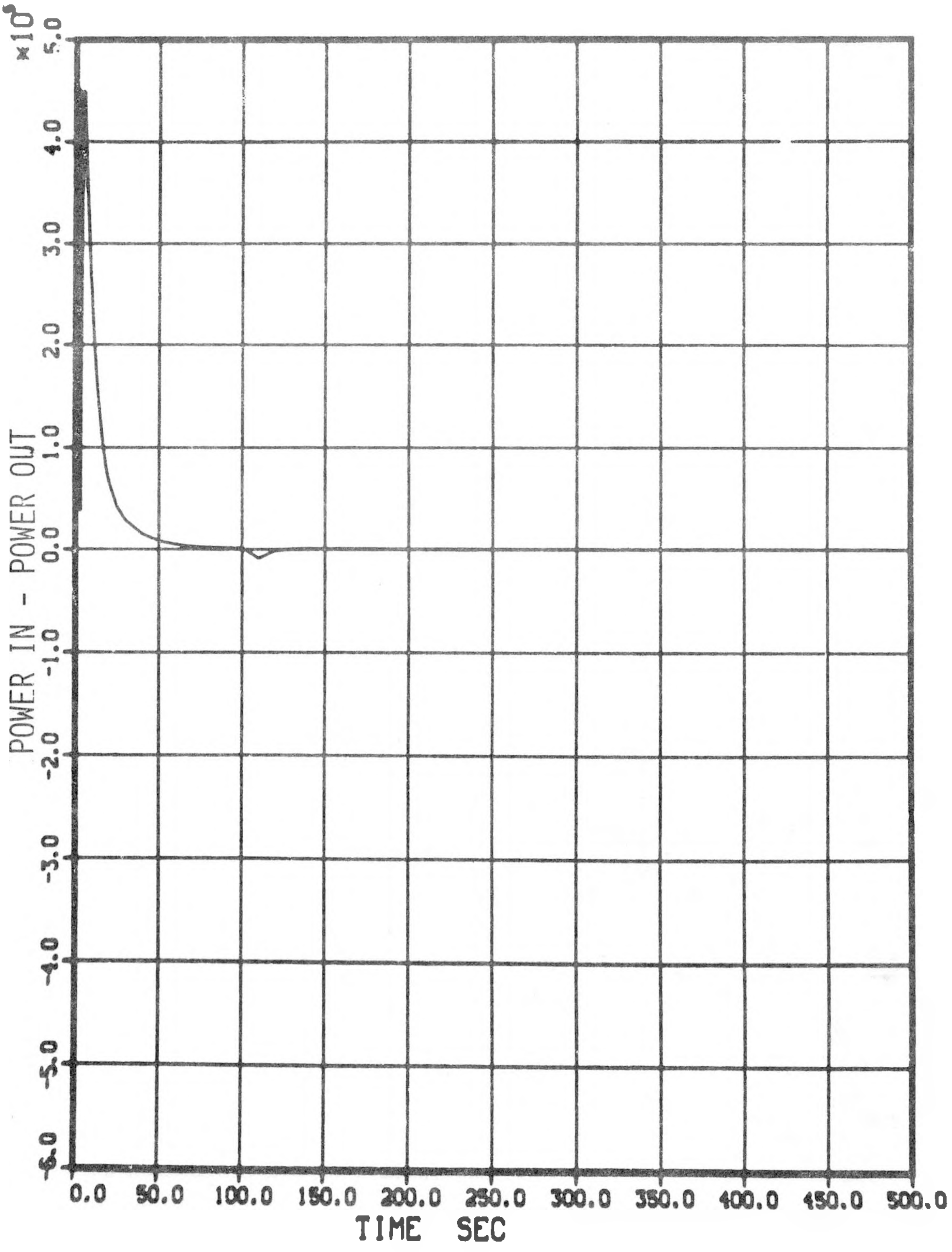


FIGURE 3.7 POWER BALANCE FOR CASE 7

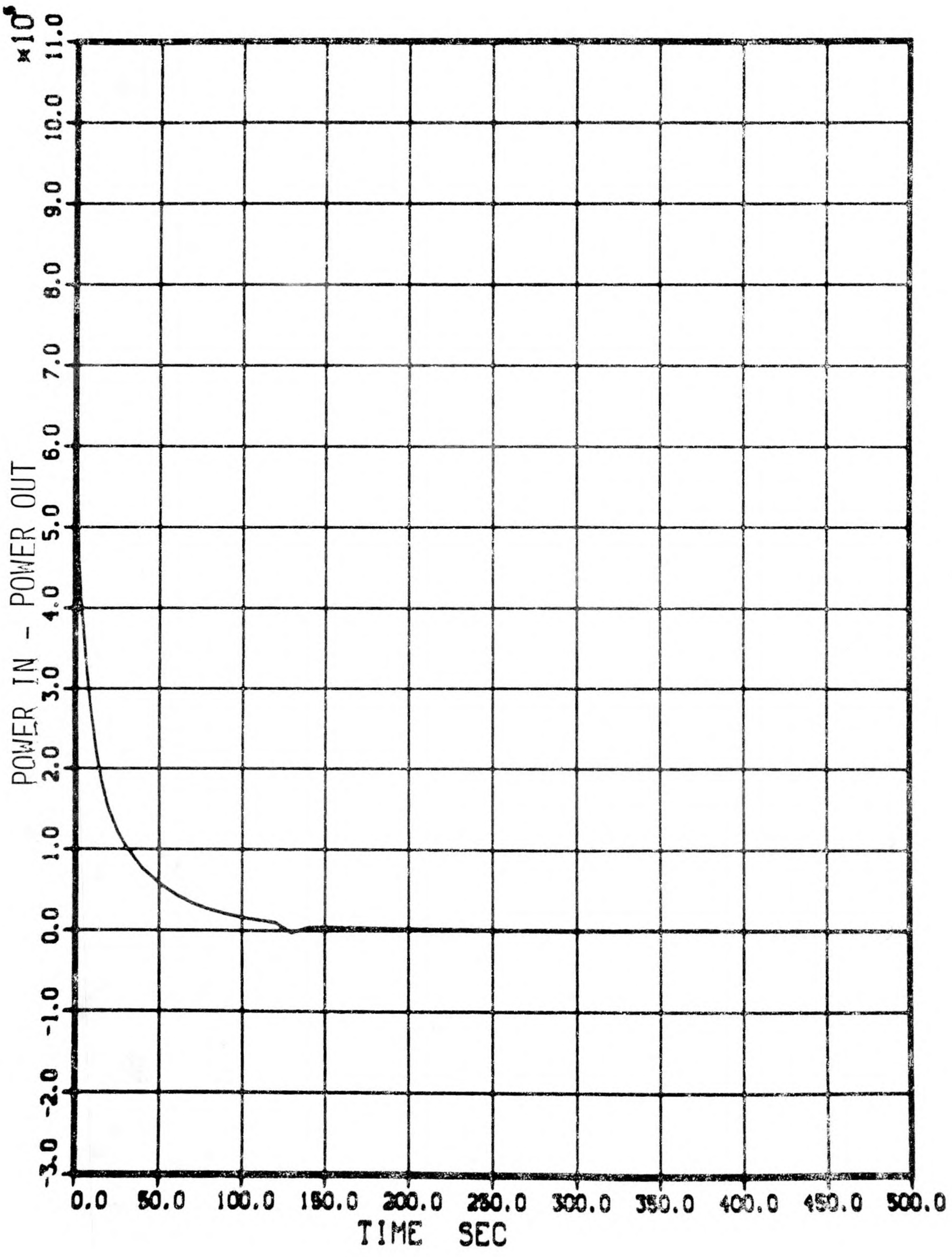


FIGURE 3.8 - POWER BALANCE FOR CASE 8

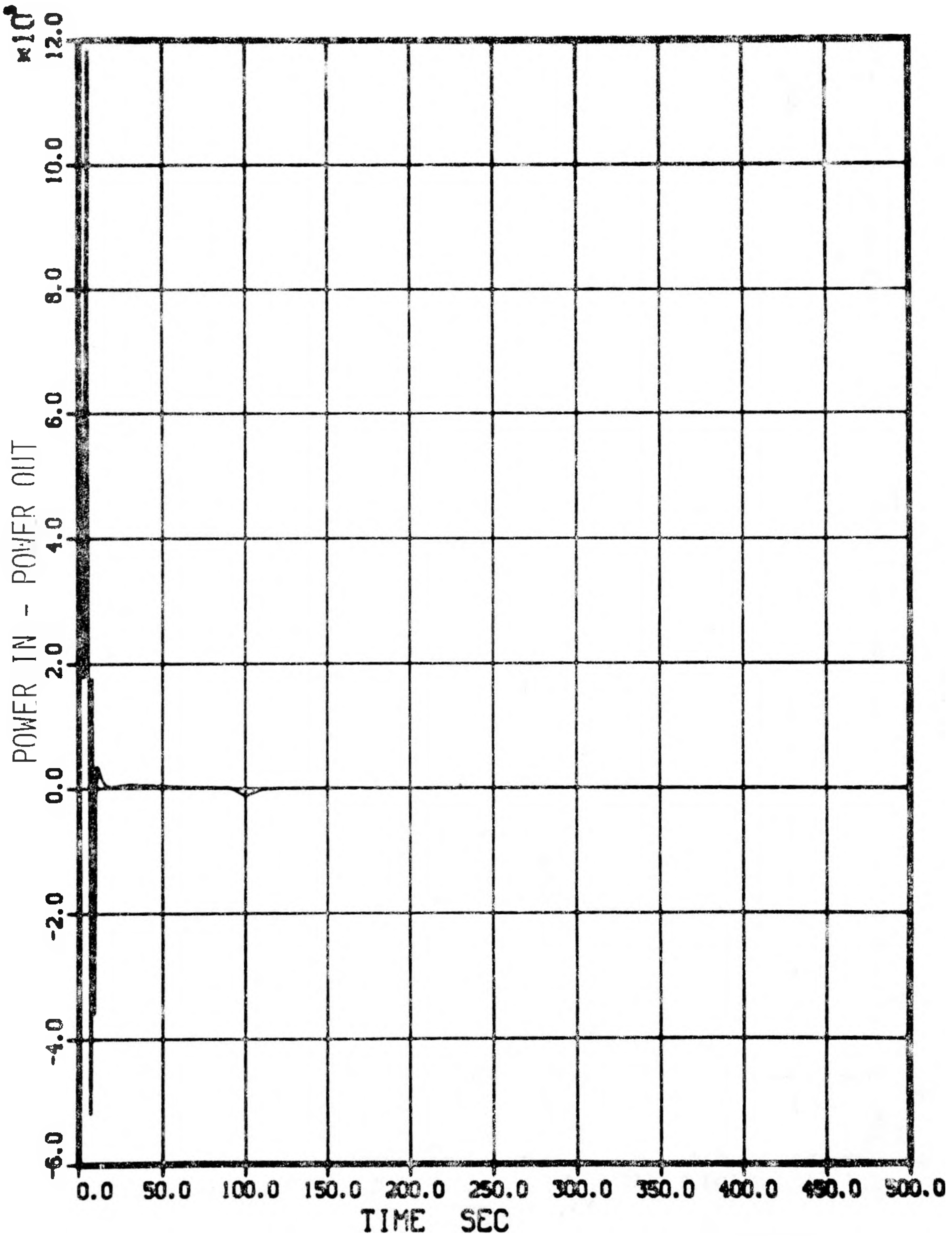


FIGURE 3.9 - POWER BALANCE FOR CASE 9

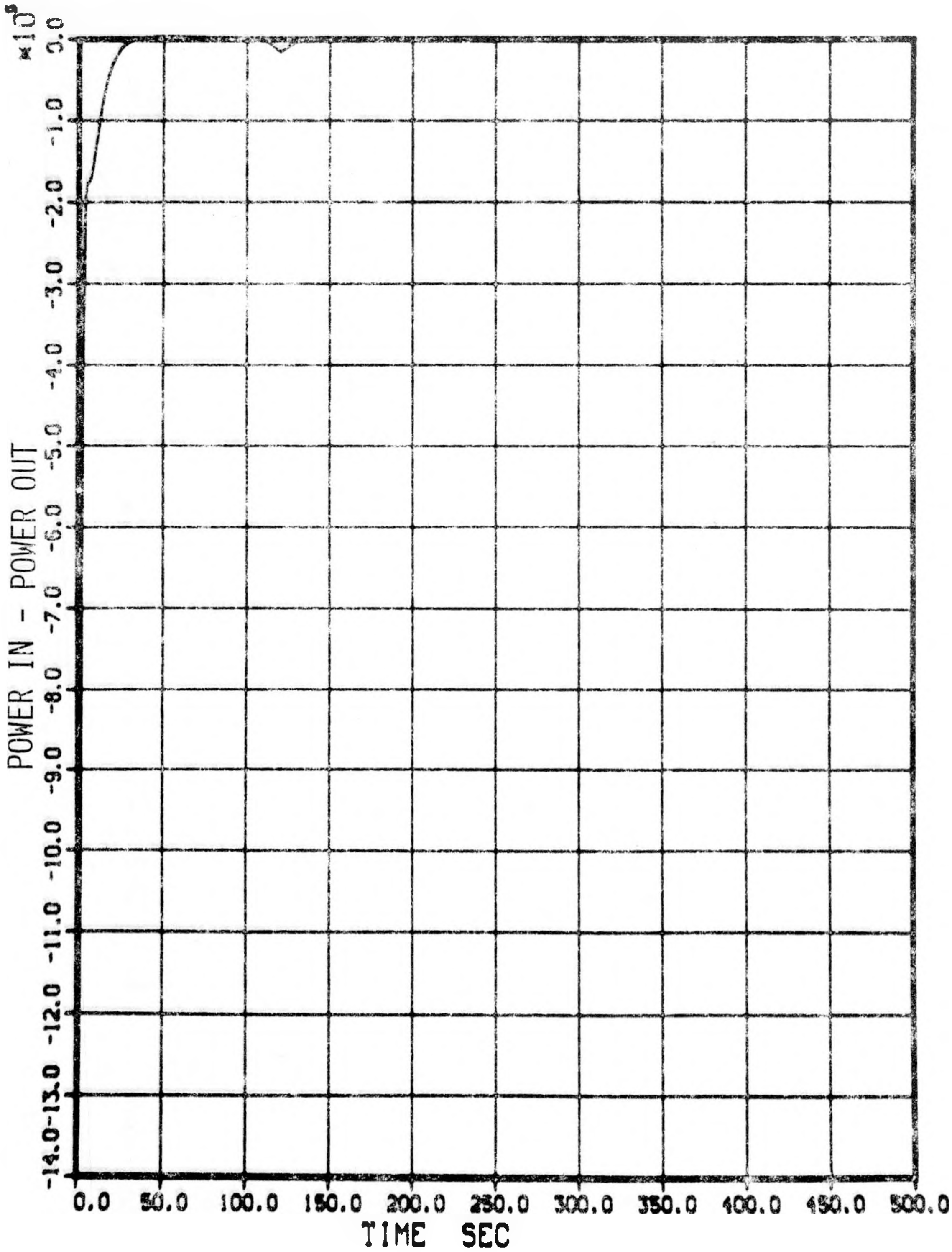


FIGURE 3.10 - AVG PRESS PSI
VOL - 3, CASE 1

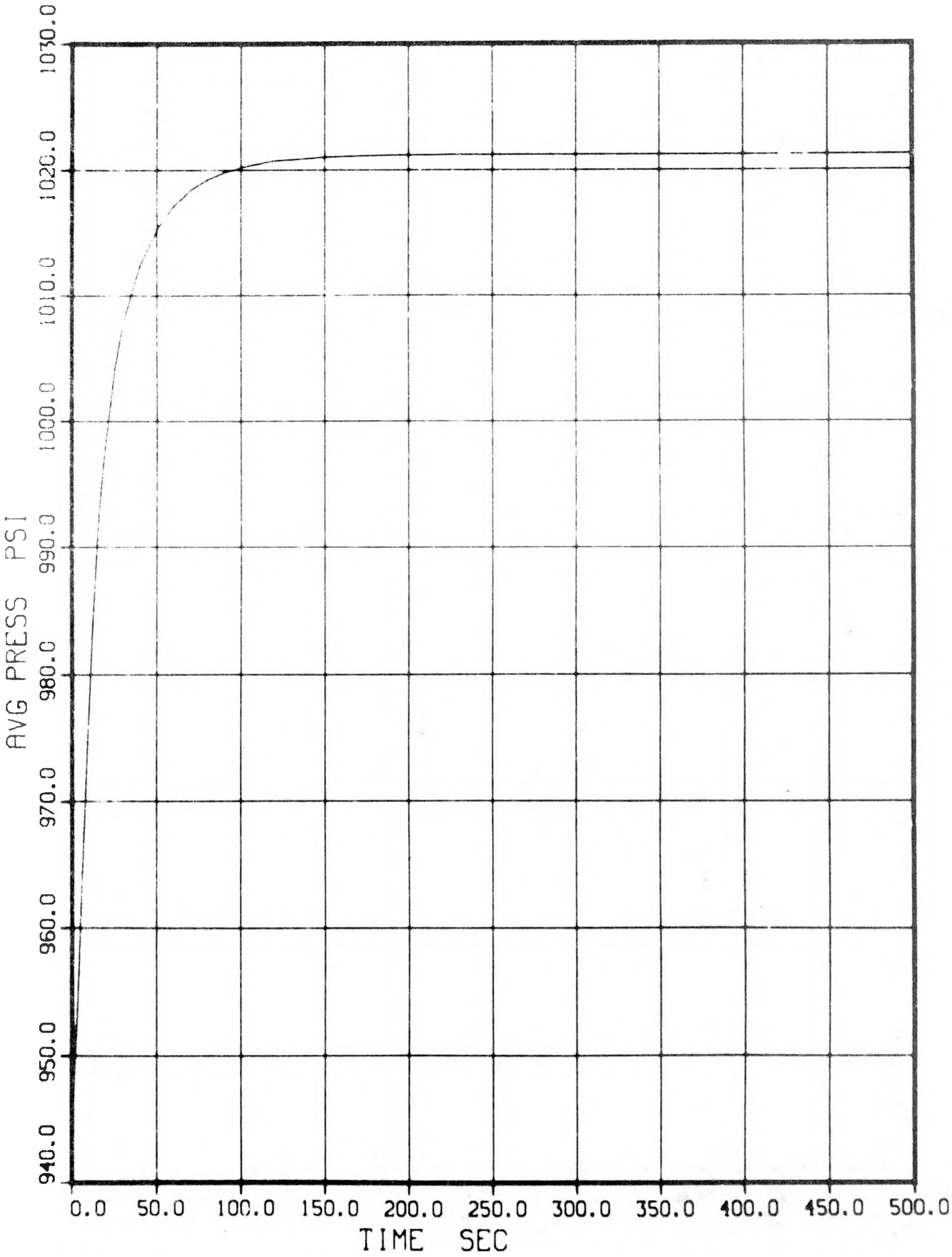


FIGURE 3.11 **AVG PRESS PSI**

VOL - 3, CASE 2

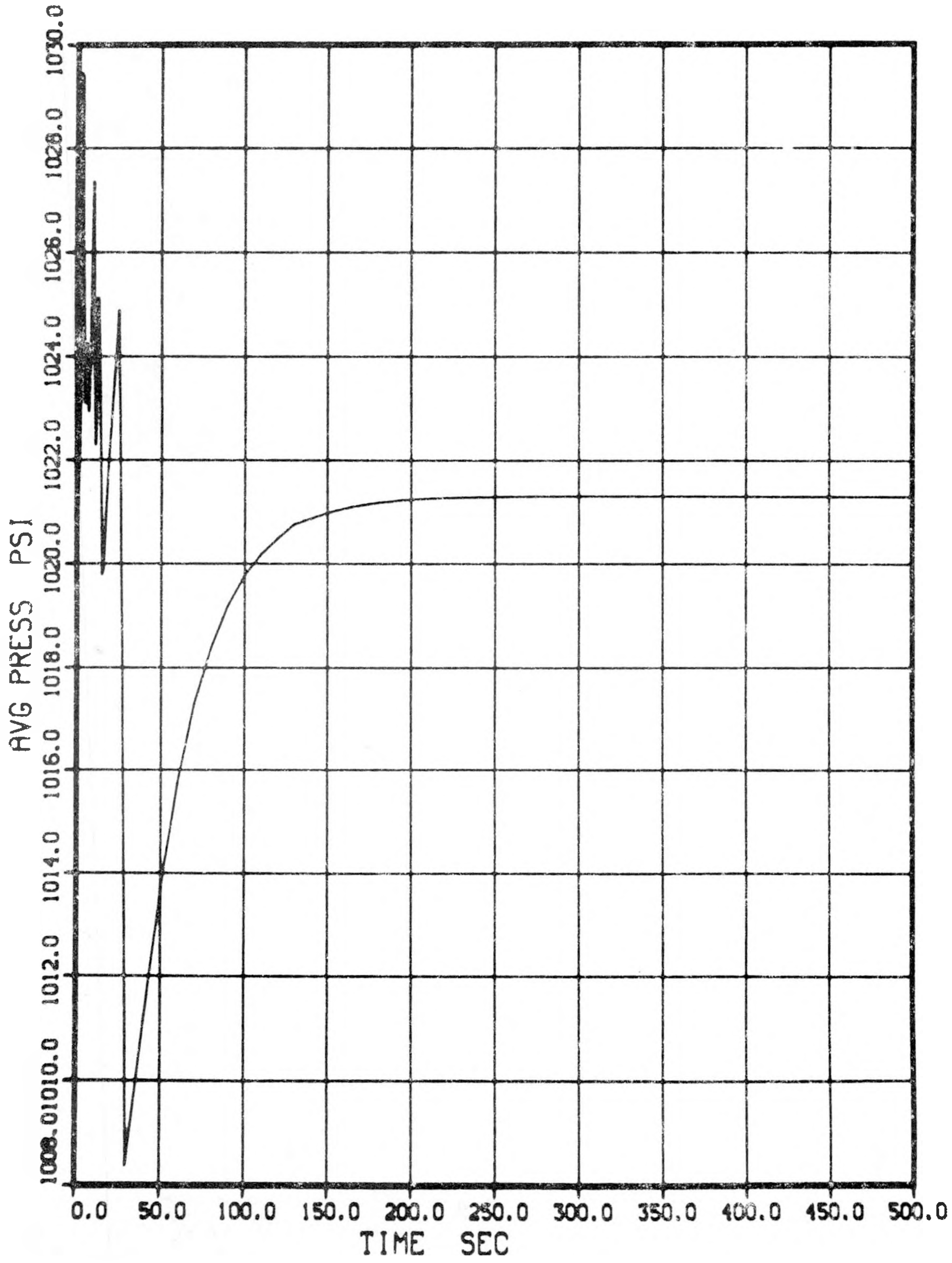


FIGURE 3.12 - AVG PRESS PSI

VOL - 3, CASE 3

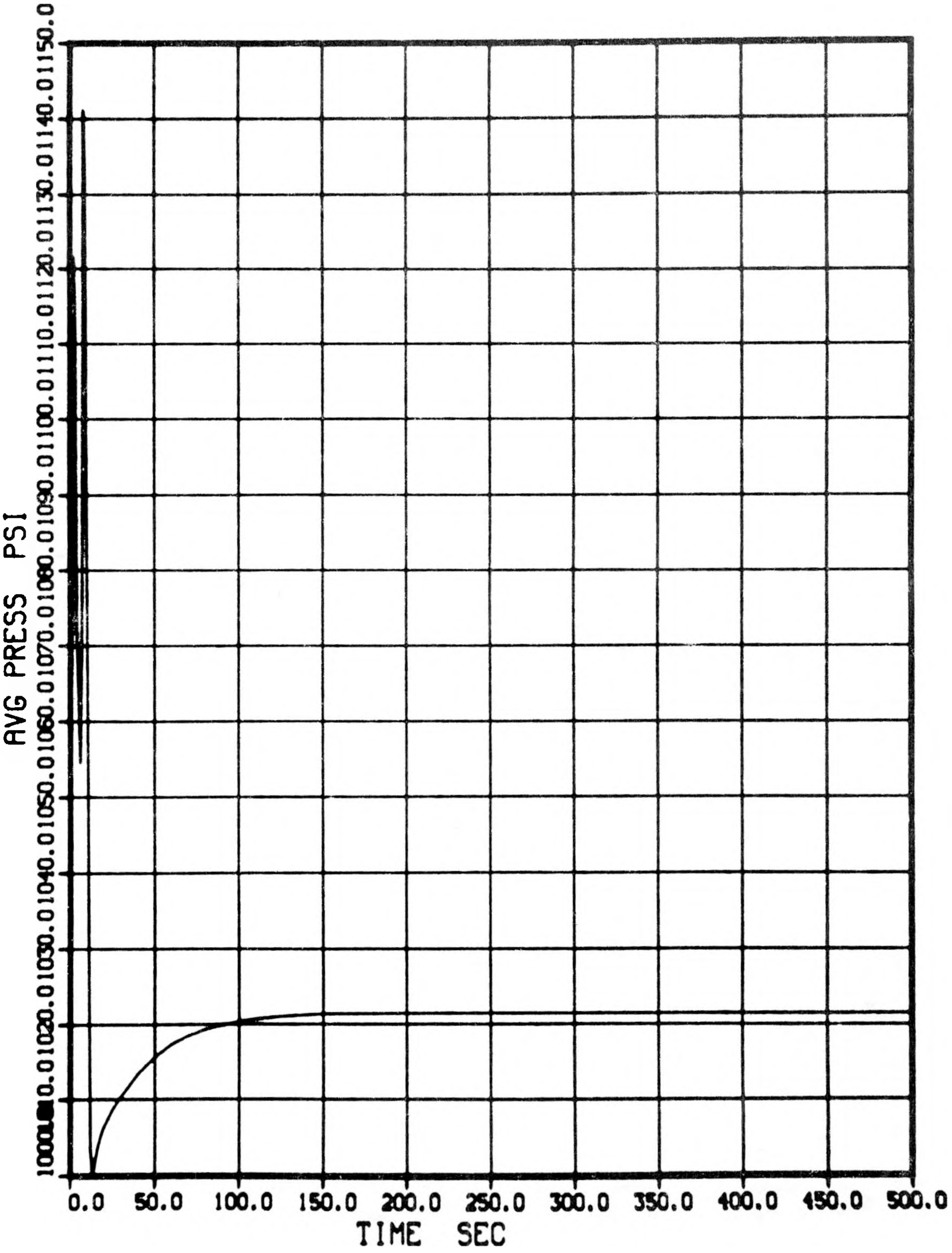


FIGURE 3.13 - AVG PRESS PSI

VOL = 3, CASE 4

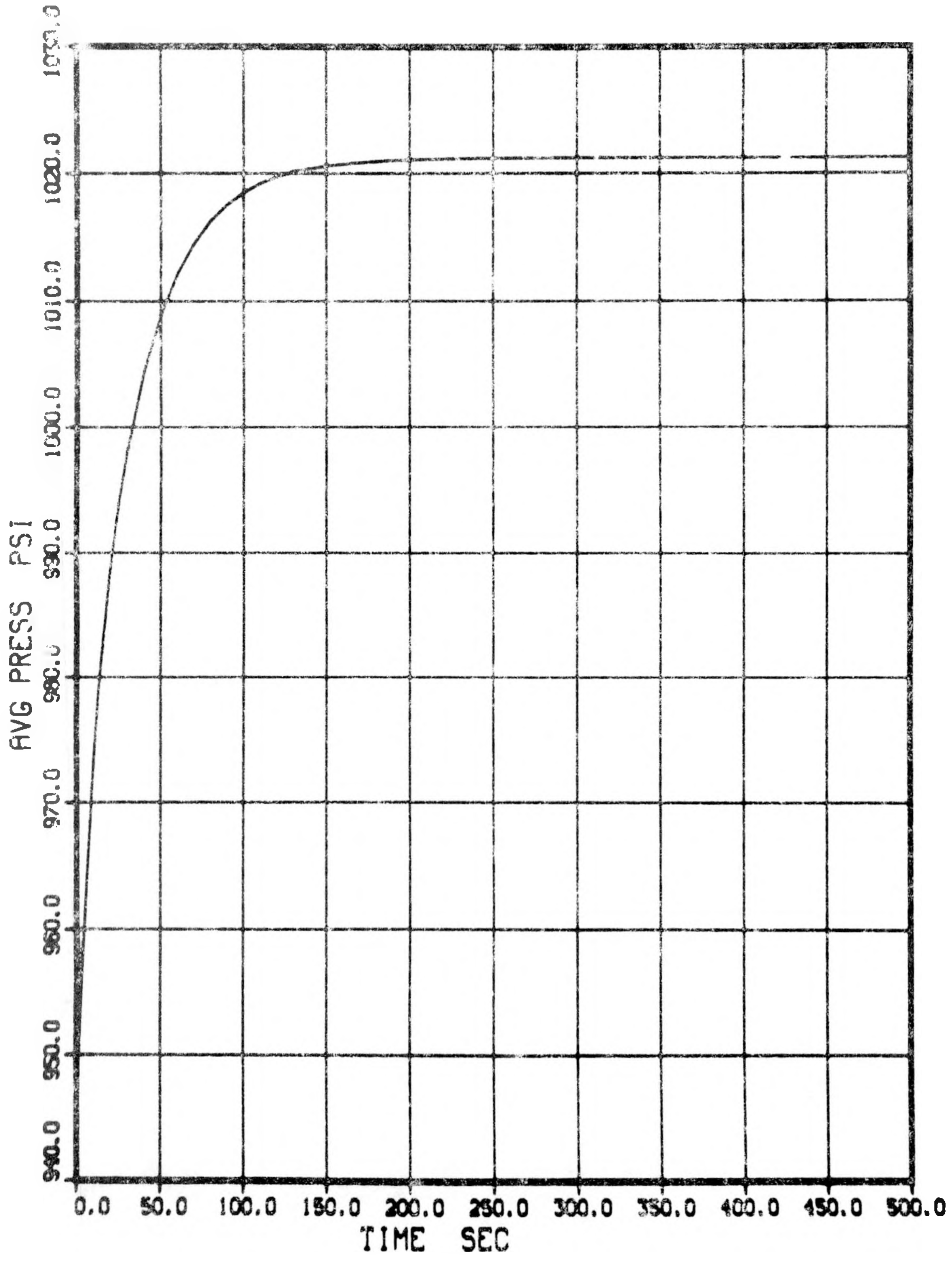


FIGURE 3.14 -AVG PRESS PSI

VOL - 3, CASE 5

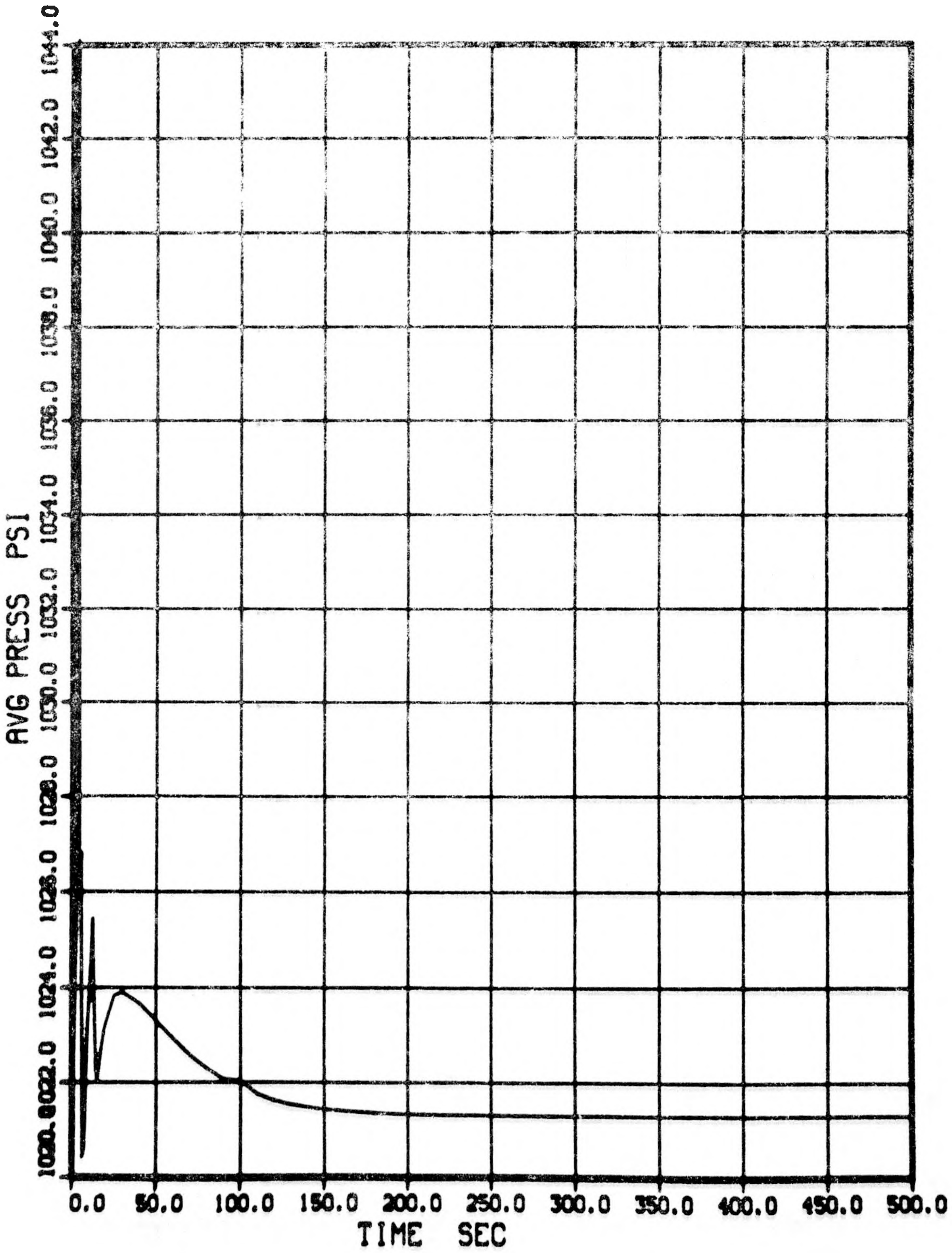


FIGURE 3.15 - AVG PRESS PSI
VOL - 3, CASE 6

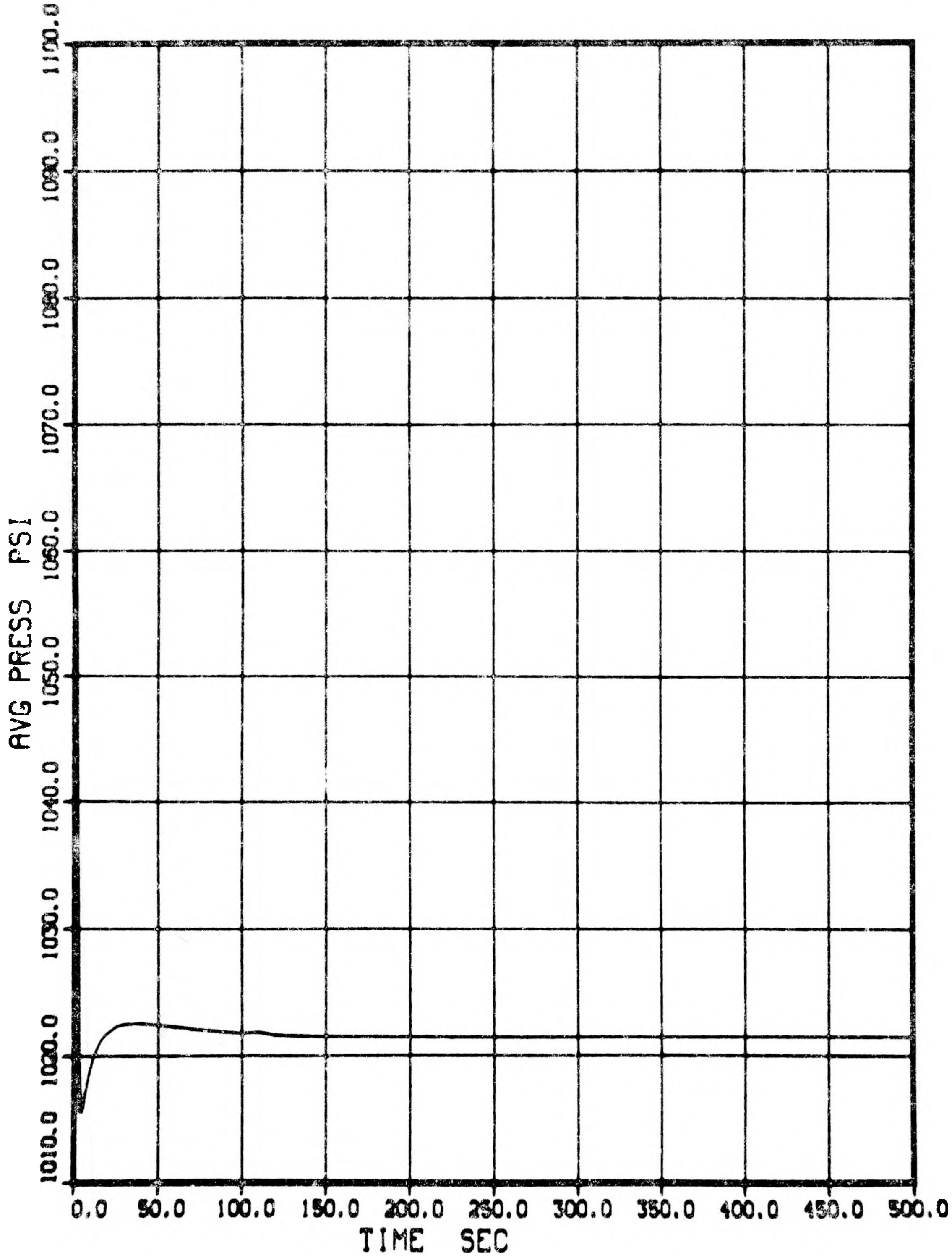


FIGURE 3.16 - AVG PRESS PSI

VOL - 3, CASE 7

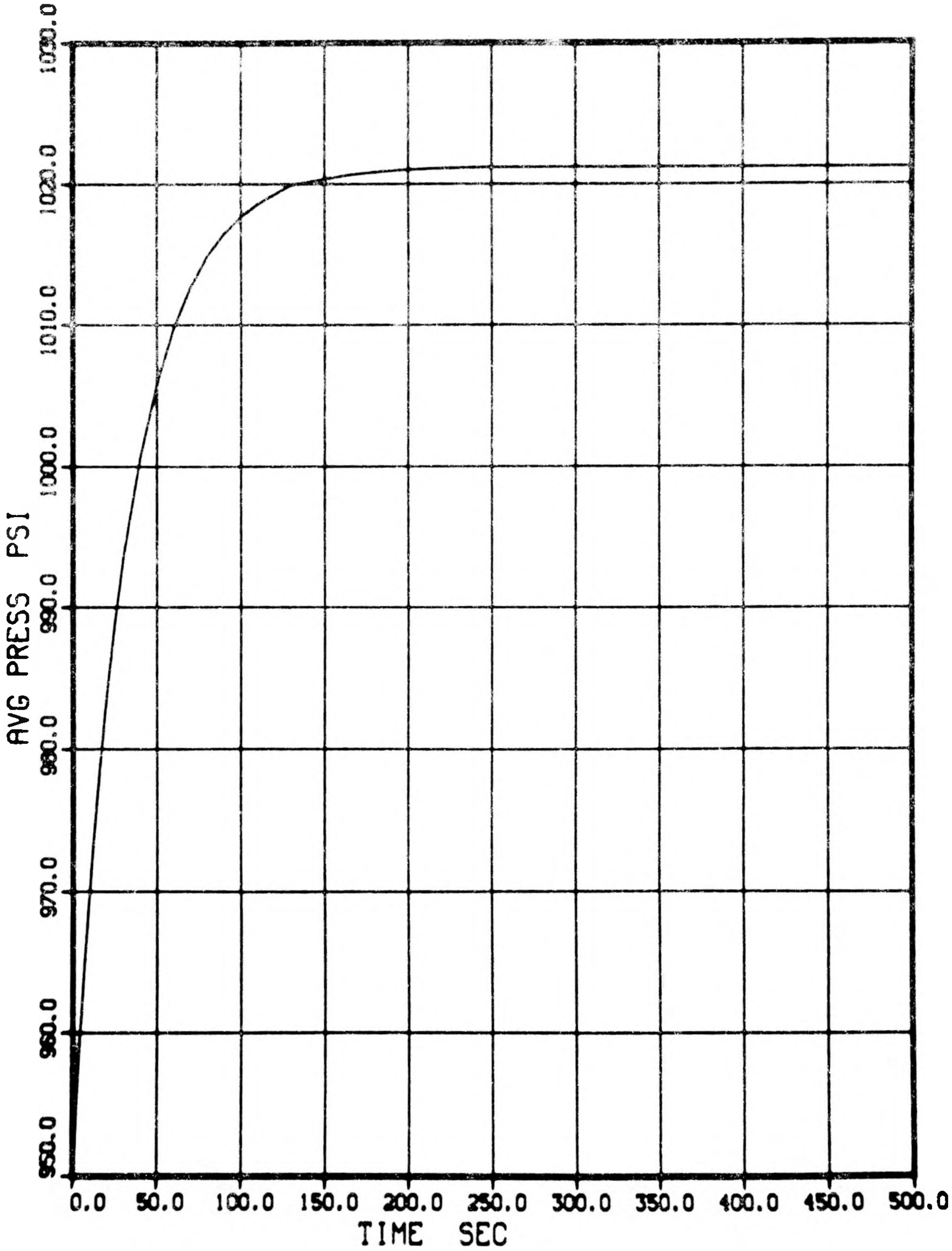


FIGURE 3.17 - AVG PRESS PSI

VOL - 3, CASE 8

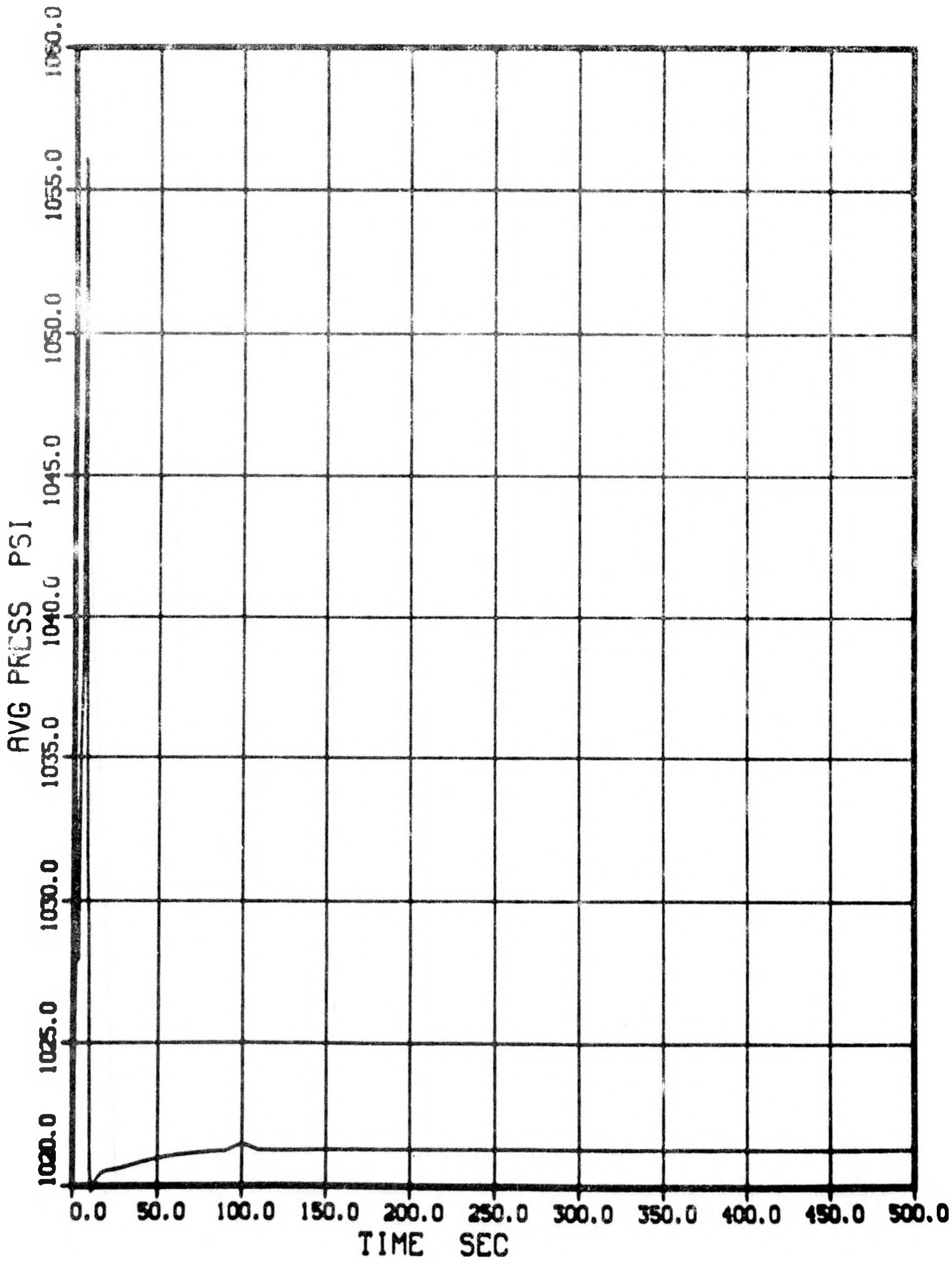
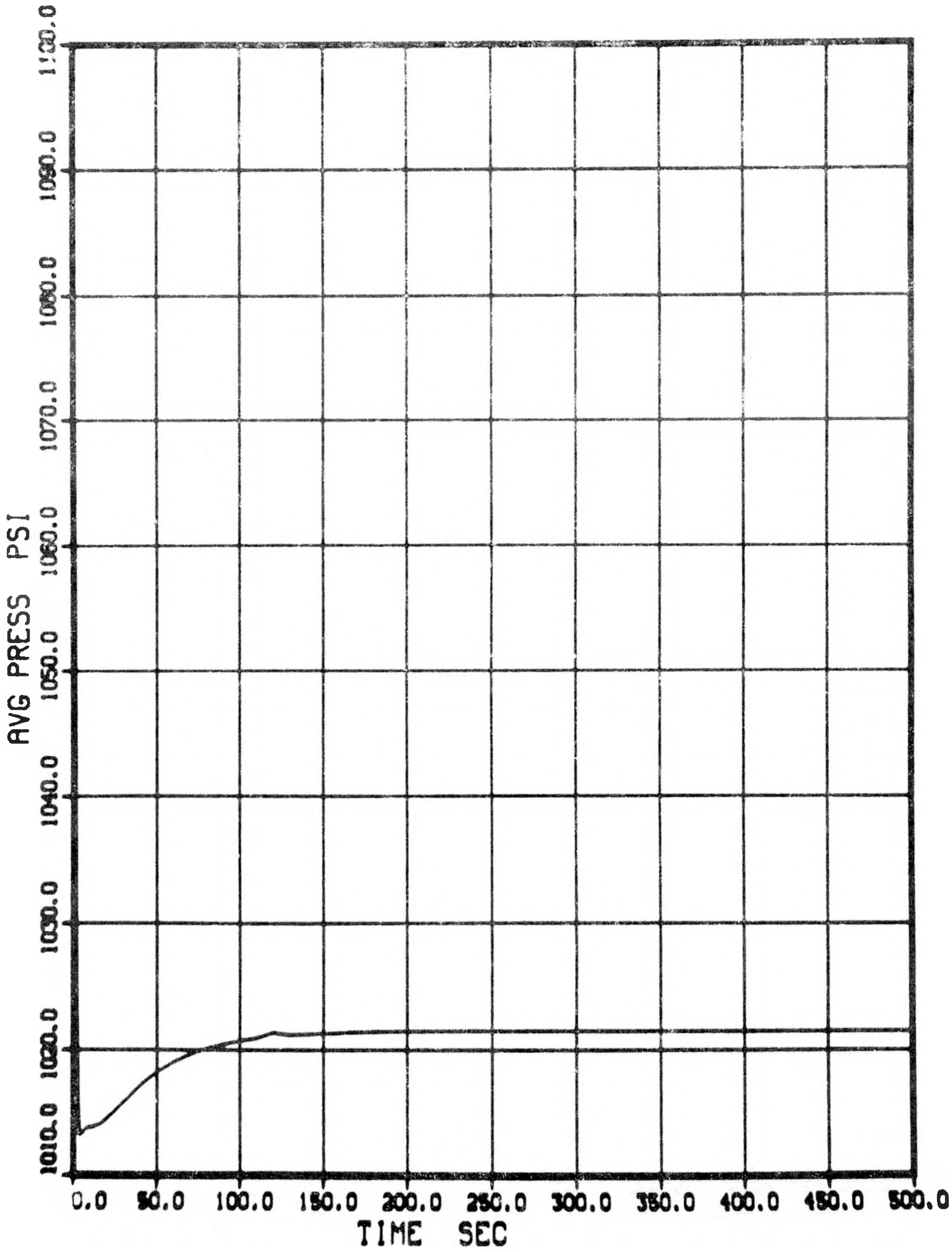


FIGURE 3.18 - AVG PRESS PSI
VOL - 3, CASE 9



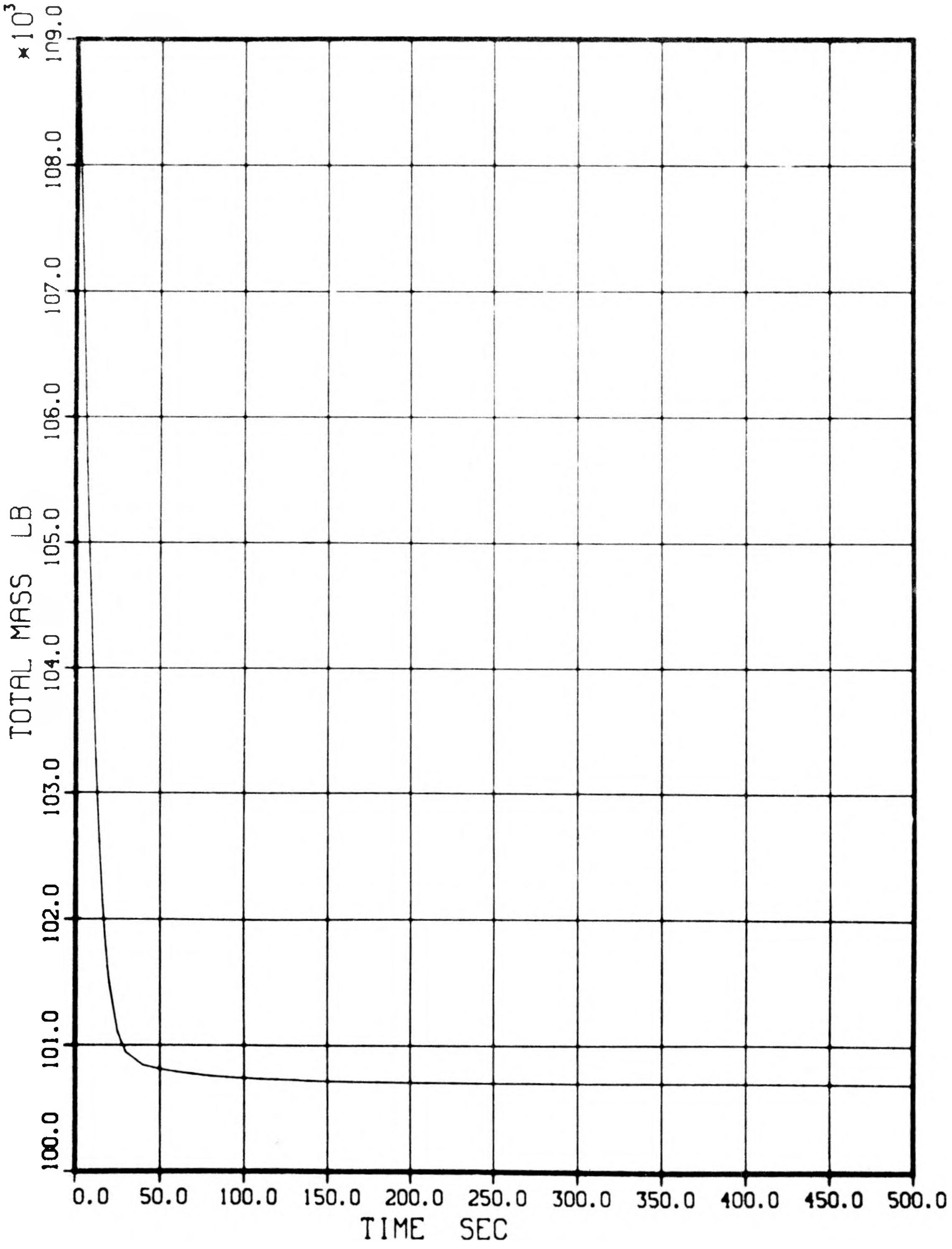


FIGURE 3.19 - TOTAL MASS LB
VOL - 10, CASE 1

FIGURE 3.20 - **TOTAL MASS LB**

VOL - 10, CASE 2

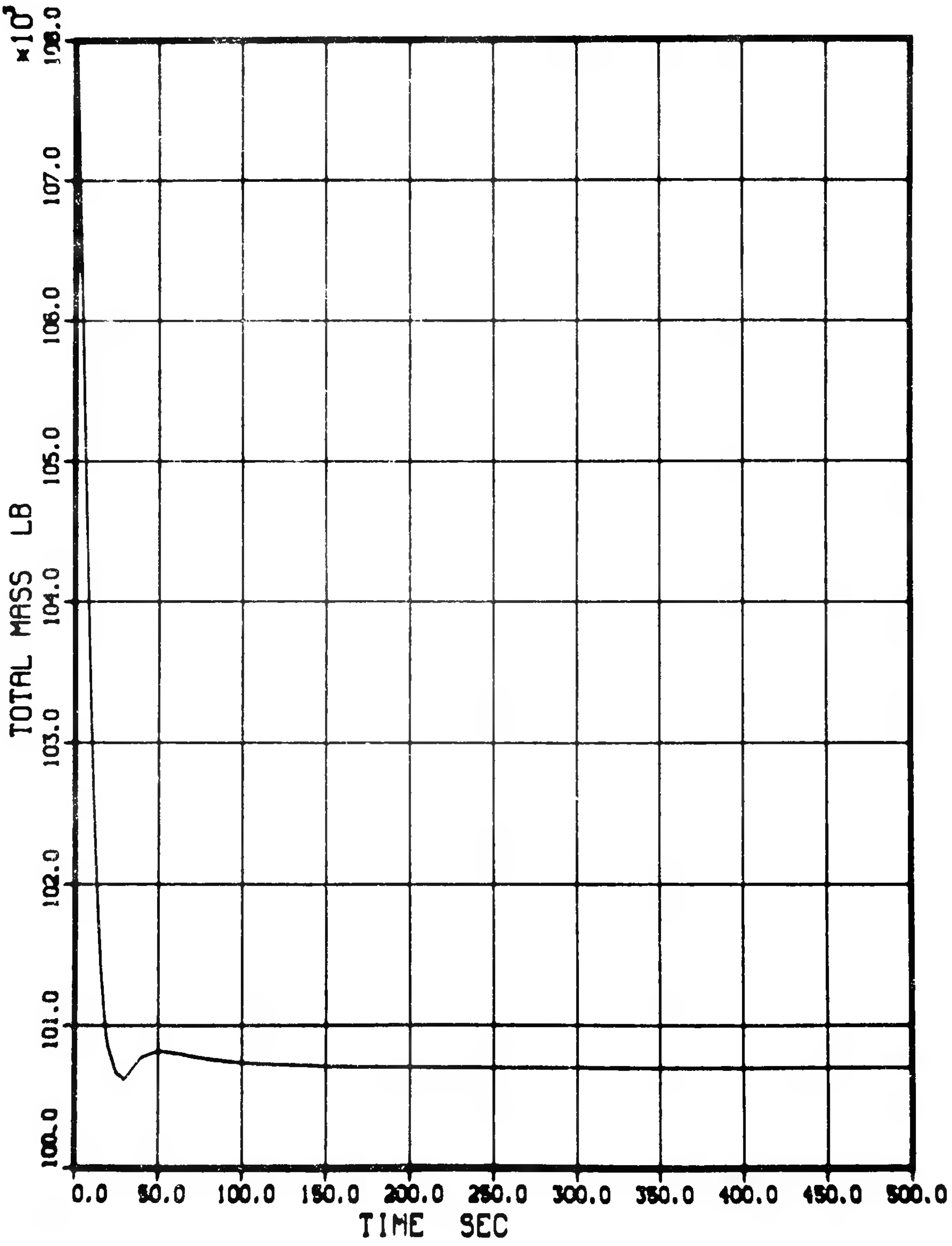


FIGURE 3.21 - TOTAL MASS LB

VOL - 10, CASE 3

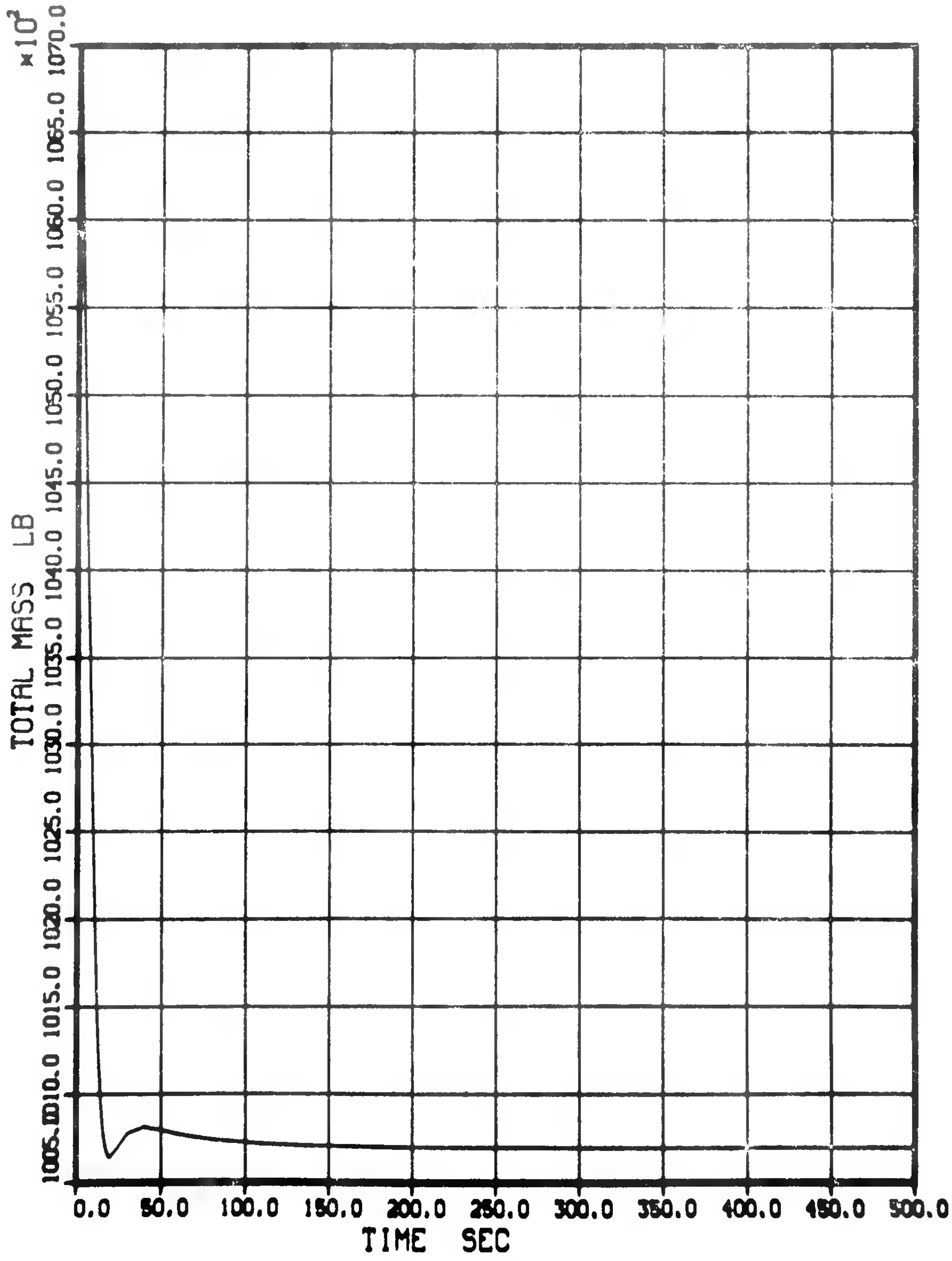


FIGURE 3.22 - TOTAL MASS LB

VOL - 10, CASE 4

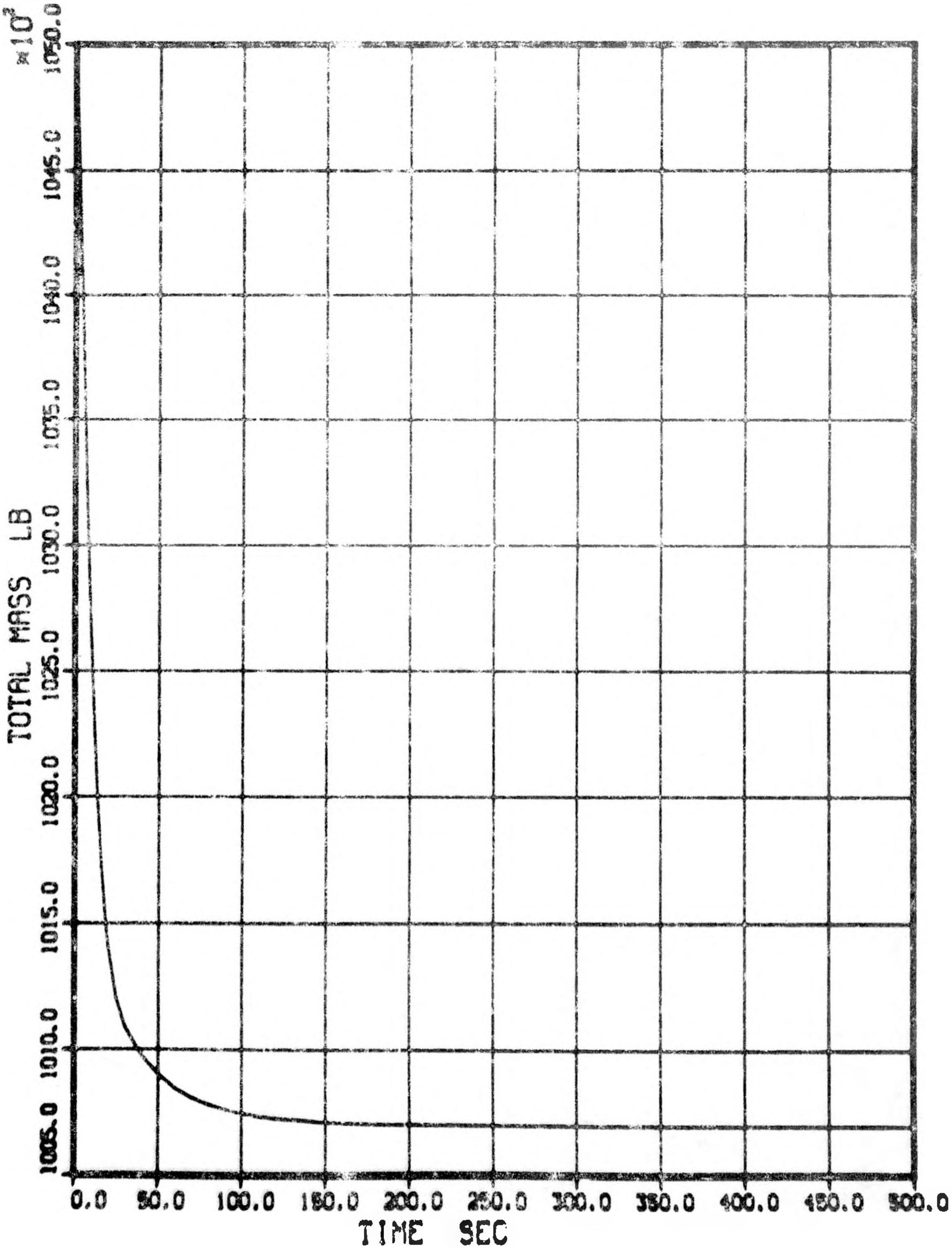


FIGURE 3.23 - TOTAL MASS LB

VOL - 10, CASE 5

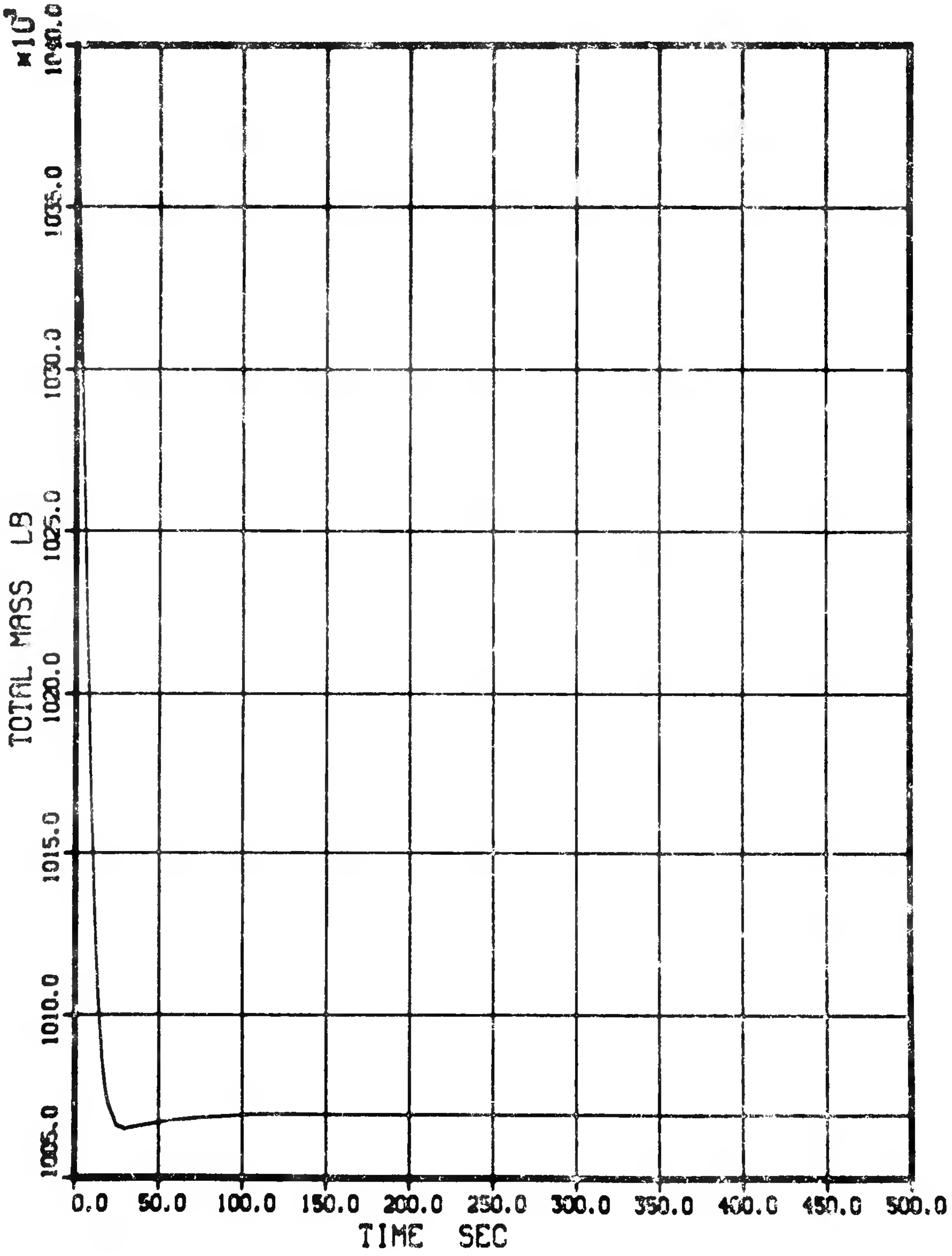


FIGURE 3.24 - **TOTAL MASS LB**

VOL - 10, CASE 6

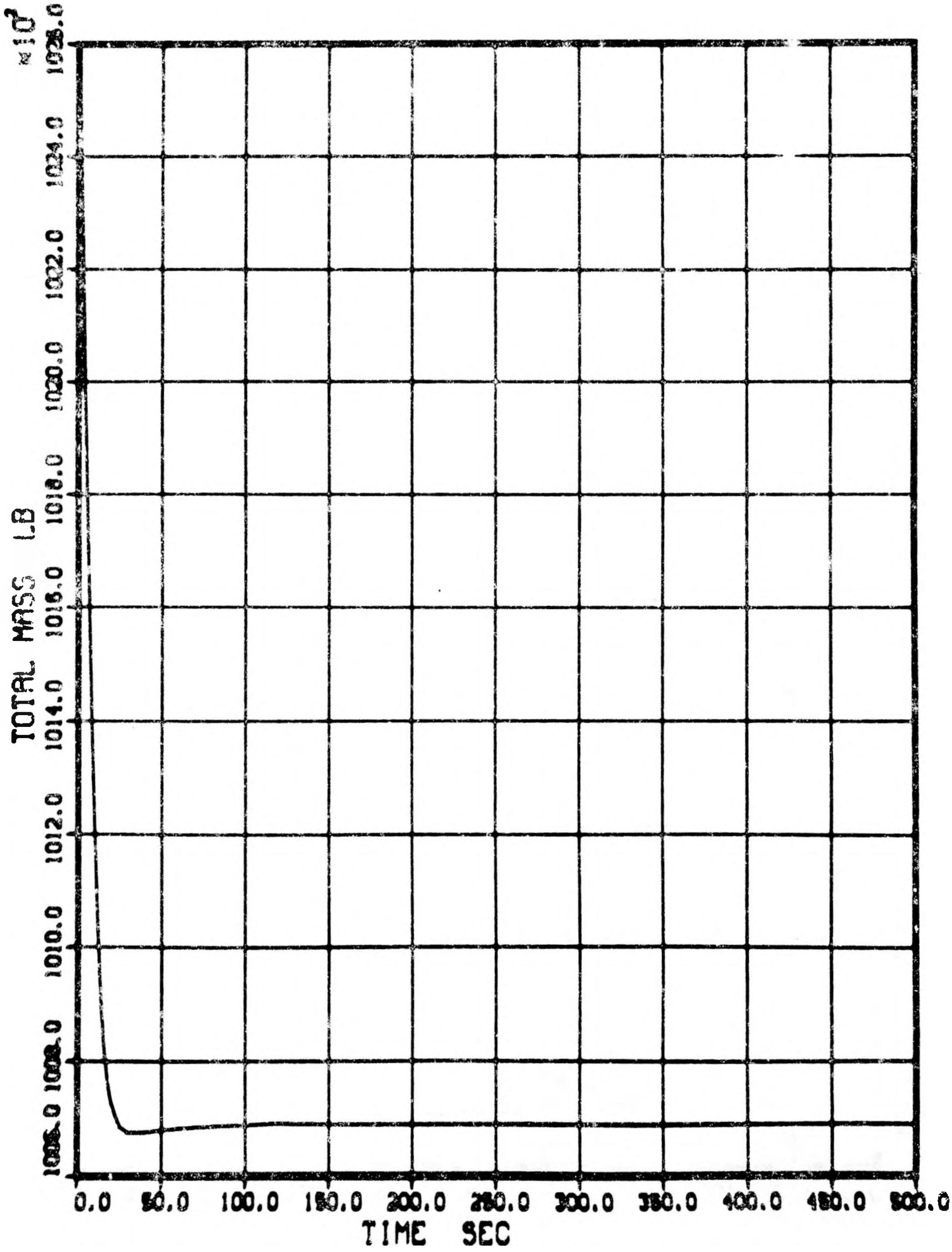


FIGURE 3.25 - TOTAL MASS LB
VOL - 10, CASE 7

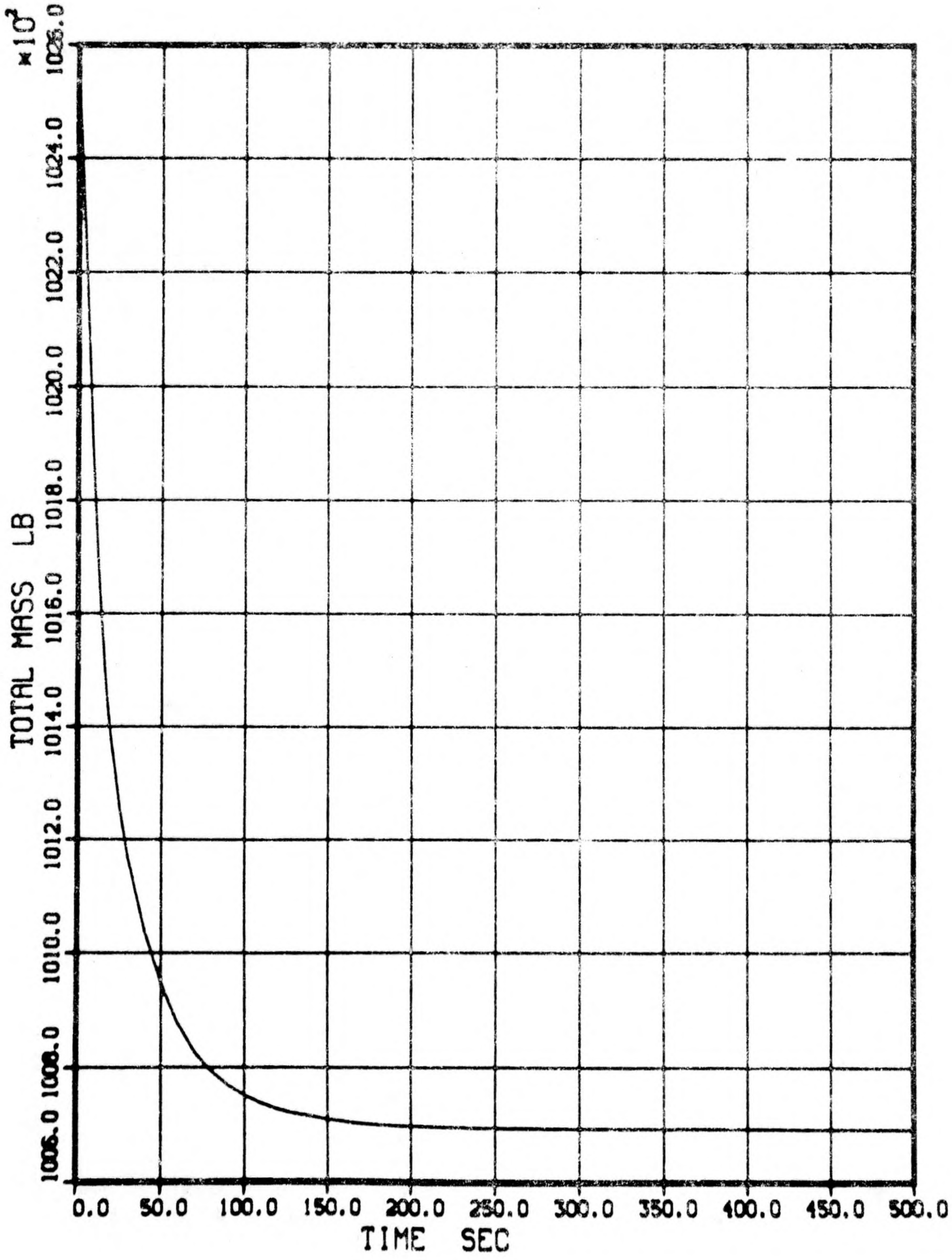


FIGURE 3.26 - **TOTAL MASS LB**

VOL - 10, CASE 8

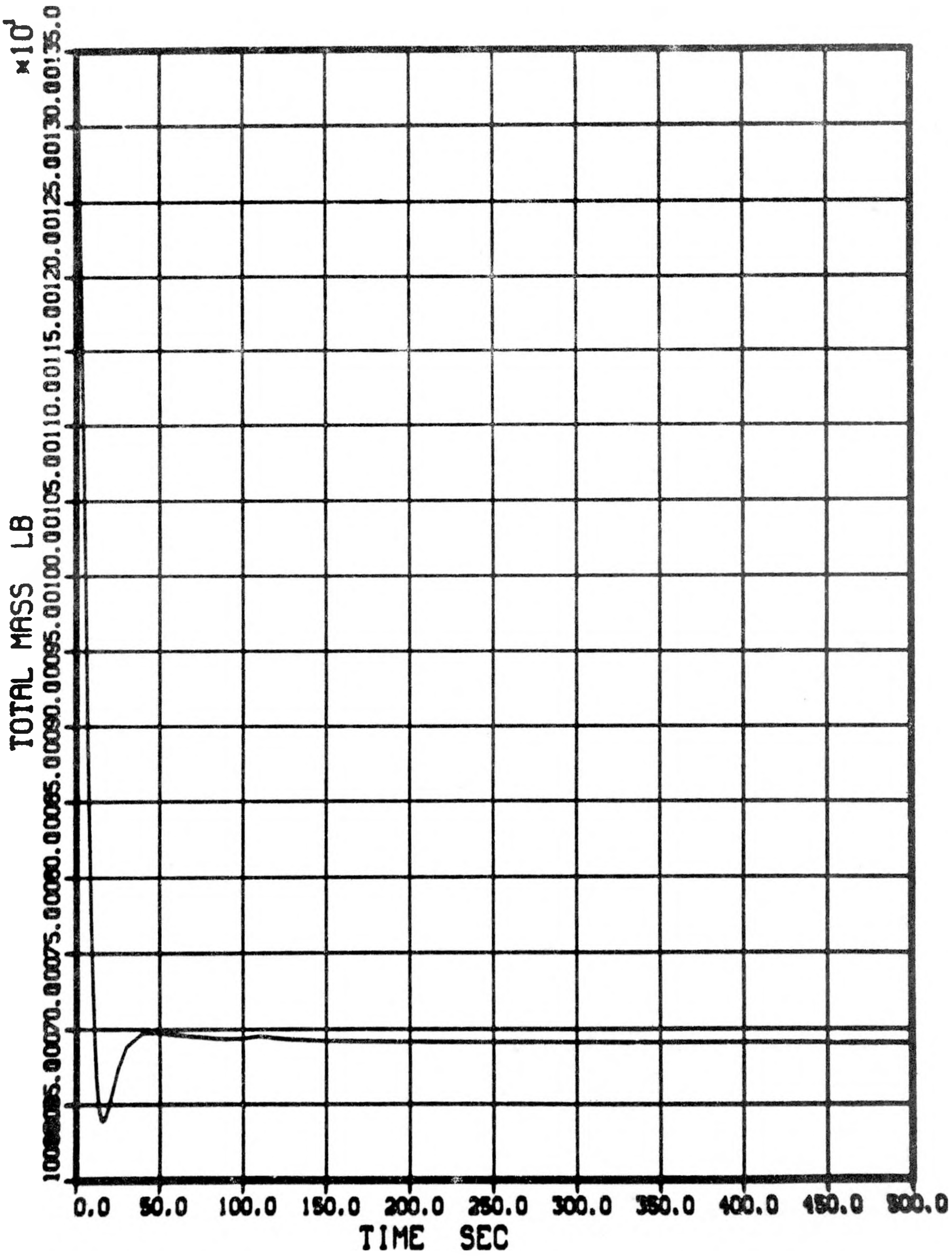


FIGURE 3.27 - **TOTAL MASS LB**
VOL - 10, CASE 9

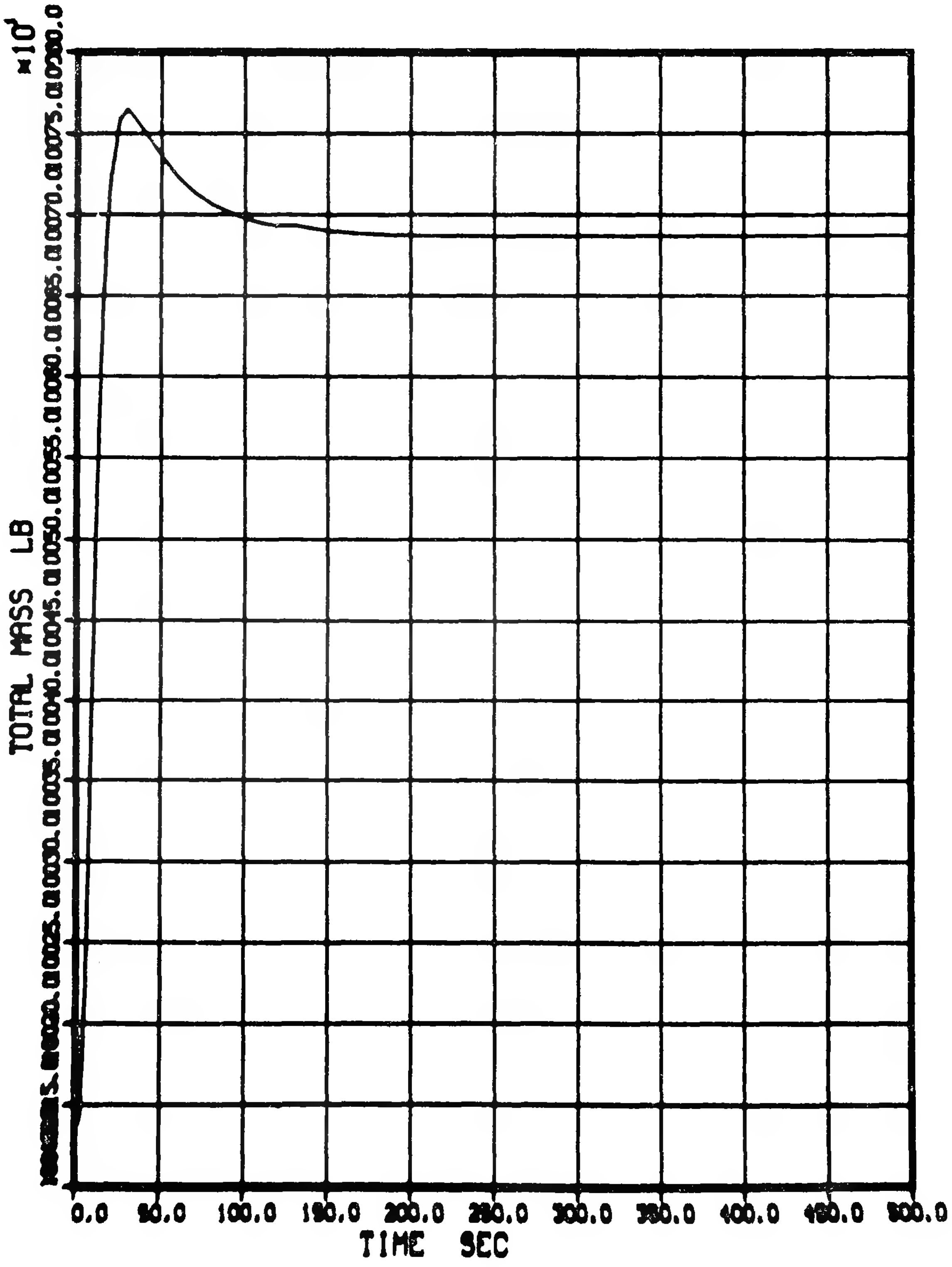


FIGURE 3.28 - TOT ENERGY BTU
VOL - 10, CASE 1

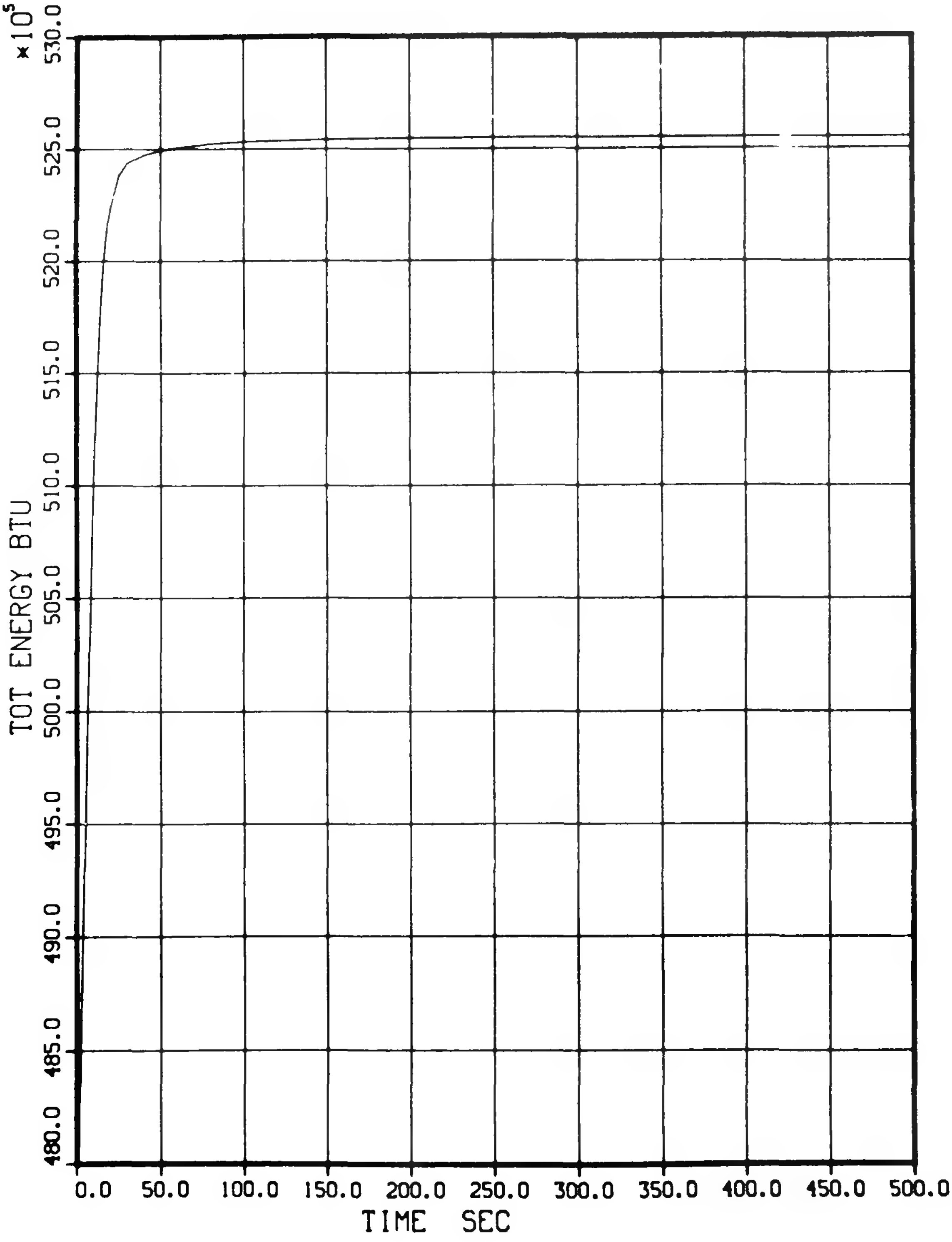


FIGURE 3.29 - **TOT ENERGY BTU**

VOL - 10, CASE 2

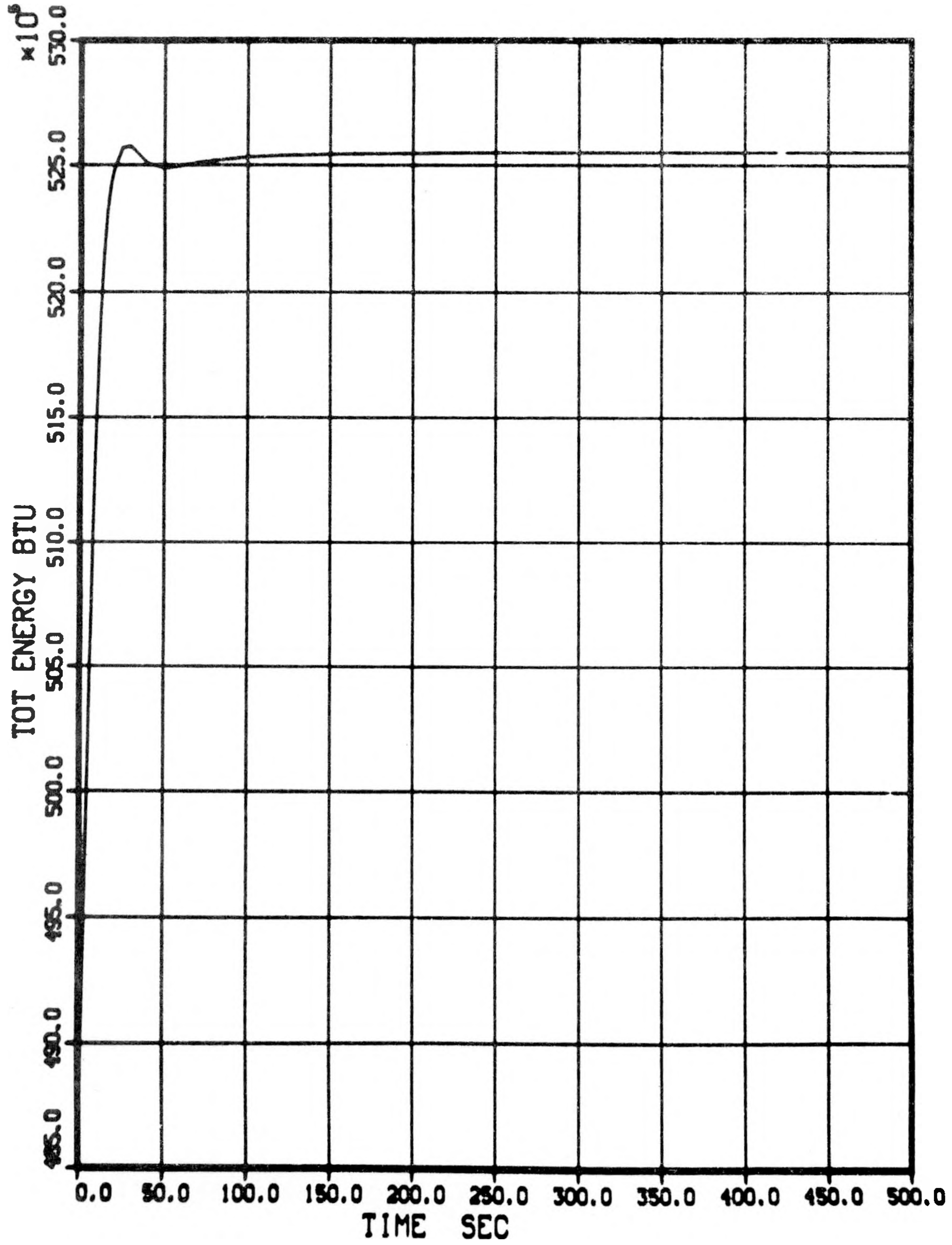


FIGURE 3.30 - TOT ENERGY BTU

VOL = 10, CASE 3

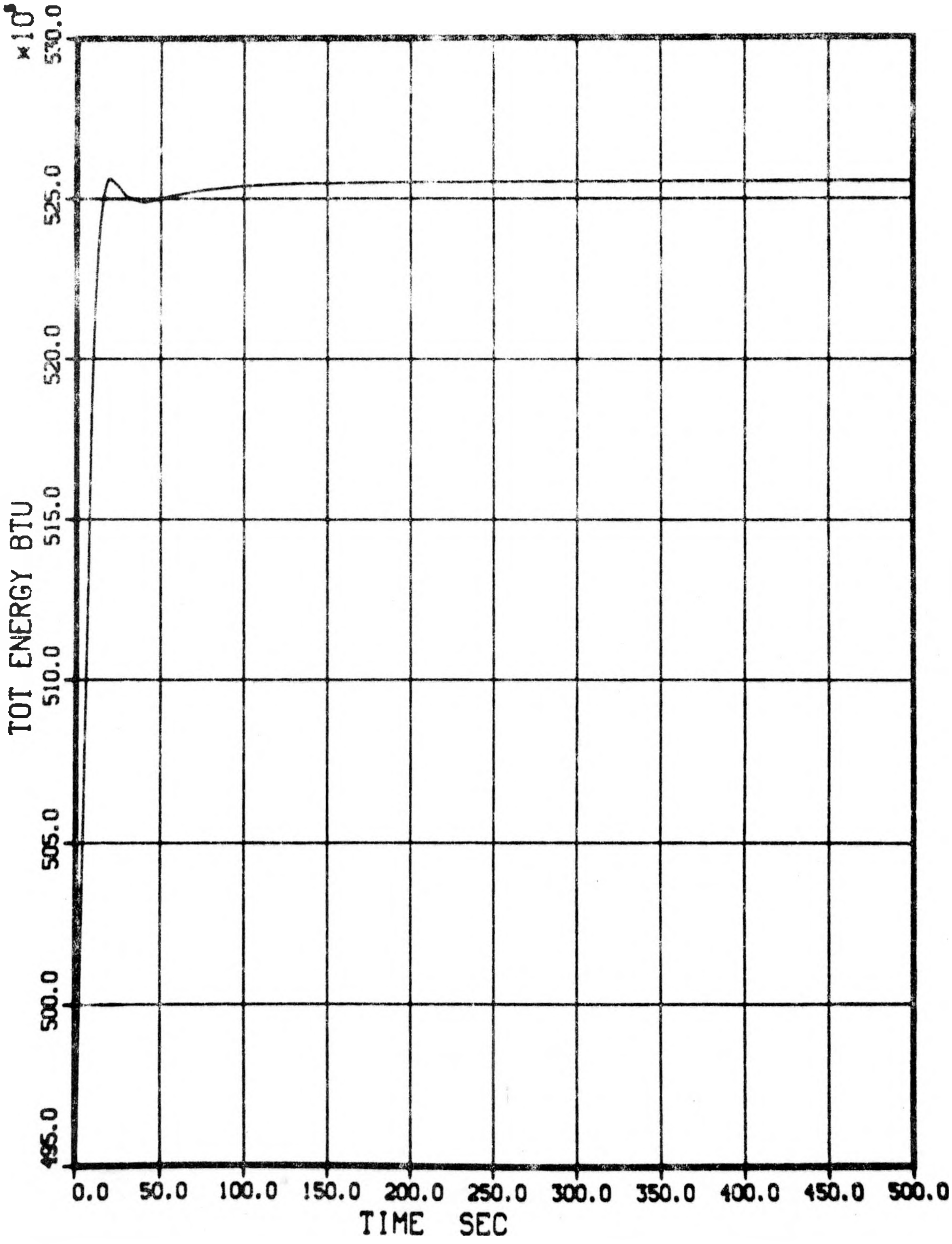


FIGURE 3.31 - TOT ENERGY BTU

VOL = 10, CASE 4

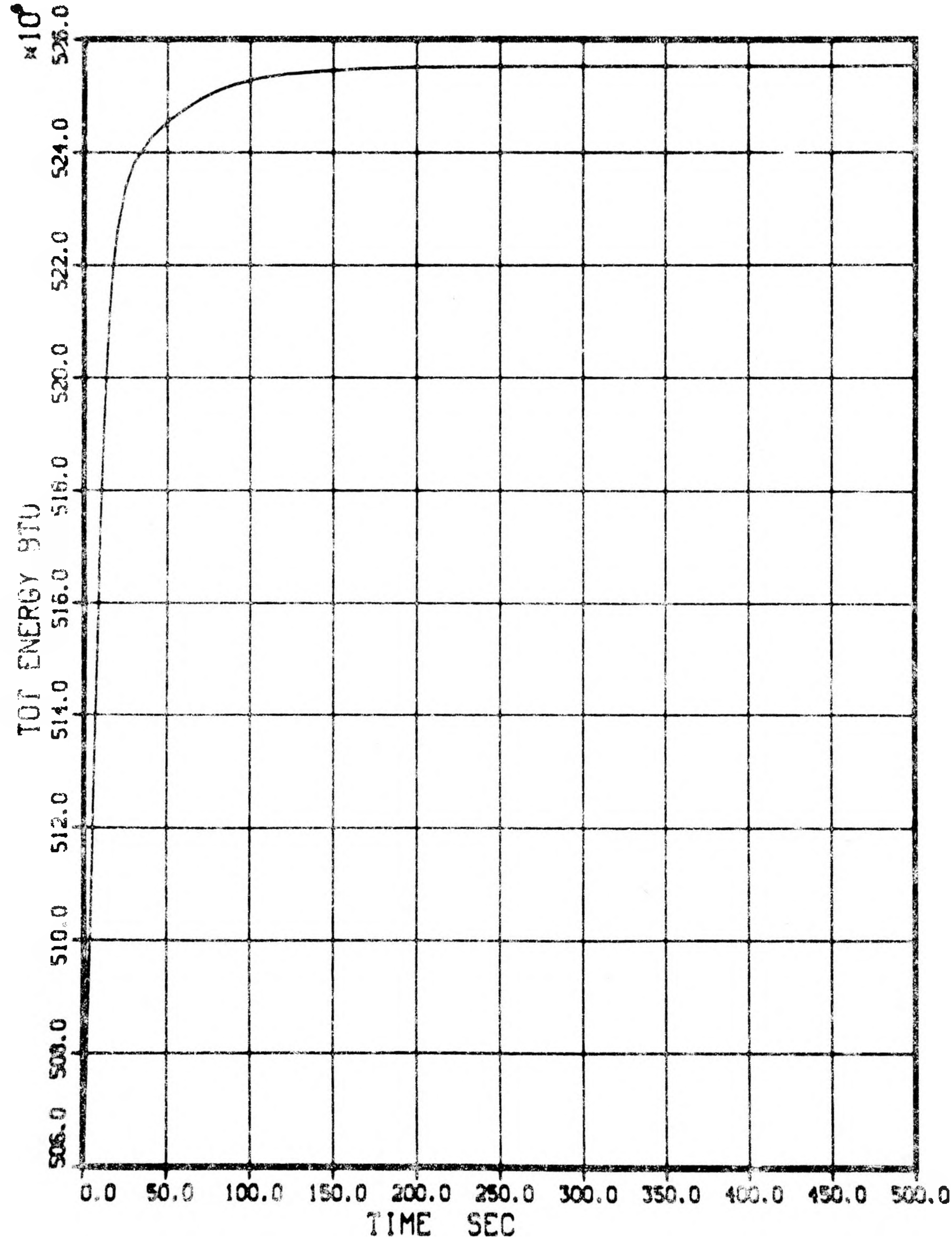


FIGURE 3.32 - TOT ENERGY BTU

VOL - 10, CASE 5

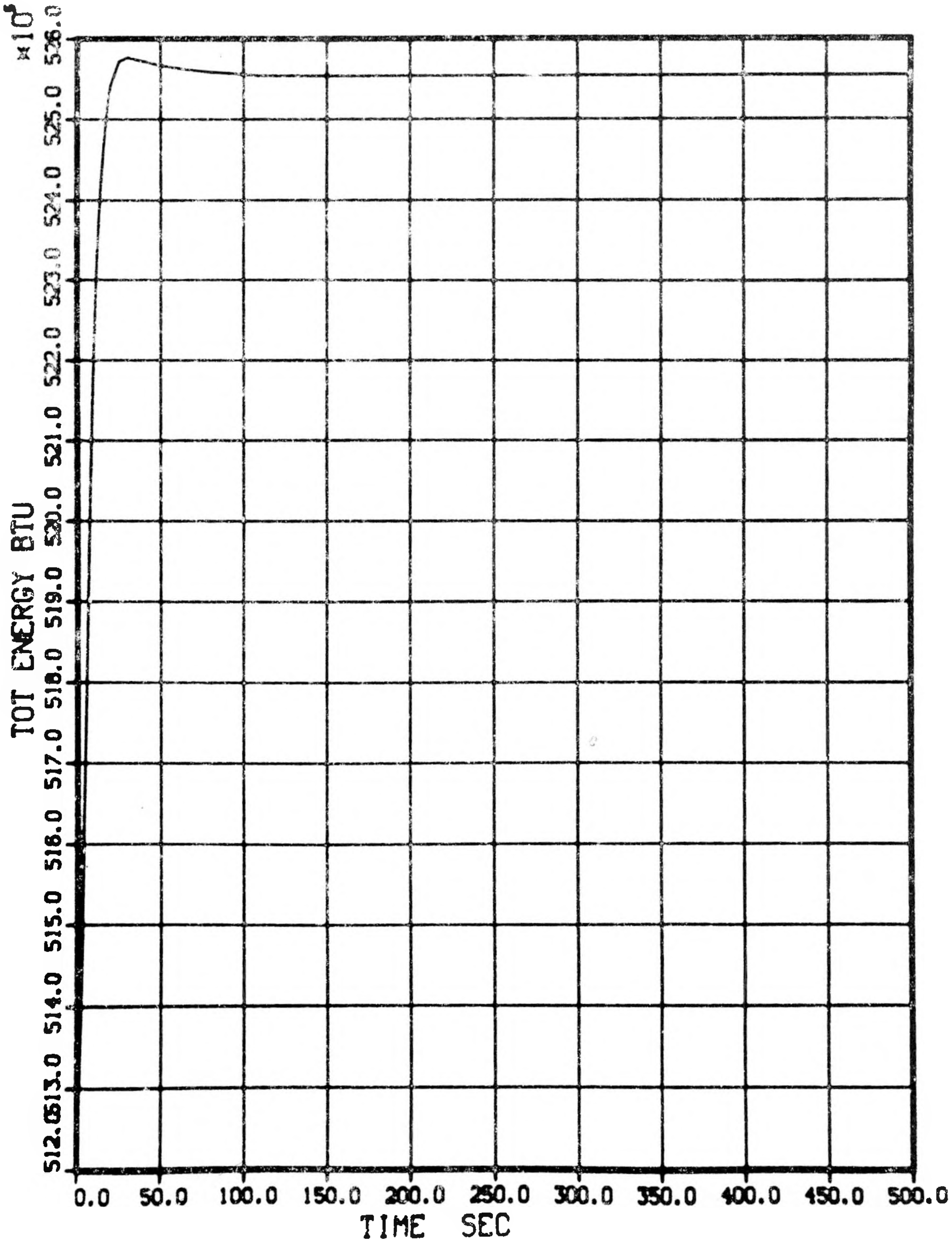


FIGURE 3.33 - TOT ENERGY BTU
VOL - 10, CASE 6

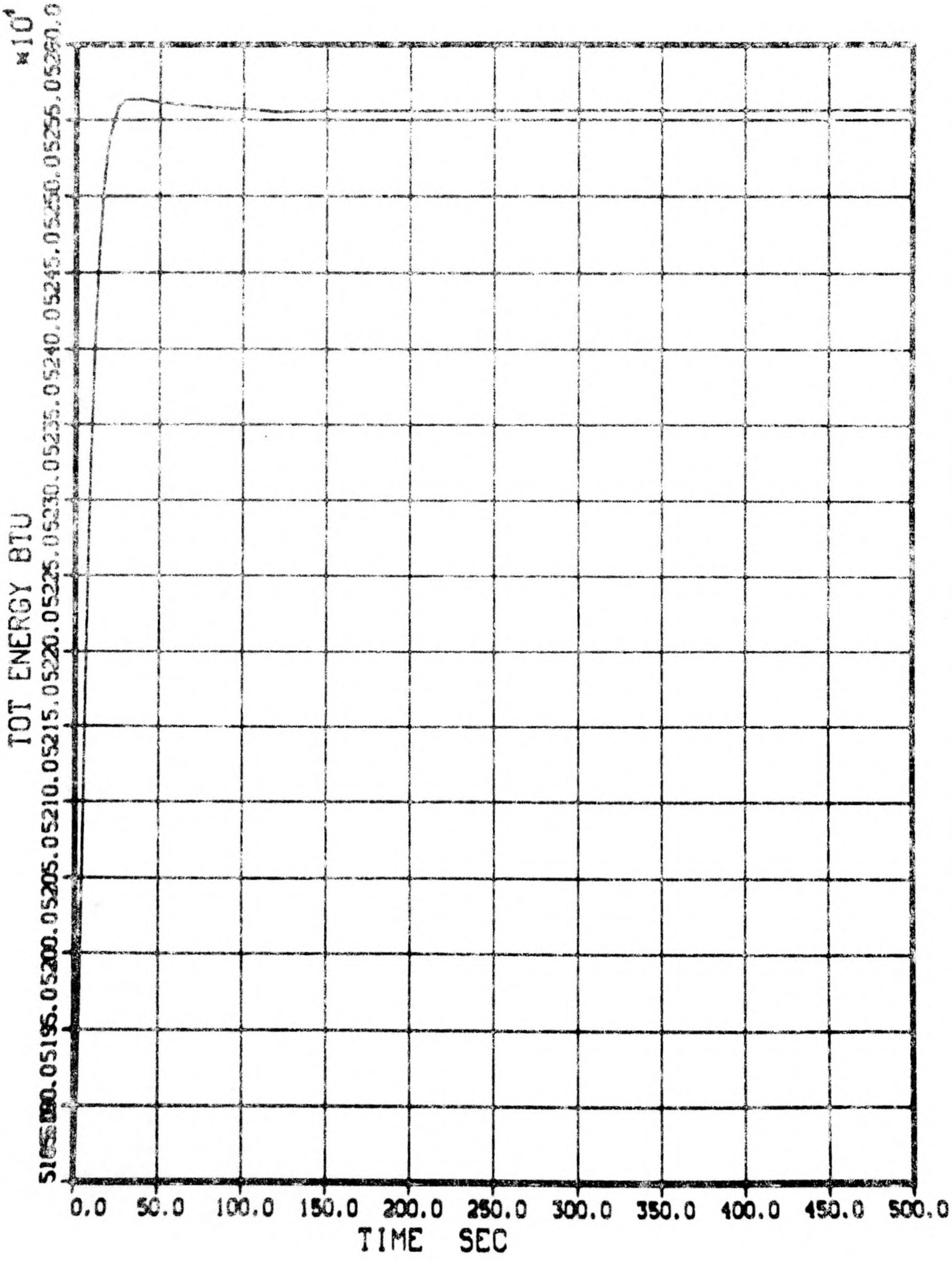


FIGURE 3.34 - **TOT ENERGY BTU**

VOL = **10**, CASE 7

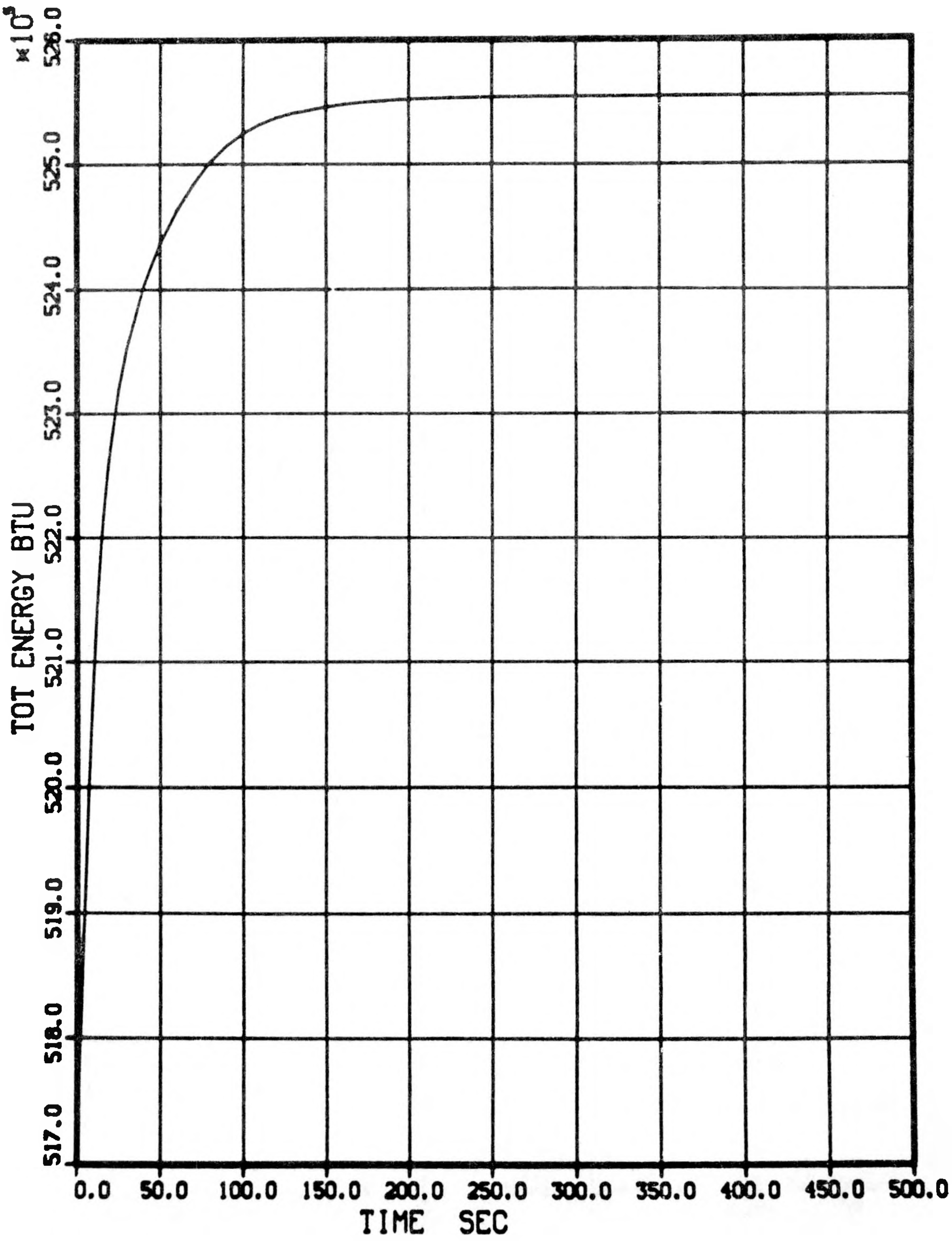


FIGURE 3.35 - **TOT ENERGY BTU**

VOL - 10, CASE 8

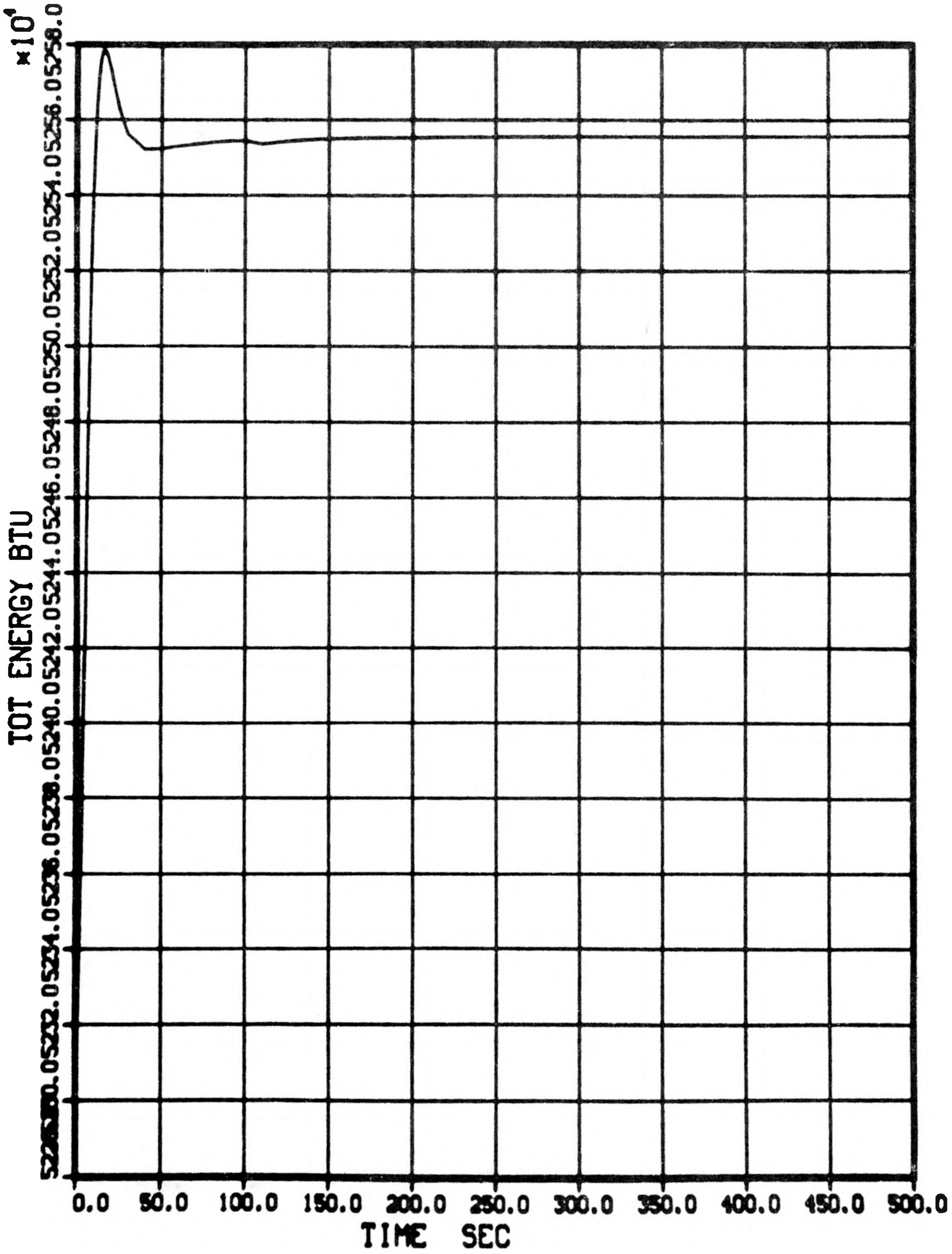


FIGURE 3.36 - **TOT ENERGY BTU**

VOL - 10, CASE 9

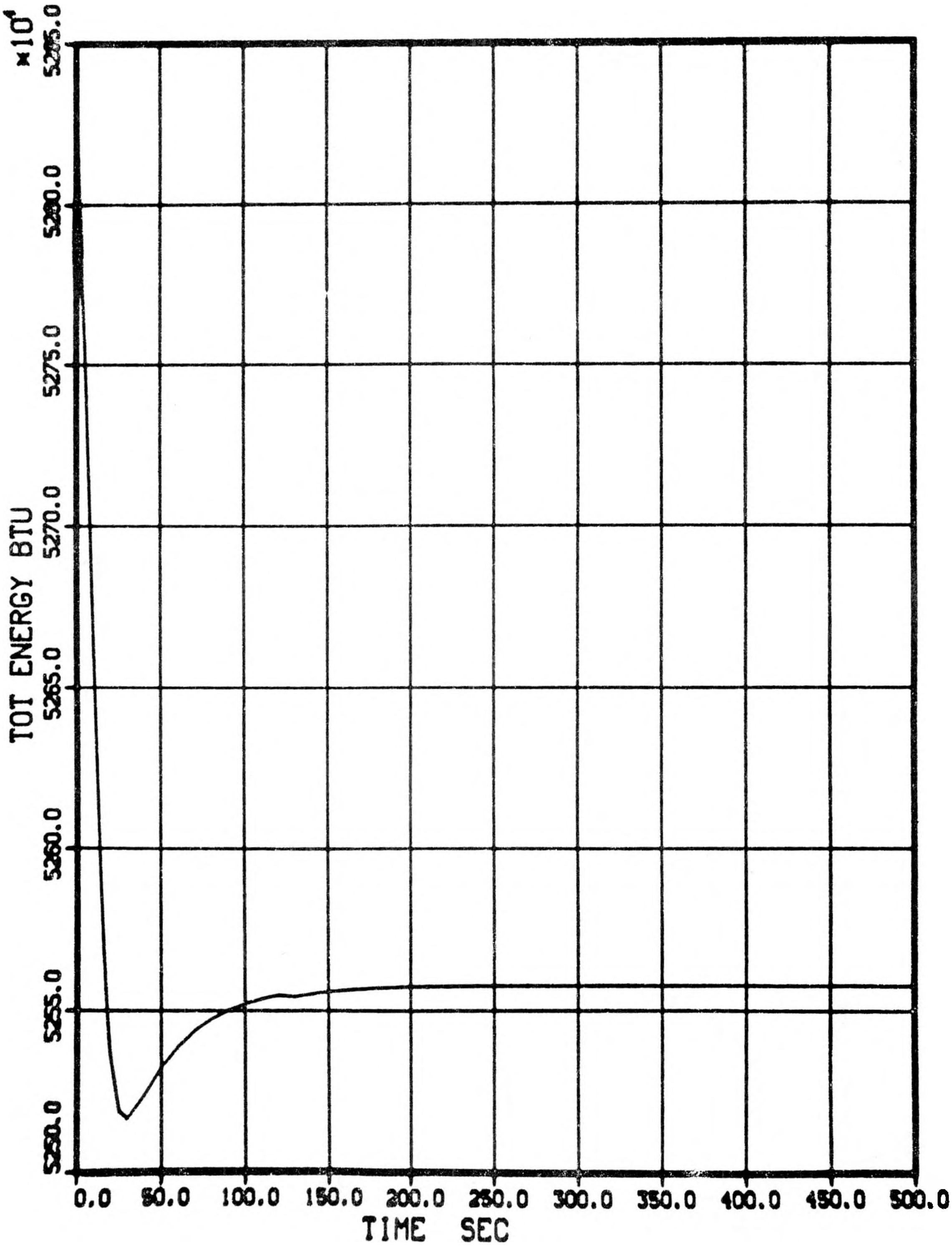


FIGURE 3.37 - FLOW LB/SEC

JUNC - 1, CASE 1

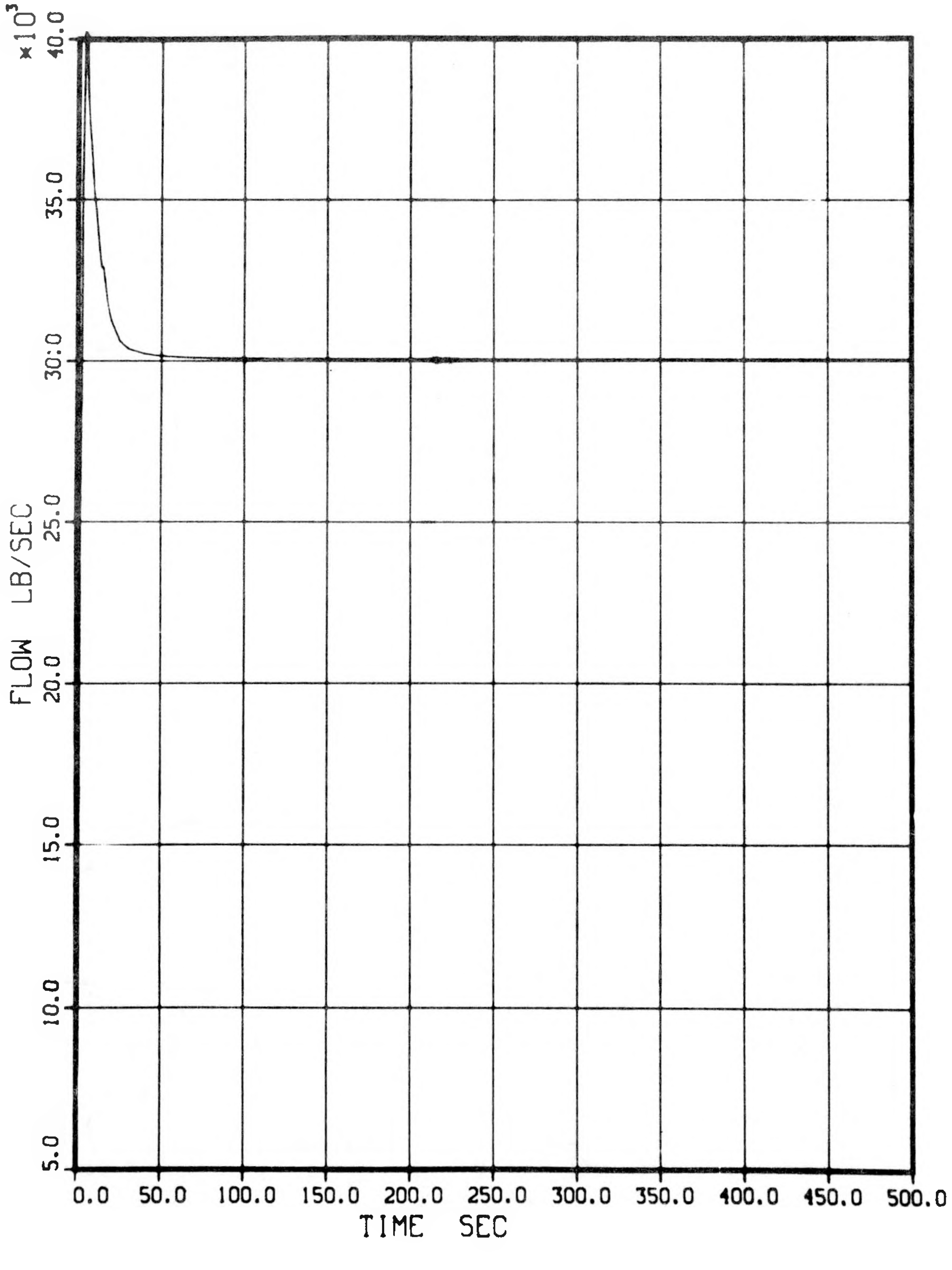


FIGURE 3.38 - FLOW LB/SEC
JUNC = 1, CASE 2

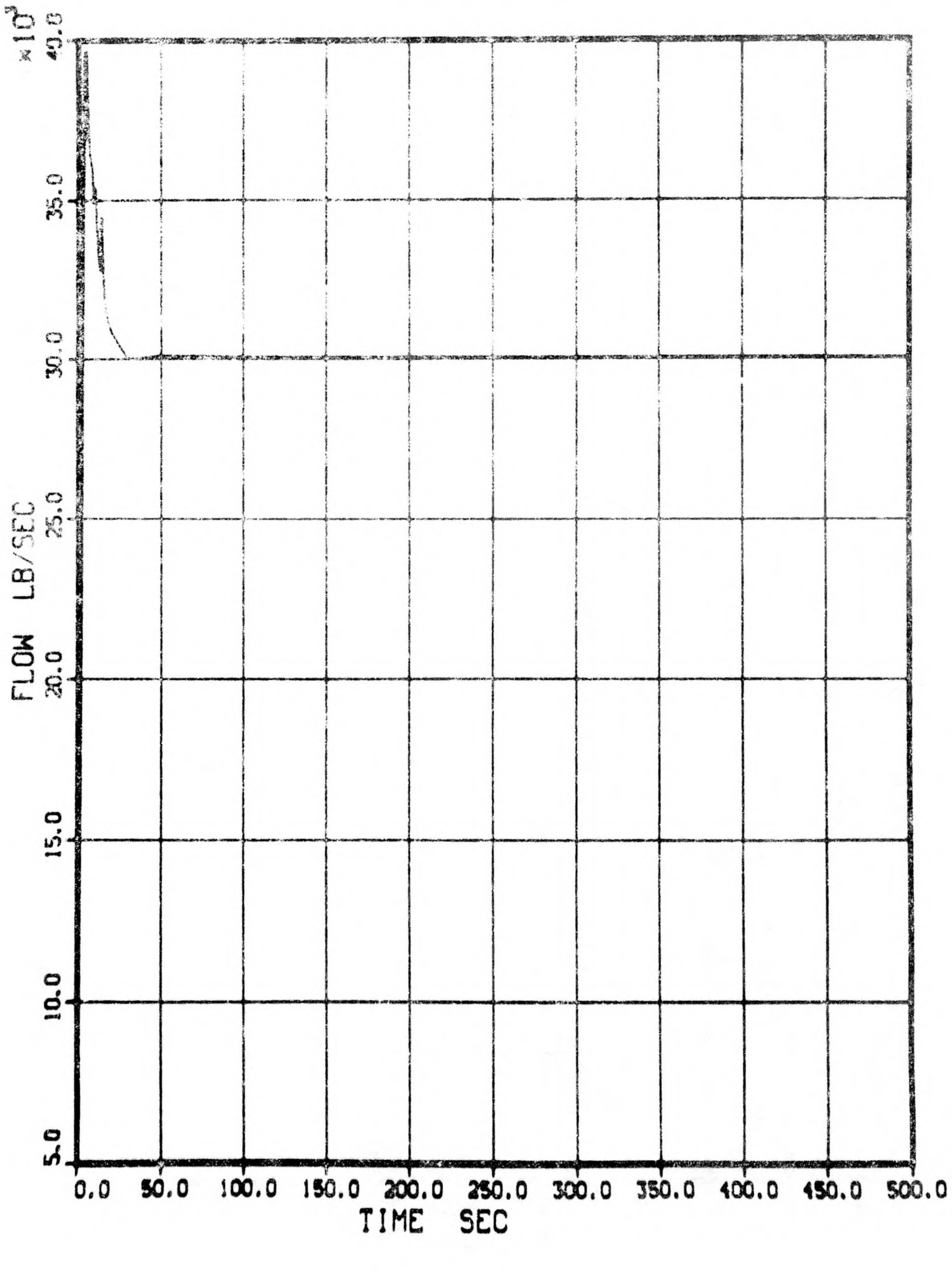


FIGURE 3.39 - FLOW LB/SEC

JUNC = 1, CASE 3

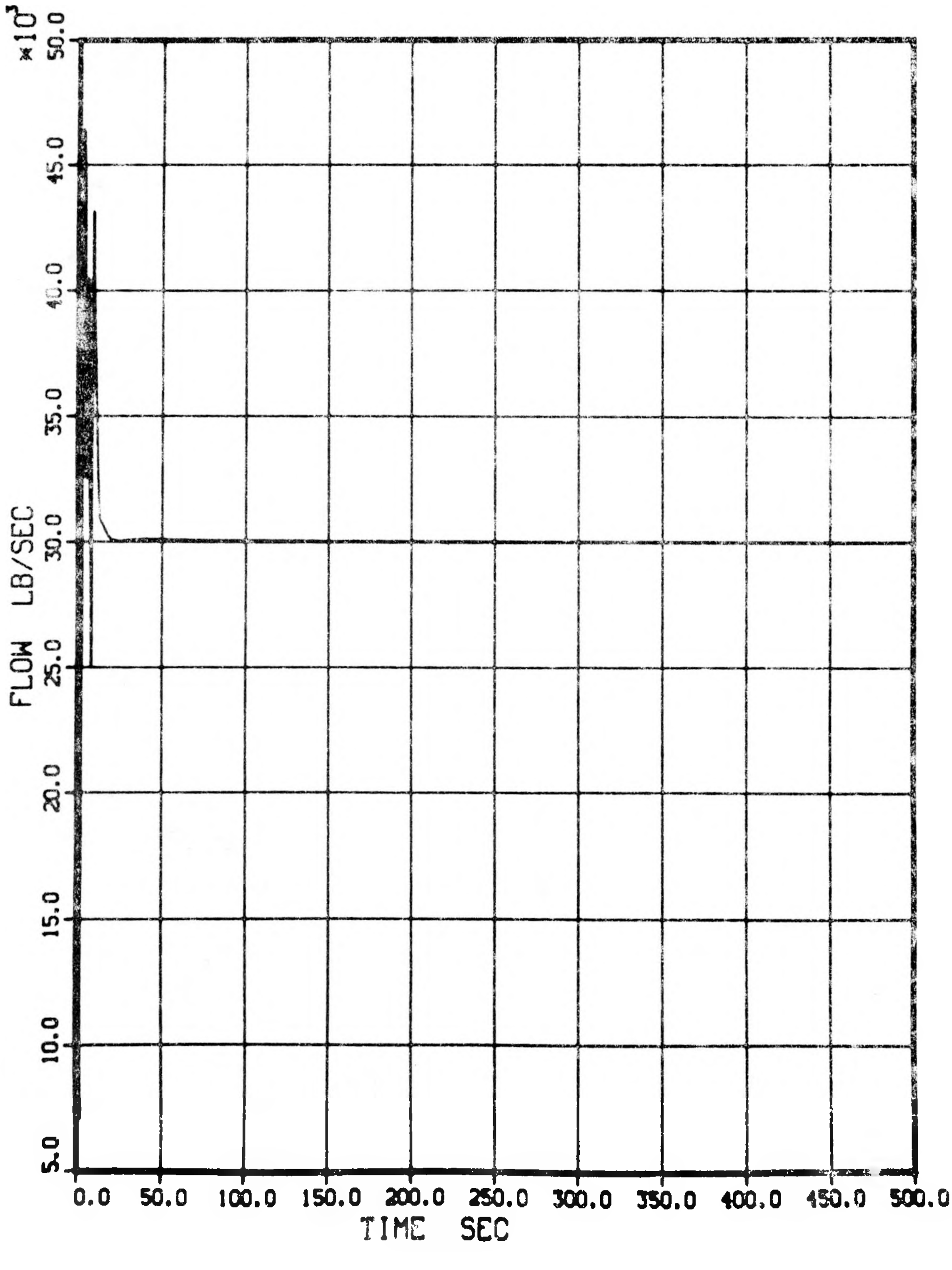


FIGURE 3.40 - **FLOW LB/SEC**
JUNC = 1, CASE 4

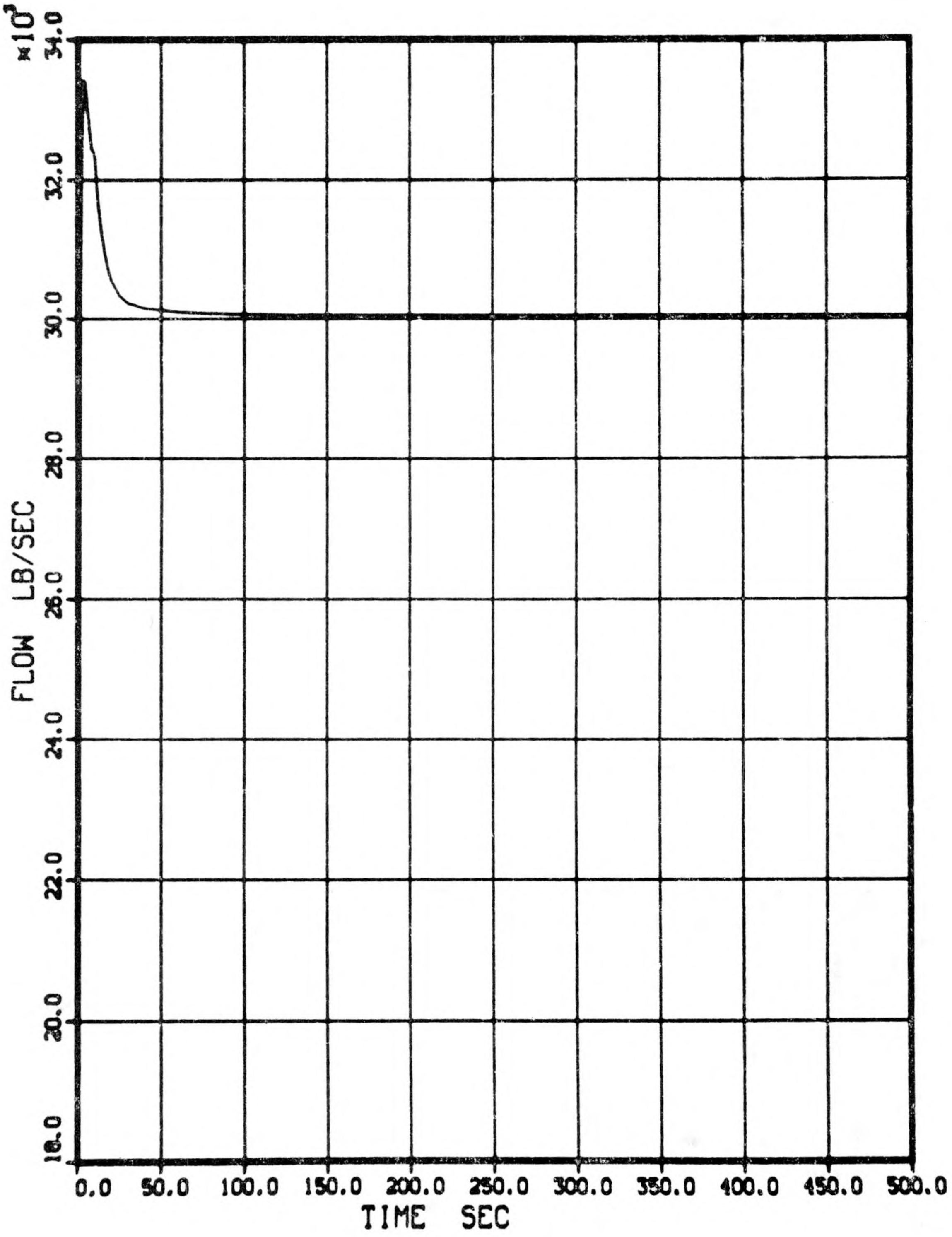


FIGURE 3.41 - **FLOW LB/SEC**
JUNC - 1, CASE 5

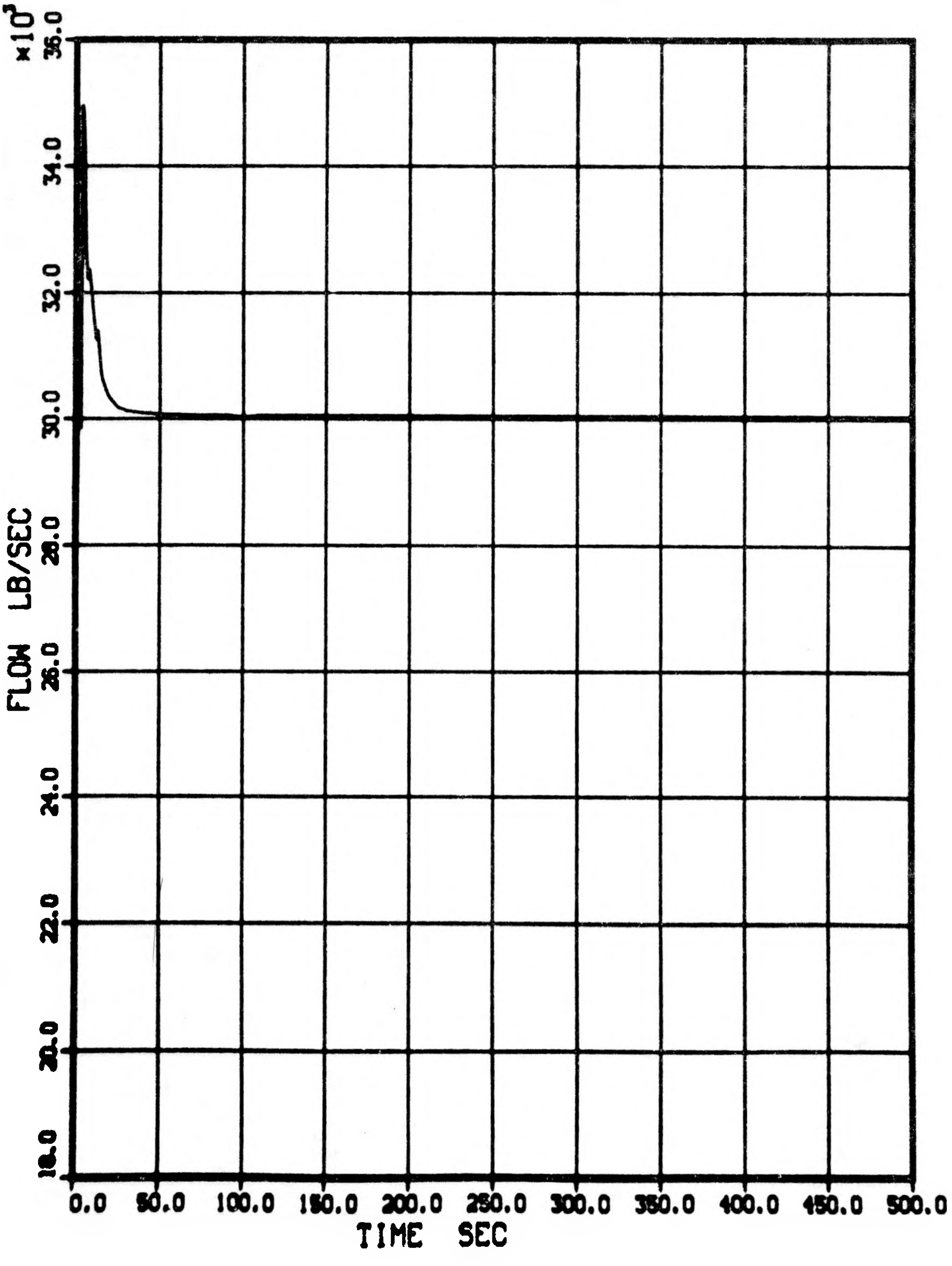


FIGURE 3.42 - FLOW LB/SEC

JUNC = 1, CASE 6

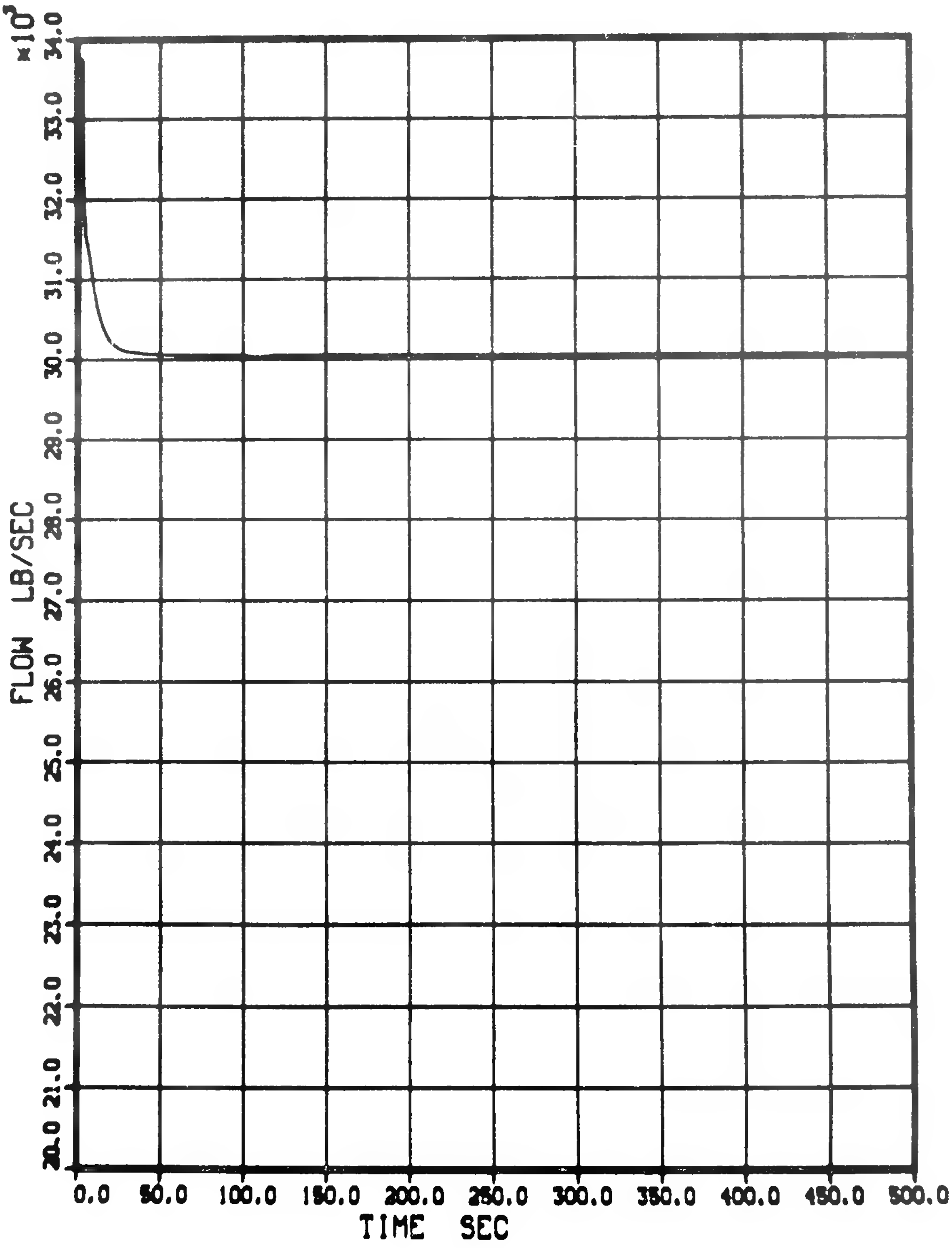


FIGURE 3.43 - FLOW LB/SEC
JUNC = 1, CASE 7

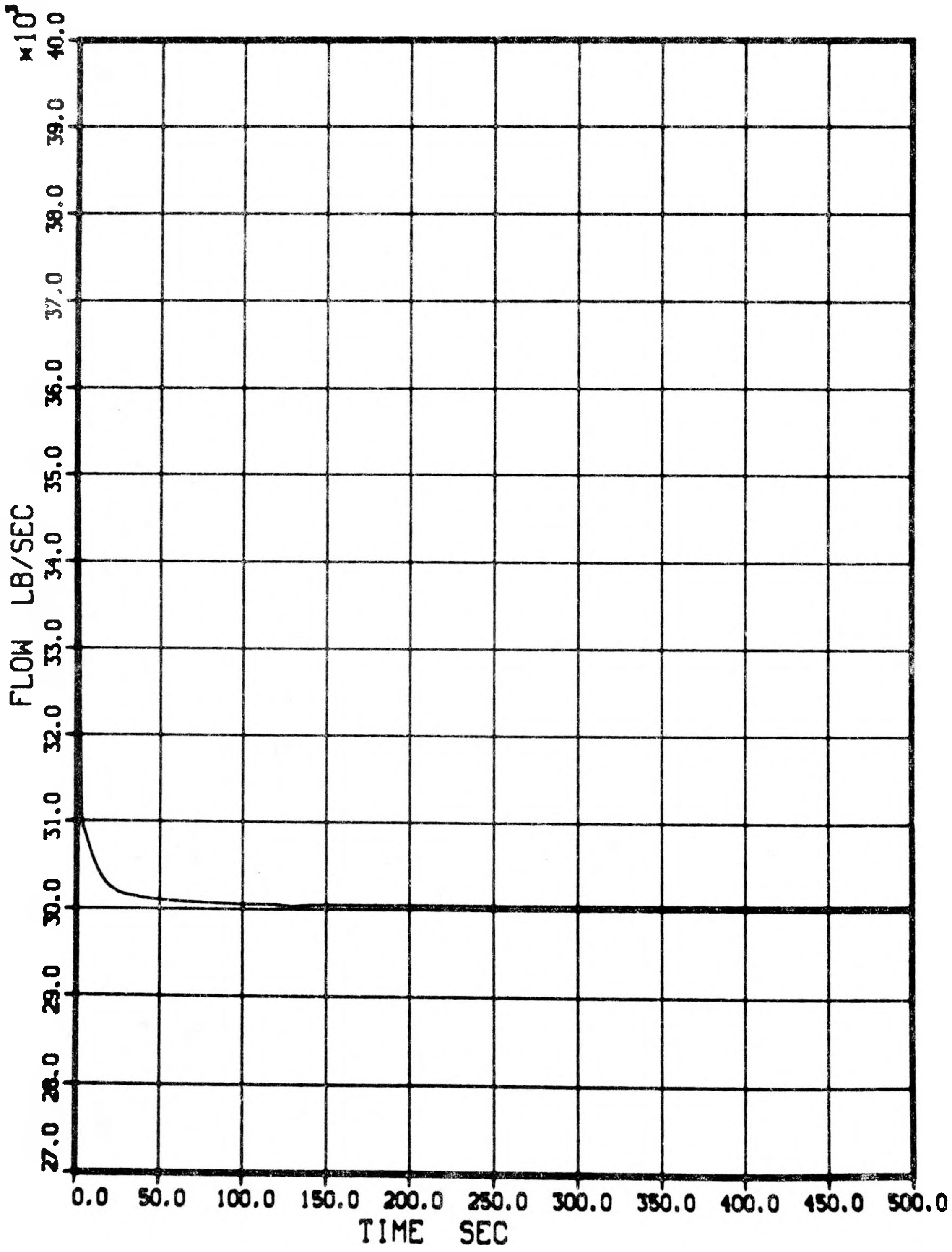


FIGURE 3.44 - FLOW LB/SEC

JUNC - 1 , CASE 8

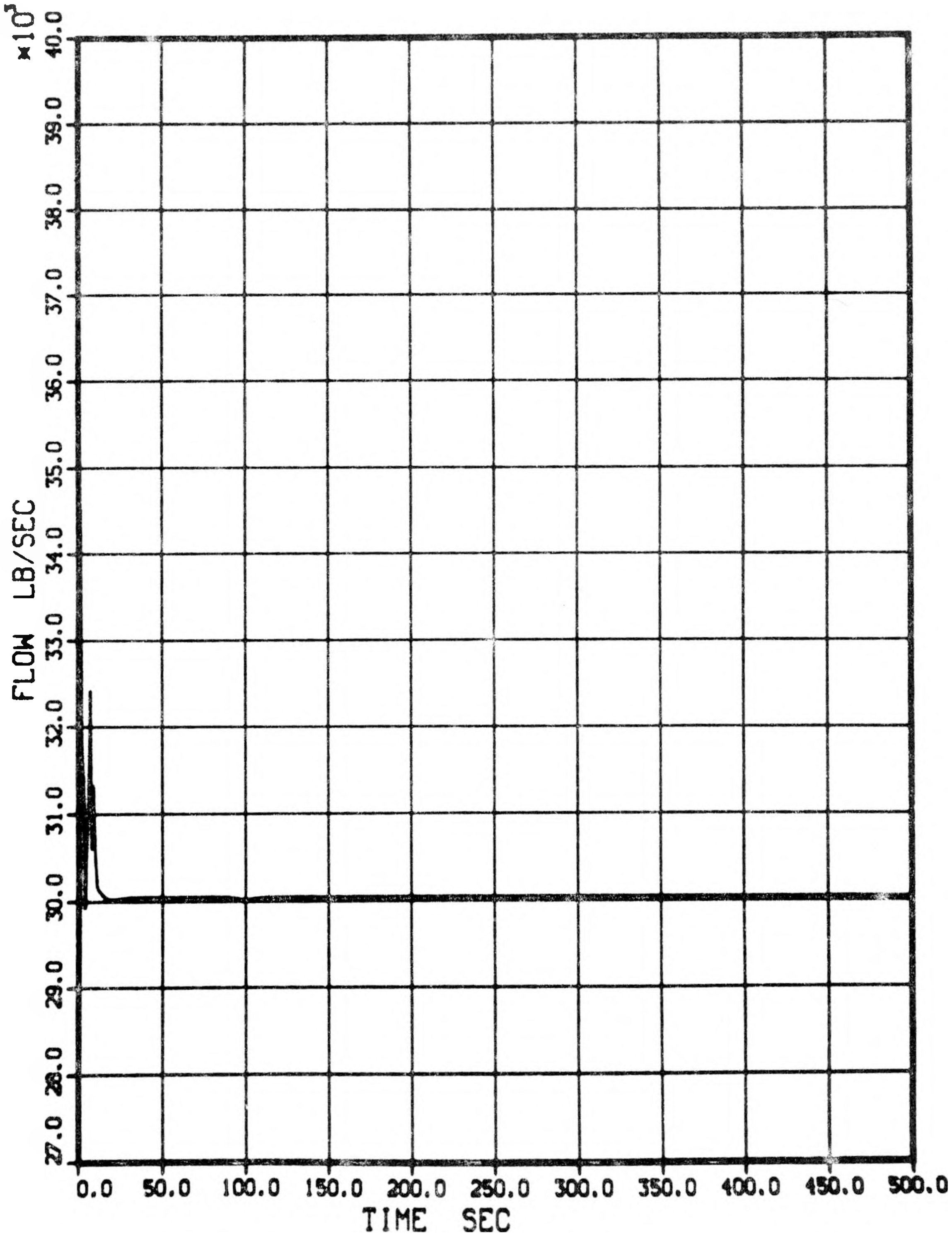


FIGURE 3.45 - FLOW LB/SEC
JUNC = 1, CASE 9

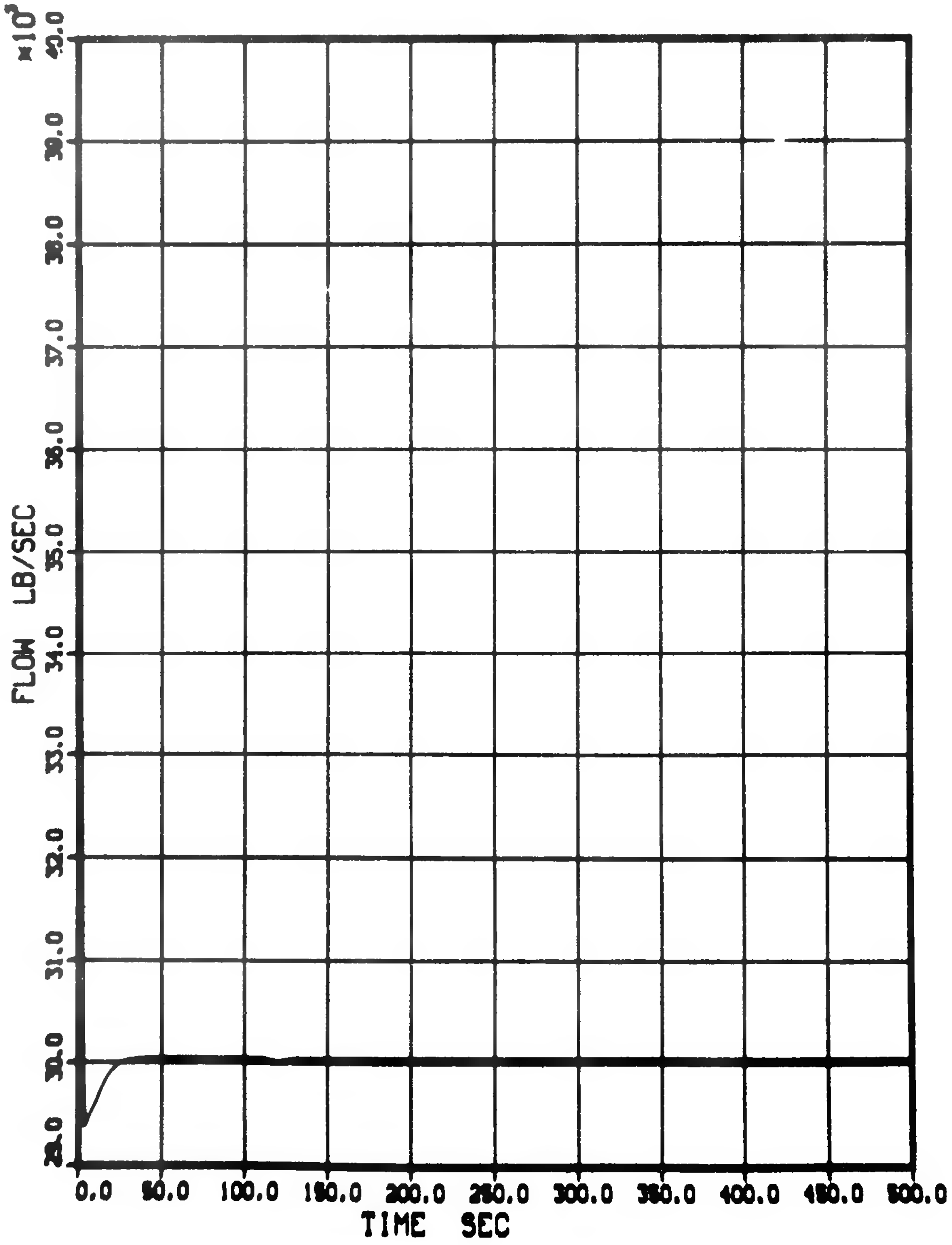


FIGURE 3.46 - FLOW LB/SEC
JUNC - 14, CASE 1

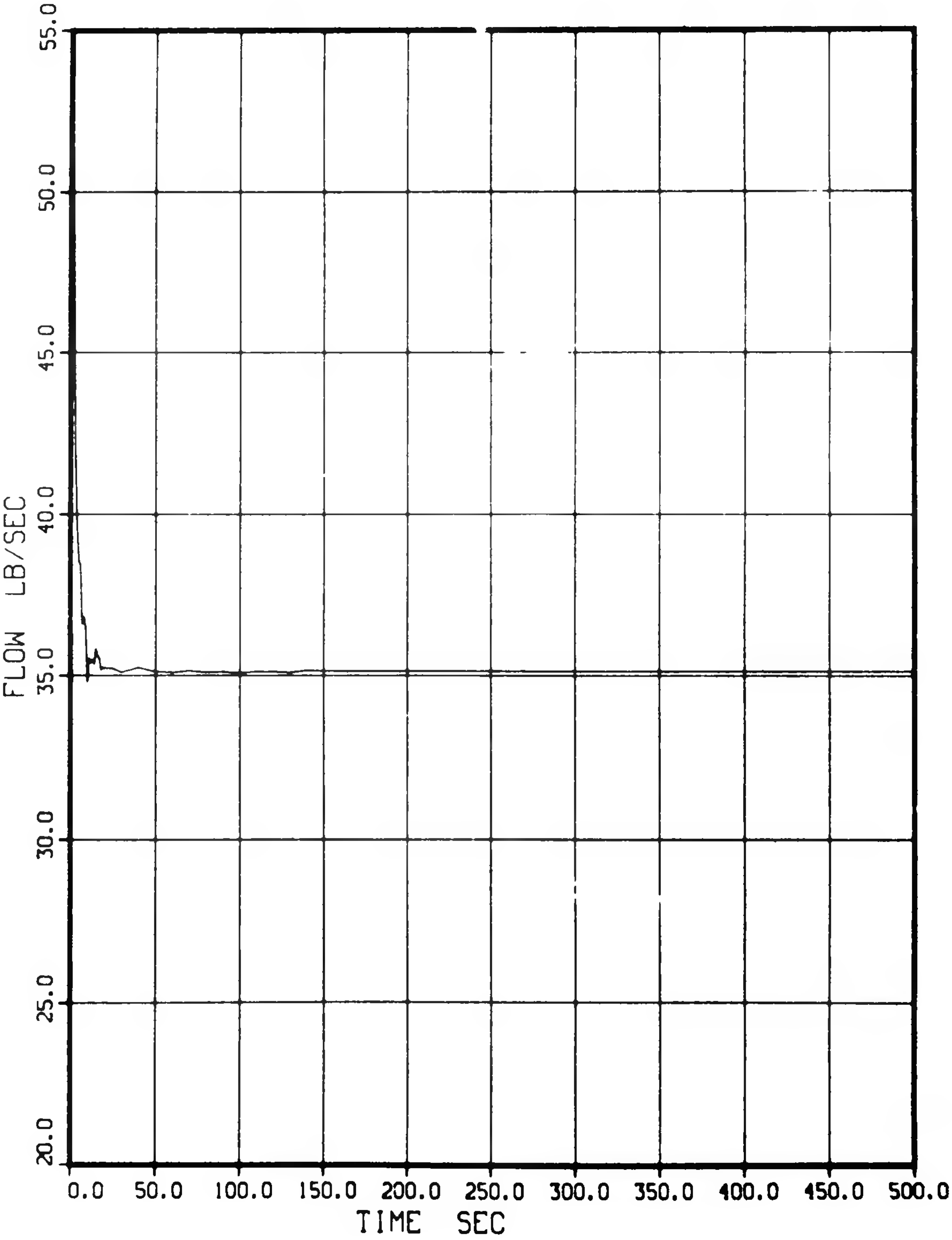


FIGURE 3.47 - FLOW LB/SEC

JUNC - 14, CASE 2

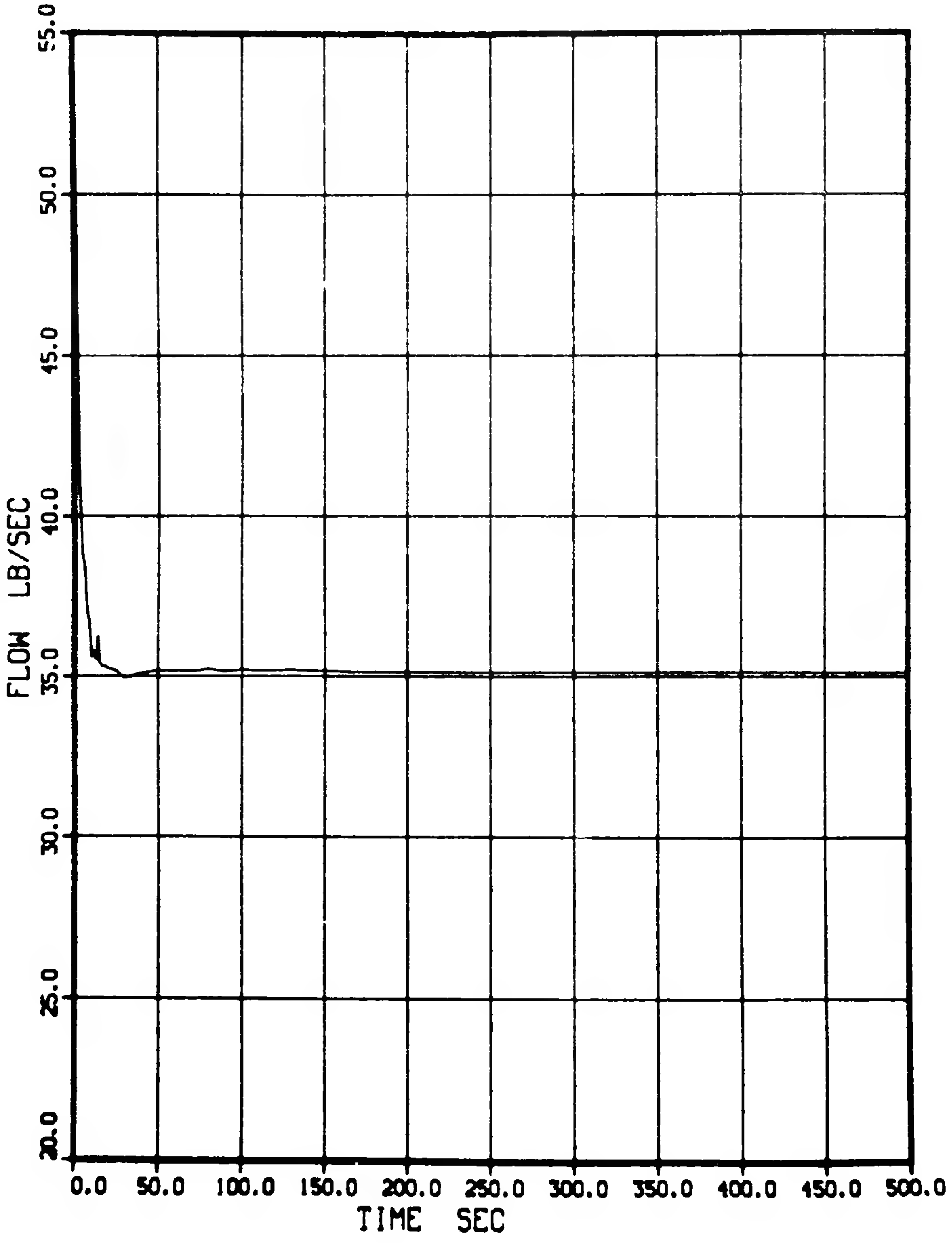


FIGURE 3.48 - **FLOW LB/SEC**
JUNC - 14, CASE 3

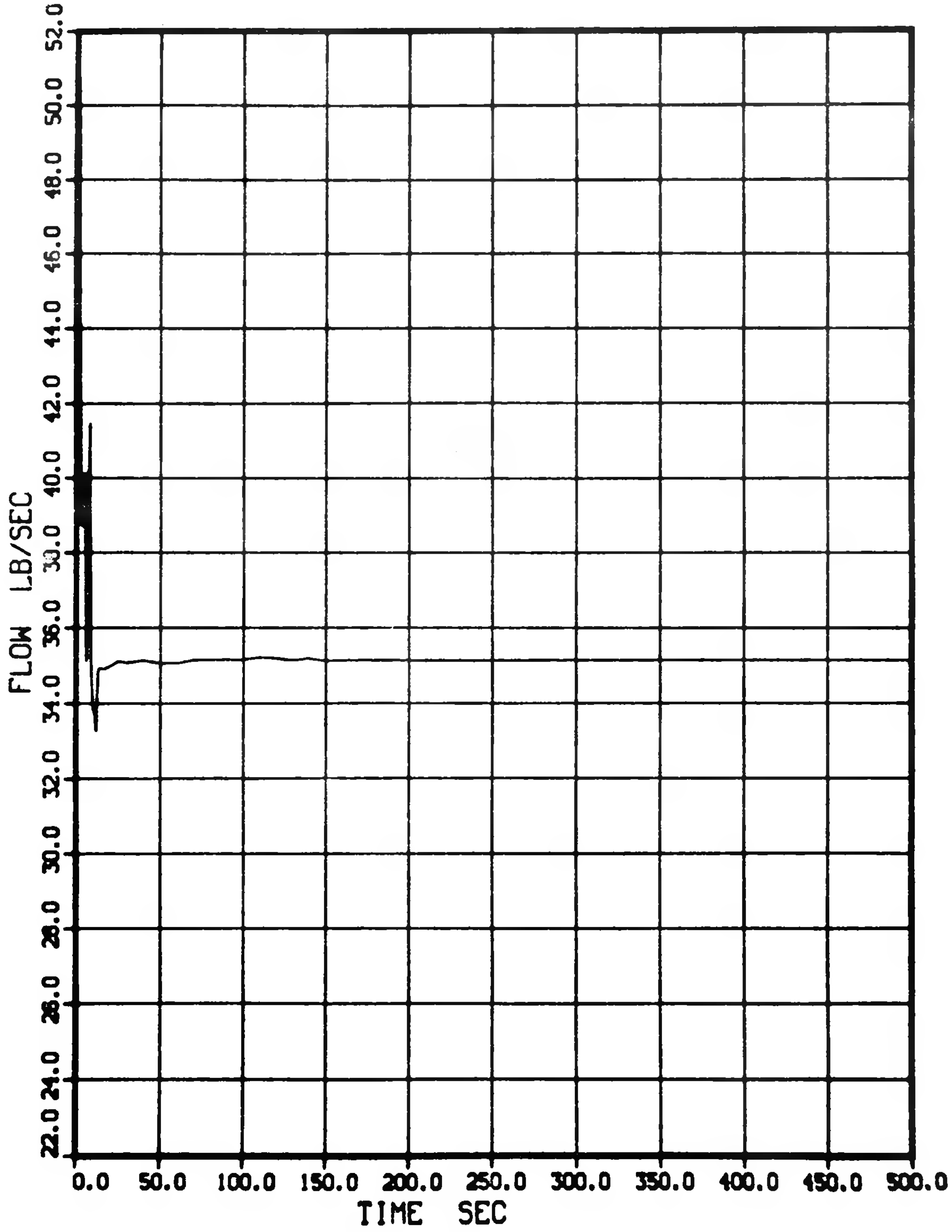


FIGURE 3.49 - FLOW LB/SEC
JUNC - 14, CASE 4

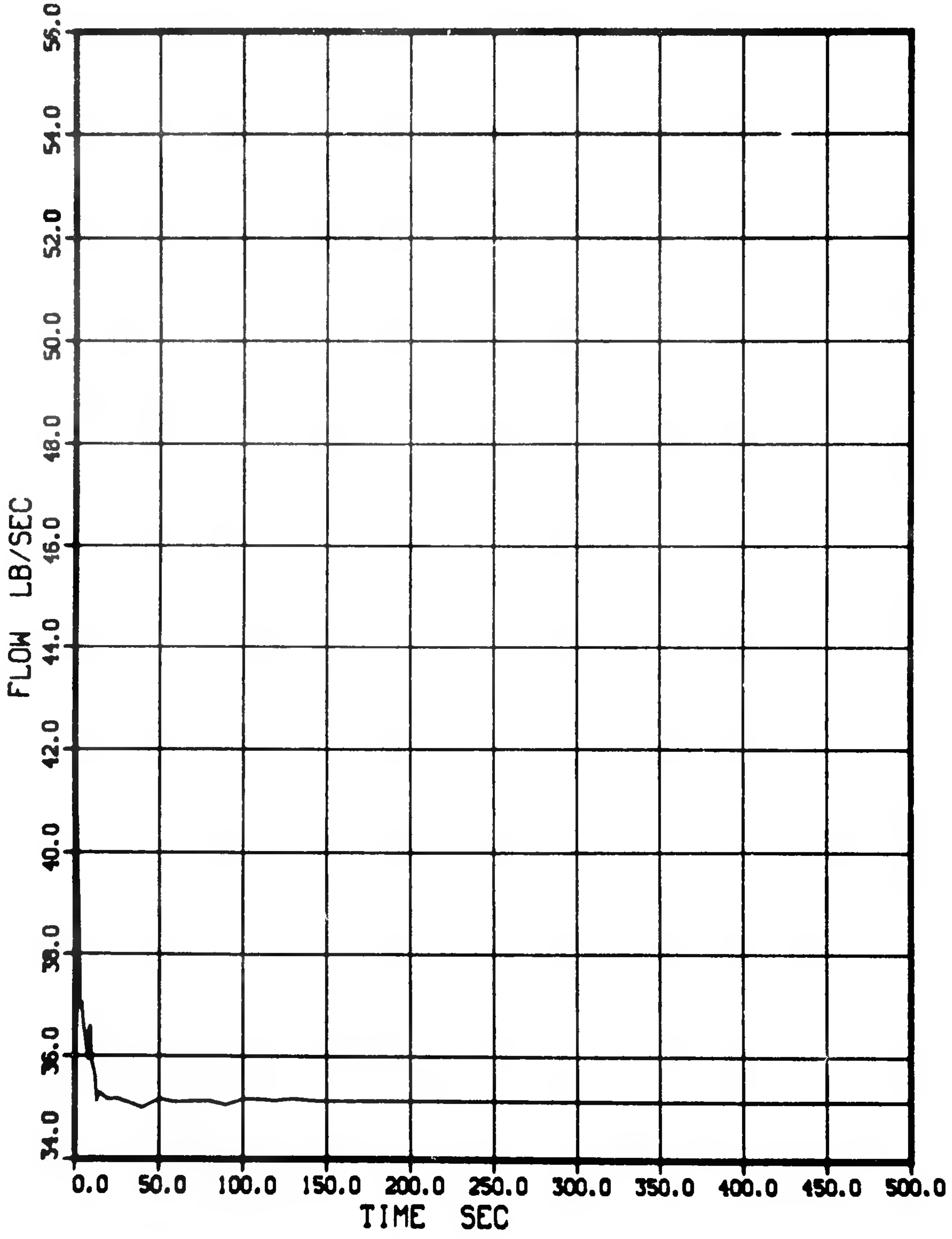


FIGURE 3.50 - **FLOW LB/SEC**

JUNC - 14, CASE 5

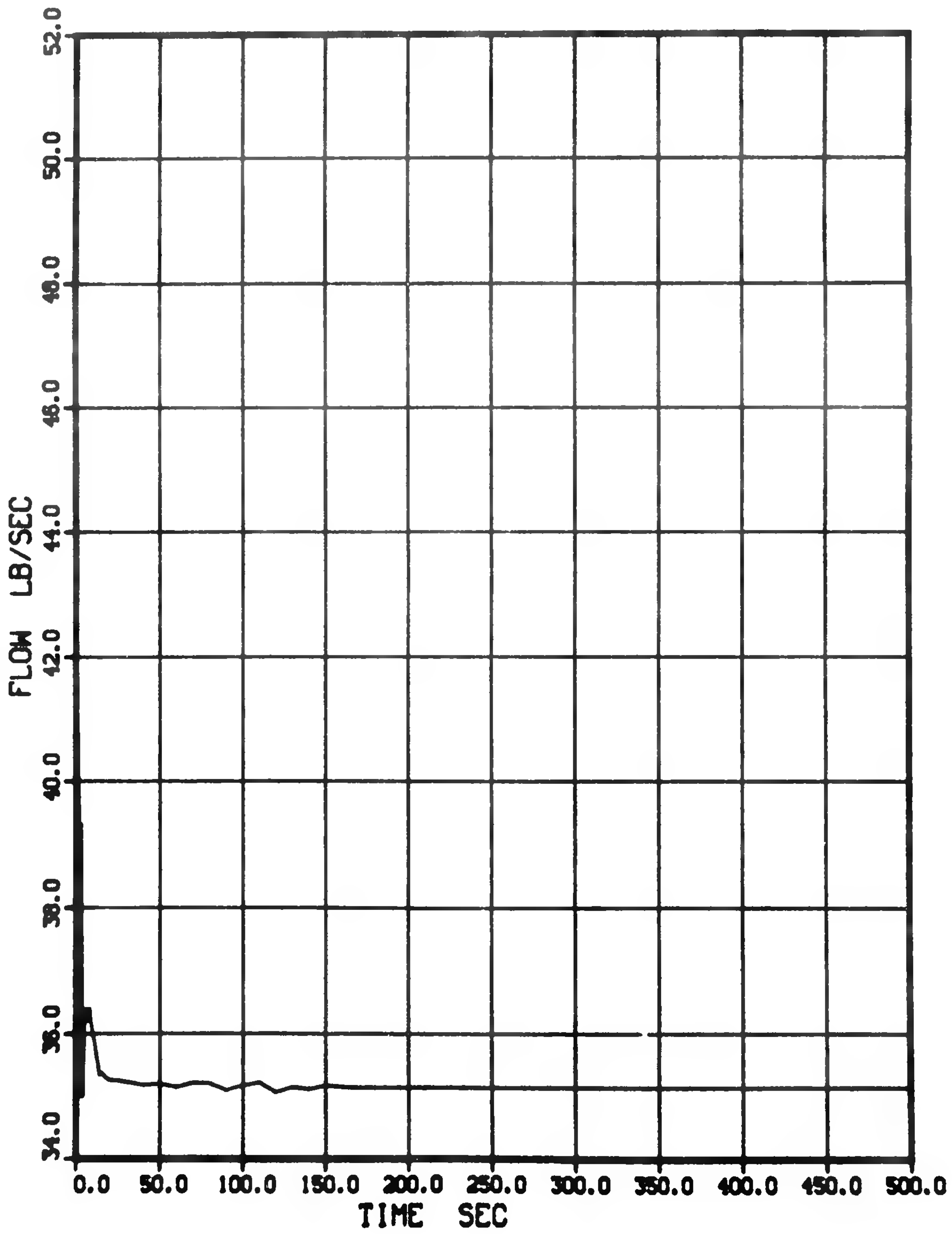


FIGURE 3.51 - FLOW LB/SEC
JUNC = 14, CASE 6

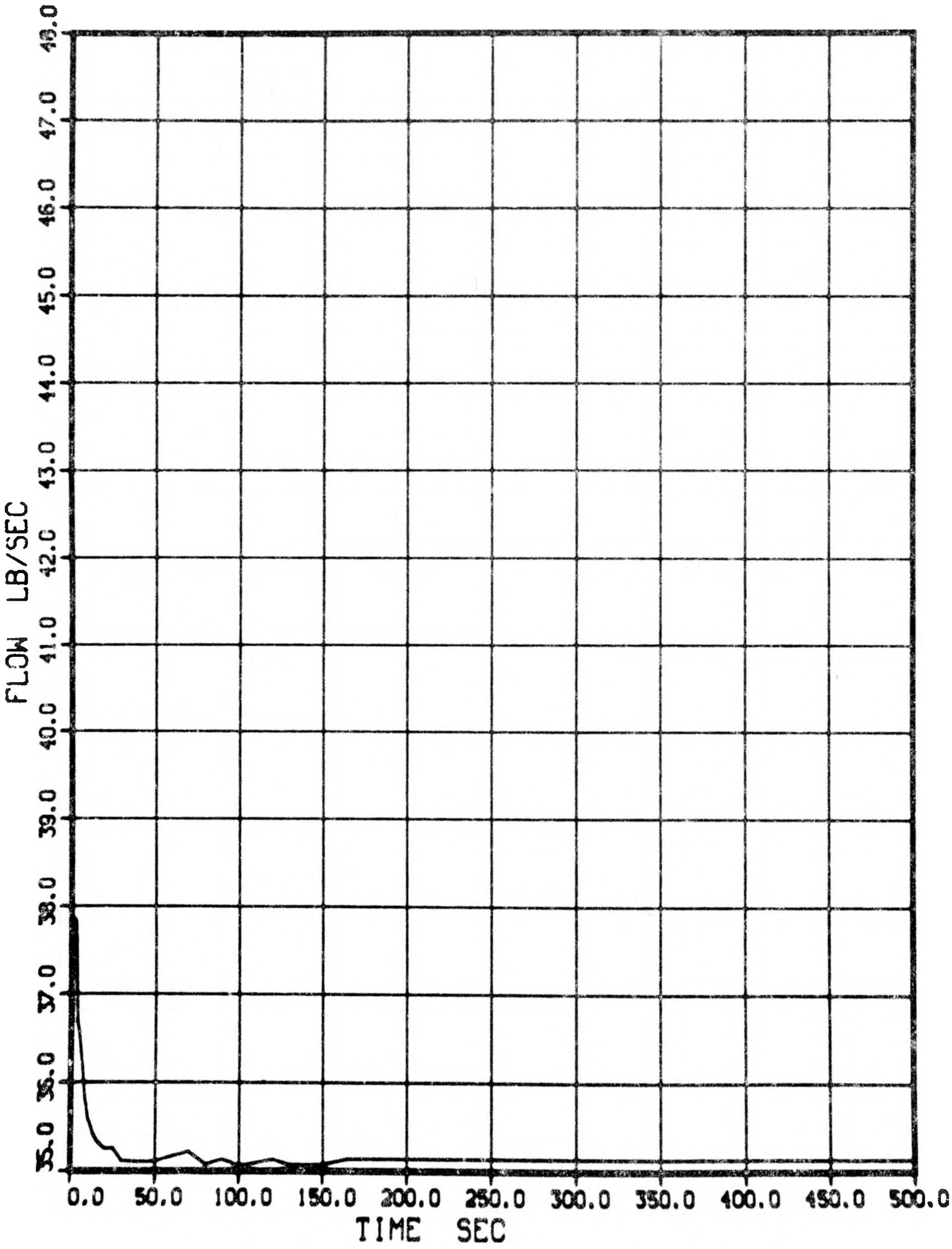


FIGURE 3.52 - FLOW LB/SEC
JUNC - 14, CASE 7

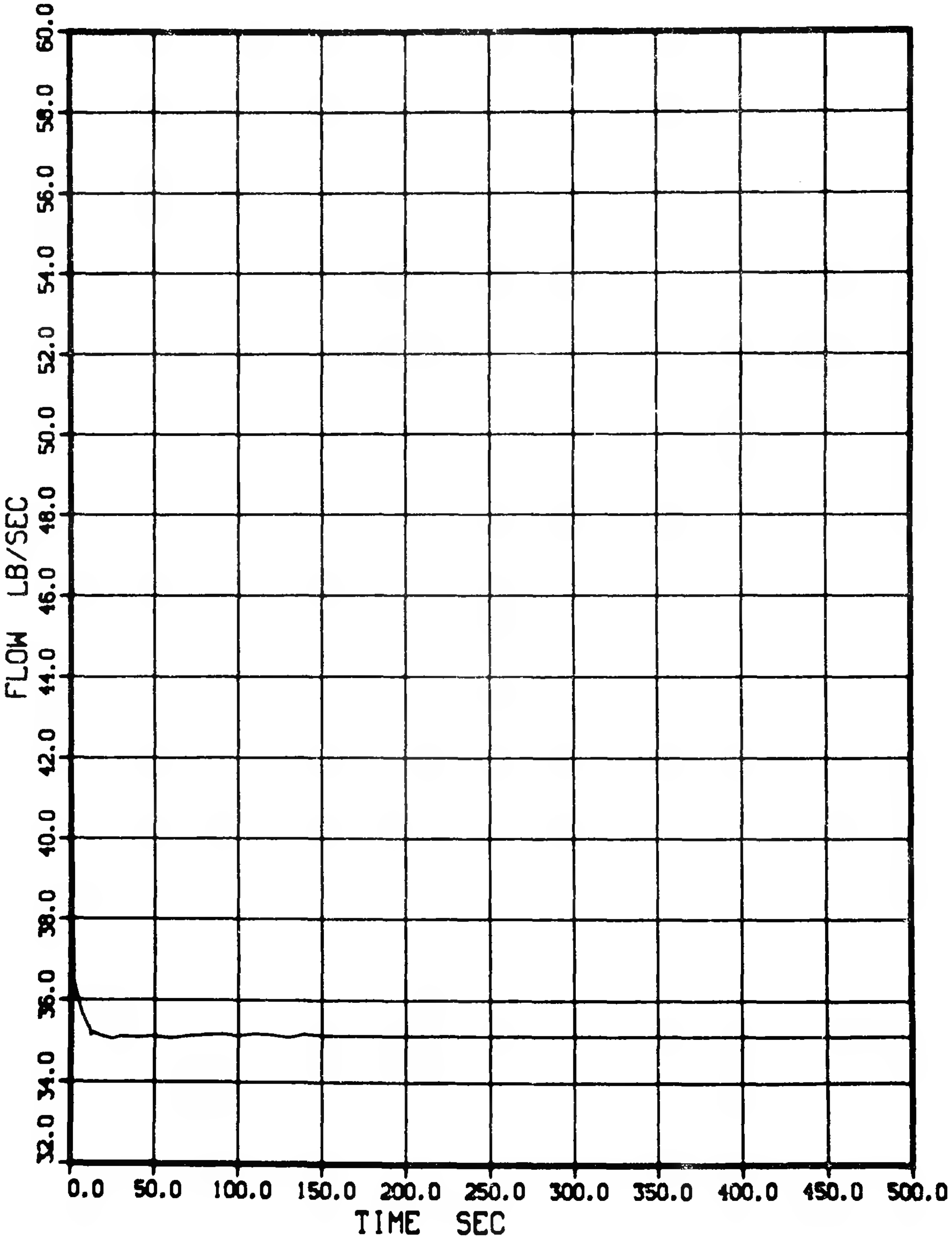


FIGURE 3.53 - FLOW LB/SEC

JUNC - 14, CASE 8

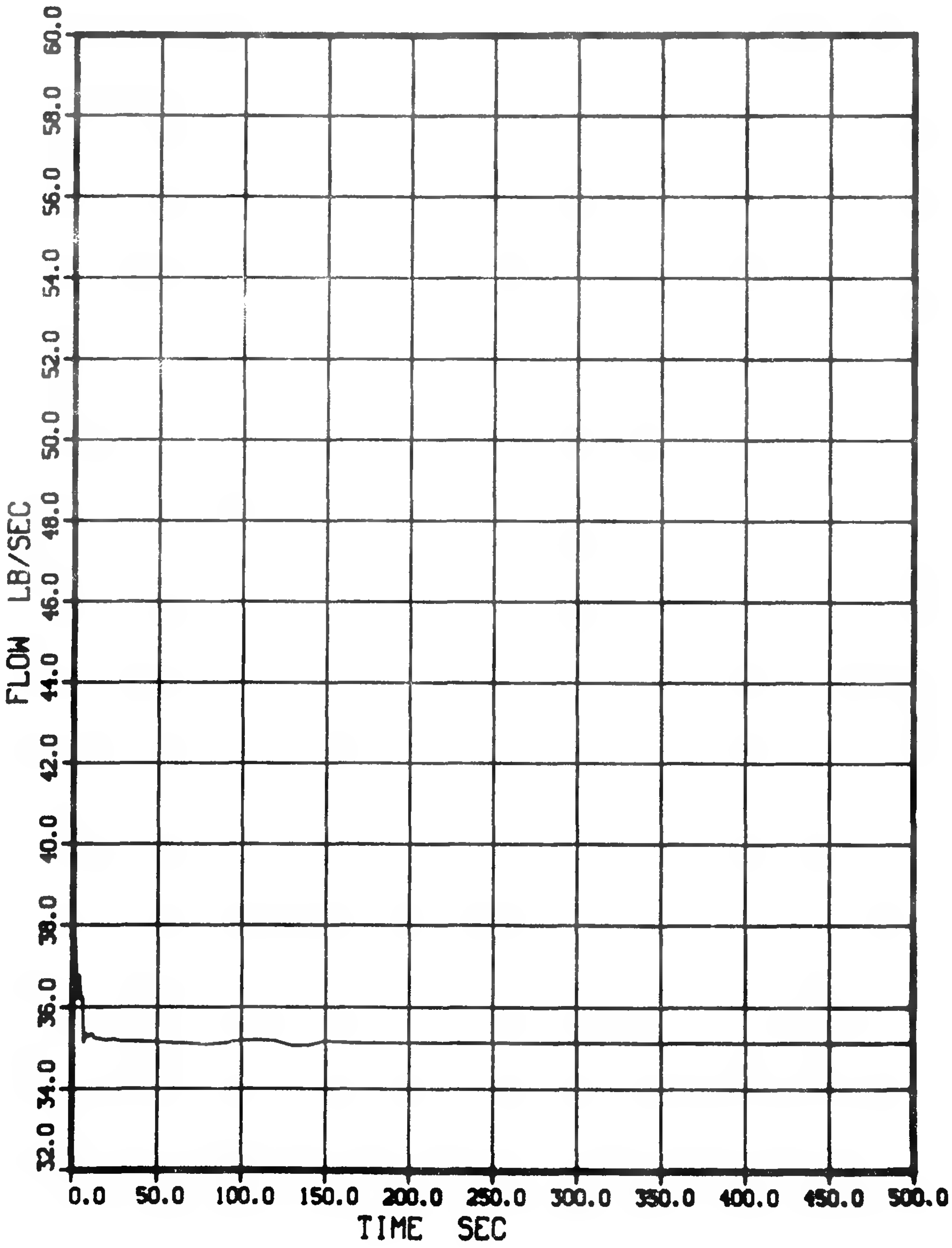
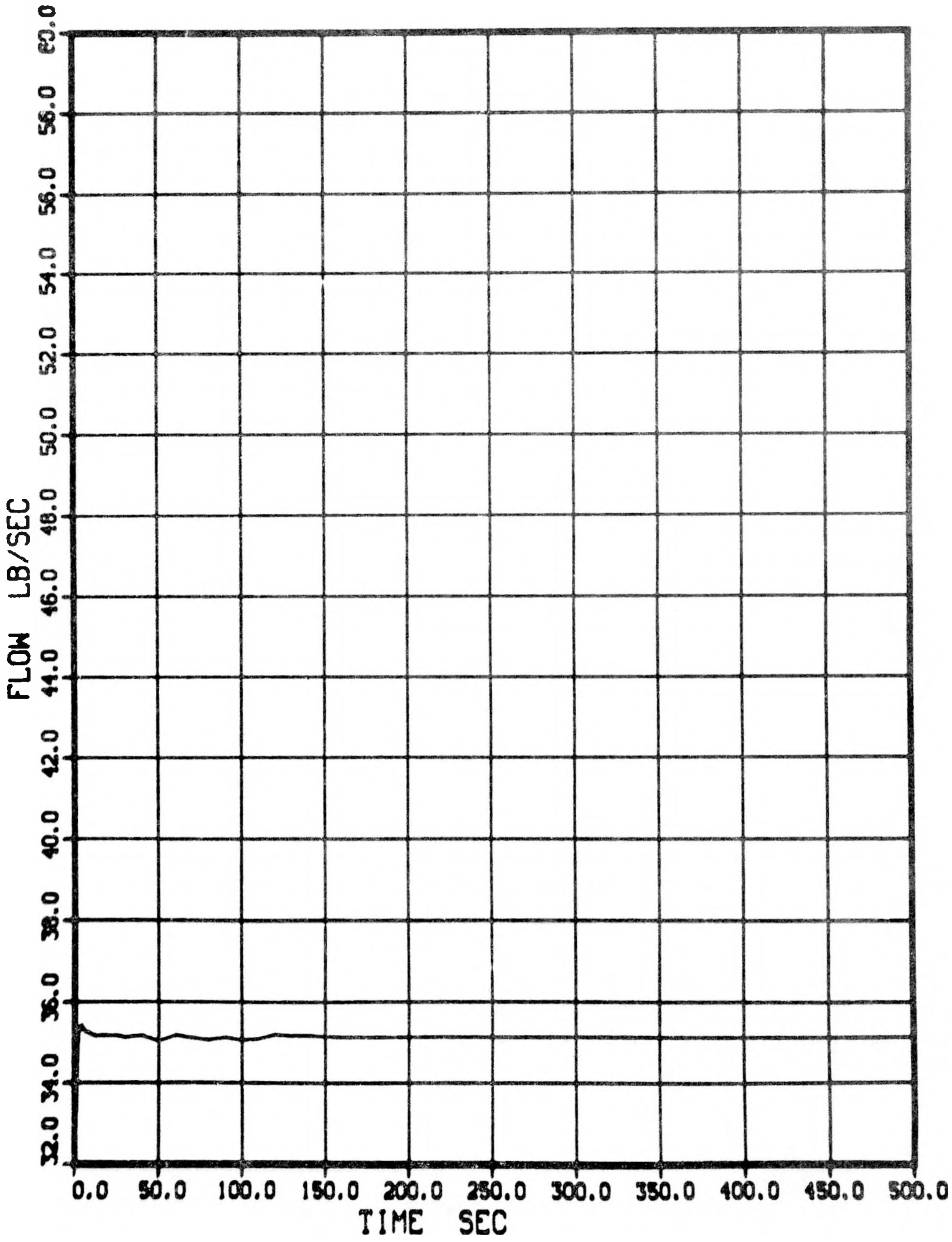


FIGURE 3.54 - **FLOW LB/SEC**
JUNC - 14, CASE 9



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