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COMPUTER MODELING OF ROCKET ENGINE IGNITION TRANSIENTS

FINAL REPORT

CONTRACT NAS7-467

MAY 1970

BY

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OF MARSHALL INDUSTRIES
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IRVINE, CALIFORNIA

FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
JET PROPULSION LABORATORY
PASADENA, CALIFORNIA

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Jet Propulsion Laboratory
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FOREWORD

This report was prepared for the National Aeronautics and Space Administration, Jet Propulsion Laboratory, Pasadena, California. Project Monitor on this contract was Richard M. Clayton, Liquid Propulsion Section.

This is the final report of a research program conducted to develop a mathematical model of how design and operating parameters influence combustion chamber pressures during the starting transient of a rocket engine. As such, it is based upon work completed and reported in two previous interim reports published under this contract (NAS7-467); "Study of Random Wave Phenomena in Hypergolic Propellant Combustion," June 1967 (Ref. 16), and "Transients Influencing Rocket Engine Ignition and Popping," April 1969 (Ref. 17).

SUMMARY

The objective of this program was to predict the dominant engineering parameters influencing the occurrence of start spiking in rocket engines. A computer program was written to describe transient propellant flow and the pressure/temperature and O/F histories with the chamber prior to ignition. Experimental tests were performed which confirmed the analytical findings. Ignition spiking occurred with fuel leads at low fuel temperature, and even at high fuel temperatures with long vacuum leads; while spiking was reduced by controlled valve opening sequences at nominal temperatures.

The analytical study resulted in a propellant transient flow digital computer program and a chamber pressurization transient digital computer program which was used to obtain the engine starting characteristics. The data from the pressurization program is used in the NASA/Lewis chemical equilibrium/detonation program to predict maximum pressures possible from the transient chamber fuel/oxidizer mixture environment.

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NOMENCLATURE

A_ℓ	Cross-sectional area of propellant line, in^2
A_o	Total cross sectional area of orifices, in^2
A_v	Open area of valve (which varies as the valve opens) in^2
A_{vo}	Area of valve when full open, in^2
B	Compressive bulk modulus, lb/in^2
C_D	Discharge coefficient
C_o	Loss coefficient of orifices
C_m	Capacitance of the propellant manifold (which is variable as the manifold fills), $ft^3 - in^2/lb$
C_v	Loss coefficient of valve
D	Diffusion coefficient of oxidizer vapors to droplet ft^3/sec
d	Diameter of line, in
f	Friction factor
g	Gravitational constant, 32.2 ft/sec^2
K	Concentration of oxidizer vapor surrounding a droplet, mass fraction
$\bar{K}$	Local concentration of oxidizer in vapor surrounding a droplet, mass fraction
K_ℓ	Loss coefficient for bends and abrupt line size changes
L_ℓ	Inductance of the propellant line between the tank and the valve, $lb\text{-}sec^2/ft^3 - in^2$
$L_{\dot{m}}$	Inductance of the propellant manifold (which is variable as the manifold fills), $lb\text{-}sec^2/ft^3\text{-}in^2$
ℓ	Length of propellant line, ft
ℓ_f	Length of line over which friction acts, ft
ℓ_m	Length of propellant manifold, in
M	Mach number
N_i	Number density of droplets with radius σ_i

P_a	Ambient pressure, lb/in^2
P_c	Chamber pressure, lb/in^2
P_f	Final manifold pressure after filling, lb/in^2
P_i	Initial manifold pressure before flow starts, lb/in^2
P_{line}	Pressure in the line upstream of the valve, lb/in^2
P_m	Pressure in propellant manifold, lb/in^2
P_v	Vapor pressure of the propellant, lb/in^2
q	Volumetric flow rate, ft^3/sec
q_1	Volumetric flow rate of propellants through the valve, ft^3/sec
q_2	Volumetric flow rate of propellants through the orifices, ft^3/sec
R_ℓ	Resistance of the propellant line between the tank and the valve, $lb\text{-}sec/ft^3\text{-}in^2$
R_o	Resistance of the orifices, $lb\text{-}sec/ft^3\text{-}in^2$
R_v	Resistance of the valve (which is variable as the valve opens), $lb\text{-}sec/ft^3\text{-}in^2$
r	Radial distance from the surface of the droplet
T	Temperature of gases in the propellant manifold ^oR
t	Time, seconds
t_f	Time of final manifold pressure after filling, sec
t_i	Time of initial flow into manifold, sec
V_m	Volume of propellant manifold, ft^3
V_{me}	Empty volume of manifold (which varies as the manifold fills), in^3
V_{mo}	Original empty volume of the manifold, in^3
$\dot{W}_g$	Flow rate of gases initially in the propellant manifold, lb/sec
$\dot{W}_o$	Flow rate through the orifices, lb/sec
W_{og}	Weight of gases initially in the propellant manifold, lb

1. INTRODUCTION

High pressures usually referred to as pressure spikes or detonation waves can occur during the starting transient of a rocket engine. These high starting pressures can damage the combustion chamber. High pressure spiking has been encountered in both large (Ref. 1) and small scale (Ref. 2) space engines. Engine fixes were made to eliminate the spikes in specific engines while little effort was made to understand the mechanisms involved. At first it was generally accepted that the cause of the pressure waves was the explosion of accumulated propellants in the combustion chamber. However, as a result of recent experimental investigations, it was found that detonatable chemical reaction intermediates can form under start transient conditions (Refs. 3, 4, 5, and 6) and Perlee (Ref. 4) showed that observed hardware deformations could only be explained on the basis of the presence of highly detonatable material. This information provided evidence for a mechanism to explain start transient spiking; conditions within a rocket engine combustion chamber, during the start transient, that are conducive to the formation of these detonatable mixtures would lead to the magnitude of spikes observed. Thus, what was needed was an analytical model describing the occurrence of these unfavorable conditions and also describing how these unfavorable conditions could be avoided by proper engineering design and/or controlled. The details of this model are aimed at establishing temperature, pressure, and O/F conditions which control preignition and intermediate chemistry, while the overall purpose is to show how smooth starts can be engineered into a rocket engine.

The model developed is spatially one-dimensional and is based on time dependent differential equations which describe the physical and chemical processes governing the transient chamber conditions. The overall logic of the model is based on the four processes shown in Figure 1. The equations must account for the four processes shown by Roman numerals I through IV: (I) the liquid propellant transient flow, (II) vaporization, condensation, and freezing of propellants and their effect on the chamber transient pressure and temperature, (III) chemical reaction leading to the formation of detonatable mixtures with the effects of species concentration and temperature considered, and finally (IV) the strength of detonation of the accumulated mixture. The vaporization model incorporates the modeling work of Agosta (Ref. 7) and of Seamans and Dawson (Ref. 8). The present model is unique in that it incorporates the results of previous chemical

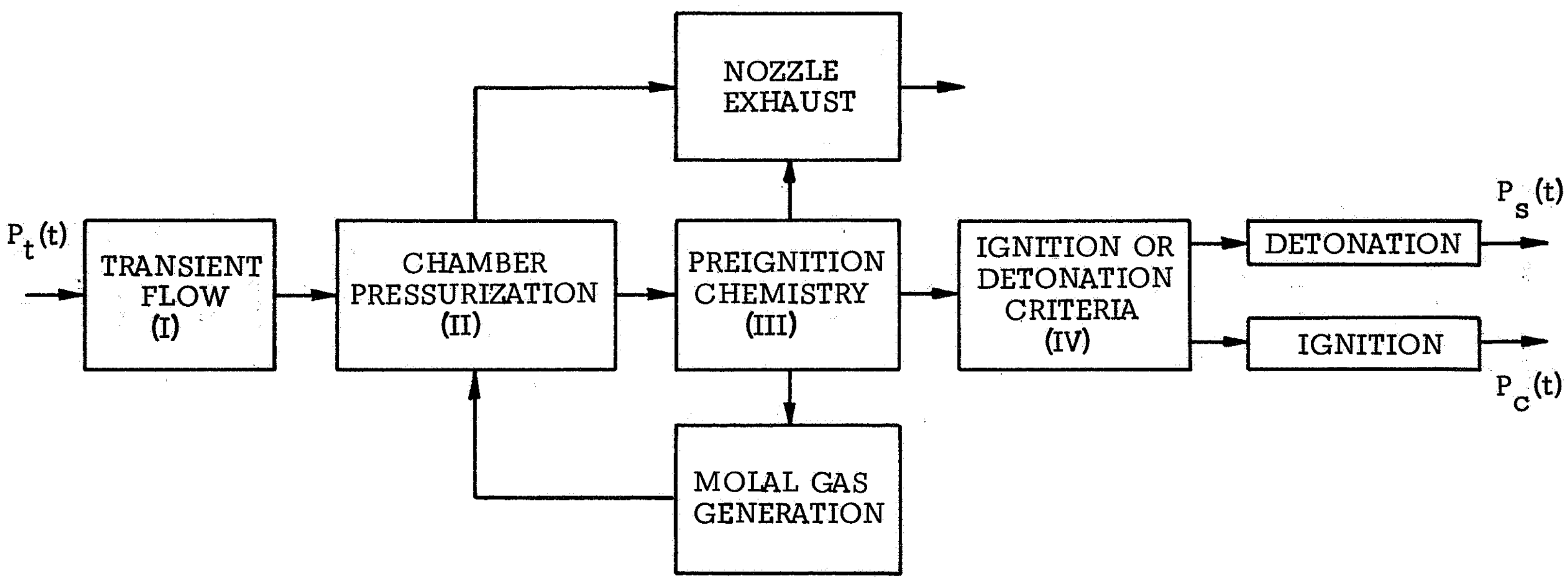
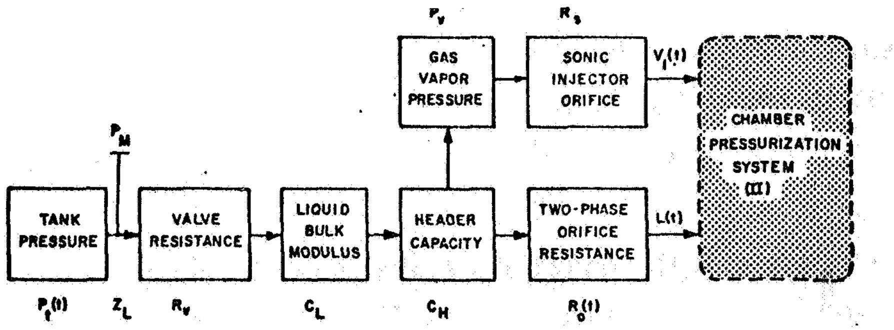
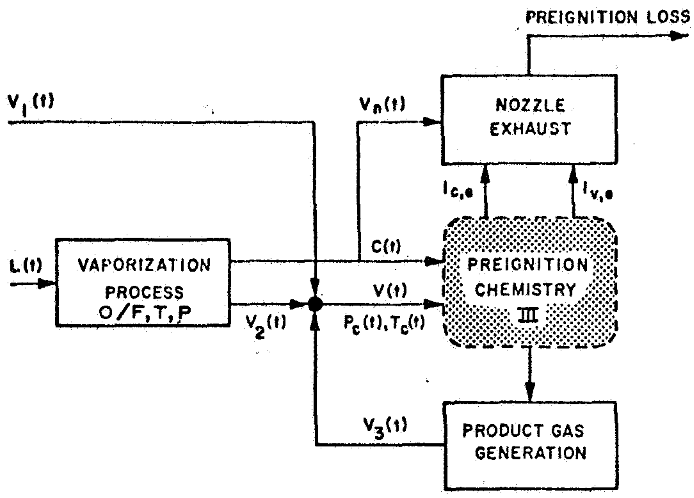


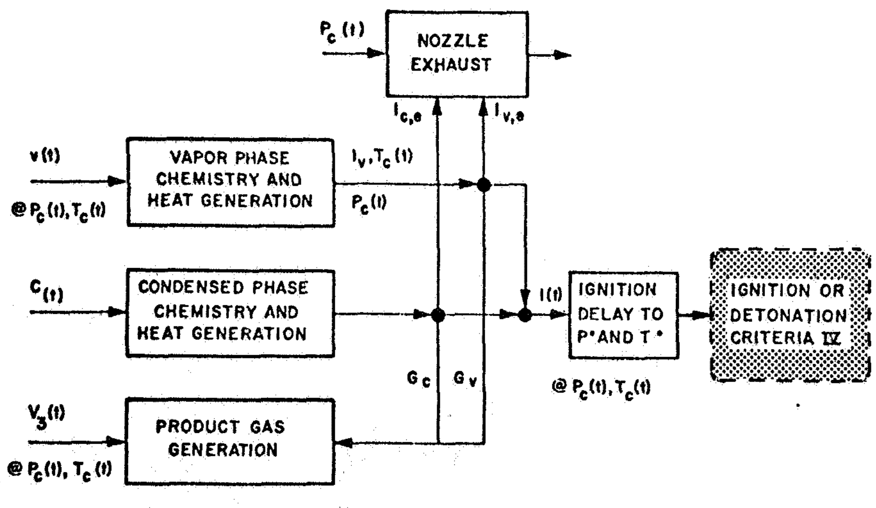
Figure 1. Rocket Chamber Ignition Model



a. Transient Flow Systems (I)



b. Chamber Pressurization System (II)



c. Preignition Chemistry System (III)

Figure 2. Individual Components of Ignition Model

intermediate research on hypergolic ignition mechanisms (Refs. 3 and 9) and on ignition chemistry (Refs. 4, 5, and 10). The model contains several constants which have been evaluated from experimental data published in these references.

The solution of the equations describing the model were performed numerically on the digital computer by a finite difference method. The main objectives of this project were to perform analytical and experimental investigations to:

(1) Analytically determine the dominant parameters that influence the production of starting transient chamber pressure spikes.

(2) Determine design criteria for the minimizing of spiking based on study developments.

(3) Experimentally verify the analytical results and determine the limitations of the analysis and of the computer programs.

In any practical rocket engine system, which relies upon hypergolic ignition, the engine will start once the liquid entering the chamber meets previously determined ignition criteria conditions of temperature and vapor pressure. From this point of view, the starting of an engine involves two characteristic flow delays:

(1) line and manifold filling, and

(2) the flow of enough liquid sensible heat to overcome hardware and vaporization heat losses.

Essentially, once enough liquid has entered the chamber so that both the fuel and the oxidizer droplet enter a chamber pressure either equal to or greater than their vapor pressure, then they do not flash vaporize and the engine starts within $\pm$ 5% of the added two flow delays above.

The individual components of the flow and heat balances are shown in Figure 2. During the first phase of this work (Ref. 16), these components were identified by calculating controlling time constants and from published experimental observations; thus, the controlling model is formulated in the first interim report of this work (Ref. 16). In the second phase of this contract (Ref. 17), the individual components of Figure 2 were described by an analytical model, and the model was programmed for solution so that the characteristics of each component of Figure 2 could be demonstrated. Generally, the importance of the transient flow characteristics was pointed out and it was shown that once enough liquid sensible heat entered the chamber to overcome the hardware heat capacity, the engine started.

In Section 2 of this report, the line manifold and chamber flow (the first delay) are described, while Section 3 describes the heat balances (the second delay) and resulting chamber conditions which the entering liquid encounters and Section 5 relates these flow and vaporization situations to experimental determinations of the occurrence and severity of spiking.

2. PROPELLANT TRANSIENT FLOW PROGRAM

Chamber pressurization transient predictions require a knowledge of the propellant flow into the combustion chamber as a function of time. Analyses were made of the propellant feed system of a typical bipropellant liquid fueled rocket engine. This system is shown schematically in Figure 3. The feed system and the analysis are general and can be used in any gas-pressurized injection scheme regardless of the size of the engine. Likewise, the analysis can be used to predict the response of a future system design or analyze an existing system.

Analysis of the feed system of Figure 3 is similar to a pipeline flow problem. There are two general methods of approach; the controlling parameters can be assumed to be either (1) distributed along the flow line, or (2) lumped at one point in the circuit. Solution of systems (Ref. 11) by a distributed approach involves partial differential equations in space and time. Discontinuities in the system, such as the valves and propellant tank of Figure 3, are the boundary conditions for the problem. Solutions are obtained by methods of characteristics (such as water hammer analysis, Ref. 1). The difficulties in applying this approach are: (1) the solutions are difficult to generalize or only simple configurations may be generalized, and (2) the flow downstream of the valve requires a separate solution which must be matched at the discontinuity (the valve). This second condition requires detailed knowledge of the pressure wave interactions within the propellant manifolds which are difficult to obtain. The approach may be applied to simple configurations where detailed information about the wave interaction effects are desired but overall the more microscopic nonlinear effects of unfilled vs. filled manifolds and time dependent valve resistance and cavitating flow in the orifice are more important to the starting characteristics of the engine.

Solutions of flow systems by a lumped parameter approach are made by considering solutions of quasi-steady-state flow (Ref. 11) or by use of an electrical analogy model. Quasi-steady-state solutions assume (1) no injector flow until the manifolds are full, (2) all loss terms are linear or constant, (3) no inertia or fluid elasticity effects are considered, and (4) all pressure in and flow out of the manifolds occurs discontinuously. These restrictions are quite severe and the results of such analyses give trends only for design changes and minimal details of the flow transient.

By considering a lumped parameter model wherein each element of the fluid system is considered analogous to those of a passive electrical system, the details of the distributed system are retained with the simplicity of the quasi-steady-state approach (Refs. 13 and 14). Basically, the analog model which was decided upon is described on the following pages.

Electrical/Hydraulic Analog Model: The electrical/hydraulic analogy is developed by considering all pressure loss terms lumped in a hydraulic resistance, R_h, all fluid inertia effects lumped in a hydraulic inductance, L_h, and all fluid elasticity effects lumped in a hydraulic capacitance C_h. The lumped hydraulic capacitance can be taken as the compressibility of the vapor because in the case of vacuum starts there always exists a point of cavitation and, therefore, a compressible vapor point. For one side (fuel or oxidizer) of the system shown in Figure 3a, an analogous system can be constructed, Figure 3b.

Writing the pressure drops around the loops of the circuit shown in Figure 3b, the following differential equations result:

$$L_\ell \frac{dq_1}{dt} + R_\ell q_1 + R_v q_1 + \frac{1}{C_m} \int (q_1 - q_2)\, dt = \Delta P \tag{1}$$

$$L_m \frac{dq_2}{dt} + R_o q_2 + \frac{1}{C_m} \int (q_2 - q_1)\, dt = 0 \tag{2}$$

Converting the analogous terms to fluid flow parameters as follows:

$$L_\ell = \frac{\rho \ell}{g A_\ell} \text{ (for the line)}$$

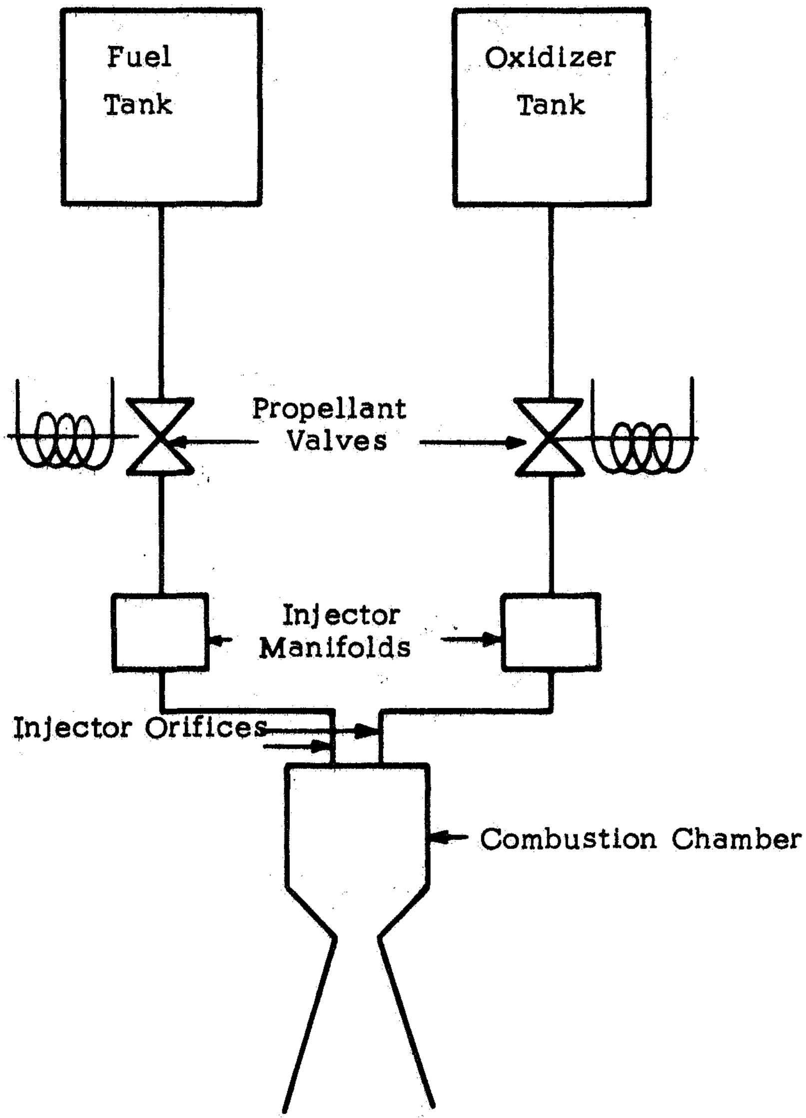
$$L_m = \frac{\rho \ell_m^2}{g V_m} \text{ (for the manifold)}$$

$$C_m = \frac{V}{B} = \frac{V}{P_v}$$

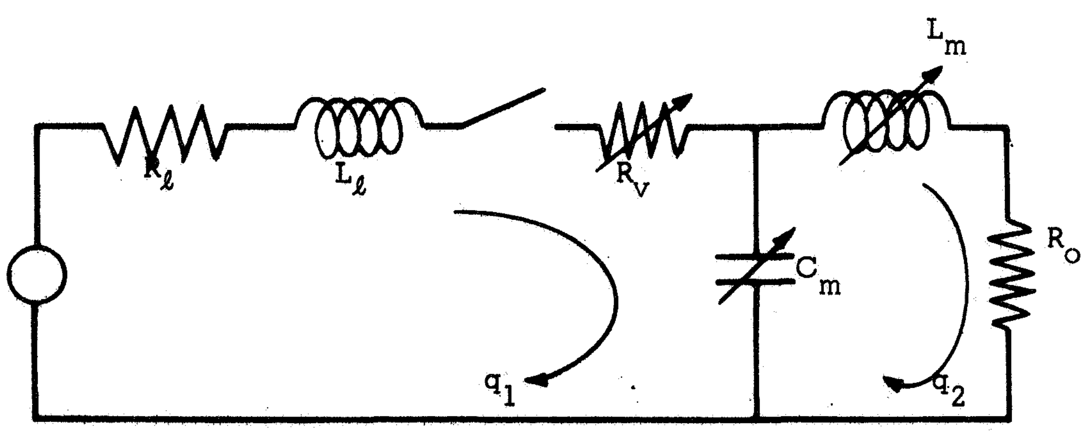
$$R_v = \frac{\rho}{2g (C_v A_v)^2}\, q \text{ (for the valve)}$$

$$R = K_\ell\, \rho \frac{q}{2gA_\ell^2} \text{ (for bends and line size changes)}$$

$$R = f \frac{\ell_f}{d}\, \rho \frac{q}{2gA_\ell^2} \text{ (for friction losses)}$$



a. Schematic Diagram of Propellant Feed System.



b. Analogous Electrical System to Propellant Feed System

Figure 3. Propellant Feed System. Schematic and Analogous Diagrams.

the final differential equations result:

$$\frac{\rho \ell}{gA_\ell}\frac{dq_1}{dt} + (K_\ell + f\frac{\ell_f}{d})\,\rho\,\frac{q_1^2}{2gA_\ell^2} + \frac{\rho}{2g(C_vA_v)^2}\,q_1^2 + \frac{P_v}{V_m}\int(q_1-q_2)dt = \Delta P \qquad (3)$$

$$\frac{\rho \ell_m^2}{gV_m}\frac{dq_2}{dt} + \frac{\rho}{2g(C_oA_o)^2}\,q_2^2 + \frac{P_v}{V_m}\int(q_2-q_1)\,dt = 0 \qquad (4)$$

Solution of the Model: Standard digital computer integration procedures are available for solving nonlinear differential equations shown by Equations (3) and (4). A standard integration subroutine was found to be perfectly satisfactory. The method employed used a 4th order Runge-Kutta start and a 4th order Adams-Moulton fixed step predictor-corrector method used to continue the integration. Comparing predicted and corrected values at each step, the integration step size was halved, doubled, or maintained the same so that the truncation error would remain within prescribed error bounds. The time varying valve area, A_v, is prescribed by either an input table or for valves which open nearly linearly, by the equation:

$$A = A_{vo}\left(\frac{t}{\tau_{vo}}\right)^n . \qquad (5)$$

Within the framework of this analysis, the following assumptions are made:

(1) The liquid propellants are incompressible.

(2) The compressibility effect in the propellant manifold is due to the vapor in the manifold and is equal to the bulk modulus of vapor. The formation of vapor in the manifold is accomplished adiabatically.

(3) Wave effects within the system have negligible effects on the transient flow.

(4) The chamber pressure is constant.

Parametric Effects: Initial cases were calculated to determine the effects of the various system parameters and empirical constants in the analysis. Figures 4 through 10 show the results of these initial cases. Table I shows those parameters which were not varied for these cases. Most of the cases were performed with $n = 1.0$ (linear valve opening); however, a limited number of cases were run for $n = 3$.

TABLE I

TRANSIENT FLOW PARAMETERS HELD CONSTANT DURING INITIAL PROPELLANT FLOW TEST CASES

line diameter, inches	DI	=	.1875 in.
valve coefficient	CV	=	.7
injector coefficient	CØ	=	.7
orifice diameter, inches	DØI	=	.02 in.
number of orifices	XNØRF	=	4.0
steady-state flow, lb/sec	WSS	=	.08 lb/sec (oxidizer)
			.067 lb/sec (fuel)

Figure 4 shows the effect on flow rate of varying K_ℓ, the loss coefficient. K_ℓ is approximately 1.0 for one bend or abrupt area change (Ref. 15).

Figure 5 shows the effect on flow rate of varying the valve opening time from 2.5 to 10 ms. There is little effect on the transient shape in each case except to delay the transient as the valve opening time is increased.

The effect of the manifold volume is seen in Figure 6 where manifold volumes of .05, and .025 in^3 were considered with a valve having an opening time of 10 ms. For the smaller manifold volume steady-state flow is achieved sooner, however, the overshoot of $\dot{W}_o$ is greater than for the larger volume (.0901 lb/sec vs .0857 lb/sec).

Figure 7 shows the effect of varying the valve area. The effect of reducing the area is to throttle the flow.

Figure 8 shows the effect of varying the valve transient shape for two valve areas. It is seen that by reducing the initial opening rate the valve can more effectively control the flow through the orifices.

Figure 9 shows the effects of temperature on the start transient. Oxidizer at 540 and 580^{o}R was used for these tests. The differences in transients noted here are due to the difference in vapor pressure (18.5 psia vs 49 psia) of the propellant (N_2O_4) at these two temperatures.

The calculations were made for fuel (hydrazine) at 500^{o}R (Figure 10). Both calculations show flow rate overshoot and extremely rapid flow rise rates. Although both conditions show overshoots, the recovery to steady-state flow is rapid.

Originally the analysis considered the compressibility of the vapors inside the manifold to take place isothermally. Campbell (Ref. 14) showed that rapid compression of gases occur nearly adiabatically. This effect results in the following:

$$C_m = \frac{P_{vm} V_o^{\gamma} \gamma}{V_{me}^{\gamma+1}} \tag{6}$$

where C_m is the capacitance. For nonvacuum starts the propellant manifolds contain air which is expelled as the manifold is filled with propellant. The capacitance pressure term in the differential equation accounts for the change

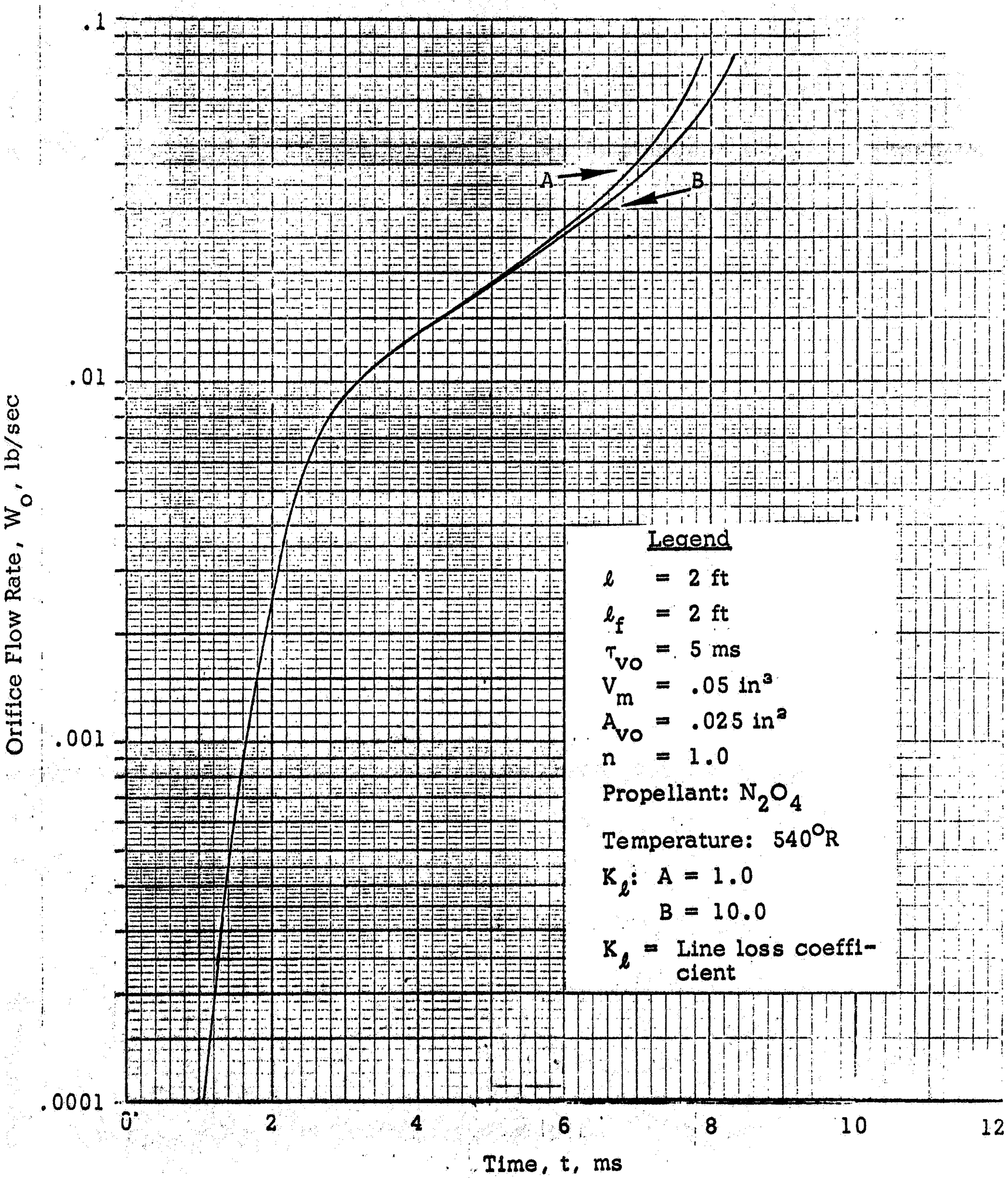


Figure 4. Effect of Loss Coefficient, K_ℓ, on Flow Transient.

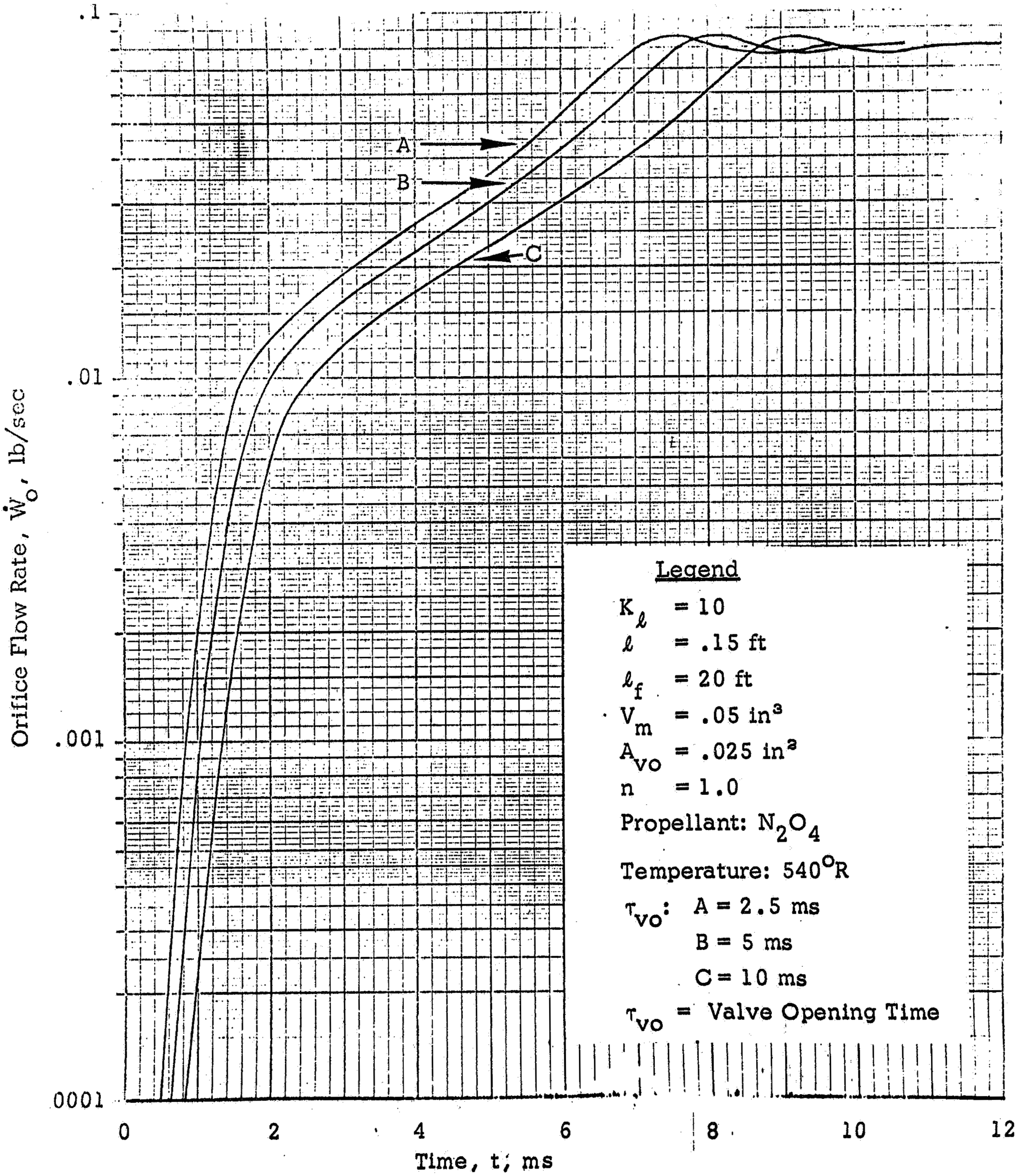


Figure 5. Effect of Valve Opening on Flow Transient.

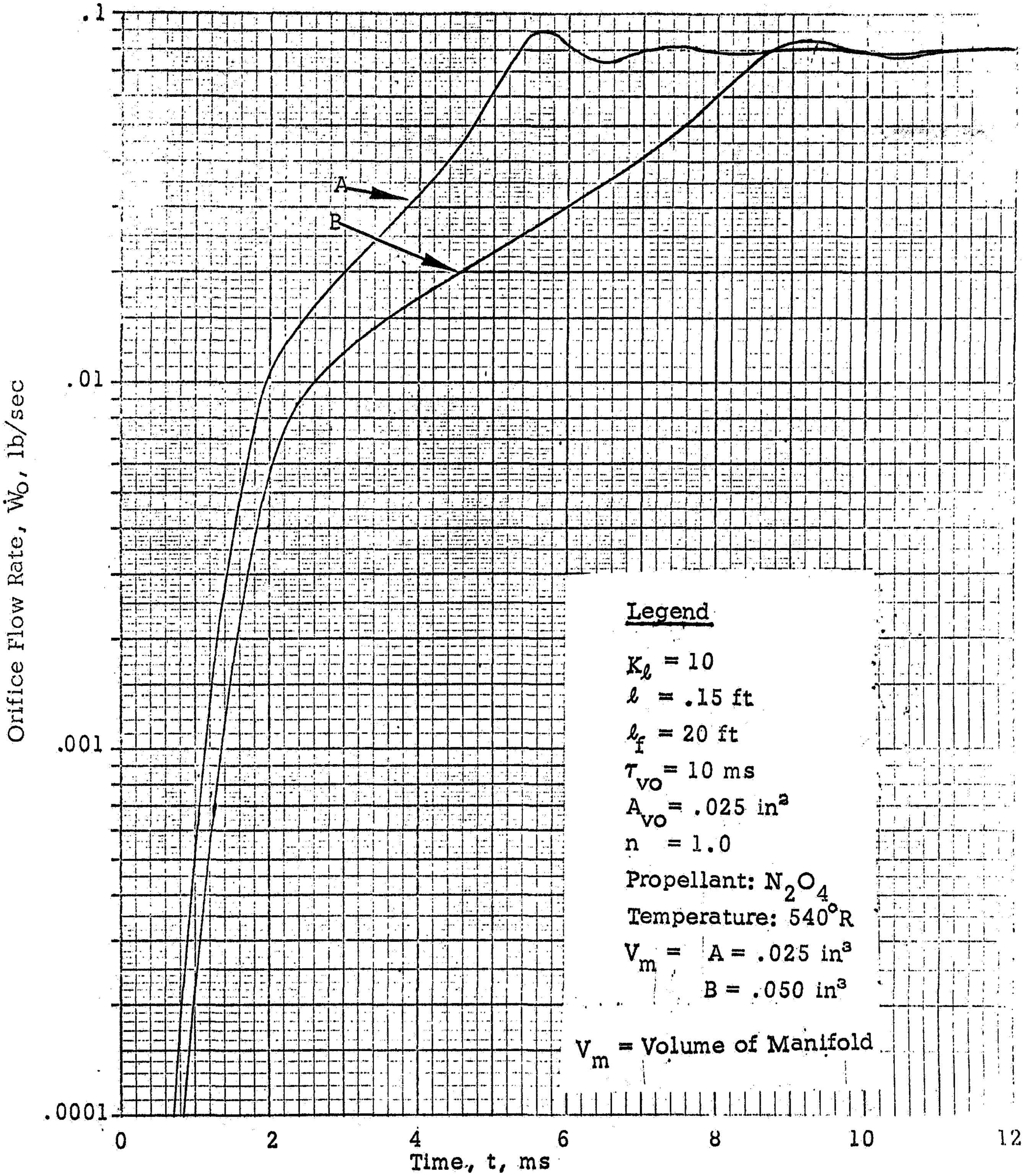


Figure 6. Effect of Manifold Volume on Flow Transient.

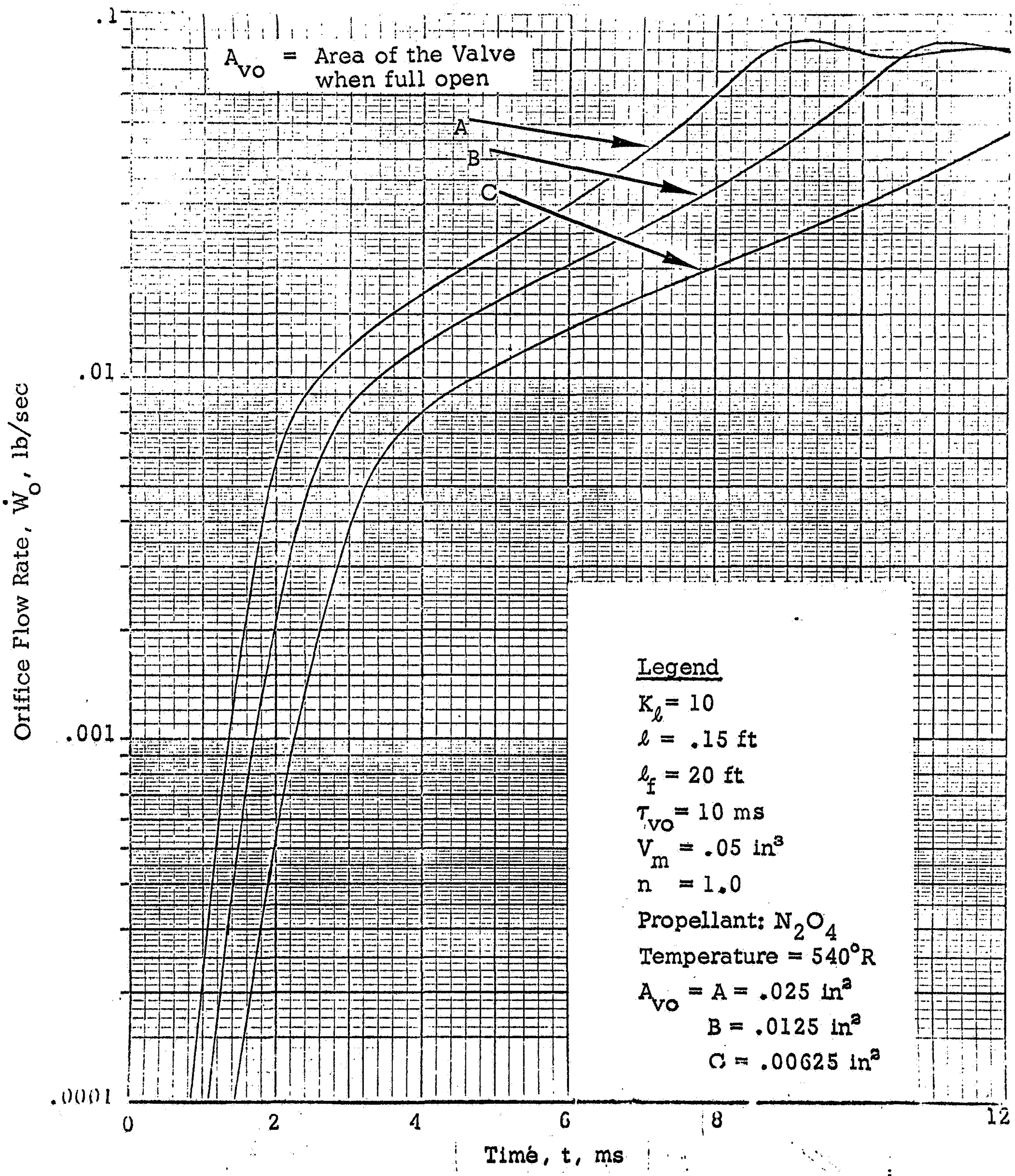


Figure 7. Effect of Valve Open Area on Flow Transient.

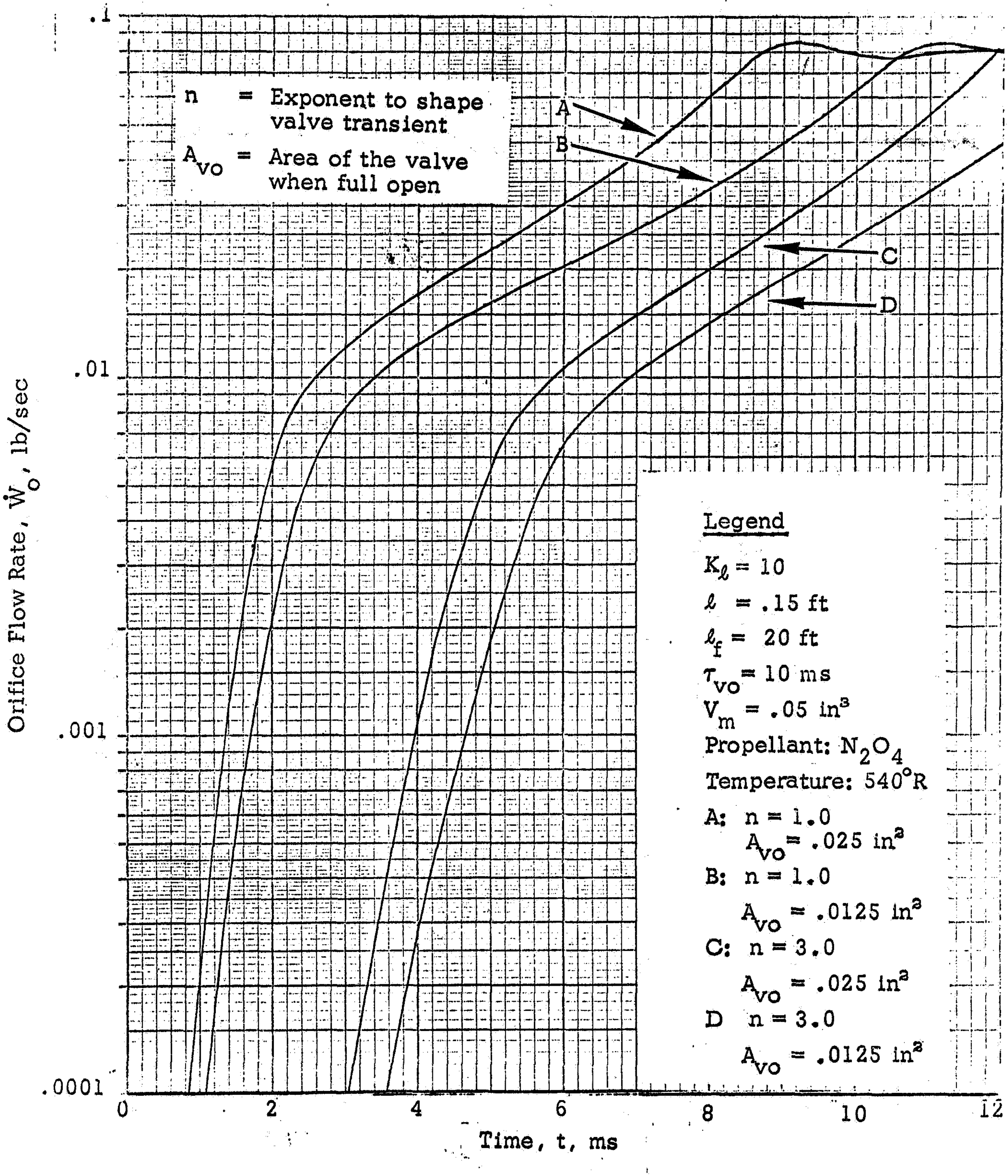


Figure 8. Effect of Valve Transient and Open Area on Flow Transient.

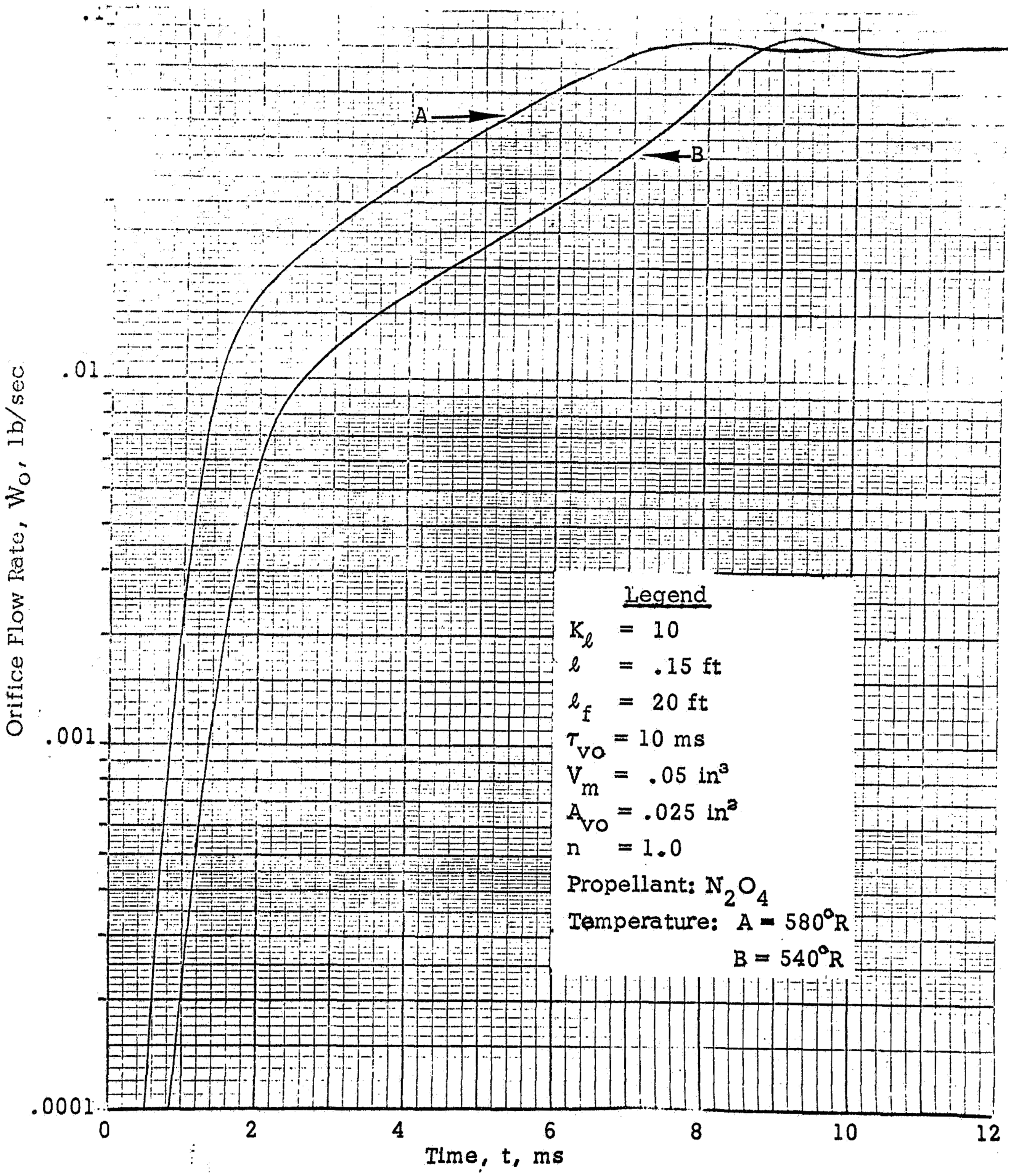


Figure 9. Effect of Oxidizer Temperature on Flow Transient.

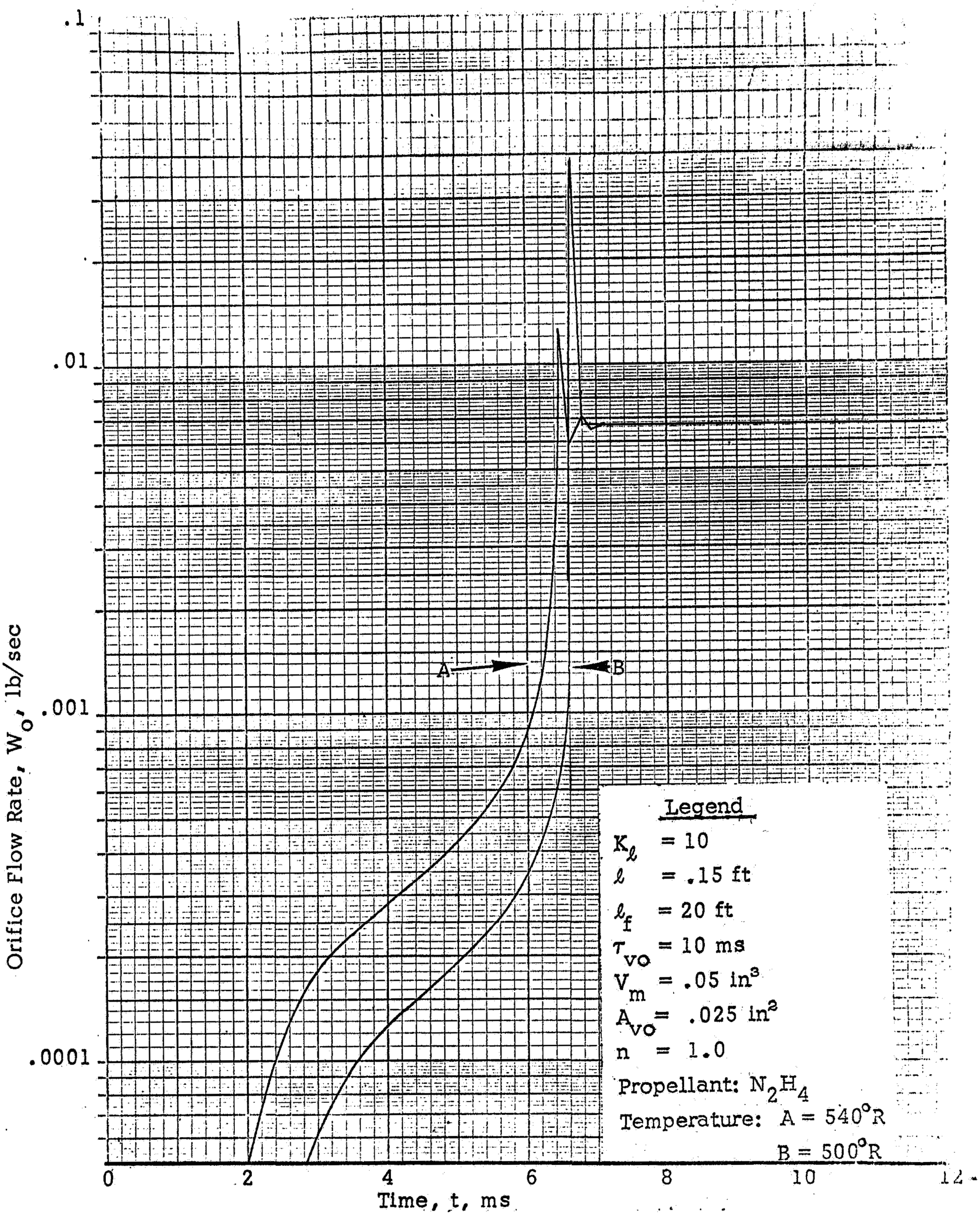


Figure 10. Effect of Fuel Temperature on Flow Transient.

in the manifold volume due to the incoming propellants and the expelled air. This differential equation is:

$$\frac{dP_m}{dt} = P\gamma \frac{\dot{W}_g}{W_{og} - \int \dot{W}_g dt} - P\gamma \frac{q_1 - q_2}{V_{me}} \quad (7)$$

where

$$\dot{W}_g = Ao\sqrt{\frac{\gamma g}{RT}}\, P_m \frac{M}{(1+\frac{\gamma-1}{2} M^2)^{\frac{\gamma+1}{2(\gamma-1)}}} \quad (8)$$

and

$$M = \left\{\frac{2}{\gamma-1}\left[\left(\frac{P_m}{P_a}\right)^{\frac{\gamma-1}{\gamma}} -1\right]\right\}^{1/2} \quad (9)$$

For vacuum starts, the manifold pressure was the vapor pressure of the entering propellants until the manifold was full. Thus, the pressure rises from zero to the vapor pressure, remains at vapor pressure until the manifold fills, and then becomes equal to the system fluid pressure.

Valve Opening Effects: Five calculations were made under these conditions (Figures 11 through 15). These cases considered three linear valve openings and two step-wise openings. Table II shows the conditions. The three linear openings are 10, 50, and 100 ms. Figures 11, 12, and 13 show the effect of these opening rates. It is seen that no control of the propellant flow rate is achieved. When the manifold fills a substantial pressure and flow rate overshoot occurs.

To simulate flow control, two step-wise valve openings were considered, Figures 14 and 15. Figure 14 shows the results of a low level step. Under these conditions a substantial reduction in the flow and pressure rise occurs. For the oxidizer flow, no overshoot occurred, and for the fuel flow, the overshoot was reduced. When a medium level step-wise opening was used the results were equivalent to a 50 ms valve opening.

From the propellant transient studies it can be concluded that:

(1) Propellant flow from the injector prior to the manifold pressure reaching the vapor pressure is controlled by the valve opening transient.

(2) Propellant flow from the injector prior to the manifold filling after the manifold pressure rises to the vapor pressure, will

be controlled by the injector orifices, the chamber pressure, and finally by the vapor pressure of the propellants in the manifold. The flow control which is possible during this period, therefore, is by controlling the propellant temperature and thus the vapor pressure.

(3) Propellant flow from the injector can be controlled by valves if the initial valve opening area is small.

TABLE II

INPUT FOR PROPELLANT TRANSIENT FLOW TEST CASES

(See Figures 9 - 13)

	Oxidizer System			Fuel System		
density, lb/ft^3	RØ	=	88.9	RØ	=	62.6
line length, ft	XL	=	8.	XL	=	8.
vapor pressure, lb/in^2	PVI	=	18.5	PVI	=	.32
resistance coeff.	XKL	=	16000.	XKL	=	11000.
line dia., in	DI	=	.305	DI	=	.305
discharge coeff.	CV	=	.7	CV	=	.7
resistance length, ft	XLF	=	8.	XLF	=	8.
manifold length, in	XLMI	=	4.	XLMI	=	4.
discharge coeff.	CO	=	.86	CO	=	1.
orifice dia, in	DOI	=	.02	DOI	=	.02
viscosity, lb/ft-sec	XMU	=	.00026	XMU	=	.00058
manifold volume, in^3	VMOI	=	.1037	VMOI	=	.172
number of orifice	XNORF	=	4.	XNORF	=	4.
heat ratio	GAM	=	1.2	GAM	=	1.4
ambient pressure, lb/ft^2	PAMBI	=	0.	PAMBI	=	0.

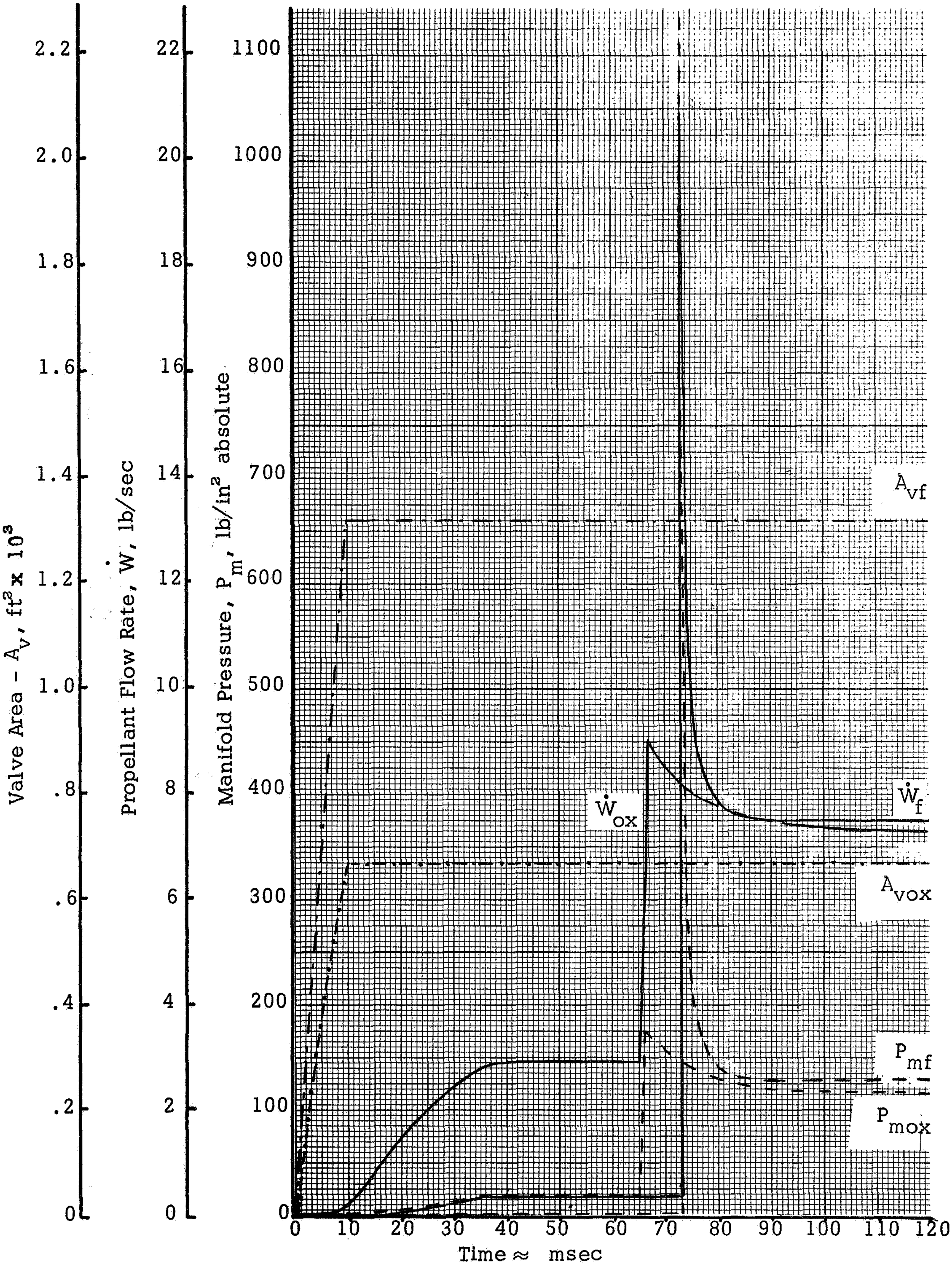


Figure 11. Propellant Flow Transient with Fast Opening Valve.

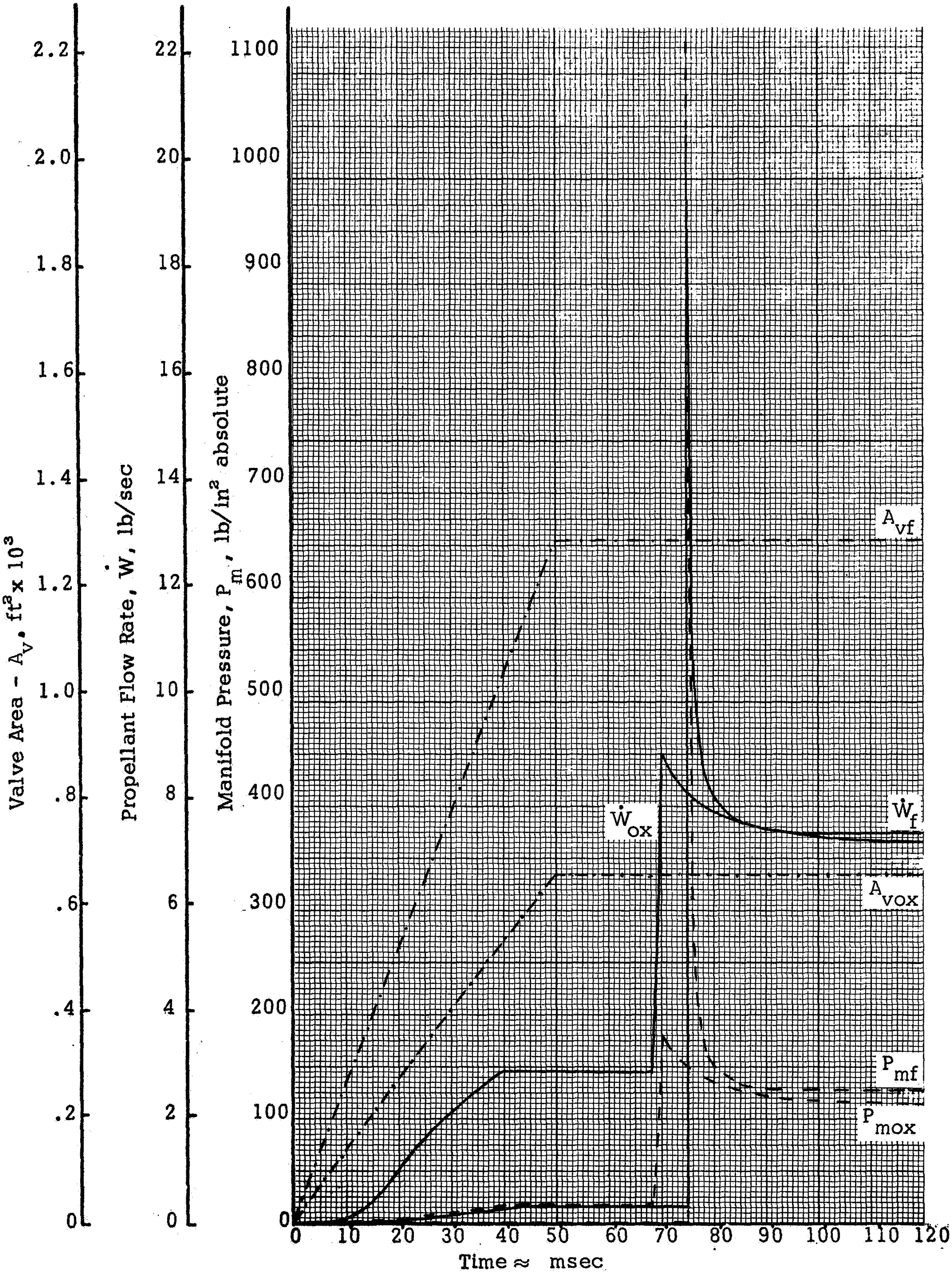


Figure 12. Propellant Flow Transient with Medium Opening Valve.

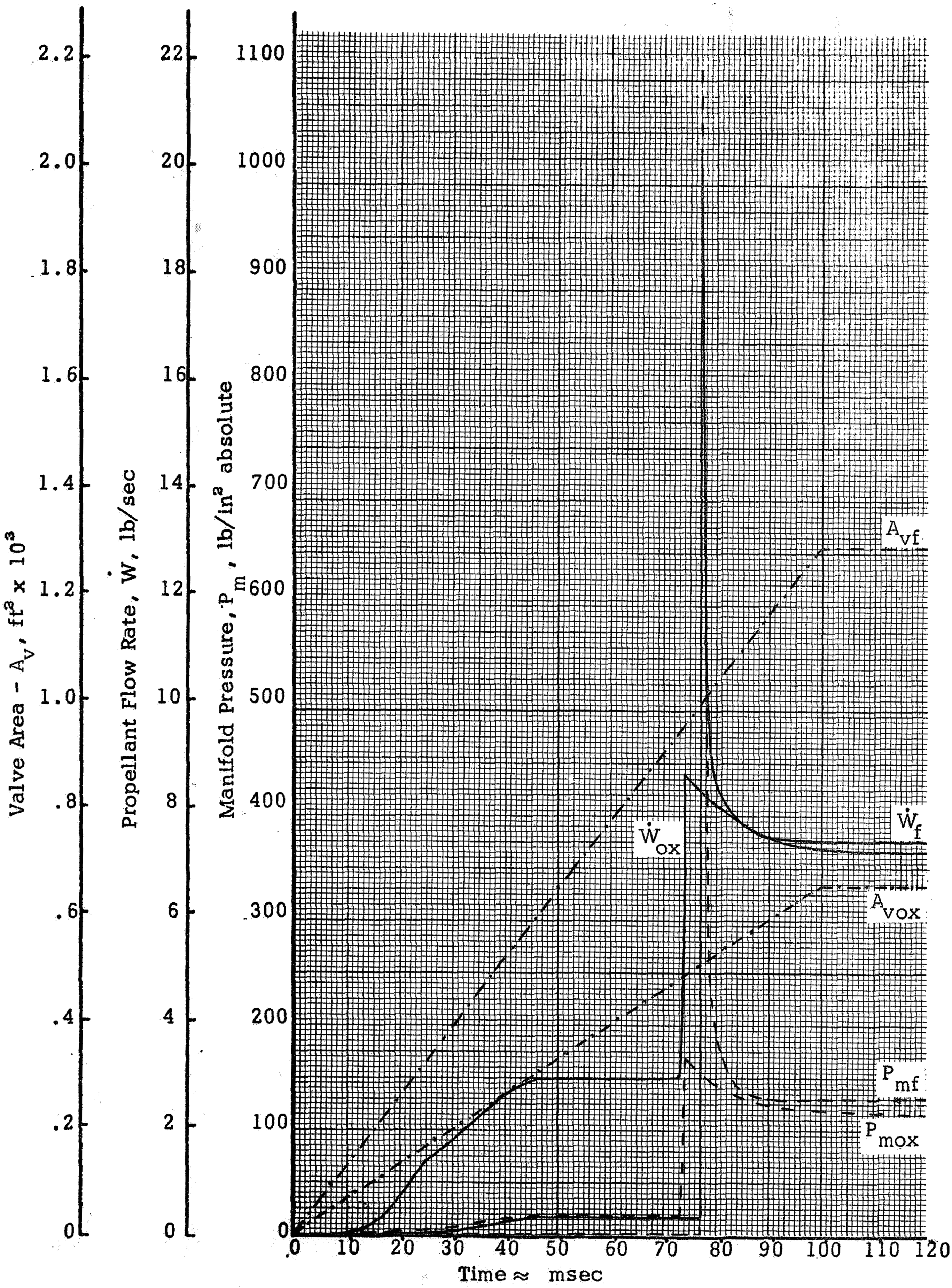


Figure 13. Propellant Flow Transient with Slow Opening Valve.

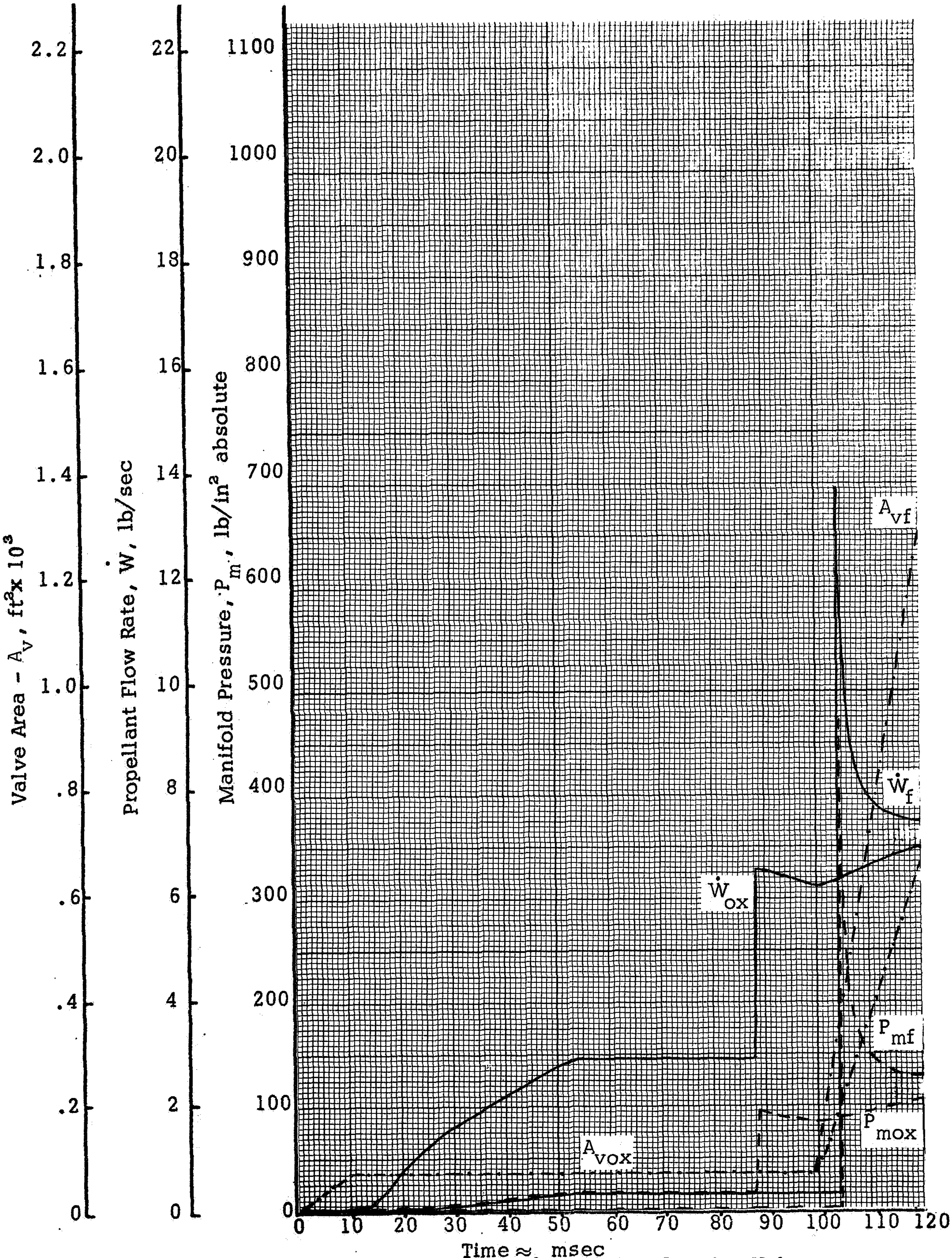


Figure 14. Propellant Flow Transient with Low Step Opening Valve.

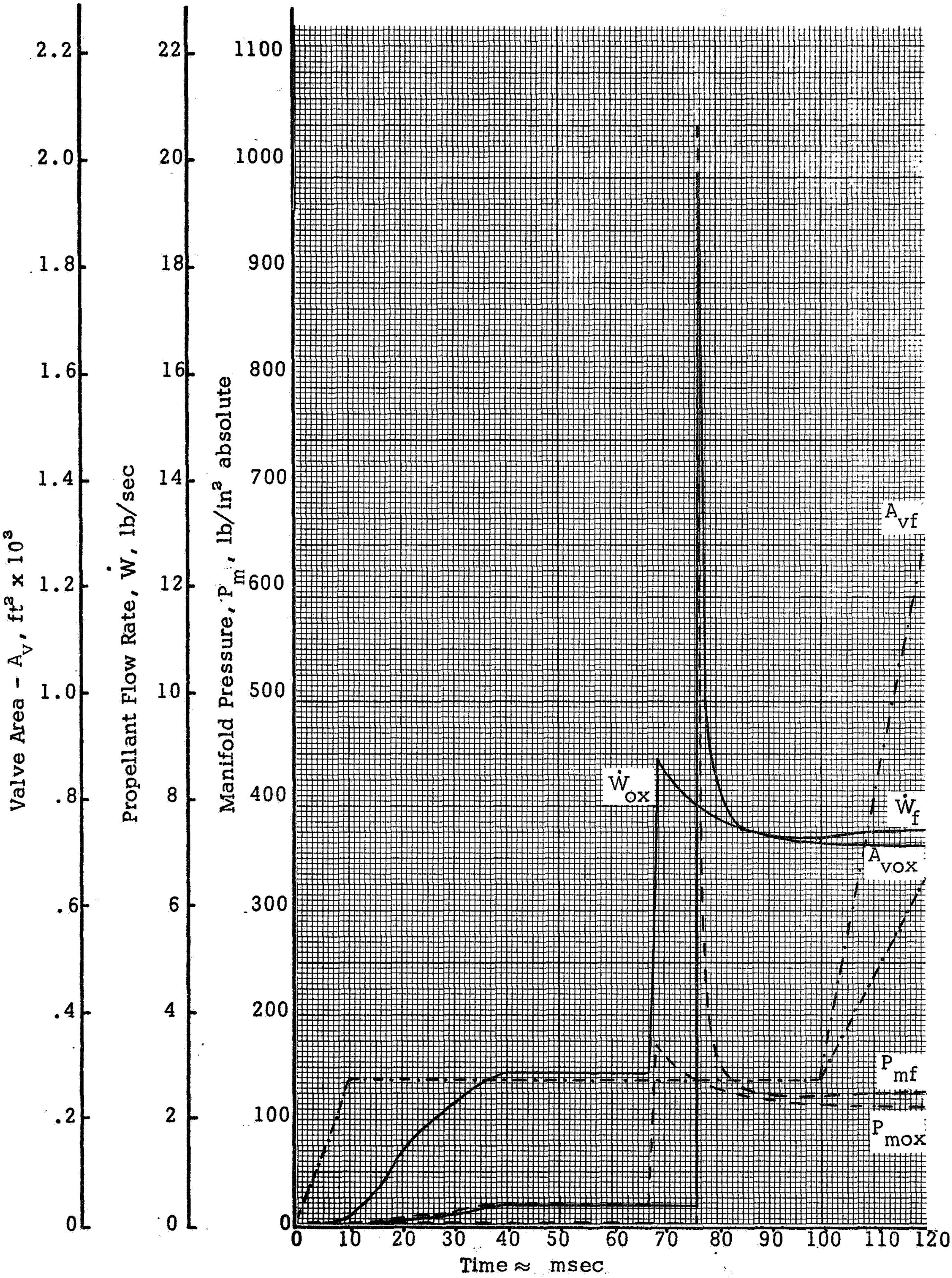


Figure 15. Propellant Flow Transient with Medium Step Opening Valve.

Model Applications

To explore the model's applicability to simulate the start transient of real engines exploratory studies were undertaken to determine if the program was applicable for larger engines, higher density ambient environments, and could predict the preignition pressurization transients.

To accurately predict the initial preignition pressurization transient, it was found from last year's effort that a very small initial step size was needed. The step size was increased as time increased according to the time step-time formula:

$$\Delta t = (t+.1)^{\frac{1}{2}} \times 10^{-5}$$

However, the step size had to remain small to accurately portray the transient. It was found also in the propellant transient model where the step size was controlled by error bounds, that the step size did not increase sufficiently fast, if the valve opened rapidly, in order to calculate long transients. While exploring these conditions, the propellant transient was programmed to simulate a water flow test (Ref. 12) in an attempt to determine the empirical constants within the equation. The test was also performed at atmospheric pressure. Figure 16 shows the experimental and analytical results of this study. The propellant transient model was able to perform the calculation only because the valve opening was very gradual. The calculations were not possible when the valve transient of Figure 17 (Ref. 15) was used, since they program an inordinate amount of time to perform.

From a more basic standpoint, it can be shown that when the propellant flow rate per unit volume of the chamber is low, it is possible for the program to handle the calculations. For instance, if the flow rate per unit volume of the chamber for the experimental engine used in this program is compared to that of the larger engine of Reference 12, it is seen that the flow/volume for the larger engine is twice that of the smaller engine.

Engine	Flow Rate	Volume	Flow/Volume
Large	85 lb/sec	1.169 ft^3	72.7 lb/ft^3-sec
Small	.147 lb/sec	.00376 ft^3	39.1 lb/ft^3-sec

Furthermore, the valve opening time and manifold volumes also contribute long transient periods which are difficult to simulate by the techniques developed here. Due to the large amount of computer time needed to perform these calculations (the propellant transient model and the chamber pressurization transient model), it was decided that the basic program was not applicable to large run times and was applicable only to short transient studies in its present form. From Figure 25, it appears that the propellant transient program will handle transients starting at other than vacuum conditions. The chamber pressurization program has been modified to handle other than vacuum starts and, lacking confirmation from any experimental data, will handle atmospheric starts within the framework of the model.

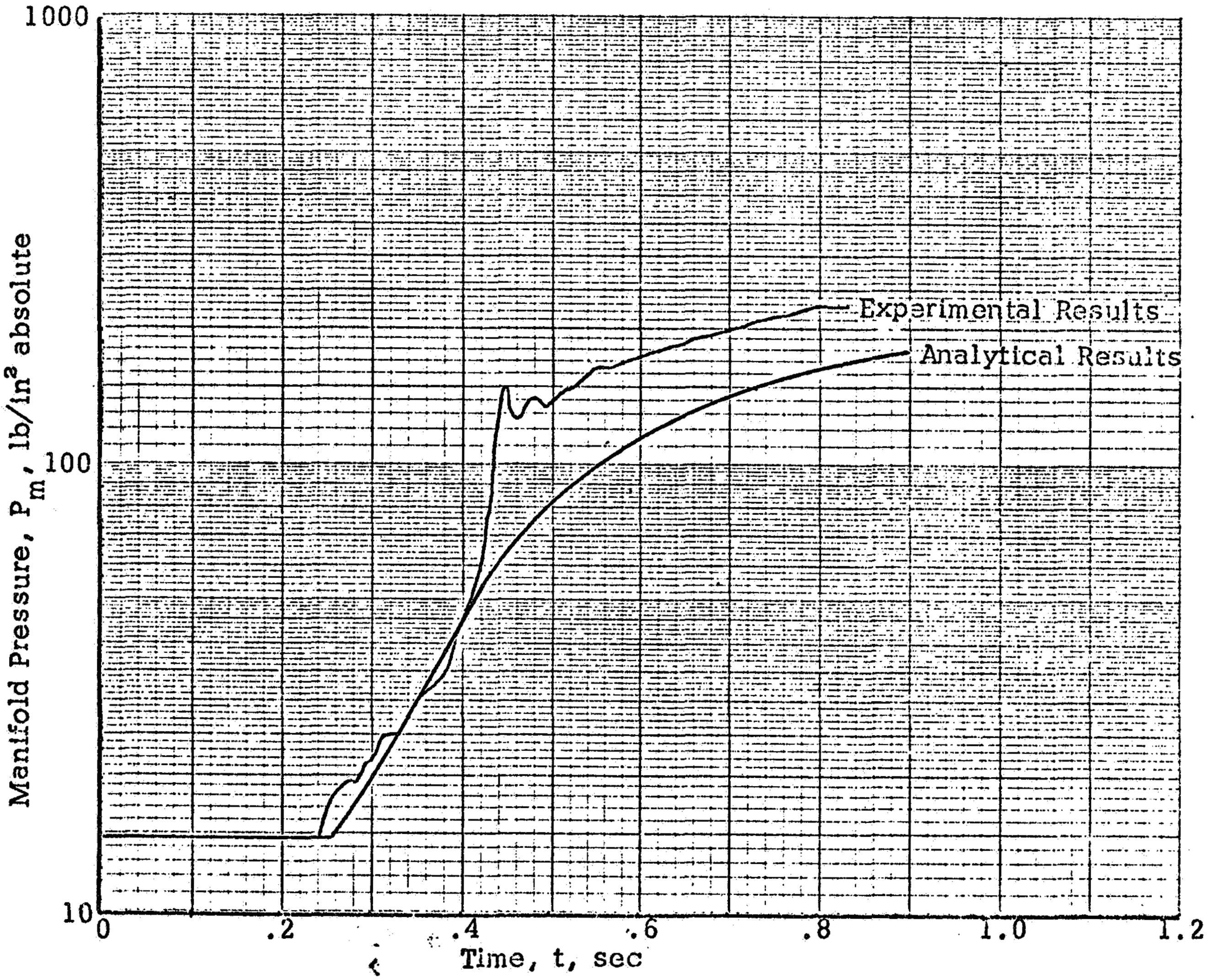


Figure 16. Comparison Between Experimental and Analytical Water Flow Tests on a Large Engine (see Ref. 12).

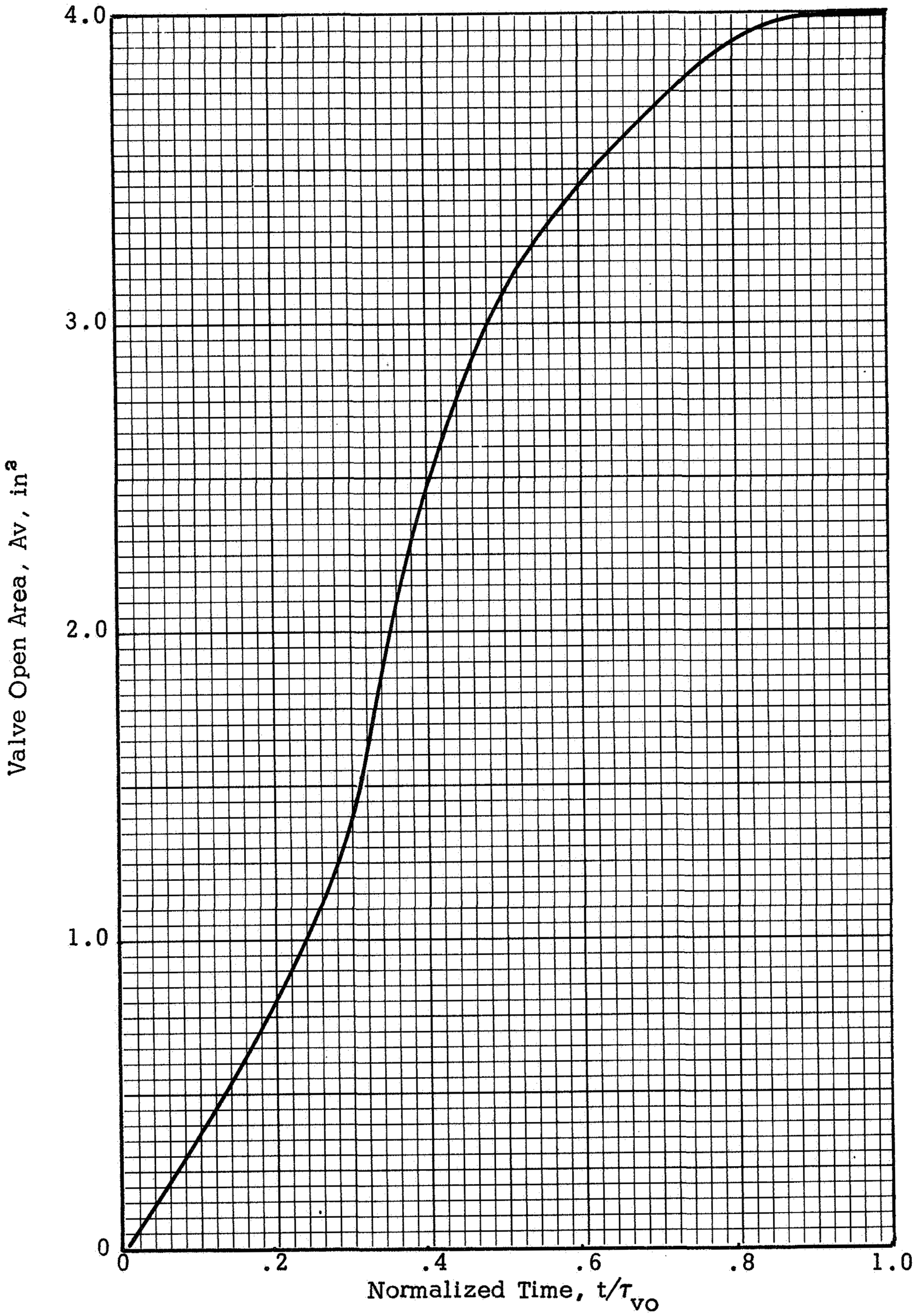


Figure 17. Valve Opening Transient for Larger Engine (see Ref. 12)

3. CHAMBER PRESSURIZATION TRANSIENT PROGRAM

Vaporization Program

The pressurization of a thrust chamber is treated mathematically as a sequence of steady-state processes in very short time intervals. At the start of each new time interval, a new set of drops enter the thrust chamber. These drops undergo vaporization during the time interval as do the drops which entered previously. At any time, each drop has a unique radius, temperature and physical state (solid fraction). The equations used in this part of the program (vaporization) were outlined by Agosta (Ref. 7) and later incorporated into computer programs by Seamans, et al (Ref. 8), and Dynamic Science (Ref. 16).

Basically, the vaporization program accounts for massive operation rates during each time interval to compute the chamber pressure for an arbitrary and transient fuel and oscillator input. Condensation on the chamber wall and mass loss through the nozzle are calculated and used to correct the chamber pressure. The temperature of the gas is based on the mass weighted average of gas, while the different temperatures of each droplet of both the propellant and the fuel for each time interval is accounted for. In accounting for each time interval drop temperature, the radius and also the fraction frozen is accounted for.

Several analytical studies were conducted to improve the operation of the vaporization program and to make it more realistic. These studies investigated the effect of (1) the time step size, (2) the number of initial drop sizes, and (3) the heat transfer between the combustion chamber gases and the chamber wall. Mechanistic additions to the previous year's program of Reference 16 to make it more realistic were (1) preignition reactions, and (2) variable propellant flow rate (by means of tabulated flow rates versus time and/or an orifice flow equation which depends on the chamber pressure).

The ability to use variable time step was particularly important during the initial or zero pressure starting of the calculation. Reduction in time increments from 25×10^{-6} seconds down to the range of 5×10^{-6} seconds showed significant influence on the solution. Reductions from one microsecond to one-half microsecond showed no significant change in pressurization solution. Calculations based on this short time step can be speeded up by drop averaging of drops which have been in the chamber for 5 to 10 time steps because all of these older drops behave in an average way.

The vaporization model was initially set up with a drop size distribution containing three radii of 7.00×10^{-4}, 2.05×10^{-3}, and 4.61×10^{-3} inches, each radius representing respectively 30%, 40%, and 30% of the total propellant injected. This scheme also resulted in high computing costs. In an effort to reduce these costs, a comparison between the three-drop distribution and a one-drop distribution of radius 2.05×10^{-3} inches was made. Nitrogen tetroxide only was injected and from these results there is very little difference in chamber pressure between these two distributions. As a result, the vaporization program now uses a single droplet model having a radius of 2.05×10^{-3} inches.

Preignition Chemistry

Preignition chemical reactions were considered so that ignition could ultimately be achieved. The analytical framework for treating preignition chemistry is as follows: the vapor reaction stoichiometry, heat of reaction and rate of reaction are governed by chamber temperature and reactant vapor partial pressures which are continually computed and followed by the vaporization program. Within this framework shown in Figure 18, the chemical and the controlling physical mechanism limits measured by Zung (Ref. 3) were used.

Preignition reaction intermediates (Refs. 3, 4, and 6) provide both the initiating mechanism for the detonations and the chemical energy to sustain them. Combination of hardware designs (valve configurations, propellant manifolds and manifold volumes, injector configurations, feed system configurations, etc.) combined with the proper operating modes of the system could produce those conditions which are most susceptible to ignition detonations.

To reduce the number of the engineering variables other studies were performed using the Chamber Pressurization Transient Model. Reference 3, a study of N_2O_4/N_2H_4 ignition mechanisms, indicates that hydrazine temperature controls ignition. As the hydrazine temperature is varied, distinct regions (Fig. 19, Ref. 3) are encountered wherein the ignition's mechanisms are different. At the lower temperatures (below approximately $560^{\circ}R$), reaction between liquid hydrazine and vapor nitrogen tetroxide occurs by reactions on the surface of the hydrazine leading to detonable reaction intermediates.

Detonation Program

Following the running of the vaporization program to ignition or for a specified time, detonation properties were computed for various selected times.

Detonation properties were calculated by the NASA/Lewis detonation program given in Reference 16. This program is well documented in References 16 and 17, so a discussion of the basic principles used is not needed here. To fit the data from the vaporization program to the detonation program, some modifications to the data are necessary. The detonation program is written for gaseous reactants while the reactants calculated by the vaporization program contain liquid droplets in a gaseous atmosphere. Table III is a tabulation of some of the data calculated from the vaporization program; the "f" listed in Table III is the fraction of a liquid propellant species to the total propellant species (liquid and gaseous). This f factor is used to convert the liquid propellant to a pseudo equivalent amount of gaseous reactants. Inherent with this conversion is that all of the liquid will be consumed in the detonation process.

All of each propellant species is converted to vapor reactants having a molecular weight in the ratio: weight of liquid + weight of vapor propellant/ weight of vapor propellant $(\mathcal{W}_\ell+\mathcal{W}_g/\mathcal{W}_g)$. The new propellant enthalpy is obtained by adding the gaseous molar enthalpy to the liquid molar enthalpy which has been corrected by the liquid to vapor ratio: $[\bar{H}=H_\ell+H_g(\mathcal{W}_\ell/\mathcal{W}_g)]$. Thus, each liquid propellant species is converted to a pseudo vapor wherein the molecular weight and enthalpy are obtained as outlined above.

Results

Ignition transient studies were conducted using the Chamber Pressurization Transient Program where the propellant temperatures were varied (Ref. 17). In Figure 20, reproduced higher detonation pressures occur as the temperature is decreased. Further, as the time to detonation is increased, and more reaction intermediates are produced, the detonation pressure is increased.

From an empirical standpoint (Refs. 2 and 18), the occurrence and level of spiking is influenced by the sequence in which propellants enter the combustion chamber. Figure 21 from Reference 19 shows the results of these tests. These tests were performed with N_2O_4/UDMH-N_2H_4. These results can best be explained by considering the analytical cases shown in Figure 22. When N_2O_4 is injected into a vacuum atmosphere, its high vapor pressure results in a low vapor temperature. The subsequent injection of hydrazine into this low temperature results in the formation of liquid phase reaction intermediates. Figure 23 (Ref. 3) shows the effects of oxidizer vapor temperature on the ignition of N_2O_4/N_2H_4. If the N_2O_4 temperature regions in this figure are lowered to a level indicated in the preignition transient of Figure 24, no immediate ignition will occur, but reaction intermediates would form until the heat of reaction raises the temperature to a level high enough for ignition. Furthermore, it appears that for colder propellant temperatures and for longer fuel leads, the time to detonation increases, as well.

In conclusion, from the analytical studies using the Propellant Transient Flow Program and the Chamber Pressurization Transient Program, the following are considered to be the dominant engineering parameters influencing the occurrence of start transient spiking.

(1) The fuel temperature should be high enough to prevent the formation of detonable reaction intermediates.

(2) Short oxidizer leads are conducive to spiking if, during the lead condition, the gaseous chamber temperature is reduced to a level where reaction intermediates may form.

(3) Cold propellant fuel lead conditions become more conducive to spiking than do other lead conditions.

(4) Controlled propellant transient to achieve rapid ignition will reduce transient spiking.

TABLE III

RESULTS OF VAPORIZATION AND DETONATION COMPUTATIONS

Run No.	t (ms)	T_{ox} (°R)	T_{fu} (°R)	T_w (°R)	Lead	P_c (psia)	T_c (°R)	O/F	f (N_2O_4)	f (N_2H_4)	Weight N_2O_4 (lb)	Weight N_2H_4 (lb)	Weight $N_2H_5NO_3$ (lb)	Weight NH_4NO_3 (lb)	P_D (psia)	P_p (psia)	T_D (°R)	Ign. (ms)
1	1	540	540	540	o/-	.83	499	1.67	.655	.953	1.38×10^{-4}	8.27×10^{-5}		5.44×10^{-8}	375	201	3285	-
	2					2.12	525	2.15	.710	.945	4.16×10^{-4}	1.94×10^{-4}		6.19×10^{-7}	757	405	3504	
	3					3.00	551	2.23	.766	.946	6.79×10^{-4}	3.03×10^{-4}		2.20×10^{-6}	1139	610	3520	
2	3	540	540	540	2/F	.92	538	.89	.748	.942	1.94×10^{-4}	2.18×10^{-4}	2.27×10^{-9}	1.91×10^{-7}	498	267	3467	5+
	4					2.17	568	1.44	.770	.945	4.76×10^{-4}	3.29×10^{-4}	2.27×10^{-9}	1.45×10^{-6}	984	526	3668	
	5					4.27	717	1.67	.799	.954	7.35×10^{-4}	4.34×10^{-4}	2.27×10^{-9}	3.75×10^{-6}	1367	731	3664	
3	3	540	540	540	2/Ox	2.52	526	5.65	.768	.974	6.31×10^{-4}	1.11×10^{-4}		5.44×10^{-7}	695	378	2728	-
	4					3.26	545	3.99	.804	.972	8.94×10^{-4}	2.22×10^{-4}		2.21×10^{-6}	1160	626	3067	
	5					3.94	553	3.42	.828	.976	1.15×10^{-3}	3.30×10^{-4}		4.64×10^{-6}	1596	859	3211	
4	1	500	500	540	o/-	.46	478	1.30	.716	.983	9.59×10^{-5}	7.40×10^{-5}		9.64×10^{-9}	237	126	3461	-
	2					1.58	496	2.06	.743	.992	3.82×10^{-4}	1.86×10^{-4}		1.52×10^{-7}	717	383	3514	
	3					2.42	505	2.23	.776	.994	6.62×10^{-4}	2.97×10^{-4}		5.62×10^{-7}	1317	706	3382	
5	4	500	500	540	3/F	.66	487	.70	.761	.994	1.65×10^{-4}	2.36×10^{-4}	6.59×10^{-10}	3.59×10^{-8}	552	294	3558	-
	5					1.65	505	1.31	.682	.998	4.56×10^{-4}	3.48×10^{-4}	6.59×10^{-10}	2.47×10^{-7}	1006	538	3675	
	6					2.40	514	1.60	.805	.996	7.33×10^{-4}	4.58×10^{-4}	6.59×10^{-10}	7.47×10^{-7}	2004	1072	3750	
6	4	500	500	540	3/Ox	2.52	586	7.76	.820	.991	8.85×10^{-4}	1.14×10^{-4}		1.58×10^{-7}	821	451	2389	-
	5					2.75	501	5.12	.853	.994	1.16×10^{-3}	2.26×10^{-4}		6.08×10^{-7}	1385	752	2838	
	6					2.83	500	4.23	.879	.996	1.42×10^{-3}	3.36×10^{-4}		1.12×10^{-6}	1944	1060	3038	
7	1	540	540	580	o/-	.81	498	1.66	.655	.954	1.35×10^{-4}	8.16×10^{-5}		5.23×10^{-8}	375	202	3285	3.6
	2					2.18	543	2.14	.710	.945	4.15×10^{-4}	1.93×10^{-4}		7.78×10^{-7}	756	404	3502	
	3					3.24	590	2.23	.776	.954	6.76×10^{-4}	3.01×10^{-4}		3.35×10^{-6}	1145	613	3513	
8	1	540	540	500	o/-	.81	498	1.66	.655	.954	1.35×10^{-4}	8.16×10^{-5}		5.23×10^{-8}	375	202	3285	-
	2					2.06	511	2.15	.708	.943	4.16×10^{-4}	1.94×10^{-4}		5.22×10^{-7}	759	406	3505	
	3					2.84	522	2.24	.763	.941	6.81×10^{-4}	3.04×10^{-4}		1.48×10^{-6}	1129	604	3525	
9	1	580	540	540	o/-	.95	573	1.65	.665	.956	1.41×10^{-4}	8.54×10^{-5}		2.19×10^{-7}	326	174	3487	2.0
	2					4.63	886	1.95	.688	.975	3.81×10^{-4}	1.88×10^{-4}		1.03×10^{-6}	678	363	3468	
	3																	
10	1	500	540	540	o/-	.59	581	1.51	.716	.955	1.17×10^{-4}	7.78×10^{-5}		2.48×10^{-8}	293	156	3488	-
	2					1.72	502	2.16	.749	.943	4.10×10^{-4}	1.90×10^{-4}		2.95×10^{-7}	726	388	3496	
	3					2.55	514	2.29	.783	.940	6.88×10^{-4}	3.01×10^{-4}		1.02×10^{-6}	1196	646	3511	
11	1	540	580	540	o/-	.95	503	1.82	.658	.874	1.56×10^{-4}	8.54×10^{-5}		9.08×10^{-8}	269	143	3435	3.6
	2					2.28	534	2.21	.709	.860	4.34×10^{-4}	1.96×10^{-4}		9.35×10^{-7}	606	324	3467	
	3					3.30	581	2.27	.776	.869	6.95×10^{-4}	3.03×10^{-4}		3.62×10^{-6}	890	477	3482	
12	1	540	500	540	o/-	.66	495	1.46	.651	.985	1.14×10^{-4}	7.81×10^{-5}		2.07×10^{-8}	322	172	3499	-
	2					1.93	517	2.07	.831	.993	3.96×10^{-4}	1.91×10^{-4}		3.22×10^{-7}	886	474	3538	
	3					2.73	528	2.19	.762	.998	6.62×10^{-4}	3.02×10^{-4}		1.03×10^{-6}	1431	766	3560	

$400 \le T \le 530^{o}R$

$O/F \le .5 \qquad \Delta H = 1123$ Btu/lb

$9N_2O_4 + 25N_2H_4 \rightarrow 10N_2O + NO + 19NH_3 + 3\frac{1}{2} N_2 + 4H_2O + 7N_2H_5NO_3$

$O/F > .5 \qquad \Delta H = 2220$ Btu/lb

$63N_2O_4 + 64N_2H_4 \rightarrow 80N_2O + 16NO + 11N_2 + 72H_2O + 28NH_4NO_3$

$530 < T \le 600^{o}R$

$O/F \le .5$ and $O/F > .5 \qquad \Delta H = 2605$ Btu/lb

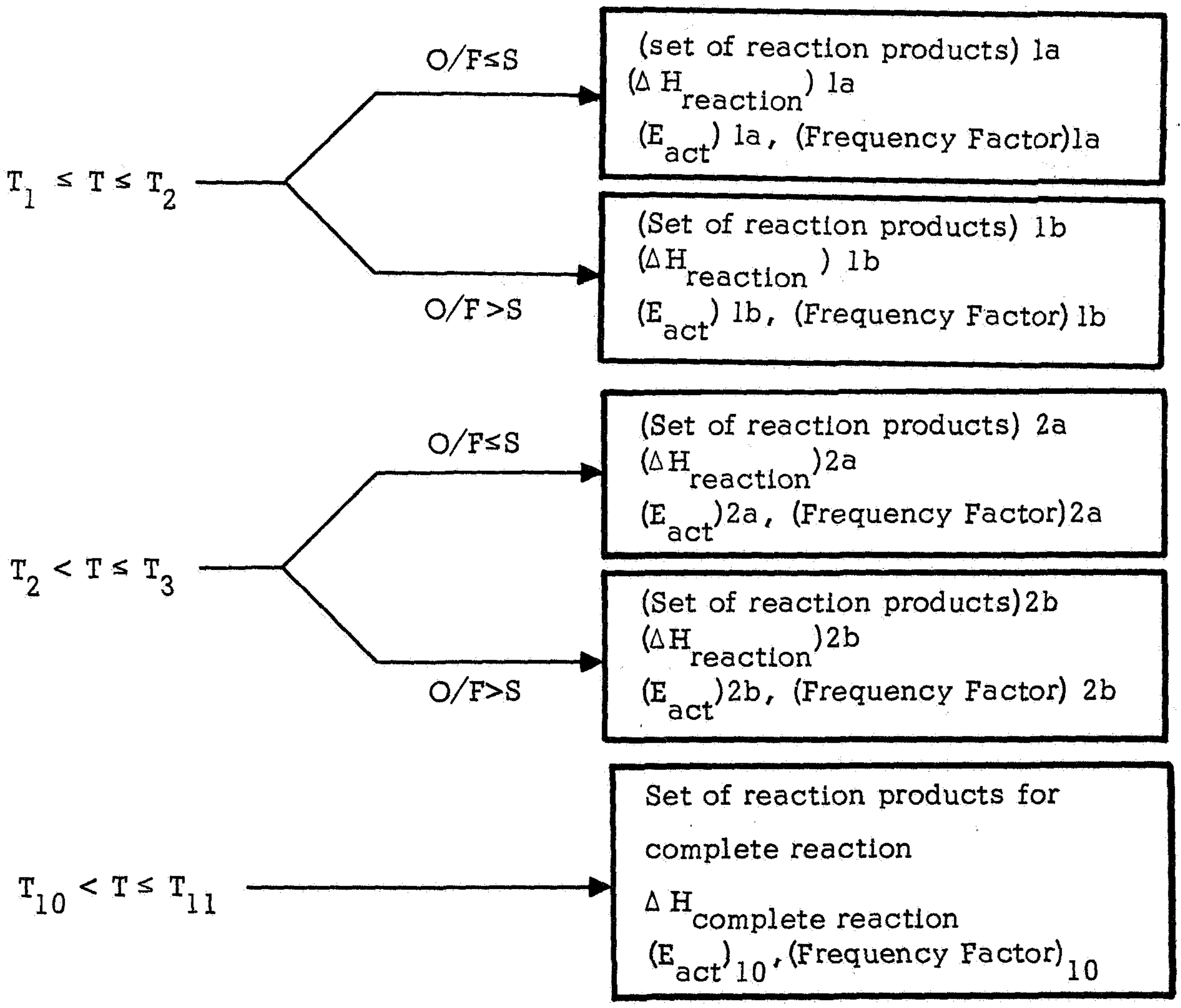
$2N_2O_4 + 4N_2H_4 \rightarrow 2N_2O + NO + 2\frac{1}{2} N_2 + 2H_2O + NH_4NO_3 + 4H_2$

$600 < T \le 10{,}000^{o}R$

$O/F \le .5$ and $O/F > .5 \qquad \Delta H = 4860$ Btu/lb

$N_2O_4 + 2N_2H_4 \rightarrow 3N_2 + 4H_2O$

E = 7500 cal/gmole



where, T = gas temperature,

S = stoichiometric oxidizer to fuel ratio

Figure 18. Temperature and O/F Dependent Reaction Paths Measured by Zung (Ref. 3)

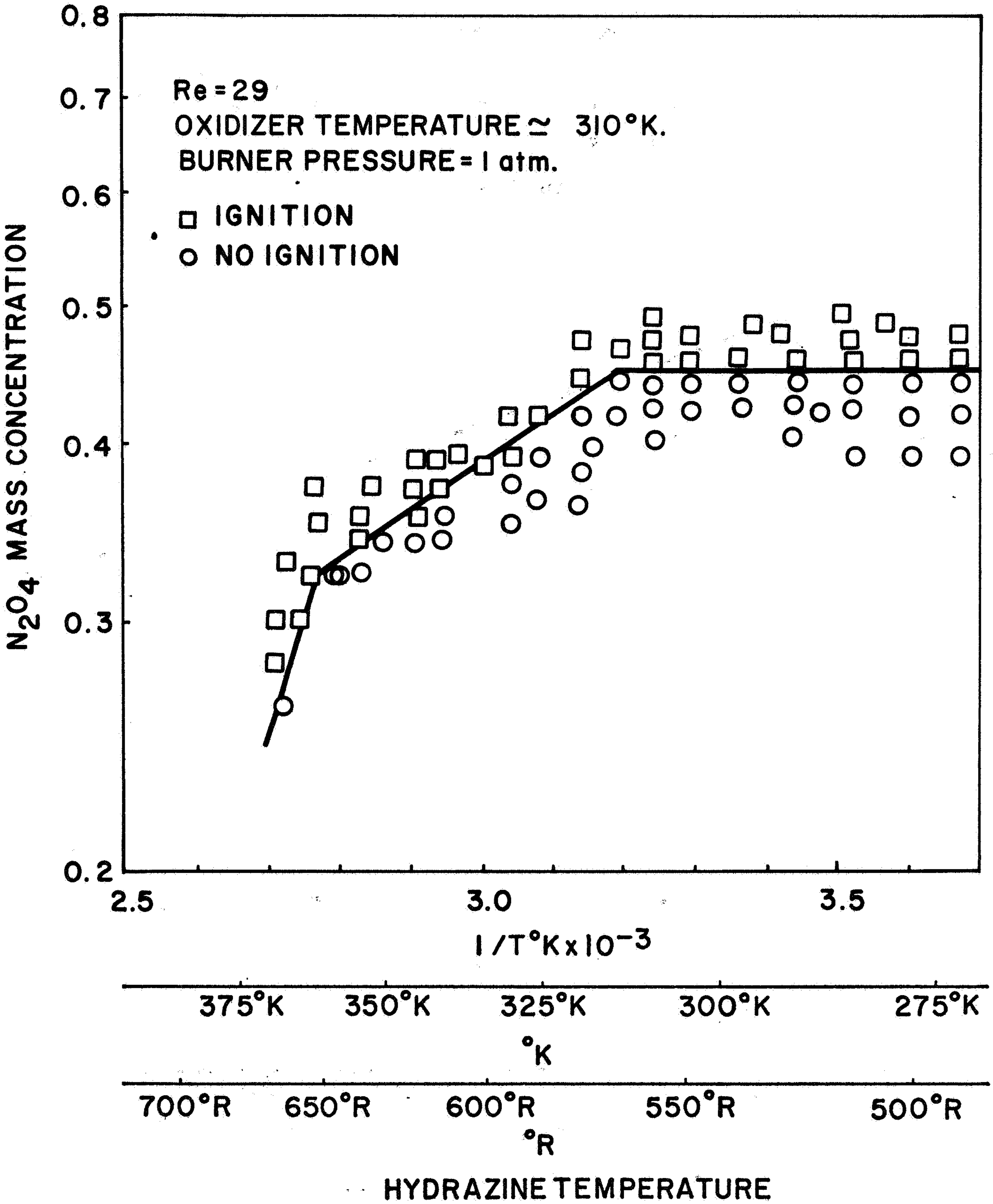


Figure 19. Ignition Threshold
(From Ref. 3)

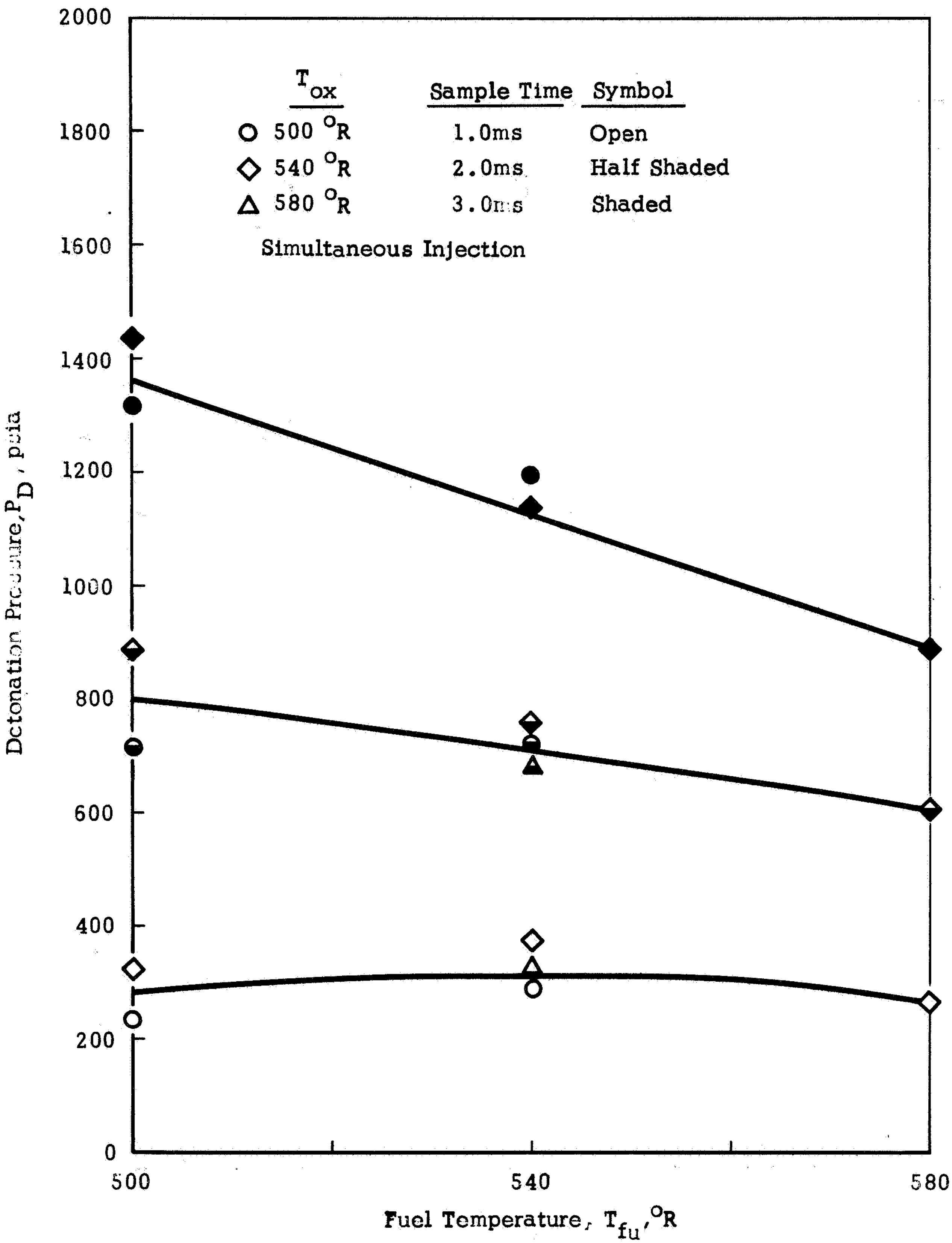


Figure 20.Effect of Fuel Temperature on Detonation Pressure

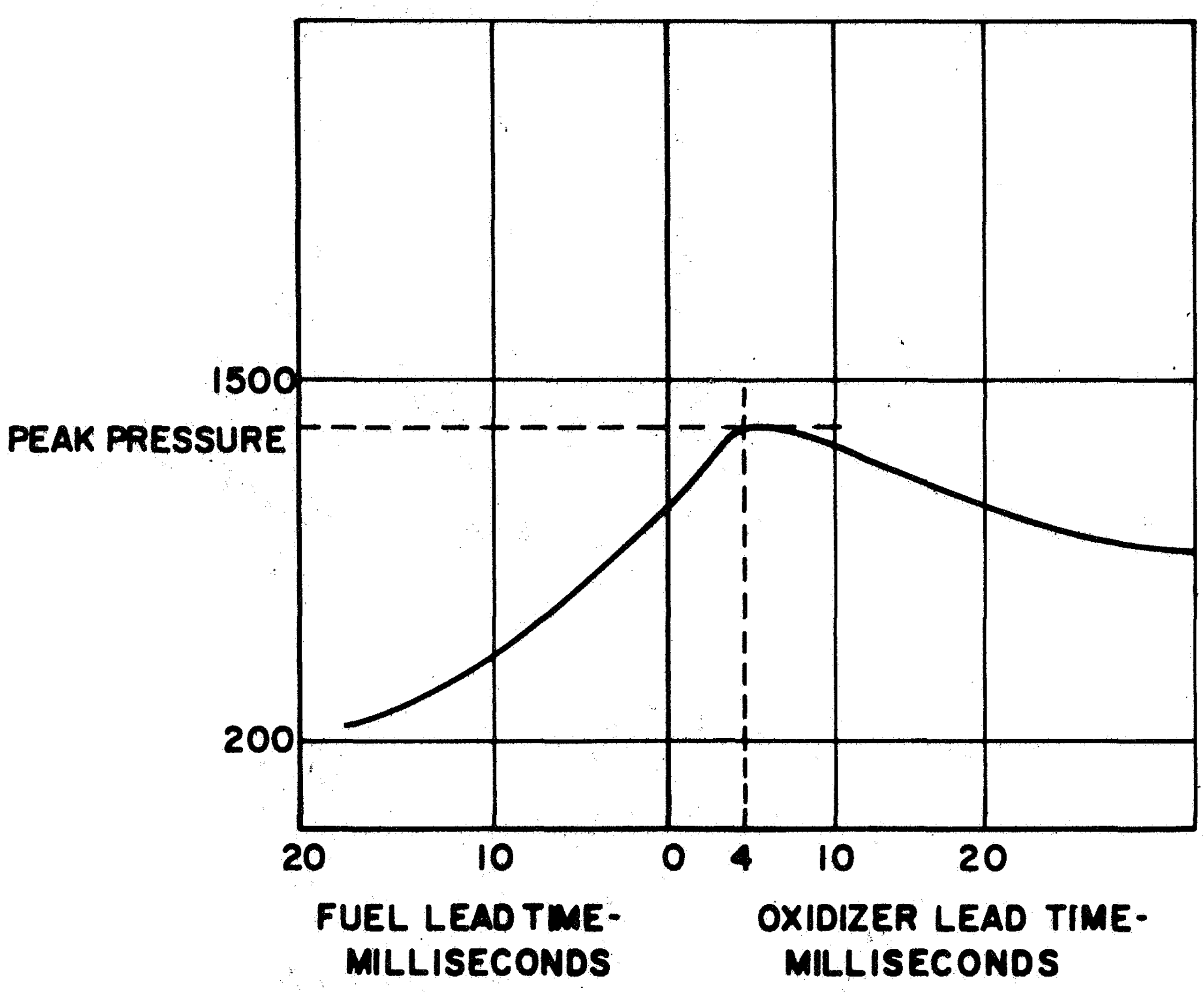
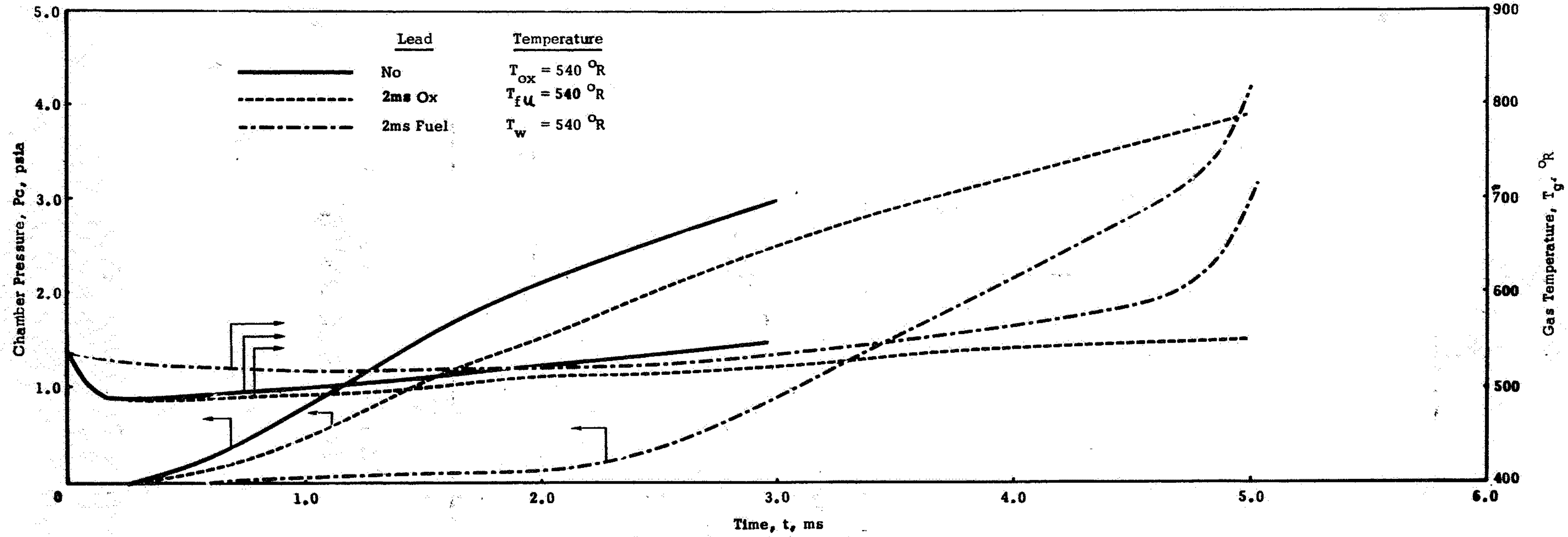
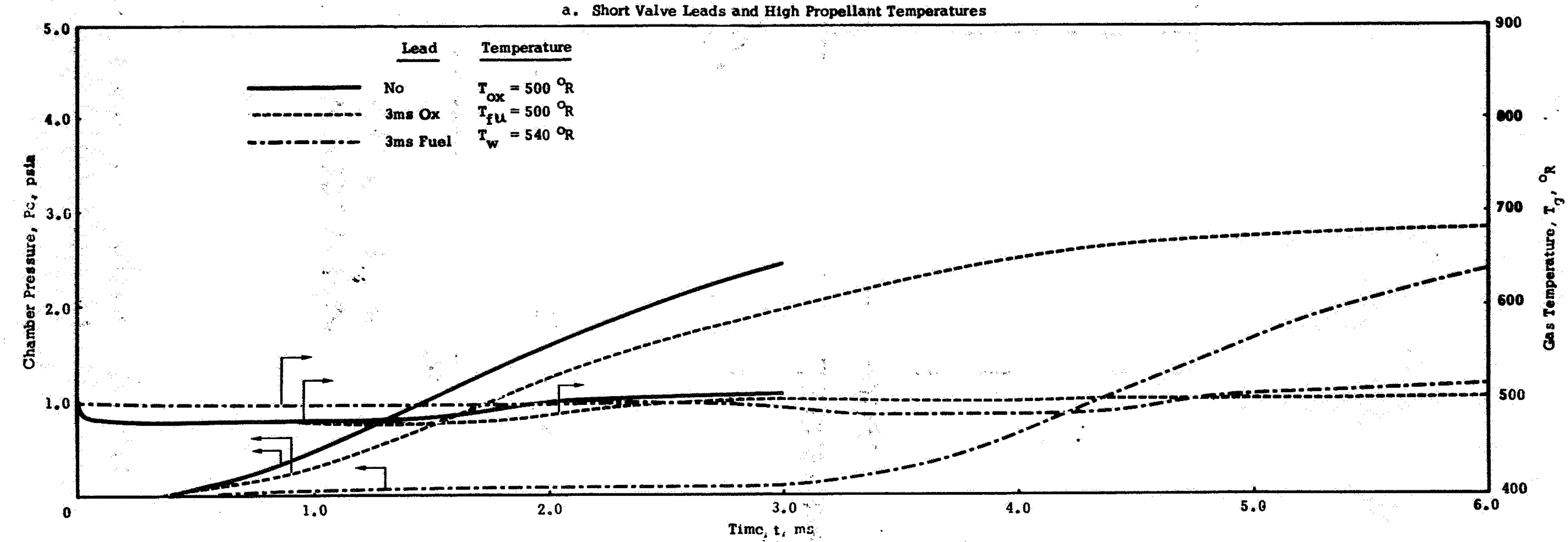


Figure 21. Pressure Peak as a Function of Oxidizer or Fuel Lead. (From Ref. 19.)



a. Short Valve Leads and High Propellant Temperatures



b. Longer Valve Leads and Low Propellant Temperature

Figure 22. The Effect of Variable Valve Leads and Initial Temperature on Transient Chamber Pressure and Chamber Gas Temperature.

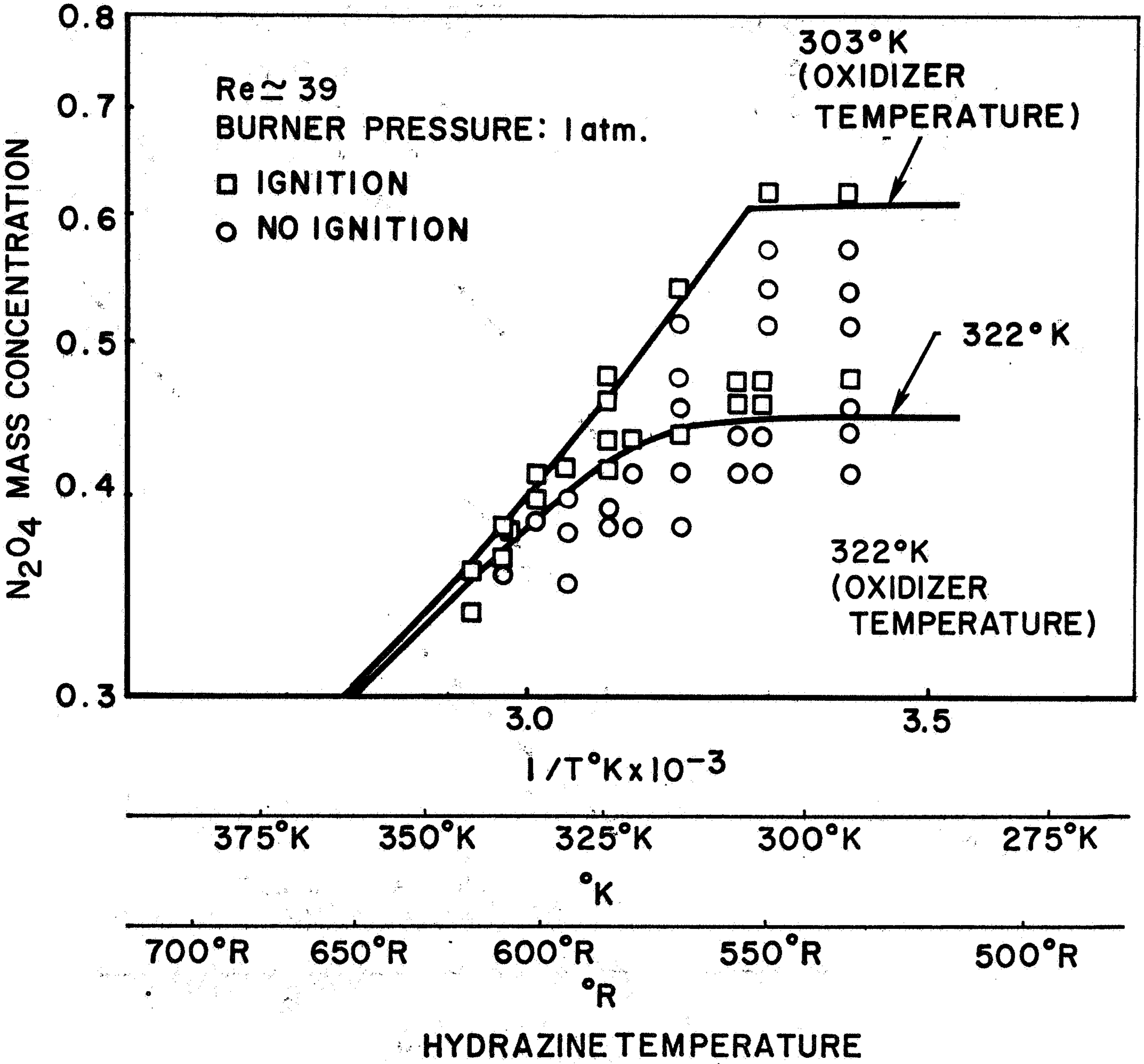


Figure 23 . Ignition Threshold
(From Ref. 3)

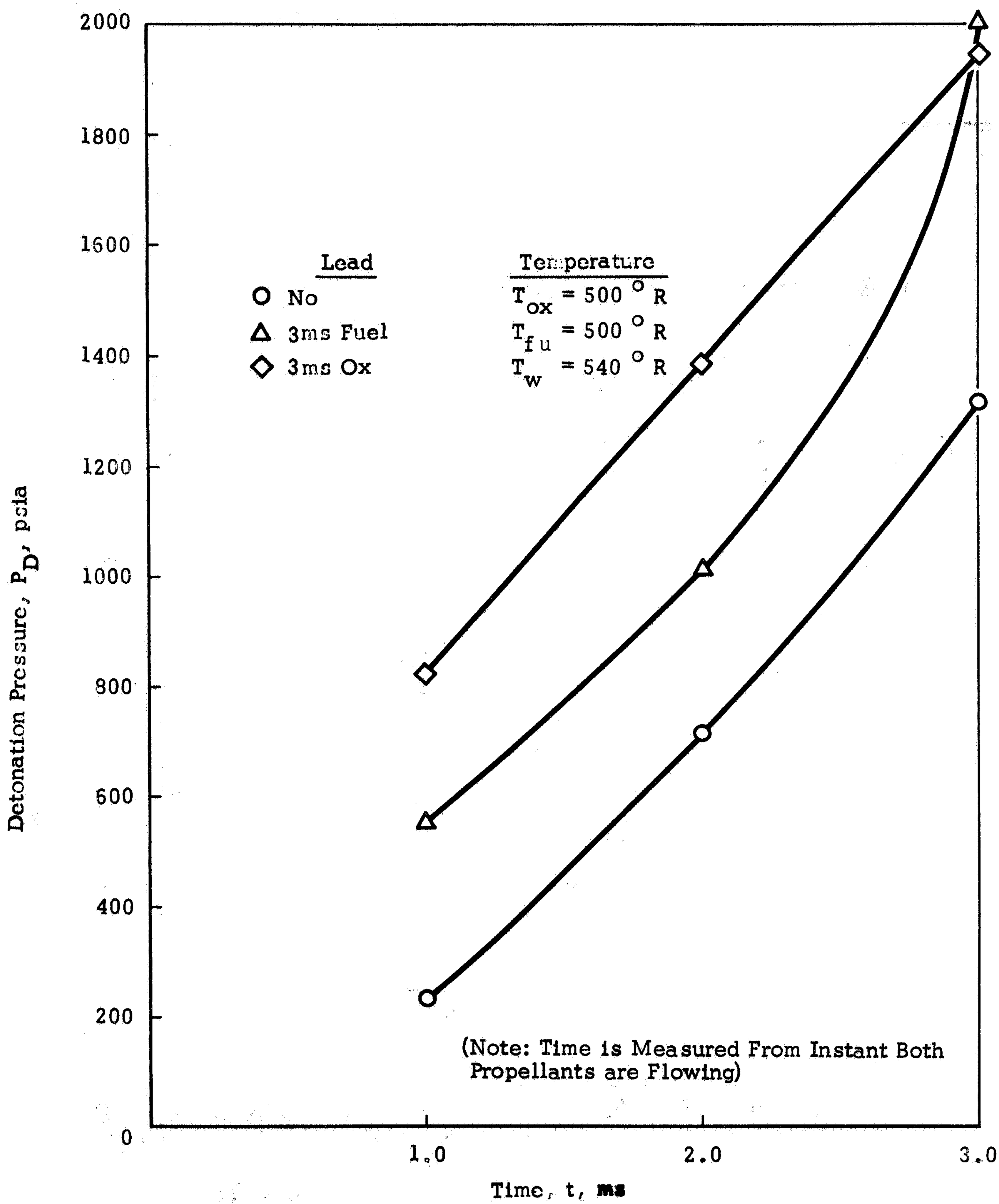


Figure 24. **Effect of Propellant Leads and Initial Temperature on Detonation Pressure**

4. EXPERIMENTAL PROGRAM

Experiments were performed wherein engineering assumptions and engine parameters influencing spiking could be evaluated in order to determine the applicability of the Start Transient Programs (the Propellant Transient Flow Program and the Chamber Pressurization Transient Program) to predict engine starts.

Hardware and Experimental

From the Start Transient Programs, the following variables were important in influencing the start transient and the start transient spiking behavior: (1) propellant temperature, (2) propellant leads, and (3) the transient behavior of the entering propellants (length and shape of propellant transient). In an attempt to accommodate these assumptions in the experimental hardware, two injectors were fabricated. The first injector (Figure 25), Injector Pattern A (like-on-like) attempts to accommodate the assumption of vapor phase mixing. Pattern A consists of four like-on-like doublet elements which impinge such that the fuel and oxidizer fans do not intersect (Figure 26). This injector keeps the liquid propellants apart while they are being injected and vaporizing, but allow mixing of the propellant vapors. Injector Pattern B (unlike), on the other hand, consists of four mixed twin elements. This injector pattern is used in current high-performance attitude control engines. The effects on the start transient of these two injectors were observed experimentally. These patterns were drilled into a propellant manifold configuration which is the same for both patterns (Fig. 27). Completing the injector-manifold is a cover plate (Fig. 28) which incorporates the instrumentation for the fuel side and which forms the cover for the fuel and temperature conditioning fluid manifolds (Fig. 29). The central oxidizer inlet and manifold is connected to an AN cross into which is plumbed the main propellant valve, the Freon flush valve, the gaseous nitrogen purge valve, and the oxidizer manifold pressure port. The fuel enters the backing plate through two inlets which are similarly connected to an AN cross via two 1/8 inch tubes. The fuel cross is plumbed to the main propellant valve, the gaseous nitrogen purge valve, and the Freon flush valve. During the initial tests, the manifold volumes consisted of the crosses, the connecting tubing, and the injector body. These volumes were .232 in^3 and .252 in^3 for the oxidizer and the fuel manifolds, respectively.

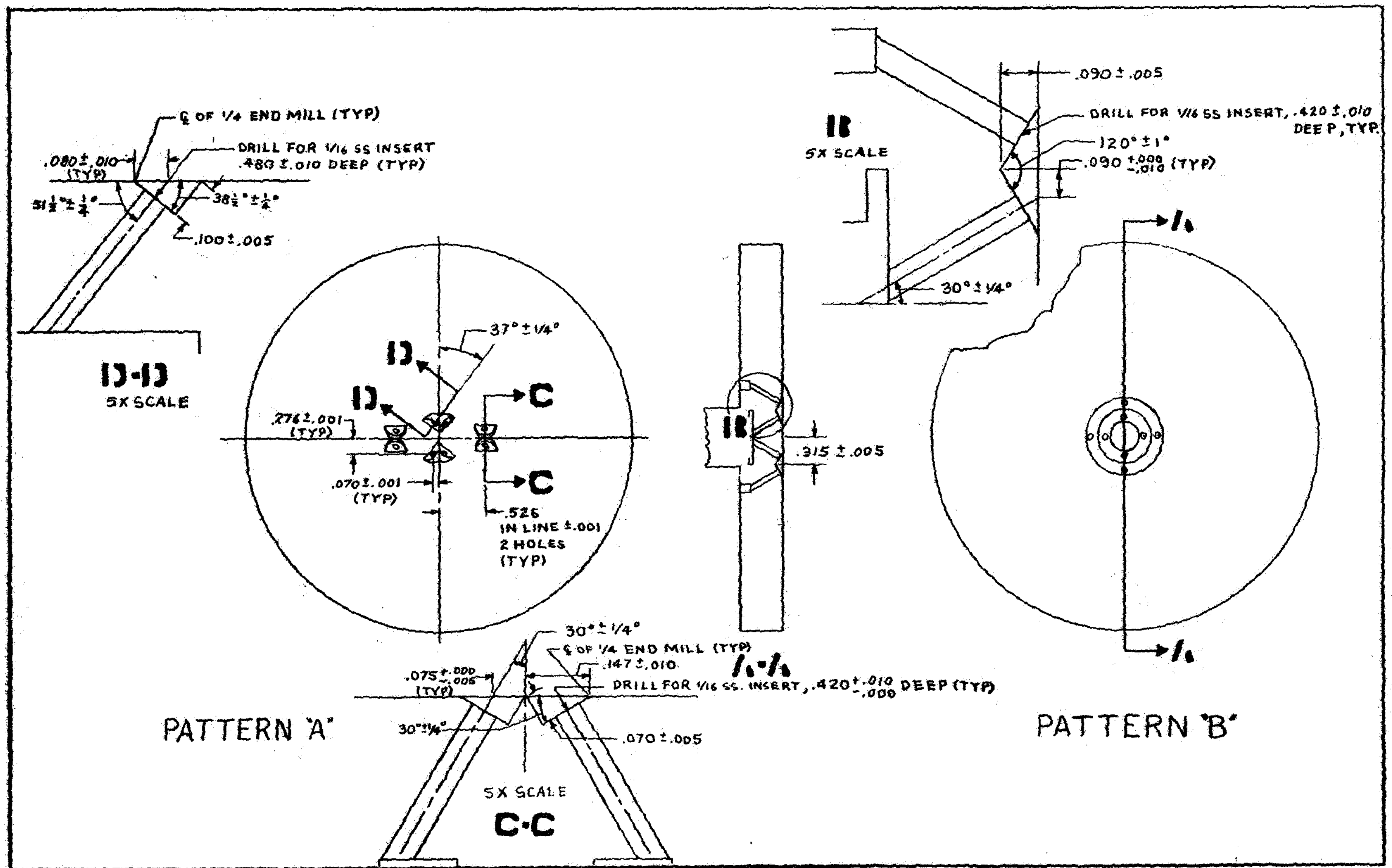
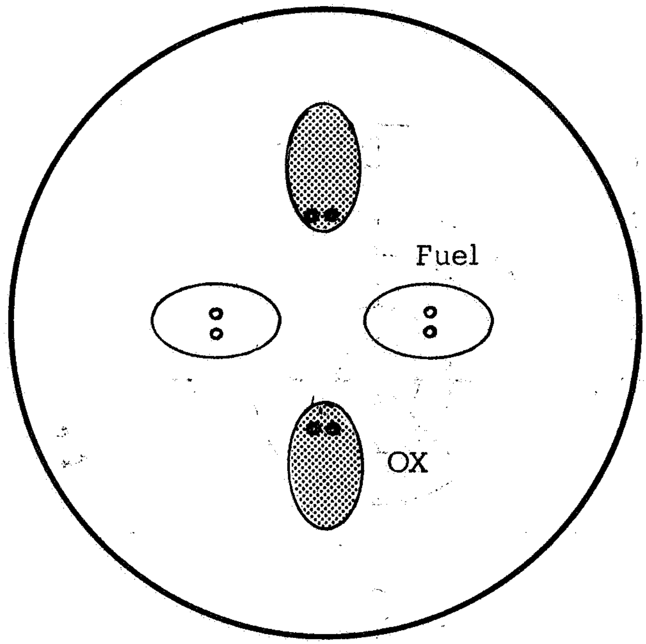
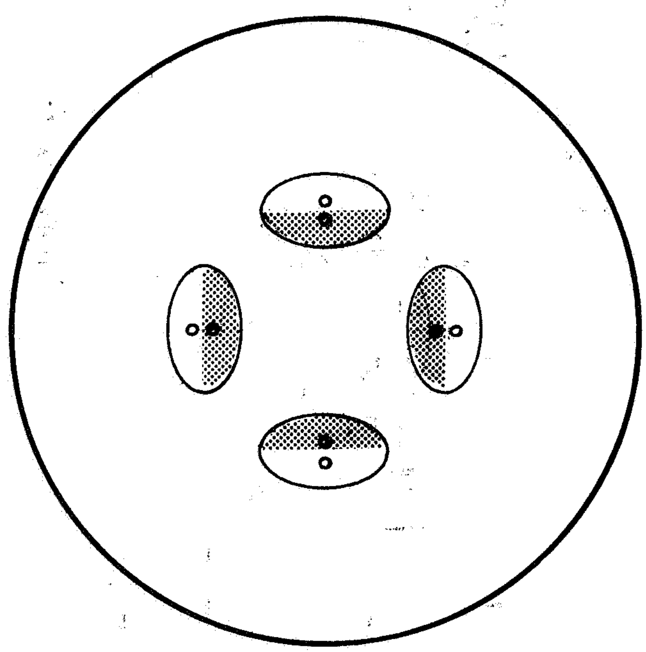


Figure 25. Injector Patterns



Pattern A



Pattern B

Figure 26. Propellant Spray Patterns from Experimental Injectors.

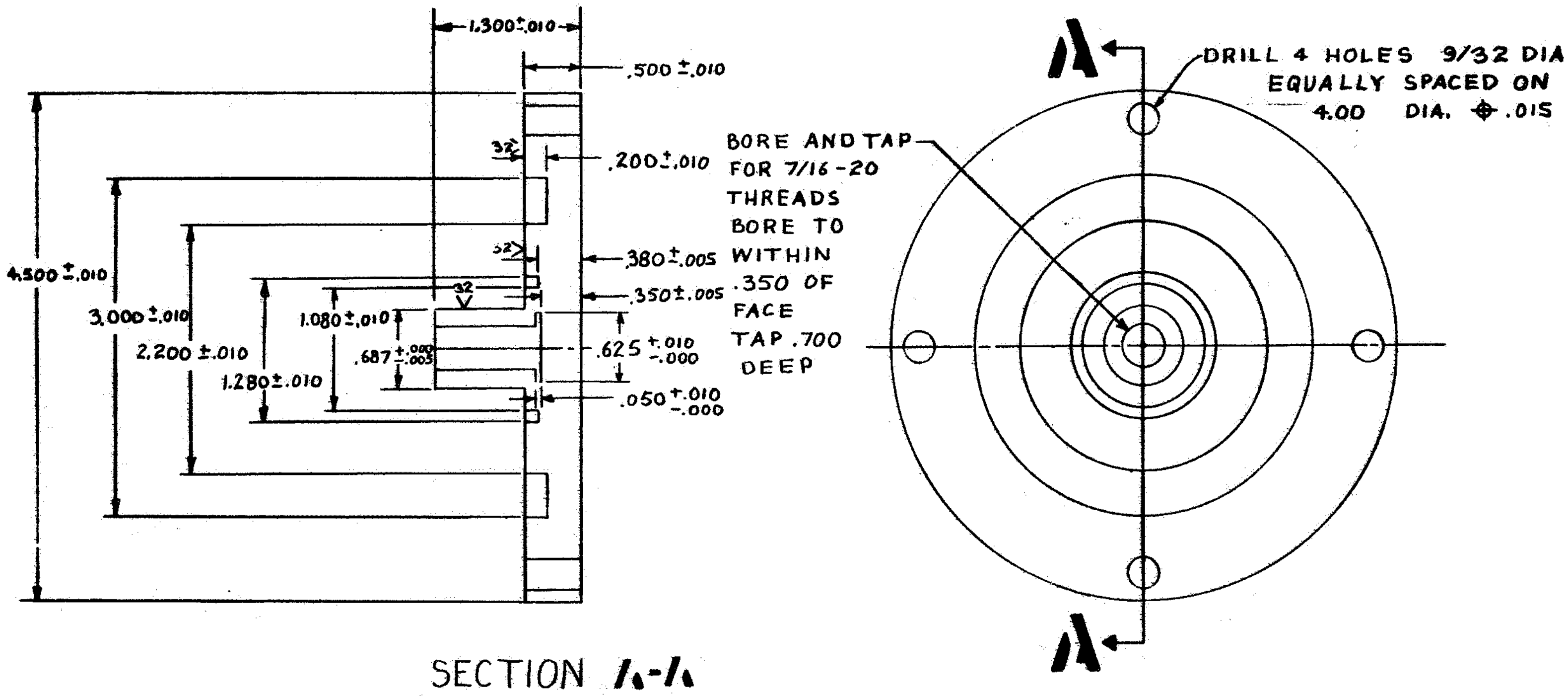


Figure 27. Injector Blank.

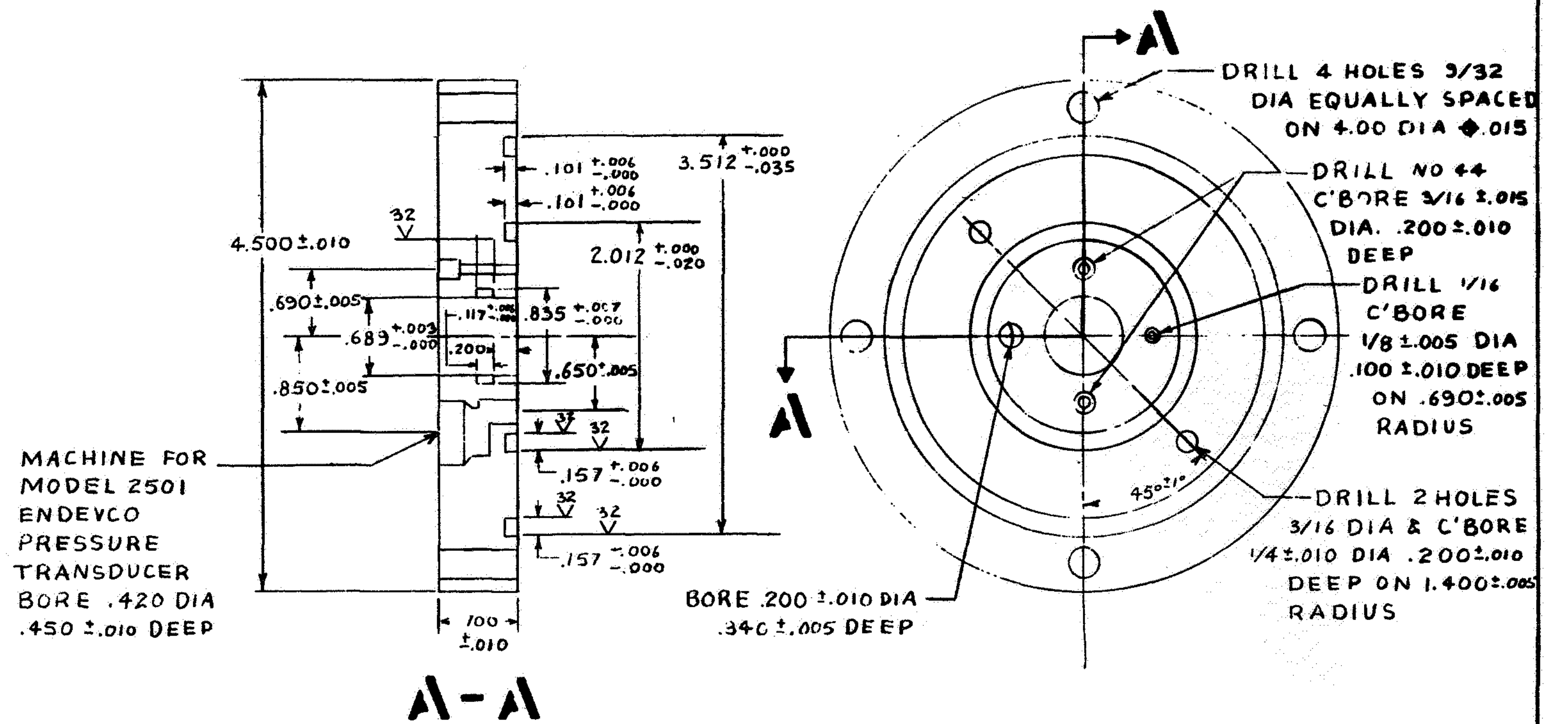
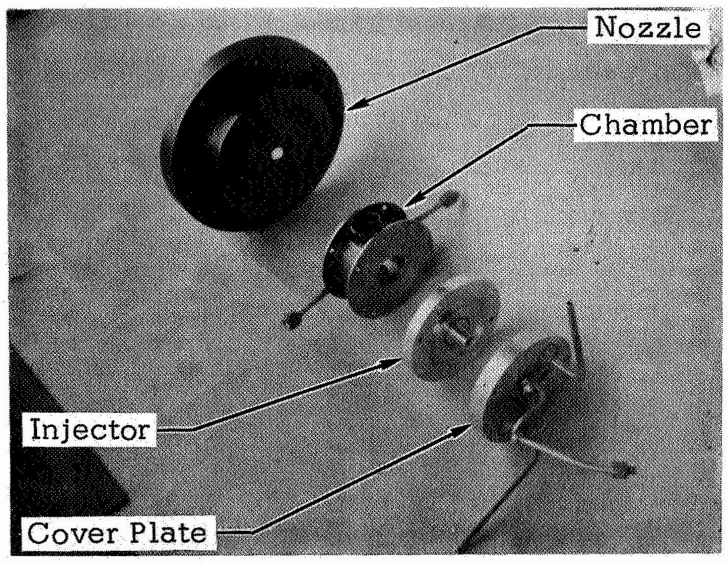


Figure 28. Cover Plate



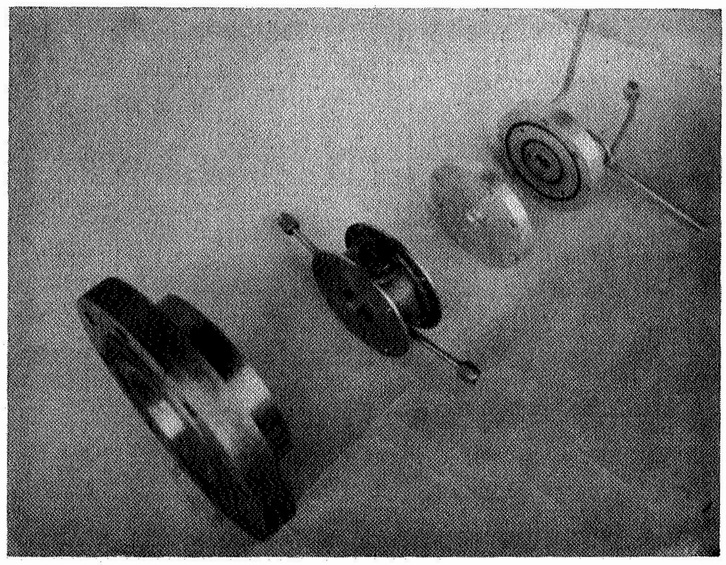


Figure 29. Exploded View of Combustion Chamber and Injector Assembly.

These volumes were subsequently reduced by solder filling some of the manifolds. The final tests were conducted with manifolds having volumes of .1037 in^3 for the oxidizer and fuel manifolds, respectively.

Completing the experimental hardware are the combustion chamber and the nozzle (Figs. 28 and 29). This hardware was designed to operate under those conditions listed in Table IV. The experimental work was done with a chamber length of 1.75 in. The chamber had two high response pressure transducer ports, a chamber wall thermocouple port and two fluid flow lines leading to the temperature conditioning jacket surrounding the chamber. The assembled components are seen in Figure 30.

During the initial tests, the main propellant valves used were solenoid valves (Echel Valve AF 56C-35). Subsequent tests utilized a pneumatically controlled pintle valve. This valve consists of a pneumatic cylinder with the plunger attached to a yoke which, in turn, lifts the tapered pintles. The valve opening time can be controlled by varying the orifice opening and supply pressure to the pneumatic cylinder. Propellant leads can be varied by adjusting each pintle at the yoke.

The experimental engine was fired downward into an eight cubic foot vacuum tank (Figs. 31 and 32). Between each test, the injector manifolds combustion chamber and vacuum tank were purged with Freon and gaseous nitrogen.

The combustion chamber and the propellants were temperature conditioned by circulating heated or cooled water through jackets surrounding the combustion chamber, the propellant lines, and the injector. High response, flush mounted piezeoelectric pressure transducers (Endevco Model 2501 Pressure Transducers) provided the high response pressure data for the tests. Endevco Model 2501-500 (0-500 psia pressure range) pressure transducers were used to measure propellant manifold pressures. These transducers were connected to Endevco Model 2808 charge amplifiers with the amplified signal being recorded on a CEC oscillograph using a 7-361 model galvanometer. Chamber pressure was measured by an Endevco Model 2501-200 (0-2000 psia pressure range) pressure transducer with an Endevco Model 2811 charge amplifier and was recorded on a CEC oscilloscope using a sweep rate of .5μ sec/cm and a 7-361 model galvanometer, and paralleled onto a Tektronix type 535A oscilloscope.

TABLE IV

EXPERIMENTAL OPERATING CONDITIONS

Oxidizer: Nitrogen Tetroxide, N_2O_4

Steady State Flow Rate: $\dot{W}_{ox}$ = .080 lb/sec

Fuel: Hydrazine, N_2H_4

Steady State Flow Rate: $\dot{W}_f$ = .067 lb/sec

Mixture Ratio: 1.2

(equal stream momentum for equal fuel and oxidizer orifices)

Steady State Chamber Pressure: 100 psia

Nozzle Throat Diameter: .503 in.

(Nozzle Throat Area: .266 in^2)

Nozzle Area Ratio: 40

Thrust: 50 lbf

Manifold Volumes

Oxidizer: 172 in^3

Fuel: .1037 in^3

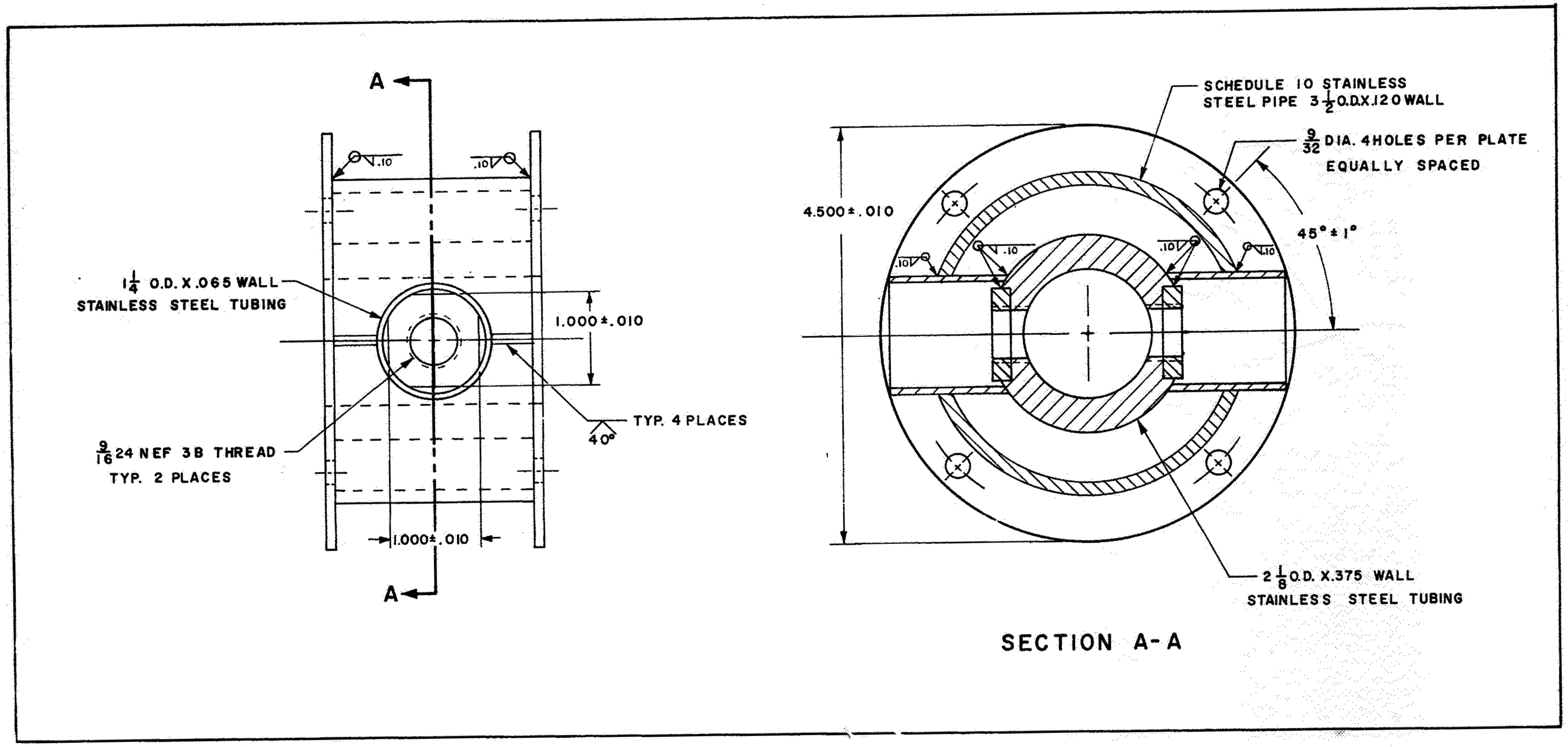
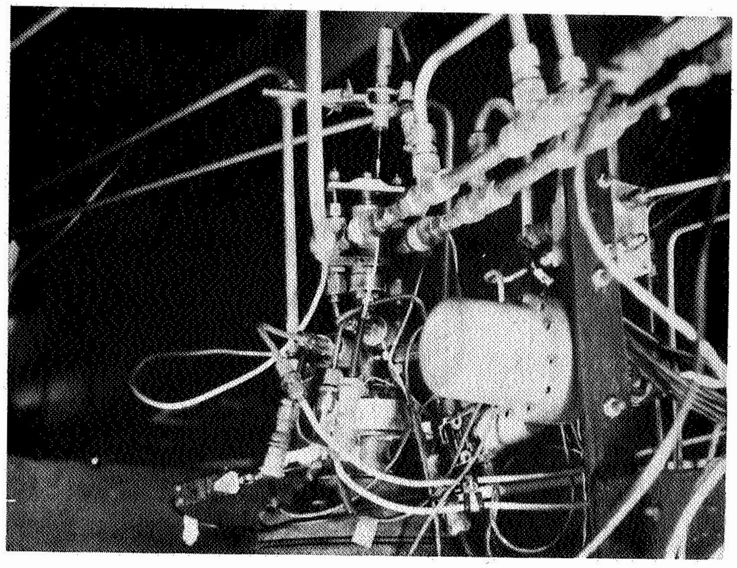
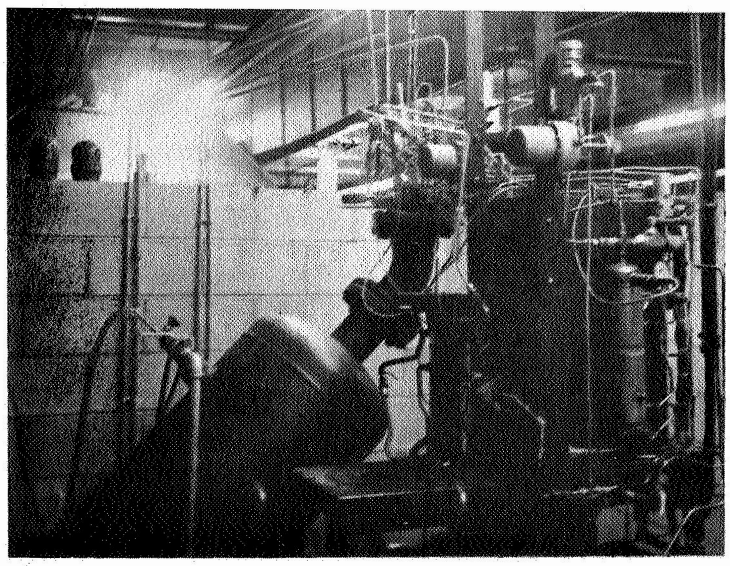


Figure 30. Experimental Combustion Chamber



A. Assembled Experimental Hardware



B. Experimental Test Stand

Figure 31. Experimental Setup

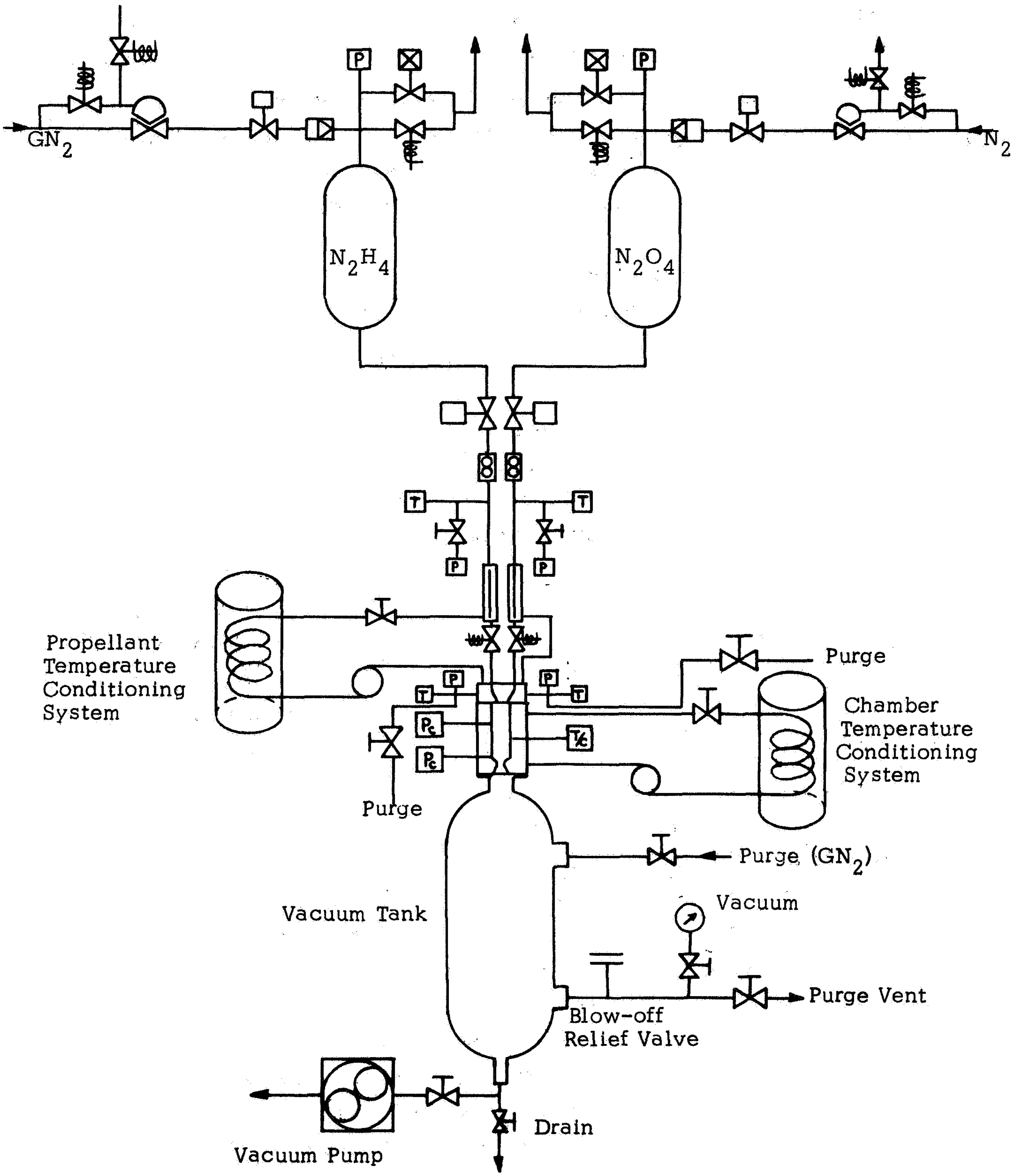


Figure 32. Experimental Test Stand.

Several lower range Taber pressure transducers were used to measure the lower preignition chamber pressure. The signal from the transducer was fed to a Dana amplifier and then recorded on a CEC oscillograph using a 7-346 model galvanometer.

The pressure in the vacuum tank was measured by a General Electric Thermistor Vacuum Gage (Recorder Model 22GC310, Vacuum Gage Tube 22GT). Propellant injection temperatures and chamber wall temperatures are measured with Iron-Constantin thermocouples which are recorded on a CEC oscillograph using a 7-349 model galvanometer. The fuel injection thermocouple was located in the injector fuel manifold opposite the injection pressure transducer port. The oxidizer injection thermocouple was located in the AN cross opposite the injection pressure transducer port.

Results

Table V shows test conditions and pressures resulting from the experimental program. The injector used to obtain the data was a like-on-like doublet which most closely simulated the conditions portrayed in the chamber pressurization model. The propellant temperatures were: 540^{o}R (nominal), 580^{o}R, and 500^{o}R; the propellant valve openings were varied from 5 ms to 40 ms and the propellant leads were varied. The propellant lead conditions were determined from the time difference between the first noticeable increase in chamber pressure and ignigion and, therefore, includes any ignition delay. The valve opening was measured by a linear potentiometer which coupled to the valve stem opening. Propellant temperatures were measured by thermocouples located in the injector manifold.

It was found that fuel lead conditions produced highest pressures with cold propellant temperatures (500 to 530^{o}R). The results of this test program demonstrate the influence of fuel leads in the production of detonatable intermediates. Low fuel temperature gave consistent spiking, and long fuel leads at even relatively higher fuel temperatures (175^{o}F) also lead to spiking. Although relatively little time and funding was available for these experiments, the results demonstrate the importance of preignition chemistry and condensed phase reactions of the hydrazine droplet surface. These reactions can be followed with vaporizing fuel droplets (long fuel leads even at higher temperatures) to analytically determine worst or unacceptable start sequences. The effect of propellant leads are seen where the fuel leads produced ignition spikes while the oxidizer lead conditions at low temperature produced none. Lengthening the valve opening time of the fuel system did not significantly reduce or eliminate the spiking tendency which exists at this condition.

TABLE V

EXPERIMENTAL RESULTS

Date Test	Propellant Leads Ox (ms)	Propellant Leads Fuel (ms)	Valve Opening Time Ox (ms)	Valve Opening Time Fuel (ms)	Temperature (°R) Ox	Temperature (°R) Fuel	Temperature (°R) Wall	Spike (psi)
(6/27)								
8	25		4.8	4.8	540	540	540	No
9	10		6.0	6.0	540	540	540	2900
(7/1)								
3	21.9		17.0	17.0	540	540	540	No
4	26.6		21.0	21.0	540	540	540	No
(7/2)								
6	3.8		12.9	12.9	540	540	540	No
7		7.6	18.3	28.3	540	540	540	No
8		12.1	9.0	9.0	540	540	540	No
11	13.1		43.9	43.9	540	540	540	No
(7/3)								
1	7.6		15.7	15.7	540	540	540	No
3	6.2		13.2	13.2	540	540	540	No
4	22.5		43.9	16.0	540	540	540	No
5	10.0		38.2	13.7	530	500	540	No
6	8.3		31.2	9.2	520	500	540	No
7		8.8	21.2	12.2	520	500	540	Yes
8	34.2		37.4	10.2	560	590	540	No
12	15.5		44.0	19.5	570	630	540	No
13		19.6	12.9	39.7	570	640	540	Yes
14		19.3	12.4	34.6	570	630	540	Yes
15		21.8	13.35	39.9	570	640	540	No
16		17.1	13.3	36.2	570	640	540	No
17		9.1	12.6	12.6	530	510	540	3000
18		3.8	13.75	27.2	530	500	540	3500

5. CONCLUSIONS

A computer program has been written to describe rocket engine ignition transients. This program is useful in order of magnitude studies to determine what is influencing time delays and subsequent ISP pulse shape, and, also, the details of chemistry and O/F ratios which control the smoothness of ignition and spiking; finally, a short experimental firing program also performed to demonstrate the predicted trends.

The influence of design and operating variables upon what is going on as the engine starts can be evaluated by a computer program which essentially consists of an accounting system of enthalpy and mass balances with arbitrary propellant input. The propellant input may be calculated from a compatible flow program which essentially consists of a lump parameter analog model of the input hardware influences which affect the input flow. These programs, listed in the Appendix, thus describe flow, vaporization, chemistry, ignition, and/or detonation strength. Hardware parameter can be evaluated by one run after another with changing such things as chamber volume, heat capacity, injection velocity, etc.

Conclusions

The program is useful in evaluation of such things as an order of magnitude study of what design or physical processes are controlling ignition delay. For example, injected drop size or vaporization surface area are not particularly important, because the start is controlled by an enthalpy balance for which the engine starts when the accumulated enthalpy overcomes the engine's heat capacity. Such simplifications can be graphically demonstrated by various size engines, and often the start problem can be reduced to one of propellant flow and a known time delay for enthalpy accumulation. The program is also useful in evaluating the extremes of O/F ratio which can be encountered with hardware fuel or oxidizer leads. These calculations can often be used to interpret the relevance of purely chemical observations.

Chemical observations have shown that condensed phase fuel often reacts without ignition, but with the formation of detonation-sensitive intermediates. This fact was predicted by the computer program and was observed experimentally. Cold fuel gave rise to severe spiking and, also relatively warm fuel, even above 125°F, showed a tendency to spiking with long fuel leads in vacuum environment.

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APPENDIX A

USER'S MANUAL
For
PROPELLANT TRANSIENT FLOW PROGRAM

This section is divided into the following subsections:

1. Operating Procedures
2. Description of Program Input
3. Description of Program Output

1. Operating Procedures

This program was developed on the CDC 6400 using FORTRAN IV language. Standard FORTRAN IV CØMMØN is used for all input data.

2. Description of Program Input

This program requires the following groups of data.

a. Propellant Properties
b. Hardware Parameters
c. Flow Properties
d. Computational Control Information

a. Propellant Properties:

Item Name		Input Quantity	Units
RØ	=	density of propellant at the temperature considered	lb/ft^3
PVI	=	vapor pressure of propellant at the temperature considered	lb/in^2 absolute
XMU	=	viscosity of the propellant at the temperature considered	lb/ft-sec
GAM	=	specific heat ratio of the vapor propellant	none

b. Hardware Properties:

Item Name		Input Quantity	Units
XL	=	length of propellant line which contains accelerating propellant	ft
XLF	=	length of propellant line over which friction acts	ft
XLMI	=	length of propellant manifold	inches
XKL	=	accumulated pressure loss coefficient of system from tank to valve	none

DI	=	diameter of propellant line	inches
DOI	=	diameter of orifices in injector	inches
XNØRF	=	number of orifices in injector	none
VMOI	=	volume of propellant manifold	$inches^3$
AVOI	=	area of the valve when full open*	$inches^2$
TVO	=	time for valve to open*	seconds
XN	=	exponent on valve transient to shape its opening*	none
TI(1)	=	points in time table used to specify valve transient ≤ 100*	seconds
AVTI(1)	=	valve opening areas corresponding to time values TI ≤ 100*	$inches^2$
NT	=	number of tabular values used to describe valve opening*	none

c. Flow Properties:

Item Name		Input Quantity	Units
CV	=	discharge coefficient of valve	none
CO	=	discharge coefficient for injector orifices	none
WSS	=	steady state propellant flow rate*	lb/sec
PCSSI	=	steady state combustion chamber pressure	lb/in^2 absolute
PSSI	=	pressure drop across the injector	lb/in^2
DPI	=	overall pressure drop from propellant tank through injector*	lb/in^2
QI(1)	=	initial values of volumetric flow rate*	ft^3/sec
		QI(1) = propellant flow out of tank QI(2) = propellant flow out of injector QI(3) = d/dt [$\int$QI(1)] QI(4) = d/dt [$\int$QI(2)] QI(5) = gas flow out of manifold QI(6) = d/dt [$\int$QI(5)]	 ft^3 /sec
TEMPØ	=	temperature of propellants considered*	^oR
XMØWT	=	molecular weight of propellants* (not needed if PAMBI = 0.)	none
PAMBI	=	initial ambient pressure*	lb/in^2-absolute

*See computational control information section.

d. Computational Control Information:

Item Name		Input Quantity	Units
TMAX	=	maximum computational time	seconds
TS	=	starting time for computations, $\neq 0$	seconds
HO	=	initial step size	seconds
HMIN	=	minimum step size	seconds
HMAX	=	maximum step size	seconds
ELR	=	minimum relative error on integrated flow parameters	none
EUR	=	maximum relative error on integrated flow parameters (should be a minimum of 32 times longer than ELR)	none
DRP	=	print suppression index (printout will occur at every time interval DRP)	seconds
FLAG	=	option defining the form of the flow parameters FLAG = 0. requires that WSS, PCSSI, and PSSI be input and DPI be undefined. FLAG = 1.0 requires that DPI be input and WSS, PCSSI, and PSSI be undefined.	none
FLAGT	=	option which provides for use of tabular values of valve areas instead of formula. FLAGT = 1. uses table FLAGT = 0. uses formula $AVOI = [time/TVO]^{XN}$ (when FLAGT = 1. option is used, AVOI, TVO, and XN are not needed for input)	none

TABLE A-I shows a typical input listing.

3. Description of Program Output:

Item Name		Input Quantity	Units
T	=	time	seconds
H	=	time step taken at time I	seconds
WI	=	propellant flow rate from propellant tank	lb/sec
W2	=	propellant flow rate from injector orifices	lb/sec
Q1	=	propellant flow rate from propellant tank	ft^3/sec

Q2	=	propellant flow rate from injector orifices	$ft^3 sec$
DQ1	=	the derivative of Q1	ft^3/sec^2
DQ2	=	the derivative of Q2	ft^3/sec^2
IQ1	=	the integral of Q1	ft^3
IQ2	=	the integral of Q2	ft^3
VMF	=	the volume of the propellant manifold which is full	ft^3
VME	=	the volume of the propellant manifold which is empty	ft^3
PVV	=	the pressure inside the propellant manifold	lb/in^2-absolute
AV	=	the open area of the valve	ft^2
WGØUT	=	the amount of gas which has left the propellant manifold if the start occurred in other than vacuum conditions.	lb
WGDØT	=	the flow rate of gas out of the propellant manifold if the start occurred in other than vacuum condition.	lb/sec

TABLE A-II shows a typical output using the input data from TABLE A-I.

TABLE A-I

TYPICAL INPUT DATA FOR OXIDIZER FLOW TRANSIENT

```
$DATA
RO=88.9,
XL=8.,
PVI=18.5,
XKL=16000.,
DI=.305,
CV=.7,
XLF=8.,
XLMI=4.,
CO=.86,
DOI=.02,
XMU=.00026,
VMOI=.1037,
TS=.000001,
TMAX=.1,
XNORF=4.,
DRP=.001,
GAM=1.2,
FLAG=1.,
PAMBI=0.,
FLAGT=1.,
DPI=490.,
TI(1)=0.,.001,.0015,.002,.0025,.003,.024,
.025,.026,.027,.028,.029,.030,.0306,
.031,.0315,.032,.033,.034,.035,.036,
.037,.038,.0382,.1,
AVTI(1)=0.,.00012,.00045,.0008,.00086,
.00085,.00082,.00067,.0006,.00102,
.0015,.00222,.00265,.00285,
.00275,.0026,.00275,.00305,
.0035,.00425,.00532,.00695,
.00905,.00962,.00962,
NT=25,
$END
```

TABLE A-II - TRANSIENT FLOW ANALYSIS

T H	W1 W2	Q1 Q2	DQ1 DQ2	IQ1 IQ2	VMF VME	PVV AV
.000001000 .000000100	0. 0.	0. 0.	1.619567E+00 0.	0. 0.	0. 6.001157E-05	0. 8.333333E-10
.000001100 .000000100	9.872364E-06 7.861421E-27	1.110502E-07 8.842993E-29	6.697786E-01 3.981357E-21	6.774347E-15 2.370407E-36	6.774347E-15 6.001157E-05	1.253013E-09 9.166667E-10
.000001200 .000000100	1.266291E-05 1.477725E-25	1.424399E-07 1.662233E-27	3.065376E-01 3.572874E-20	2.029368E-14 6.816535E-35	2.029368E-14 6.001157E-05	3.753606E-09 1.000000E-09
.000001300 .000000100	1.437527E-05 7.575105E-25	1.617015E-07 8.520929E-27	1.777336E-01 1.109431E-19	3.576036E-14 5.174538E-34	3.576036E-14 6.001157E-05	6.614391E-09 1.083333E-09
.000001400 .000000100	1.614646E-05 2.345993E-24	1.816250E-07 2.638912E-26	5.112456E-02 2.383630E-19	5.241690E-14 2.124360E-33	5.241690E-14 6.001157E-05	9.695256E-09 1.166667E-09
.001003600 .000012800	1.120698E-02 6.258298E-09	1.260628E-04 7.039705E-11	1.641536E-01 3.500162E-07	6.344402E-08 1.179012E-14	6.344401E-08 5.994813E-05	1.176222E-02 8.498333E-07
.002002000 .000102400	5.027899E-02 4.198832E-07	5.655679E-04 4.723095E-09	3.181782E-01 1.567434E-05	4.217726E-07 1.241780E-12	4.217714E-07 5.958980E-05	7.923258E-02 5.557222E-06
.003077200 .000102400	5.781477E-02 5.630830E-06	6.503349E-04 6.333892E-08	-9.694469E-04 1.094957E-04	1.100825E-06 2.879081E-11	1.100796E-06 5.891078E-05	2.120720E-01 5.902012E-06
.004101200 .000204800	5.775195E-02 2.308917E-05	6.496282E-04 2.597207E-07	-6.094335E-04 2.890066E-04	1.766387E-06 1.785206E-10	1.766208E-06 5.824537E-05	3.488766E-01 5.891853E-06
.005125200 .000409600	5.769356E-02 6.106386E-05	6.489714E-04 6.868825E-07	-5.261726E-04 5.612711E-04	2.431285E-06 6.394035E-10	2.430646E-06 5.758093E-05	4.923950E-01 5.881694E-06
.006354000 .000409600	5.763066E-02 1.460383E-04	6.482639E-04 1.642725E-06	-8.680425E-04 1.019055E-03	3.228278E-06 2.013137E-09	3.226264E-06 5.678531E-05	6.738850E-01 5.869504E-06
.007173200 .000409600	5.758039E-02 2.340082E-04	6.476984E-04 2.632263E-06	-6.524592E-04 1.408310E-03	3.759093E-06 3.742410E-09	3.755350E-06 5.625622E-05	8.007191E-01 5.861377E-06
.008402000 .000409600	5.751628E-02 4.254891E-04	6.469773E-04 4.786154E-06	-1.001369E-03 2.124122E-03	4.554483E-06 8.210227E-09	4.546273E-06 5.546530E-05	1.000031E+00 5.849187E-06

APPENDIX B

USER'S MANUAL
For
CHAMBER PRESSURIZATION TRANSIENT
PROGRAM

This section deals with the use of the program and is divided into the following subsections:

1. Operating Procedures
2. Description of Program Input
3. Description of Program Output

1. Operating Procedures

This program was developed on the CDC 6400 using FORTRAN IV language. Standard FORTRAN IV CØMMØN is used for all input data.

2. Description of Program Input

a. Propellant Properties
b. Chemical Reaction Parameters
c. Transport Properties
d. Hardware Properties
e. Computational Control Information

a. Propellant Properties:

Item Name		Input Quantity	Units
RØN(1,1)	=	table of oxidizer density (up to 10 values may be used)	lb/ft^3
TRØN(1,1)	=	table of temperatures corresponding to oxidizer density RØN(1,1) (up to 10 values may be used)	^oR
RØN(1,2)	=	table of fuel density (up to 10 values may be used)	lb/ft^3
TRØN(1,2)	=	table of temperatures corresponding to fuel density RØN(1,2) (up to 10 values may be used)	^oR
NØRØ	=	number of values used to define density table used	none
CPN(1,1)	=	table of specific heat at constant pressure of liquid oxidizer (up to 10 values may be used)	Btu/lb^oR

TCPN(1,1)	=	table of temperatures, corresponding to liquid oxidizer specific heat (up to 10 values may be used)	°R
CPN(1,2)	=	table of specific heat at constant pressure of liquid fuel (up to 10 values may be used)	Btu/lb°R
TCPN(1,2)	=	table of temperatures corresponding to liquid fuel specific heat (up to 10 values may be used)	°R
NØCP	=	number of values used to define liquid propellant specific heat table	none
CPGN(1,1)	=	table of specific heat at constant pressure of vapor oxidizer (up to 10 values may be used)	Btu/lb°R
TCPGN(1,1)	=	table of temperatures corresponding to oxidizer vapoe specific heat at constant pressure(up to 10 values may be used)	°R
CPGN(1,2)	=	table of specific heat at constant pressure of vapor fuel (up to 10 values may be used)	Btu/lb°R
TCPG(1,2)	=	table of temperatures corresponding to fuel vapor specific heat at constant pressure (up to 10 values may be used)	°R
NØCPG	=	number of values used to define vapor propellant specific heat table	none
CPGP	=	specific heat of vapor product	Btu/lb°R
PVN(1,1)	=	table of vapor pressure for oxidizer (up to 10 values may be used)	lb/ft^2
TPVN(1,1)	=	table of temperatures corresponding to oxidizer vapor pressure (up to 10 values may be used)	°R
PVN(1,2)	=	table of vapor pressure for fuel (up to 10 values may be used)	lb/ft^2
TPVN(1,2)	=	table of temperatures corresponding to fuel vapor pressure (up to 10 values may be used)	°R
NØPV	=	number of values used to describe vapor pressure tables	none
GAM (1)	=	specific heat ratio of vapor oxidizer and vapor fuel	none
GAMP	=	specific heat ratio of vapor products	none

XMU(1)	=	viscosity of oxidizer vapor and fuel vapor	lb/ft-sec
XK(1)	=	thermal conductivity of oxidizer vapor and fuel vapor	Btu/ft-sec^{o}R
XM(1)	=	molecular weight of oxidizer and fuel	none
XMP	=	molecular weight of vapor products	none
TAU(1)	=	heat of vaporization for oxidizer and fuel	Btu/lb
TAUF(1)	=	heat of fusion for oxidizer and fuel	Btu/lb
TAUS(1)	=	heat of sublimation for oxidizer and fuel	Btu/lb
TFP(1)	=	freezing temperature of oxidizer and fuel	^{o}R
PVW(1)	=	vapor pressure of oxidizer and fuel evaluated at the chamber wall temperature	lb/in^2
TGI(1)	=	initial vapor temperatures of the oxidizer and the fuel	^{o}R
PG(1)	=	initial partial pressure in the chamber due to oxidizer vapor, and fuel vapor	lb/in^2

b. Chemical Reaction Parameters:

Item Name		Input Quantity	Units
CFØRPR	=	stoichiometric oxidizer to fuel ratio	none
RM	=	experimentally determined exponent for fuel concentration in reaction rate equation	none
RN	=	experimentally determined exponent for oxidizer concentration in reaction rate equation	none
EACTT(1)	=	activation energy for each preignition reaction path	ft/lb/mole
AAT(1)	=	Arrhenius reaction rate constant for each preignition reaction path	cc/mole-sec
A(J,I,1)	=	relative formula weights of species in balanced preignition reactions for oxidizer rich reactions	
A(J,I,2)	=	relative formula weights of species in balanced preignition reactions for fuel rich reactions	
		I corresponds to reaction paths within the temperature range TTABLE (I) and TTABLE (I+1). Maximum I is NN	

		J corresponds to specified species in balanced reaction. Maximum J is 12, where J=1 is reactant species on which the enthalpy of reaction is based. J=2 species is second reactant species. All other species are unspecified.	
TTABLE(1)	=	table of temperatures which define reaction paths (must be NN+1 values)	^{o}R
YREACT(1,1)	=	enthalpy of reaction for fuel rich reactions	Btu/lb
YREACT(1,2)	=	enthalpy of reaction for oxidizer rich reactions	Btu/lb
CØNCR	=	critical oxidizer vapor concentration below which liquid fuel and oxidizer vapor reaction takes place (concentration of oxidizer vapor/concentration of all vapors)	none
TCR	=	critical temperature below which liquid fuel and oxidizer vapor reaction takes place	^{o}R
HEATX	=	heat of reaction for liquid fuel - oxidizer vapor reaction	Btu/lb
HFLIQ(1)	=	heat of formation of liquid oxidizer and fuel	calories/mole

c. Transport Properties:

Item Name		Input Quantity	Units
HC(1,1)	=	heat transfer coefficient between oxidizer vapors and wall when Tw > Tg, between oxidizer vapors and wall when Tw < Tg, and between gaseous products and wall when Tw > Tg	Btu/ft^2 -sec^{o}R
HC(1,2)	=	heat transfer coefficient between fuel vapors and wall when Tw> Tg, between fuel vapors and wall when Tw< Tg, and between gaseous products and wall when Tw < Tg	Btu/ft^2-sec^{o}R
VDRØP(1)	=	velocity of oxidizer and fuel drops	ft/sec
ALPHA	=	accommodation coefficient (fraction of vapor that impinges on chamber wall and remains as condensate)	none
RGI(1)	=	initial radius of oxidizer and fuel droplet	ft

WLIQ(1,1)	=	table of transient propellant flow rates of first entering species (up to 25 values may be used)	lb/sec
TLIQ(1,1)	=	time table corresponding to values of WLIQ(1,1) (up to 25 values may be used)	sec
NLIQ(1)	=	number of entries in WLIQ(1,1) table	none
WLIQ(1,2)	=	table of transient propellant flow rates of second entering species (up to 25 values may be used)	lb/sec
TLIQ(1,2)	=	time table corresponding to values of WLIQ(1,2) (up to 25 values may be used)	sec
NLIQ(2)	=	number of entries in WLIQ(1,2) table	none
PGADD(1,1)	=	table of time variable backpressures affecting the oxidizer transient pressure (up to 10 values may be used)	lb/in^2-absolute
PGADDT(1,1)	=	time table corresponding to values of PGADD(1,1) (up to 10 values may be used)	sec
PGADD(1,2)	=	table of time variable backpressures affecting the fuel transient pressure (up to 10 values may be used)	lb/in^2-absolute
PGADDT(1,2)	=	time table corresponding to values of PGADD(1,2) (up to 10 values may be used)	sec
WGI(1)	=	initialized flow rate of oxidizer and fuel (small number needed to start program)	lb/sec

d. Hardware Properties:

Item Name		Input Quantity	Units
AC	=	combustion chamber internal surface area	ft^2
VC	=	combustion chamber volume	ft^3
TW	=	combustion chamber wall temperature	^oR
ASTAR	=	chamber nozzle throat area	ft^2

e. Computational Control Information:

Item Name		Input Quantity	Units
NN	=	number of preignition paths used (up to 10 paths may be specified)	none
M(1)	=	starting time in terms of number of calculations for oxidizer and fuel	none
TMAX	=	maximum running time	sec
DELTN	=	initial step size	sec
ND1	=	first integration step to be selected for print	none
ND2	=	last integration step to be selected for print	none
ND3	=	print every ND3rd step between ND1 and ND2	none
IUNIT	=	unit on which punched output will be written	
MSPEC	=	number of chemical species (must be 10)	
IFPLØT	=	option for plot routine IFPLØT=1 will plot	
PLTIME	=	real time for plot generation such that job does not run to maximum time plots are generated	real sec
IDEBUG	=	provides intermediate output when IDEBUG=T or .TRUE.	none
TDETØN(1)	=	specifies time at which detonation calculations are to be performed (up to 40 values may be specified)	sec
TCRIT(1)	=	normalized averaging criteria based on stored droplet temperature for oxidizer and fuel	none
RCRIT(1)	=	normalized averaging criteria based on stored droplet radius for oxidizer and fuel	none
XCRIT(1)	=	normalized averaging criteria based on stored droplets' percent frozen for oxidizer and fuel	none

A typical input listing is shown in Table B-I

3. Description of Program Output

Item Name		Output Quantity	Units
TIME	=	time	milliseconds
F	=	ratio of liquid propellant species to total propellant (liquid and gaseous) species	none
GEVAP	=	mass of propellant evaporated	lb
GCØND	=	mass of propellant condensed	lb
PG(1)	=	partial pressure due to oxidizer	lb/in^2-absolute
PG(2)	=	partial pressure due to fuel vapors	lb/in^2-absolute
PGP	=	partial pressure of gaseous reaction products	lb/in^2=absolute
PGTØTAL	=	total pressure due to oxidizer, fuel, and product vapors	lb/in^2-absolute
TFINAL	=	temperature of gaseous chemical species in chamber after reaction	^oR
TAVERG	=	temperature of gaseous chemical species in chamber before reaction	^oR
TG	=	temperature of vapors in chamber (when only one propellant is flowed)	^oR
TQP	=	temperature of gaseous products	^oR
REACT	=	amount of material which has reacted	lb
WTØTAL	=	total accumulated propellant flow	lb

Table B-II shows typical output from this program.

TABLE B-I

TYPICAL OUTPUT FROM CHAMBER PRESSURIZATION TRANSIENT PROGRAM

```
$DATA
* 0.828E+03, 0.8E+03, 0.0, 0.0, 0.0, 0.44E+03, 0.3E+02, 0.323E+03, 0.98E+02, 0.72E+02,
  0.665E+03, 0.0, 0.184E+03, 0.128E+03, 0.0, 0.0, 0.0, 0.88E+02, 0.3E+02, 0.0, 0.7E+02,
  0.36E+02, 0.0, 0.8E+02, 0.92E+02, 0.64E+02, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.84E+02,
  0.72E+02, 0.0, 0.0, -0.13582279375555-271, 0.25135643210431-275, -0.39700464175606+147,
 -0.17273786375623-269, 0.21617297246502-234, 0.21614890238669-234, -0.65534496091041E+05,
  0.11858914554931-275, 0.15298744170073-275, 0.85050255900059-276, 0.21294757227603-275,
 -0.39715158738624+147, 0.19482294932728+287, 0.75729000761011-276, 0.21272721163444-275,
 -0.25599253535527E+03, 0.21745243943817-234, 0.11532780805385-275, -0.15806768428534E+48,
  0.20016840476187-215, 0.20016840476194-215, 0.87313303684335-135, 0.14250811913572-229,
  0.5566370259428-232, -0.17188269222276-163, -0.18244976066085E+85, -0.2901670524926E+67,
 -0.43367745686545E-18, -0.43367664695243E-18, -0.36122077587999+135, 0.69510155693575-233,
  0.40458470762016E+21, -0.33776806730399E+17, -0.17120435812387-163, 0.41269788332367+302,
  0.37081433997814-196, -0.16148792519923-163, -0.15499222954431E+73, 0.78520130321385-218,
  0.13835549509949-275, -0.26496672796006-168, 0.37079804194034-196, 0.3438392644259E+17,
  0.21795183860989-234, -0.55696707465143+257, -0.89298649031397-188, -0.14627079234395+258,
  0.90178952900987E+19, 0.17024994049059-236, -0.53405579132036-188, -0.26496716631387-168,
 -0.17244699917004+258, -0.73708312970777+166, 0.25014013182887-234, -0.26507694759199-188,
 -0.13524857809596E+26, 0.87420566905358-234, 0.58571722199409-125, 0.27287358476128-235,
 -0.39711591501974+147, -0.17385318083065-269, -0.33819589202512E+74, 0.21336625749504-275,
  0.69253647379666-233, -0.39708542323283+147, -0.39686440695086+147, -0.53175839015117-255,
  0.14653336088908-217, -0.68468170399224-191, -0.1735380313286-190, -0.3469390758793-190,
  0.17502901446447-233, -0.70607336520797E+82, -0.48636605007671E+52, -0.51015653789851-196,
 -0.15153138406057-175, 0.78976594956068-218, -0.34707606213463-190, 0.17524401099971-233,
 -0.70607336520797E+82, -0.48636605007671E+52, -0.51108736227436-196, -0.15211458466793-175,
 -0.17385318087708-269, 0.5796E+04, 0.2048E+04, 0.0, 0.0, 0.0, 0.352E+04, 0.48E+03, 0.0,
  0.308E+03, 0.1296E+04, 0.0, 0.224E+04, 0.184E+03, 0.128E+03, 0.0, 0.0, 0.0, 0.88E+02,
  0.3E+02, 0.0, 0.7E+02, 0.36E+02, 0.0, 0.8E+02, 0.92E+02, 0.64E+02, 0.0, 0.0, 0.0, 0.0
  0.0, 0.0, 0.84E+02, 0.72E+02, 0.0, 0.0, 0.46269146330188E+33, -0.6487850186703-272,
  0.79031924002696-218, 0.41310995316056-184, 0.21930331691454E+33, 0.46269242560684E+33,
  0.79031924002696-218, -0.2445712346419-137, -0.3970490572155+147, 0.22098265131588-234,
  0.46269146330188E+33, -0.85733688869182-197, -0.15211458466793-175, 0.22113562008227-234,
  0.46269146330188E+33, -0.1505680185945-175, -0.15153138406057-175, -0.6487850186703-272,
  0.79031924002696-218, -0.23408345934477-137, 0.34659246864352-236, -0.86507489716579E+52,
  0.30329584251388E+29, -0.24457123263982-137, 0.88623173567032-234, 0.46269014795905E+33,
  0.13354590447402-122, -0.2445712296367-137, 0.88684601178035-234, 0.46269014795905E+33,
 -0.1503991749263-182, -0.13149105550894-196, 0.1288184591094-122, 0.34680511081317-236,
 -0.89495827701724-186, -0.27344789860833-185, 0.80000182318689-218, -0.36171062886348E+28,
  0.11804053703866-234, -0.73500696324619-272, -0.13149105550894-196, -0.7336305025346-272, 0.0,
 -0.9153239052129-270, 0.10922959988258+296, 0.23974342629277-275, 0.69859767480929-177,
```

TABLE B-I (Cont.)

```
             0.73238925511 1-276, -0.39719535049498+147, -0.39723841204938+147,  0.73238925511 1-276,
             0.16923831535475E+25, -0.64876668238 21-272, -0.26431679984573E-47, -0.14672699925017-271,
             0.16788215973156-217, -0.51295136597974E+49,  0.48819422307768-125,  0.12329896117195-105,
            -0.18333588760831-115,  0.46762093357675-228,  0.46810401973417-228,  0.16271707886418-230,
             0.21686999106624-275, -0.73363049513185-272, -0.38509981049 8-199,  0.11645692916435-275,
             0.22107887995052-275, -0.73363049513185-272,  0.23006959412719-275, -0.73363049513185-272,
             0.74417567714993-218, -0.39715287610795+147, -0.36111518427087+135, -0.39705052868656+147,
             0.22351671305538-234,  0.86581137308285-218, -0.43123213095907-217,  0.86581137308285-218,
            -0.39719842324784+147, -0.36125093989162+135, -0.39690403555 39+147, -0.28206023569569-262,
             0.84653067452 06-276,

AA1      =   0.16E+12,  0.16E+12,  0.16E+12,  0.35127160464166-136, -0.39692199010461+147,
             0.14430402263376+157,  0.69609817666483+299,  0.63541241302893-218, -0.72672044054601-272,
            -0.39691684652829+147,

AC       =   0.131E+00,

ALPHA    =   0.1E+01,

ASTAR    =   0.411E-02,

CFORPF   =   0.5E+00,

CPGN     =   0.5E+00,  0.217E+01,  0.225E+01,  0.215E+01,  0.45E+00, -0.10538736143429E+38,
            -0.52212481170547E+49,  0.76425449454233-233, -0.58307572521864E+28,  0.24106190683431-234,
             0.57E+00,  0.53E+00,  0.5E+00,  0.455E+00,  0.393E+00, -0.15865561076711E-25,
            -0.10361104677475E+5 ,  0.47853628469866-234, -0.96741857422103E+37,  0.12051563018877-234,

CPGP     =   0.1E+01,

CPN      =   0.14E+00,  0.17E+00,  0.288E+00,  0.354E+00,  0.366E+00,  0.379E+00,  0.395E+00,  0.421E+00
             0.47608795211186-234, -0.25091369874178-167,  0.229E+00,  0.314E+00,  0.477E+00,  0.726E+00
             0.814E+00,  0.836E+00,  0.865E+00,  0.925E+00,  0.18643962778021-236,  0.31279380290997-229

CVG      =   0.97E+00,  0.36E+00,

DELIN    =   0.1E-03,

DIMAX    =   0.2629442201171-255,

DIMIN    =  -0.25280208745032-115,
```

TABLE B-I (Continued)

```
EACTT   =  0.95175E+07,  0.95175E+07,  0.95175E+07, -0.41946499645271-166,  0.13242285259015-132,
           0.53895123674893-135, -0.30562437387381-161,  0.71564366645498E+18,  0.52773796146447-135,
          -0.12041903310426-196,

GAM     =  0.11E+01,  0.13E+01,

GAMP    =  0.12E+01,

HC      =  0.5E+00,  0.5E+00,  0.5E+00,  0.5E+00,  0.5E+00,  0.5E+00,

M       =  1,  1110,

NN      =  3,

NOCP    =  8,

NOCPG   =  5,

NOPV    =  5,

NORO    =  6,

NIRAN   =  13,

PCT     =  0.0,  0.825E+00,  0.33E+01,  0.1655E+02,  0.359E+02,  0.535E+02,  0.634E+02,  0.737E+02,
           0.828E+02,  0.10035E+03,  0.112E+03,  0.125E+03,  0.144E+04,  0.90594454943999-234,
          -0.89675259788801-186, -0.14807298883444-189,  0.35085568061287-236,  0.81604724670906-218,
          -0.23813175395622-267, -0.48438828135501E-47,  0.0,  0.528E+00,  0.15E+01,  0.343E+01,  0.1E+02,
           0.135E+02,  0.142E+02,  0.146E+02,  0.15E+02,  0.1515E+02,  0.153E+02,  0.153E+02,  0.144E+04,
          -0.14717424894447-175, -0.15091444457511-175, -0.39719535049498+147, -0.36124725229215+135,
          -0.36122076775349+135,  0.62277436148692+303, -0.36103350454208+135,

PG      =  0.0,  0.0,

PTAN    =  0.2905E+05,  0.2905E+05,  0.2905E+05,  0.2905E+05,  0.2905E+05,  0.2905E+05,  0.2905E+05,
           0.2905E+05,  0.2905E+05,  0.2905E+05,  0.2905E+05,  0.2905E+05,  0.2905E+05,
          -0.14759262775665-271, -0.39692066872124+147, -0.36099376997954+135,  0.48393876122638-237,
           0.17810131349481-236,  0.45729715194399-234, -0.43367633648501E-18,  0.1484E+05,  0.1484E+05,
           0.1484E+05,  0.1484E+05,  0.1484E+05,  0.1484E+05,  0.1484E+05,  0.1484E+05,  0.1484E+05,
           0.1484E+05,  0.1484E+05,  0.1484E+05,  0.1484E+05, -0.39702009568111+147,  0.14990567699751-229,
           0.88332641879185E+31,  0.21930123271565E+33, -0.73796278043895-272, -0.40424333205163-173,
          -0.39692252615324+147,
```

TABLE B-I (Continued)

```
PVN     =  0.388E+03,  0.108E+04,  0.347E+04,  0.965E+04,  0.3355E+05,  0.23548742654185E-28,
          -0.86362310107237E-46,  0.3149142587426-229, -0.2647264706350 4-188, -0.1030992882977-115,
           0.75E+01,  0.72E+02,  0.288E+03,  0.864E+03,  0.432E+04, -0.10363959172866E+50,
           0.23999759440685-234, -0.15768365533513-167, -0.94344033341068E+37,  0.16394307667248-124,

PVV     =  0.965E+04,  0.864E+03,

PVW     =  0.954E+03,  0.111E+02,

RGI     =  0.171E-03,  0.171E-03,

RM      =  0.1E+01,

RN      =  0.1E+01,

RON     =  0.1182E+03,  0.945E+02,  0.829E+02,  0.775E+02,  0.698E+02,  0.63E+02,  0.21897600125851-21
           0.24310650678934-231,  0.64194584375651E+29,  0.44770967259614E+68,  0.715E+02,  0.639E+02,
           0.576E+02,  0.502E+02,  0.455E+02,  0.416E+02, -0.36108468761147+135, -0.91693967686746E+87,
           0.26443248729552-191,  0.88484977820118-218,

TAU     =  0.178E+03,  0.607E+03,

TAUF    =  0.654E+02,  0.171E+03,

TAUS    =  0.237E+03,  0.85E+03,

TCPGN   =  0.455E+03,  0.544E+03,  0.558E+03,  0.572E+03,  0.65E+03,  0.48424542321814-234,
           0.40868652358879E+18,  0.58849049613707E-26, -0.56339302605008-198, -0.39708732972202+147,
           0.54E+03,  0.68E+03,  0.8E+03,  0.94E+03,  0.108E+04, -0.36124938348506+135,
           0.87524932660122-218, -0.40422959548899-173,  0.11532780805385-275,  0.12887998751133-275,

TCPN    =  0.15E+03,  0.204E+03,  0.4719E+03,  0.472E+03,  0.52E+03,  0.546E+03,  0.564E+03,  0.582E+03
           0.13924832134815+312, -0.36116851752959+135,  0.181E+03,  0.271E+03,  0.4949E+03,  0.495E+03
           0.76E+03,  0.81E+03,  0.86E+03,  0.96E+03, -0.31941333363523-185, -0.36101595031962+135,

TFP     =  0.47184E+03,  0.4954E+03,

TGI     =  0.54E+03,  0.54E+03,

TMAX    =  0.5E-01,
```

TABLE B-I (Continued)

```
TP     =  0.0,  0.1E-03,  0.2E-03,  0.3E-03,  0.4E-03,  0.5E-03,  0.6E-03,  0.7E-03,  0.8E-03,  0.9E-03,
          0.1E-02,  0.2E-02,  0.1E-01, -0.62215047248848-186,  0.27843927066593+300,  0.22945112349065-234,
         -0.36099875312807+135,  0.12229748460903+301, -0.60564471776888+142,  0.30121894453724-229,  0.0,
          0.1E-03,  0.2E-03,  0.3E-03,  0.4E-03,  0.5E-03,  0.6E-03,  0.7E-03,  0.8E-03,  0.9E-03,  0.1E-02,
          0.2E-02,  0.1E-01, -0.12486896688438+146, -0.84304868051574-187, -0.7711924024834-187,
         -0.43367753441506E-18,  0.14840264188531-232,  0.96783951745301-237,  0.21245588808235-215,

TPVN   =  0.472E+03,  0.505E+03,  0.55E+03,  0.595E+03,  0.66E+03,  0.72908384548722-276,
          0.77730653632408-233,  0.77738356048447-233, -0.25817327871111-213, -0.36122111704602+135,
          0.492E+03,  0.552E+03,  0.6E+03,  0.65E+03,  0.74E+03, -0.96488042731694-111,
         -0.21133930616936E+38,  0.86957809932183-218, -0.39693946305476+147, -0.36119894922707+135,

TRUN   =  0.3495E+03,  0.4737E+03,  0.61E+03,  0.66E+03,  0.71E+03,  0.74E+03, -0.53065213082936E+37,
          0.59676220492351-207, -0.10363959171499E+50,  0.24063187367222-234,  0.483E+03,  0.485E+03,
          0.69E+03,  0.834E+03,  0.776E+03,  0.105E+04,  0.0, -0.36942527263909-114,  0.15788132967566-229,
          0.61671866389451-232,

TTABLE =  0.4E+03,  0.53E+03,  0.6E+03,  0.1E+05,  0.54467632976101E+17, -0.50179273861745-187,
          0.11386091566665E+37, -0.44888219770582E+47,  0.92828559979 86-237,  0.60830850963552-232,

TW     =  0.54E+03,

VC     =  0.376E-02,

VDROP  =  0.8E+02,  0.8E+02,

WGI    =  0.1E-07,  0.1E-07,

XK     =  0.14E-04,  0.36E-05,

XM     =  0.92E+02,  0.32E+02,

XMP    =  0.4E+02,

XMU    =  0.5E-05,  0.6E-06,

XR     =  0.1E+01,  0.1E+01,

YK     =  0.129E-03,  0.129E-03,  0.344E-03,  0.989E-03,  0.1633E-02,  0.215E-02,  0.243E-02,  0.2663E-02,
          0.2808E-02,  0.295E-02,  0.3E-02,  0.305E-02,  0.305E-02, -0.17510348878417-199,
         -0.17273822881578-269, -0.36114857035082+135, -0.36119893568853+135, -0.17385317893791-269,
         -0.15513717557568+145, -0.36120715723279+135,  0.132E-03,  0.132E-03,  0.298E-03,  0.507E-03,
          0.1E-02,  0.123E-02,  0.132E-02,  0.143E-02,  0.15E-02,  0.152E-02,  0.153E-02,  0.154E-02,
          0.154E-02,  0.19329969043184E+37,  0.27837352882358E+18, -0.12486868173244+146,
         -0.27707513863968-190,  0.15465256161618 3E+38,  0.22651353260289-234, -0.14807298884747-189,
```

TABLE B-I (Continued)

```
YREACT  =  0.1123E+04,  0.2605E+04,  0.486E+04, -0.13573062411117-185, -0.43675050068 75-161,
          -0.38818110362597E+70, -0.42381131515697-161, -0.21134411462655E+71, -0.38818110362597E+70,
          -0.39704905721 55+147,  0.222E+04,  0.2605E+04,  0.486E+04, -0.21134610568706E+71,
          -0.38756238516339E+70, -0.36122333971234+135, -0.14193448067777-175, -0.73363051931988-272,
          -0.10478531855812-108,  0.10752873506502E+56,

ICASE   =  1000,

MSPEC   =  10,

HFLIQ   = -0.25E+04,  0.12E+05,

IUNIT   =  6,

ND1     =  1,

ND2     =  100000,

ND3     =  2,

PGP     =  0.0,

TFINAL  =  0.1E+01,

IFPLOT  =  0,

PLTIME  =  0.3E+02,

TDETON  =  0.2E+02,  0.4E+02,  0.6E+02,  0.8E+02,  0.9E+02,  0.1E+03,  0.11E+03,  0.12E+03,  0.1E+11,
           0.1E+11,  0.1E+11,  0.1E+11,  0.1E+11,  0.1E+11,  0.1E+11,  0.1E+11,  0.1E+11,  0.1E+11,  0.1E+11,
           0.1E+11,  0.1E+11,  0.1E+11,  0.1E+11,  0.1E+11,  0.1E+11,  0.1E+11,  0.1E+11,  0.1E+11,  0.1E+11,
           0.1E+11,  0.1E+11,  0.1E+11,  0.1E+11,  0.1E+11,  0.1E+11,  0.1E+11,  0.1E+11,  0.1E+11,  0.1E+11,
           0.1E+11,

TCRIT   =  0.1E-02,  0.5E-03,

RCRIT   =  0.2E-02,  0.1E-02,

XCRIT   =  0.1E+11,  0.1E-09,

PGADD   =  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,
           0.0,  0.0,  0.0,  0.0,

NPG     =  0,
```

TABLE B-I (Continued)


```
CONCR    = 0.5E+00,

TCR      = 0.53999E+03,

XKBAR    = -0.41508296559865E-52,

HEATX    = 0.1E+04,

IDEBUG   = T,

WLIQ     = 0.0,  0.1E-03,  0.1E-02,  0.37E-02,  0.134E-01,  0.196E-01,  0.293E-01,  0.293E-01,  0.825E-01,
           0.775E-01,  0.752E-01,  0.74E-01,  0.727E-01,  0.72E-01,  0.72E-01, -0.10445673036381E+50,
           0.19154274902884-236, -0.24091362111454-109, -0.39720938686675+147,  0.43536385125157-124,
           0.19178802719029-149, -0.40424548216055-173,  0.14650569636576-217,  0.11845692916435-275,
          -0.22669644116145+140,  0.0,  0.5E-03,  0.11E-02,  0.23E-02,  0.33E-02,  0.375E-02,  0.375E-02,
           0.1283E+00,  0.95E-01,  0.835E-01,  0.812E-01,  0.775E-01,  0.763E-01,  0.753E-01,  0.751E-01,
           0.46559493824895-237, -0.38977326688899+147, -0.35445304385506+135,  0.48819551563344-125,
          -0.35443593837752+135, -0.35443572163346+135, -0.35443433491784+135, -0.35444265254616+135,
          -0.35444126544977+135, -0.35443871070643+135,

TLIQ     = 0.0,  0.5E-02,  0.1E-01,  0.15E-01,  0.25E-01,  0.35E-01,  0.48E-01,  0.765E-01,  0.775E-01,
           0.85E-01,  0.9E-01,  0.95E-01,  0.105E+00,  0.12E+00,  0.128E+00,  0.0,  0.0,  0.0,  0.0,  0.0,
           0.0,  0.0, -0.71394244806269-260, -0.12549005199996+246, -0.31361169113931E+42,  0.43E-01,
           0.5E-01,  0.55E-01,  0.6E-01,  0.65E-01,  0.7E-01,  0.105E+00,  0.106E+00,  0.1075E+00,
           0.109E+00,  0.11E+00,  0.113E+00,  0.115E+00,  0.12E+00,  0.128E+00,  0.86352889272752-165,
          -0.48445441158777E-59,  0.31242941009043-235, -0.52212333520125E+49,  0.97001590942197-237,
           0.55947490410617E+17,  0.78258962961875-236,  0.77937455705288-177,  0.94720862006616E+55,
           0.10465980011779+299,

NLIQ     = 15,  15,

$END
```

TABLE B-II

TYPICAL OUTPUT FROM CHAMBER PRESSURIZATION TRANSIENT PROGRAM

```
                            TIME(MILLISEC) = 1.1000E-02

PRESSURES(PSIA)        TEMPERATURES(DEGR)   REACTION PARAMETERS    WEIGHTS AND FACTORS
OXID  = 2.4512E-05   TFINAL= 5.5069E+02   REACT(O)= 5.1816E-19   WTOTAL(O)= 9.9981E-09
FUEL  = 9.6188E-07   TAVERG= 5.5069E+02   REACT(F)= 3.6046E-19   WTOTAL(F)= 9.9999E-09
TOTAL = 2.5474E-05   TWP    = 5.5223E+02   DELTRE   = 4.7421E-07   F(O)      = 8.5643E-01
PGP   = 1.3815E-13                                               F(F)      = 9.9804E-01

PRODUCT CONCENTRATIONS

N2O4   = 9.9981E-09    N2H4   = 9.9999E-09    NO2   = 0.           N2O   = 1.3816E-18
NO     = 4.7099E-19    NH3    = 8.2725E-26    N2    = 1.0990E-18   H2O   = 5.6519E-19
N3H5O3= 4.6229E-25    N2H4O3= 1.2560E-18
```

Output with oxidizer and fuel flowing

TIME	PG	GEVAP	GCOND	TG	WTOTAL	F
1.0000E-03	2.1043E-06	1.2564E-10	0.	5.4000E+02	1.0000E-08	9.8744E-01
2.0000E-03	8.1998E-06	3.6519E-10	0.	5.4000E+02	3.0000E-08	9.8364E-01
3.0200E-03	2.2061E-05	8.3219E-10	0.	5.3868E+02	7.0000E-08	9.8110E-01
4.0502E-03	4.7007E-05	1.5018E-09	0.	5.3770E+02	1.3040E-07	9.7834E-01
5.0907E-03	8.6093E-05	2.3594E-09	0.	5.3666E+02	2.1140E-07	9.7548E-01
6.1416E-03	1.4245E-04	3.4097E-09	0.	5.3562E+02	3.1322E-07	9.7257E-01
7.2030E-03	2.1931E-04	4.6602E-09	0.	5.3465E+02	4.3605E-07	9.6961E-01
8.2751E-03	3.2004E-04	6.1173E-09	0.	5.3378E+02	5.8010E-07	9.6662E-01
9.3578E-03	4.4808E-04	7.7872E-09	0.	5.3302E+02	7.4560E-07	9.6359E-01
1.0451E-02	6.0696E-04	9.6753E-09	0.	5.3234E+02	9.3275E-07	9.6053E-01

Output with oxidizer only flowing

APPENDIX C

PROPELLANT TRANSIENT FLOW PROGRAM

```
      COMMON/NAME1/EU(6),EL(6),TEMPS(9,6),Q(6),DQ(6),H,T
      COMMON/NAMES/TV0,XN,AV,AV0,VME,VM0,   XKL,F(3),XL,D,PM
     1 ,DP,VMF,PSS
     2 ,XNRE,DRP
     3 ,NN
     4 ,W(3),RO,XLF
     5, COE,PVV,PV,PVI,GAM
      COMMON/NAMEC/CRE,C1,C2,C3,C4,C5
      COMMON/MARKET/ TEMPO,XMOWT,PAMB,A0
C
      DIMENSION QI(6)
C
      EXTERNAL AUXSUB
C
      NAMELIST/DATA/RO,XL,PVI,XKL,DI,CV     ,XLF,XLMI,C0,D0I
     1 ,XMU,AV0I,TV0,XN,VM0I,WSS ,TMAX,TS,XNORF,XNRE
     2 ,H0,ELR,EUR,HMAX,HMIN,DRP
     3 ,GAM,PCSSI
     4 ,COE
     5 ,FLAG,PSSI,DPI
     6 ,QI
     5    ,TEMPO,XMOWT,PAMBI
C
      G=32.174
      PI=3.14159265
      PAMB=0.0

      GAM=1.
      FLAG=0.
      PCSSI=0.
      COE=.5
      XN=1.
      TS=0.
      XNRE=.25
      H0=1.E-7
      ELR=.00003
      EUR=.002
      HMAX=1.E-3
      HMIN=1.E-7
      DRP=0.
      LC=18
C
C
 1    CONTINUE
      NN=4
      DO 100 K=1,NN
 100  QI(K)=0.
      READ (5,DATA)
      WRITE(6,DATA)
      NN=4
      PAMB=PAMBI*144.0
      IF(PAMBI .NE. 0.0) NN=6
C
      D=DI/12.
      XLM=XLMI/12.
```

```
      D0=D0I/12.
      AV0=AV0I/12.**2
      VM0=VM0I/12.**3
      PCSS=PCSSI*12.**2
      PV=PVI*12.**2
      PM=GAM*PV
C
      AL=PI*(D/2.)**2
      A0=PI*(D0/2.)**2*XNORF
C
      CRE=4.*RO/PI/XMU/D
      C1=G*AL/RO/XL
      C2=RO/(2.*G*AL**2)
      C3=RO/(2.*G*CV**2)
      C4=G/RO/XLM**2
      C5=RO/(2.*G*(C0*A0)**2)
C
      QQ=WSS/RO
      CALL FSUB(QQ,CRE,XNRE,FQ)
      IF(FLAG .EQ. 0.) GO TO 15
      PSS=PSSI*144.
      DP=DPI*144.
      GO TO 16
 15   CONTINUE
      PSS=C5*QQ**2
      DP=PSS+((XKL+FQ*XLF/D)*C2*C3/AV0**2)*QQ**2+PCSS
      PSSI=PSS/144.
      DPI=DP/144.
 16   CONTINUE

      WRITE(6,900) AV0,VM0,AL,A0,CRE,C1,C2,C3,C4,C5,PSSI,DPI
 900  FORMAT(///,* AV0,VM0,AL,A0,CRE =*,5E15.5
     1 ,/,* C1,C2,C3,C4,C5 =*,5E15.5
     2 ,/,* PSS,DP =*,2E15.5)
C
C
      T=TS
      H=H0
      DO 21 K=1,NN
 21   Q(K)=QI(K)
      ICNT=0
      DO 2 K=1,NN
      DO 2 J=1,9
 2    TEMPS(J,K)=0.
C
      CALL AUXSUB
      L=0
      CALL PRINT(L)
C
 10   CONTINUE
      DO 3 K=1,NN
      EU(K)=ABS(Q(K))*EUR+1.E-20
 3    EL(K)=ABS(Q(K))*ELR+1.E-20
      CALL RKAM(T,H,Q,DQ,AUXSUB,NN,0.,EU,EL,HMAX,HMIN,ICNT,TEMPS,NH)
      IF(L .GT. LC) L=0
      CALL PRINT(L)
      IF(T+H .LT. TMAX) GO TO 10
C
```

```
      H=TMAX-T
      ICNT=0
      CALL RKAM(T,H,Q,DQ,AUXSUB,NN,0.,EU,EL,HMAX,HMIN,ICNT,TEMPS,NH)
      CALL PRINT(L)
      GO TO 1
C
C
      END
```

```
      SUBROUTINE AUXSUB
C
      COMMON/NAME1/EU(6),EL(6),TEMPS(9,6),Q(6),DQ(6),H,T
      COMMON/NAMES/TV0,XN,AV,AV0,VME,VM0,   XKL,F(3),XL,D,PM
     1 ,DP,VMF,PSS
     2 ,XNRE,DRP
     3 ,NN
     4 ,W(3),RO,XLF
     5, COE,PVV,PV,PVI,GAM
      COMMON/NAMEC/CRE,C1,C2,C3,C4,C5
C
C
      CT=AMAX1( .005 ,AMIN1(1.,(T/TV0)**XN))
      AV=AV0*CT
      VMF=Q(3)-Q(4)
      VME=VM0-VMF
      PVV=COE * PM * VMF * VM0**GAM / VME**(GAM+1.0)
      PVV=AMAX1(PVV,PV)                                                 ******
      CALL GAS(VM0,GAM,VME,VMF,DQ(5),Q(5) ,PVV,Q(6),DQ(6),Q)
      CALL FSUB(Q(1),CRE,XNRE,F(1) )
C
      DQ(1)=C1*(DP-(XKL+F(1)*XLF/D)*C2*Q(1)**2-C3*Q(1)**2/AV**2
     1  -PVV )
      IF (VMF .LE. .7 *VM0) GO TO 10
      DQ(2)=C4*VMF*(-C5*Q(2)**2
     1  +PVV-PVI )
      GO TO 11
 10   DQ(2)=0.
 11   CONTINUE
      DQ(3)=Q(1)
      DQ(4)=Q(2)
C
      RETURN
      END
```

```
      SUBROUTINE GAS(VM0,GAM,VME,VMF,WDOT,WGOUT,PVV,PMAN,DPVV,Q)
      COMMON/MARKET/ TEMPO,XMOWT,PAMB,A0
      COMMON/CHECK/TM,XM
      DIMENSION Q(1)
      NAMELIST/BUG/PVV,WGLEFT,WO,WGOUT,VSP,TM,PRAT,XM,WDOT,DPVV,Q,VME
      DATA IST/0/
      IF(PAMB.EQ. 0.0)RETURN
      IF(IST .EQ. 1)GO TO 100
      IST=1
      PMAN=PAMB
      R=1545./XMOWT
      WO= VM0*PAMB/R/TEMPO
      CON1= VM0/WO
      CON2=  CON1**GAM
      CON3=  CON2/CON1
      CON4= GAM*PAMB*CON2
      CON5= A0*SQRT( 32.174*GAM/R )
      XPON= (GAM+1.0)/2.0/(GAM-1.0)
      GM102= (GAM-1.0)*0.5
100   CONTINUE
      PVV=PMAN
      WGLEFT=WO-WGOUT
      VSP=VME/WGLEFT
      TM=PVV*VSP/R
      PRAT=(PVV/PAMB)**( (GAM-1.0)/GAM)
      PRAT=AMAX1(PRAT,1.0)
      XM=  SQRT(  2.0*( PRAT-1.0)/(GAM-1.0) )
      IF( XM .GT. 1.0) XM=1.0
      WDOT= CON5*PVV*XM/SQRT(TM)/( 1.0+ GM102*XM**2)**XPON
      DPVV=PVV*GAM*( Q(1)-Q(2)-WDOT*VME/WGLEFT)/VME
      WRITE(6,BUG)
      RETURN
      END
```

```
      SUBROUTINE FSUB(Q,CRE,XNRE,F)
C
C
      RE=CRE*Q
      IF(RE.LT.1187.0)      F = 64.0 / RE
      IF(RE.GE.1187.0)      F = 0.3164 / (RE**XNRE)
      IF(RE.LT.1.0)         F = 64.0
C
      RETURN
      END
```

```
      SUBROUTINE PRINT(L)
C
      COMMON/NAME1/EU(6),EL(6),TEMPS(9,6),Q(6),DQ(6),H,T
      COMMON/NAMES/TV0,XN,AV,AV0,VME,VM0,  XKL,F(3),XL,D,PM
     1 ,DP,VMF,PSS
     2 ,XNRE,DRP
     3 ,NN
     4 ,W(3),RO,XLF
     5, COE,PVV,PV,PVI,GAM
      COMMON/NAMEC/CRE,C1,C2,C3,C4,C5
      COMMON/CHECK/TM,XM
C
C
      IF(L .NE. 0) GO TO 1
C
      PNEXT=T-4.*DRP
      WRITE(6,900)
 900  FORMAT(1H1,40X,23HTRANSIENT FLOW ANALYSIS,//
     1 ,*      T                    W1                    Q1                    DQ1
     2       IQ1                 VMF                   PVV                   WG OUT*/
     3 ,*      H                    W2                    Q2                    DQ2
     4       IQ2                 VME                   AV                    WG DOT*/)
 1    CONTINUE
      IF(T .LT. PNEXT) RETURN
      PNEXT=PNEXT+DRP
      L=L+1
      DO 2 I=1,2
 2    W(I)=Q(I)*RO
      PVVI=PVV/144.
C
      WRITE(6,90) T,W(1),Q(1),DQ(1),G(3),VMF,PVVI,Q(5)
      WRITE(6,91) H,W(2),Q(2),DQ(2),G(4),VME,AV,DQ(5)
      WRITE(6,903)TM,XM
 903  FORMAT(1X,2E15.9)
 90   FORMAT(/,F15.9,7E16.6)
 91   FORMAT(F15.9,7E16.6)
C
      RETURN
      END
```

APPENDIX D

CHAMBER PRESSURIZATION TRANSIENT PROGRAM

```
                  PROGRAM PRESS(INPUT,OUTPUT,PUNCH,TAPE5=INPUT,TAPE6=OUTPUT,
                 1               TAPE7=PUNCH)
            C
            C        TRANSIENT PRESSURE HISTORY PROGRAM
            C
000003            COMMON/CPLT/ IFPLOT, PLTIME, IPLT1, TMAX
            C
            C
000003            LOGICAL AVERGE, IDEBUG
000003            COMMON/DOLOOP/ ND1,ND2,ND3
000003            COMMON /A/        TFP(2),TAU(2),TAUF(2),TAUS(2),XM(2),GAM(2),TC
                 1PG(2),      M(2),GEVAP(2),XI(2),XR(2)     ,                  TO(
000003            COMMON/ABCDEF/ X(400,2), T(400,2), R(400,2), W(400,2)
000003            COMMON/COM1/AX(5,10),COEF(5,10),ENTHPY(10),FORO(10),SPNAME(1(
000003            COMMON/COM2/ICASE,IUNIT,F(2),HFLIQ(2),MSPEC,PGTOTAL,PROD(10),
                 1               TFINAL,WDROP(2),WTOTAL(2),IFIRST
000003            COMMON/OUTA/ PG1(2),PGP1,REACT(2),TAVERG,DELTRE,TIME,TQP
000003            COMMON/OUTB/ NPAGE
            C
000003            DIMENSION TDETON(40)
000003            DIMENSION ROL(2),CPL(2)
000003            DIMENSION PTANK(2),PCPV(2),PVV(2),CONST7(2),YREACT(10,2)
000003            DIMENSION TTABLE(10),A(12,10,2),EACTT(10),YK(20,2),PCT(20,2),
                 1PTAN(20,2),TP(20,2),AAT(10)
000003            DIMENSION PV(10), TD(10),TAG(2),PVW(2),PVF(4),TDK(4)
000003            DIMENSION W1(20,2),T1(20,2)
000003            DIMENSION TA(4),CPLA(4),G(2),GCOND(2),XMNOZ(2),TQ(2)
000003            DIMENSION XMMM(2),RR2(2)
000003            DIMENSION ROP(2)
000003            DIMENSION VDROP(2),XMU(2),CPG(2),XK(2),HC(3,2), RE(2
                 1  ), PR(2),H(2),Z(2),QBIG(2),PHE(2),GAN(2),CVG(2),EPCOE(2)
000003            DIMENSION RON(10,2),CPN(10,2),CPGN(10,2),PVN(10,2),TRON(10,2)
                 1(10,2),TCPGN(10,2),TPVN(10,2)
000003            DIMENSION TGI(2),RGI(2),WGI(2)
000003            DIMENSION RELWT(10)
000003            DIMENSION NUPPER(2), AVERGE(2), TCRIT(2), RCRIT(2), XCRIT(2)
000003            DIMENSION DELTXS(2), DELRXS(2)
000003            DIMENSION DELTX(2), DELRX(2), DELXX(2)
000003            DIMENSION PGADD(10,2), PGADDT(10,2),PADD(2)
000003            DIMENSION WLIQ(25,2),TLIQ(25,2) ,NLIQ(2),WXXX(2)
            C
000003            NAMELIST /DATA/
                 1 A, AAT, AC, ALPHA, ASTAR,    CFORPR, CPGN, CPGP, CPN, CVG,
                 2 DELTN, DTMAX, DTMIN,    EACTT,    GAM,GAMP,    HC,    M,
                 3 NN, NOCP, NOCPG, NOPV, NORO, NTRAN,
                 4 PCT, PG, PTAN, PVN, PVV, PVW,    RGI, RM, RN, RON,
                 5 TAU, TAUF, TAUS, TCPGN, TCPN, TFP, TGI, TMAX, TP, TPVN, TRON
                 6 TTABLE, TW,
                 7 VC, VDROP,    WGI,    XK, XM, XMP, XMU, XR,
                 8 YK, YREACT
                 * , ICASE, MSPEC, HFLIQ, IUNIT
                 * ,ND1, ND2, ND3,PGP, TFINAL
                 * , IFPLOT, PLTIME
                 * , TDETON
                 * , TCRIT, RCRIT, XCRIT
                 * , PGADD, NPG, PGADDT
                 * , CONCR, TCR, XKBAR, HEATX
```

```
            *  , IDEBUG
            *  , WLIQ , TLIQ,NLIQ
        C
000003    1     CONTINUE
        C
000003          CALL SECOND(EXTIME)
000005          CALL PSECOND(PSEC)
000007          WRITE(6,4444) EXTIME, PSEC
000017    4444 FORMAT(1H0,30X, 9HCP TIME =,F8.3,5X, 9HPP TIME =,F8.3)
        C
000017          IDETON = 1
000020          DO 1886 I = 1,40
000022    1886 TDETON(I) = 1.0E10
        C
        C       ZERO ARRAYS
        C
000026          IDEBUG = .FALSE.
000027          DO 1888 I = 1,5
000030          DO 1888 J = 1,10
000031          COEF(I,J) = 0.0
000034    1888   CONTINUE
000041          DO 2 L=1,2
000042          NUPPER(L) = 0
000043          DELTXS(L) = 1.E30
000045          DELRXS(L) = 1.E30
000046          DO 2 I = 1,400
000050          X(I,L)=0.
000053          T(I,L)=0.
000056        2 R(I,L)=0.
000065          DO 6 I=1,10
000066          PGADDT(I,1) = 0.0
000067          PGADDT(I,2) = 0.0
000070          PGADD(I,1) = 0.0
000071          PGADD(I,2) = 0.0
000072          PROD(I) = 0.0
000073    6     CONTINUE
000075          NPG = 0
000076          ND1 = 1
000077          ND2 = 100000
000100          ND3 = 2
000101          PGP=0.
000102          TFINAL=1.
000104          NLIQ(1) = 1
000105          NLIQ(2) = 1
        C
000106          IFPLOT = 0
000107          PLTIME= 30.0
000110          IPLT1 = -1
000111          READ(5,DATA)
000114          WRITE(6,DATA)
        C
        C       READ SPECIES INFO IN FORM OF ODE INPUT
        C
000117          DO 150 I = 1,MSPEC
000121          READ(5,190)(AX(J,I),COEF(J,I),J=1,5), ENTHPY(I),FORO(I),SPNAME(
000145          WRITE(6,191)(AX(J,I),COEF(J,I),J=1,5), ENTHPY(I),FORO(I),SPNAME
000172    190   FORMAT(5(A2,F7.5),8X,F9.0,9X,A1,2X,A6)
000172    191   FORMAT(1H0,5(A2,F7.5),8X,F9.0,9X,A1,2X,A6)
```

```
000172     150  CONTINUE
000175          DO 24 N=1,2
000176          DO 24 I=1,NOPV
000177       24 PVN(I,N)=ALOG10(PVN(I,N))
000212          NSAVE1=1
000213          NSAVE2=2
000214          NSAVE3=3
000215          NSAVE4=4
000216          IWSAVE = 1
          C
          C           COMPUTE INITIAL CONDITIONS
          C
000217          RC = 1545.0
000220          NSTOP=520
000221          NPAGE=1
000222          DO 10 I = 1,2
000224          T(1,I) = TGI(I)
000227          TG(I) = TGI(I)
000231          R(1,I) = RGI(I)
000234          W(1,I) = WGI(I)
000237          TAG(1) = 0.0
000240          REACT(I) = 0.0
000241          GCOND(I) = 0.0
000242          WTOTAL(I) = 0.0
000243          WDROP(I) = 0.0
000244          XMNOZ(I) = 0.0
000245          RR2(I) = R(1,I)**3
000250      10  CONTINUE
000252          IF(XM(1) .GT. 0.) XMMM(1)=SQRT(XM(1))
000256          IF(XM(2) .GT. 0.) XMMM(2)=SQRT(XM(2))
000262          GEVAP1=0.
000263          GEVAP2=0.
000264          DT1000=1000.*DELTN
000266          RPN=0.
000267          XMNOZP=0.
000270          TRUE=0.
000271          INDICA = 0
000272           GCONDP=0.
000273          TGP=TG(1)
000274          TQP=TGP
000275          PGTOTAL=0.
000276          DENOMP=0.
000277          PGTOTL=0.
000300          IFIRST=0
000301              CONST1= 4.*ALPHA*       3.1415/SQRT(6.2831853*RC/32.2)
000311              CONST2= 3.*ALPHA/       SQRT(6.2831853*RC/32.2)
000320              CONST3= CONST2*AC/3.
000322              CONST4 = ASTAR*SQRT(32.2/1545.)
000326          CONST5=SQRT((32.2*XMP/RC)*(2./(GAMP+1.))**((GAMP+1.)/(GAMP-1.
               1        ASTAR
          C
000345          TIME1=DELTN
000346          TIME=DELTN*1000.
000350          N22=NOW-1
000352              NSTOP = NSTOP+1
          C
          C           SELECT THE CORRECT PROBLEM
          C
```

```
              NPP = 0
              NPF = 0
              IF(M(1).EQ.0) NPF = 2
              IF(M(2).EQ.0) NPF = 1
              IF(NPF .EQ. 0) NPF=3
              IF(M(1).EQ.M(2)) NPF =4
              IF((M(1).LE.M(2)).AND.(M(1).GE.1))      N=1
              IF((M(2).LE.M(1)).AND.(M(2).GE.1))      N=2
           IF(NPF.LT.3) N=NPF
C
C             THE TIME LOOP
C
          L=0
       25 L=L+1
          GEVAP2=GEVAP1
          QBIG(1)=0.
          QBIG(2)=0.
          TAG(N)=0.
                GEVAP(1) =0.
                GEVAP(2) =0.
                   X1(1) =0.
                   X1(2) =0.
          LX=L
           IF(NPF.NE.4) GO TO 205
       50 N=1
          TAG(N)=0.
           LX=L-M(1)+1
          IF((LX.GE.1).AND.(M(1).GT.0)) GO TO 205
      100 N=2
          TAG(N)=0.
          LX=L-M(2)+1
          IF((LX.GE.1).AND.(M(2).GT.0)) GO TO 205
          GO TO 800
      205 BB=XMMM(N)
          AVERGE(N) = .FALSE.
          NUP = LX - NUPPER(N)
          IF(NUP.GT.399) GO TO 999
          DO 700 NNN = 1,NUP
          CC = W(NNN,N)
          J = NUP - NNN + 1
          TT=T(J,N)
          RR=R(J,N)
          XX=X(J,N)
          CALL LINI(TRON(1,N),RON(1,N),NORO,TT,ROL(N),NSAVE1)
          CALL LINI(TCPN(1,N),CPN(1,N),NOCP,TT,CPL(N),NSAVE2)
          CALL LINI(TCPGN(1,N),CPGN(1,N),  NOCPG,TT,CPG(N),NSAVE3)
          CALL LINI(TPVN(1,N),PVN(1,N),NOPV,TT,PP,NSAVE4)
          PP=10.**PP
      310 CONTINUE
          IF(XX .GE. 1.) GO TO 312
          G(N)= ((PP-PG(N))*RR**2/SQRT(TT))*CONST1*BB*DELTN
            IF(G(N).LT.0.) G(N)=0.
           GO TO 316
      312 G(N)=0.
      316 TOG=(G(N)*CC*XR(N)/(ROL(N)*RR2(N)))*.2387
           GEVAP(N) = GEVAP(N)+ TOG
          TAG(N)=TAG(N)+TOG*TT
          IF(IDEBUG) WRITE(6,6400) NNN,LX,J,N, TT,RR,XX,PP,
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0

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               1  G(N),TOG,GEVAP(N),TAG(N),CC
000651       6400 FORMAT(1H0,* NNN,LX,J,N*,4I10/ * TT,RR,XX,PP*,4E20.8/
               1   * G(N),TOG,GEVAP(N),TAG(N) * , 4E16.8,* CC *,E15.7)
000651            IF(XX .GE. 1.) X(J+1,N)=1.
000660            IF(PP .LE. PG(N)) GO TO 315
000663            IF(XX .GE. 1.) GO TO 315
000665            XTEMPX=    (1.-BB*(PP-PG(N))*DELTN*CONST2/(ROL(N)*SQRT(TT)  *RR)
000701            IF(XTEMPX.LE.0.0) GO TO 315
000702            R(J+1,N) =RR* XTEMPX**0.3333
000711            GO TO 320
000711        315 R(J+1,N)=RR
000715        320 RE(N)=2.*RR*VDROP(N)*XM(N)*PG(N)/(XMU(N)*RC*TG(N))
000725            PR(N)= CPG(N)*XMU(N)/XK(N)
000731            PRO = PR(N)**.33333
000734            REO = RE(N)**.5
000740             H(N) = XK(N)*(2.+.6*PRO*REO)/(2.*RR)
000750            Z(N) = G(N)*CPG(N)/(12.566*H(N)*DELTN*RR**2)
000756            IF(Z(N) .GT. 30.) Z(N)=30.
000762            IF(Z(N) .LT. 1.E-10) GO TO 325
000765            Z(N) = Z(N)/(2.71828**Z(N)-1.)
000772            GO TO 326
000773        325 Z(N)=1.
000775        326 PHE(N)=3.*H(N)*(TG(N)-TT)*RR**2               *Z(N)*DELTN/(ROL(N
               1CPL(N)*RR**3)
001010            QBIG(N)=QBIG(N)+3.*H(N)*RR**2       *Z(N)*DELTN*(TG(N)-TT)*
               1XR(N)*CC       /(RR2(N)*ROL(N))
001025            IF(XX .GE. 1.) GO TO 360
001030            IF(PP .GT. PG(N)) GO TO 340
001034            T(J+1,N)=TT
001037            IF(T(J+1,N) .LE. TFP(N)) GO TO 350
001044            GO TO 370
001044        340 T(J+1,N)=  TT       -CONST2*DELTN*TAU(N)*(PP-PG(N))/(ROL(N)
               1*CPL(N)*RR       *SQRT(TT) )       *BB+PHE(N)
001066            IF(T(J+1,N) .LT. TFP(N)) T(J+1,N)=TFP(N)
001077            IF(T(J+1,N) .GT. TFP(N)) GO TO 370
001105        350 X(J+1,N)=XX            + (G(N)*TAUS(N)/(ROL(N)*      RR**3*TAUF(
               1*.2387-CPL(N)*PHE(N)/TAU(N)
001122             GO TO 370
001122        360 T(J+1,N)=TFP(N)
001126        370                            CONTINUE
001126        700      CONTINUE
           C
           C      COMPUTE DIFFERENCE TERMS BETWEEN DROPS WITH LONGEST RESIDENCE
           C
001131            DELTX(N)= ABS(T(NUP+1,N)-T(NUP,N)) /(T(NUP,N)+1.0E-35)
001142            DELRX(N)= ABS(R(NUP+1,N)-R(NUP,N)) /(R(NUP,N)+1.0E-35)
001152            DELXX(N)= ABS(X(NUP+1,N)-X(NUP,N)) /(X(NUP,N)+1.0E-35)
001162            IF(IDEBUG) WRITE(6,6405)N,NUPPER(N),DELTX(N),DELRX(N)
001177       6405 FORMAT(1H , *N,NUPPER(N),DELTX(N),DELRX(N) *,2I5,2E20.8)
001177            IF(L.LE.2) GO TO 7000
001202            IF(ABS(DELTXS-DELTX).GT.1.0E-12)  GO TO 6990
001207            IF(ABS(DELRXS-DELRX).GT.1.0E-12)  GO TO 6990
           C
           C      AUTOMATIC AVERAGING
           C
001214            GO TO 6995
001214       6990 CONTINUE
001214            IF(DELTX(N).GT.TCRIT(N)) GO TO 7000
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001220        IF(DELRX(N).GT.RCRIT(N))  GO TO 7000
001223        IF(DELXX(N).GT.XCRIT(N))  GO TO 7000
001226   6995 CONTINUE
001226        AVERGE(N)  =  .TRUE.
001230        T(NUP,N)  =  (T(NUP+1,N)  +  T(NUP,N))  /  2.0
001236        R(NUP,N)  =  (R(NUP+1,N)  +  R(NUP,N))  /  2.0
001243        X(NUP,N)  =  (X(NUP+1,N)  +  X(NUP,N))  /  2.0
001247   7000 CONTINUE
001247        DELTXS(N)  =  DELTX(N)
001251        DELRXS(N)  =  DELRX(N)
001253        PPG=PG(N)
001254        IF(NPF .EQ. 4)  PPG=PGTOTL
001260        DO 2500 K1=1,NTRAN
001262        IF(PPG .GE. PCT(K1,N) .AND. PPG .LE. PCT(K1+1,N))  GO TO 2507
001276        K1=K1
001277   2500 CONTINUE
001301   2507 CONST7(N)=(YK(K1+1,N)-YK(K1,N))*(PCT(K1+1,N)-PPG)/(PCT(K1,N)
             1-PCT(K1+1,N))+YK(K1+1,N)
001321        DO 2600 K=1,NTRAN
001322        IF(TIME1.GE. TP(K,N)  .AND. TIME1.LE. TP(K+1,N))  GO TO 2607
001336        K=K
001337   2600 CONTINUE
001341   2607 PTANK(N)=(PTAN(K+1,N)-PTAN(K,N))*(TP(K+1,N)-TIME1)/(TP(K,N)
             1-TP(K+1,N))+PTAN(K+1,N)
001361        PCPV(N)= PG(N)
001362        IF(PG(N)  .LE.  PVV(N))  PCPV(N)=PVV(N)
001367            IF(NPF.EQ.1)  GO TO 800
001371            IF(NPF.EQ.2)  GO TO 800
001373            IF(NPF.EQ.3)  GO TO 710
001374           IF((NPF.EQ.4).AND.(N.EQ.2))  GO TO 800
001402            IF((NPF.EQ.4).AND.(N.EQ.1))  GO TO 100
001411    710     IF(N.EQ.1)  MPF=2
001414            IF(N.EQ.2)  MPF=1
001417            IF(M(MPF).EQ.L)  NPF=4
001423            IF(NPF.NE.4)  GO TO 800
001425        IF(MPF.EQ.2)  GO TO 100
001427        IF(MPF.EQ.1)  GO TO 50
001430    800     CONTINUE
       C
001430            IF(NPF.EQ.4)  N=1
001433    810  GCOND(N)=((PG(N)-PVW(N))*CONST3*DELTN/SQRT(TG(N)))*BB
001444         IF(GCOND(N).LT.0.)  GCOND(N)=0.
001447        LX  =  L  -  M(N)  +  1  -  NUPPER(N)
001453        WTOTAL(N)=WTOTAL(N)+W(LX,N)-XMNOZ(N)-REACT(N)
001461        TO(N)=WTOTAL(N)
001463        WDROP(N)=W(LX,N)   -GCOND(N)-GEVAP(N)+WDROP(N)
001471        F(N)=WDROP(N)/WTOTAL(N)
001473         XMNOZ(N)  =  (PG(N)/SQRT(TG(N)))*CONST4*BB*SQRT(GAM(N)*(2./(GAM
             11.))**((GAM(N)+1.)/(GAM(N)-1.)))
001521        XMNOZ(N)=XMNOZ(N)*DELTN
       C      IF THE COMPUTED VALYE OF MASS OUT NOZZLE IS GREATER THAN
       C      THE MASS OF GASS PRESENT, ADJUST XMNOZ
001522        QUALX  =  PG(N)  *  VC  /  (RC  *  TG(N))
001526        IF(IDEBUG)WRITE(6,9513)  QUALX,XMNOZ(N),N
001541   9513 FORMAT(1H ,*   QUALX,XMNOZ(N),N    *,2E16.5,I5)
001541        IF(XMNOZ.GE.QUALX)  XMNOZ  =  QUALX
001545        DENOM=GEVAP(N)+VC*XM(N)*PG(N)/(RC*TG(N))-GCOND(N)-XMNOZ(N)
001557        X1(N)=DENOM
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001561          C1=0.
001561          C2=0.
001562          IF(PG(N) .LT. 144.) GO TO 4
001565          IF(TW.GT.TG(N)) GO TO 3
001570          C2=HC(2,N)*AC*(TG(N)-TW)*DELTN/CPG(N)
001575          C1=0.
001576          GO TO 4
001576        3 C1=HC(1,N)*AC*(TW-TG(N))*DELTN/CPG(N)
001605          C2=0.
001606        4 TQ(N)=(TAG(N)+VC*XM(N)*PG(N)/RC-(GCOND(N)+XMNOZ(N))*TG(N)+C1-(
               1DENOM
        C
001623          PG(N)=GEVAP(N)*RC*TQ(N)/(VC*XM(N))-RC*TQ(N)*GCOND(N)/(VC*XM(N)
               1-RC*TQ(N)*XMNOZ(N)/(VC*XM(N))+PG(N)*TQ(N)/TG(N)
001641          IF(NPG.EQ.0) GO TO 7850
001642          CALL LINI (PGADDT(1,N),PGADD(1,N),NPG,TIME1,PADD(N),ISAVE)
001651          PG(N) = PG(N) + PADD(N)
001654     7850 CONTINUE
001654           PG1(N)=PG(N)/144.
        C       COMPUTE LIQUID WEIGH T FLOW FROM INPUT TABLES
001657          CALL LINI(TLIQ(1,N),WLIQ(1,N),NLIQ(N),TIME1,WXXX(N),IWSAVE)
001666          IF(IDEBUG)WRITE(6,4487)N,IWSAVE,TIME1,WXXX(N)
001703     4487 FORMAT(1H0,* N,IWSAVE,TIME1,WXXX(N)   *,2I5,2E20.8)
001703          W(LX+1,N) = WXXX(N)
001707          IF(.NOT.AVERGE(N)) GO TO 6710
        C
        C       AVERAGE W FOR GROUPS WITH LONGEST RESIDENCE TIME I.E. 1 AND 2
        C
001711          NUPPER(N) = NUPPER(N) + 1
001713          W(1,N) = W(1,N) + W(2,N)
001717          IF(LX.LT.2)  GO TO 6701
001721          DO 6700 J = 2,LX
001723          W(J,N) = W(J+1,N)
001732     6700 CONTINUE
001735     6701 CONTINUE
001735     6710 CONTINUE
        C
001735                IF(NPF.NE.4) GO TO 820
001737          IF((NPF.EQ.4) .AND. (N.EQ.2)) GO TO 1100
001746                N=2
001747                GO TO 810
001747      815 PGTOTL=PG1(1)+PG1(2)
001751               GO TO 825
001752      820 PGTOTL=PG(N)
001754      825 IF(NPAGE .EQ. 1) WRITE(6,2000)
001762          IF(NPF .EQ. 4) GO TO 900
001764          IF(N .EQ. 1) GO TO 920
001766          WRITE(6,2030) TIME,PG1(2),GEVAP(2),GCOND(2),TG(2),WTOTAL(2),F(
002010          NPAGE=NPAGE+1
002012          IF(NPAGE.GE.60) NPAGE=1
002015          GO TO 990
002016      920 WRITE(6,2030) TIME,PG1(1),GEVAP(1),GCOND(1),TG(1),WTOTAL(1),F(
002040          NPAGE=NPAGE+1
002042          IF(NPAGE.GE.60) NPAGE=1
002045          GO TO 990
002046      900 WRITE(6,2030)  TIME,PG1(1),PG1(2),GEVAP(1),GEVAP(2),GCOND(1),G
               1(2),TG(1),TG(2)
002074          NPAGE=NPAGE+1
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002076          IF(NPAGE.GE.60) NPAGE=1
002101      990 CONTINUE
002101     2000 FORMAT(1H1,4X,4HTIME,9X,2HPG,12X,5HGEVAP,9X,5HGCOND,9X,2HTG,12X
              2WTOTAL,8X,2HF )
              1P(2),5X,8HGCOND(1),5X,8HGCOND(2),5X,5HTG(1),8X,5HTG(2))
002101     2010 FORMAT(1H ,E13.4,13X,E13.4,13X,E13.4,13X,E13.4,13X,E13.4)
002101     2020 FORMAT(1H ,E13.4,E13.4,13X,E13.4,13X,E13.4,13X,E13.4,E13.4)
002101     2030 FORMAT(1H ,9E13.4)
002101     3000   CONTINUE
002101          TG(N)=TQ(N)
002103          LLLLLL=L+1
002105          IF((NPF .EQ. 3) .AND. (M(MPF) .EQ. LLLLLL)) NPF=4
002116           GO TO 1150
002117     1100 CONTINUE
          C
          C     COMPUTE TFINAL ON FIRST TIME STEP
          C
002117          IF(L.NE.1) GO TO 425
          C
002121          TOP1= PG(1)*XM(1)*CPG(1)
002124          TOP2= PG(2)*XM(2)*CPG(2)
002126          BOT1= TOP1 * TQ(2)
002130          BOT2= TOP2 * TQ(1)
          C
002132          TFINAL = TQ(1)*TQ(2) * ( (TOP1+TOP2) / (BOT1+BOT2) )
002136          WRITE(6,424) TFINAL
002144      424 FORMAT(1H0,* COMPUTED TFINAL ON FIRST STEP = *,E20.8)
002144      425 CONTINUE
          C
          C
002144          TAVERG=(PG(1)*XM(1)*CPG(1)+PG(2)*XM(2)*CPG(2)+PGP*XMP*CPGP)/(PG
              1*XM(1)*CPG(1)/TQ(1)+PG(2)*XM(2)*CPG(2)/TQ(2)+PGP*XMP*CPGP/TFINA
              2-(QBIG(1)+QBIG(2))/(XI(1)*CPG(1)+XI(2)*CPG(2)+DENOMP*CPGP)
          C
          C
          C
002202          CON=PG(1)*VC/(RC*TQ(1))
002206          CFN=PG(2)*VC/(RC*TQ(2))
002210          IF(L.LT.3) GO TO 9270
          C
          C     UNDER CERTAIN TEMP AND OX CONC CONDITIONS HAVE DIFFUSION AND A
          C     SURFACE REACTION
          C
          C     COMPUTE TOTAL VAPOR MASS TO DETERMINE MASS FRACTION OF OX
002213          VAPMAS = CON + CFN
002215          DO 8270 I = 3,8
002216     8270 VAPMAS = VAPMAS + PROD(I)
002222          OXMF = CON / VAPMAS
002224          IF(OXMF.LT.CONCR) GO TO 9270
          C
002226          FOURPI = 4.0*3.14159
          C     COMPUTE DENSITY OF OXIDIZER VAPOR
002230          ROGAS = PG(1) / (RC * TAVERG)
002233          WOXDIF = 0.0
          C
          C     MUST CONSIDER DIFFUSION ONLY FOR FUEL DROPLETS BELOW T CRITICAL
          C
002234          NUPX = L - M(2) + 1 - NUPPER(2)
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002237          DO 9255 MXZ = 1,NUPX
002241          MXY = NUPX - MXZ + 1
002243          IF(T(MXY,2).GE.TCR) GO TO 9255
          C
          C     MUST CONSIDER DIFFUSION AND SURFACE REACTION
          C     CALCULATE DIFFUSION COEF  (UNITS  FT2/SEC)(FROM T-DEGK, P-ATM
          C
002246          TUSE = T(MXY,2) / 1.8
002250          PUSE = PGTOTL / 14.696
          C
002252          DIFX = 2.5E-8 * TUSE**1.5 / PUSE
          C
          C     CALCULATE VAPOR DIFFUSED, OVER ALL DROPLETS
          C
002260          CONST = ROGAS * DIFX * OXMF * DELTN
002263          TEMPX = FOURPI * R(MXY,2) * W(MXZ,2)
          C
002266          WRITE(6,9246) MXY,MXZ,R(MXY,2),W(MXZ,2),TEMPX
002304     9246 FORMAT(1H0, * MXY,MXZ,R(MXY,2),W(MXZ,2),TEMPX *,2I5,3E18.6)
002304          WOXD = TEMPX * CONST
002306          WOXDIF = WOXDIF + WOXD
          C
          C     ADJUST HEAT BALANCE FOR THE DROPLET TO REFLECT SURFACE REACTI
          C
002310          DTX = HEATX * WOXD / CPL
002312          T(MXY,2) = T(MXY,2) + DTX
          C     MAY ALSO HAVE TO ADJUST RADIUS
          C
          C     ADJUST MASS
          C
002314          W(MXZ,1) = W(MXZ,1) - WOXD
002317          AMTFL = WOXD * (32./92.) * 2.0
002322          W(MXZ,2) = W(MXZ,2) - AMTFL
002324     9255 CONTINUE
          C
          C     ADJUST TOTAL MASS
          C
002327          WTOTAL(1) = WTOTAL(1) - WOXDIF
002331          WTOTAL(2) = WTOTAL(2) - 2.0 * (32./92.) * WOXDIF
          C
          C     ADJUST LIQUID DROPLET MASS TO REFLECT SURFACE REACTION
          C
002335          WDROP(2) = WDROP(2) - 2.0 * (32./92.) * WOXDIF
          C
          C     DISTRIBUTE PRODUCTS (N2O,NH3,N2H5NO3)
          C
002342          PROD(4) = PROD(4) + WOXDIF * (44./92.)
002346          PROD(6) = PROD(6) + WOXDIF * (17./92.)
002351          PROD(9) = PROD(9) + WOXDIF* (95./92.)
002354     9270 CONTINUE
002354          DO 1105 K=1,NN
002356          IF(TAVERG .GE. TTABLE(K) .AND. TAVERG .LE. TTABLE(K+1)) GO TO
002367          K=K
002370     1105 CONTINUE
002372     1107 AA=AAT(K)
002374          EACT=EACTT(K)
002376          K3=1
002377          IF(CON/CFN .GT. CFORPR) K3=2
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```
002403          HREACT=YREACT(K,K3)
002407          REACT(1)=VC*AA*XM(1)*(CON/VC)**RN*(CFN/VC)**RM*2.71828**(-EACT/
               1(RC*TAVERG))*DELTN
002433          RPN=0.
002434          C1=0.
002435          C2=0.
002436          IF(REACT(1) .GT. CON*XM(1)) REACT(1)=CON*XM(1)
002442          REACT(2)=A(2,K,K3)*REACT(1)/A(1,K,K3)
002454          IF(REACT(2) .LT. CFN*XM(2)) GO TO 1110
002457          REACT(2)=CFN*XM(2)
002460          REACT(1)=A(1,K,K3)*REACT(2)/A(2,K,K3)
002465     1110 DO 1120 I=1,10
002467          DPRN=REACT(1)*A(I+2,K,K3)/A(1,K,K3)
002500          IF(I .GT. 8) GO TO 1120
002504          RPN=RPN+DPRN
002506     1120 PROD(I)=PROD(I)+DPRN
002513          DENOMR=(X1(1)-REACT(1))*CPG(1)+(X1(2)-REACT(2))*CPG(2)+DENOMP*C
002523          DELTRE=REACT(1)*HREACT/DENOMR
002525          TFINAL=TAVERG+DELTRE
002527          DO 1130 NX=1,2
002531          PG(NX)=PG(NX)*TFINAL/TQ(NX)
002534          PG(NX)=PG(NX)-REACT(NX)*RC*TFINAL/(XM(NX)*VC)
002543          IF(PG(NX) .LT. 0.) PG(NX)=0.
002546          PG1(NX)=PG(NX)/144.
002551     1130 CONTINUE
002553          PGP=TFINAL*(RPN*RC/(VC*XMP)-RC*XMNOZP/(VC*XMP)+PGP/TGP)
002562          XMNOZP=(PGP*ASTAR*DELTN/SQRT(TFINAL))*CONST5*DELTN
002571          DENOMP = RPN+VC*XMP*PGP/(RC*TGP)-XMNOZP
002600          IF(PGP .LT. 144.) GO TO 1140
002602          IF(TW.GT.TGP) GO TO 1135
002605          C1=0.
002605          C2=HC(3,2)*AC*(TGP-TW)*DELTN/CPGP
002612          GO TO 1140
002612     1135 C2=0.
002613          C1=HC(3,1)*AC*(TW-TGP)*DELTN/CPGP
002621     1140 TGP = (RPN*TGP+VC*XMP*PGP/RC    -XMNOZP*TGP-C2+C1)/DENOMP
002634          TG(1)=TFINAL
002635          TG(2)=TFINAL
002636          TGP    =TFINAL
002637          PGP1=PGP/144.
002641          PGTOTAL=PGP1+PG1(1)+PG1(2)
002644          PGTOTL=PG(1)+PG(2)+PGP
002646          IF(L.GE.ND1.AND.L.LE.ND2.AND.MOD(L-ND1,ND3).EQ.0) CALL OUT1
          C
002666          IF(IFPLOT.NE.0) CALL PLTSUB(TIME,TFINAL)
          C
          C
          C     TEST FOR PUNCH DATA FOR DETONATION CALC
          C
002671          IF(TIME.LT.TDETON(IDETON)) GO TO 4341
002674          CALL OUTX
002675          IF(IDETON.LT.40) IDETON = IDETON + 1
002701     4341 CONTINUE
          C
002701     1150 CONTINUE
002701          TIME=TIME+DT1000
002703          TIME1=TIME1+DELTN
002705     1000   CONTINUE
```

```
002705          DELTN=(TIME+.1)/1.E+5
002710          IF(IDEBUG) WRITE(6,3794) DELTN
002717     3794 FORMAT(1H0,*NEW TIME STEP IS*,E20.8)
002717          IF(PGTOTAL .GE.100.) GO TO 1
002722          IF(TIMEI .GE. TMAX) GO TO 1
002724          IF( L .GE. NSTOP) GO TO 1
002727          DT1000=DELTN*1000.
002731          GO TO 25
002731     999  CONTINUE
002731          WRITE(6,9999)
002735     9999 FORMAT(1H0, * VARIABLE DIMENSIONS EXCEEDED *)
002735          GO TO 1
002736          END
        *DECK,DSCPLT
```

```
              SUBROUTINE DSCPLT(X,Y,XLABEL,YLABEL,PLABEL,N,KX,KY,KP,IFIRST
             1 ,SCALEP,XUNITS,YUNITS,SYMHIT,ILINE,ISYMBL)
        C
000023        DIMENSION X(1),Y(1),PLABEL(1)
000023        DIMENSION XLABEL(1),YLABEL(1)
        C
000023        NN = N
000023        IF(IFIRST.EQ.1) CALL PLOTS ( 9HDSC PLOTS,9)
        C
000034        CALL MAXMIN(X,Y,NN,XMIN,YMIN,XMAX,YMAX)
        C
000042        CALL SCAL (XMAX,XMIN,XUNITS,XSCALE,XADJM,XEFF)
000047        CALL SCAL (YMAX,YMIN,YUNITS,YSCALE,YADJM,XEFF)
        C
000054        IF(YMIN.NE.YMAX) GO TO 5
000062        YADJM = YMIN * 0.5
000063        YSCALE = 2.0 * YMAX / YUNITS
000066   5    CONTINUE
        C
000066        Y(NN+1) = YADJM
000070        X(NN+1) = XADJM
        C
000072        Y(NN+2) = YSCALE
000073        X(NN+2) = XSCALE
        C
000075        ICARX = 10 * KX
000077        ICARY = 10 * KY
        C
000102        CALL AXIS(0.0,0.0,XLABEL,-ICARX,XUNITS,0.0,XADJM,XSCALE)
000113        CALL AXIS (0.0,0.0,YLABEL,+ICARY,YUNITS,90.,YADJM,YSCALE)
        C
000130        CALL LINE(X,Y,NN,1,ILINE,ISYMBL)
        C
000137        ILAB = 10*KP
        C
000142        CALL SYMBOL(0.0,YUNITS,SYMHIT,PLABEL(1),0.0,ILAB)
        C
000153        XNEXT = XUNITS + XUNITS*0.5
        C
000156        CALL PLOT(XNEXT,0.0,-3)
        C
000161        RETURN
000162        END
        *DECK,LINI
```

```
              SUBROUTINE LINI(X,Y,N,ARG,YARG,NSAVE)
        C
        C          LINEAR INTERPOLATION ROUTINE
        C
000011        DIMENSION X(1),    Y(1)
000011        NN=N
000011        XV=ARG
000012        IF (XV.GE.X(NN))GO TO 40
000016        IF(XV.LE.X(1))GO TO 50
        C
000020        J= NSAVE
000021        IF(J .LT. 1 .OR. J .GT. NN) J=1
000033        K= SIGN(1.0,(XV-X(J)))
000041      5    J=J+K
000043        IF( (XV-X(J) )* FLOAT(K) ) 10,30,5
000047     10 IF(K.EQ.-1)J=J+1
000053        I=J-1
        C
        C               INTERPOLATION CALC
        C
000055        H=X(J)-X(I)
000060        DX=XV-X(I)
000063        DY=Y(J)-Y(I)
000066        YARG= Y(I) +  DX*DY/H
000072        NSAVE=I
000073        RETURN
000073     30 YARG=Y(J)
000075        NSAVE=J
000076        RETURN
000076     40 YARG=Y(NN)
000100        RETURN
000101     50 YARG=Y(1)
000102        RETURN
000103        END
        *DECK,MAXMIN
```

```
                  SUBROUTINE MAXMIN (X,Y,N,XMIN,YMIN,XMAX,YMAX)
            C
000012            DIMENSION X(1),Y(1)
000012            XMIN = X(1)
000013            YMIN = Y(1)
000014            YMAX = Y(1)
000015            XMAX = X(1)
000016            DO 10 I = 2,N
000020            XMIN = AMIN1(XMIN,X(I))
000024            YMIN = AMIN1(YMIN,Y(I))
000030            XMAX = AMAX1(XMAX,X(I))
000034            YMAX = AMAX1(YMAX,Y(I))
000040       10   CONTINUE
000042            RETURN
000042            END
            *DECK,OUTX
```

```
              SUBROUTINE OUTX
        C
000002        COMMON/COM1/A(5,10),COEF(5,10),ENTHPY(10),FORO(10),SPNAME(10)
000002        COMMON/COM2/ICASE,IUNIT,F(2),HFLIQ(2),MSPEC,PGTOTAL,PROD(10),
             1              TFINAL,WDROP(2),WTOTAL(2),IFIRST
000002        DIMENSION RELWT(10),FACTOR(2)
000002        DIMENSION SUMX(2), XCOEF(5,10), AX(5,10)
000002        LOGICAL DETN, PSIA
        C
000002        DATA REACTX,REACTY / 6HREACTA,3HNTS/ , FUELX/1HF/
000002        DATA XNAME,XLISTS/ 4HNAME,5HLISTS/, XEND/4H$END/
000002        DATA XINPT2 /6H$INPT2/ , XPIS,XTIS/2HP=,2HT=/, COMMA /1H,/
000002        DATA XFPCT,XOF,XKASE/5HFPCT=,3HOF=,5HKASE=/, XTRUE/6H.TRUE./
000002        DATA TFPSIA,TFDETN /6HPSIA= ,6HDETN= /
000002        DATA BLANK /2H  /
        C
        C
000002        DO 300 I = 1,5
000004        DO 300 J = 1,10
000005        AX(I,J) = BLANK
000011        XCOEF(I,J) = 0.0
000014    300 CONTINUE
000017        DO 310 J = 1,10
000021        DO 310 I = 1,5
000022        IF(COEF(I,J).LE.0.0) GO TO 310
000026        AX(I,J) = A(I,J)
000033        XCOEF(I,J) = COEF(I,J)
000036    310 CONTINUE
        C
        C     OXIDIZER / FUEL WT RATIO
        C
000042        OF = WTOTAL(1) / WTOTAL(2)
        C
        C     COMPUTE COEF MULTIPLICATIVE FACTORS
        C
000044        FACTOR(1) = F(1) / (1.0-F(1))
000047        FACTOR(2) = F(2) / (1.0-F(2))
        C
        C     COMPUTE OXID AND FUEL COEFFICIENTS FOR DETONATION CALC
        C
000051        DO 410 N = 1,2
000052        DO 400 I = 1,5
000053        IF(COEF(I,N).EQ.0.0) GO TO 400
000056        AX(I,N) = A(I,N)
000063        XCOEF(I,N) = COEF(I,N) * FACTOR(N)
000070    400 CONTINUE
        C
        C     COMPUTE ENTHALPY
        C
000072        ENTHPY(N) = ENTHPY(N) + HFLIQ(N)*FACTOR(N)
        C
000077        PROD(N) = WTOTAL(N)
        C
000102    410 CONTINUE
        C
        C     COMPUTE TOTAL WEIGHTS OF OX AND FUEL
        C
```

```
000104          SUMX(1) = 0.0
000105          SUMX(2) = 0.0
000106          DO 14 I = 1,10
000107          N = 1
000110          IF(FORO(I).EQ.FUELX) N = 2
000114          SUMX(N) = SUMX(N) + PROD(I)
000120     14   CONTINUE
          C
          C     COMPUTE RELATIVE WEIGHTS
          C
000121          DO 420 I = 1,10
000123          N = 1
000124          IF(FORO(I).EQ.FUELX) N = 2
000130          RELWT(I) = PROD(I) / SUMX(N)
000135    420   CONTINUE
          C
000137          DO 200 I = 1,10
000140          IF(PROD(I).LE.0.0) GO TO 200
000142          IF(RELWT(I).GE.1.0E-5) GO TO 200
000145          WRITE(6,176)
000151    176   FORMAT(1H0,*NO DETONATION CARDS PUNCHED*)
000151          RETURN
000152    200   CONTINUE
          C     WRITE REACTANTS CARD
          C
000154          WRITE(IUNIT,900) REACTX,REACTY
000164    900   FORMAT(A6,A3,71X)
          C
          C
          C     WRITE REACTANT CARDS
          C
000164          DO 430 I = 1,10
000166          IF(RELWT(I).LE.0.0) GO TO 430
000170          WRITE(IUNIT,191)(AX(J,I),XCOEF(J,I),J=1,5),RELWT(I),ENTHPY(I)
               1                                                       ,FORO(I)
000222    191   FORMAT(5(A2,F7.5),F7.5,1X,F9.0,9X,A1)
000222    430   CONTINUE
000224          WRITE(IUNIT,192)
000230    192   FORMAT(80X)
          C
          C     WRITE NAMELISTS CARD
          C
000230          WRITE(IUNIT,193) XNAME,XLISTS
000240    193   FORMAT(A4,A5)
          C
000240          TI = TFINAL / 1.8
000242          PI = PGTOTAL
          C
          C     CONSTRUCT NAMELIST $INPT2
          C
000244          WRITE(IUNIT,194) XINPT2
000251    194   FORMAT(1X,A6)
000251          WRITE(IUNIT,195) XPIS,PI,COMMA, XTIS,TI,COMMA
000271    195   FORMAT(1X,A2,E20.8,A1,5X,A2,E20.8,A1)
000271          WRITE(IUNIT,196) TFPSIA,XTRUE,COMMA,TFDETN,XTRUE,COMMA
000311    196   FORMAT(1X,A6,A6,A1,5X,A6,A6,A1)
000311          WRITE(IUNIT,197) XOF,OF,COMMA,XKASE,ICASE,COMMA
000331    197   FORMAT(1X,A3,E16.7,A1,3X,A5,I7,A1)
```

```
000331           WRITE(IUNIT,198) XEND
000337     198   FORMAT(1X,A4)
          C
000337           ICASE = ICASE + 1
          C
000341           RETURN
000341           END
          #DECK,OUT1
```

```
                SUBROUTINE OUT1
          C
000002          COMMON /A/    TFP(2),TAU(2),TAUF(2),TAUS(2),XM(2),GAM(2),TG(2),
               1              PG(2),M(2),GEVAP(2),XI(2),XR(2),T0(2)
000002          COMMON/COM1/ DUMXYZ(120),SPNAME(10)
000002          COMMON/COM2/ ICASE,IUNIT,F(2),HFLIQ(2),MSPEC,PGTOTAL,PROD(10),
               1              TFINAL,WDROP(2),WTOTAL(2),IFIRST
000002          COMMON/DOLOOP/ ND1,ND2,ND3
000002          COMMON/OUTA/ PG1(2),PGP1,REACT(2),TAVERG,DELTRE,TIME,TQP
000002          COMMON/OUTB/ NPAGE
000002     899  FORMAT(1H1)
000002          IF(NPAGE.LE.4) GO TO 10
000005          WRITE(6,899)
000010          NPAGE = 0
000011      10  NPAGE= NPAGE + 1
          C
000013          DO 20 N = 1,2
000014          PROD(N) = WTOTAL(N)
000017      20  CONTINUE
          C
000020     900  FORMAT(1H0,35X,16HTIME(MILLISEC) =,E11.4//
               1 1X,41HPRESSURES(PSIA)          TEMPERATURES(DEGR)
               2     42HREACTION PARAMETERS     WEIGHTS AND FACTORS)
000020     901  FORMAT(1H ,7HOXID   =,E11.4,2X,7HTFINAL=,E11.4,3X,9HREACT(O)=,E1
               11,3X,10HWTOTAL(O)=,E11.4)
000020     902  FORMAT(1H ,7HFUEL   =,E11.4,2X,7HTAVERG=,E11.4,3X,9HREACT(F)=,E1
               11,3X,10HWTOTAL(F)=,E11.4)
000020     903  FORMAT(1H ,7HTOTAL  =,E11.4,2X,7HTQP    =,E11.4,3X,9HDELTRE   =,E1
               11,3X,10HF(O)      =,E11.4)
000020     904  FORMAT(1H ,7HPGP    =,E11.4, 46X,10HF(F)      =,E11.4)
000020     905  FORMAT(1H0,22HPRODUCT CONCENTRATIONS//)
000020     906  FORMAT(1H ,4(1H ,A6,1H=,E11.4,3X))
000020          WRITE(6,900) TIME
000026          WRITE(6,901) PG1(1), TFINAL, REACT(1), T0(1)
000042          WRITE(6,902) PG1(2), TAVERG, REACT(2), T0(2)
000056          WRITE(6,903) PGTOTAL,TQP, DELTRE, F(1)
000072          WRITE(6,904) PGP1,F(2)
000102          WRITE(6,905)
000106          WRITE(6,906) (SPNAME(I),PROD(I),I=1,MSPEC)
000124          RETURN
000125          END
          *DECK,PLTPAK
```

```
                 SUBROUTINE PLTPAK(X,Y,PLABEL,XLABEL,YLABEL,NPTS,IDEBUG)
000012           DIMENSION X(1),Y(1),PLABEL(6),XLABEL(2),YLABEL(2)
000012           DATA IFIRST/0/
000012           XUNITS= 10.0
000013           YUNITS= 10.0
000013           SCALEP=  1.0
000015           ILINE =     1
000016           ISYMBL=     3
000017           SYMHIT=   0.2
000020           IPLNUM=     6
000021           IXLNUM=     2
000022           IYLNUM=     2
000024      1    IFIRST = IFIRST + 1
000026           IF(NPTS.LE.0) GO TO 210
000027           IF(IDEBUG.EQ.0) GO TO 10
000031           WRITE(6,110)(PLABEL(I),I=1,6),(XLABEL(I),I=1,2),(YLABEL(I),I=1
000067      110  FORMAT(1H1,9X,*PLOT LABEL  *,3X,6A10//10X,*X AXIS LABEL*,3X,2A
               1          //10X,*Y AXIS LABEL*,3X,2A10)
000067           WRITE(6,111) NPTS, (I,X(I),Y(I),I=1,NPTS)
000125      111  FORMAT(1H0,9X,*NUMBER OF POINTS =*,I10//10X,1HI,14X,1HX,14X,1H
               1       (8X,I5,2E16.8))
000125      10   CONTINUE
000125           CALL DSCPLT (X,Y,XLABEL,YLABEL,PLABEL,NPTS,IXLNUM,IYLNUM,IPLNU
               1 IFIRST,SCALEP,XUNITS,YUNITS,SYMHIT,ILINE,ISYMBL)
000147           RETURN
000150      210  WRITE(6,211) NPTS
000162      211  FORMAT(1H0,*NPTS =*,I10,3X,*MUST BE .GE. 1*)
000162           RETURN
000163           END
            *DECK,PLTSUB
```

```
                SUBROUTINE PLTSUB (TIME,TFINAL)
          C
000005          COMMON/CPLT/ IFPLOT,PLTIME,IPLT1,TMAX
          C
000005          DIMENSION X(100),Y(100),PLABEL(6),XLABEL(6),YLABEL(6)
          C
000005          DATA (PLABEL(I),I=1,6)/10HTRANSIENT ,10HSTART PROG, 3HRAM,1H ,
               1  1H ,1H /
000005          DATA (XLABEL(I),I=1,2)/10HTIME(MILLI,10HSEC)       /
000005          DATA (YLABEL(I),I=1,2)/10HTFINAL (DE,10HG-R)       /
000005          CALL SECOND(CPSEC)
000006          TEST = TIME / 1.0E3
          C
000011          IF(CPSEC.GT.(PLTIME-5.0)) IPLT1 = +1
000016          IF(ABS(TEST-TMAX).LE.1.0E-8) IPLT1 = +1
          C
000024          CALL TABGEN(IPLT1,100,X,Y,NUM,TIME,TFINAL,IX)
000034          IF(IPLT1.NE.+1) GO TO 998
          C
          C     PURGE PLOTS
          C
000037          NUM = MIN0 (100,NUM)
000043          IDEBUG = 1
000044          CALL PLTPAK(X,Y,PLABEL,XLABEL,YLABEL,NUM,IDEBUG)
000052          IFPLOT = 0
000053      998 IPLT1 = 0
000054          RETURN
000055          END
          *DECK,SCAL
```

```
                 SUBROUTINE SCAL (XMAX,XMIN,XI,DX,X0,XE)
          C
          C      FORTRAN IV PLOT SCALE OPTIMIZATION ROUTINE.
          C
000011           DIMENSION S(3)
          C
000011           DATA S/1.,2.,5./
          C
          C
000011           DX=0.0
000011           X0=0.0
000012           XE=0.0
000012           W=(XMAX-XMIN)/XI
000014           IF(W)21,21,6
000016         6 DO 20 I=1,3
000020           A=1.0+ALOG10(W/S(I))
000026           B=AINT(A)
000027           IF((A.EQ.B).OR.(A.LT.0.0))B=B-1.0
000041           C=S(I)*10.0**B
000046           D=AINT(XMIN/C)
000054           IF(C*D.GT.XMIN)D=D-1.0
000062           D=C*D
000063           IF(XI*C-XMAX+D)20,15,15
000066        15 E=W/C
000070           IF(XE-E)17,20,20
000072        17 DX=C
000073           X0=D
000074           XE=E
000075        20 CONTINUE
000077        21 RETURN
000100           END
          *DECK,TABGEN
```

```
                 SUBROUTINE TABGEN (IFLAG,LTABLE,XTAB,YTAB,LUSED,X,Y,IERROR)
           C
000013           DIMENSION XTAB(1), YTAB(1)
           C
           C     IFLAG DENOTES THE TYPE OF ENTRY TO THIS SUBROUTINE. (3 TYPES)
           C        IFLAG = -1  FIRST ENTRY FOR A PARTICULAR TABLE
           C        IFLAG =  0  NORMAL ENTRY (NEITHER FIRST NOR LAST ENTRY)
           C        IFLAG = +1  LAST ENTRY TO THE SUBROUTINE FOR THIS TABLE
           C
           C     THE ABOVE OPTIONS ALLOW THE ASSURANCE THAT THE FIRST AND LAST
           C     EVENTS WILL ALWAYS BE TABULATED IN THE FINAL TABLE.
           C
           C     IF THIS IS THE FIRST ENTRY TO THIS SUBROUTINE, MUST INITIALIZE
           C     FLAGS AND VARIABLES.
           C
000013           IF(IFLAG.NE.-1) GO TO 10
           C
000015           N = 0
000015           LUSED = 0
000016           IENTER = 0
000017           IXMOD = 1
000020           IEVENT = 0
000021           IEVM1  = 0
000021           IEVLST = 0
           C
           C     FORCE THE TABLE DIMENSION TO BE USED TO AN EVEN NUMBER.
           C
000022           LTAB = (LTABLE/2) * 2
           C
000024      10   CONTINUE
000024           IENTER = IENTER + 1
000026           IEVENT = IEVENT + 1
           C
           C     CHECK FOR TABLE OVERFLOW PRIOR TO PROCESSING ENTRY
           C
000027           LOVFL = LUSED + 1
000027           IF(LOVFL.LE.LTAB) GO TO 30
           C
           C     OVERFLOW COULD BE CAUSED BY THIS ENTRY, REPACK TABLE.
           C
000032           WRITE(6,100) LUSED,N,LTAB
000044      100  FORMAT(1H0,*AM REPACKING TABLE,LUSED,N,LTAB*,3I10)
000044           INEW = 0
000045           DO 20 I = 1,LTAB, 2
000052           INEW = INEW + 1
000054           XTAB(INEW) = XTAB(I)
000057           YTAB(INEW) = YTAB(I)
000061      20   CONTINUE
           C
           C     RESET THE CURRENT NUBER OF TABLE ENTRIES (LUSED)
           C
000063           LUSED = INEW
000063           IENTER = IEVENT - IEVM1
000065           IEVLST = IEVM1
000066           N = N + 1
000070           IXMOD = 2**N
           C
```

```
000073    30   CONTINUE
          C
          C    DETERMINE IF CURRENT CALL IS TO RESULT IN AN ENTRY IN THE TABL
          C
000073         IF(IFLAG.EQ.1) GO TO 35
000075         IF(MOD(IENTER,IXMOD).NE.0) GO TO 40
000101    35   CONTINUE
000101         LUSED = LUSED + 1
000102         XTAB(LUSED) = X
000104         YTAB(LUSED) = Y
000106         IEVM1 = IEVLST
000107         IEVLST = IEVENT
000111    40   CONTINUE
000111   999   RETURN
000112         END
```

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