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Technical Memorandum 33-604

A Method for Calculating Transient Thrust and Flow-Rate Levels for Mariner Type Attitude Control Nitrogen Gas Jets

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PREFACE

The work described in this report was performed by the Guidance and Control Division of the Jet Propulsion Laboratory.

CONTENTS

FIGURES (contd)

ABSTRACT

The purpose of this report is to define and program the transient pneumatic flow equations necessary to determine, for a given set of conditions (geometry, pressures, temperatures, valve on time, etc.), the total nitrogen impulse and mass flow per pulse for the single pulsing of a Mariner type reaction control assembly valve. The rates of opening and closing of the valves are modeled, and electrical pulse durations of from 20 to 100 ms are investigated. In developing the transient flow analysis, maximum use was made of the steady-state analysis undertaken in Ref. 1. The impulse results are also compared to an equivalent "square-wave" impulse for both the Mariner Mars 1971 (MM'71) and Mariner Mars 1964 (MM'64) systems. It is demonstrated that, whereas in the MM'64 system, the actual impulse was as much as 56% higher than an assumed impulse (which is the product of the steady-state thrust and value on time -- i.e., the square wave), in the MM'71 system, these two values were in error in the same direction by only approximately 4% because of the larger nozzle areas and shorter valve stroke used.

I. INTRODUCTION

This memorandum is a supplement to Technical Report 32-1353 (Ref. 1) and is intended to be used in conjunction with it. The work presented in that report is limited to steady-state thrust and flow-rate determinations vs. varying design parameters for the Mariner type ball valve/nozzle configuration, in which a subsonic orifice is in series with a sonic nozzle throat separated by a chamber volume of approximately 0.2 cm^3. Design variables investigated include inlet pressures of 6.9×10^4 to 2.1×10^5 N/m^2 (10 to 30 psi), ambient pressure of 1×10^{-4} N/m^2 (1×10^{-6} torr), inlet temperatures of -100 to 150°C, valve orifice areas of 0.32 to 2.6 mm^2 (5×10^{-4} to 40×10^{-4} $in.^2$), nozzle throat diameters of 0.13 to 1.3 mm (5×10^{-3} to 50×10^{-3} in.), nozzle geometric area ratios of 25 to 275, and nozzle cone half-angles of 15 to 40 deg. The thrust levels considered are in the millinewton range, and the propellant is cold nitrogen gas. The equations used to determine nozzle losses are based on flat-plate analogies.*

The work described here extends the analysis and computer program presented in Ref. 1 (using the same ranges of parameters) to include an investigation of the transient thrust and flow-rate effects for both the Mariner Mars 1964 and 1971 cases. Of particular concern was the total quantity of gas consumed in the firing of each axis of the MM'71 reaction control assembly. The results were used in the Mariner Mars 1971 program to aid in the flight analysis of total gas consumption, and tended to correlate with in-flight data. The resulting Univac 1108 program can easily be modified to investigate other valve geometrics and conditions.

*The dimensions in the equations are in English units to correspond to the computer program on which they are based.

II. FLOW ANALYSIS

The model used to represent the MM'71 RCA jet valve is shown in Fig. 1, where the subscripts 0, c, and N refer to conditions at the jet valve orifice, in the plenum chamber between the jet valve orifice and nozzle, and in the nozzle throat, respectively.

For this model, the weight of gas in the thrust chamber W_c at any time t is assumed to be given by the perfect gas law,

$$W_c = \rho_c V_c = \frac{V_c}{RT} P_c \tag{1}$$

where ρ is the gas density, V_c is the chamber volume, R is the gas constant, T is the gas temperature, and P_c is the chamber pressure. For an adiabatic process, the change in weight is proportional to the change in pressure, or

$$\frac{\partial W_c}{\partial t} = \frac{V_c}{RT} \frac{\partial P_c}{\partial t} \tag{2}$$

For the case to be considered in this report, at t = 0 (i.e., immediately prior to the initiation of valve opening), P_0 equals the supply pressure of 1.0×10^5 N/m^2 (15.0 psia), and the chamber pressure P_c and ambient pressure P_a equal zero (i.e., vacuum condition). Between the time the valve starts to open and the time that the chamber pressure reaches a steady-state level (see Fig. 2), there is a difference in flow rates between the solenoid valve orifice W_0 and the nozzle W_N. This flow-rate difference causes an accumulation of gas in the chamber, thereby building up the chamber pressure. The differential equation of the rate of gas accumulation is

$$\frac{dW_c}{dt} = W_0 - W_N \tag{3}$$

Because the local ambient is vacuum, the flow rate through the nozzle is always sonic and is given by

$$W_N = C_{DN} A_N P_c \left[\frac{g_0 \gamma}{RT} \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}} \right]^{\frac{1}{2}} \qquad (4)$$

where C_{DN} is the nozzle discharge coefficient, and A_N is the nozzle cross-sectional area.

The flow rate through the valve orifice W_0 is sonic initially, since $P_c/P_0 < 0.528$. During this period $(0 < P_c/P_0 \leq 0.528,\ 0 < t < t_{r1}$, from Fig. 2), the sonic orifice flow rate is given by

$$W_0 = C_{DV} A_0(t) P_0 \left[\frac{g_0 \gamma}{RT} \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}} \right]^{\frac{1}{2}} \qquad (5)$$

where $A_0(t)$ is the valve orifice area as a function of time, and C_{DV} is the valve discharge coefficient. During the subsequent period, when the pressure ratio P_c/P_0 is greater than 0.528 $(t_{r1} < t < t_{r2})$, the flow rate through the orifice is subsonic and is given by the following equation:

$$W_0 = \frac{P_0 A_0(t) a^*}{RT} \left(\frac{P_c}{P_0} \right)^{\frac{1}{\gamma}} \left\{ \frac{2}{\gamma - 1} \left[1 - \left(\frac{P_c}{P_0} \right)^{\frac{\gamma-1}{\gamma}} \right] \right\}^{\frac{1}{2}} \qquad (6)$$

where a^* is the characteristic sonic velocity (equal to $\sqrt{g_0 \gamma RT}$). At a time $t = t_{r2}$, the rate of pressure buildup in the chamber becomes zero (i. e., chamber pressure is constant), and the flow through the orifice equals the flow out of the nozzle until such time t_2 as the valve starts to close. This is the steady-state thrust case and is described in detail, along with performance losses, in Ref. 1, where

$$W_N = W_0, \qquad \frac{dP_c}{dt} = 0$$

From the time (t_2) the valve starts to close until the time (t_3) when it is fully closed, the flow through the valve orifice is subsonic and is given by Eq. (6). For $t \geq t_3$, the valve is fully closed ($W_0 = 0$), and the gas accumulated in the chamber is discharged by an isentropic process through the nozzle ($W_N = -W_0$). The density ratio for isentropic expansion is

$$\frac{\rho}{\rho_3} = \left(\frac{P_c}{P_{c_3}}\right)^{\frac{1}{\gamma}} \tag{7}$$

where the subscript 3 refers to conditions at $t = t_3$ and ρ is the gas density. Using Eq. (1) for the initial weight of gas trapped in the chamber, Eq. (7) becomes

$$W_N = \frac{V_c P_{c_3}}{RT_{c_3}} \left(\frac{P_c}{P_{c_3}}\right)^{\frac{1}{\gamma}} \tag{8}$$

Differentiating P_c with respect to time, and substituting Eq. (4) and the equation

$$\frac{T_c}{T_{c_3}} = \left(\frac{P_c}{P_{c_3}}\right)^{\frac{\gamma-1}{\gamma}} \tag{9}$$

into the results and then integrating from t_3 to any time $t > t_3$ gives the following equation for decay pressure as a function of time:

$$P_c(t) = P_{c_3} \left[1 - \frac{(1 - \gamma)\, A_2 (t - t_3)}{2}\right]^{\frac{2\gamma}{1-\gamma}} \tag{10}$$

where A_2 is defined in Table 1.

Equations (5) and (6) require that the valve area as a function of time, $A_0(t)$, be known. Appendix A of Ref. 1 details the derivation of the steady-state (valve full open) valve orifice effective area (A_{0-ss}). This value as a function of valve ball travel T_B and for a ball radius of 0.24 cm (0.094 in.) and a seat radius of 0.17 cm (0.066 in.) (MM'71 data) is (Eq. A-11 of Ref. 1)

$$A_0 = \frac{(0.2073)(T_B)(0.134 + T_B)}{\left[0.008836 + T_B(0.134 + T_B)\right]^{1/2}}$$

Since it can be demonstrated (Ref. 2) that the particular solenoid valve will open (t_1) and close ($t_3 - t_2$) in both cases in less than 1 ms, and since the total on time t_2 is 20 ms or greater, it is a reasonable approximation that the ball opening and closing is a linear function of time. Figures 3a-c demonstrate the typical electrical and pneumatic properties of the valve under study as a function of time. Figure 3d is, therefore, the mathematical representation of the valve orifice area as a function of time as developed from Fig. 3c. With reference to Fig. 3d, the following equations for $A_0(t)$ can be developed:

$$A_0(t) = \frac{(A_0)(t)}{(t_1)} \qquad 0 < t < t_1 \qquad (11a)$$

$$A_0(t) = A_0 \qquad t_1 < t < t_2 \qquad (11b)$$

$$A_0(t) = \frac{(A_0)(t_3 - t)}{(t_3 - t_2)} \qquad t_2 < t < t_3 \qquad (11c)$$

$$A_0(t) = 0 \qquad t > t_3 \qquad (11d)$$

For this study, the values of t_1, t_2, t_3 which represent the MM'71 flight data are taken from Ref. 2 and tabulated in Table 2. In this table, the appropriate values for the MM'64 valves are also tabulated such that the computer program results for the two flight programs can be compared.

With the value for $A_0(t)$ thus determined, the chamber pressure $P_c(t)$ and the flow rates $W_N(t)$, $W_0(t)$, and $W_c(t)$ can be calculated using the appropriate equations previously defined. With the flow rates known, the accumulated mass (m_0, m_N, or m_c) is determined by solving the integral

$$m = \int_t W dt \tag{12}$$

with the appropriate flow rate equation over the appropriate time interval. The total effective impulse I is given by the integral

$$I = \int_{t=0}^{t=\infty} F_{net}(t) dt \tag{13}$$

where, from Ref. 1,

$$F_{net} = (1 - \text{losses}) P_c A_t C_{DN} \left[\frac{2\gamma^2}{\gamma - 1} \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}} \right]^{\frac{1}{2}} \tag{14}$$

and thus,

$$I = K \int_{t=0}^{t=\infty} P_c(t)\, dt$$

where

$$K = A_t C_{DN} (1 - \text{losses}) \left[\frac{2\gamma^2}{\gamma - 1} \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}} \right]^{\frac{1}{2}}$$

The thrust losses are taken into account in Eq. (14). These losses, derived and explained in Ref. 1, are assumed here to be a constant as a function of time. It is also assumed that both the inlet pressure P_0 and the inlet temperature T_0 stay constant as a function of time. The actual specific impulse I_{sp} for nitrogen at ambient temperature T_0 is

$$I_{sp}(\text{at } T_0) = \frac{I}{m_0} \tag{15}$$

Reference 3 gives an estimated temperature profile for the entire MM'71 mission, including Mars occultation. If the specific impulse at any other temperature T is desired, the following equation can be used:

$$I_{sp}(\text{at } T) = I_{sp}(\text{at } T_0)\left(\frac{T}{T_0}\right)^{\frac{1}{2}} \tag{16}$$

However, it should be remembered that the total impulse I does not change, since $I_{sp} \propto \sqrt{T}$ and $m_0 \propto 1/\sqrt{T}$ (see Eq. 15).

For the purposes of this report, an "effective" valve on time will be defined as

$$\Delta t_e \equiv \frac{I}{\text{steady-state thrust}} \tag{17}$$

Furthermore, an equivalent "tailoff" on time, t_{t0}, will be defined as

$$t_{t0} \equiv \Delta t_e - (\text{actual valve on time})$$

$$t_{t0} \equiv \Delta t_e - t_2 \tag{17}$$

The use of the two time values, Δ_{te} and t_{t0}, in the sizing of a gas system for attitude control system application is explained in Ref. 2.

III. DIGITAL COMPUTER SOLUTIONS

With all the relevant equations available, a number of methods may be used to obtain the sought after solutions. Reference 4, from which much of the above discussion is abstracted, details a solution assuming a constant flow density. Reference 5 describes a solution that can readily be implemented on an analog computer. The solution method used in this study involves numerical differentiation and integration programmed for a Univac 1108 computer using in part the existing program for the steady-state analysis discussed in Ref. 1. The computer flowchart for the steady-state portion of this analysis is given in Ref. 1, along with a list of nomenclature. For the transient analysis, which is the principal concern here, the equations previously derived must be written in the appropriate computer format for numerical differentiation and integration. This has been done for all the equations and is summarized in Table 1. The computer flow diagram for the transient analysis is given in Fig. 4. The transient analysis is added onto the end of the steady-state analysis program and is called up at statement number 600 in the main program, as can be seen by the list-print (Fig. 5). The input to the entire program is via a single read card (the variable NZ controls the number of possible read cards) which uses a 7F10.5 format to read in the seven variables on a single horizontal line in Table 2. All other data, including those in Table 3, are fixed and already in the program for this study.

In addition to the steady-state printout shown in Fig. 6, the program is also set up to print out in tabular form, in 0.1-ms intervals, the values of the following variables: t, $A_0(t)$, $M_c(t)$, $M_0(t)$, M_N, $P_c(t)$, $\Delta P/\Delta T$, I(t), $W_c(t)$, $W_0(t)$, and $W_N(t)$. The program also plots out the last nine of these variables as a function of time (see Figs. 7-10).

IV. CONCLUSIONS

Figures 7-10 show the plots for the four cases (defined in Table 2) studied for this report. Table 4 summarizes these plots. From the table, a number of conclusions can be drawn.

(1) On the MM'64 pitch and yaw valves, the area ratio (ratio of valve seat area to nozzle throat area) was 24.5:1. As a result, the transient flow rate for a short period of time is greater than 15 times the steady-state flow, with a 56% increase in impluse per pulse for a nominal 20-ms valve on time.

The equivalent area ratios for the MM'71 pitch/yaw and roll valves are 6.24 and 2.38, respectively. With these much lower ratios, the resulting increase in impulse per pulse is only 4 and 3%, respectively, for a nominal 79.5- and 27.3-ms value on time. Note that the 4% figure would have increased only slightly had the nominal on time been closer to 20 ms.

From these test points, it is concluded that for area ratios of less than 10:1, the impulse per pulse (and gas consumed per pulse) calculated by the much simpler steady-state approach would be in error on the low side by less than 10%.

(2) As expected, the gas vacuum specific impulse is the same (within 4%) when calculated by either the transient or steady-state approach.

(3) All computer runs were made assuming a local ambient temperature of 25°C. No attempt was made to determine an in-flight ambient or gas temperature, although this could be done.

(4) The shortest electrical valve on time assumed was 20 ms. Since pressure and flow rate build up to their steady-state value in a short period of time (usually less than 2.0 ms), steady-state approximations for value times of somewhat less than 20 ms should be valid.

(5) For this study, it was assumed that the discharge coefficients (losses) stay constant over the relatively short transient flow periods.

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4. Greer, H., Analytical Investigation of Nitrogen Jet Reaction Control Systems, TDR-469(5560-30)-1, Aerospace Corporation, El Segundo, Calif., Nov. 30, 1964.

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Table 1. Summary of computer equations[a]

		(a)	(b)	(c)	(d)	(e)	(f)	(g)
	$t(N)$[b]	$t < t_1$			$t_1 \le t \le t_2$		$t_2 < t < t_3$	$t \ge t_3$
	P[c]	$0 \le P \le 0.528$	$0.528 \le P \le P_{css}$	$P_c = P_{css}$	$0.528 \le P \le P_{css}$	$P = P_{css}$	$0.528 \le P \le P_{css}$	$0 > P > P_{css}$
1	$A_0(N)$	$A_0 \frac{t(N)}{t_1}$	Same as (a)	Same as (a)	A_0	Same as (d)	$A_0 \frac{t_3 - t(N)}{t_3 - t_2}$	0
2	$\frac{\partial P}{\partial t}(N)$	$A_3A_0(N) - A_2P(N-1)$	$A_1A_0(N)P(N-1)^{\frac{1}{\gamma}}\left[1 - P(N-1)^{\frac{\gamma-1}{\gamma}}\right]^{\frac{1}{2}} - A_2P(N-1)$	0	Same as (b)	0	Same as (b)	$\frac{P(N) - P(N-1)}{\Delta T}$
3	$P(N)$	$P(N-1) + \frac{\partial P}{\partial t}(N)\Delta T$	Same as (a)	P_{css}	Same as (a)	Same as (c)	Same as (a)	$P_{ccc}\left\{1 - \frac{(1-\gamma)A_2[t(N) - t_3]}{2}\right\}^{\frac{2\gamma}{1-\gamma}}$
4	$W_N(N)$	$A_5C_{DN}A_tP_0P(N)$	Same as (a)	Same as (a)	Same as (a)	Same as (a)	Same as (a)	Same as (a)
5	$W_0(N)$	$A_5C_{DV}P_0A_0(N)$	$\frac{C_{DV}P_0A^*}{RT_0}\left(\frac{2}{\gamma-1}\right)^{\frac{1}{2}} A_0(N)P(N)^{\frac{1}{\gamma}} \times \left[1 - P(N)^{\frac{\gamma-1}{\gamma}}\right]^{\frac{1}{2}}$, or $A_1A_4P_0A_0(N)P(N)^{\frac{1}{\gamma}}\left[1 - P(N)^{\frac{\gamma-1}{\gamma}}\right]^{\frac{1}{2}}$	$W_N(N)$	Same as (b)	Same as (c)	Same as (b)	0
6	$W_c(N)$	$A_4P_0\frac{\partial P}{\partial t}(N)$	Same as (a)	0	Same as (a)	0	Same as (a)	$-W_N(N)$
7	$M_N(N)$	$M_N(N-1) + W_N(N)\Delta T$	Same as (a)	Same as (a)	Same as (a)	Same as (a) with $\Delta T = \Delta T1$	Same as (a)	Same as (a)
8	$M_0(N)$	$M_0(N-1) + W_0(N)\Delta T$	Same as (a)	Same as (a)	Same as (a)	Same as (a) with $\Delta T = \Delta T1$	Same as (a)	Same as (a)
9	$M_c(N)$	$M_c(N-1) + W_c(N)\Delta T$	Same as (a)	Same as (a)	Same as (a)	Same as (a)	Same as (a)	Same as (a)
10	$I(N)$	$I(N-1) + A_6P_0\Delta TP(N)$	Same as (a)	Same as (a)	Same as (a)	Same as (a) with $\Delta T = \Delta T1$	Same as (a)	Same as (a)
11	$P_c(N)$	$P_0P(N)$	Same as (a)	Same as (a)	Same as (a)	Same as (a)	Same as (a)	Same as (a)

[a] $A^* = \sqrt{g_0\gamma RT_0}$; $A_1 = C_{DV}A^*\frac{\sqrt{2/(\gamma-1)}}{V_c}$; $A_2 = \frac{C_{DN}A^*A_t}{V_c}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$; $A_3 = \frac{C_{DV}A^*}{V_c}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$; $A_4 = \frac{V_c}{RT_0}$; $A_5 = \left[\frac{g_0\gamma}{RT_0}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\right]^{\frac{1}{2}}$;

$A_6 = (1 - \text{FLTOT})A_t\gamma\left[\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}} \frac{2}{\gamma-1}\right]^{\frac{1}{2}}$

[b] t_1, t_2, t_3 are defined in Fig. 3.

[c] $P = \frac{P_c}{P_0}$, $P_{css} = \frac{P_c(\text{steady-state})}{P_0}$, and $P_{ccc} = P(N-1)$ at $t = t_3$.

Table 2. Jet valve characteristics (computer input cards)

Mission	Axis	P_0, N/m^2 (psi)	T_0, °C	D_t,[a] mm (in.)	T_B, mm (in.)	t_1, s[b]	t_2, s[b]	t_3, s[b]
MM'71	Pitch/yaw	1.0×10^5 (15)	25	0.513 (0.0202)	0.173 (0.0068)	0.001	0.0795	0.0805
MM'71	Roll	1.0×10^5 (15)	25	0.831 (0.0327)	0.173 (0.0068)	0.001	0.0273	0.0283
MM'64	Pitch/yaw	1.0×10^5 (15)	25	0.290 (0.0114)	0.216 (0.0085)	0.001	0.020[c]	0.021[c]
MM'64	Roll	1.0×10^5 (15)	25	0.374 (0.0147)	0.216 (0.0085)	0.001	0.020[c]	0.021[c]

[a]Nozzle throat diameter.

[b]See Fig. 3 for definition.

[c]Estimate.

Table 3. MM'71 jet valve parameters (fixed)

Parameter	Value
Nozzle discharge coefficient C_{DN}	1.0
Valve discharge coefficient C_{DV}	0.63
Ambient temperature T_0, °C	25
Valve ball diameter, cm (in.)	0.478 (0.188)
Valve seat diameter, cm (in.)	0.335 (0.132)
Nozzle geometric area ratio	250:1
Nozzle exit geometry half-angle, deg	25
Ratio of specific heats (nitrogen)	1.4
Nitrogen gas constant, N-m/kg K (ft-lbf/lbm °R)	2.967×10^2 (55.16)
Ambient pressure, N/m^2 (psi)	0
Valve inlet pressure P_0, N/m^2 (psi)	1.0×10^5 (15.0)
Valve chamber volume V_C, cm^2 (in.^{2})	7.48×10^2 (0.0116)
Time differential, s (DELT)	0.0001

Table 4. Computer program results

Mission	Parameter[a]												
	Throat diameter, cm (in.)	Chamber pressure (steady-state), N/m^2 (psi)	Thrust (steady-state), $N \times 10^{-3}$ (mlb)	Flow rate (steady-state) g/s (lb/s)	Flow rate (transient), max, g/s (lb/s)	$\frac{\text{Flow rate, max}}{\text{Flow rate, s-s}}$	$\frac{\text{Mass}}{\text{Pulse}}$, g (lb)	$\frac{\text{Impulse}}{\text{Pulse}}$, N-s (lb-s)	$I_{sp} = \frac{I}{M}$, s	$I_{sp} = \frac{F_{ss}}{W_{ss}}$, s[b]	Δt_e, ms	t_2 (valve on time), ms	t_{t0} $(\Delta t_e - t_2)$, ms	$\frac{\Delta t_e}{t_2}$, %
MM'71 pitch/yaw	0.0513 (0.0202)	10.20×10^4 (14.8)	33.85 (7.61)	4.85×10^{-2} (0.107×10^{-3})	1.94×10^{-1} (0.428×10^{-3})	4.0	4.03×10^{-3} (0.889×10^{-5})	2.80×10^{-3} (0.629×10^{-3})	70.8	71.2	82.7	79.5	3.2	104
MM'71 roll	0.0831 (0.0327)	9.37×10^4 (13.6)	82.82 (18.62)	11.70×10^{-2} (0.258×10^{-3})	1.94×10^{-1} (0.428×10^{-3})	1.7	3.29×10^{-3} (0.726×10^{-5})	2.32×10^{-3} (0.522×10^{-3})	71.9	72.3	28.0	27.3	0.7	103
MM'64 pitch/yaw	0.0290 (0.0114)	10.33×10^4 (14.98)	10.59 (2.38)	1.56×10^{-2} (0.345×10^{-4})	2.42×10^{-1} (0.534×10^{-3})	15.1	5.16×10^{-2} (0.113×10^{-5})	0.331×10^{-3} (0.744×10^{-3})	66.1	68.9	31.3	20	11.3	156
MM'64 roll	0.0374 (0.0147)	10.31×10^4 (14.96)	17.88 (4.02)	2.60×10^{-2} (0.573×10^{-4})	2.42×10^{-1} (0.534×10^{-3})	9.3	7.12×10^{-2} (0.157×10^{-5})	0.476×10^{-3} (0.107×10^{-3})	68.2	70.0	26.7	20	6.7	133

[a]Valve inlet pressure = 1.0×10^5 N/m^2 (15.0 psi); valve inlet temperature = 25°C.

[b]F_{ss} = steady-state thrust (see column 3); W_{ss} = steady-state flow rate (see column 4).

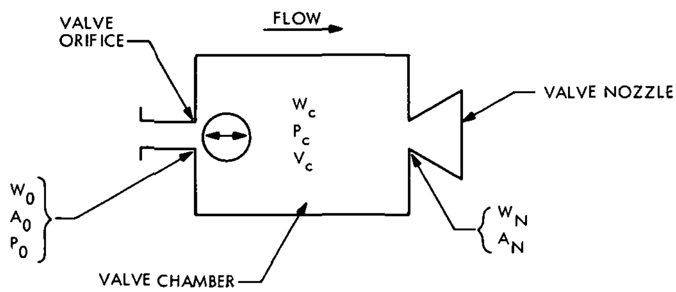


Fig. 1. MM'71 jet valve model

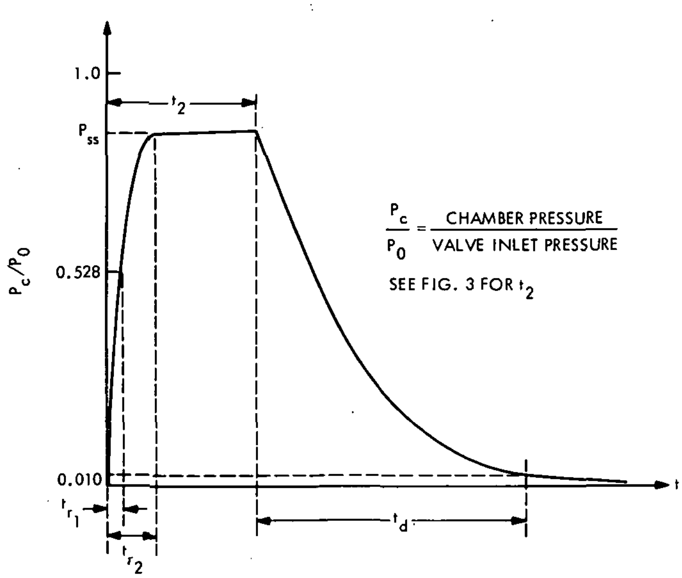


Fig. 2. Typical valve chamber pressure profile

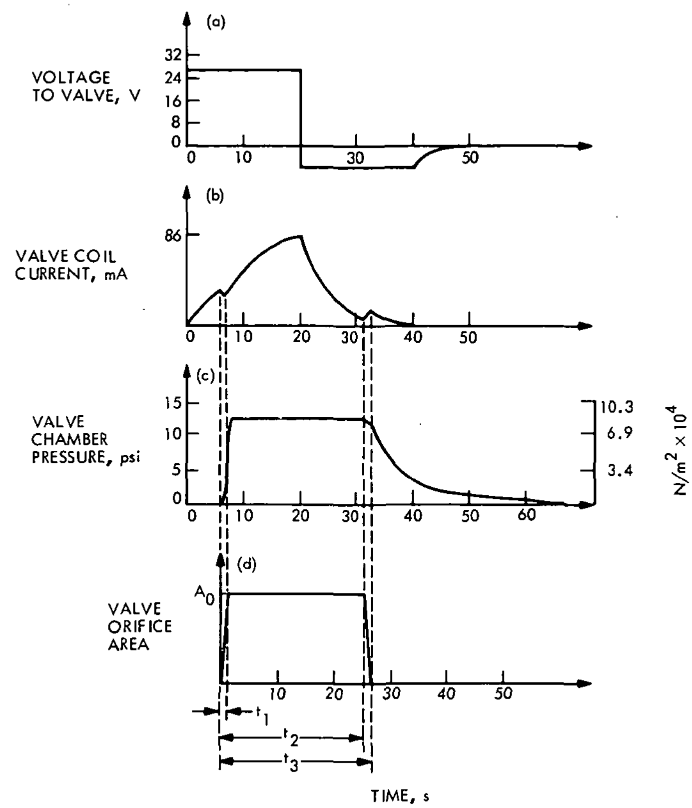


Fig. 3. Typical valve electrical and pneumatic characteristics: (a) voltage to valve, (b) valve coil current, (c) valve chamber pressure, (d) valve orifice area

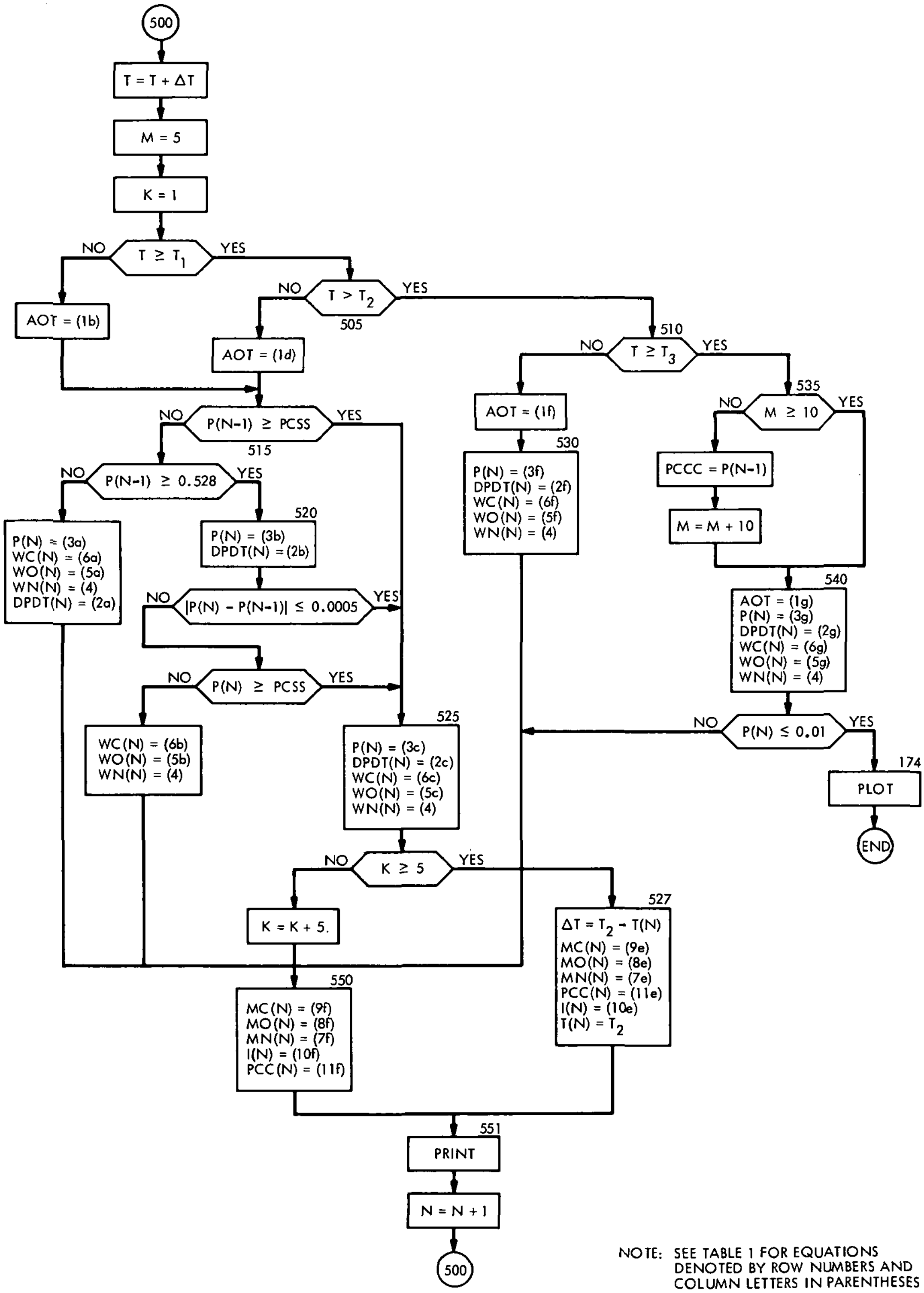


Fig. 4. Computer program flow chart

```
C       NET THRUST PREDICTION PROGRAM
        INTEGER TEST
        TEST=0
        N2=5
     50 DO 175 I=1,N2
        READ (5,2) PO,TO,DT,TB,T1,T2,T3
      2 FORMAT (7F10.5)
        CDV=0.63
        CDN=1.0
        MAX1=30.
        MAX2=30.
        MAX3=30.
        EPS1=.0001
        EPS2=.0001
        EPS3=.01
        PI=3.1416
        GO=386.06773
        R=661.92
        PA=0.
        CNINIT=6.0
        DB=0.188
        DS=0.132
        ARTGEO=250.0
        CV=4290.
        SIGDEG=25.
        GAMMA=1.401
        PCINIT=PO-0.3
      5 RS=DS/2.
     10 RB=DB/2.
     11 A1=SQRT ((RB**2)-(RS**2))
     12 A2=A1+T3
     13 PHI2=ATAN (RS/A2)
     14 Q=(RS/SIN (PHI2))-RB
     15 B=RB*RS/(RB+Q)
     16 E=A2*B/RS
     17 H=A2-E
     18 AO=PI*(RS+B)*SQRT ((H**2)+((RS-B)**2))
     19 AOX=PI*RS*RS
     20 IF(AO-AOX)22,21,21
     21 AO=AOX
     22 PRINT 23,PO
     23 FORMAT(1H1,4X16HINLET PRESSURE =,F7.3,1X9H(LBS/IN2))
     24 PRINT 25,CDV
     25 FORMAT(5X37HVALVE ORIFICE DISCHARGE COEFFICIENT =,F7.4)
     26 PRINT 27,T3
     27 FORMAT(5X13HBALL TRAVEL =,F7.5,1X4H(IN))
     28 PRINT 29,ARTGEO
     29 FORMAT(5X29HNOZZLE GEOMETRIC AREA RATIO =,F8.3)
     30 PRINT 31,SIGDEG
     31 FORMAT(5X19HNOZZLE HALF-ANGLE =,F5.1,1X5H(DEG))
     32 PRINT 33,TO
     33 FORMAT(5X23HINLET GAS TEMPERATURE =,F6.1,1X7H(DEG C))
     34 PRINT 35
     35 FORMAT(5X19HNITROGEN PROPELLANT)
     36 PRINT 37,AO
     37 FORMAT(5X30HVALVE ORIFICE EFFECTIVE AREA =,F7.5,1X5H(IN2))
     38 PRINT 39,AOX
     39 FORMAT(5X17HVALVE SEAT AREA =,F7.5,1X5H(IN2)//)
     40 PRINT 41
     41 FORMAT(5X10HNET THRUST,11X6HNOZZLE,7X5HVALVE,9X6HTHRUST,10X6HWEIG-
       1T,3X9HEXIT MACH)
     43 PRINT 44
     44 FORMAT(7X5H(LBS),14X5HTHROAT,6X8HPRESSURE,7X6HLOSSES,9X8HFLOWRATE,
       19X6HNUMBER)
     45 PRINT 47
     47 FORMAT(25X8HDIAMETER,7X4HDROP,7X10H(PER CENT),7X9H(LBS/SEC))
     48 PRINT 49
     49 FORMAT(27X4H(IN),6X9H(LBS/IN2) /)
        RT=DT/2.
     51 AT=PI*RT*RT
     52 AE=ARTGEO*AT
     53 DE=SQRT (4.*AE/PI)
```

Fig. 5. Computer list printout of steady-state and transient thrust prediction program

```
54 RE=DE/2.
55 SIGMA=(SIGDEG/360.)*2.*PI
56 SL=(RE-RT)*COS (SIGMA)/SIN (SIGMA)
57 FGAM=(GAMMA+1.)/(GAMMA-1.)
58 PC=PCINIT
59 CPC=((GAMMA-1.)/2.)*((AT*CDN/(AO*CDV))**2.)*((2./(GAMMA+1.))**FGAM
  1)
60 IN1=1
61 FPC=((PC/PO)**((2.-(2.*GAMMA))/GAMMA))-((PC/PO)**((1.-GAMMA)/GAMMA
  1))-CPC
63 DFPC=(((2.-(2.*GAMMA))/GAMMA)*(PO**(((2.*GAMMA)-2.)/GAMMA))*(PC**(
  1(2.-(3.*GAMMA))/GAMMA)))-(((1.-GAMMA)/GAMMA)*(PO**((GAMMA-1.)/GAMM
  2A))*(PC**((1.-(2.*GAMMA))/GAMMA)))
66 PCN=PC-(FPC/DFPC)
67 IF(TEST .NE. 1) GO TO 71
68 PRINT 69,FPC,DFPC,PCN,IN1
69 FORMAT(2X5HFPC =,E15.8,5X6HDFPC =,E15.8,5X5HPCN =,E15.8,5X10HITER(
  1PC) =,I4)
71 IN1=IN1+1
72 IF(ABS (PCN-PC)-EPS1)78,78,73
73 PC=PCN
74 IF(MAX1-IN1)75,75,61
75 PRINT 76,PC
76 FORMAT(2X24HITERATION LIMIT EXCEEDED,5X9HPC(DIV) =,E15.8)
77 GO TO 175
78 PC=PCN
79 DELP=PO-PC
80 TR=(9.*TO)/5.+491.69
81 WODOT=AO*CDV*PO*((PC/PO)**(1./GAMMA))*SQRT ((2.*GO/(R*TR))*(GAMMA/
  1(GAMMA-1.))*(1.-((PC/PO)**((GAMMA-1.)/GAMMA))))
83 WTDOT=CDN*PC*AT*SQRT ((GAMMA*GO/(R*TR))*((2./(GAMMA+1.))**((GAMMA+
  11.)/(GAMMA-1.))))
85 ARTERO=.5*ARTGEO
86 CN=CNINIT
87 IN3=1
88 IN2=0
89 C1=(GAMMA+1.)/(2.*(GAMMA-1.))
90 C2=(GAMMA-1.)/2.
91 C3=((GAMMA+1.)/2.)**C1
92 FCN=C3*CN*((1.+(C2*CN*CN))**(-C1))-(1./ARTERO)
93 DFCN=C3*(2.*C2*CN*CN*(-C1)*((1.+(C2*CN*CN))**(-C1-1.))+((1.+(C2*CN
  1*CN))**(-C1)))
95 CNN=CN-(FCN/DFCN)
96 IN2=IN2+1
97 IF(TEST .NE. 1) GO TO 100
98 PRINT 99,FCN,DFCN,CNN
99 FORMAT(2X5HFCN =,E15.8,5X6HDFCN =,E15.8,5X5HCNN =,E15.8)
100 IF(ABS (CNN-CN)-EPS2)105,105,101
101 CN=CNN
102 IF(MAX2-IN2)103,103,92
103 PRINT 104,CN
104 FORMAT(2X24HITERATION LIMIT EXCEEDED,5X9HME(DIV) =,E15.8)
    GO TO 175
105 CN=CNN
106 TRAT=1.+((GAMMA-1.)*CN*CN/2.)
107 UO=(2.270E-08)*(TR**(3./2.))/(TR+198.6)
108 RENOU=(CN/UO)*SQRT (GAMMA/((GAMMA-1.)*CV*TR))*(TRAT**((GAMMA-2.)/(
  1GAMMA-1.)))*(((TR/TRAT)+198.6)/(TR+198.6))
110 RENO=12.*RENOU*SL*PC
111 DELTA=.645*SL/SQRT (RENO)
112 IF(CN-6.5)113,113,116
113 DELSTR=DELTA*(-.00022*CN**6+.00671*CN**5-.07610*CN**4+.39770*CN**3
  1-.30376*CN**2+.99230*CN+2.28324)
115 GO TO 123
116 IF(CN-7.5)117,117,119
117 DELSTR=DELTA*(8.6*CN-25.9)
118 GO TO 123
119 IF(CN-9.0)120,120,122
120 DELSTR=DELTA*(10.0*CN-36.4)
121 GO TO 123
122 DELSTR=DELTA*(10.9*CN-44.4)
123 REEFF=RE-DELSTR
```

Fig. 5 (contd)

```
  124 IF(REEFF)129,129,125
  125 ARITER=(REEFF*REEFF)/(RT*RT)
  126 IF(ABS (ARTERO-ARITER)-EPS3)133,133,127
  127 IF(MAX3-IN3)131,131,128
  128 IN3=IN3+1
  129 ARTERO=(ARTERO+ARITER)/2.
  130 GO TO 88
  131 PRINT 132,ARITER
  132 FORMAT(2X24HITERATION LIMIT EXCEEDED,5X13HARTERO(DIV) =,E15.8)
      GO TO 125
  133 SIGEFF=ATAN (REEFF/SL)
  134 PE=PC*((1.+(((GAMMA-1.)/2.)*CN*CN))**(-GAMMA/(GAMMA-1.)))
  135 TE=TR/TRAT
  136 CE=SQRT (GC*GAMMA*R*TE)
  137 VE=CE*CN
  138 VEF=VE/12.
  139 CFP=PE*ARITER*GO*AT/(WODOT*VE)
  140 FP=(1.-.5*(1.+COS (SIGEFF)))/(1.+CFP)
  141 FDEL=2.*(RE-(DELTA/2.))*DELTA/((RE-DELSTR)*(RE-DELSTR))
  142 FMAX=PC*AT*SQRT (2.*GAMMA*GAMMA*((2./(GAMMA+1.))**FGAM)/(GAMMA-1.)
     1)
  144 CF=SQRT (((2.*GAMMA*GAMMA)/(GAMMA-1.))*((2./(GAMMA+1.))**FGAM)*(1.
     1-((PE/PC)**((GAMMA-1.)/GAMMA)))) +((PE-PA)*ARITER/PC)
  146 FTHEOR=CF*PC*AT
  147 FN=(FMAX-FTHEOR)/FMAX
  148 FLTOT=1.-((1.-FP)*(1.-FDEL)*(1.-FN))
  149 FLTOTP=FLTOT*100.
  150 FNET=FMAX*(1.-FLTOT)
  151 PRINT 152,FNET,DT,DELP,FLTOTP,WODOT,CN
  152 FORMAT(2X,E15.8,7X,F9.5,5X,F7.4,8X,F6.2,6X,E15.8,6X,F6.3)
      PRINT 153
  153 FORMAT (1H1)
      IF(TEST.NE.1) GO TO 600
  154 PRINT 155,WTDOT,IN2
  155 FORMAT(2X7HWTDOT =,E15.8,5X10HITER(ME) =,I4)
  156 PRINT 157,ARTERO,ARITER,IN3
  157 FORMAT(2X13HAE/AT(INIT) =,E15.8,5X13HAE/AT(ITER) =,E15.8,5X10HITER
     1(BL) =,I4)
  159 PRINT 160,PC,PE,TE,CE,VEF
  160 FORMAT(2X4HPC =,E15.8,5X4HPE =,E15.8,5X4HTE =,E15.8,5X4HCE =,E15.8
     1,5X5HVEF =,E15.8)
  162 PRINT 163,TRAT,UO,RENOU,RENO
  163 FORMAT(2X6HTRAT =,E15.8,5X7HMU(O) =,E15.8,5X10HRENO(MU) =,E15.8,5X
     16HRENO =,E15.8)
  165 PRINT 166,DELTA,DELSTR,REEFF
  166 FORMAT(2X7HDELTA =,E15.8,5X13HDELTA(STAR) =,E15.8,5X7HREEFF =,E1
     15.8)
  168 PRINT 169,FTHEOR,FMAX
  169 FORMAT(2X8HFTHEOR =,E15.8,5X6HFMAX =,E15.8)
  170 PRINT 171,FP,FDEL,FN,FLTOT
  171 FORMAT(2X4HLP =,E15.8,5X6HLDEL =,E15.8,5X4HLN =,E15.8,5X7HLFTOT =,
     1E15.8)
  600 DIMENSION  P(350),DPDT(850),ZC(850),ZO(850),ZN(350),WC(950),WO(650
     1),WN(850),PCC(850),T(850),X(650),Y(650),EMP(850)
      M=5
      PCSS=PC/PC
      DELT=0.0001
      T(1)=0.
      P(1)=0.
      DPDT(1)=0.
      K=1
      N=2
      ZC(1)=0.
      ZC(1)=0.
      ZN(1)=0.
      EMP(1)=0.
      VC=0.0115339
      ASTAR=SQRT(GC*GAMMA*R*TR)
      A1=CDV*ASTAR*(SQRT(2./(GAMMA-1.)))/VC
      A2=CDN*ASTAR*AT/(VC*C3)
      A3=CDV*ASTAR/(VC*C3)
      A4=VC/(R*TR)
```

Fig. 5 (contd)

```
      A5=SQRT(GO*GAMMA/(R*TR))/C3
      AE=(1.-FLTOT)*AT*GAMMA/(C3*SQRT(C2))
  500 T(N)=T(N-1)+DELT
      IF(T(N).GE.T1) GO TO 505
      AOT=AO*T(N)/T1
      GO TO 515
  505 IF(T(N).GT.T2) GO TO 510
      AOT=AO
      GO TO 515
  510 IF(T(N).GE.T3) GO TO 535
      AOT=AO*(1.-(T(N)-T2)/(T3-T2))
      GO TO 530
  515 IF(P(N-1).GE.PCSS) GO TO 525
      IF(P(N-1).GE.0.528) GO TO 520
      DPOT(N)=A3*AOT-A2*P(N-1)
      P(N)=P(N-1)+DPOT(N)*DELT
      WC(N)=A4*DPOT(N)*PO
      WO(N)=A5*COV*AOT*PO
      WN(N)=A5*CON*AT*P(N)*PO
      GO TO 550
  520 DPOT(N)=A1*AOT*(P(N-1)**(1./GAMMA))*SQRT(1.-P(N-1)**((GAMMA-1.)/GA
     1MMA))-A2*P(N-1)
      P(N)=P(N-1)+DPOT(N)*DELT
      IF(ABS(P(N)-P(N-1)).LE.0.0005) GO TO 525
      IF(P(N).GE.PCSS) GO TO 525
      WC(N)=A4*DPOT(N)*PO
      WO(N)=COV*AOT*PO*(P(N)**(1./GAMMA))*SQRT(2.*GO*GAMMA*(1.-P(N)**((G
     1AMMA-1.)/GAMMA))/(R*TR*(GAMMA-1.)))
      WN(N)=A5*CON*AT*P(N)*PO
      GO TO 550
  525 WC(N)=0.
      P(N)=PCSS
      DPOT(N)=0.
      WN(N)=A5*CON*AT*P(N)*PO
      WO(N)=WN(N)
      IF(K.GE.5) GO TO 527
      K=K+5
      GO TO 550
  527 DELT1=T2-T(N)
      ZC(N)=ZC(N-1)+WC(N)*DELT
      ZO(N)=ZO(N-1)+WO(N)*DELT1
      ZN(N)=ZN(N-1)+WN(N)*DELT1
      EMP(N)=EMP(N-1)+AE*P(N)*PO*DELT1
      PCC(N)=P(N)*PO
      T(N)=T2
      GO TO 551
  530 DPOT(N)=A1*AOT*(P(N-1)**(1./GAMMA))*SQRT(1.-P(N-1)**((GAMMA-1.)/GA
     1MMA))-A2*P(N-1)
      P(N)=P(N-1)+DPOT(N)*DELT
      WC(N)=A4*DPOT(N)*PO
      WO(N)=COV*AOT*PO*(P(N)**(1./GAMMA))*SQRT(2.*GO*GAMMA*(1.-P(N)**((G
     1AMMA-1.)/GAMMA))/(R*TR*(GAMMA-1.)))
      WN(N)=A5*CON*AT*P(N)*PO
      GO TO 550
  535 IF(M.GE.10) GO TO 540
      PCCC=P(N-1)
      M=M+10
  540 P(N)=PCCC*(1.-(1.-GAMMA)*A2*(T(N)-T3)/2.)**(2.*GAMMA/(1.-GAMMA))
      DPOT(N)=(P(N)-P(N-1))/DELT
      AOT=0.
      WO(N)=0.
      WN(N)=A5*CON*AT*P(N)*PO
      WC(N)=-WN(N)
      IF(P(N).LE.0.010) GO TO 174
  550 ZC(N)=ZC(N-1)+WC(N)*DELT
      ZO(N)=ZO(N-1)+WO(N)*DELT
      ZN(N)=ZN(N-1)+WN(N)*DELT
      EMP(N)=EMP(N-1)+AE*P(N)*PO*DELT
      PCC(N)=P(N)*PO
  551 PRINT 1000,N,T(N) ,AOT,ZC(N),ZO(N),ZN(N),PCC(N),DPOT(N),EMP(N),WC(
     1N),WO(N),WN(N)
 1000 FORMAT (2X,I4,11E11.5)
```

Fig. 5 (contd)

```
      N=N+1
      GO TO 500
  174 L=N-1
      DIMENSION TITLE(14),XNAME(14),YNAM1(10),YNAM2(10),YNAM3(10),YNAM4(
     110),YNAM5(10),YNAM6(10),YNAM7(10),YNAM8(10),YNAM9(10),ROW1(2,1)
      REAL ROW2(1)
      DATA TITLE /'
     .                                        '/
      DATA XNAME /'                                   TIME,MILLISECONDS
     .                                        '/
      DATA YNAM1 /'                           CHAMBER PRESSURE-PSIA
     .         '/
      DATA YNAM2 /'                           TOTAL MASS-NOZZLE-LB
     .         '/
      DATA YNAM3 /'                           TOTAL MASS-CHAMBER-LB
     .         '/
      DATA YNAM4 /'                           TOTAL MASS-VALVE-LB
     .         '/
      DATA YNAM5 /'                           FLOWRATE-NOZZLE-LB/SEC
     .         '/
      DATA YNAM6 /'                           FLOWRATE-CHAMBER-LB/SEC
     .         '/
      DATA YNAM7 /'                           FLOWRATE-VALVE-LB/SEC
     .         '/
      DATA YNAM8 /'                           TOTAL IMPULSE-LB SEC
     .         '/
      DATA YNAM9 /'                       CHAMBER PRESSURE DERIVATIVE
     .         '/
      DATA ROW1  /'               '/
      DATA ROW2  /0./
      INTERP=1
      DO 800 N=1,L
      X(N)=T(N)*1000.
      Y(N)=PCC(N)
  800 CONTINUE
      CALL EZPLOT (X ,Y ,L,INTERP,TITLE,XNAME,YNAM1,ROW1,ROW2,0)
      DO 801 N=1,L
      Y(N)=ZN(N)
  801 CONTINUE
      CALL EZPLOT (X ,Y ,L,INTERP,TITLE,XNAME,YNAM2,ROW1,ROW2,0)
      DO 802 N=1,L
      Y(N)=ZC(N)
  802 CONTINUE
      CALL EZPLOT (X ,Y ,L,INTERP,TITLE,XNAME,YNAM3,ROW1,ROW2,0)
      DO 803 N=1,L
      Y(N)=ZO(N)
  803 CONTINUE
      CALL EZPLOT (X ,Y ,L,INTERP,TITLE,XNAME,YNAM4,ROW1,ROW2,0)
      DO 804 N=1,L
      Y(N)=WN(N)
  804 CONTINUE
      CALL EZPLOT (X ,Y ,L,INTERP,TITLE,XNAME,YNAM5,ROW1,ROW2,0)
      DO 805 N=1,L
      Y(N)=WC(N)
  805 CONTINUE
      CALL EZPLOT (X ,Y ,L,INTERP,TITLE,XNAME,YNAM6,ROW1,ROW2,0)
      DO 806 N=1,L
      Y(N)=WC(N)
  806 CONTINUE
      CALL EZPLOT (X ,Y ,L,INTERP,TITLE,XNAME,YNAM7,ROW1,ROW2,0)
      DO 807 N=1,L
      Y(N)=EMP(N)
  807 CONTINUE
      CALL EZPLOT (X ,Y ,L,INTERP,TITLE,XNAME,YNAM8,ROW1,ROW2,0)
      DO 808 N=1,L
      Y(N)=DPDT(N)
  808 CONTINUE
      CALL EZPLOT (X ,Y ,L,INTERP,TITLE,XNAME,YNAM9,ROW1,ROW2,0)
  175 CONTINUE
      END

END OF COMPILATION:        NO  DIAGNOSTICS.
```

Fig. 5 (contd)

(a)

```
INLET PRESSURE = 15.000 (LBS/IN2)
VALVE ORIFICE DISCHARGE COEFFICIENT =  .6300
BALL TRAVEL = .00680 (IN)
NOZZLE GEOMETRIC AREA RATIO = 250.000
NOZZLE HALF-ANGLE = 25.0 (DEG)
INLET GAS TEMPERATURE =  25.0 (DEG C)
NITROGEN PROPELLANT
VALVE ORIFICE EFFECTIVE AREA = .00200 (IN2)
VALVE SEAT AREA = .01368 (IN2)
```

NET THRUST (LBS)	NOZZLE THROAT DIAMETER (IN)	VALVE PRESSURE DROP (LBS/IN2)	THRUST LOSSES (PER CENT)	WEIGHT FLOWRATE (LBS/SEC)	EXIT MACH NUMBER
.76137258-02	.02020	.2235	11.19	.10652035-03	6.878

(b)

```
INLET PRESSURE = 15.000 (LBS/IN2)
VALVE ORIFICE DISCHARGE COEFFICIENT =  .6300
BALL TRAVEL = .00690 (IN)
NOZZLE GEOMETRIC AREA RATIO = 250.000
NOZZLE HALF-ANGLE = 25.0 (DEG)
INLET GAS TEMPERATURE =  25.0 (DEG C)
NITROGEN PROPELLANT
VALVE ORIFICE EFFECTIVE AREA = .00200 (IN2)
VALVE SEAT AREA = .01368 (IN2)
```

NET THRUST (LBS)	NOZZLE THROAT DIAMETER (IN)	VALVE PRESSURE DROP (LBS/IN2)	THRUST LOSSES (PER CENT)	WEIGHT FLOWRATE (LBS/SEC)	EXIT MACH NUMBER
.19618040-01	.03270	1.4196	3.83	.25751027-03	7.085

(c)

```
INLET PRESSURE = 15.000 (LBS/IN2)
VALVE ORIFICE DISCHARGE COEFFICIENT =  .6300
BALL TRAVEL = .00850 (IN)
NOZZLE GEOMETRIC AREA RATIO = 250.000
NOZZLE HALF-ANGLE = 25.0 (DEG)
INLET GAS TEMPERATURE =  25.0 (DEG C)
NITROGEN PROPELLANT
VALVE ORIFICE EFFECTIVE AREA = .00250 (IN2)
VALVE SEAT AREA = .01368 (IN2)
```

NET THRUST (LBS)	NOZZLE THROAT DIAMETER (IN)	VALVE PRESSURE DROP (LBS/IN2)	THRUST LOSSES (PER CENT)	WEIGHT FLOWRATE (LBS/SEC)	EXIT MACH NUMBER
.23761739-02	.01140	.0147	14.19	.34534640-04	6.565

(d)

```
INLET PRESSURE = 15.000 (LBS/IN2)
VALVE ORIFICE DISCHARGE COEFFICIENT =  .6300
BALL TRAVEL = .00850 (IN)
NOZZLE GEOMETRIC AREA RATIO = 250.000
NOZZLE HALF-ANGLE = 25.0 (DEG)
INLET GAS TEMPERATURE =  25.0 (DEG C)
NITROGEN PROPELLANT
VALVE ORIFICE EFFECTIVE AREA = .00250 (IN2)
VALVE SEAT AREA = .01368 (IN2)
```

NET THRUST (LBS)	NOZZLE THROAT DIAMETER (IN)	VALVE PRESSURE DROP (LBS/IN2)	THRUST LOSSES (PER CENT)	WEIGHT FLOWRATE (LBS/SEC)	EXIT MACH NUMBER
.40152763-02	.01470	.0406	12.65	.57323874-04	6.710

Fig. 6. Steady-state printout: (a) MM'71 pitch/yaw, (b) MM'71 roll, (c) MM'64 pitch/yaw, (d) MM'64 roll

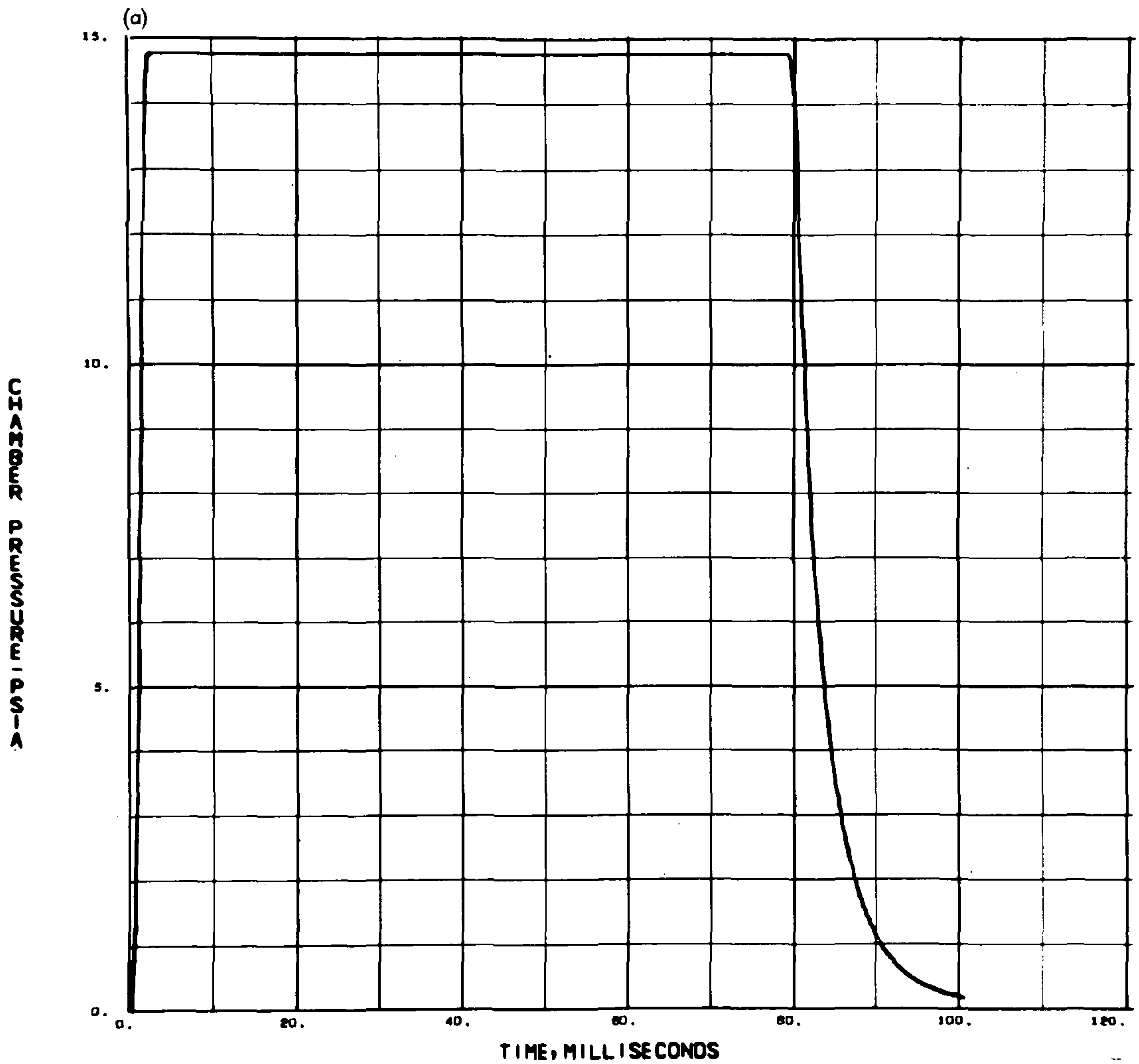
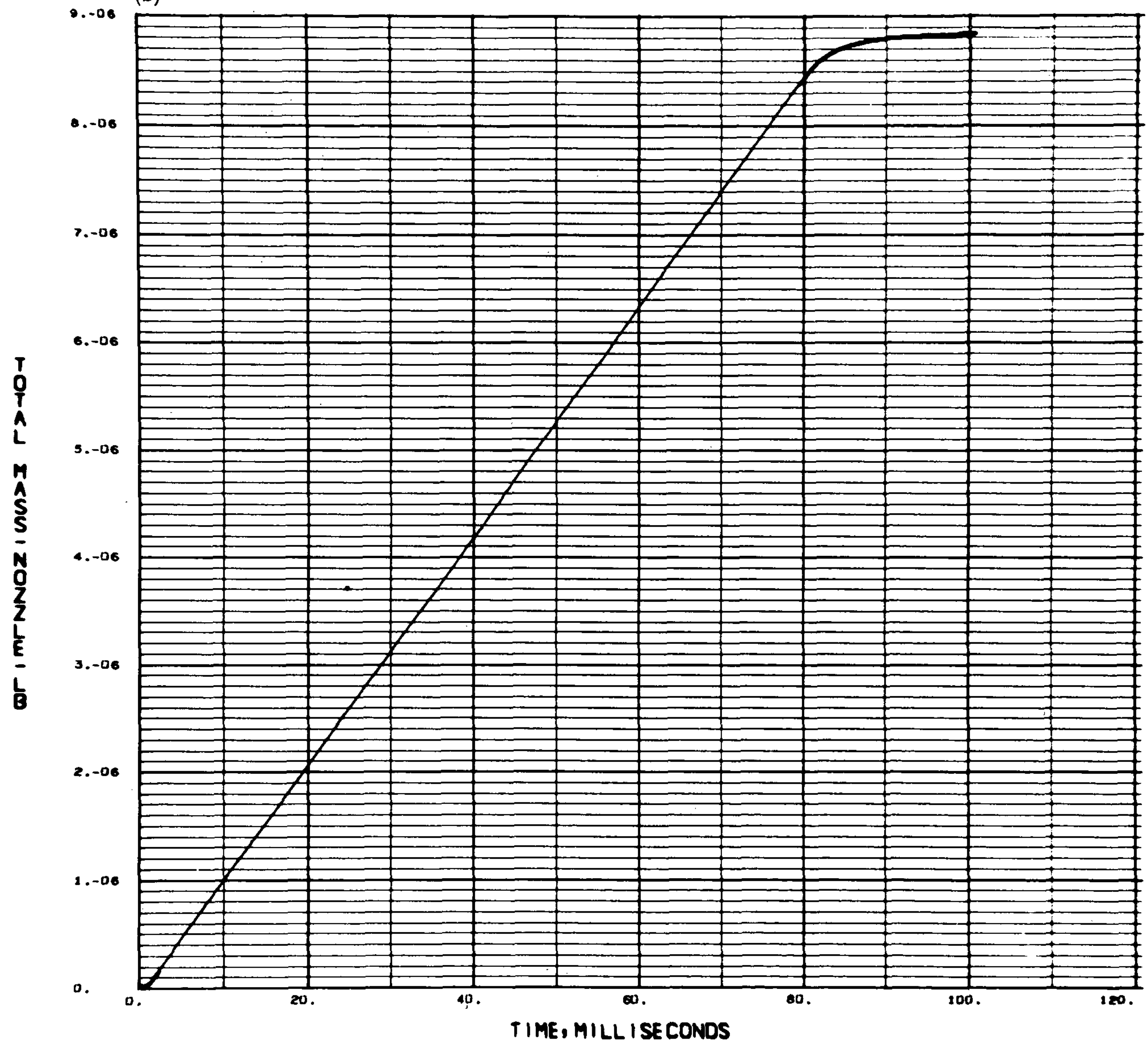


Fig. 7. MM'71 pitch/yaw valve parameters as a function of time: (a) chamber pressure, (b) total mass, nozzle, (c) total mass, chamber, (d) total mass, valve, (e) nozzle flow rate, (f) chamber flow rate, (g) valve flow rate, (h) total impulse, (i) chamber pressure derivative

(b)



9.-06
8.-06
7.-06
6.-06
5.-06
4.-06
3.-06
2.-06
1.-06
0.
TOTAL MASS-NOZZLE-LB
0.
20.
40.
60.
80.
100.
120.
TIME, MILLISECONDS

Fig. 7 (contd)

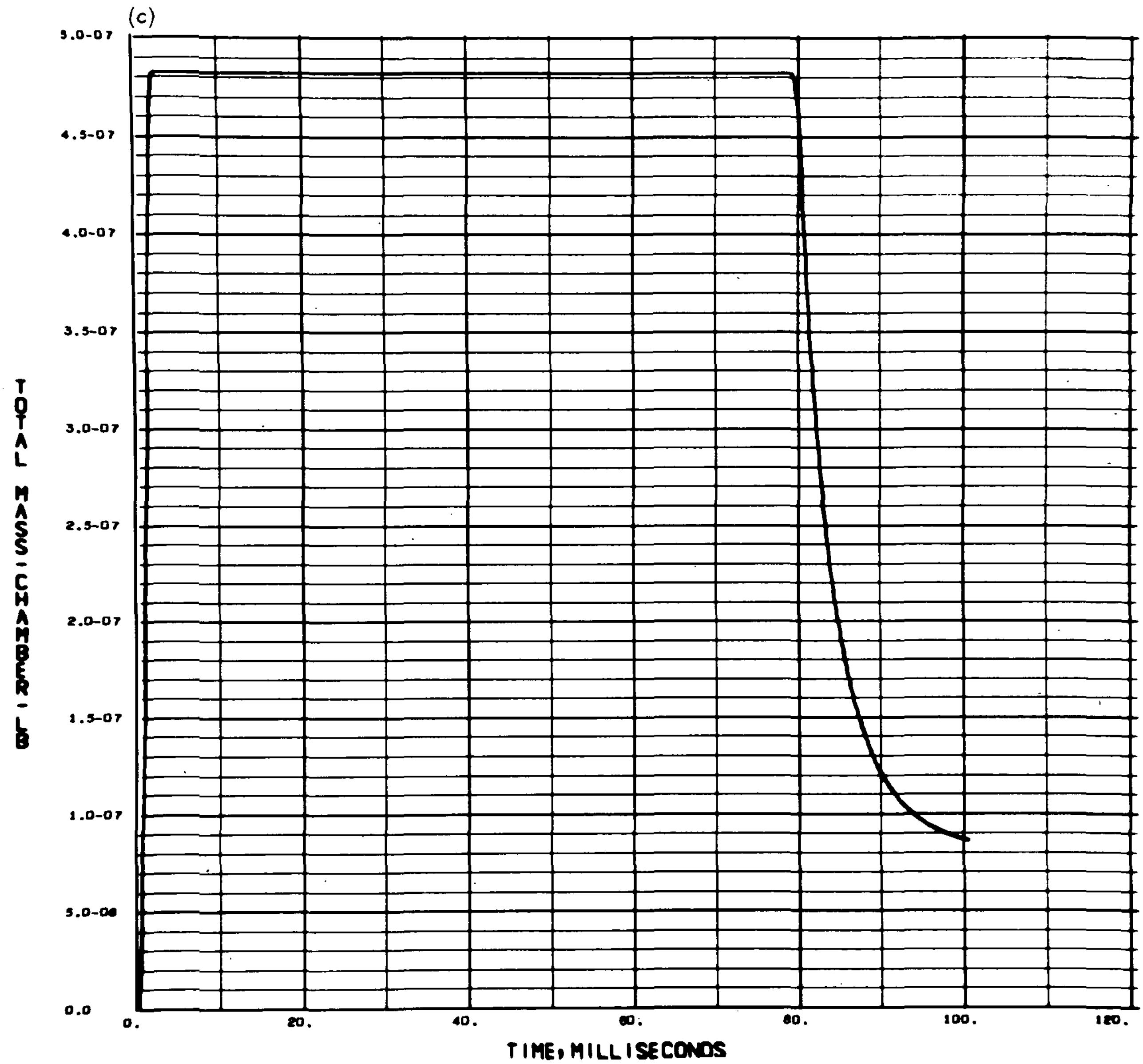

(c)
5.0-07
4.5-07
4.0-07
3.5-07
3.0-07
2.5-07
2.0-07
1.5-07
1.0-07
5.0-08
0.0
TOTAL MASS-CHAMBER-LB
0.
20.
40.
60.
80.
100.
120.
TIME, MILLISECONDS

Fig. 7 (contd)

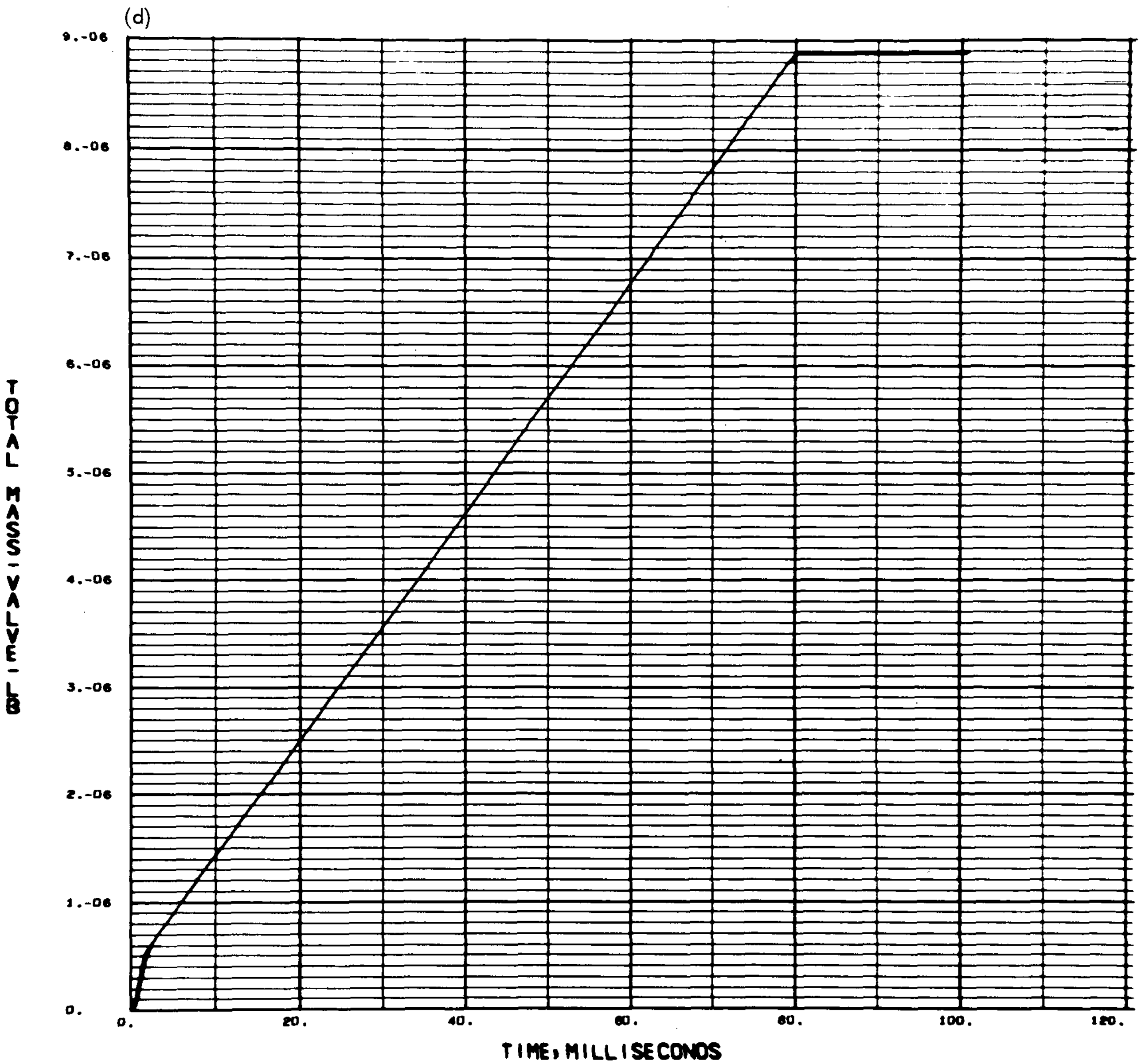

(d)
9.-06
8.-06
7.-06
6.-06
5.-06
4.-06
3.-06
2.-06
1.-06
0.
0.
20.
40.
60.
80.
100.
120.
TOTAL MASS-VALVE-LB
TIME, MILLISECONDS

Fig. 7 (contd)

(e)

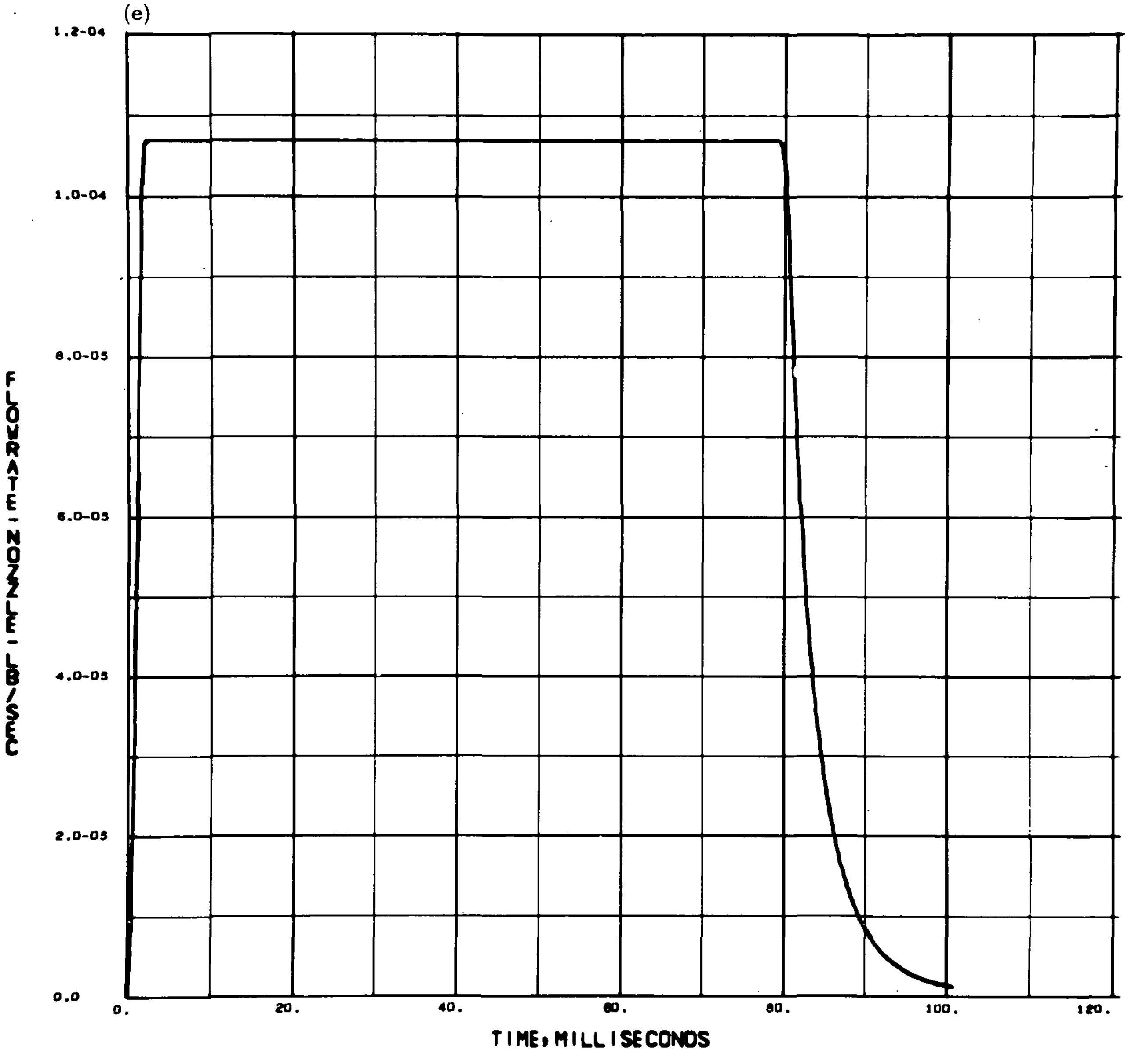

1.2-04
1.0-04
8.0-05
6.0-05
4.0-05
2.0-05
0.0
FLOWRATE-NOZZLE-LB/SEC
0.
20.
40.
60.
80.
100.
120.
TIME, MILLISECONDS

Fig. 7 (contd)

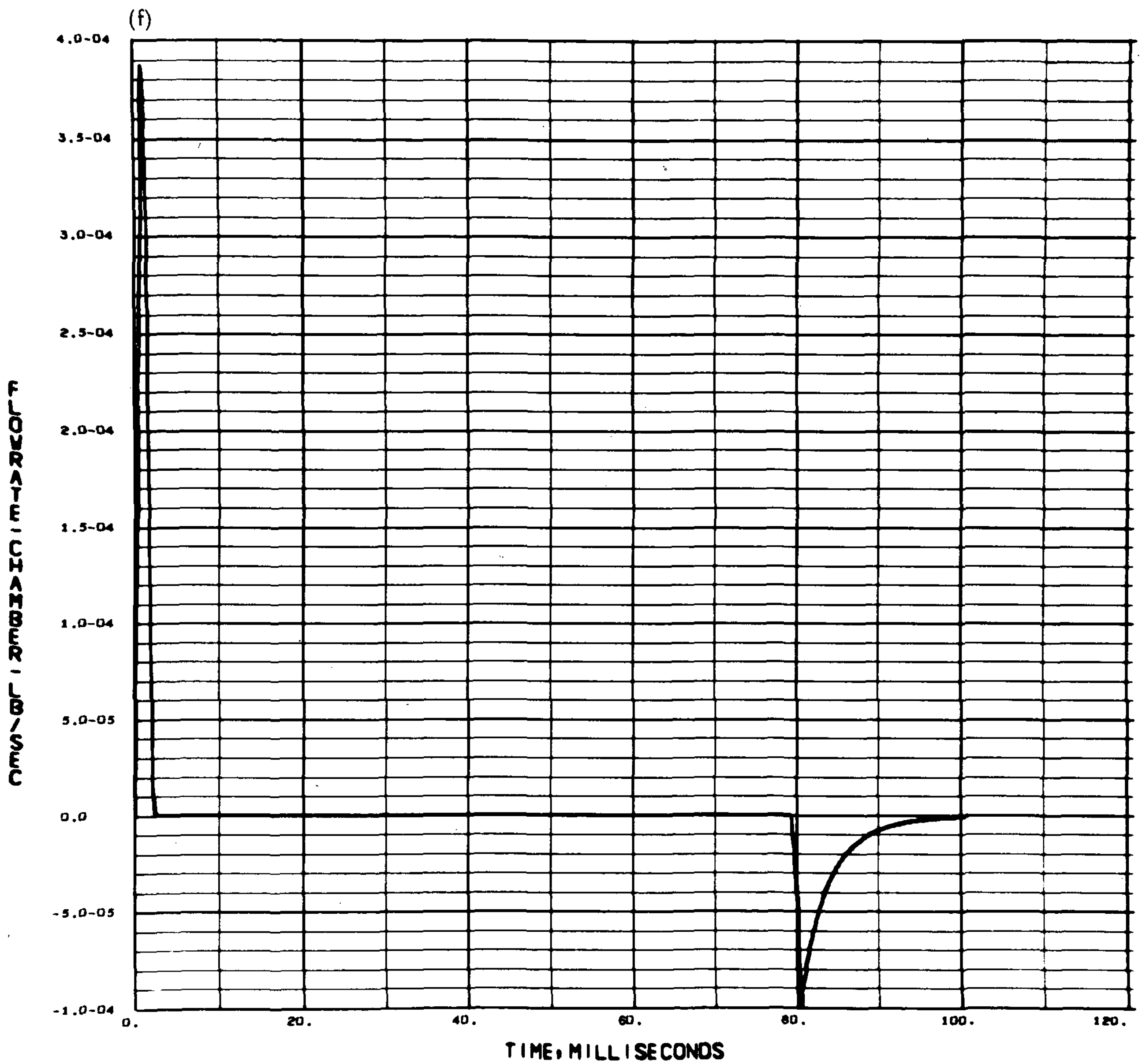

(f)
4.0-04
3.5-04
3.0-04
2.5-04
2.0-04
1.5-04
1.0-04
5.0-05
0.0
-5.0-05
-1.0-04
FLOWRATE, CHAMBER, LB/SEC
0.
20.
40.
60.
80.
100.
120.
TIME, MILLISECONDS

Fig. 7 (contd)

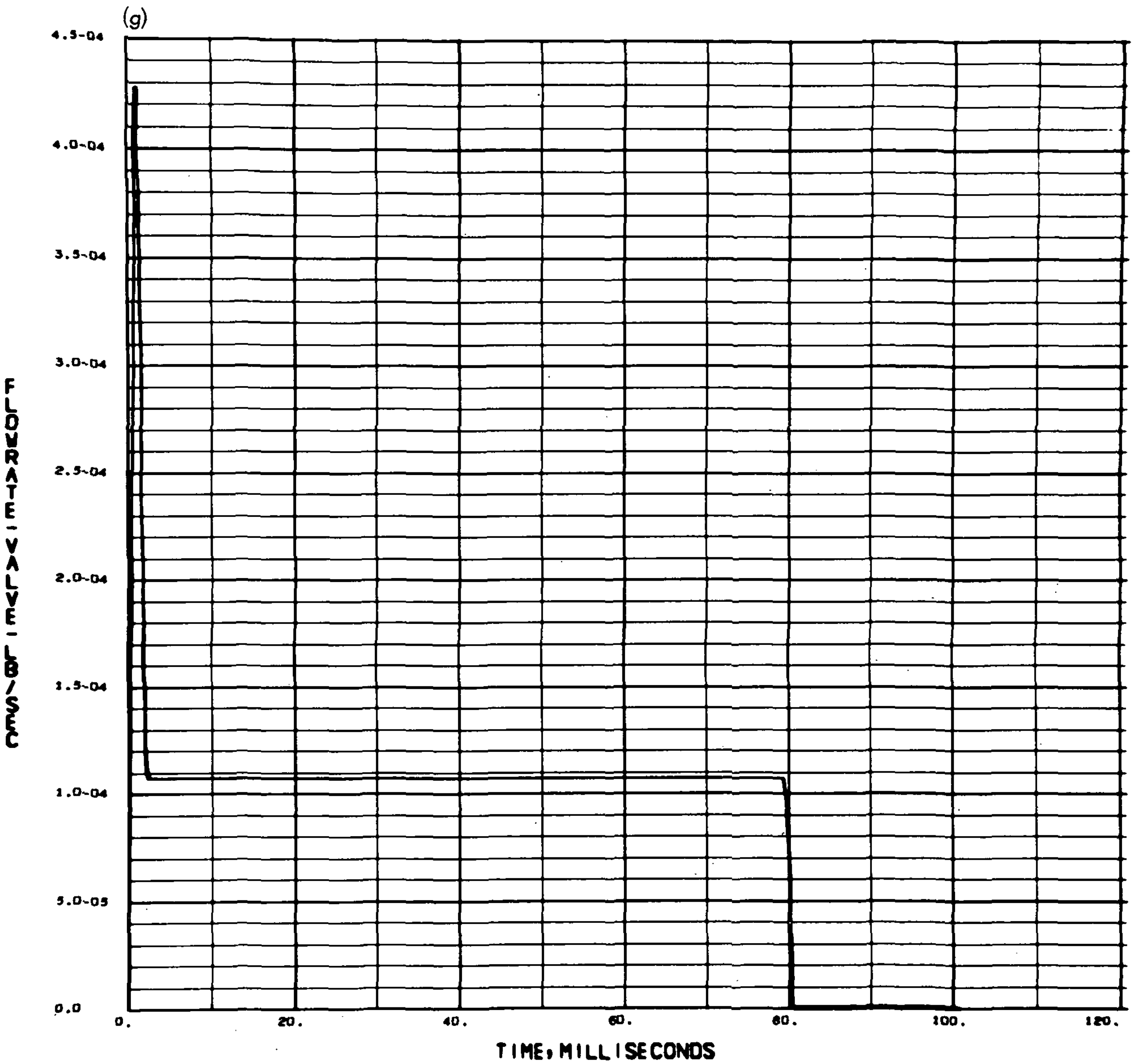
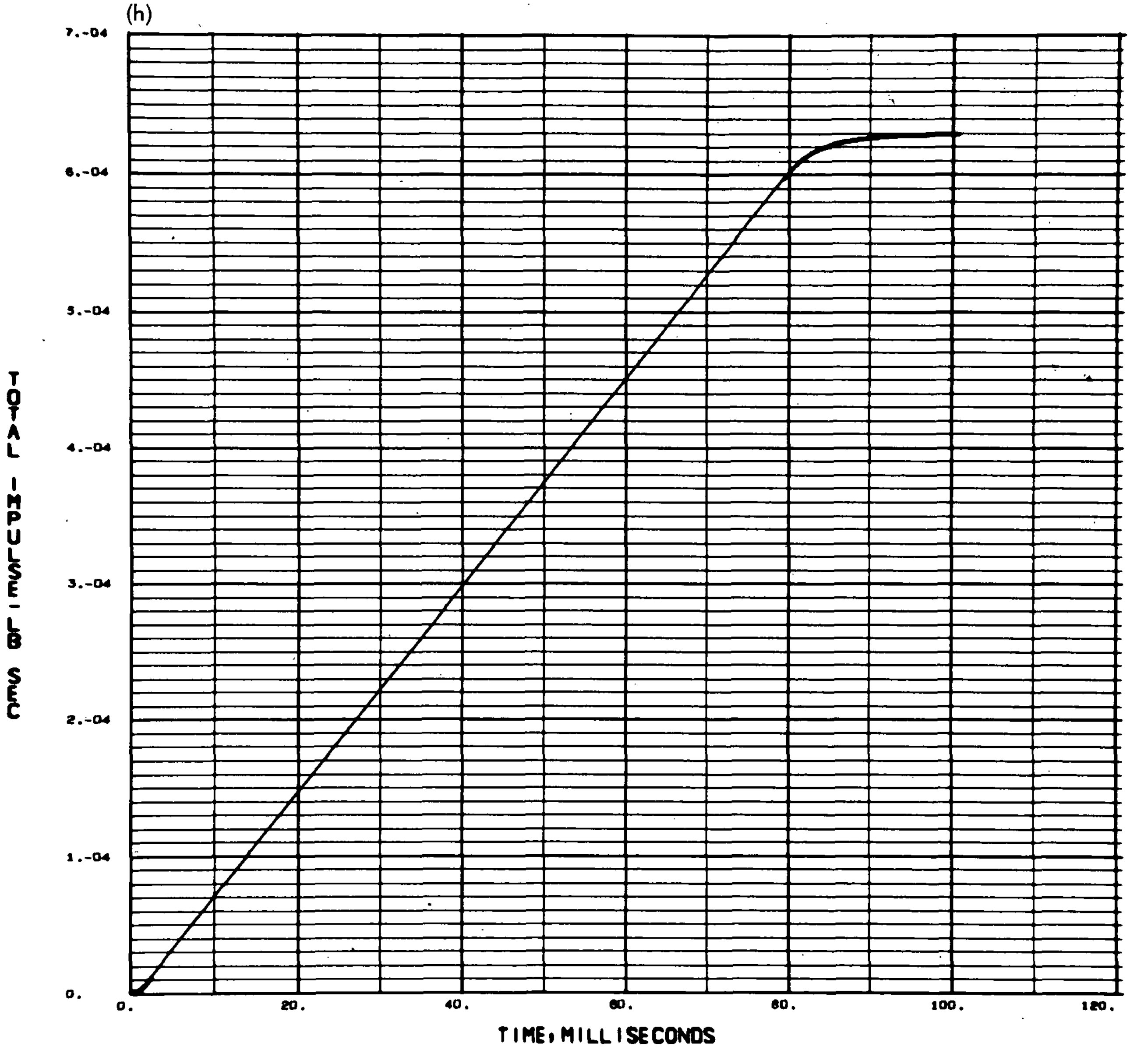

(g)
4.5-04
4.0-04
3.5-04
3.0-04
2.5-04
2.0-04
1.5-04
1.0-04
5.0-05
0.0
FLOWRATE, VALVE, LB/SEC
0.
20.
40.
60.
80.
100.
120.
TIME, MILLISECONDS

Fig. 7 (contd)

(h)



7.-04
6.-04
5.-04
4.-04
3.-04
2.-04
1.-04
0.
TOTAL IMPULSE, LB SEC
0.
20.
40.
60.
80.
100.
120.
TIME, MILLISECONDS

Fig. 7 (contd)

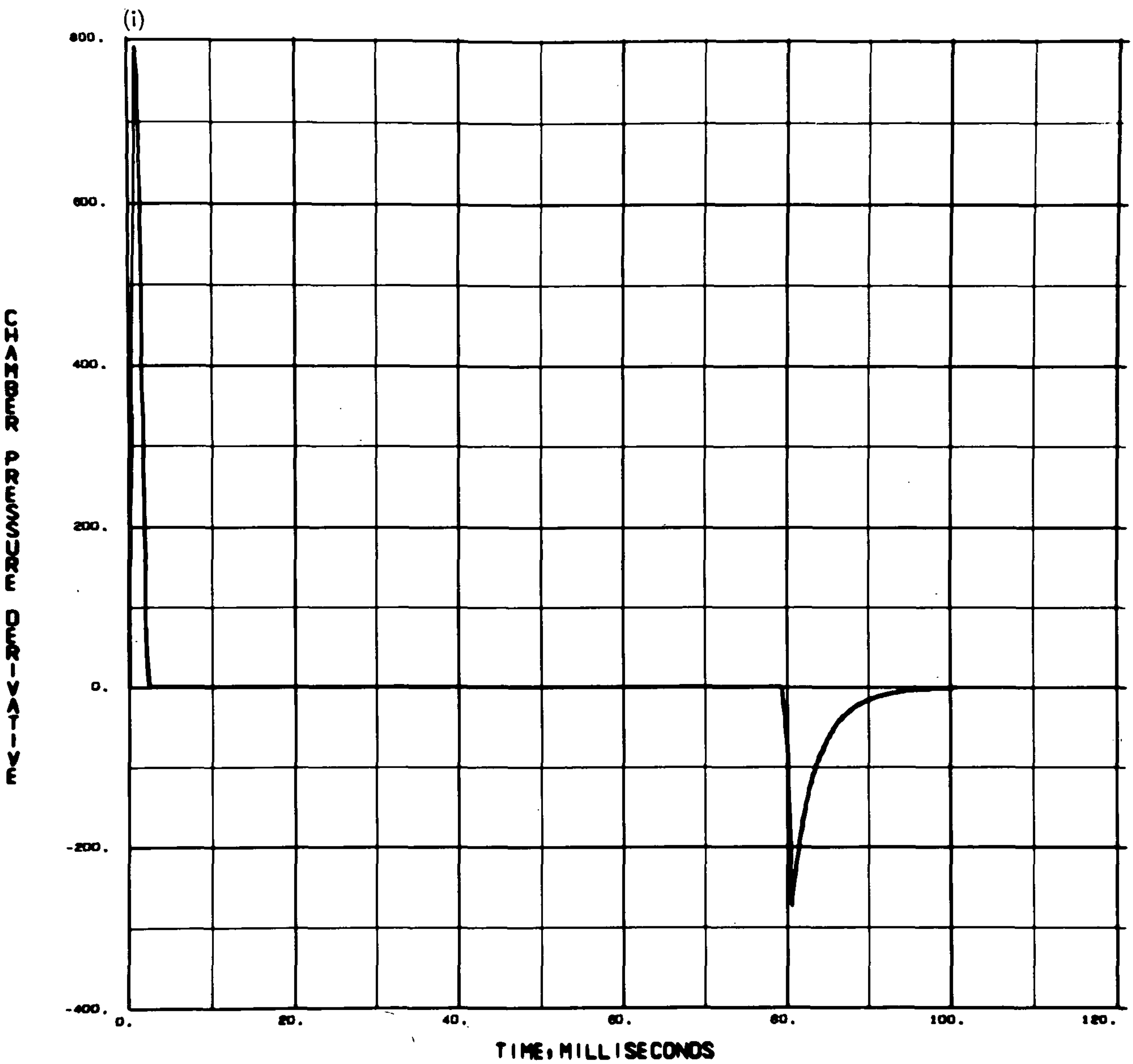

(i)
800.
600.
400.
200.
0.
-200.
-400.
CHAMBER PRESSURE DERIVATIVE
0.
20.
40.
60.
80.
100.
120.
TIME, MILLISECONDS

Fig. 7 (contd)

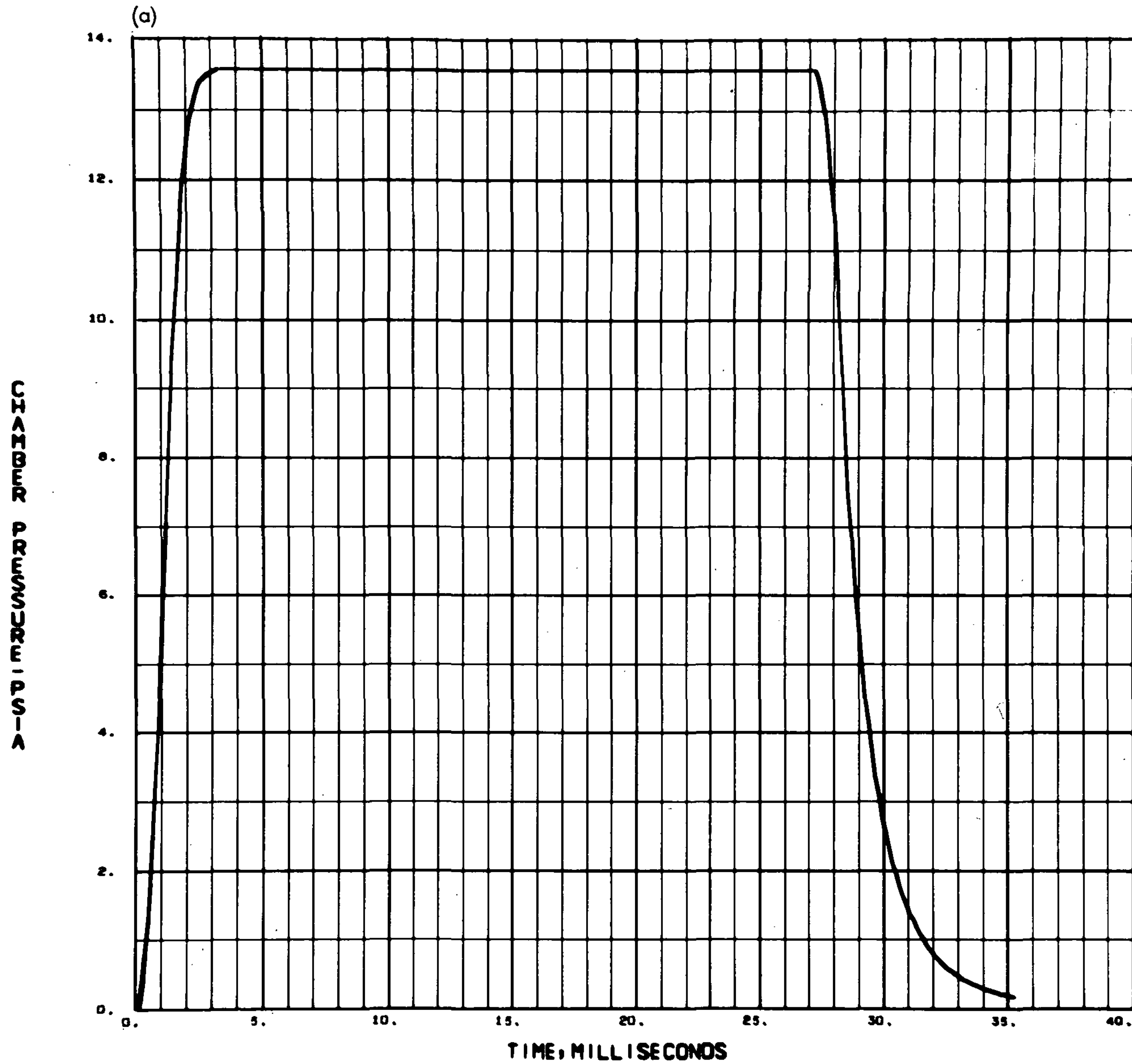


Fig. 8. MM'71 roll valve parameters as a function of time: (a) chamber pressure, (b) total mass, nozzle, (c) total mass, chamber, (d) total mass, valve, (e) nozzle flow rate, (f) chamber flow rate, (g) valve flow rate, (h) total impulse, (i) chamber pressure derivative

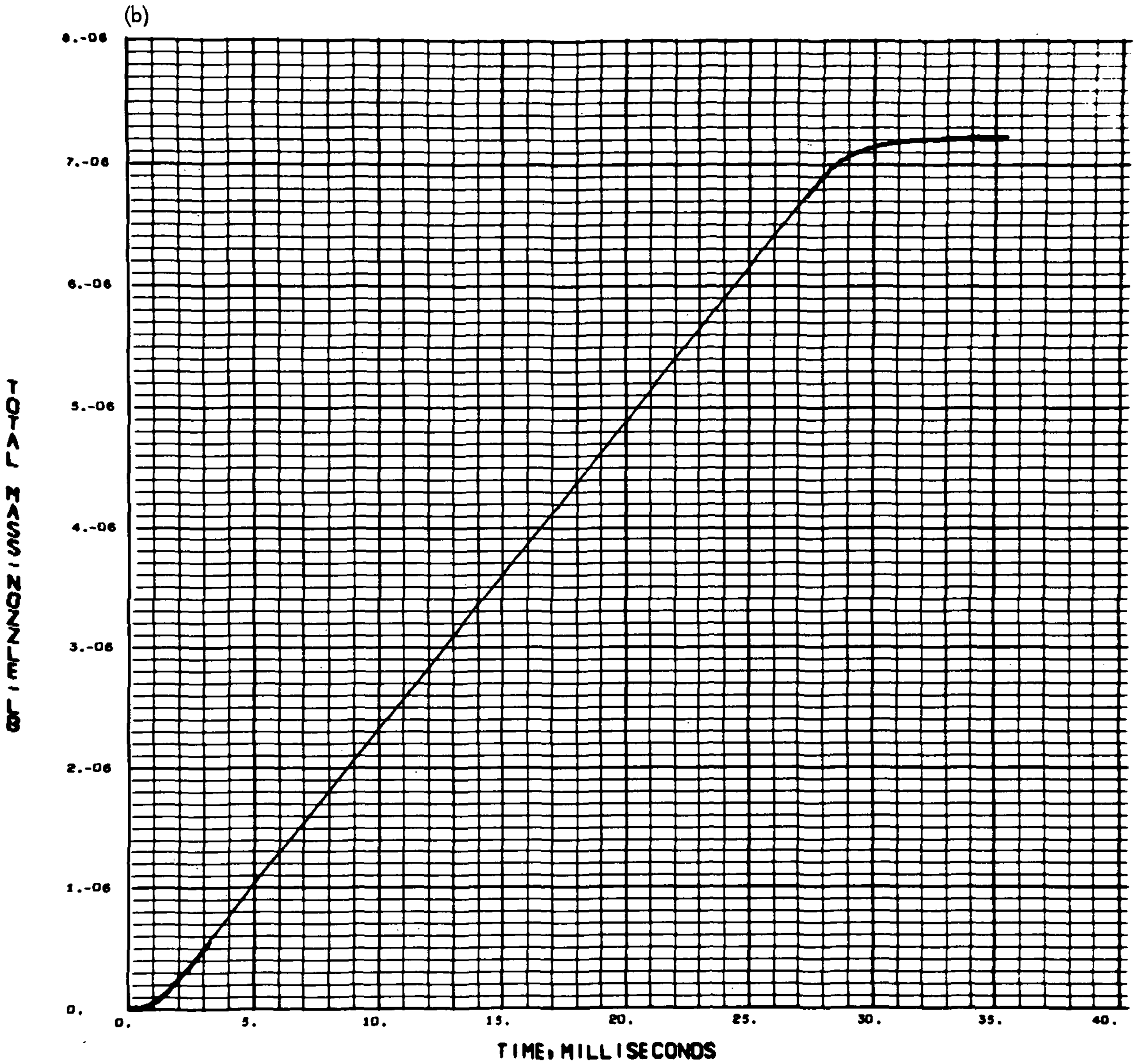

(b)
8.-06
7.-06
6.-06
5.-06
4.-06
3.-06
2.-06
1.-06
0.
TOTAL MASS, NOZZLE, LB
0.
5.
10.
15.
20.
25.
30.
35.
40.
TIME, MILLISECONDS

Fig. 8 (contd)

(c)

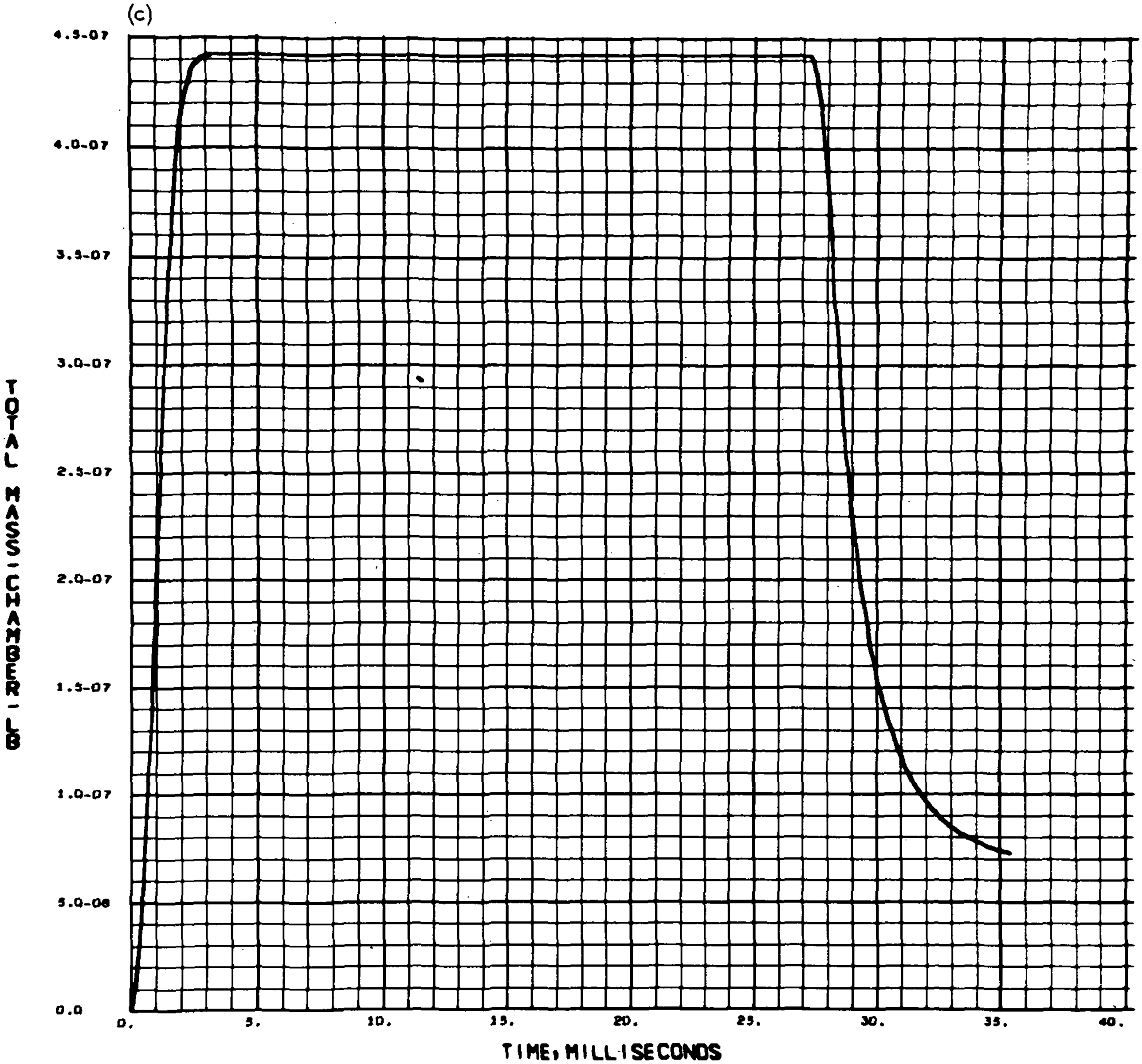
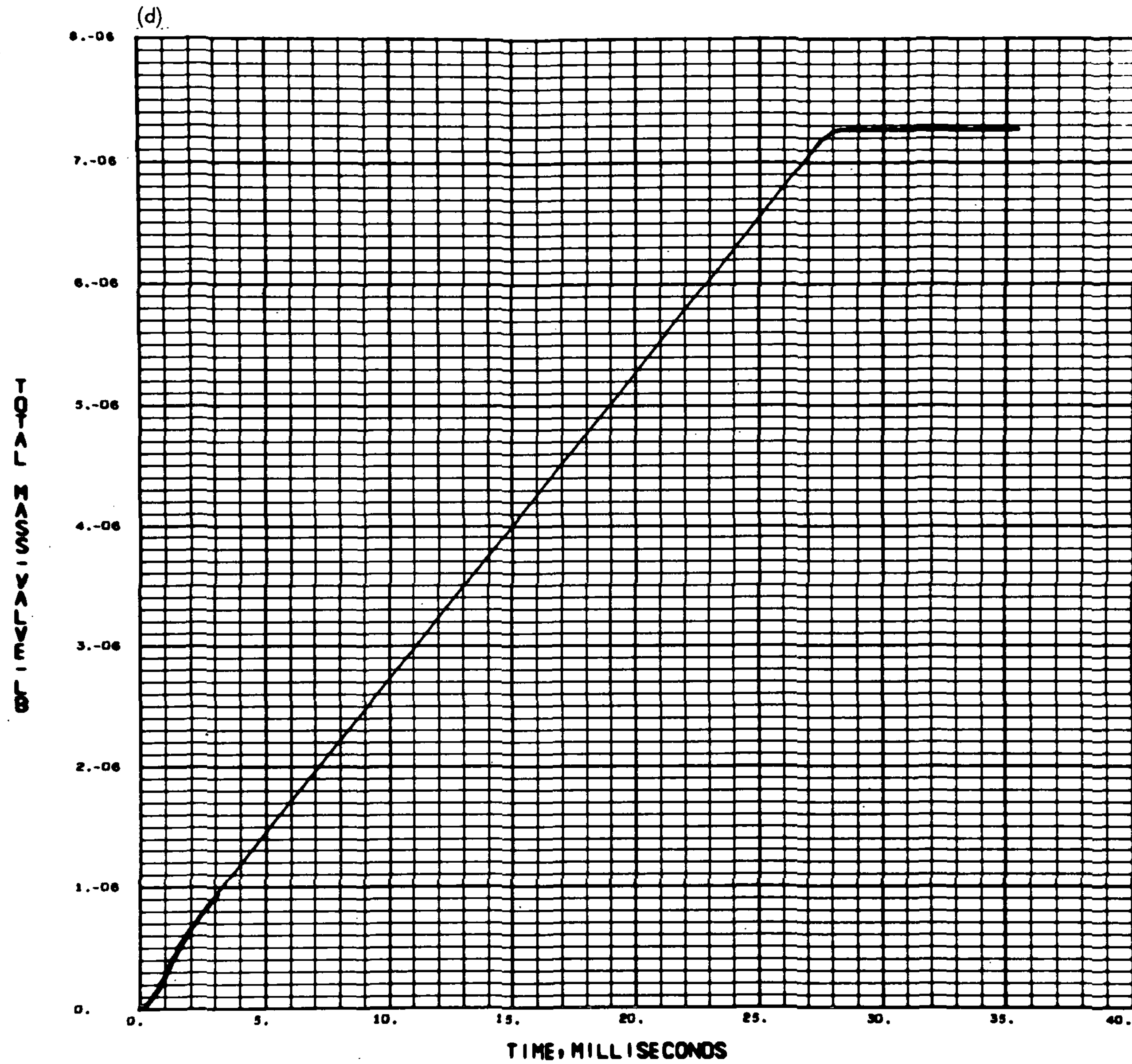

4.5-07
4.0-07
3.5-07
3.0-07
2.5-07
2.0-07
1.5-07
1.0-07
5.0-08
0.0
TOTAL MASS-CHAMBER-LB
0.
5.
10.
15.
20.
25.
30.
35.
40.
TIME, MILLISECONDS

Fig. 8 (contd)



(d)
8.-06
7.-06
6.-06
5.-06
4.-06
3.-06
2.-06
1.-06
0.
TOTAL MASS-VALVE-LB
0.
5.
10.
15.
20.
25.
30.
35.
40.
TIME, MILLISECONDS

Fig. 8 (contd)

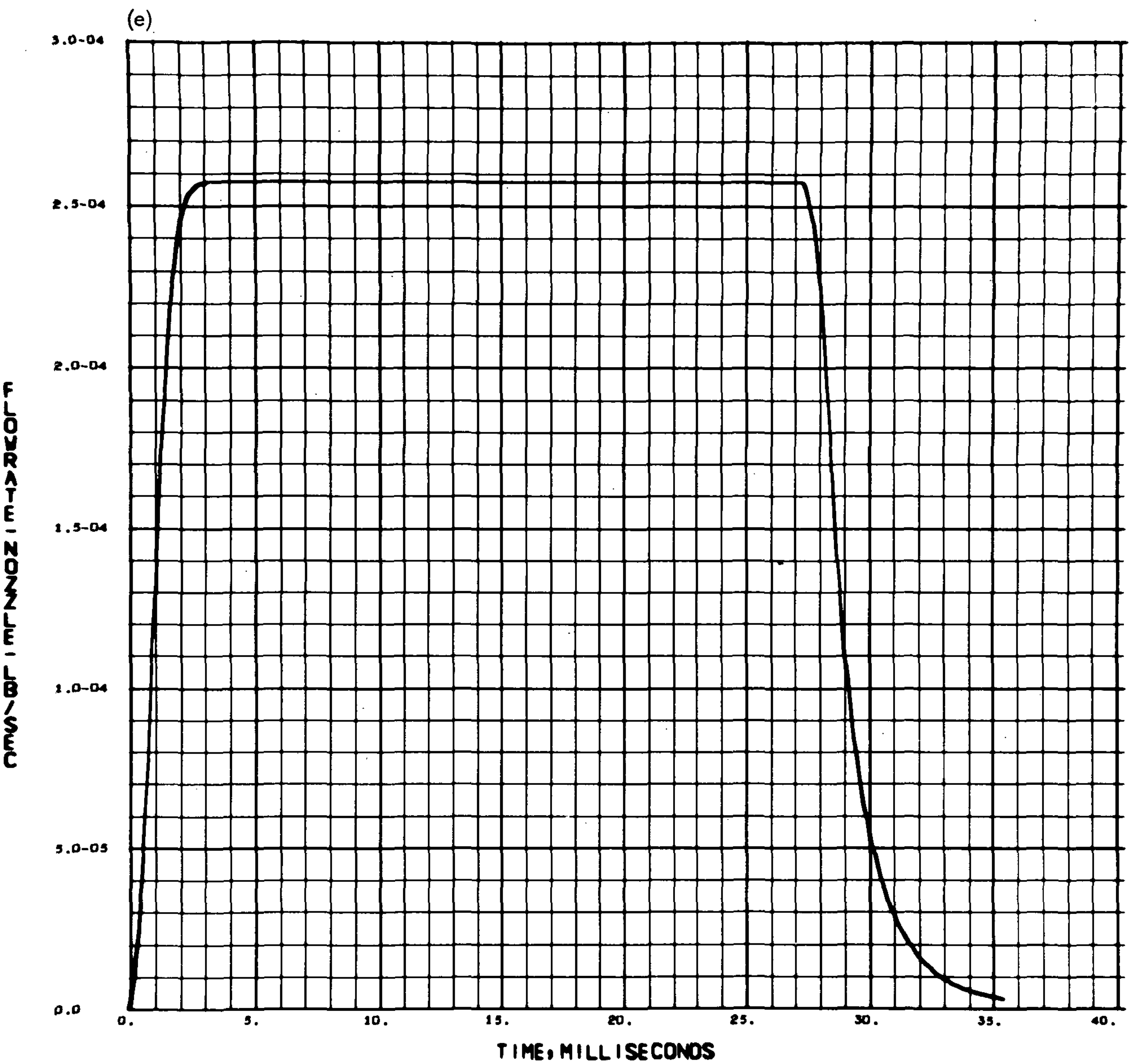
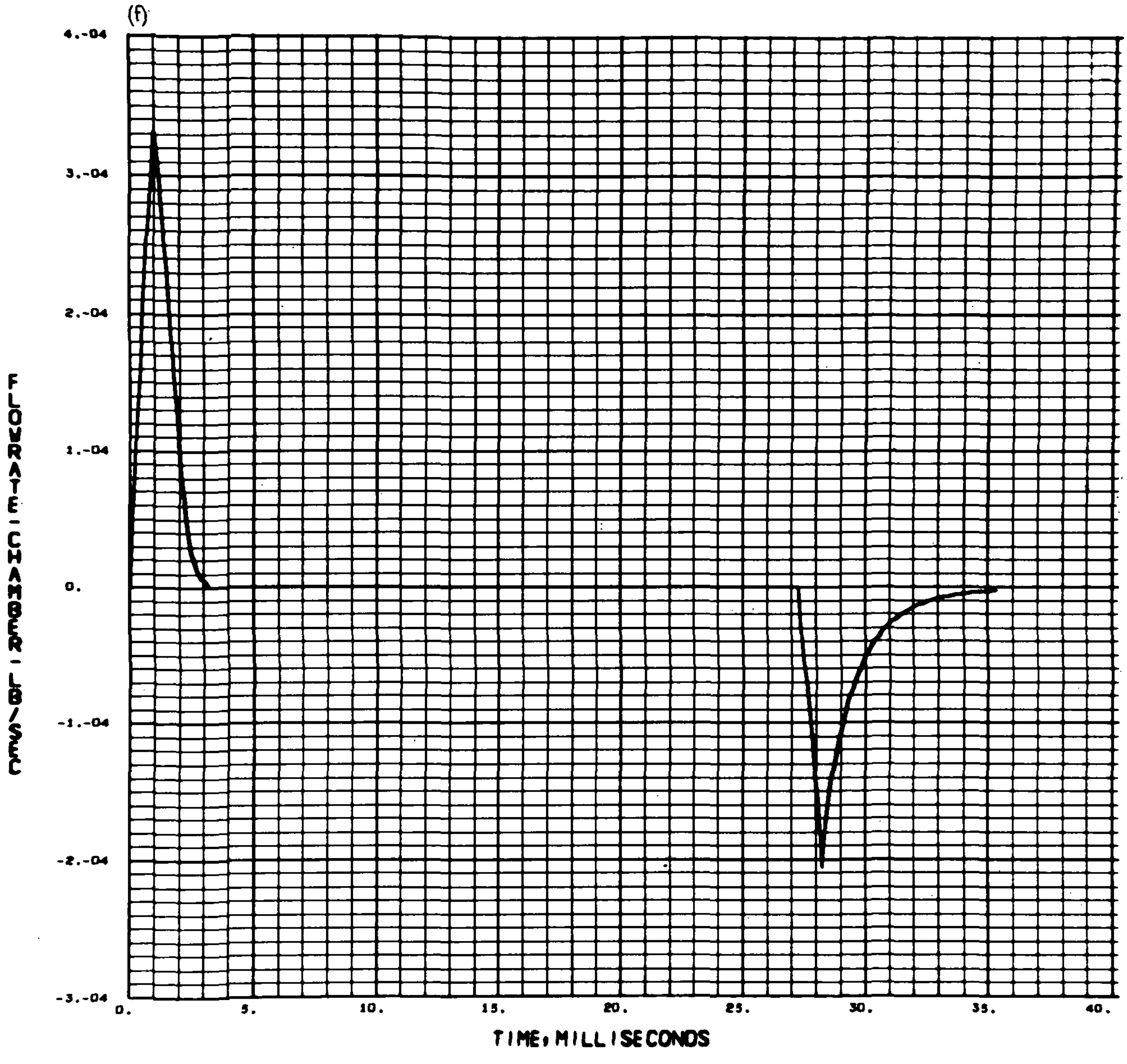

(e)
3.0-04
2.5-04
2.0-04
1.5-04
1.0-04
5.0-05
0.0
FLOWRATE-NOZZLE-LB/SEC
0.
5.
10.
15.
20.
25.
30.
35.
40.
TIME, MILLISECONDS

Fig. 8 (contd)



(f)
4.-04
3.-04
2.-04
1.-04
0.
-1.-04
-2.-04
-3.-04
FLOWRATE-CHAMBER-LB/SEC
0.
5.
10.
15.
20.
25.
30.
35.
40.
TIME, MILLISECONDS

Fig. 8 (contd)

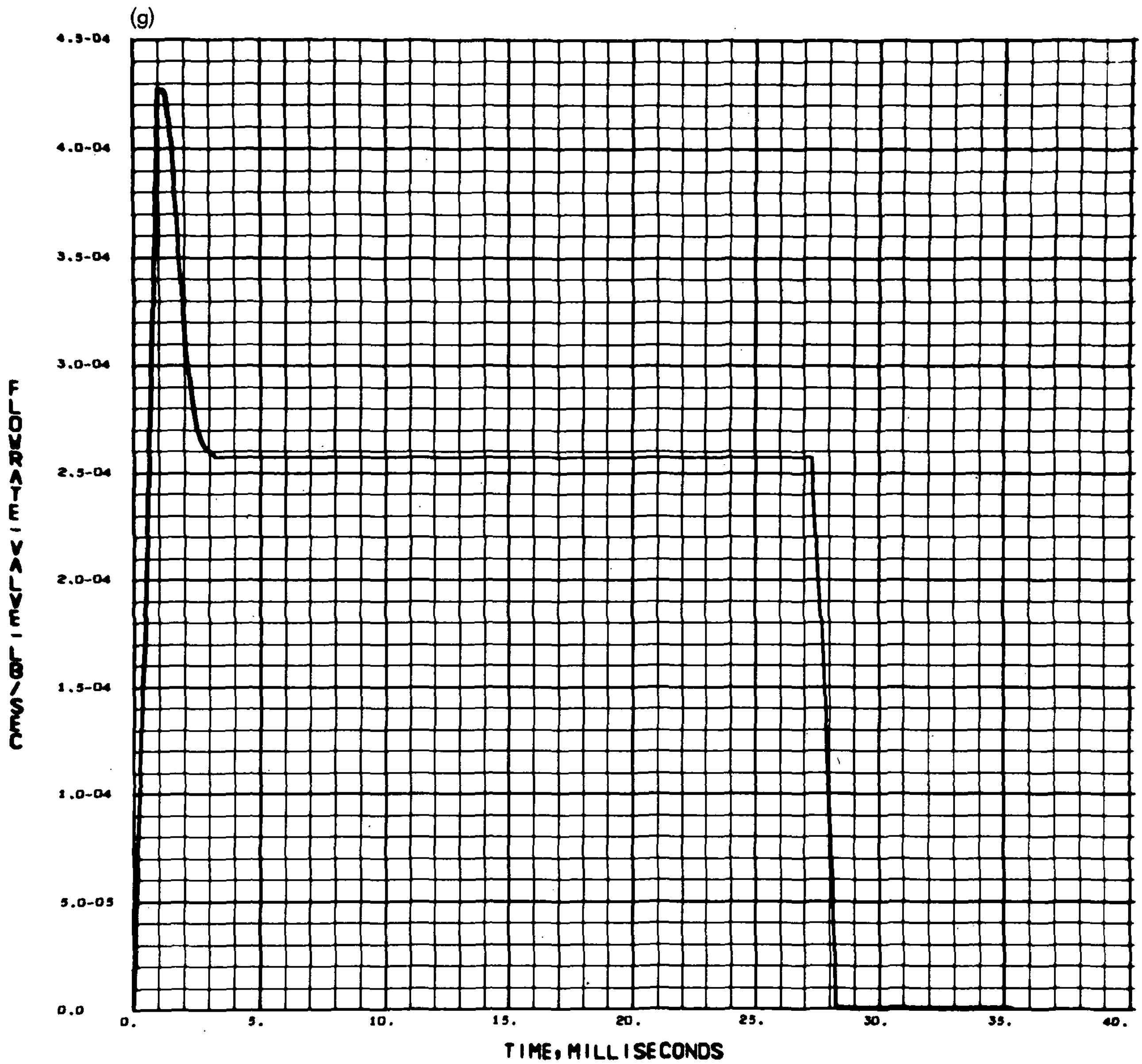

(g)
4.5-04
4.0-04
3.5-04
3.0-04
2.5-04
2.0-04
1.5-04
1.0-04
5.0-05
0.0
FLOWRATE, VALVE, LB/SEC
0.
5.
10.
15.
20.
25.
30.
35.
40.
TIME, MILLISECONDS

Fig. 8 (contd)

(h)

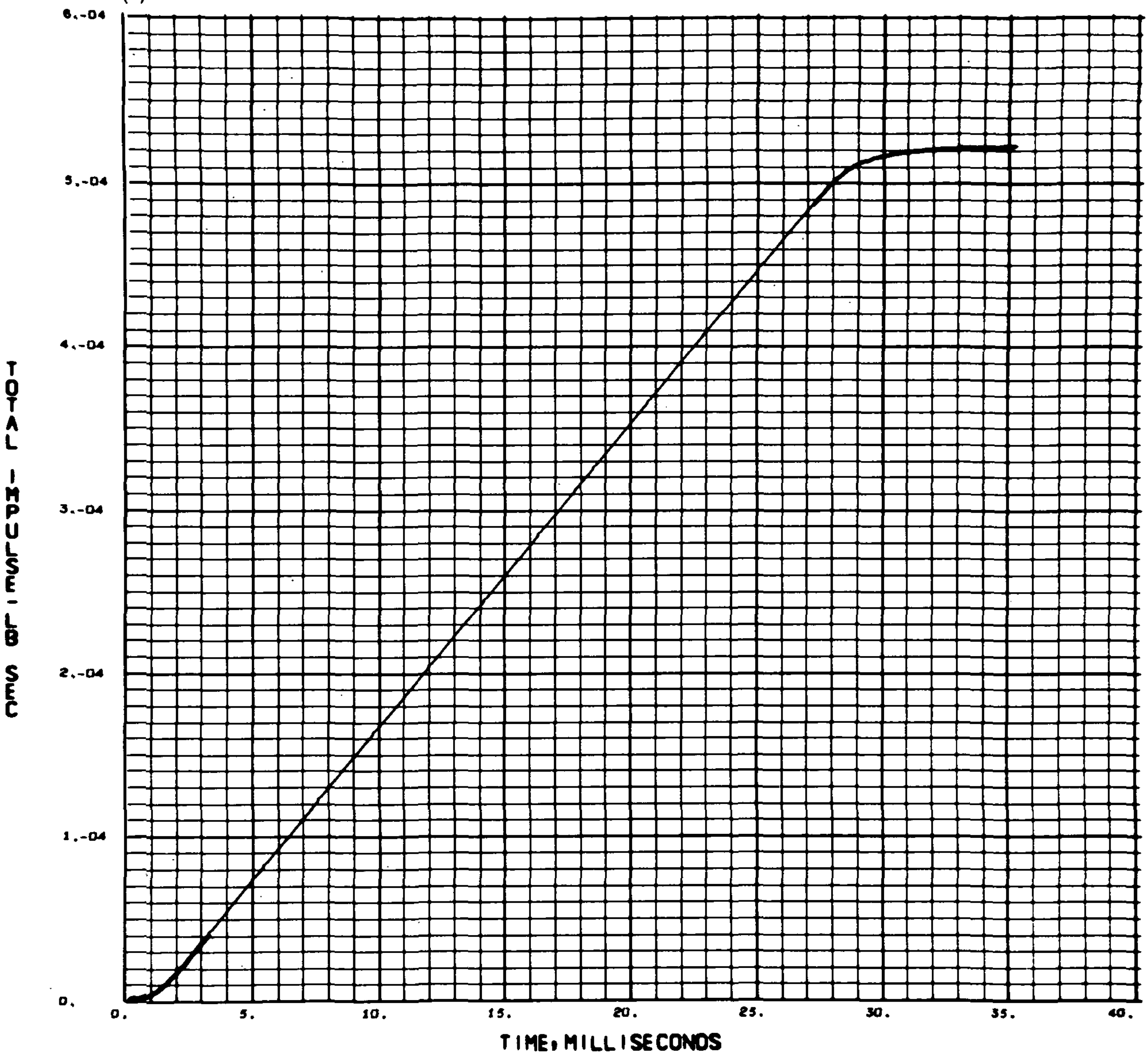

6.-04
5.-04
4.-04
3.-04
2.-04
1.-04
0.
TOTAL IMPULSE, LB SEC
0. 5. 10. 15. 20. 25. 30. 35. 40.
TIME, MILLISECONDS

Fig. 8 (contd)

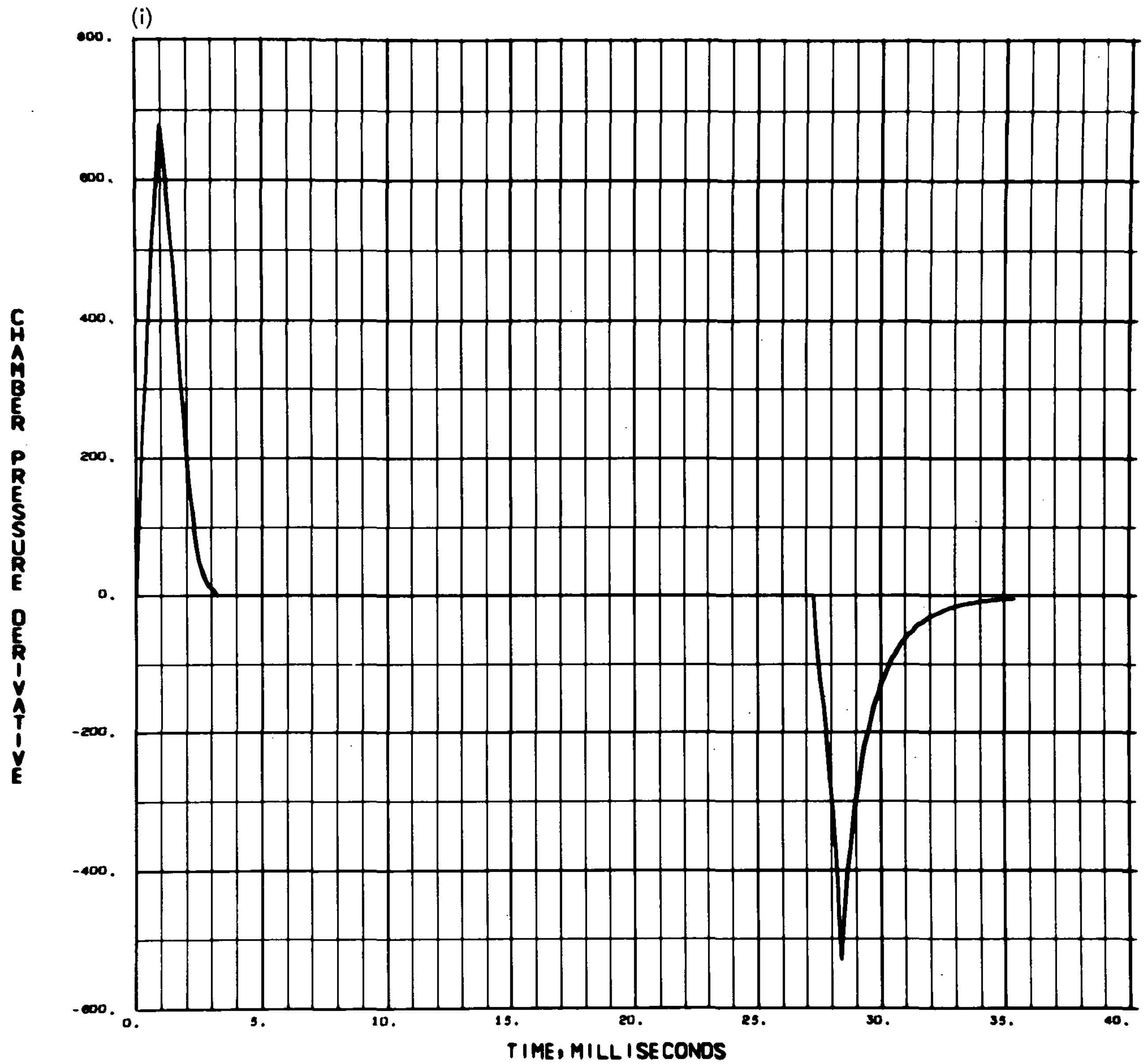

(i)
800.
600.
400.
200.
0.
-200.
-400.
-600.
CHAMBER PRESSURE DERIVATIVE
0.
5.
10.
15.
20.
25.
30.
35.
40.
TIME, MILLISECONDS

Fig. 8 (contd)

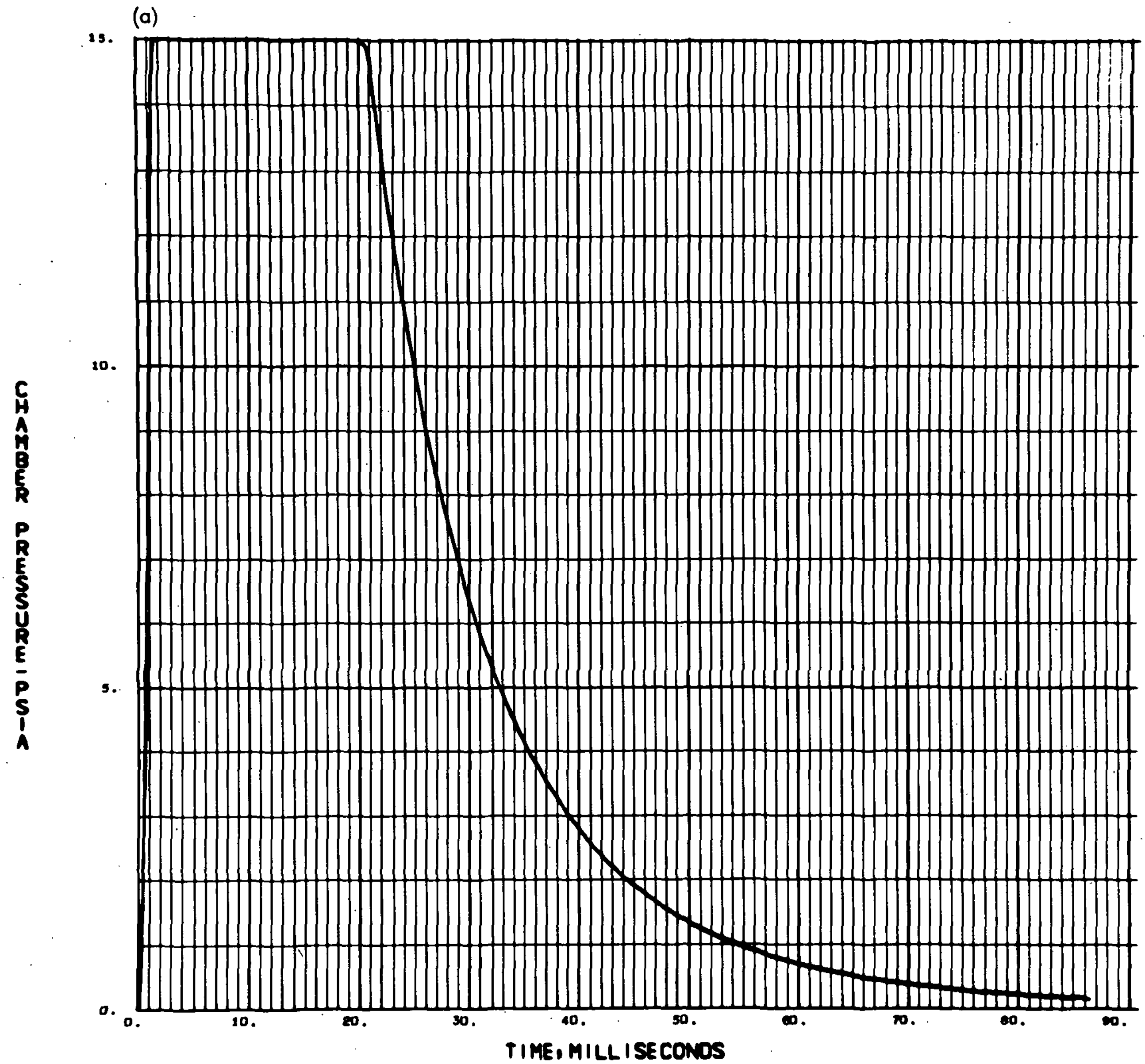


Fig. 9. MM'64 pitch/yaw valve parameters as a function of time: (a) chamber pressure, (b) total mass, nozzle, (c) total mass, chamber, (d) total mass, valve, (e) nozzle flow rate, (f) chamber flow rate, (g) valve flow rate, (h) total impulse, (i) chamber pressure derivative

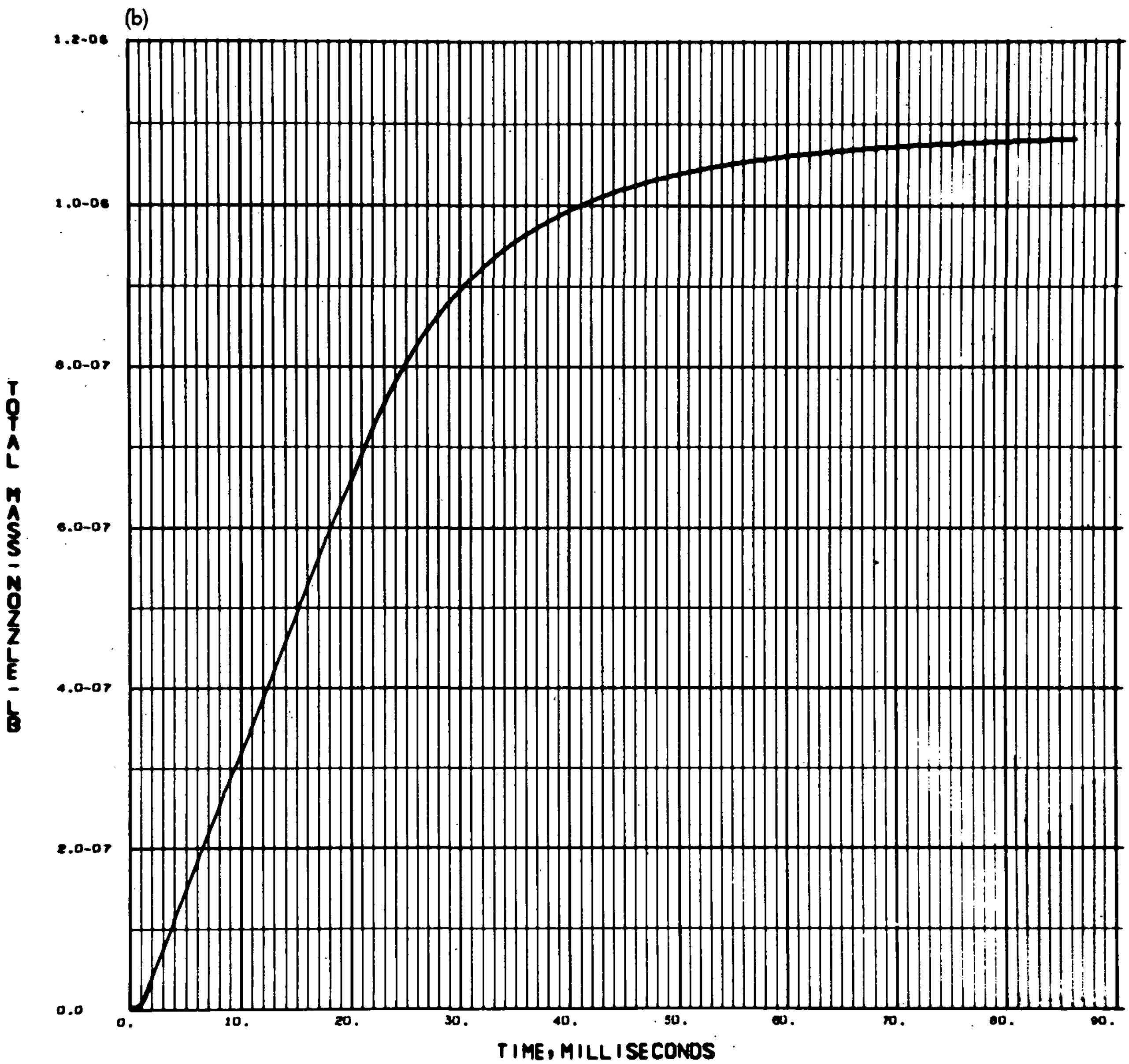

(b)
1.2-06
1.0-06
8.0-07
6.0-07
4.0-07
2.0-07
0.0
0.
10.
20.
30.
40.
50.
60.
70.
80.
90.
TIME, MILLISECONDS
TOTAL MASS, NOZZLE-LB

Fig. 9 (contd)

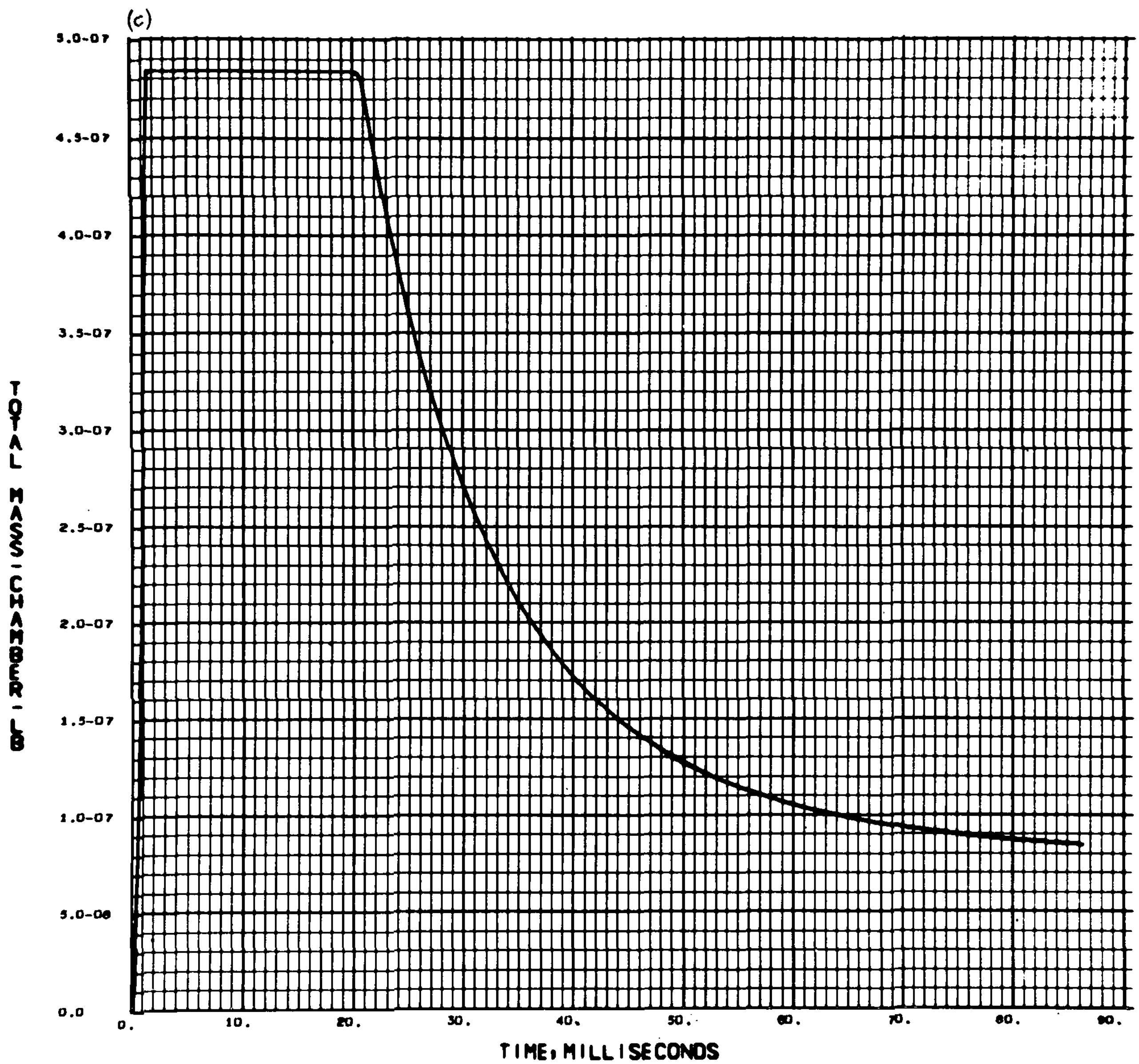
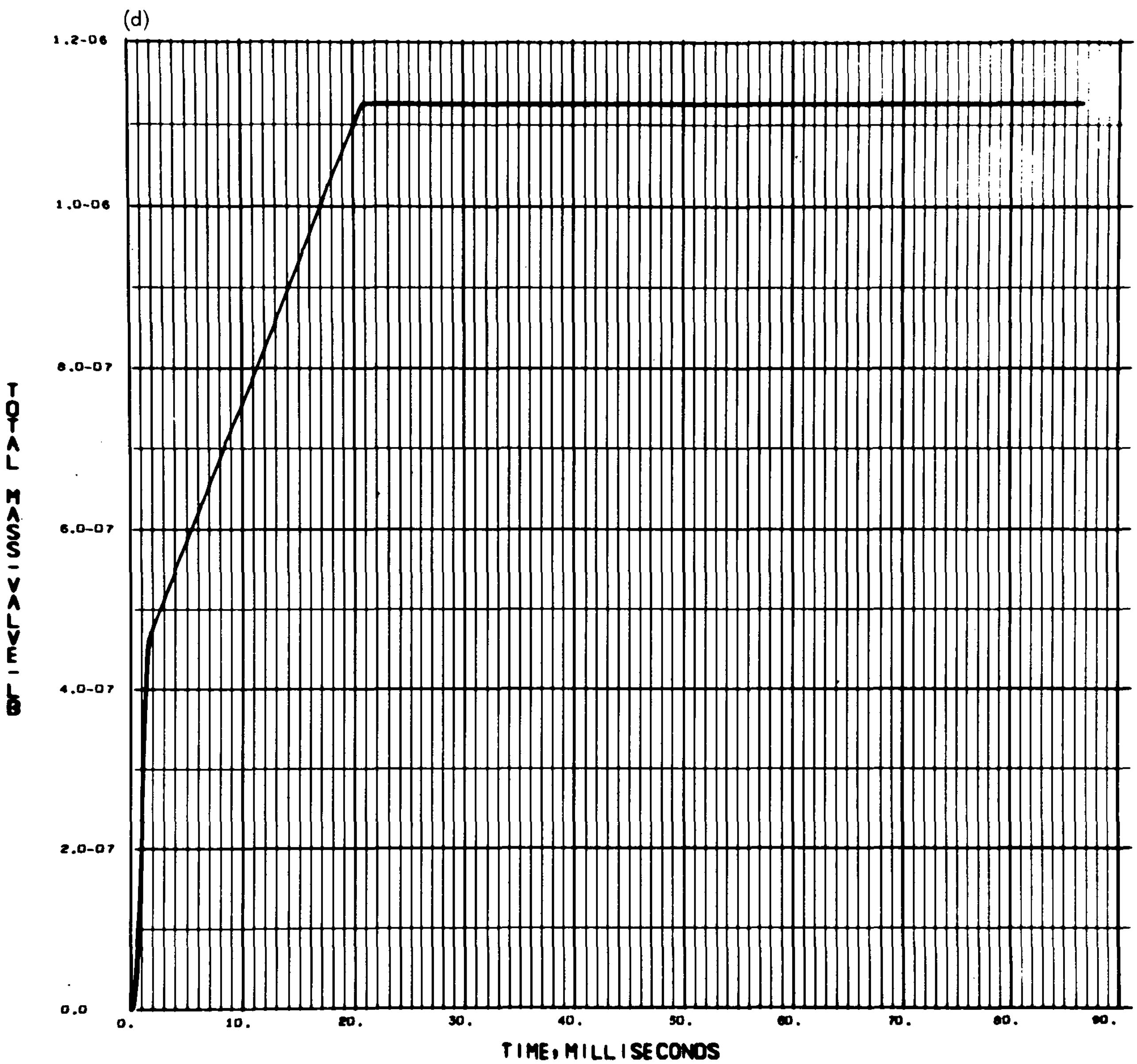

(c)
5.0-07
4.5-07
4.0-07
3.5-07
3.0-07
2.5-07
2.0-07
1.5-07
1.0-07
5.0-08
0.0
TOTAL MASS-CHAMBER-LB
0.
10.
20.
30.
40.
50.
60.
70.
80.
90.
TIME, MILLISECONDS

Fig. 9 (contd)



(d)
1.2-06
1.0-06
8.0-07
6.0-07
4.0-07
2.0-07
0.0
TOTAL MASS-VALVE-LB
0.
10.
20.
30.
40.
50.
60.
70.
80.
90.
TIME, MILLISECONDS

Fig. 9 (contd)

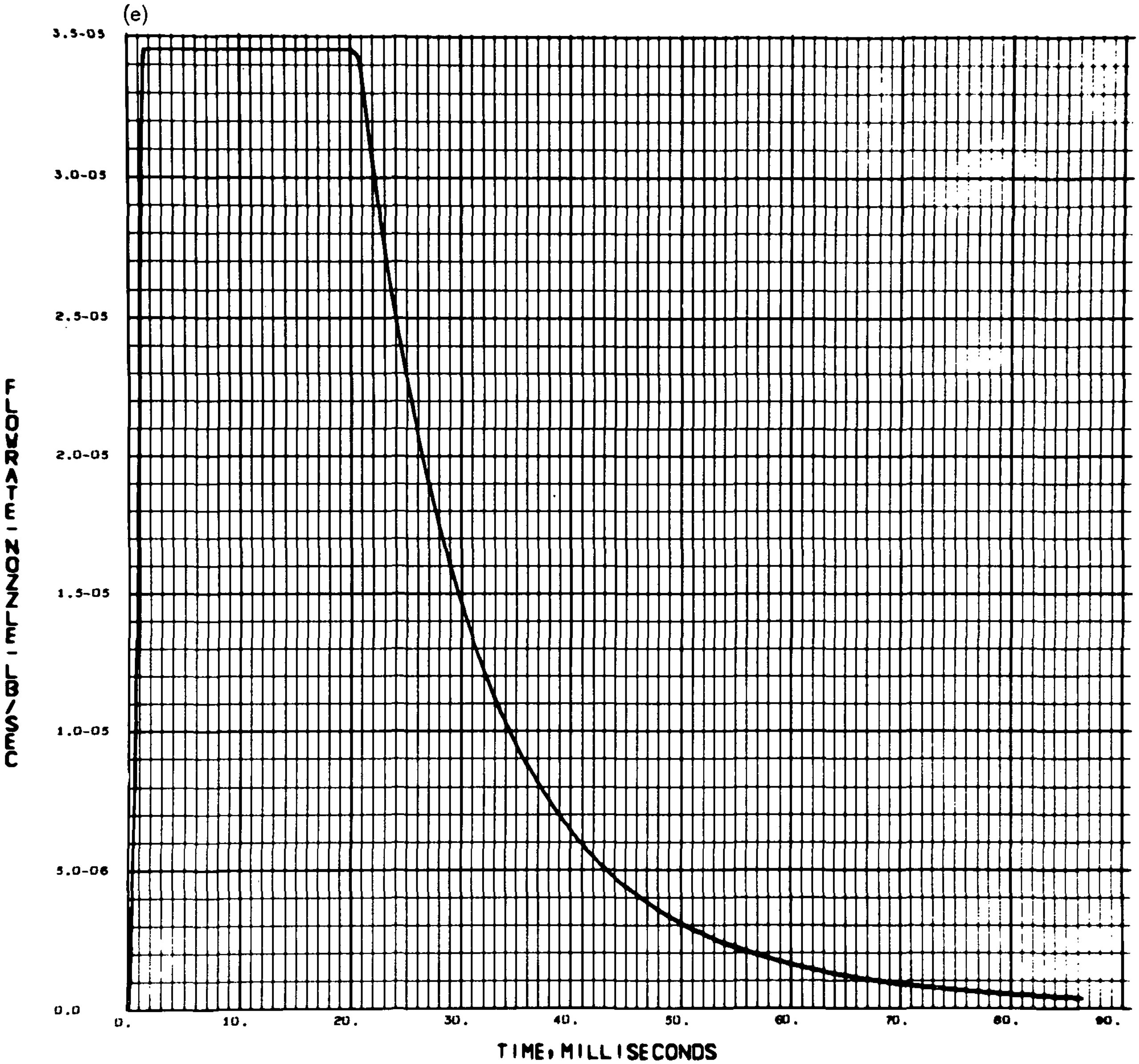

(e)
3.5-05
3.0-05
2.5-05
2.0-05
1.5-05
1.0-05
5.0-06
0.0
FLOWRATE-NOZZLE-LB/SEC
0.
10.
20.
30.
40.
50.
60.
70.
80.
90.
TIME, MILLISECONDS

Fig. 9 (contd)

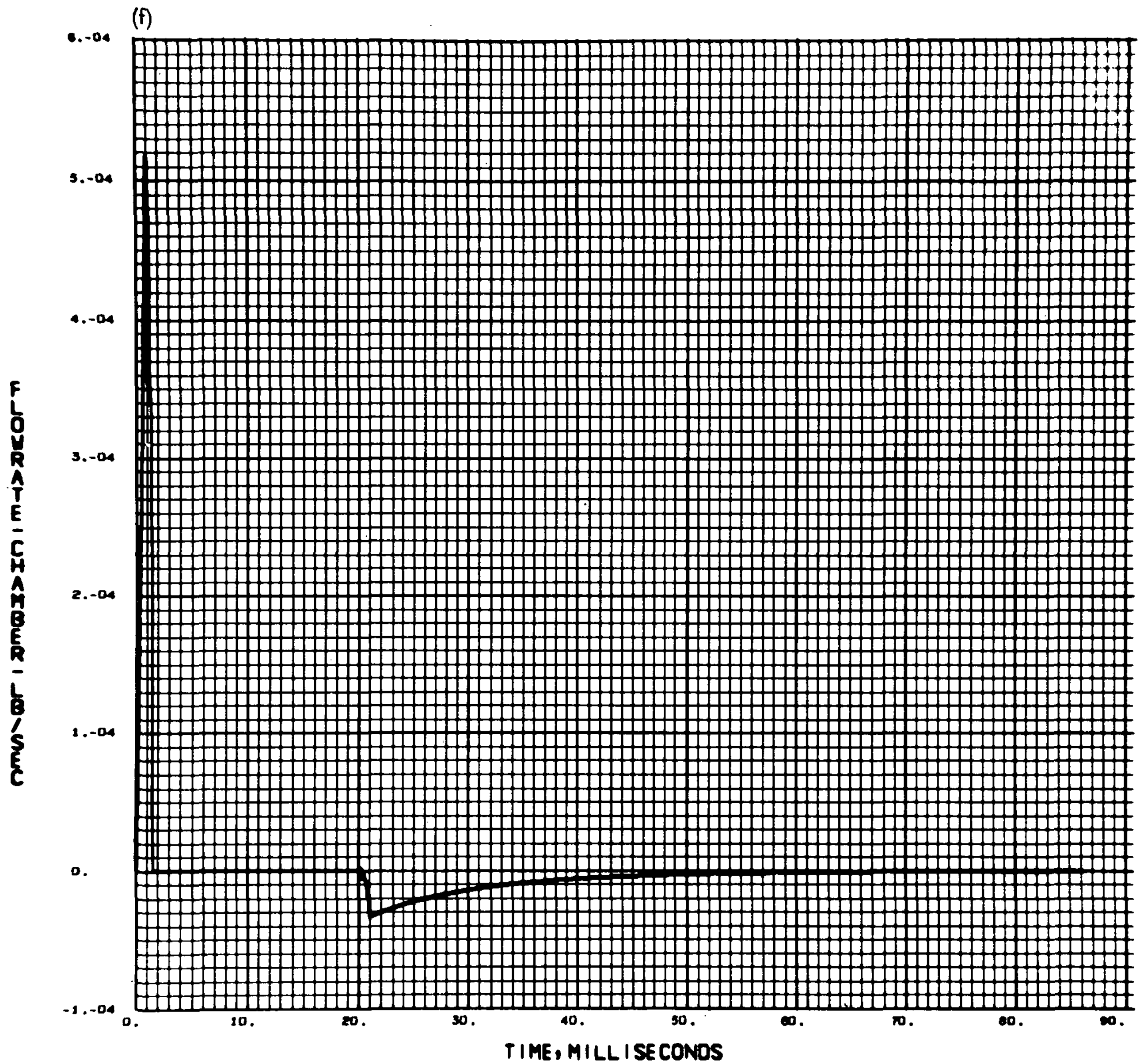

(f)
6.-04
5.-04
4.-04
3.-04
2.-04
1.-04
0.
-1.-04
FLOWRATE-CHAMBER-LB/SEC
0.
10.
20.
30.
40.
50.
60.
70.
80.
90.
TIME, MILLISECONDS

Fig. 9 (contd)

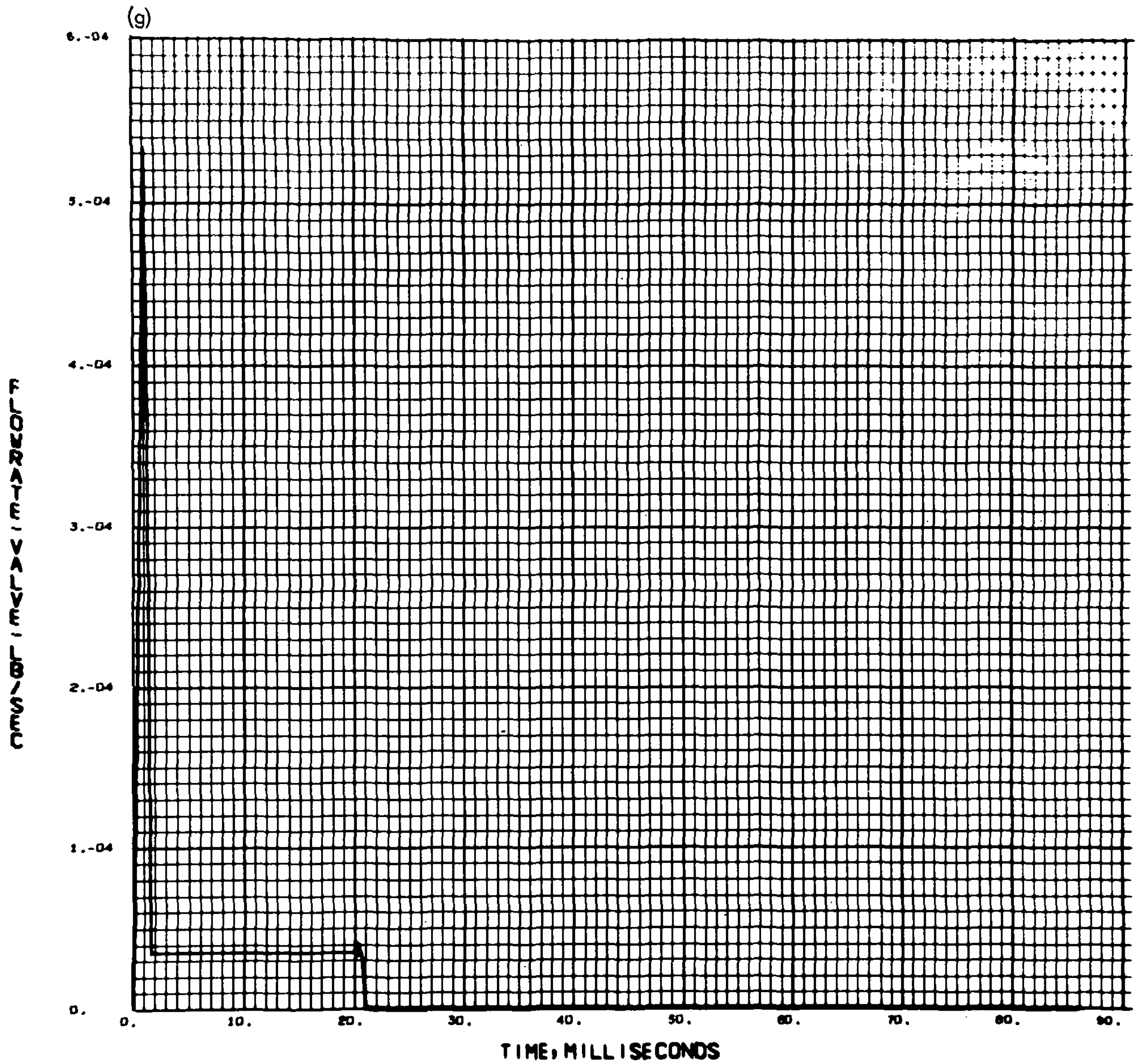

(g)
6.-04
5.-04
4.-04
3.-04
2.-04
1.-04
0.
FLOWRATE, VALVE, LB/SEC
0.
10.
20.
30.
40.
50.
60.
70.
80.
90.
TIME, MILLISECONDS

Fig. 9 (contd)

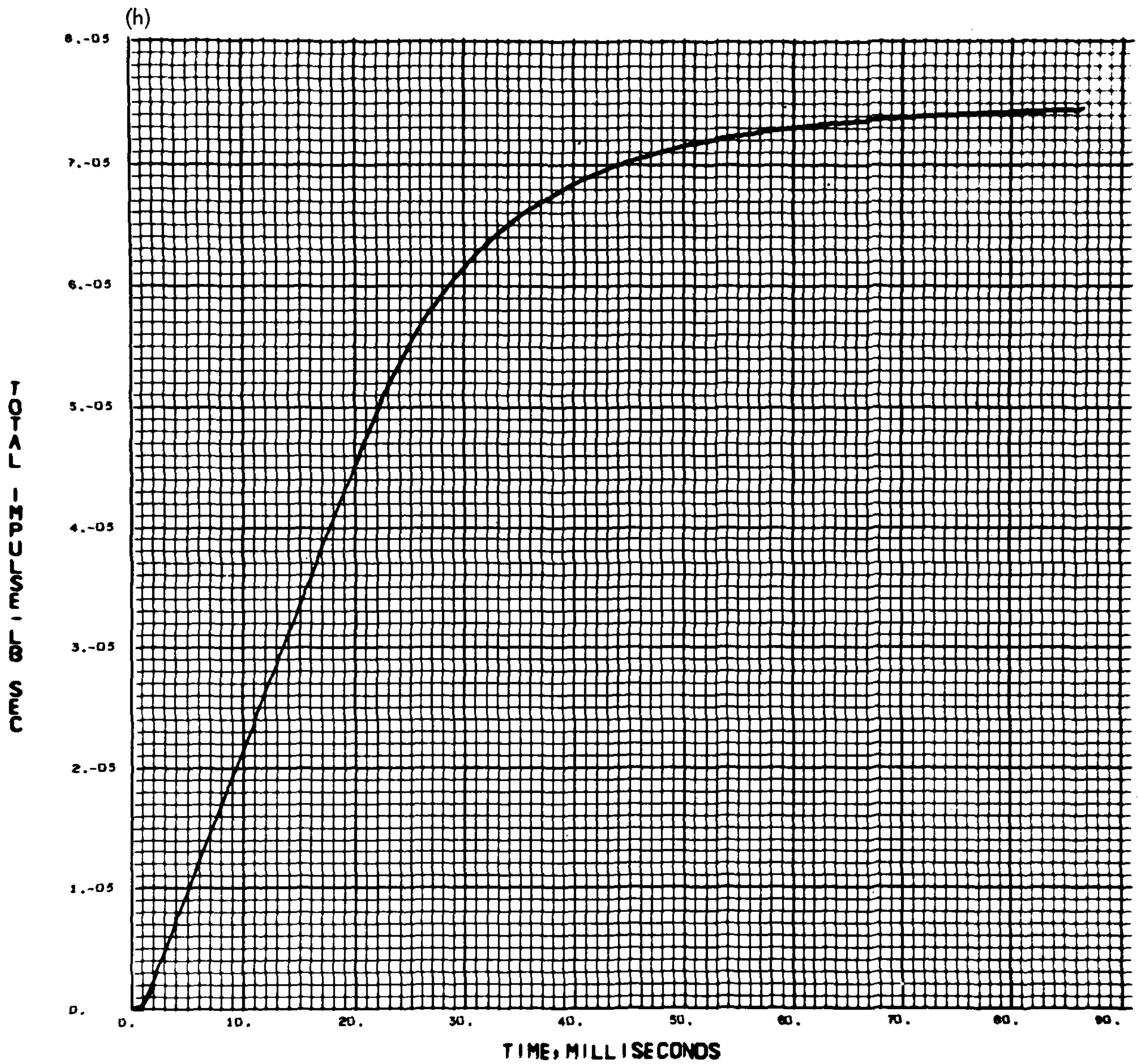

(h)
8.-05
7.-05
6.-05
5.-05
4.-05
3.-05
2.-05
1.-05
0.
TOTAL IMPULSE-LB SEC
0.
10.
20.
30.
40.
50.
60.
70.
80.
90.
TIME, MILLISECONDS

Fig. 9 (contd)

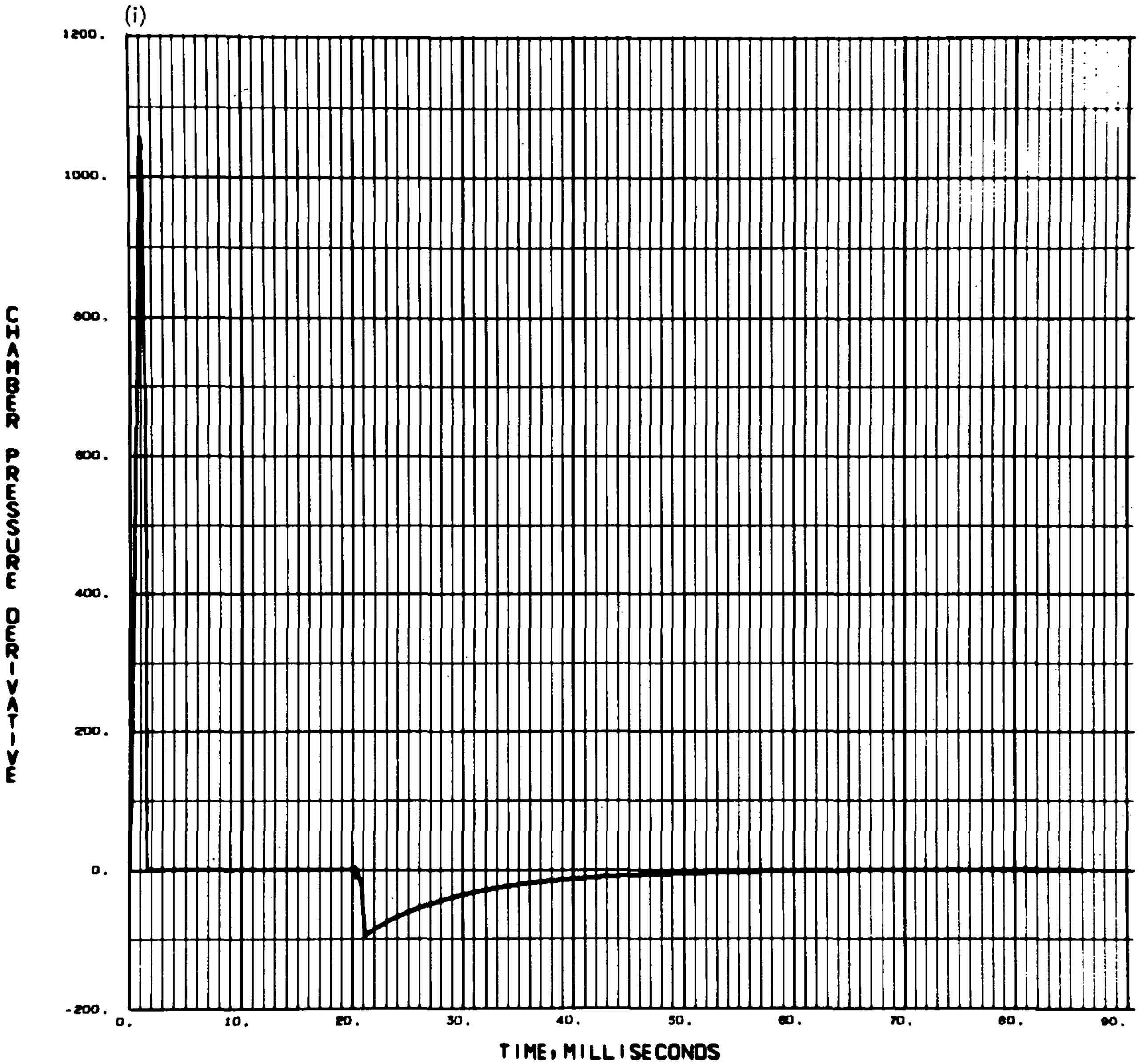

(i)
CHAMBER PRESSURE DERIVATIVE
1200.
1000.
800.
600.
400.
200.
0.
-200.
0.
10.
20.
30.
40.
50.
60.
70.
80.
90.
TIME, MILLISECONDS

Fig. 9 (contd)

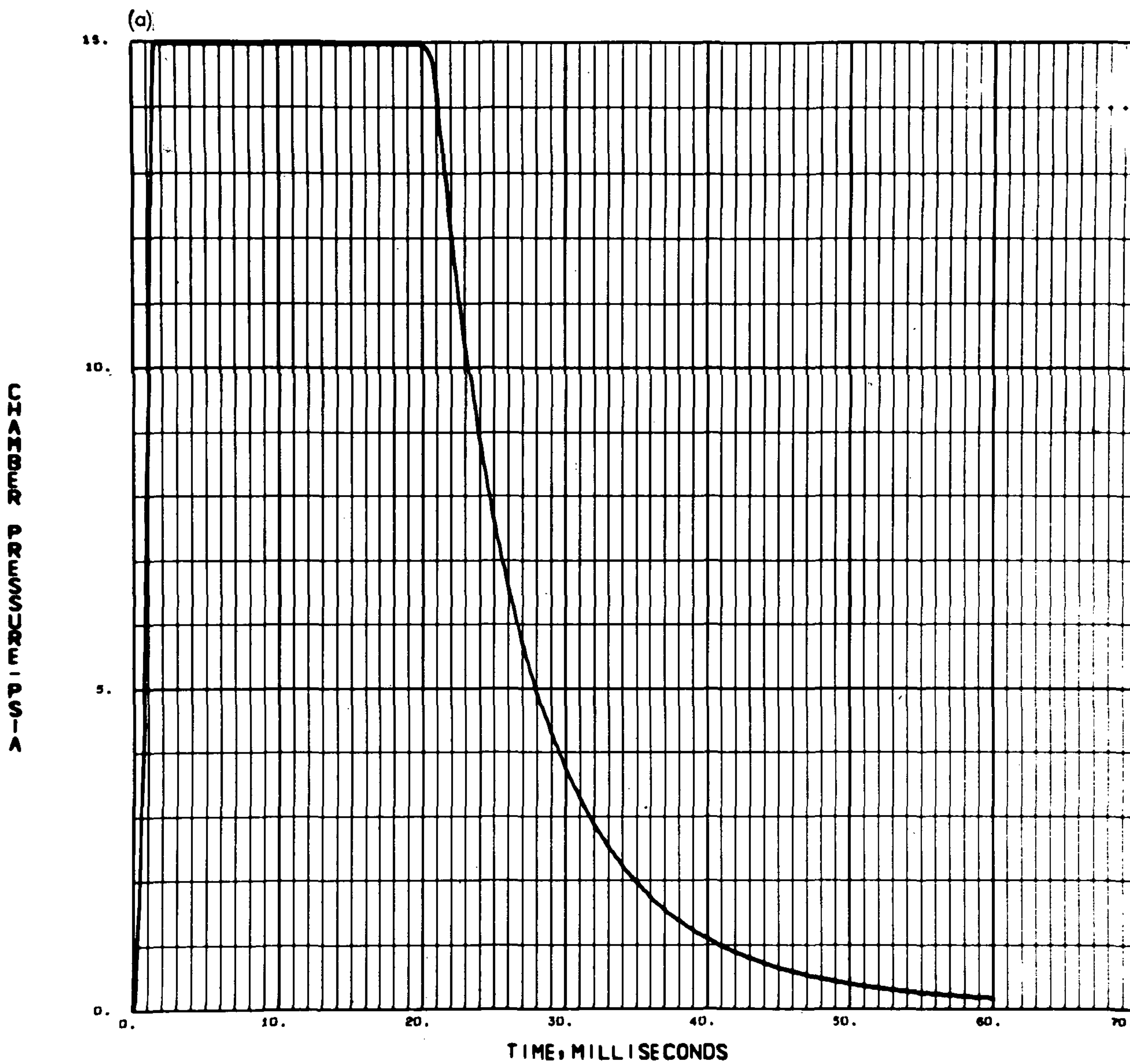


Fig. 10. MM'64 roll valve parameters as a function of time: (a) chamber pressure, (b) total mass, nozzle, (c) total mass, chamber, (d) total mass, valve, (e) nozzle flow rate, (f) chamber flow rate, (g) valve flow rate, (h) total impulse, (i) chamber pressure derivative

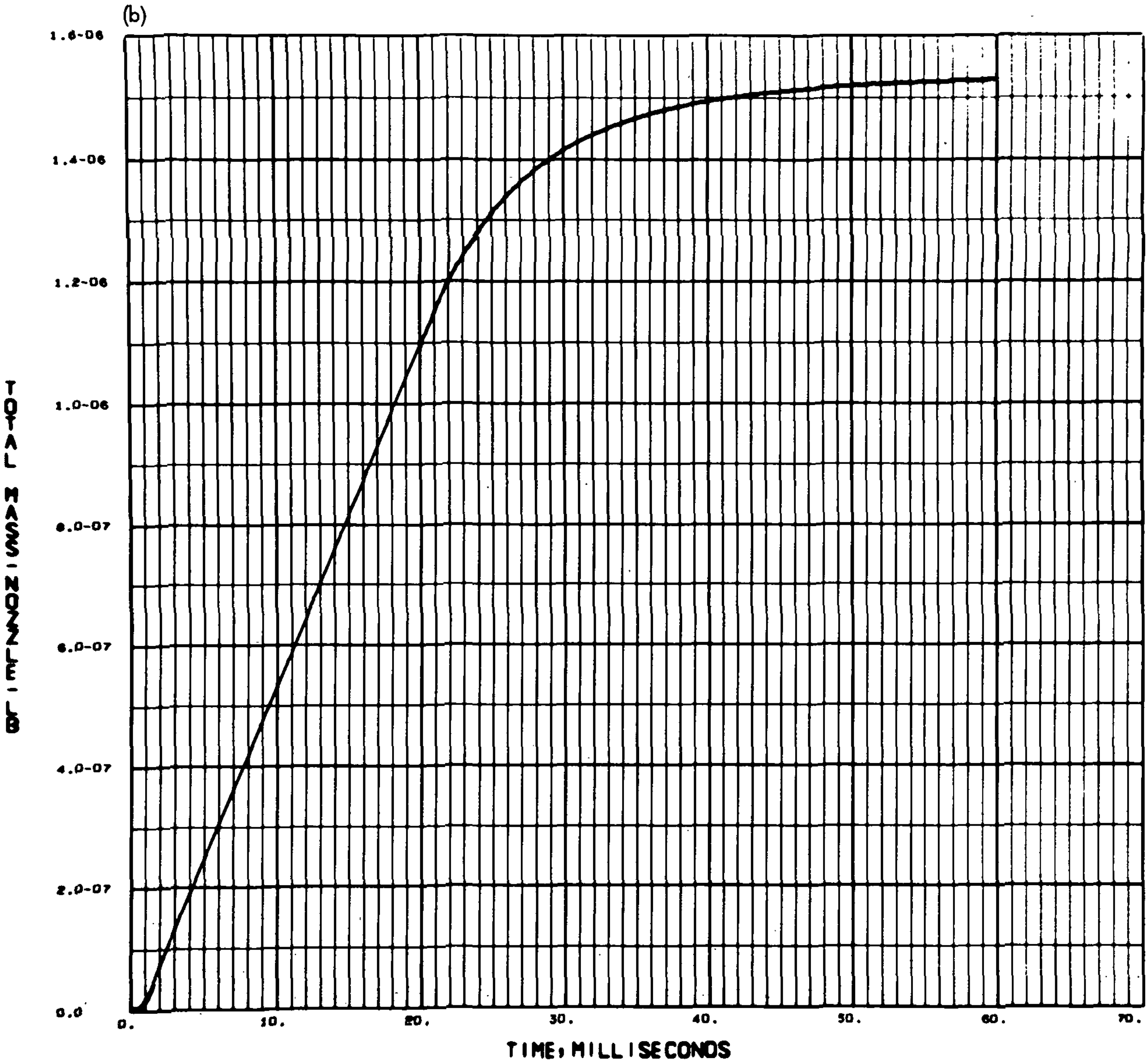

(b)
1.6-06
1.4-06
1.2-06
1.0-06
8.0-07
6.0-07
4.0-07
2.0-07
0.0
TOTAL MASS-NOZZLE-LB
0.
10.
20.
30.
40.
50.
60.
70.
TIME, MILLISECONDS

Fig. 10 (contd)

(c)

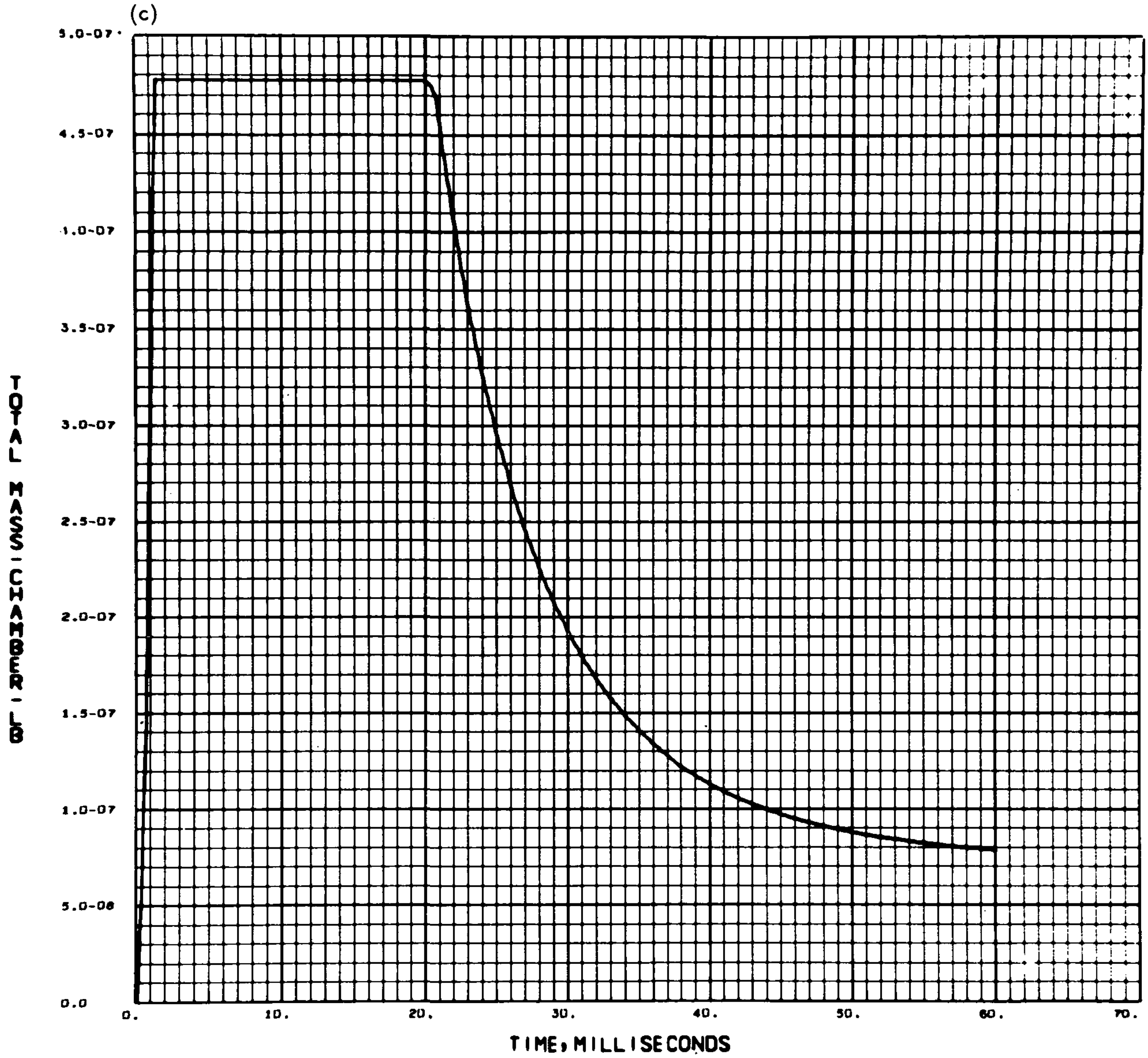


Fig. 10 (contd)

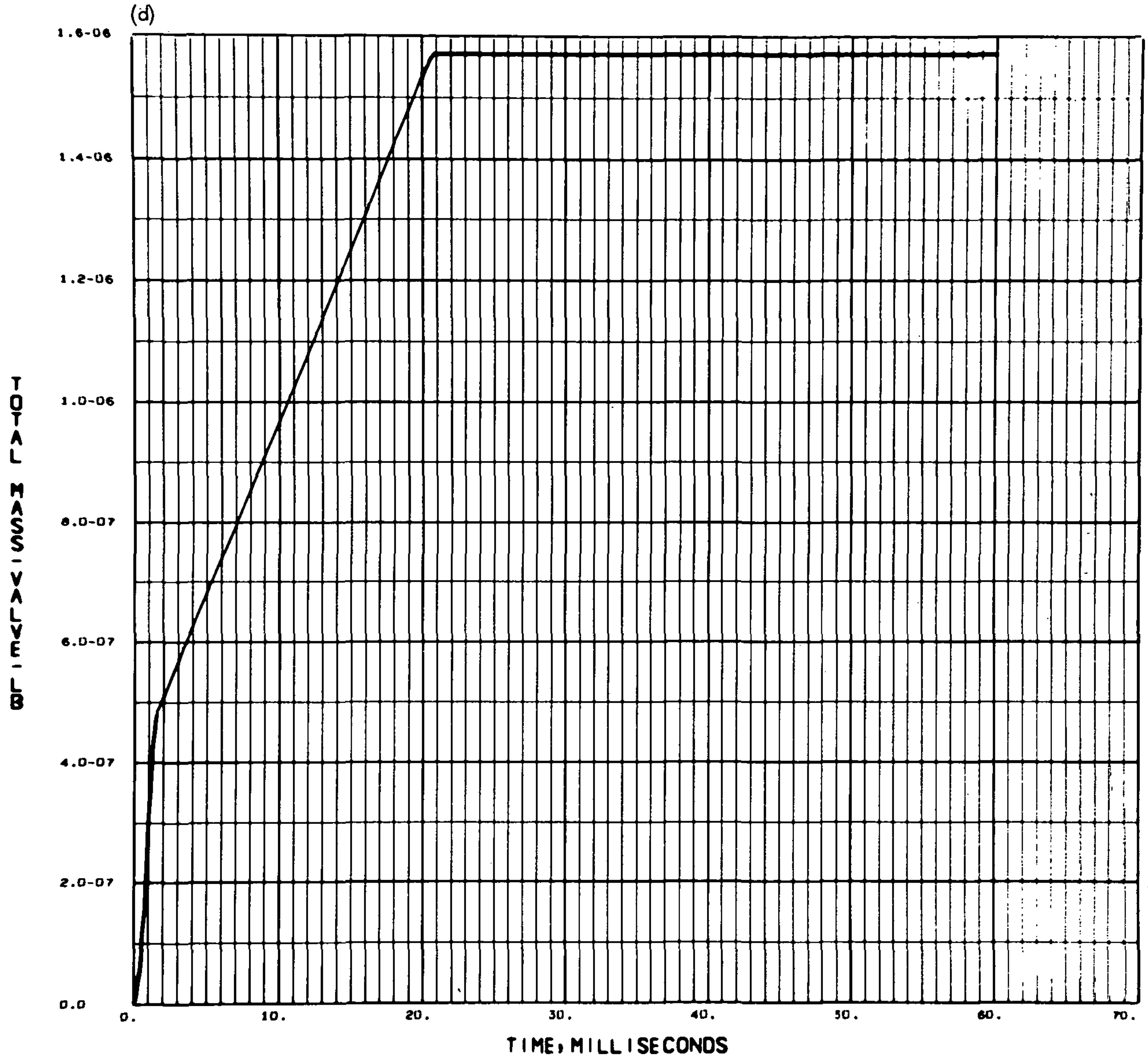

(d)
1.6-06
1.4-06
1.2-06
1.0-06
8.0-07
6.0-07
4.0-07
2.0-07
0.0
TOTAL MASS-VALVE-LB
0.
10.
20.
30.
40.
50.
60.
70.
TIME, MILLISECONDS

Fig. 10 (contd)

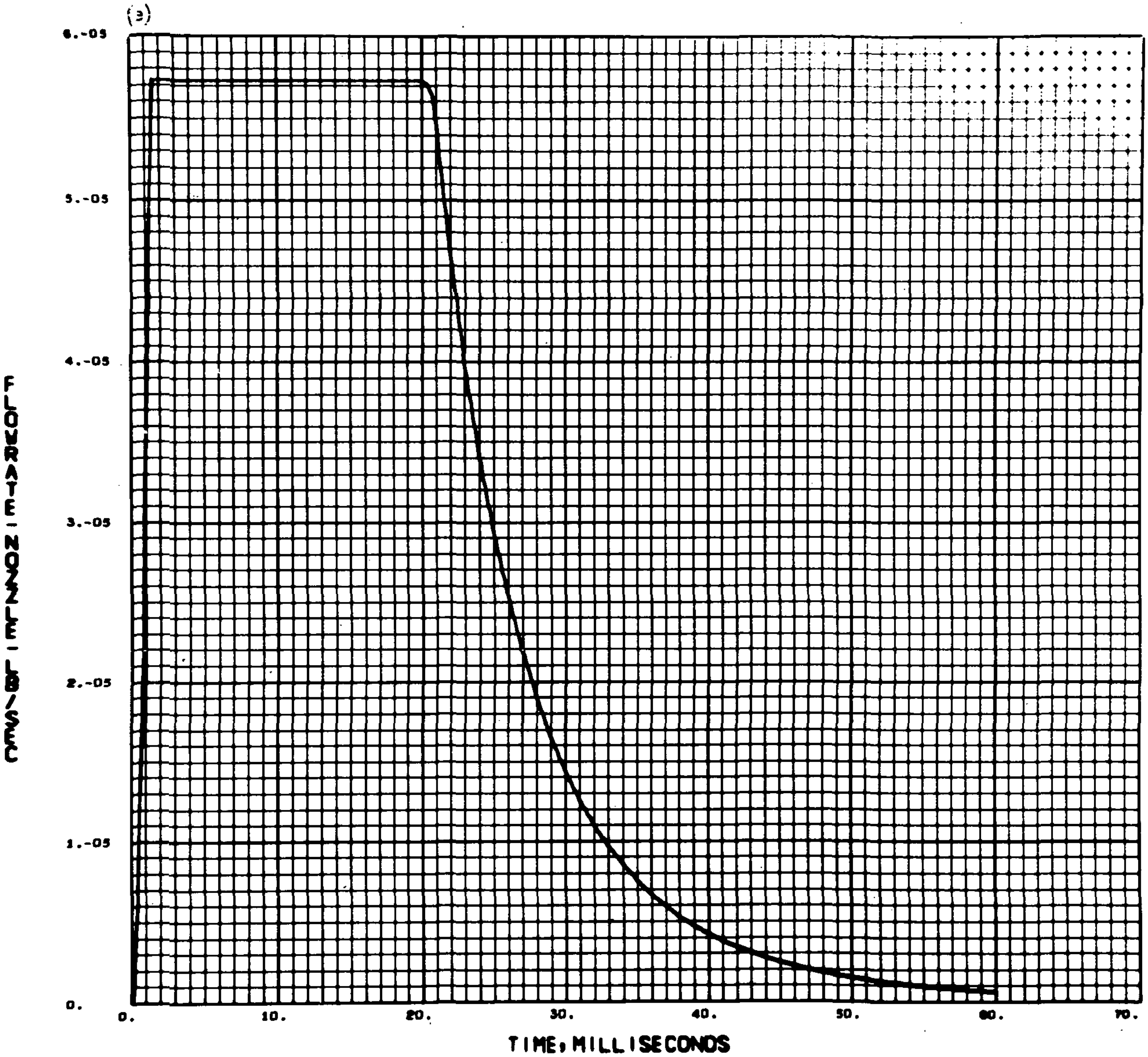

(3)
6.-05
5.-05
4.-05
3.-05
2.-05
1.-05
0.
FLOWRATE, NOZZLE, LB/SEC
0.
10.
20.
30.
40.
50.
60.
70.
TIME, MILLISECONDS

Fig. 10 (contd)

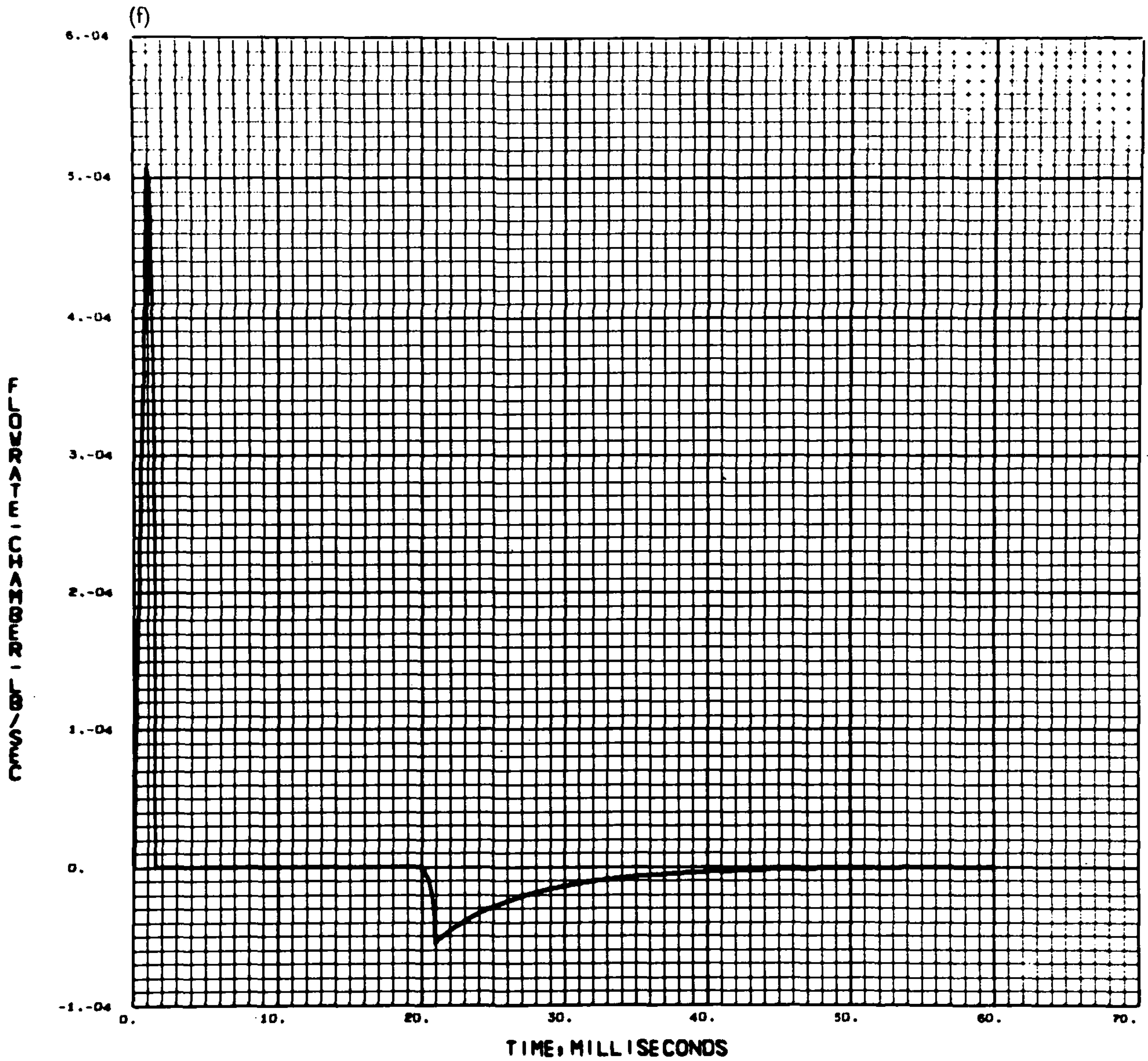

(f)
6.-04
5.-04
4.-04
3.-04
2.-04
1.-04
0.
-1.-04
FLOWRATE-CHAMBER-LB/SEC
0.
10.
20.
30.
40.
50.
60.
70.
TIME, MILLISECONDS

Fig. 10 (contd)

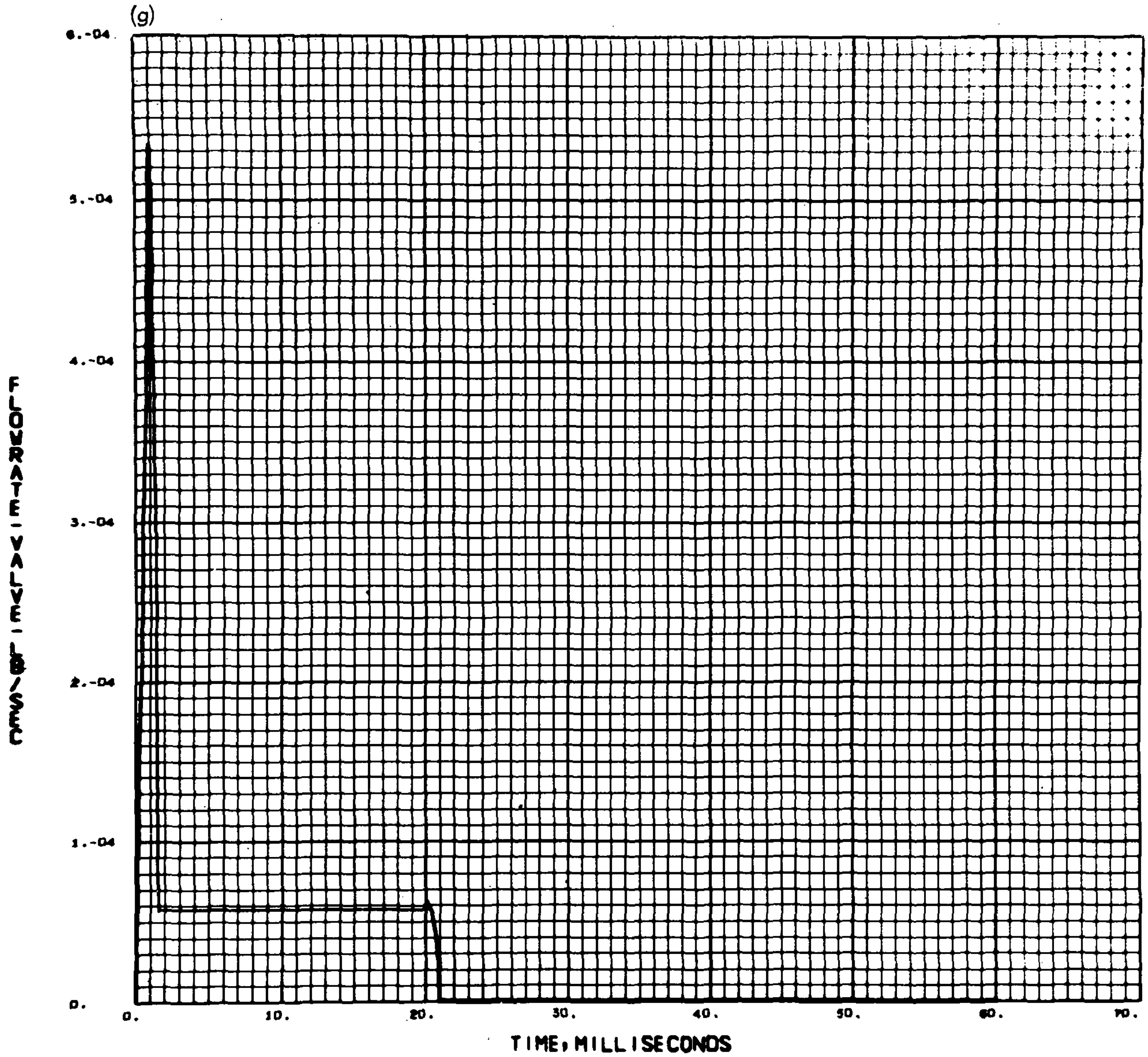

(g)
6.-04
5.-04
4.-04
3.-04
2.-04
1.-04
0.
FLOWRATE-VALVE-LB/SEC
0.
10.
20.
30.
40.
50.
60.
70.
TIME, MILLISECONDS

Fig. 10 (contd)

(h)

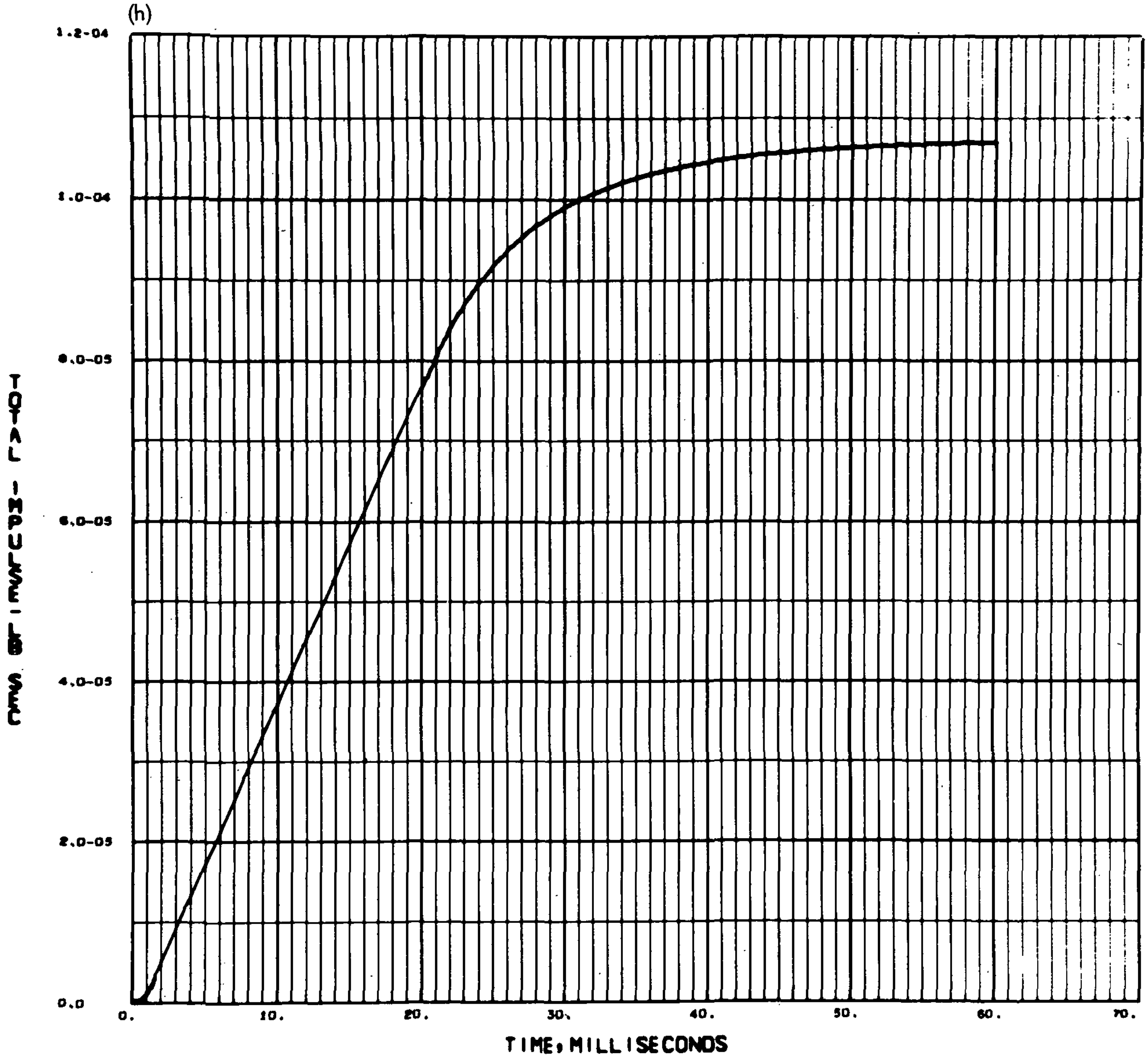


Fig. 10 (contd)

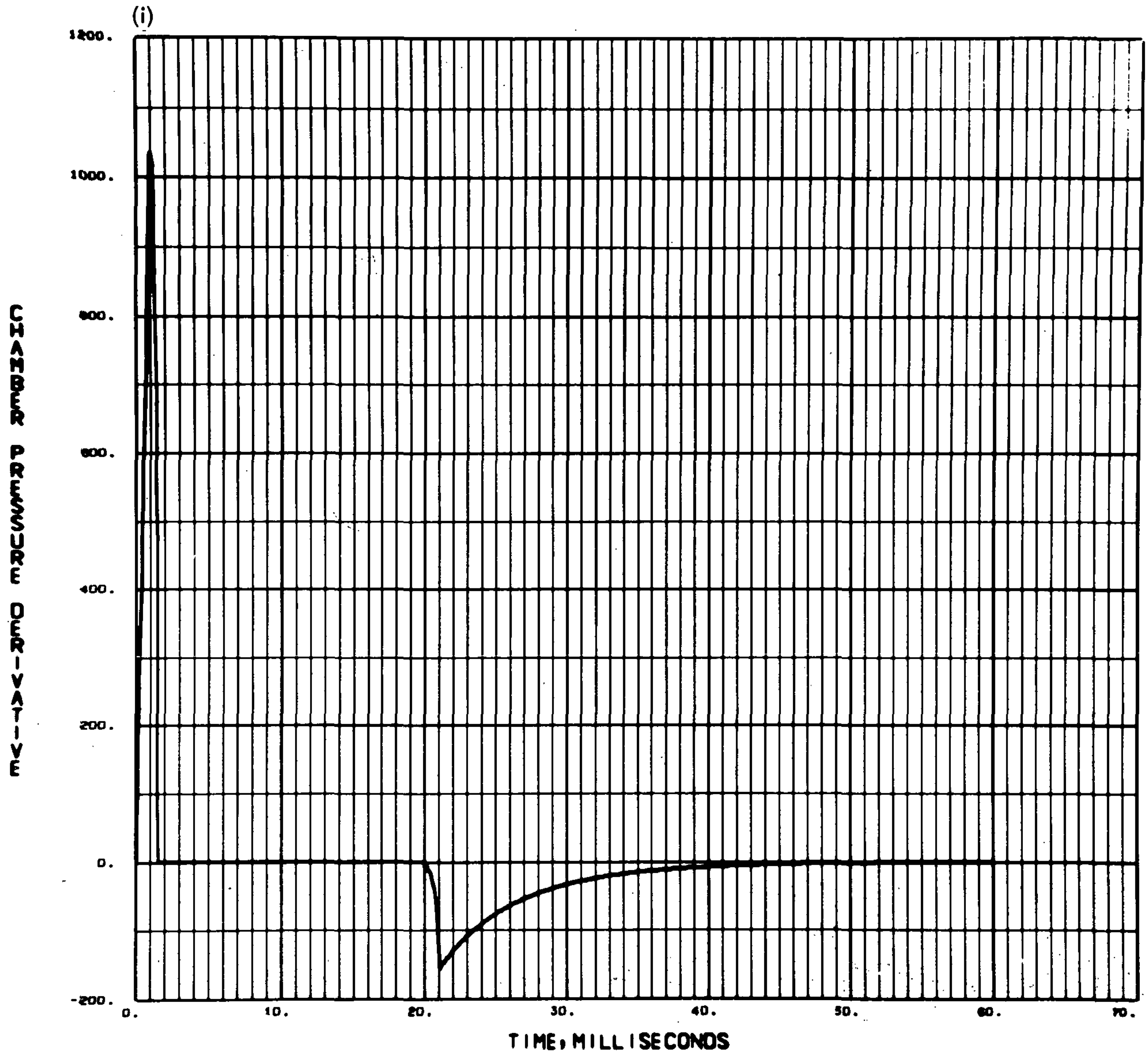


Fig. 10 (contd)

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