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ORBITAL MANEUVERING ENGINE FEED SYSTEM COUPLED STABILITY INVESTIGATION

COMPUTER USER'S MANUAL

NAS9-14315

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PREPARED FOR

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FOREWORD

This document was prepared by Rocketdyne Division, Rockwell International Corporation, in accordance with Article I and Line Item Nos. 2, 3, and 4 of the Data Requirements List of Contract NAS9-14315 with the National Aeronautics and Space Administration. The contract period of performance was 6 August 1974 to 1 September 1975. The NASA/JSC Technical Monitor was Mr. F. D. Freeburn. The Rocketdyne Program Manager was Mr. R. H. Helsel for the first three months; he was replaced by Mr. R. D. Paster for the remainder of the program. Mr. J. A. Nestlerode served as the Principal Engineer, assisted by Dr. D. R. Kahn.

Several technical people at Rocketdyne performed work or served as consultants regarding specific areas of the various program tasks: Mssrs. J. K. Hunting, R. L. Nelson, and L. E. Sack with respect to the feed system hydrodynamics, Mr. F. R. Linow with respect to combustion dynamics, Mr. M. D. Schuman with respect to combustion dynamics, chamber dynamics, engineering model formulation, and computer programming, and Mr. K. W. Fertig with respect to numerical analysis, computer programming, and checkout.

ABSTRACT

This report is an operating manual for the Feed System Coupled Stability Model. It is submitted as partial fulfillment of an 11-month program designed to develop, verify, and document a digital computer model that can be used to analyze and predict engine/feed system coupled instabilities in pressure-fed storable propellant propulsion systems over a frequency range of 10 to 1000 Hz.

The first section describes the analytical approach to modeling the feed system hydrodynamics, combustion dynamics, chamber dynamics, and overall engineering model structure, and presents the governing equations in each of the technical areas. This is followed by the Program User's Guide, which is a complete description of the structure and operation of the computerized model. Last, appendixes provide an alphabetized FØRTRAN symbol table, detailed program logic diagrams, computer code listings, and sample case input and output data listings.

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INTRODUCTION

Historically, during the development of pressure-fed propulsion systems, feed system/engine coupled instabilities have been frequently encountered. Resolution of these problems usually included increasing injector pressure drop to decouple the feed system from the combustor, the result being substantial system weight penalties. A dynamic computer model would be a useful tool in obviating coupled stability problems during the development of the Space Shuttle Orbit Maneuvering System (SS/OMS). A model could be used both as a system design tool to optimize component location and pressure profile (minimize system weight) and a system development tool to define test programs for assessing stability margins of the OMS.

This document is an operating manual for the Feed System Coupled Stability Model (FSCSM) and is submitted as partial fulfillment of an 11-month program conducted by Rocketdyne to develop and verify an engineering digital computer model for the NASA/JSC which can be used to analyze feed system/engine coupled instabilities in pressure-fed, storable propellant, propulsion systems over a frequency range of 10 to 1000 Hz (frequencies lower than the chamber transverse frequencies). The model is sufficiently general so that it may be readily applicable to present and future engine and propulsion programs. For scaling purposes, the baseline configuration chosen is the OMS engine. The model has been written for use on the NASA/JSC Univac 1110, EXEC-8 computer system, and provides NASA a tool which can be used to:

1. Conduct preliminary design tradeoff for feasibility studies prior to propulsion concept selection.
2. Guide the design of propulsion systems to ensure stability at all operating ranges and with minimum penalties.
3. Guide testing programs by predicting the least stable operating regimes thereby reducing the number of stability tests required.
4. Provide stability verification in the event system changes are made and hot-fire verification is impractical.
5. Diagnose problems on existing systems and evaluate potential solutions.

The work performed in completing the requirements of the program's technical effort is described in a separate companion document, entitled OME Feed System-Coupled Stability Model, Final Report (Ref. 1). This includes the mathematical formulation of the model, development of the model into an overall engineering structure, and verification of the model's operation and capabilities by comparing the model's theoretical predictions with experimental data from an OMS engine and test rig with known feed system/engine chugging history.

The present document contains a detailed description of the structure and operation of the FSCSM. In the first section, the mathematical formulation of the model is reviewed. The analytical approach to modeling the feed system hydrodynamics, combustion dynamics, chamber dynamics, and overall engineering structure is described and the equations utilized by the model in each of the technical areas are presented. The reader may consult Ref. 1 for more details pertaining to the derivation of the equations.

The Program User's Guide section contains the instructions necessary to operate the computer model and interpret the results. First, the structure and logic of the main program and all subroutines are described, followed by a description of the input data required to run FSCSM. The input is divided into four major sections: (1) main control, (2) nozzle admittance control, (3) hydrodynamics control, and (4) combustion dynamics control. The format, content, and description of each input data card is clearly specified for each control section. The output of the FSCSM computer program is then discussed in terms of each tabular page of printout. Finally, additional details on program operation are presented, including program size, overlay structure, computer time, and program input/output data set file information. Appendixes provide an alphabetized FØRTRAN symbol table, detailed program logic diagrams, computer code listings, and sample case input and output data listings.

MATHEMATICAL FORMULATION OF MODEL

INTRODUCTION

During certain periods of a rocket engine's operation, conditions within the combustion chamber and feed system are time variant, i.e., the operation is not steady with respect to time. Prime interest of this computer model is focused on abnormal transient operation during unstable combustion, i.e., pressure oscillations in a combustion device which are driven by the feed system and sustained by the combustion process. Start and stop transients are not considered.

The deviations from steady-state combustion which occur during unstable burning depend upon the kind of instability experienced. Liquid rocket instabilities are classified according to their dominant time-varying processes. They may be divided initially into two categories, depending upon whether the instability oscillation wave length is long or short compared with the chamber dimensions.

If the instability wave length is considerably longer than the chamber length and diameter, pressure disturbances propagate rapidly through the combustion space compared with rates of change due to the instability. As a result, wave motion in the chamber may be neglected and chamber pressure can be considered to vary only with time but not to vary spatially (i.e., P_c is a lumped parameter). These instabilities depend upon a fluid mechanical coupling between the propellant feed system(s) dynamics (fluctuating injection rates), the propellant combustion rates (delay times), and the combustion gas exhaust rates (pressure relaxation). Such instabilities can be further subdivided into various categories depending on the extent of wave motion in the feed system.

The breakpoint at which chamber wave motion becomes important is not abrupt. In reality, chamber wave motion is always present and, in effect, lumped chamber instabilities are really "zero order mode" limits of more general wave motion instabilities. In practice, it is found that the chamber gases can be considered to act as a lump until the frequency of oscillation exceeds roughly one-fourth of the frequency of the lowest chamber acoustic resonance mode. At and above such frequencies wave motion becomes important and cannot be neglected in analysis. Chamber wave motion instabilities are characterized by the wave-length of the oscillatory motion being comparable to the chamber dimensions. As with lumped chamber instabilities, the driving energy comes from oscillatory spray combustion. With wave motion instabilities, however, in addition to the effects of injection rate fluctuations, there is the combustion response of burning propellant sprays as they are disturbed by passage of a pressure wave through them. Wave motion may increase local burning rates by any of several mechanisms: (1) a pressure effect on the drop vapor gas phase burning rates; (2) enhanced mixing between gases and between sprays and gases; and (3) increased spray gasification rates. Increased spray gasification may be due to transient increases in convective flow velocities, to increased temperature or concentration gradients, and/or spray droplet shattering. The instability amplitude depends upon the magnitude of the response, and vice versa; typically, the interacting processes are driven to a limit represented by abrupt, essentially complete consumption of the propellant sprays. This direct response can be so great that injection rate fluctuations may be of secondary importance. As a result this class of instability can also be further subdivided as to the importance of feed system coupling. In the absence of feed system coupling, the instability is referred to as "classical acoustic instability." Only longitudinal chamber modes with feed system coupled instabilities are considered in this program.

FEED SYSTEM DYNAMICS

Development of the Waterhammer Equations

Consider the differential control volume of a fluid element in a duct shown in Fig. 1.

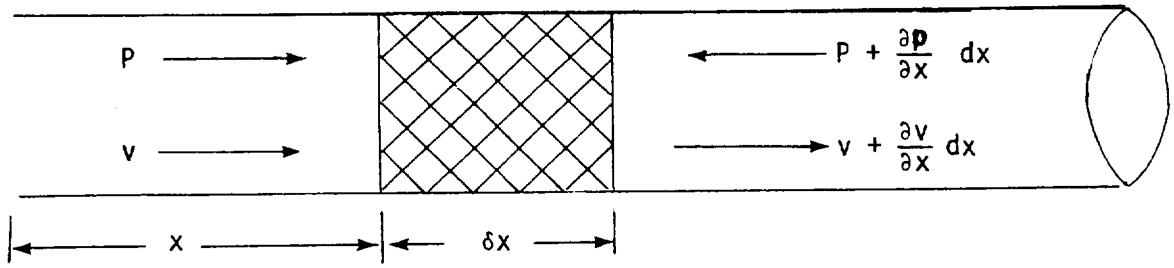

Fig. 1. Differential Pressures Developed Across the Incremental Length of a Fluid Element

Fluid compressibility and Newton's second law leads to the following pair of differential equations:

$$\frac{\partial p}{\partial t} = -\beta \frac{\partial v}{\partial x} = -c^2 \rho \frac{\partial v}{\partial x} \qquad (1)$$

$$\frac{\partial p}{\partial x} = -\rho \frac{\partial v}{\partial t} = -\frac{\beta}{c^2} \frac{\partial v}{\partial t}, \qquad (2)$$

where

p = fluid pressure
v = fluid velocity
β = fluid bulk modulus
ρ = fluid density
c = acoustic velocity = $(\beta/\rho)^{\frac{1}{2}}$

There are several ways in which to solve these equations. The solution method presented here follows that of Ezekiel (Ref. 2). The general form of the solution that satisfies either of equations (1) and (2) is

$$p = F_1\left(t + \frac{x}{c}\right) + F_2\left(t - \frac{x}{c}\right) \qquad (3)$$

where F_1 and F_2 are arbitrary functions.

Taking the partial derivative of p with respect to x and t separately and substituting the results in equations (1) and (2) gives:

$$\frac{\partial v}{\partial x} = - \frac{1}{\beta} \frac{\partial p}{\partial t} = - \frac{1}{\beta} \left[F_1' \left(t + \frac{x}{c}\right) + F_2' \left(t - \frac{x}{c}\right) \right] \qquad (4)$$

$$\frac{\partial v}{\partial t} = - \frac{1}{\rho} \frac{\partial p}{\partial x} = - \frac{1}{\rho c} \left[F_1' \left(t + \frac{x}{c}\right) - F_2' \left(t - \frac{x}{c}\right) \right] \qquad (5)$$

where

$$F' (\xi) = \frac{\partial F (\xi)}{\partial \xi} \quad .$$

The expression for v is obtained from either equation (4) or (5):

$$zv = - F_1 \left(t + \frac{x}{c}\right) + F_2 \left(t - \frac{x}{c}\right) \qquad (6)$$

where

$$z \equiv (\rho \beta)^{\frac{1}{2}} \quad . \qquad (7)$$

Letting the subscript o denote x=0, the upstream position, and the subscript L denote x=L, the downstream position, and defining $\tau = L/c$ as the signal propagation time between the two positions, equations (3) and (6) become

$$p_o = F_1(t) + F_2(t) \qquad (8)$$

$$p_L = F_1(t+\tau) + F_2(t-\tau) \qquad (9)$$

$$zv_o = - F_1(t) + F_2(t) \qquad (10)$$

$$zv_L = - F_1(t+\tau) + F_2(t-\tau) \qquad (11)$$

Combining Eqs. (8) and (10), and Eqs. (9) and (11) separately, yields four additional relations:

$$p_o + zv_o = 2 F_2(t) \qquad (12)$$

$$p_o - zv_o = 2 F_1(t) \qquad (13)$$

$$p_L + zv_L = 2\ F_2(t-\tau) \tag{14}$$

$$p_L - zv_L = 2\ F_1(t+\tau). \tag{15}$$

Eliminating the functions F_1 and F_2 gives the final result as:

$$\left[p_o + zv_o\right]_{(t-\tau)} = p_L + zv_L \tag{16}$$

$$\left[p_L - zv_L\right]_{(t-\tau)} = p_o - zv_o \tag{17}$$

Consider now Fig. 2, which depicts a generalized line segment forming a portion of a feed system with many such segments.

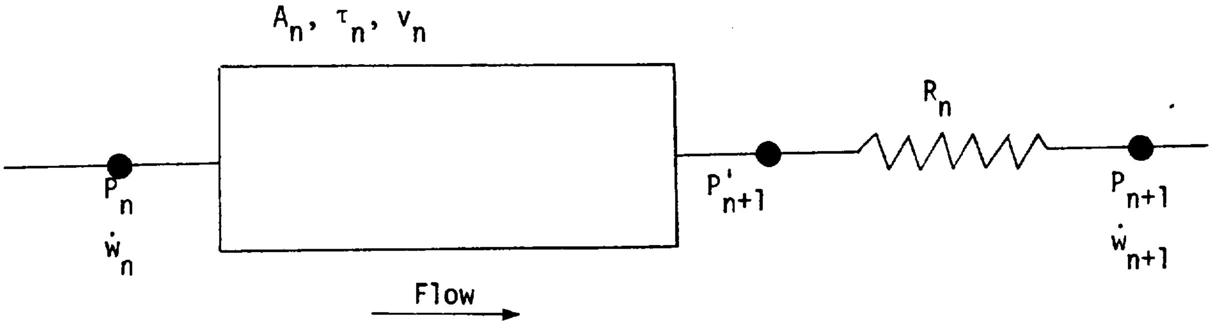

Figure 2. Generalized Line Segment

The equations which describe the pressure and flows as functions of time and of each other for the generalized line segment are obtained from Eqs. (16) and (17):

$$p_n - \left(\frac{v_n}{A_n g}\right) \dot{w}_n = \left[p'_{n+1} - \left(\frac{v_n}{A_n g}\right) \dot{w}_{n+1}\right]_{(t-\tau_n)} \tag{18}$$

$$p'_{n+1} + \left(\frac{v_n}{A_n g}\right) \dot{w}_{n+1} = \left[p_n + \left(\frac{v_n}{A_n g}\right) \dot{w}_n\right]_{(t-\tau_n)} \tag{19}$$

The expression, $t - \tau_n$, indicates values at τ_n seconds before, and

$$p'_{n+1} = p_{n+1} + R_n |\dot{w}_n| \dot{w}_n \tag{20}$$

$$\dot{w}_n = \rho_n A_n v_n \ . \tag{21}$$

Equations (18) and (19) are solutions of the wave equation, and equation (20) is the flow through a nonlinear fluid resistance. Letting

$$\alpha_n = \frac{v_n}{A_n g} \tag{22}$$

these equations can be combined to give:

$$p_n - \alpha_n \dot{w}_n = \Big[p_{n+1} + R_n |\dot{w}_{n+1}| (\dot{w}_{n+1} - \alpha_n) \Big]_{(t-\tau_n)} \tag{23}$$

$$p_n + R_{n-1} |\dot{w}_n| \dot{w}_n + \alpha_{n-1} \dot{w}_n = \Big[p_{n-1} + \alpha_{n-1} \dot{w}_{n-1} \Big]_{(t-\tau_{n-1})} \ . \tag{24}$$

Eliminating p_n and rearranging into quadratic form results in

$$\begin{aligned} R_{n-1} \dot{w}_n^2 + (\alpha_{n-1} + \alpha_n) \dot{w}_n - \Big[p_{n-1} + \alpha_{n-1} \dot{w}_{n-1} \Big]_{(t-\tau_{n-1})} & \\ + \Big[p_{n+1} + R_n |\dot{w}_{n+1}| (\dot{w}_{n+1} - \alpha_n) \Big]_{(t-\tau_{n-1})} &= 0 \end{aligned} \tag{25}$$

which can be solved for the appropriate solution using the quadratic formula. The tank end parameters are obtained using a solution of Eq. (23) only. The injector end solution is obtained using the quadratic formula for equation (25).

The linear model incorporated in the Hydrodynamics subprogram utilizes the same basic equations, (23) and (24), but in the following linearized form:

$$(\delta p_n) - \alpha_n \, (\delta \, \dot{w}_n) = \Big[(\delta \, p'_{n+1}) - \alpha_n \, (\delta \, \dot{w}_{n+1}) \Big]_{(t-\tau_n)} \tag{26}$$

$$(\delta \, p'_{n+1}) + \alpha_n \, (\delta \, \dot{w}_{n+1}) = \Big[(\delta \, p_n) + \alpha_n \, (\delta \, \dot{w}_n) \Big]_{(t-\tau_n)} \, , \tag{27}$$

where

$$(\delta \, p'_{n+1}) = (\delta \, p_{n+1}) + 2R_n \, \bar{\dot{w}}_{n+1} \, (\delta \, \dot{w}_{n+1}). \tag{28}$$

These equations are then combined, resulting in

$$\alpha_n(\delta \, \dot{w}_n) - (\delta \, p_n) + \Big[(\delta \, p_{n+1}) + (\overline{R}_n - \alpha_n)(\delta \, \dot{w}_{n+1}) \Big]_{(t-\tau_n)} = 0 \tag{29}$$

$$(\overline{R}_n + \alpha_n)(\delta \, \dot{w}_{n+1}) + (\delta \, p_{n+1}) - \Big[(\delta \, p_n) + \alpha_n \, (\delta \, \dot{w}_n) \Big]_{(t-\tau_n)} = 0 \, , \tag{30}$$

where

$$\overline{R} = 2 \, R_N \, \bar{\dot{w}}_{n+1} \tag{31}$$

At the tank end, the term $\delta \, p_n$ is zero for constant tank pressure. At the injector end, $\delta \, p_{n+1}$ is the independent variable.

Injector Dynamics

The injector dynamics are included by treating the injector as a lumped compressible volume as shown in the figure below.

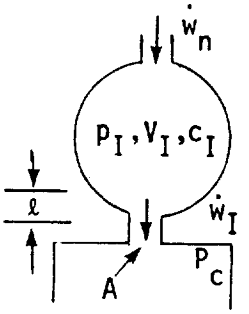

Figure 3. Schematic of the Injector as a Lumped Compressible Volume

The pressure in the injector manifold, p_I, is related to the entering flow, $\dot{w}_n$, from the upstream pipe segment and the injector flow, $\dot{w}_I$, as follows:

$$\frac{dp_I}{dt} = \frac{c_I^2}{V_I g} (\dot{w}_n - \dot{w}_I) \tag{32}$$

where V_I is the injector volume and c_I is the fluid sonic velocity.

The injector flow is controlled by the differential pressure across the injector as well as by the resistance and inertia of the injector orifices. Thus,

$$p_I - p_c = R_I \dot{w}_I^2 + \frac{\ell}{Ag} \frac{d}{dt} \dot{w}_I , \tag{33}$$

where p_c is the thrust chamber pressure, R_I is the injector hydraulic resistance and ℓ/Ag is the equivalent inertance of all the injector orifices combined, i.e.,

$$\frac{1}{\ell/Ag} = g \sum_{i=1}^{n} \frac{1}{\ell_i/A_i} . \tag{34}$$

In the preceding equation, ℓ_i and A_i are the length and area, respectively, of an individual injector orifice.

An additional factor which can have a significant effect on the response of the feed system to chamber pressure oscillations is injector face flexibility. This effect can be expressed as a change in injector volume proportional to a change in injector pressure drop:

$$\frac{d\,V_I}{dt} = K\left(\frac{d\,p_I}{dt} - \frac{d\,p_c}{dt}\right) \tag{35}$$

Also,

$$\frac{dp}{dt} = \frac{c^2}{g}\,\frac{d}{dt}\,\left(\frac{w}{V}\right) , \tag{36}$$

which can be rewritten as

$$\frac{dp}{dt} = \frac{c^2}{Vg}\,\dot{w} - \frac{c^2\,\rho}{Vg}\,\dot{V} . \tag{37}$$

Combining Eqs. (35) and (37) gives

$$\frac{d\,p_I}{dt} = \frac{c_I^2}{V_I g}\,(\dot{w}_n - \dot{w}_I) - \frac{c_I^2\,\rho_I}{V_I g}\left[K\left(\frac{dp_I}{dt} - \frac{dp_c}{dt}\right)\right] , \tag{38}$$

which can be rewritten as

$$\left(1 + \frac{c_I^2\,\rho_I\,K}{V_I\,g}\right)\frac{dp_I}{dt} = \frac{c_I^2}{V_I g}\,(\dot{w}_n - \dot{w}_I) + \frac{c_I^2\,\rho_I\,K}{V_I\,g}\,\frac{dp_c}{dt} \tag{39}$$

This expression reduces to Eq. (32) if no injector flexibility exists (K = 0).

Two-Phase Flow Acoustic Velocity

In the waterhammer equations the acoustic velocity, c, of the fluid appears in two places; (1) directly in the constant relating flow to pressure, and (2) indirectly in the time delay value, τ, which equals ℓ/c seconds, where ℓ is the pipe segment length. The acoustic velocity of a fluid is a property of that fluid. However, its effective value can be reduced by the elastic walls of the flow passage or by the entrainment of gas and vapor in the liquid (two phase flow). Gas in the liquid can appear from two sources. One source is direct entrainment from mixing of gas and liquid in the propellant tank, while the other can result from the evolution of dissolved gas as the pressure drops along the feed system.

Given the steady-state pressure at each point in the feed system and data on the solubility of the pressurant gas in the propellant as a function of pressure and temperature, the amount of gas in the fluid can be determined for each feed system segment. Then, knowing the amount of gas in the liquid, the effective acoustic velocity of the mixture may be calculated.

Assuming isentropic compression of the gas, the change in volume of the gas is

$$dV_g = - \frac{V_g}{Kp} \, dp, \tag{40}$$

and for the liquid

$$dV_\ell = \frac{V_\ell}{\beta} \, dp \tag{41}$$

Defining a constant, $\alpha \equiv \frac{V_g}{V_\ell}$

the following relation is obtained:

$$\frac{dV_t}{V_t} = \frac{-\,dp}{\left[\dfrac{1+\alpha}{\dfrac{1}{\beta} + \dfrac{\alpha}{Kp}}\right]} \tag{42}$$

The bracketed term is the compressibility of the mixture. The density of the mixture can be shown to be

$$\rho_m = \frac{\alpha \rho_g + \rho_\ell}{(1 + \alpha)} \quad . \tag{43}$$

The acoustic velocity of a liquid in an elastic pipe is

$$c = \sqrt{\frac{1}{\frac{\rho}{g}\left(\frac{1}{\beta} + \frac{Dc_f}{eE}\right)}} \tag{44}$$

Using the above expressions for density and compressibility, the acoustic velocity, can be written as

$$c = \left[\frac{1}{\frac{\rho_m}{1+\alpha}\left(\frac{\alpha}{\rho_\ell\ c_\ell^{\ 2}} + \frac{1}{P_g\ c_g^{\ 2}} + \frac{1+\alpha}{g}\ \frac{Dc_f}{Ee}\right)}\right]^{\frac{1}{2}} \tag{45}$$

This expression can be used to define the acoustic velocity of a feed system segment with two phase flow. For an all liquid system, $\alpha = 0$ and the same equation can be used.

In the Hydrodynamics subprogram the effect of the wall compressibility term, $\frac{Dc_f}{Ee}$, on the fluid acoustic velocity is handled automatically (assuming input value of $\frac{Dc_f}{Ee}$ are provided for each feed system segment). However, the program does not compute the effects of two-phase flow. If such flow occurs in the feed system being modeled, an effective fluid acoustic velocity must be pre-calculated for each affected segment. Equation (45) above, with the $\frac{Dc_f}{Ee}$ term set equal to zero can be used for this calculation.

Simulation of Branch Lines

In the Hydrodynamics subprogram, branched lines are handled by assuming that each branch has zero internal volume and that its flows are incompressible. Thus, the pressures at the end of all segments which meet at a branch are set equal. The continuity of flow is then used to provide the additional equations in combination with the waterhammer equations to solve for the overall feed system dynamic response.

Generalized Feed System Model

A schematic of the generalized feed system which is modeled by the hydrodynamics subprogram is shown in Fig. 4. The configuration chosen is based on design and operating mode data for the OMS, PBK, and RCS feed systems obtained from McDonnell Douglas/St. Louis. The system is comprised of 30 individual line segments, each denoted in Fig. 4, as the lines between the black dots. A continuous parameter representation of each line segment is obtained through the use of separate sets of waterhammer equations. Each line segment can have a different line length, area, wall compliance, fluid acoustic velocity and resistance, and hence can model a wide variety of feed system components by merely choosing the appropriate values from these parameters. Also included in the generalized model are lumped parameter descriptions of two injectors (designated "0" and "F" on Fig. 4). Parameters for the injectors are volume, resistance, inertance, fluid acoustic velocity and face flexibility.

The system of 57 equations describing the generalized Fig. 4 feed system is listed in Table 1. The equations are shown in the linearized, LaPlace transformed format required by the frequency response subroutine.

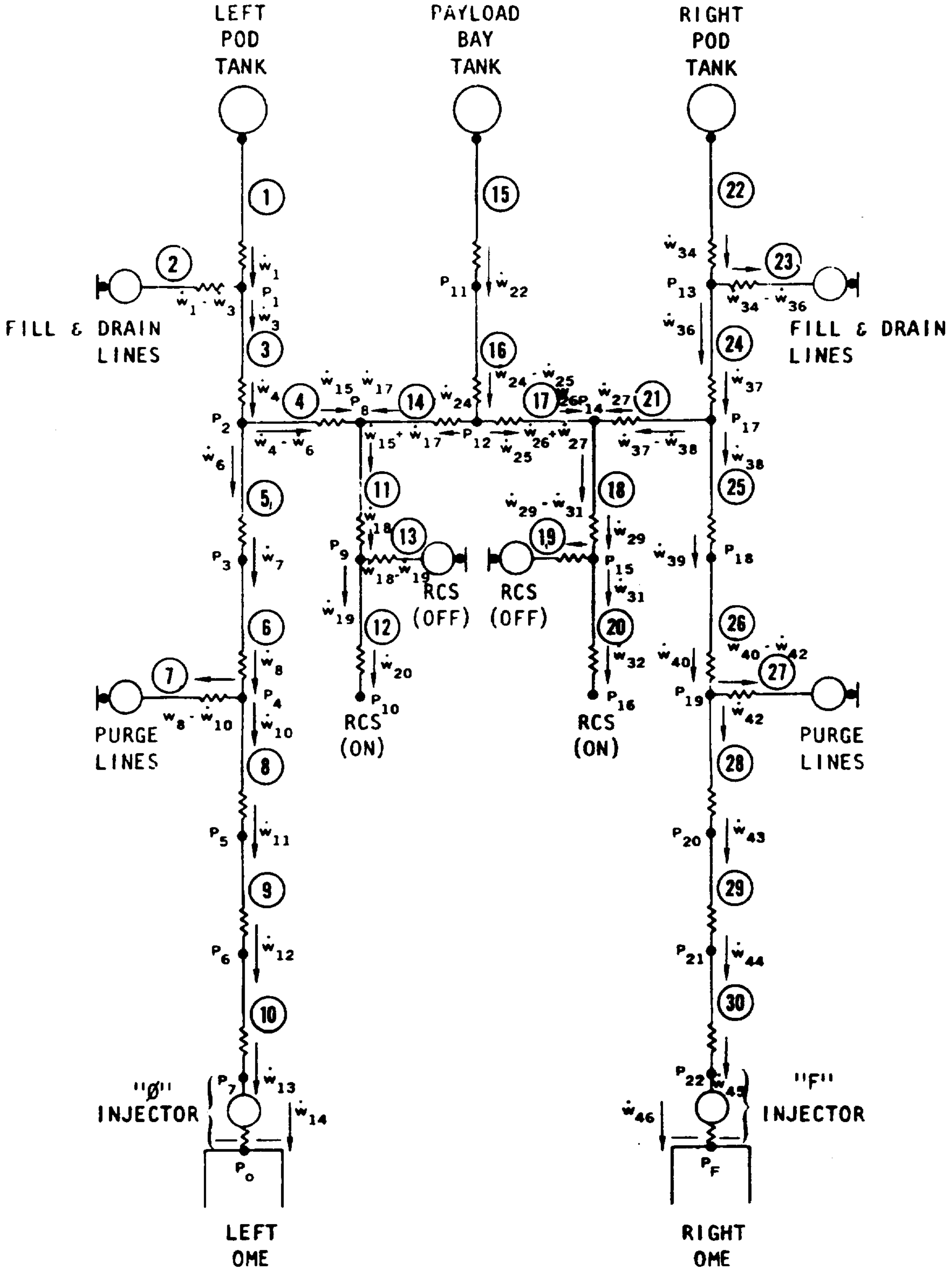

Figure 4. Generalized OME Feed System Schematic

TABLE 1. HYDRODYNAMIC EQUATIONS

$$P_1 + (R_1 + a_1)\,\dot{w}_1 + [P_1 + (R_1 - a_1)\,\dot{w}_1]\,e^{-2T_1 s} = 0 \qquad 1\text{-}1$$

$$P_1 - a_3\dot{w}_3 - [P_2 + (R_3 - a_3)\,\dot{w}_4]\,e^{-T_3 s} = 0 \qquad 1\text{-}2$$

$$P_2 + (R_3 + a_3)\,\dot{w}_4 - [P_1 + a_3\dot{w}_3]\,e^{-T_3 s} = 0 \qquad 1\text{-}3$$

$$P_1 - (R_2 + a_2)\,(\dot{w}_1 - \dot{w}_3) - [P_1 - (R_2 - a_2)\,(\dot{w}_1 - \dot{w}_3)]\,e^{-2T_2 s} = 0 \qquad 1\text{-}4$$

$$P_2 - a_5\dot{w}_6 - [P_3 + (R_5 - a_5)\,\dot{w}_7]\,e^{-T_5 s} = 0 \qquad 1\text{-}5$$

$$P_2 - a_4\,(\dot{w}_4 - \dot{w}_6) - [P_8 + (R_4 - a_4)\,\dot{w}_{15}]\,e^{-T_4 s} = 0 \qquad 1\text{-}6$$

$$P_8 + (R_4 + a_4)\,\dot{w}_{15} - [P_2 + a_4\,(\dot{w}_4 - \dot{w}_6)]\,e^{-T_4 s} = 0 \qquad 1\text{-}7$$

$$P_3 + (R_5 + a_5)\,\dot{w}_7 - [P_2 + a_5\,\dot{w}_6]\,e^{-T_5 s} = 0 \qquad 1\text{-}8$$

$$P_3 - a_6\,\dot{w}_7 - [P_4 + (R_6 - a_6)\,\dot{w}_8]\,e^{-T_6 s} = 0 \qquad 1\text{-}9$$

$$P_4 - (R_7 + a_7)\,(\dot{w}_8 - \dot{w}_{10}) - [P_4 - (R_7 - a_7)\,(\dot{w}_8 - \dot{w}_{10})]\,e^{-2T_7 s} = 0 \qquad 1\text{-}10$$

$$P_4 - a_8\,\dot{w}_{10} - [P_5 + (R_8 - a_8)\,\dot{w}_{11}]\,e^{-T_8 s} = 0 \qquad 1\text{-}11$$

$$P_5\,(R_8 + a_8)\,\dot{w}_{11} - [P_4 + a_8\,\dot{w}_{10}]\,e^{-T_8 s} = 0 \qquad 1\text{-}12$$

$$P_5 - a_9\,\dot{w}_{\cancel{11}} - [P_6 + (R_9 - a_9)\,\dot{w}_{12}]\,e^{-T_9 s} = 0 \qquad 1\text{-}13$$

TABLE 1. (Continued)

$$P_6 + (R_9 + a_9)\,\dot{w}_{12} - [P_5 + a_9\,\dot{w}_{11}]\,e^{-T_9 s} = 0 \qquad \text{1-14}$$

$$P_6 - a_{10}\,\dot{w}_{12} - [P_7 + (R_{10} - a_{10})\,\dot{w}_{13}]\,e^{-T_{10} s} = 0 \qquad \text{1-15}$$

$$P_7 + (R_{10} + a_{10})\,\dot{w}_{13} - [P_6 + a_{10}\,\dot{w}_{12}]\,e^{-T_{10} s} = 0 \qquad \text{1-16}$$

$$P_7 - Z_o s\,\dot{w}_{14} - R_o\,\dot{w}_{14} = P_o \qquad \text{1-17}$$

$$sP_7 - \left(\frac{c^2}{gV}\right)_o \dot{w}_{13} + \left(\frac{c^2}{gV}\right)_o \dot{w}_{14} + \left(\frac{c^2}{gV}\right)_o K_o\,sP_7 = \left(\frac{c^2}{gV}\right)_o K_o\,sP_o \qquad \text{1-18}$$

$$P_8 + a_{14}\,\dot{w}_{17} - [P_{12} - (R_{14} - a_{14})\,\dot{w}_{24}]\,e^{-T_{14} s} = 0 \qquad \text{1-19}$$

$$P_{12} - (R_{14} + a_{14})\,\dot{w}_{24} - [P_8 - a_{14}\,\dot{w}_{17}]\,e^{-T_{14} s} = 0 \qquad \text{1-20}$$

$$P_8 - a_{11}\,(\dot{w}_{15} + \dot{w}_{17}) - [P_9 + (R_{11} - a_{11})\,\dot{w}_{18}]\,e^{-T_{11} s} = 0 \qquad \text{1-21}$$

$$P_9 + (R_{11} + a_{11})\,\dot{w}_{18} - [P_8 + a_{11}\,(\dot{w}_{15} + \dot{w}_{17})]\,e^{-T_{11} s} = 0 \qquad \text{1-22}$$

$$P_9 - (R_{13} + a_{13})\,(\dot{w}_{18} - \dot{w}_{19}) - [P_9 - (R_{13} - a_{13})\,(\dot{w}_{18} - \dot{w}_{19})]\,e^{-2T_{13} s} = 0 \qquad \text{1-23}$$

$$P_9 - a_{12}\,\dot{w}_{19} - [X + R_{12} - a_{12})\,\dot{w}_{20}]\,e^{-T_{12} s} = 0 \qquad \text{1-24}$$

$$P_{11} + (R_{15} + a_{15})\,\dot{w}_{22} + [P_{11} + (R_{15} - a_{15})\,\dot{w}_{22}]\,e^{-2T_{15} s} = 0 \qquad \text{1-25}$$

$$P_{11} - a_{16}\,\dot{w}_{22} - [P_{12} + (R_{16} - a_{16})\,(\dot{w}_{24} + \dot{w}_{25})]\,e^{-T_{16} s} = 0 \qquad \text{1-26}$$

TABLE 1. (Continued)

$$P_{12} + (R_{16} + a_{16}) (\dot{w}_{24} + \dot{w}_{25}) - [P_{11} + a_{16} \dot{w}_{22}] e^{-T_{16}s} = 0 \tag{1-27}$$

$$P_{13} + (R_{22} + a_{22}) \dot{w}_{34} + [P_{13} + (R_{22} - a_{22}) \dot{w}_{34}] e^{-2T_{22}s} = 0 \tag{1-28}$$

$$P_{13} - a_{24} \dot{w}_{36} - [P_{17} + (R_{24} - a_{24}) \dot{w}_{37}] e^{-T_{24}s} = 0 \tag{1-29}$$

$$P_{13} - (R_{23} + a_{23}) (\dot{w}_{34} - \dot{w}_{36}) - [P_{13} - (R_{23} - a_{23}) (\dot{w}_{34} - \dot{w}_{36})] e^{-2T_{23}s} = 0 \tag{1-30}$$

$$P_{12} - (R_{17} + a_{17}) \dot{w}_{25} - [P_{14} - a_{17} \dot{w}_{26}] e^{-T_{17}s} = 0 \tag{1-31}$$

$$P_{14} + a_{17} \dot{w}_{26} - [P_{12} - (R_{17} - a_{17}) \dot{w}_{25}] e^{-T_{17}s} = 0 \tag{1-32}$$

$$P_{17} - a_{21} (\dot{w}_{37} - \dot{w}_{38}) - [P_{14} + (R_{21} - a_{21}) \dot{w}_{27}] e^{-T_{21}s} = 0 \tag{1-33}$$

$$P_{14} + (R_{21} + a_{21}) \dot{w}_{27} - [P_{17} + a_{21} (\dot{w}_{37} - \dot{w}_{38})] e^{-T_{21}s} = 0 \tag{1-34}$$

$$P_{14} - a_{18} (\dot{w}_{26} + \dot{w}_{27}) - [P_{15} + (R_{18} - a_{18}) \dot{w}_{29}] e^{-T_{18}s} = 0 \tag{1-35}$$

$$P_{15} + (R_{18} + a_{18}) \dot{w}_{29} - [P_{14} + a_{18} (\dot{w}_{26} + \dot{w}_{27})] e^{-T_{18}s} = 0 \tag{1-36}$$

$$P_{15} - (R_{19} + a_{19})(\dot{w}_{29} - \dot{w}_{31}) - [P_{15} - (R_{19} - a_{19})(\dot{w}_{29} - \dot{w}_{31})] e^{-2T_{19}s} = 0 \tag{1-37}$$

$$P_{15} - a_{20} \dot{w}_{31} - [Y + (R_{20} - a_{20}) \dot{w}_{32}] e^{-T_{20}s} = 0 \tag{1-38}$$

$$P_{16} + (R_{20} + a_{20}) \dot{w}_{32} - [P_{15} + a_{20} \dot{w}_{31}] e^{-T_{20}s} = 0 \tag{1-39}$$

TABLE 1. (Continued)

$$P_{17} - a_{25}\,\dot{w}_{38} - [P_{18} + (R_{25} - a_{25})\,\dot{w}_{39}]\,e^{-T_{25}s} = 0 \tag{1-40}$$

$$P_{18} + (R_{25} + a_{25})\,\dot{w}_{39} - [P_{17} + a_{25}\,\dot{w}_{38}]\,e^{-T_{25}s} = 0 \tag{1-41}$$

$$P_{18} - a_{26}\,\dot{w}_{39} - [P_{19} + (R_{26} - a_{26})\,\dot{w}_{40}]\,e^{-T_{26}s} = 0 \tag{1-42}$$

$$P_{19} + (R_{26} + a_{26})\,\dot{w}_{40} - [P_{18} + a_{26}\,\dot{w}_{39}]\,e^{-T_{26}s} = 0 \tag{1-43}$$

$$P_{19} - (R_{27} + a_{27})(\dot{w}_{40} - \dot{w}_{42}) - [P_{19} - (R_{27} - a_{27})(\dot{w}_{40} - \dot{w}_{42})]\,e^{-2T_{27}s} = 0 \tag{1-44}$$

$$P_{19} - a_{28}\,\dot{w}_{42} - [P_{20} + (R_{28} - a_{28})\,\dot{w}_{43}]\,e^{-T_{28}s} = 0 \tag{1-45}$$

$$P_{20} + (R_{28} + a_{28})\,\dot{w}_{43} - [P_{19} + a_{28}\,\dot{w}_{42}]\,e^{-T_{28}s} = 0 \tag{1-46}$$

$$P_{20} - a_{29}\,\dot{w}_{43} - [P_{21} + (R_{29} - a_{29})\,\dot{w}_{44}]\,e^{-T_{29}s} = 0 \tag{1-47}$$

$$P_{21} + (R_{29} + a_{29})\,\dot{w}_{44} - [P_{20} + a_{29}\,\dot{w}_{43}]\,e^{-T_{29}s} = 0 \tag{1-48}$$

$$P_{21} - a_{30}\,\dot{w}_{44} - [P_{22} + (R_{30} - a_{30})\,\dot{w}_{45}]\,e^{-T_{30}s} = 0 \tag{1-49}$$

$$P_{22} + (R_{30} + a_{30})\,\dot{w}_{45} - [P_{21} + a_{30}\,\dot{w}_{44}]\,e^{-T_{30}s} = 0 \tag{1-50}$$

$$P_{22} - Z_F s\,\dot{w}_{46} - R_F\,\dot{w}_{46} = P_F \tag{1-51}$$

$$s\,P_{22} - \left(\frac{c^2}{gV}\right)_F (\dot{w}_{45} - \dot{w}_{46}) + \left(\frac{c^2}{gV}\right)_F K_F\,sP_{22} = \left(\frac{c^2}{gV}\right)_F K_F\,s\bar{P}_F \tag{1-52}$$

TABLE 1. (Concluded)

$$P_4 + (R_6 + a_6)\,\dot{w}_8 - [P_3 + a_6\,\dot{w}_7]\,e^{-T_6 s} = 0 \qquad 1\text{-}53$$

$$P_{10} + (R_{12} + a_{12})\,\dot{w}_{20} - [P_9 + a_{12}\,\dot{w}_{19}]\,e^{-T_{12} s} = 0 \qquad 1\text{-}54$$

$$P_{17} + (R_{24} + a_{24})\,\dot{w}_{37} - [P_{13} + a_{24}\,\dot{w}_{36}]\,e^{-T_{24} s} = 0 \qquad 1\text{-}55$$

$$X = P_{10} \qquad 1\text{-}56$$

$$Y = P_{16} \qquad 1\text{-}57$$

NOTE: $a_N = \frac{c_N}{A_N g}$

It should be noted that the hydrodynamics subprogram solves the complete system of 57 equations (describing the complete Fig. 4 feed system) each time it is called. Thus the frequency response of the entire system is calculated each time. It has been shown, however, that simpler feed systems, representing only a portion of the Fig. 4 schematic, can be modeled by merely assigning values to the parameters of the unneeded line segments which will exclude them from any effect on the system frequency response. This is accomplished automatically by the hydrodynamics subprogram via the assignment of very large resistances and very short lengths to all line segments for which no data is entered.

COMBUSTION DYNAMICS

Analytical Approach

In the past, the combustion response has been modeled with a simple time delay(s) (Ref. 3 through 9). This time delay represents the time required for the propellants to travel at their injected velocity from the point where they are injected to another point where they burn, and implies the burning is concentrated at a fixed plane some arbitrary distance from the injector face. The procedure outlined above is obviously an oversimplification of the burning process which is distributed in some fashion throughout the combustion chamber.

Steady-state combustion models (Ref. 10 and 11 for example) provide insight to determine the droplet burning distribution as well as additional information required to relate the distribution to a combustion response as a function of frequency. Combustion models are designed to march incrementally down the combustion chamber from a set of specified initial conditions. In so doing, the model calculates the rate at which the propellants are consumed as a function of the axial position in the combustion chamber (burning rate profile).

The analytical technique selected to describe the combustion dynamics is based on employing the mathematical expressions used in the steady-state combustion models (in particular the JANNAF DER program, Ref. 11). These mathematical expressions are expanded into time average and oscillatory components and are described in the following sections.

Atomization Process

A very essential part of the combustion field initialization is the assignment of propellant spray droplet sizes and flowrates. Analytical descriptions of the atomization process are not available but empirical correlations that relate droplet diameter to injector geometry and flow conditions are available (Refs. 12, 13, and 14). For like-doublets, one empirical relations~~hi~~p is (Ref. 12).

$$D_d = 4.85 \times 10^4 \, v_j^{-0.75} \, (p_c/p_j)^{-0.52} \, d_j^{0.57} \tag{46}$$

where v_j is the liquid jet velocity and d_j is the liquid jet diameter at the atomization plane. (For steady-state analysis, the velocity is the injection velocity and the diameter is the orifice diameter.)

For purposes of the current analysis, the atomization process is described by:

$$D_d = K(d_j)^a_{x=x_{imp}} \quad (v_j)^b_{x=x_{imp}} \tag{47}$$

where x_{imp} is the location of the atomization plane or the impingement point. Expanding Eq. 47 into time-averaged and oscillatory parts, yields the oscillatory droplet diameter

$$\frac{\tilde{D}_d}{\bar{D}_d} = a\left(\frac{\tilde{d}_j}{\bar{d}_j}\right)_{x=x_{imp}} + b\left(\frac{\tilde{v}_j}{\bar{v}_j}\right)_{x=x_{imp}} \tag{48}$$

In order to evaluate the oscillatory droplet diameter, the oscillatory liquid jet diameter and velocity (and therefore the jet flowrate) are required at the atomization plane. Therefore, the dynamics of the fluid from the injector to the atomization plane is required and outlined in the following section.

Klystron Effect

The dynamics of the liquid propellant jet from the injector face to any location in the chamber are described by the continuity and momentum equations:

$$\frac{\partial}{\partial t}\left(A_j\rho_j\right) + \frac{\partial}{\partial x}\left(A_j\rho_j v_j\right) = 0 \tag{49}$$

$$\frac{\partial}{\partial t}\left(A_j\rho_j v_j\right) + \frac{\partial}{\partial x}\left(A_j\rho_j v_j^2\right) = -A_j\frac{\partial p}{\partial x} \tag{50}$$

Assuming

$$\rho_j = \text{constant} \tag{51}$$

$$\frac{\partial p}{\partial x} = 0 \tag{52}$$

$$\phi = \bar{\phi} + \tilde{\phi} \qquad (\phi \text{ any variable}), \tag{53}$$

where

$$\bar{\phi} = f(x) \qquad \text{(time average value)} \tag{54}$$

$$\tilde{\phi} = \phi' e^{-i\omega t} \qquad \text{(oscillatory value)} \tag{55}$$

$$\phi' = g(x), \tag{56}$$

the preceding equations can be expanded into time average and oscillatory parts and integrated between the injector face and any location in the chamber to yield:

$$\left(\frac{\tilde{v}_j}{\bar{v}_j}\right) = e^{i\omega x/\bar{v}_j} \left(\frac{\tilde{\dot{m}}_j}{\bar{\dot{m}}_j}\right)_{inj} \tag{57}$$

$$\left(\frac{\tilde{A}_j}{\bar{A}_j}\right) = \frac{-i\omega x}{\bar{v}_j} \quad e^{i\omega x/\bar{v}_j} \left(\frac{\tilde{\dot{m}}_j}{\bar{\dot{m}}_j}\right)_{inj} \tag{58}$$

$$\left(\frac{\tilde{\dot{m}}_j}{\bar{\dot{m}}_j}\right) = e^{i\omega x/\bar{v}_j} \left[1 - \frac{i\omega x}{\bar{v}_j}\right] \left(\frac{\tilde{\dot{m}}_j}{\bar{\dot{m}}_j}\right)_{inj} \tag{59}$$

where ω is the angular frequency and the oscillatory injection rate, $(\tilde{\dot{m}}_j)_{inj}$ is determined by the feed system dynamics. Equation 59 is the oscillatory jet flowrate at x and is usually referred to as the Klystron effect (Ref. 15). The Klystron time delay, τ_K, is therefore given by

$$\tau_{K_j} = \frac{x_{K_j}}{\bar{v}_j} \tag{60}$$

Considerable amplification of the injector face flow oscillations are possible when the Klystron effect is present and could explain the periodic burst of acoustic resonances called resurging and the steep-fronted waves seen in low and intermediate frequency instabilities.

Droplet Vaporization

Theories of droplet combustion (Refs. 10, 16, 17) are available which may be used to evaluate the extent of coupling between droplet burning rate and local pressure and velocity fluctuations. In general, droplet burning is enhanced by increased turbulence levels or by periodic directional variations in velocity, because droplets are relatively heavy and resist following gas streamlines.

Calculation of the spray heating and vaporization is usually accomplished through specification of the corresponding individual droplet processes and summation over all the droplets that constitute the spray(s) being analyzed. The calculation of single droplet evaporation is usually based on a spherically symmetric model of simultaneous heat transfer and mass transfer across the gas side boundary, or film, separating the liquid droplet from the surrounding hot combustion gas. Forced convection and resultant nonspherical transfer processes are accounted for through empirical Nusselt number correlations for both heat and mass transfer.

For the fuel or oxidizer spray, the droplet continuity equation is

$$\frac{d}{dx}(A\rho_k v_k) = -A\, N_k\, \dot{m}_{vap_k} \tag{61}$$

and the vaporization rate is (Ref. 10)

$$\dot{m}_{vap_k} = \frac{\pi D_k\, k_{f_k}\, Nu_{H_k}\, Z_k}{C_{p_{v_k}}} \tag{62}$$

where ρ_k is the spray density (mass of spray per unit chamber volume), N_k is the number of droplets per unit chamber volume, and

$$Z_k \equiv \frac{c_{p_{v_k}} \, Nu_{m_k} \, p \, MW_{v_k} \, \mathcal{D}_{v_k}}{k_{f_k} \, Nu_{H_k} \, R \, T_{f_k}} \, \ell n \left(\frac{p}{p - p_{v_k}} \right) \tag{63}$$

Noting that

$$\rho_k = N_k m_k = N_k \, \rho_{\ell_k} \, \frac{\pi D_k^3}{6} \tag{64}$$

the droplet number flowrate can be written as

$$\dot{N}_k = v_k \, A \, N_k = \frac{A \, v_k \rho_k}{m_k} \tag{65}$$

Therefore, Eq. 61 can be written as

$$\frac{d}{dx} (m_k \dot{N}_k) = - \frac{\dot{N}_k}{v_k} \, \dot{m}_{vap_k} \tag{66}$$

For steady-state combustion models, the preceding equation (along with Eq. 62) is numerically integrated allowing the droplet diameter, D_k, to vary along the length of the combustion and maintaining constant droplet number flowrate ($\dot{N}_k$). Combs (Ref. 18) has shown that changing from a variable droplet diameter to a variable droplet number flowrate yields approximately the same results for steady-state vaporization. Therefore, in order to simplify the integration for stability analysis, the droplet diameter was held constant and the droplet number flowrate was assumed to vary.

Summing Eq. 61 over all fuel or oxidizer droplet size groups yields

$$\sum_k \frac{d}{dx} (A \, \rho_k v_k) = -A \sum_k \rho_k \frac{\dot{m}_{vap_k}}{m_k} = -A \sum_k \frac{\rho_k \, (6) Z_k \, k_{f_k} \, Nu_{H_k}}{\rho_{\ell_k} \, D_k^2 \, c_{p_{v_k}}} \tag{67}$$

which can be written as

$$\frac{d}{dx}\left(A\rho_s v_s\right) = -\frac{A\rho_s}{\tau_s} = -A\,\dot{m}_{vap_s} \quad , \tag{68}$$

where

$$\rho_s \equiv \sum_k \rho_k \tag{69}$$

$$v_s \equiv \frac{1}{\rho_s}\sum_k \left(\rho_k v_k\right) \tag{70}$$

$$\frac{1}{\tau_s} \equiv \frac{1}{\rho_s}\sum_k \frac{\rho_k (6) Z_k\ k_{f_k}\ Nu_{H_k}}{\rho_{\ell_k}\ D_k^2\ c_{p_{v_k}}} \tag{71}$$

Letting Z_k, k_{f_k}, $c_{p_{v_k}}$ be independent of k and assuming

$$\tau_s = f(t) \tag{72}$$

yields:

$$\tau_s = \frac{\rho_{\ell_s}\ c_{p_{v_s}}\ D_s^2}{(6) Z_s\ k_{f_s}\ Nu_{H_s}} \tag{73}$$

where

$$D_s^2 = \left(\dot{m}_s\right)_{inj} \Big/ \sum_k \left(\frac{\dot{m}_k}{D_k^2}\right)_{inj} \quad . \tag{74}$$

From Eq. 68

$$\frac{d\left(A\rho_s v_s\right)}{A\rho_s\ v_s} = -\frac{dx}{\tau_s v_s} \tag{75}$$

Integrating Eq. 75 between x_0, the start of vaporization plane, and any location x yields

$$A\rho_s v_s = (\dot{m}_x)_{x=x_0} \quad \exp\left[-\int_{x_0}^{x} \frac{dx}{\tau_s v_s}\right] \tag{76}$$

substituting Eq. 76 into Eq. 68 yields the fuel or oxidizer spray vaporization rate:

$$\dot{m}_{vap_s} = \frac{(\dot{m}_s)_{x=x_0}}{A\tau_s v_s} \quad \exp\left[-\int_{x_0}^{x} \frac{dx}{\tau_s v_s}\right] \tag{77}$$

Using perturbation techniques, the time average vaporization rate can be written as

$$\bar{\dot{m}}_{vap_s} = \frac{(\bar{\dot{m}}_s)_{x=x_0}}{A\bar{\tau}_s \bar{v}_s} \quad \exp\left[-\frac{(x-x_0)}{\bar{\tau}_s \bar{v}_s}\right] \tag{78}$$

and the oscillatory vaporization rate can be written as

$$\tilde{\dot{m}}_{vap_s} = \bar{\dot{m}}_{vap_s} \left\{ \frac{(\dot{m}_s)_{x=x_{K_s}}}{(\bar{\dot{m}}_s)_{x=x_0}} - \frac{\tilde{\tau}_s}{\bar{\tau}_s} - \frac{\tilde{v}_s}{\bar{v}_s} + \int_{x_0}^{x} \left(\frac{\tilde{\tau}_s}{\bar{\tau}_s} + \frac{\tilde{v}_s}{\bar{v}_s} \right) \frac{dx}{\bar{\tau}_s \bar{v}_s} \right\} \tag{79}$$

Assuming

$$v_s \approx (v_s)_{x=x_{k_s}} \tag{80}$$

yields

$$\frac{\tilde{v}_s}{\bar{v}_s} = \left(\frac{\tilde{v}_s}{\bar{v}_s}\right)_{x=x_{k_s}} \tag{81}$$

Letting ρ_{ℓ_s}, $c_{p_{v_s}}$, and k_{f_s} be constant, the oscillatory time delay can therefore be expressed as

$$\frac{\tilde{\tau}_s}{\bar{\tau}_s} = 2\,\frac{\tilde{D}_s}{\bar{D}_s} - \frac{\tilde{Z}_s}{\bar{Z}_s} - \frac{\widetilde{Nu}_{H_s}}{\overline{Nu}_{H_s}} + \left(\frac{\partial \tau_s}{\partial MR}\right)\frac{\widetilde{MR}}{\bar{\tau}_s} \tag{82}$$

The oscillatory spray droplet diameter (D_s) is given by Eq. 48 and the oscillatory flowrate is given by Eq. 59. The above formulation results in a linear oscillatory vaporization model similar to, but more realistic than Crocco's n-τ model (Ref. 4). The formulation includes the effects of: (1) distributed energy release, (2) oscillations in the injection rate, (3) oscillations in droplet diameter, (4) oscillations in droplet temperature, (5) gas pressure and velocity oscillations, and (6) oscillations in the local mixture ratio.

Nusselt Number. It may be observed that one of the dominant terms in both the expressions for the average and oscillatory time delay is the Nusselt number. The Nusselt number, for longitudinal modes, is (Ref. 19).

$$Nu_{H_s} = 2.0 + 0.6\, Pr_s^{1/3} \left[\frac{\rho D_s}{\mu}\,|v - v_s|\right]^{1/2} \tag{83}$$

In order to evaluate the oscillatory Nusselt number, the oscillatory droplet spray velocity is required. The droplet spray velocity can be obtained from the drag equation.

$$m_s \frac{dv_s}{dt} = \frac{\pi}{8}\,\rho\, D_s^2\, |v - v_s|\,(v - v_s)\, C_{D_s} \tag{84}$$

Letting

$$\tau_{drag_s} \equiv \frac{\rho_{\ell_s} D_s^2}{(18)\,\alpha_s\,\mu} \tag{85}$$

where

$$\alpha_s \equiv \frac{C_{D_s}}{24}\left(\frac{D_s\,\rho}{\mu}\,|v - v_s|\right) , \tag{86}$$

the oscillatory droplet spray velocity can be written as

$$\tilde{v}_s = \left[\frac{1 + i\omega\,\tau_{drag_s}}{1 + (\omega\,\tau_{drag_s})^2}\right]\tilde{v} = R_{v_s}\,\tilde{v} \tag{87}$$

Defining

$$F_\rho \equiv \left(\frac{\rho}{\bar{\rho}}\right)^{\frac{1}{2}} , \quad F_{v_s} = \left[\frac{|v-v_s|}{c\Delta M_s}\right]^{1/2} \tag{88}$$

where

$$\Delta M_s \equiv \left[\frac{|v-v_s|}{c}\right]_{\text{steady state}} , \tag{89}$$

the Nusselt number can be written as

$$Nu_{H_s} = 2.0 + 0.6\,Pr_s^{1/3}\left[\frac{\bar{\rho}\bar{D}_s}{\mu}\;c\Delta M_s\right]^{1/2} F_\rho\;F_{v_s}\left(\frac{D_s}{\bar{D}_s}\right)^{1/2} \tag{90}$$

Expanding the preceding equation into time average and oscillatory parts yields

$$\overline{Nu}_{H_s} = 2.0 + 0.6 \, Pr_s^{1/3} \left[\frac{\bar{\rho} \, \bar{D}_s}{\mu} \, c\Delta M_s \right]^{\frac{1}{2}} \bar{F}_\rho \bar{F}_{v_s} \tag{91}$$

$$\frac{\widetilde{Nu}_{H_s}}{\overline{Nu}_{H_s}} = \left(\frac{\overline{Nu}_{H_s} - 2}{\overline{Nu}_{H_s}} \right) \left[\frac{1}{2} \left(\frac{\tilde{D}_s}{\bar{D}_s} \right) + \frac{\tilde{F}_\rho}{\bar{F}_\rho} + \frac{\tilde{F}_{v_s}}{\bar{F}_{v_s}} \right] \tag{92}$$

Letting

$$\frac{\tilde{F}_{v_s}}{\bar{F}_{v_s}} = R_{F_{v_s}} \frac{\tilde{v}}{\bar{c}} \text{, and} \tag{93}$$

$$\frac{\tilde{F}_\rho}{\bar{F}_\rho} = R_{F_\rho} \frac{\tilde{\rho}}{\bar{\rho}} \text{ ,} \tag{94}$$

the oscillatory Nusselt number is

$$\frac{\widetilde{Nu}_{H_s}}{\overline{Nu}_{H_s}} = \frac{\overline{Nu}_{H_s} - 2}{\overline{Nu}_{H_s}} \left[\frac{1}{2} \left(\frac{\tilde{D}_s}{\bar{D}_s} \right) + R_{F_\rho} \left(\frac{\tilde{\rho}}{\bar{\rho}} \right) + R_{F_{v_s}} \left(\frac{\tilde{v}}{\bar{c}} \right) \right] \tag{95}$$

For small perturbations in the pressure, the linear response factors and the time average values for F_ρ and F_v are

$$\bar{F}_\rho = 1 \; , \; \bar{F}_{v_s} = 1 \tag{96}$$

$$R_{F_\rho} = \frac{1}{2} \; , \; R_{F_{v_s}} = \frac{1}{2} \left(\frac{1-R_{v_s}}{\Delta M_s} \right) \tag{97}$$

Calculations have been made which indicate that, for large droplet diameters, the average and oscillatory Nusselt numbers are quite sensitive to pressure and velocity oscillations. Therefore, the Nusselt number can have a significant effect on engine stability.

Droplet Heat Transfer Blockage Term. The oscillatory combustion time delay given by Eq. 82 requires the evaluation of the heat transfer blockage term (Z_s) which is related to the combustion gas and liquid vapor properties by Eq. 63. Because the vapor pressure (P_{v_s}) at the droplet surface is related to the droplet temperature, the blockage term also depends on the oscillatory droplet surface temperature inside the droplet which is given by:

$$\frac{\partial}{\partial t} (\rho_\ell \, c_{v_\ell} \, T_\ell) = \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \, k_{eff_\ell} \frac{\partial T_\ell}{\partial r} \right) \tag{98}$$

Therefore, the oscillatory heat transfer rate to the droplet can be related to the oscillatory droplet surface temperature by

$$\tilde{Q}_s = R_{T_s} \tilde{T}_s \tag{99}$$

The droplet heating rate can also be written as (Ref. 10)

$$Q_s = Z_s \, k_{f_s} \, Nu_{H_s} \left[\frac{(T - T_s)}{(e^{Z_s} - 1)} - \frac{\Delta H_{vap_s}}{c_{p_{v_s}}} \right] (\pi D_s) \tag{100}$$

Assuming that

$$\left(\frac{d\bar{T}_s}{dt} \right) = 0 \qquad \text{(droplet at "wet bulb" temperature)} \tag{101}$$

and

$$\frac{\tilde{p}_v}{\bar{p}_v} = R_{p_v} \quad \frac{\tilde{p}}{\bar{p}} \qquad , \tag{102}$$

etc. for the other variables, the response factor for the heat transfer blockage term can be related to droplet and gas properties and flow conditions.

Examination of the response factor for the heat transfer blockage term indicates that this term is not important at low frequencies (also see Ref. 20 and 21). Therefore, the oscillatory heat blockage term has not been included in the computer program. Detailed equations for this term are presented in Appendix B of Ref. 1.

Generalized Vaporization Rate Expression

In order to maintain generality in representing the combustor dynamics, the spray vaporization rates (fuel and oxidizer) were written as:

$$\begin{aligned}\tilde{\dot{m}}_{vap_s} = \bar{\dot{m}}_{vap_s} \Bigg\{ & c_{1_s}\left(\frac{\tilde{p}}{\bar{p}}\right)_{x=0} + c_{2_s}\left(\frac{\tilde{p}}{\bar{p}}\right) + c_{3_s}\left(\frac{\tilde{\rho}}{\bar{\rho}}\right)_{x=0} \\ & + c_{4_s}\left(\frac{\tilde{\rho}}{\bar{\rho}}\right) + c_{5_s}(\widetilde{MR})_{x=0} + c_{6_s}(\widetilde{MR}) \\ & + c_{7_s}\left(\frac{\tilde{v}}{\bar{c}}\right)_{x=0} + c_{8_s}\left(\frac{\tilde{v}}{\bar{c}}\right) + \int_{x_0}^{x} \Bigg[c_{9_s}\left(\frac{\tilde{p}}{\bar{p}}\right)_{x=0} \\ & + c_{10_s}\left(\frac{\tilde{p}}{\bar{p}}\right) + c_{11_s}\left(\frac{\tilde{\rho}}{\bar{\rho}}\right)_{x=0} + c_{12_s}\left(\frac{\tilde{\rho}}{\bar{\rho}}\right) + c_{13}(\widetilde{MR})_{x=0} \\ & + c_{14_s}(\widetilde{MR}) + c_{15_s}\left(\frac{\tilde{v}}{\bar{c}}\right)_{x=0} + c_{16_s}\left(\frac{\tilde{v}}{\bar{c}}\right) \Bigg] \frac{dx}{\bar{\tau}_s \bar{v}_s} \Bigg\}\end{aligned} \tag{103}$$

Combining the expressions of the preceding sections with this generalized vaporization rate expression yielded the combustion coefficients:

$$c_{1_s} = R_{m_s} - R_{v_s} - 2 R_{D_s} + \left(\frac{\bar{\bar{Nu}}_s - 2}{\bar{Nu}_s}\right) \frac{R_{D_s}}{2} \tag{104}$$

$$c_{4_s} = R_{F_{\rho_s}} \left(\frac{\bar{Nu}_s - 2}{\bar{Nu}_s}\right) \tag{105}$$

$$c_{6_s} = - \left(\frac{\partial \tau_s}{\partial \, MR} \right) \frac{1}{\bar{\tau}_s} \tag{106}$$

$$c_{8_s} = R_{F v_s} \left(\frac{\overline{Nu}_s - 2}{\overline{Nu}_s} \right) \tag{107}$$

$$c_{9_s} = 2 \, R_{D_s} - \left(\frac{\overline{Nu}_s - 2}{\overline{Nu}_s} \right) \frac{R_{D_s}}{2} + R_{V_s} \tag{108}$$

$$c_{12_s} = - c_{4_s} \tag{109}$$

$$c_{14_s} = - c_{6_s} \tag{110}$$

$$c_{16_s} = - c_{8_s} \tag{111}$$

$$c_{2_s} = c_{3_s} = c_{5_s} = c_{7_s} = c_{10_s} = c_{11_s} = c_{13_s} = c_{15_s} = 0 \tag{112}$$

where the subscript s denotes the fuel or oxidizer and

$$R_{m_s} = G_{inj_s} \left(1 - \frac{i\omega \, x_{k_s}}{\bar{v}_s} \right) \tag{113}$$

$$R_{u_s} = G_{inj_s} \tag{114}$$

$$R_{D_s} = \left[b_s - a_s \frac{i\omega \, x_{imp_s}}{\bar{v}_s} \right] G_{inj_s} \tag{115}$$

In the above expressions G_{inj_s} is the oscillatory injection rate divided by the oscillatory pressure at the injector face and is calculated by the hydrodynamics subprogram.

The main function of the combustion dynamics subprogram is the calculation of the combustion coefficients. The general spray vaporization rate expressions are used in the chamber dynamic subprogram which is discussed in the following section.

CHAMBER DYNAMICS

Analytical Approach

Two methods of approach were considered for solving the chamber dynamics. The first method used a linear lump chamber coefficient. This method is valid only at low frequencies (less than 500 Hz) and results in a set of nonlinear algebraic equations to be solved.

The second method employed a first-order perturbation model to define the chamber frequency and growth coefficient along with the oscillatory pressure distribution in the chamber. This method is valid for all frequencies of interest in the present program (10 to 1000 Hz). For the oscillatory variables, solutions of the form $\tilde{\phi} = \phi' e^{-i\omega t}$, where ω is the complex frequency, were assumed. These forms yielded a set of nonlinear differential equations which were numerically integrated between the injector face and the nozzle inlet plane. Using iteration techniques and the requisite boundary conditions at the injector and nozzle inlet plane, the chamber frequency and growth coefficient are obtained.

Consideration of the degree of complexity in solving the governing equations by each of the above methods as well as the range of validity of each approach resulted in choosing the first-order perturbation models as the best method for describing the chamber dynamics. In the following paragraphs, the derivation and solution to the first-order perturbation model stability equations are presented.

First-Order Perturbation Model

In this section, chamber model equations are stated without showing their detail derivations. Complete derivation of the basic equations is presented in Ref. 1. Assumptions used in the derivation of the basic equations are: (1) ideal gas flow is a valid state equation; (2) dilute sprays occupy a negligible fraction of chamber volume; (3) the spray can be represented by a finite number of dropsize groups; each dropsize group contains a large number of locally identical drops; and, each size group constitutes a separate liquid phase and exchange terms between liquid phases are not included; (4) drag contributes only kinetic energy to the spray energy equation; (5) secondary "shear" breakup of drops is not included; (6) negligible coupling between diffusion and thermal gradients; and (7) no body forces.

The following equations can be formulated for the gas phase:

Gas Continuity

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = \sum_n \sum_j \left(N_j^n \, \dot{m}^n_{vap_j} \right) \tag{116}$$

Gas Momentum

$$\frac{\partial}{\partial t} (\rho \vec{u}) + \nabla \cdot (\rho \vec{u};\ \vec{u}) = -\nabla p + \nabla \cdot \underline{\underline{\tau}} - \sum_n \sum_j \left[N_j^n \left(\vec{F}_j^n - \dot{m}^n_{vap_j} \, \vec{u}_j^n \right) \right] \tag{117}$$

Equation of State

$$p = \rho R T \tag{118}$$

Shear Stress

$$\underline{\underline{\tau}} = -\mu_{eff} \left[\nabla \vec{u} + (\nabla \vec{u})^t - \frac{2}{3} (\nabla \cdot \vec{u}) \, \underline{\underline{I}} \right] \tag{119}$$

Gas Energy

$$\begin{aligned} \frac{\partial}{\partial t} \left[\rho \left(h + \frac{u^2}{2} \right) \right] + \nabla \cdot \left[\rho \vec{u} \left(h + \frac{u^2}{2} \right) \right] &= - \nabla \cdot \vec{q} + \nabla \cdot (\vec{u} \underline{\underline{\tau}}) + \frac{\partial p}{\partial t} \\ &\quad + \sum_n \sum_j \left\{ N_j^n \left[\dot{m}^n_{vap_j} \left(h_j + \frac{(u_j^n)^2}{2} \right) \right. \right. \\ &\quad \left. \left. - Q_j^n - \vec{u}_j^n \cdot \vec{F}_j^n \right] \right\} \end{aligned} \tag{120}$$

Gas Mixture Ratio

$$\frac{\partial}{\partial t}(\rho MR) + \nabla\cdot(\rho\vec{u}\,MR)$$

$$- \rho\,\mathcal{D}_{eff}\left[\nabla^2 MR - \frac{2|\nabla MR|^2}{MR + 1}\right]$$

$$- (\nabla MR)\cdot\nabla(\rho\,\mathcal{D}_{eff}) =$$

$$(2\,MR + 1)\left[\sum_n \sum_j^{ox} N_j^n\,\dot{m}^n_{vap_j}\right]$$

$$- (MR)^2\left[\sum_n \sum_j^{fu} N_j^n\,\dot{m}^n_{vap_j}\right] \qquad (121)$$

Heat Transfer Rate

$$\vec{q} = -k_{eff}\nabla T - \sum_i (\rho\,\mathcal{D}_{eff})\,h_i\,\nabla y_i \qquad (122)$$

Drag Force

$$\vec{F}_j^n = \frac{\pi}{8}\left\{\rho\,(D_j^n)^2\left|\vec{u} - \vec{u}_j^n\right|(\vec{u} - \vec{u}_j^n)\;C^n_{D_j}\right\} \qquad (123)$$

Assuming

(1) Diffuser, thermal and viscous gradients are negligible,

(2) Droplet drag forces and heat transfer to the droplets are negligible,

(3) Droplet velocities are approximately equal to the gas velocity,

and letting

$$h = \left(\frac{c_p}{R}\right)_\phi RT + (h_{ref})_\phi + \left(\frac{\partial h}{\partial MR}\right)_\phi (MR - MR_\phi), \qquad (124)$$

$$\left(\frac{c_p}{R}\right)_\phi = \frac{\gamma_\phi}{(\gamma_\phi - 1)}, \qquad (125)$$

$$R = R_\phi + \left(\frac{\partial R}{\partial MR}\right)_\phi (MR - MR_\phi), \qquad (126)$$

$$\dot{m}_{vap_{ox}} \equiv \sum_{n}^{ox} \sum_{j} N_j^n \, \dot{m}^n_{vap_j} \qquad (127)$$

$$\dot{m}_{vap_{fu}} \equiv \sum_{n}^{fu} \sum_{j} N_j^n \, \dot{m}^n_{vap_j} \qquad (128)$$

where the subscript ϕ denotes that the properties are evaluated based on the overall injection mixture ratio during steady-state operation, the preceding equations can be simplified for longitudinal modes to

Gas Continuity

$$A \frac{\partial p}{\partial t} + \frac{\partial}{\partial x} (A \rho \, v) = A \left(\dot{m}_{vap_{ox}} + \dot{m}_{vap_{fu}} \right) \qquad (129)$$

Gas Momentum

$$\rho \frac{\partial v}{\partial t} + \rho v \frac{\partial v}{\partial x} + \frac{\partial p}{\partial x} = 0 \qquad (130)$$

Equation of State

$$p = \rho T \left[R_\phi + \left(\frac{\partial R}{\partial MR} \right)_\phi (MR - MR_\phi) \right] \qquad (131)$$

Gas Energy

$$\begin{aligned} A \frac{\partial p}{\partial t} + Av \frac{\partial p}{\partial x} + \gamma_\phi \, p \frac{\partial}{\partial x} (Av) = \\ (\gamma_\phi - 1) A \Bigg\{ \dot{m}_{vap_{ox}} \left[\Delta h_{ox} - \left(\frac{\partial h}{\partial MR} \right)_\phi (2\, MR + 1) \right] \\ + \dot{m}_{vap_{fu}} \left[\Delta h_{fu} + \left(\frac{\partial h}{\partial MR} \right)_\phi (MR)^2 \right] \Bigg\} \end{aligned} \qquad (132)$$

Gas Mixture Ratio

$$\rho \frac{\partial MR}{\partial t} + \rho v \frac{\partial MR}{\partial x} = (MR + 1) \left[\dot{m}_{vap_{ox}} - (MR) \, \dot{m}_{vap_{fu}} \right] \qquad (133)$$

Because of the complexity in solving nonlinear partial differential equations, perturbation techniques were used to simplify the governing dynamic equations. Assuming

$$\phi = \bar{\phi} + \tilde{\phi} \quad (\phi \text{ any variable}), \tag{134}$$

where

$$\bar{\phi} = f\,(x) \tag{135}$$

and

$$\tilde{\phi} = g\,(x,\ t), \tag{136}$$

each perturbation quantity was taken to be of order (ε), where (ε) is a small ordering parameter that is a measure of the wave amplitude. The perturbation expressions for each of the independent variables were substituted back into the nonlinear partial differential equations, where all terms of the order (ε^2) or higher were neglected. The resulting time-averaged equations were solved for the time-averaged variables and the oscillatory equations were solved by assuming solutions of the form

$$\tilde{\phi} = \phi' \, e^{-i\omega t} \tag{137}$$

where $\phi' = f(x)$ and ω is the complex frequency. The resulting equations form a system of ordinary differential equations in terms of the variables ϕ' and can be numerically integrated by employing boundary conditions and iteration techniques.

Following this approach the perturbation equations were expressed as:

$$\rho \equiv \bar{\rho} \left[1 + \rho' \, e^{-i\omega t} \right] \tag{138}$$

$$v \equiv \bar{v} + c_0 \, v' \, e^{-i\omega t} \tag{139}$$

$$T = \bar{T} \left[1 + T' \, e^{-i\omega t} \right] \tag{140}$$

$$p = \bar{p}\left[1 + p' e^{-i\omega t}\right] \tag{141}$$

$$MR = \overline{MR} + MR' e^{-i\omega t} \tag{142}$$

$$\dot{m}_{vap_{ox}} = \bar{\dot{m}}_{vap_{ox}} + \dot{m}'_{vap_{ox}} e^{-i\omega t} \tag{143}$$

$$\dot{m}_{vap_{fu}} = \bar{\dot{m}}_{vap_{fu}} + \dot{m}'_{vap_{fu}} e^{-i\omega t} \tag{144}$$

The time-averaged equations were determined to be:

(a) Gas Continuity

$$\frac{d}{dx}\left(A \bar{\rho} \bar{v}\right) = A\left(\bar{\dot{m}}_{vap_{ox}} + \bar{\dot{m}}_{vap_{fu}}\right) \tag{145}$$

(b) Gas Momentum

$$\bar{\rho} \bar{v} \frac{d\bar{v}}{dx} + \frac{d\bar{p}}{dx} = 0 \tag{146}$$

(c) Equation of State

$$\bar{p} = \bar{\rho} R_0 \bar{T}\left[1 + \frac{1}{R_0}\left(\frac{\partial R}{\partial MR}\right)_0 \left(\overline{MR} - MR_0\right)\right] \tag{147}$$

(d) Gas Energy

$$\begin{aligned} A \bar{v} \frac{d\bar{p}}{dx} + \gamma_0 \bar{p} \frac{d}{dx}\left(A \bar{v}\right) = {} & \\ (\gamma_0 - 1) A \Big\{ & \bar{\dot{m}}_{vap_{ox}}\left[\Delta h_{ox} - \left(\frac{\partial h}{\partial MR}\right)_0 \left(2\,\overline{MR} + 1\right)\right] \\ & + \bar{\dot{m}}_{vap_{fu}}\left[\Delta h_{fu} + \left(\frac{\partial h}{\partial MR}\right)_0 \left(\overline{MR}\right)^2\right]\Big\} \end{aligned} \tag{148}$$

(e) Gas Mixture Ratio

$$\bar{\rho} \bar{v} \frac{d\,\overline{MR}}{dx} = \left(\overline{MR} + 1\right)\left[\bar{\dot{m}}_{vap_{ox}} - \overline{MR}\,\bar{\dot{m}}_{vap_{fu}}\right] \tag{149}$$

and the oscillatory equations were determined to be:

(a) Gas Continuity

$$\rho' \left(\frac{-i\omega}{c_{\emptyset}}\right) + \frac{dv'}{dx} + \frac{v'}{A\bar{\rho}} \frac{d(A\bar{\rho})}{dx} + \left(\frac{\bar{v}}{c_{\emptyset}}\right) \frac{d\rho'}{dx} + \frac{\rho'}{A\bar{\rho}\, c_{\emptyset}} \frac{d}{dx} (A\bar{\rho}\, \bar{v}) = \frac{(\dot{m}'_{vap_{ox}} + \dot{m}'_{vap_{fu}})}{\bar{\rho}\, c_{\emptyset}} \tag{150}$$

(b) Gas Momentum

$$v' \left(\frac{-i\omega}{c_{\emptyset}}\right) + \frac{v'}{c_{\emptyset}} \frac{d\bar{v}}{dx} + \frac{\bar{v}}{c_{\emptyset}} \frac{dv'}{dx} - \frac{\rho'}{\bar{\rho}\, c_{\emptyset}^2} \frac{d\bar{p}}{dx} + \frac{p'}{\bar{\rho}\, c_{\emptyset}^2} \frac{d\bar{p}}{dx} + \frac{\bar{p}}{\bar{\rho}\, c_{\emptyset}^2} \frac{dp'}{dx} = 0 \tag{151}$$

(c) Equation of State

$$p' = \rho' + T' + \frac{\bar{\rho}\,\bar{T}}{\bar{p}} \left(\frac{\partial R}{\partial MR}\right)_{\emptyset} MR' \tag{152}$$

(d) Gas Energy

$$p' \left(\frac{-i\omega}{c_{\emptyset}}\right) + \left(\frac{\bar{v}}{c_{\emptyset}}\right) \left[\frac{dp'}{dx} + \frac{p'}{\bar{p}} \frac{d\bar{p}}{dx}\right] + \frac{v'}{\bar{p}} \frac{d\bar{p}}{dx} + \gamma_{\emptyset} \left[\frac{dv'}{dx} + \frac{v'}{A} \frac{dA}{dx}\right] + \frac{\gamma_{\emptyset}\, p'}{A\, c_{\emptyset}} \frac{d}{dx} (A\, \bar{v}) = \frac{(\gamma_{\emptyset} - 1)}{\bar{p}\, c_{\emptyset}} \left\{ \dot{m}'_{vap_{ox}} \left[\Delta h_{ox} \right.\right.$$

$$- \left(\frac{\partial h}{\partial MR}\right)_{\phi} \left(2\, \overline{MR} + 1\right) \Big] + \dot{m}'_{vap_{fu}} \Big[\Delta h_{fu}$$

$$+ \left(\frac{\partial h}{\partial MR}\right)_{\phi} \left(\overline{MR}\right)^2 \Big] - 2\, \bar{\dot{m}}_{vap_{ox}} \left(\frac{\partial h}{\partial MR}\right)_{\phi} MR'$$

$$+ 2\, \bar{\dot{m}}_{vap_{fu}}\, \overline{MR} \left(\frac{\partial h}{\partial MR}\right)_{\phi} MR' \Big\} \qquad (153)$$

(e) Gas Mixture Ratio

$$MR' \left(\frac{-i\omega}{c_{\phi}}\right) + \left(\frac{\bar{v}}{c_{\phi}}\right) \frac{d\, MR'}{dx} + \left[\left(\frac{\bar{v}}{c_{\phi}}\right) \rho' + v' \right] \frac{d\, \overline{MR}}{dx}$$

$$= \frac{(\overline{MR} + 1)}{\bar{\rho}\, c_{\phi}} \left[\dot{m}'_{vap_{ox}} - \overline{MR}\, \dot{m}'_{vap_{fu}} \right]$$

$$+ \frac{1}{\bar{\rho}\, c_{\phi}} \left[\bar{\dot{m}}_{vap_{ox}} - (2\, \overline{MR} + 1)\, \bar{\dot{m}}_{vap_{fu}} \right] (MR') \qquad (154)$$

In the computer model, the preceding set of ordinary differential equations are numerically integrated between the injector face and the nozzle inlet plane. The method of calculating the complex frequency for the perturbation model, based on nozzle admittances calculated from upstream and downstream variables, is discussed in the Engineering Model section.

Steady-State Solution

The boundary conditions for the steady-state differential equations are

$$@ \; x = x_0 \qquad (155)$$

$$\bar{p}_{x_0} = p_c \qquad (156)$$

$$\bar{v}_{x_0} = \bar{v}_{x=0} \qquad (157)$$

$$\overline{MR}_{x_0} = MR_{x=0} \quad (\text{if } \bar{v}_{x=0} \neq 0) \qquad (158)$$

$$(A \bar{\rho}\; \bar{v})_{x_0} = (\bar{\dot{m}})_{x=0} \quad (\text{if } \bar{v}_{x=0} \neq 0) \qquad (159)$$

Assuming small Mach numbers, i.e., $M^2 << 1$, the steady-state differential equations can be integrated between the start plane for vaporization (x_0) and any location (x) to yield

$$\bar{p} = \text{constant} = p_c \tag{160}$$

$$\overline{MR} = \frac{\left(\frac{\overline{MR}}{1+\overline{MR}}\right)_{x=0} (A\bar{\rho}\,\bar{v})_{x=0} + (\bar{\dot{m}}_{ox})_{inj}\,(1 - \phi_{ox})}{\left(\frac{1}{1+\overline{MR}}\right)_{x=0} (A\bar{\rho}\,\bar{v})_{x=0} + (\bar{\dot{m}}_{fu})_{inj}\,(1 - \phi_{fu})} \tag{161}$$

$$\begin{aligned}\bar{v} = \frac{(A\,v)_{x=0}}{A} + \frac{(\gamma_0 - 1)}{\gamma_0\,\bar{p}\,A} \Bigg\{ & (\bar{\dot{m}}_{ox})_{inj}\,(1 - \phi_{ox})\,\Delta h_{ox} \\ & + (\bar{\dot{m}}_{fu})_{inj}\,(1 - \phi_{fu})\,\Delta h_{fu} + (A\bar{\rho}\,\bar{v}\,\overline{MR})_{x=0} \left(\frac{\partial h}{\partial MR}\right)_0 \\ & - \overline{MR}\,\left(\frac{\partial h}{\partial MR}\right) \Bigg[(A\bar{\rho}\,\bar{v})_{x=0} + (\bar{\dot{m}}_{ox})_{inj}\,(1 - \phi_{ox}) \\ & + (\bar{\dot{m}}_{fu})_{inj}\,(1 - \phi_{fu}) \Bigg] \Bigg\} \end{aligned} \tag{162}$$

$$\begin{aligned}\bar{\rho} = \frac{1}{A\,\bar{v}} \Big\{ & (A\bar{\rho}\,\bar{v})_{x=0} + (\bar{\dot{m}}_{ox})_{inj}\,(1 - \phi_{ox}) \\ & + (\bar{\dot{m}}_{fu})_{inj}\,(1 - \phi_{fu}) \Big\} \end{aligned} \tag{163}$$

$$\bar{T} = \frac{\bar{p}}{\bar{\rho}\,R_0 \left[1 + \frac{1}{R_0}\left(\frac{\partial R}{\partial MR}\right)_0 (MR - MR_0)\right]} \tag{164}$$

where

$$\phi_s = e^{-(x-x_0)/\bar{\tau}_s\,\bar{v}_s} \tag{165}$$

If the gaseous injection velocity is equal to zero ($\bar{v}_{x=0} = 0$), the steady-state mixture ratio and density at $x = x_0$ are determined by

$$\overline{MR}_{x_0} = \left(\frac{\bar{\dot{m}}_{ox}}{\bar{\dot{m}}_{fu}}\right)_{inj} \left(\frac{\bar{\tau}_{fu}\ \bar{v}_{fu}}{\bar{\tau}_{ox}\ \bar{v}_{ox}}\right) \tag{166}$$

$$(\bar{\rho})_{x_0} \quad \frac{(\gamma_\phi - 1)}{\gamma_\phi\ \bar{p}} \left\{ \overline{MR}_{x_0} \left[\Delta h_{ox} - \overline{MR}_{x_0} \left(\frac{\partial h}{\partial MR}\right)_\phi\right] + \Delta h_{fu} - \overline{MR}_{x_0} \left(\frac{\partial h}{\partial MR}\right)_\phi \right\} = \overline{MR}_{x_0} + 1 \tag{167}$$

These equations were developed by taking the limit as $x \rightarrow x_0$ from a downstream distance.

Oscillatory Solution

The boundary conditions for the oscillatory differential equations are

$$@ \quad x = 0 \tag{168}$$

$$p' = \Delta p \tag{169}$$

$$v' = (v')_{x=0} \tag{170}$$

From these boundary conditions and the oscillatory differential equations the oscillatory conditions at the start plane for vaporization (x_0) can be determined and are:

$$p'_{x_0} = \left[\Delta p \cos\left(n \frac{\omega x_0}{c_\phi}\right) + i \gamma_\phi\, n\, (v')_{x=0} \sin\left(n \frac{\omega x_0}{c_\phi}\right)\right] e^{-\frac{i\omega}{c_\phi}\, n^2 \cdot \frac{\bar{v}_{x=0}}{c_\phi}\, x_0} \tag{171}$$

$$v'_{x_0} = \left[\frac{i}{\gamma_\phi} \; \frac{\Delta p}{\eta} \; \sin\left(n \, \frac{\omega x_0}{c_\phi}\right) + (v')_{x=0} \; \cos\left(n \, \frac{\omega x_0}{c_\phi}\right)\right] e^{-\frac{i\omega}{c_\phi} \, n^2 \, \frac{\bar{v}_{x=0}}{c_\phi} \, x_0} \tag{172}$$

$$\rho'_{x_0} = \frac{p'_{x_0}}{\gamma_\phi} \tag{173}$$

$$MR'_{x_0} = (MR')_{x=0} \; e^{\left(\frac{i\,\omega}{c_\phi}\right)\left(\frac{c_\phi}{\bar{v}_{x=0}}\right) \; x_0} \tag{174}$$

$$T'_{x_0} = p'_{x_0} - \rho'_{x_0} - \frac{1}{\bar{R}_{x_0}} \left(\frac{\partial R}{\partial MR}\right)_\phi MR'_{x_0} \tag{175}$$

where

$$n \equiv \sqrt{\frac{\bar{\rho}_{x_0} \, c_\phi^2}{\gamma_\phi \, \bar{p}}} \tag{176}$$

If the gaseous injection velocity is equal to zero ($\bar{v}_{x=0} = 0$), the oscillatory mixture ratio at x_0 is determined by

$$MR'_{x_0} \left[\frac{(\bar{\dot{m}}_{fu})_{inj}}{A \, \bar{\rho}_{x_0} \, c_\phi} \; (1 + \overline{MR}_{x_0}) - \frac{i\omega}{c_\phi} \; (\bar{\tau}_{fu} \; \bar{v}_{fu}) \right]$$

$$= \frac{(\overline{MR}_{x_0} + 1)}{A \, \bar{\rho}_{x_0} \, c_\phi} \; (\bar{\dot{m}}_{fu})_{inj} \; \overline{MR}_{x_0} \left(\frac{\dot{m}'_{vap_{ox}}}{\bar{\dot{m}}_{vap_{ox}}} \qquad \frac{\dot{m}'_{vap_{fu}}}{\bar{\dot{m}}_{vap_{fu}}} \right)$$

$$- \; (v'_{x_0}) \; \overline{MR}_{x_0} \; \frac{(\overline{MR}_{x_0} + 1)}{(\overline{MR}_{x_0} + 2)} \left(1 - \frac{\overline{MR}}{\overline{MR}_{inj}} \right) \tag{177}$$

This equation was developed by taking the limit of the mixture ratio equation as x → x_0 from a downstream distance.

The ordinary differential equations describing the oscillatory solution are solved using a second order implicit finite difference method. This method has the advantage of being simple to implement and modify, as well as being unconditionally stable for systems of equations which do not have exponentially growing solutions. The method as applied to the first order system

$$Y' = AY + g \tag{178}$$

where Y and g are nx1 vectors and A is an nxn matrix is as follows:

$$y_{i+1} = y_i + \frac{\Delta x}{2} \; A_{i+\frac{1}{2}} \; (y_i + y_{i+1}) + g_{i+\frac{1}{2}} \tag{179}$$

Here, the subscript i refers to the i'th mesh point in the finite difference scheme, e.g., $x_i = x_0 + i\Delta x$. The y_i approximate the Y vector at x_i. That is $y_i \sim Y_i = Y(x_i)$. The subscript $i+\frac{1}{2}$ refers to evaluation at $x_i + \Delta x/2$; e.g., $A_{i+\frac{1}{2}} = A(x_i + \frac{\Delta x}{2})$.

That the above method leads to a second order approximation (error is proportional to Δx^3) can be shown as follows:

Solving for y_{i+1} yields

$$y_{i+1} = (I - \frac{\Delta x}{2} \; A_{i+\frac{1}{2}})^{-1} \; (I + \frac{\Delta x}{2} \; A_{i+\frac{1}{2}}) \; y_i + \Delta x \; (I - \frac{\Delta x}{2} A_{i+\frac{1}{2}})^{-1} \; g_{i+\frac{1}{2}} \tag{180}$$

Without loss of generality, assume i = 0.

From the two expansions

$$Y_1 = Y_{\frac{1}{2}} + \frac{\Delta x}{2} \; Y'_{\frac{1}{2}} + \frac{\Delta x^2}{8} \; Y''_{\frac{1}{2}} + o(\Delta x^3) \tag{181}$$

$$Y_0 = Y_{\frac{1}{2}} - \frac{\Delta x}{2} \; Y'_{\frac{1}{2}} + \frac{\Delta x^2}{8} \; Y''_{\frac{1}{2}} + o(\Delta x^3) \tag{182}$$

the following are obtained

$$Y_1 = Y_0 + \Delta x \; Y'_{\frac{1}{2}} + o(\Delta x^3) \tag{183}$$

and

$$Y_{\frac{1}{2}} = (Y_0 + Y_1)/2 + o(\Delta x^2) \tag{184}$$

Let $y_0 = Y_0$; it is necessary to show $y_1 = Y_1 + o(\Delta x^3)$ in order to demonstrate second-order accuracy.

From the differential equation

$$g_{\frac{1}{2}} = Y'_{\frac{1}{2}} - A_{\frac{1}{2}} Y_{\frac{1}{2}} \tag{185}$$

Substituting (185) into (180) and noting $y_0 = Y_0$,

$$\begin{aligned} y_1 &= (I - \tfrac{\Delta x}{2} A_{\frac{1}{2}})^{-1} (I + \tfrac{\Delta x}{2} A_{\frac{1}{2}}) Y_0 + \Delta x (I - \tfrac{\Delta x}{2} A_{\frac{1}{2}})^{-1} (Y'_{\frac{1}{2}} - A_{\frac{1}{2}} Y_{\frac{1}{2}}) \\ &= (I - \tfrac{\Delta x}{2} A_{\frac{1}{2}})^{-1} \left\{ Y_0 + \Delta x Y'_{\frac{1}{2}} + A_{\frac{1}{2}} \Delta x (\tfrac{1}{2} Y_0 - Y_{\frac{1}{2}}) \right\} \end{aligned} \tag{186}$$

Using (183) and (184), gives the result

$$\begin{aligned} y_1 &= Y_1 + (I - \tfrac{\Delta x}{2} A_{\frac{1}{2}})^{-1} o(\Delta x^3) \\ &= Y_1 + o(\Delta x^3) \end{aligned} \tag{187}$$

Consider now the stability of the finite difference formula (179) for systems which do not have exponentially increasing solutions; that is, the real part of each of the eigenvalues of A is negative. To prove that they are stable for this situation, define the error $\varepsilon_i = Y_i - y_i$ and consider the two equations given by (179) and

$$\begin{aligned} Y_{i+1} = {} & (I - \tfrac{\Delta x}{2} A_{i+\frac{1}{2}})^{-1} (I + \tfrac{\Delta x}{2} A_{i+\frac{1}{2}}) Y_i + \\ & \Delta x (I - \tfrac{\Delta x}{2} A_{i+\frac{1}{2}})^{-1} g_{i+\frac{1}{2}} + o(\Delta x^3) , \end{aligned} \tag{188}$$

the latter resulting from (187). Subtracting (179) from (188)

$$\varepsilon_{i+1} = (I - \tfrac{\Delta x}{2} A_{i+\frac{1}{2}})^{-1} (I + \tfrac{\Delta x}{2} A_{i+\frac{1}{2}}) \varepsilon_i + o(\Delta x^3) \tag{189}$$

Let $B = \frac{\Delta x}{2} A_{i+\frac{1}{2}}$. The method is stable if and only if the matrix $(I-B)^{-1}$ $(I+B)$ has a spectral radius less than one, for this would produce (Ref. 22)

$$\lim_{n \to \infty} \left[(I-B)^{-1}(I+B) \right]^{n} = 0 \tag{190}$$

Since the eigenvalues of $(I-B)^{-1}$ $(I+B)$ are just equal to $(1+\beta)/(1-\beta)$, where β is an eigenvalue of B, the spectral radius of $(I-B)^{-1}$ $(I+B)$ is just

$$\max_{\beta} \left| (1+\beta)/(1-\beta) \right| \tag{191}$$

For this to be less than one,

$$|1+\beta| < |1-\beta| \tag{192}$$

for all β. This implies

$$1+\beta + \bar{\beta} + \beta\bar{\beta} < 1-\beta-\bar{\beta}+\beta\bar{\beta} \tag{193}$$

or

$$\beta + \bar{\beta} < -(\beta + \bar{\beta}) \tag{194}$$

$$\text{Real } (\beta) < 0 \tag{195}$$

Since $\beta = \frac{\Delta x}{2\alpha}$, where α is an eigenvalue of A, the method will be stable if all the eigenvalues of A have real parts less than zero, that is, the solutions to (178) are not exponentially increasing.

Nozzle Admittance

The nozzle admittance based on downstream conditions is calculated based on the following analysis.

The gas flowrate of the nozzle inlet plane is

$$\dot{m} = \frac{p\, A_t\, g}{c^*} = A \rho\, v \tag{196}$$

where the characteristic velocity is

$$c^* = \frac{\sqrt{g \gamma\, RT}}{\gamma \left[\frac{2}{\gamma+1}\right]^{(\gamma+1)/2(\gamma-1)}} \tag{197}$$

For short nozzles, the oscillatory mass flowrate can be written as

$$\frac{\dot{m}'}{\bar{\dot{m}}} = \frac{\rho'}{\bar{\rho}} + \frac{v'}{\bar{v}} = \frac{p'}{\bar{p}} - \frac{1}{2}\,\frac{T'}{\bar{T}} - \left(\frac{\partial \overline{c^*}}{\partial \overline{MR}}\right) \frac{MR'}{\overline{c^*}} \tag{198}$$

Assuming

$$\frac{\rho'}{\bar{\rho}} = \frac{1}{\gamma}\,\frac{p'}{\bar{p}} \quad , \quad \frac{T'}{\bar{T}} = \left(\frac{\gamma-1}{\gamma}\right) \frac{p'}{\bar{p}} \quad , \tag{199}$$

the nozzle admittance for a short nozzle can be written as

$$A_{N_s} = \bar{\rho}\, \bar{c}\, \bar{v} \left[\frac{(\gamma-1)}{2\gamma\, \bar{p}} - \left(\frac{\partial \overline{c^*}}{\partial \overline{MR}}\right) \frac{MR'}{\overline{c^*}\, p'}\right] \tag{200}$$

Assuming

$$A_{N_D} = A_{N_s} \left(\frac{A_{N_D}}{A_{N_s}} \right)_{MR = \text{constant}} \tag{201}$$

the nozzle admittance based on downstream conditions becomes

$$A_{N_D} = \left[1 - \left(\frac{\partial \overline{c^*}}{\partial \overline{MR}} \right) \frac{MR' \ \bar{p}}{\overline{c^*} \ p'} \left(\frac{2 \gamma}{\gamma - 1} \right) \right]_{x = \ell} A_{N_{MR = \text{constant}}} \tag{202}$$

where $A_{N_{MR = \text{constant}}}$ is calculated using the admittance program developed by Bell (Ref. 23).

The nozzle admittance based on upstream conditions is

$$A_{N_U} = \gamma_\phi \left(\frac{v'}{p'} \right)_{x = \ell} \tag{203}$$

where $(v'/p')_{x = \ell}$ is calculated from the oscillatory solution. For solutions to the chamber dynamic equations, the nozzle admittance based on upstream and downstream conditions must be equal. The method of calculating the complex frequency which satisfies this condition is discussed in the Engineering Model section which follows.

ENGINEERING MODEL

Analytical Approach

The overall model structure had the greatest variety of factors influencing its nature. Some of these factors were related to the overall confidence in the success of the effort. Factors relating to cost included the solution time and numerical stability, which bears on the number of runs which will be required for a solution. Still other factors were related to the JSC Univac 1110 capabilities. The remaining factors concerning the overall model structure reflect on its conversion cost applicability to the resolution of propulsion system problems. Its accuracy has direct bearing on the design margins involved. The type of impact and the obtainability of characterization parameters could not limit the accuracy and useability. The type and useability of the output was also given due consideration as well as the degree of generalization such that the model can be applied to a range of systems.

The structure of the Engineering Program was based on a trade-off of setup time, storage capabilities, and solution time. General input data to the program includes geometric factors, engine operating conditions and propellant properties. An equilibrium gas properties program similar to NASA ODE computer program, and the DER combustion model program are executed external to the stability program. The control program then executes the nozzle admittance and hydrodynamics programs to calculate the admittance and oscillatory injector flowrate as a function of frequency and stores the results on tapes. Steady-state distributed combustion parameters calculated from the DER Model are inputs to the combustion dynamics subprogram which are iterated with the chamber dynamic subprogram until the nozzle and injection admittance conditions are satisfied. The solution method for obtaining solutions for the complex frequency is outlined in the following section.

Determination of Complex Frequency

The complex frequency, ω, is determined such that the boundary condition in the nozzle is satisfied. Specifically, the admittance is required to be continuous across the interface between the combustion zone and the zone immediately downstream of the combustion zone. In the downstream zone, the nozzle admittance, A_{N_D}, is computed from a nozzle admittance program. In the upstream combustion zone, the nozzle admittance, A_{N_U}, is computed from the oscillatory flow parameters determined by the chamber dynamics. The complex frequency must be such that

$$A_{N_U} = A_{N_D} \tag{204}$$

Let $\omega = x + iy$ and $F = A_{N_U} - A_{N_D} = u + iv$. The numerical problem is to find x and y such that

$$u(x,y) = 0 \tag{205}$$

$$v(x,y) = 0 \tag{206}$$

Several methods were considered for solving this system of equations. Because F is not an analytic function of ω, the complex form of the Newton-Raphson method may not always work. On the other hand, one could use the two-dimensional form of Newton-Raphson (Ref. 24), but since the derivatives of u and v with respect to x and y must be computed numerically, the two-dimensional Newton-Raphson method will require three functional evaluations of F at each ω, i.e., (x,y),$(x + \Delta x,y)$,and $(x,y + \Delta y)$. Alternatively, a far more efficient method is to use the two-dimensional form of the secant method (Ref. 24) since this does not require the evaluation of any derivatives. Specifically, this method approximates the u and v surfaces with linear functions u_L and v_L (planes) based on three previous guesses for ω, (x_1,y_1), (x_2,y_2), (x_3,y_3). The next guess for ω, (x_4,y_4), is determined from the equations $u_L(x_4,y_4) = v_L(x_4,y_4) = 0$. The new value of ω then replaces one of the previous three values, normally the one with the largest error as measured by the absolute value of $F(x_j,y_j)$, and the iteration is continued until convergence is reached. The actual equations for the above process take the following form. Let $w_j = x_j + iy_j$, $u_j = u(x_j,y_j)$, and $v_j = v(x_j,y_j)$ for j = 1,2,3.

1. Determine π_j, j = 1,2,3, such that

$$\pi_1 + \pi_2 + \pi_3 = 1 \tag{207}$$

$$\pi_1 u_3 + \pi_2 u_2 + \pi_3 u_1 = 0 \tag{208}$$

$$\pi_1 v_3 + \pi_2 v_2 + \pi_3 v_1 = 0 \tag{209}$$

2. Compute $\omega_4 = \pi_1\omega_3 + \pi_2\omega_2 + \pi_3\omega_1$. (210)

3. Compute u_4 and v_4 based on x_4 and y_4.

4. Test for convergence, i.e., require that $\min |\omega_j - \omega_4|/\omega_4| < \varepsilon_1$ and $|F_4| < \varepsilon_2$.
   If the process has not converged, continue with steps 5, 6, and 7.

5. Determine the j between 1 and 3 such that $u_j^2 + v_j^2$ is maximum.

6. Replace ω_j, u_j, and v_j by ω_4, u_4, and v_4, respectively.

7. Go to 1.

Operationally, steps 4 and 5 may be altered to replace the ω's cyclically, i.e., $\omega_i \rightarrow \omega_{i-1}$, $u_i \rightarrow u_{i-1}$, $v_i \rightarrow v_{i-1}$. In fact the computer program as written alternates between these two procedures every three iterations in order to avoid any possible cycling that may occur.

The above algorithm has been found to be very efficient when the first three guesses are relatively near an actual solution. The difficult problem was to develop a searching algorithm which determines the regions in the ω plane where solutions exist.

One possible procedure would be to utilize the fact that the surface $u^2 + v^2$ has an absolute minimum at each solution. Using any reasonable value of ω as a first guess, one might be tempted to employ a gradient, or modified gradient, method to march along the surface until one comes near a relative minimum. Unfortunately, this procedure fails because the surface $u^2 + v^2$ has many relative minima which are not actual solutions. The reason for the large number of relative minima (and maxima) for this surface is undoubtedly due to the coupling between the combustion processes and the feed system oscillation in conjunction with the very rapid change of the feed system response as a function of frequency. The searching algorithm must be able to discriminate between those relative minima that are not solutions and those that are. Such a procedure was developed for this program. It takes advantage of the fact that a large portion of the computations required are only a function of the real part of ω, i.e., they use x as an independent variable and do not depend upon y. Thus, y may be changed without having to redo many of the calculations within the program.

Intuitively, the idea is to increment x through a range of values, while determining y at each x according to the criterion mentioned below, until it is determined that a solution has been crossed. This determination employs the use of a test function which changes sign when a root is crossed in the same manner that a single equation in one unknown changes sign as it goes through a zero. The task of developing a defining criterion for y and a test function for x would be easy if, for example, v were a strong function of y and u were a strong function of x. Then, each x, y could be chosen such that $v(x,y) = 0$ and, as x is incremented, a solution would be crossed when $u[x,y(x)]$ changes sign. Unfortunately, neither u nor v behaves this way.

To develop functions that do behave this way, the following procedure was developed. First, for each x, choose y such that the absolute value of F is minimized. This can be done in several ways. The program uses a method that always guarantees finding a value if one exists. Essentially, the absolute value of F squared and its gradients are computed. The value of y is altered in the direction indicated by the gradient until either the gradient changes sign or is so close to zero that convergence has been reached. Once the gradient changes sign, Muller's method (Ref. 25) is used to converge on the root. This is essentially a bisection method followed by inverse parabolic interpolation. For this searching process, it is not necessary to make the convergence criteria very tight, since only rough estimates are eventually needed in order to start the two-dimensional secant method described earlier.

Now that a criterion for y has been established, it is only necessary to find a test function that will change sign when a solution is crossed while incrementing x. Such a function is given by

$$uu_x + vv_x \tag{211}$$

This function acts as a very good test function because it represents the coordinate direction in the u,v plane along which the vector (u,v) changes most with x. When this coordinate changes sign as one goes from, say, x_1 to x_2 with y_1 and y_2 chosen so that the length of the vector (u,v) is minimized, then it is very likely that a solution has been crossed. Exceptions to this rule occur when one is near relative minima of the surface $u^2 + v^2$ that are not zero. To see this, consider the actual equations that are being solved. In order that the vector (u,v) is minimum for each y, it is necessary that $\partial(u^2 + v^2)/\partial y = 0$. That is $uu_y + vv_y = 0$. Combining this with the above equation, we see we are finding an x and y such that the matrix equation

$$\begin{pmatrix} u_x & v_x \\ u_y & v_y \end{pmatrix} \begin{pmatrix} u \\ v \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \tag{212}$$

is satisfied. The matrix is just the transpose of Jacobian of u and v with respect to x and y.

This equation can be satisfied if either u and v are zero, or the Jacobian is singular. The Jacobian is necessarily singular at all relative minima of the surface $u^2 + v^2$ except those at $u = v = 0$. In order to differentiate between those solutions to (212) that are due to singularities of the Jacobian and those that are due to u and v vanishing, we employ two different tests. First of all, when a singularity point is crossed, the determinant of the Jacobian should change sign. If this occurs, then the program rejects this point as a possible solution. Sometimes, however, the determinant does not change sign because either the convergence criterion used in the searching algorithm is too loose or because the singularity has a double root. In either case, the procedure is to test the condition number* of the transpose of the Jacobian matrix in the region near the suspected solution. If the condition number does not exceed a given input limit (e.g., around 80), then the point in question is usually a solution.

Once it is determined that a potential solution has been crossed between x_1 and x_2, for example, the procedure is to (a) determine x_3 based on the method of false position using the test function given in (211), (b) determine y_3 to minimize $|F|$, and (c) use (x_1,y_1), (x_2,y_2), and (x_3,y_3) as the required first three guesses for the two-dimensional secant method.

The above procedure has been found to be most satisfactory for the conditions tested in this program. The search algorithm described above has several salient features. First, as mentioned earlier, the search method takes advantage of the fact that many of the computations are not a function of the imaginary part of ω, namely y: This allows the minimization of $|F|$ with respect to y to proceed with high efficiency. Secondly, and more importantly,

---

*The condition number of a matrix, A, is a measure of how sensitive a solution to the system Ab=c is to perturbations in c. It is equal to the square root ratio of the absolute value of the largest eigenvalue of A'A to the smallest eigenvalue of A'A. For singular matrices, the condition number is infinite. For matrices that are nearly singular, the condition number will be quite large.

the procedure has been automated to the extent that the user only has to specify a frequency range and a maximum number of roots desired in that range. The algorithm will start at the lower end of the frequency range and will increment through it until either the maximum number of roots are found or the upper end of the frequency range is reached. This is a very powerful property since it does not require the user to have a clear knowledge of the location of any of the roots in the ω plane.

PROGRAM USER'S GUIDE

FSCSM MAIN PROGRAM

The main program for the FSCSM computer model performs much of the input/output activity of the model and controls the sequencing through the various major subprogram blocks of the model. After writing the header page (Fig. 5), the main program reads in and writes out the data described in Table 2 of the input section of this report under the heading Main Control Section Input. The program then computes the area profiles through a call to subroutine AREA. It then begins its main do loop controlling the number of solutions to the nozzle admittance boundary equation that are desired. During the iterations for each solution to be found, the main program proceeds with successive calls to subroutines NØZADM, HYDRDY, CØMBDY, and SØLVW in order to compute the downstream nozzle admittance factor, the feed system response parameters, the combustion dynamics coefficients, and performance calculations necessary to solve the nozzle admittance boundary equations respectively. Subroutine SØLVW also causes a call to subroutine CHAMDY which computes the oscillatory profiles. Further, during the first iteration in the do loop for the main program for the first solution, the main program also calls subroutine STEADY in order to obtain the steady-state profiles.

The variable ISCNT is the FØRTRAN variable set by the main program and altered in SØLVW which controls the type of iteration being performed. When ISCNT equals one or four, the search algorithm described on pages 54-56 is called out. This is the initial condition at the beginning of each set of iterations to solve the nozzle admittance boundary equation. When ISCNT equals five, the two-dimensional secant method is being performed in SØLVW.

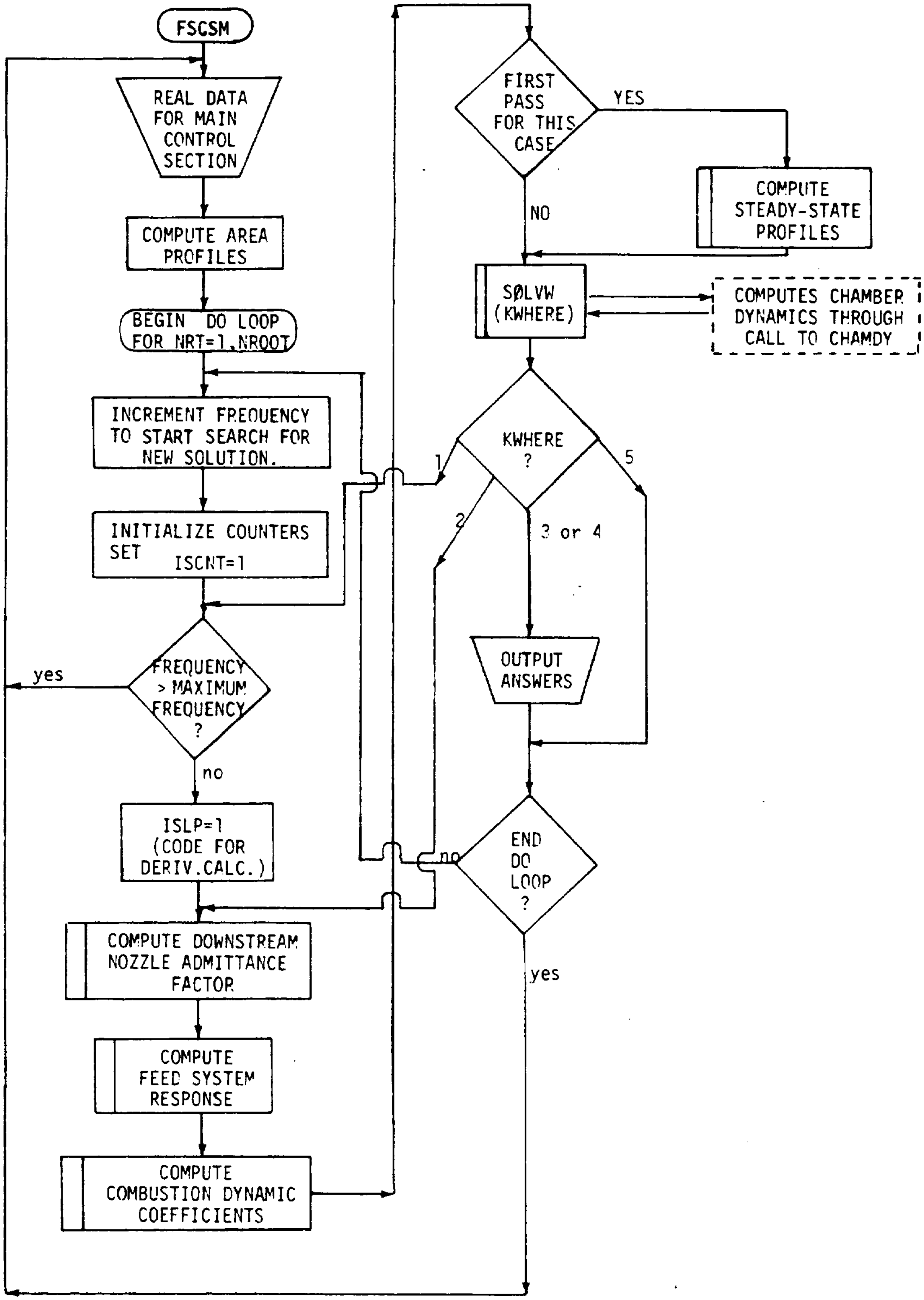

Figure 5. Logic Diagram for FSCSM Main Program

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The variable KWHERE, which is set by subroutine S0LVW, controls the logical flow in the main program subsequent to a call to S0LVW. When ISCNT equals one or four and KWHERE equals one, the control is returned to that portion of the main program which starts the calculation for the next value of ω being tried by the search algorithm. When KWHERE equals two and ISCNT equals one or four, control is passed to that portion which will perform calculations for a perturbed ω in order to compute the derivative of $A_{N_U} - A_{N_D}$ with respect to ω_R. When ISCNT equals 5 and convergence has not been reached, the normal exit from S0LVW also sets KWHERE equal to two. For this case however, no derivatives are calculated. The program will just proceed with successive calls to N0ZADM, HYDRDY, and C0MBDY in order to compute the downstream nozzle admittance factor, the feed system response, and the combustion dynamic coefficients, respectively. It then proceeds to S0LVW in order to obtain an updated estimate of ω using the two-dimensional secant method.

When KWHERE equals three or four, convergence on a solution to the nozzle admittance boundary equation has been attained. For this case, control is passed to that portion of the main program which prints the final results for that solution.

When KWHERE equals five, control is passed to the end of the main do loop in the main program. The output portion is bypassed. This only occurs when an error was detected by subroutine S0LVW.

SØLVW

This subroutine performs many of the calculations and controls most of the logical flow required to match the downstream boundary condition on the nozzle admittance. The FORTRAN variable ISCNT controls the logical flow within subroutine SØLVW (Fig. 6). If ISCNT equals one, then that portion of the subroutine used for searching the ω-plane for possible solutions to the nozzle admittance boundary equation is used. Two calls to SØLVW are used for this purpose. During the first call, the imaginary part of ω is determined so that the absolute value of the upstream nozzle admittance minus the downstream nozzle admittance is minimized. The second call is made in order to complete the computation of the Jacobian of this difference with respect to the real portion of ω. (The derivatives of the difference with respect to the imaginary part of ω are computed during the first call.) When ISCNT equals one, tests are also made to determine if a solution is nearby. The actual test function and the logic employed is described on pages 54-56.

Once it is determined that a possible solution is bracketed by two successive frequencies, the variable ISCNT is set equal to four. Subroutine SØLVW performs the same calculations for this value of the variable ISCNT as it does when ISCNT equals one. The only difference occurs at the end of the second call to SØLVW. At that point, checks are made to ensure that the potential solution is in fact an actual solution and not due to a singularity in the Jacobian. If the error passes certain criteria and at least three iterations have been performed with ISCNT equal to four, then ISCNT is set equal to five for subsequent calls to SØLVW. Between each iteration for ISCNT equal to four, as well as for the first iteration for ISCNT equal to four, the real part of the frequency is modified using the method of false position or the bisection method, depending upon the value of the iteration counter, KSCNT4.

When ISCNT equals five, no derivatives are computed. For this situation, subroutine SØLVW only computes the difference between the upstream and downstream nozzle admittances based on the current value of ω. It then checks to determine whether convergence has been obtained. If not, the

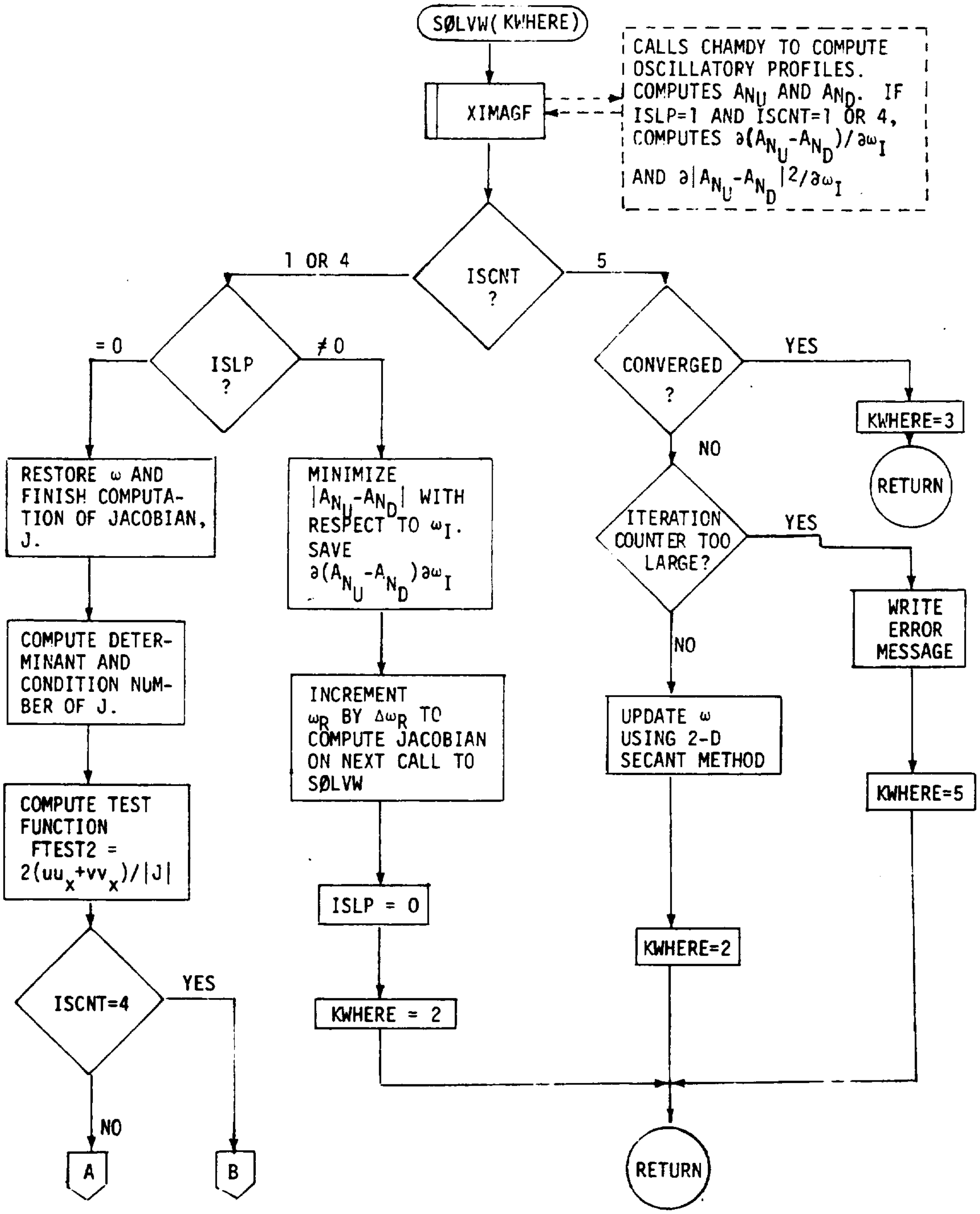

Figure 6. Logic Diagram for Subroutine SØLVW

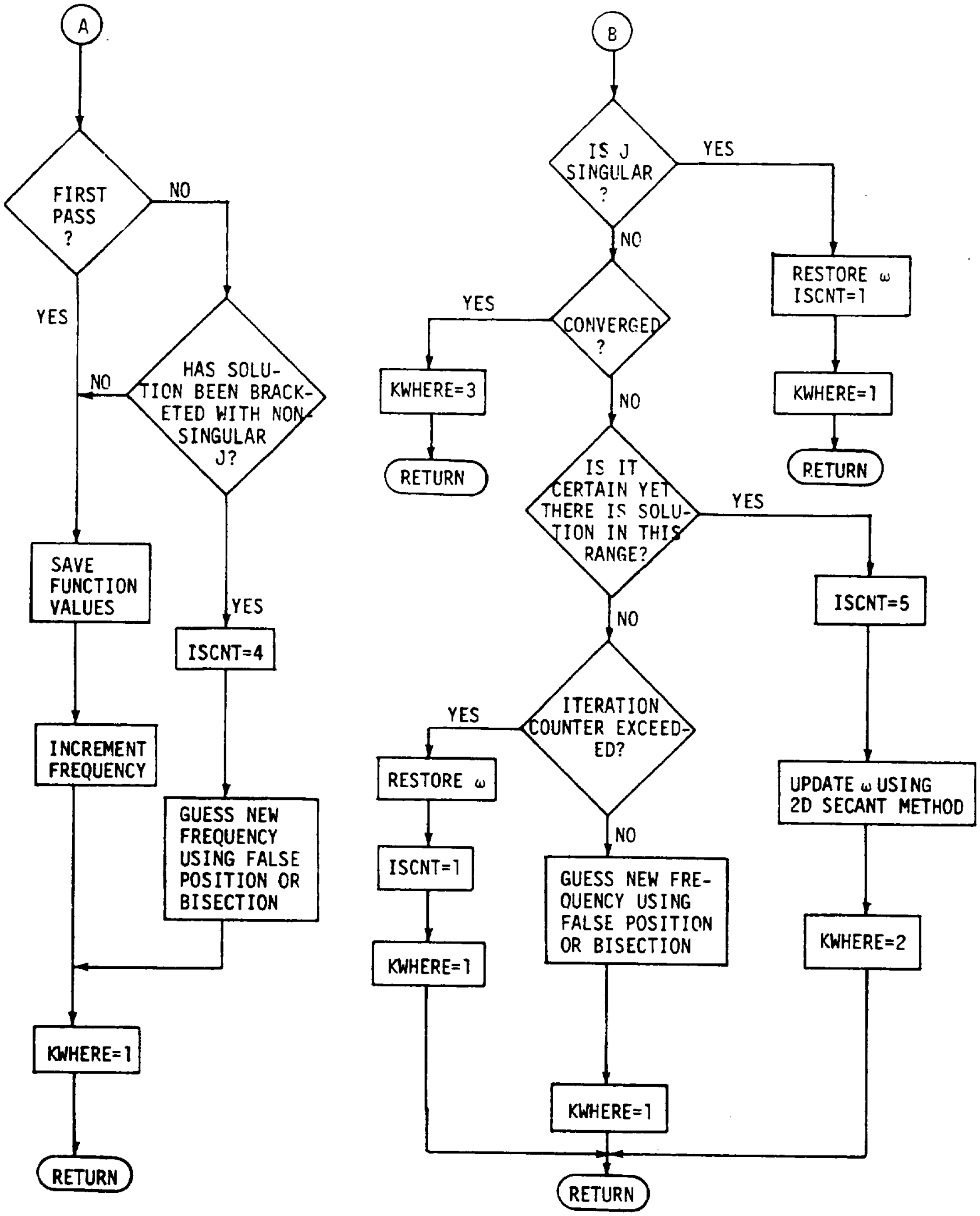

Figure 6. (Concluded)

value of ω is updated according to the two-dimensional secant method described on page 53.

The variable which controls the flow in the main program subsequent to a call to S0LVW is KWHERE and is described in the section of this report dealing with the main program.

CHAMDY

This subprogram is called by XIMAGF in order to compute the oscillatory pressure, temperature, velocity, mixture ratio, and density profiles. From these quantities (Fig. 7), it determines the upstream nozzle admittance. It solves for the oscillatory profiles by solving the linearized set of differential equations presented on pages 41 and 42. This is done using a second order implicit finite difference scheme. Those integrals appearing in the vaporization expression which cannot be integrated analytically are numerically integrated using the trapezoidal rule.

Because the differential equations represent a linear initial value problem, the finite difference equations are also linear and one can "march off" the solution from the initial plane. Since the four differential equations are coupled, replacing them at each axial position by their finite difference approximation results in a four by four system of complex linear equations. Because of the nature of the differential equations, the resulting matrix equations are essentially diagonally dominant and can therefore be solved very quickly using Gaussian elimination with the diagonal element used for pivoting.

XIMAGF

This subroutine is called by S0LVW and ZER0. Its main function is to compute the difference between the upstream and downstream nozzle admittances (Fig. 8). When the program is still performing the search algorithm, this routine computes the derivative of this difference with respect to the imaginary part of ω as well as the derivative of the absolute value of this difference squared with respect to the imaginary part of ω.

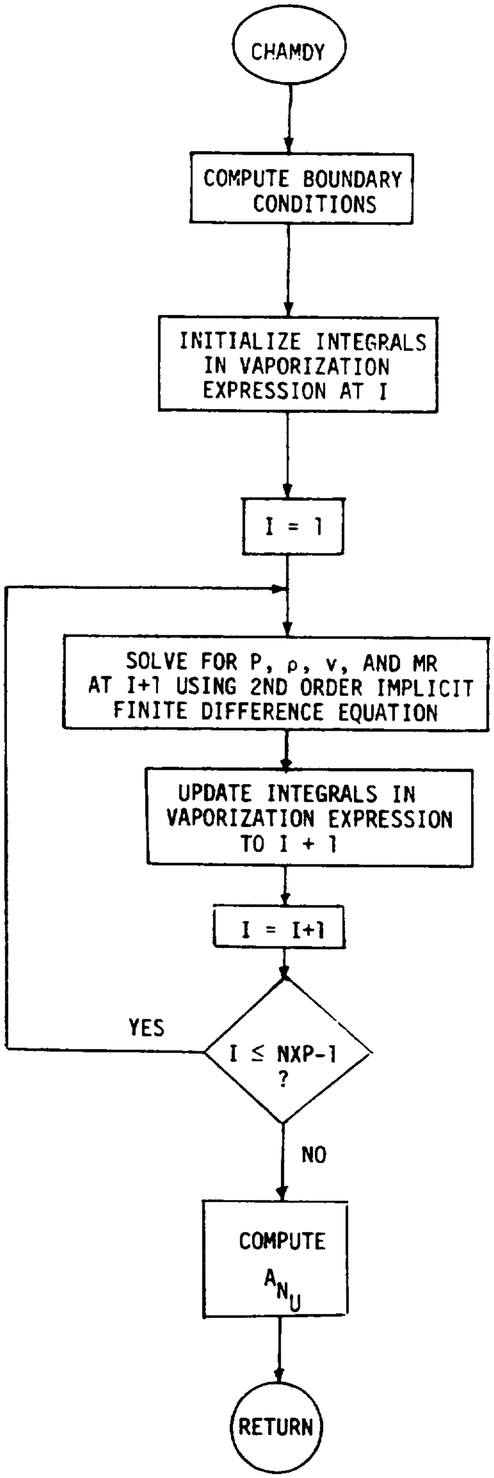

Figure 7. Logic Diagram for Subroutine CHAMDY

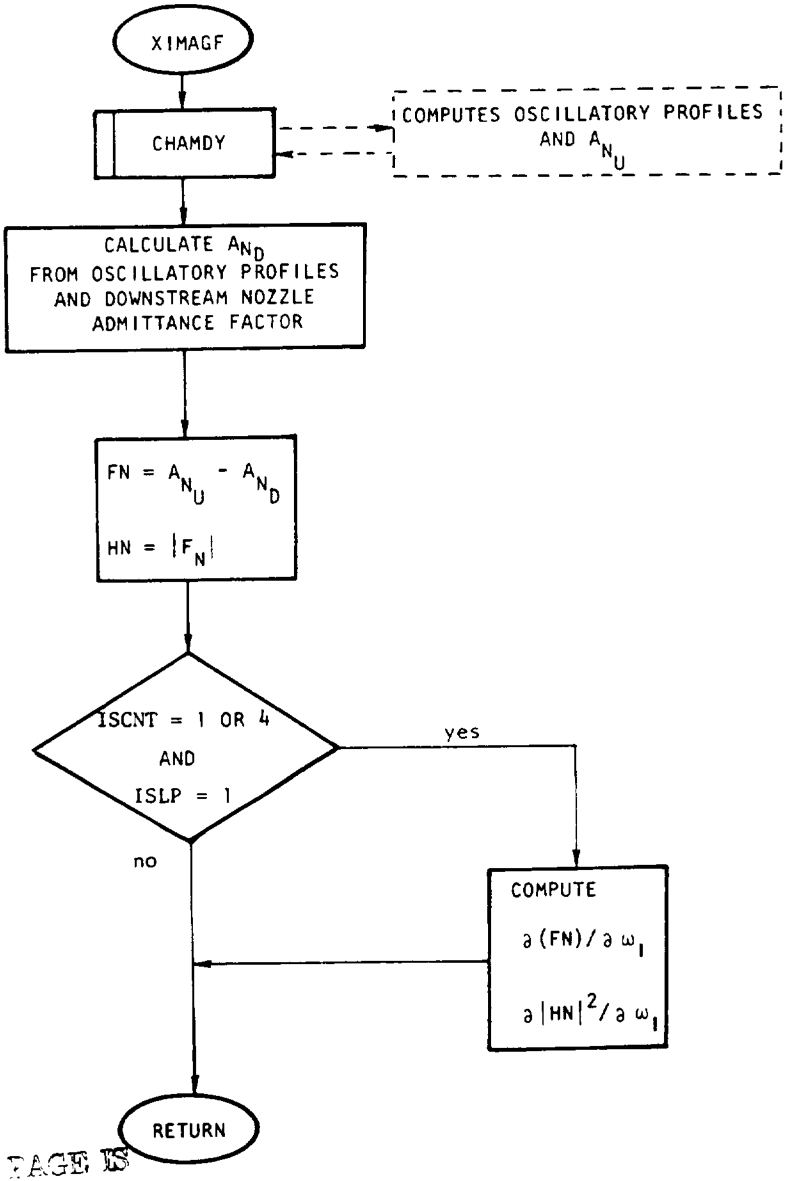

Figure 8. Logic Diagram for Subroutine XIMAGF

CHMCØN

This routine is called by CHAMDY and calculates certain parameters necessary for determining the coefficients used in CHAMDY.

CØMMAT

This routine solves the four by four complex system of linear equations discussed in the section describing subroutine CHAMDY. It uses Gaussian elimination with pivoting on the diagonal.

ZERØ

This routine is called by subroutine CHAMDY. Its function is to find the zero of a given functional when that zero is bracketed both above and below. The functional in this case is the derivative with respect to the imaginary part of ω of the absolute value squared of the difference between the upstream and downstream nozzle admittances. Finding the zero of this functional is done in order to minimize the error in the difference between the nozzle admittances with respect to the imaginary part of ω. The method used by subroutine ZERO is due to Muller (Ref. 25). It essentially involves a bisection step followed by inverse parabolic interpolation to determine the next guess.

STEADY

This routine (Fig. 9) is called by the main program to determine the time independent solution to the set of differential equations given on page 40. These equations have been analytically integrated on pages 42-44. This subroutine uses these latter equations to determine the steady state profiles. Also, several parameters which are a function of these steady state variables are computed and saved for subsequent use by the chamber dynamics subprogram, CHAMDY. If the FORTRAN variable IPRSTE is greater than zero, a printout of the steady state profiles will be given.

CØMBDY

This subprogram (Fig. 10) calculates the fuel and oxidizer combustion coupling coefficients required for the determination of the time oscillatory vaporization rates needed to solve the chamber dynamics. The equations for these parameters

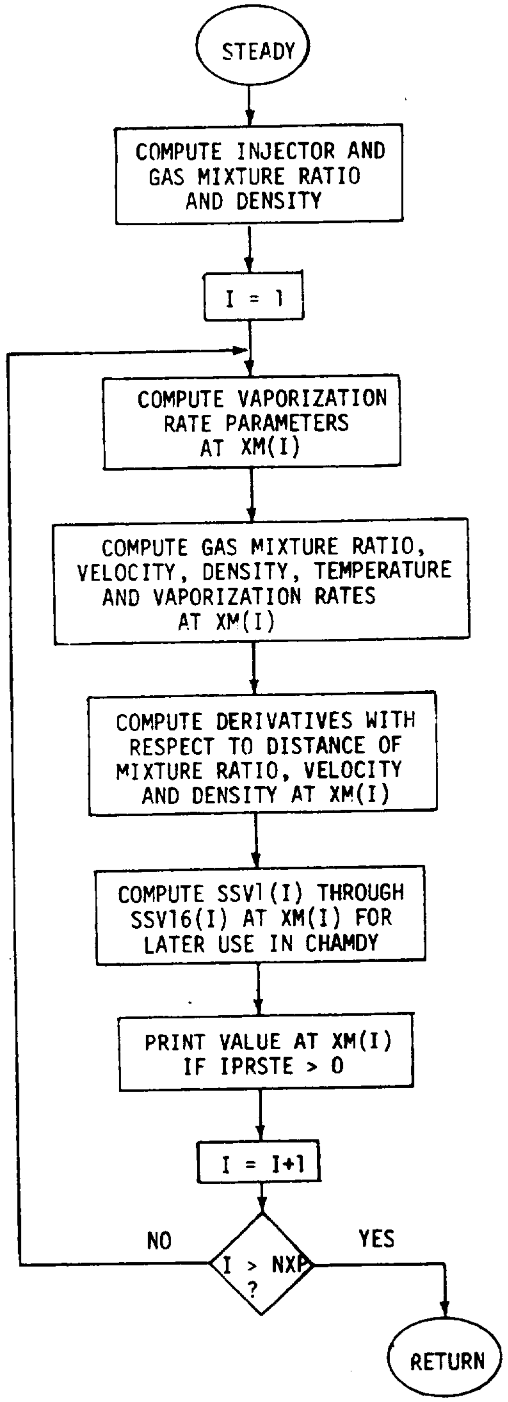

Figure 9. Logic Diagram for Subroutine STEADY

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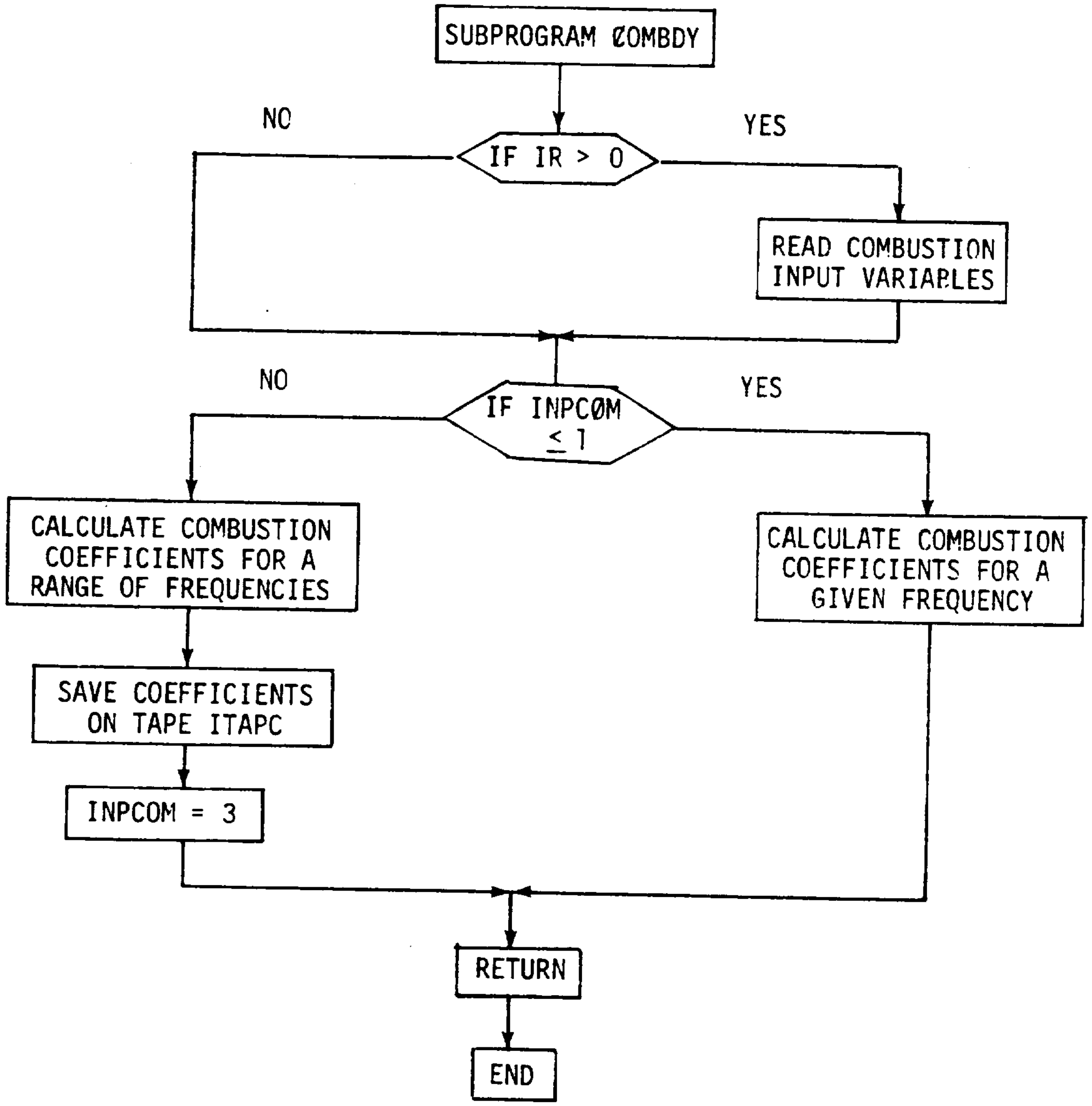

Figure 10. Logic Diagram for Subprogram COMBDY

are given on pages 33-34. During the first pass into this program, the combustion dynamic input variables are read in from input device 5 and written out onto device 6. A discussion of these variables is given in the Model Input Section. The logical flow in CØMBDY is controlled by the FØRTRAN variable INPCØM. If this variable is less than or equal to one, the combustion coefficients are computed for the current frequency only. If INPCØM is greater than one, these coefficients are computed for the entire frequency table, FREQT (e.g., from 10 to 1000 Hz), and saved on tape/disk ITAPE for subsequent use by the main program.

AREA

This subroutine is called by the main program. It computes the area profiles and axial distance profiles necessary for solution of the steady-state and transient profiles.

LØCFAC

This routine is used to determine the subscript, I, within an ordered array, TX, such that the input argument, X, is in the interval TX(I), TX(I+1). This routine also returns the interpolating factor FX = (X-TX(I)/(TX(I+1)-TX(I)) for subsequent use in linear interpolation.

HEAD

This subroutine is called by the main program to print the heading page which gives the title of the program, by whom and where it was developed, and the program sponsor.

HYDRDY

Subroutine HYDRDY (Fig. 11) is called by the main program to calculate the frequency domain characteristics of the feed system. Functions performed by HYDRDY are (1) reading of input data describing the physical attributes

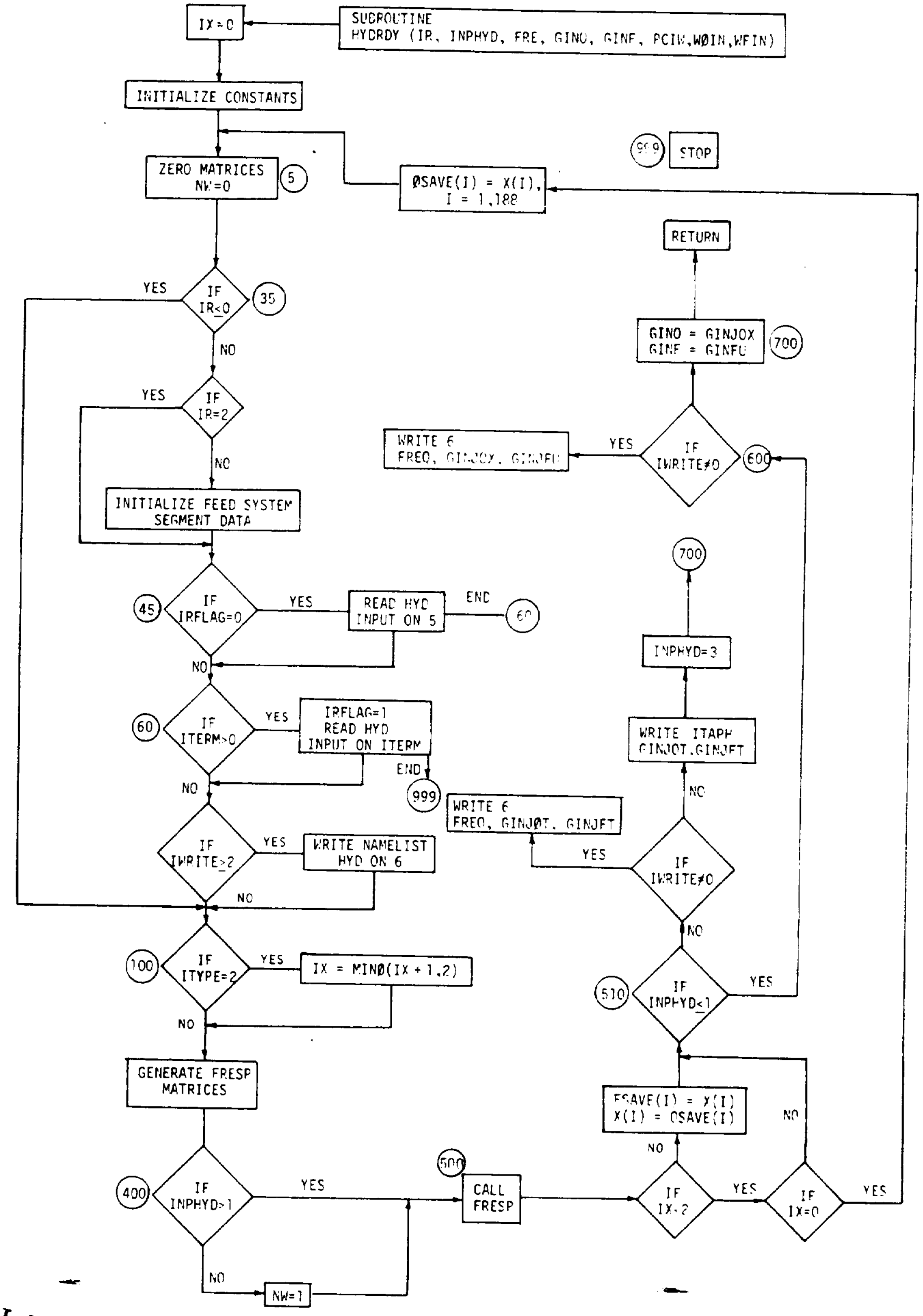

Figure 11. Logic Diagram for Subprogram HYDRDY

of the feed system components, (2) generation of a matrix of linear differential equations representing the complete feed system, (3) solution of the feed system equations to yield the amplitude and phase response of all feed system pressures and flowrates as a function of chamber pressure oscillation amplitude and frequency, and (4) generation of tabulated output of injector flowrate frequency response for use by the main program.

A basic assumption of subroutine HYDRDY is that the feed system being modeled can be represented by the generalized schematic of Fig. 4 (or by some portion of this schematic). This assumption is necessary because HYDRDY sets up and solves the complete set of simultaneous equations representing the Fig. 4 schematic. By assigning very high resistance and very short length attributes to any of the 30 numbered line segments of the generalized schematic, whose segment can effectively be excluded from having any effect on the frequency response characteristics of the rest of the system. With this approach a wide variety of feed systems can be modeled with no changes to the program other than the input data.

Figure 11 shows the functional block diagram for subroutine HYDRDY. When called, the subroutine initially zeroes the values of all of the elements of the coefficient and time delay matrices C and TD in labeled common block F. The values of various fixed input arguments required by the frequency response subroutine (FRESP) are then initialized.

Input argument IR directs the reading of subroutine HYDRDY input data. If IR is zero or less, the program assumes that all required data has previously been read and the data read function is bypassed. If IR = 1, the program assumes that no hydrodynamic data has been read and proceeds to initialize all hydrodynamic input variables to values which will exclude all 30 line segments and both injectors of the generalized Fig. 4 feed system schematic. Control is then passed to statement 45 for reading of input data. If

IR = 2, the assumption is made that most input data is already set up (such as from a previous case during the same program run). Control is passed directly to statement 45 for reading any changes to the input data.

Input data reading for HYDRDY is in the NAMELIST format (NAMELIST name HYD) and is normally in the form of card input on logical unit number 5. However, if the program is run in a timesharing environment, an option is provided for reading data from a timesharing terminal. This option is controlled by variables IRFLAG and ITERM. Both of these variables are stored in labeled common block/F/ and can be changed by input to NAMELIST HYD. Variable IRFLAG is tested in statement 45 and if non-zero specifies reading NAMELIST HYD data from unit 5. If timesharing terminal input is desired, variable ITERM is set (by input data read or block data initialization of labeled common block/F/) to the logical unit number to the timesharing terminal. If variable ITERM is non-zero, statement 46 sets IRFLAG to 1. Thus, once terminal data input has been specified, all subsequent data reads will default to the terminal. Card input can be respecified (for a subsequent data case) by entering IRFLAG = 0 in the terminal data input.

Input variables for subroutine HYDRDY are described in detail in the Hydrodynamic Input Section. The variables include the length (L), cross-sectional area (A), propellant sonic velocity (V), propellant density (RHOL), hydraulic resistance (R), and wall compliance (CW) for each of the 30 numbered waterhammer segments in the generalized Fig. 4 feed system schematic. Input variables for the left ("Ø") injector of Fig. 4 are resistance (RØ),inertance (ZØ), volume (VOLØ), propellant sonic velocity (VØ), and injector deflection constant (KØ). The corresponding input variables for the right ("F") injector are RF, ZF, VØLF, VF and KF. The designation of the two injectors as "Ø" and "F" is a notational convenience for cases in which the feed system being modeled has only one injector and sufficiently simple flow paths so that both oxidizer and fuel systems can simultaneously be laid out on the Fig. 4 schematic. Such cases have the advantage of reduced computer time because the frequency response of both fuel and oxidizer feed systems is obtained with a single call to subroutine HYDRDY. Of the fuel and oxidizer feed systems overlap when laid out on the Fig. 4 schematic, subroutine HYDRDY must be called twice - once for each feed system.

When data input is complete, a value of 2 (or greater) for variable IWRITE specifies a printout of all input data on logical unit 6. IWRITE = 0 is the default and specifies no printout of input data.

Next, control is passed to the DO loop at statement 100 in which the input values for propellant density, propellant acoustic velocity and segment wall compliance for each of the 30 waterhammer segments of the Fig. 4 schematic are combined to yield an effective acoustic velocity for each segment. The subsequent statements, up to statement 400, combine the input variables as required to yield the constant coefficients of the 57 linear waterhammer and injector equations describing the complete Fig. 4 feed system. Simultaneous solution of these 57 equations, at each specified input frequency, yields the oscillatory amplitude and phase response of all pressures and flowrates in the feed system to inputs via chamber pressure oscillations at that frequency.

At statement 500 a call to subroutine FRESP is made to obtain the frequency response solution of the feed system equations. Initially, however, at statement 400 the value of input argument INPHYD is tested to determine the desired output from FRESP. If INPHYD is greater than 1, HYDRDY will call FRESP to calculate the feed system frequency response for each of the frequencies in array FREQT. The total number of frequencies is given by variable NFREQT and may range from 1 to 100. Both the variable, NFREQT, and the array, FREQT are in labeled common block/COMTAP/. If the value of INPHYD is less than or equal to 1 HYDRDY will call FRESP to calculate the feed system frequency response for the single frequency given by input argument, FRE.

Output data from subroutine HYDRDY consists of a pair of complex numbers for each specified input frequency. If INPHYD was specified as ≤ 1 then the output numbers GINJ0X and GINJFU are returned in labeled common block/F/ and also in the HYDRDY argument list as GIN0 and GINF. The real and imaginary parts of complex number GINJ0X (GIN0) represent the amplitude and phase angle respectively of $\frac{\Delta W0}{W0IN} / \frac{\Delta PC}{PCIN}$ at frequency FREQ (FRE). Similarly, the complex number GINJFU (GINF) represents the amplitude and phase angle of $\frac{\Delta W0}{WFIN} / \frac{\Delta PC}{PCIN}$ at frequency FREQ (FRE). W0IN, WFIN and PCIN are the input normal values for the oxidizer injector flowrate, fuel injector flowrate and chamber pressure, respectively, from the HYDRDY argument list.

If INPHYD was specified as >1, then rather than a single pair of complex numbers representing oscillatory injection flowrates, HYDRDY returns two arrays, GINJ0T and GINJFT, containing the oscillatory injection flowrate amplitude and phase data for each of the NFREQT frequencies in array FREQT. The output arrays GINJOT and GINJFT are stored in labeled common block /C0MTAP/ and are also written out on the output device whose logical unit number is designated by variable ITAPH in labeled common block /C0MTAP/. The order of storage on the output device is GINJ0T(I), GINJFT(I), for I values from 1 through NFREQT. After writing the GINJ0T and GINJFT arrays on the output device HYDRDY sets the value of variable INPHYD to 3. Also, before returning control to the main program, HYDRDY tests the value of variable IWRITE. If IWRITE is non-zero, each specified frequency and the corresponding value of GINJ0T and GINJFT are written out on logical unit 6. If only one frequency was specified (INPHYD $\leq$ 1), then only the single point values of FREQ, GINJ0X and GINJFU are written out.

It should be noted that although output from a single call to HYDRDY contains values for both "oxidizer" and "fuel" oscillatory injection flowrates (at one or more frequencies), the output values actually refer to the "0" and "F" injectors of the Fig. 4 schematic. Thus, unless both oxidizer and fuel feed systems can simultaneously be modeled with the Fig. 4 layout, it is necessary to call HYDRDY twice - once for the oxidizer feed system and once for the fuel feed system.

FRESP

Subroutine FRESP (Fig. 12) is used to obtain the frequency domain characteristics of the feed system indirectly from input data that describes the physical

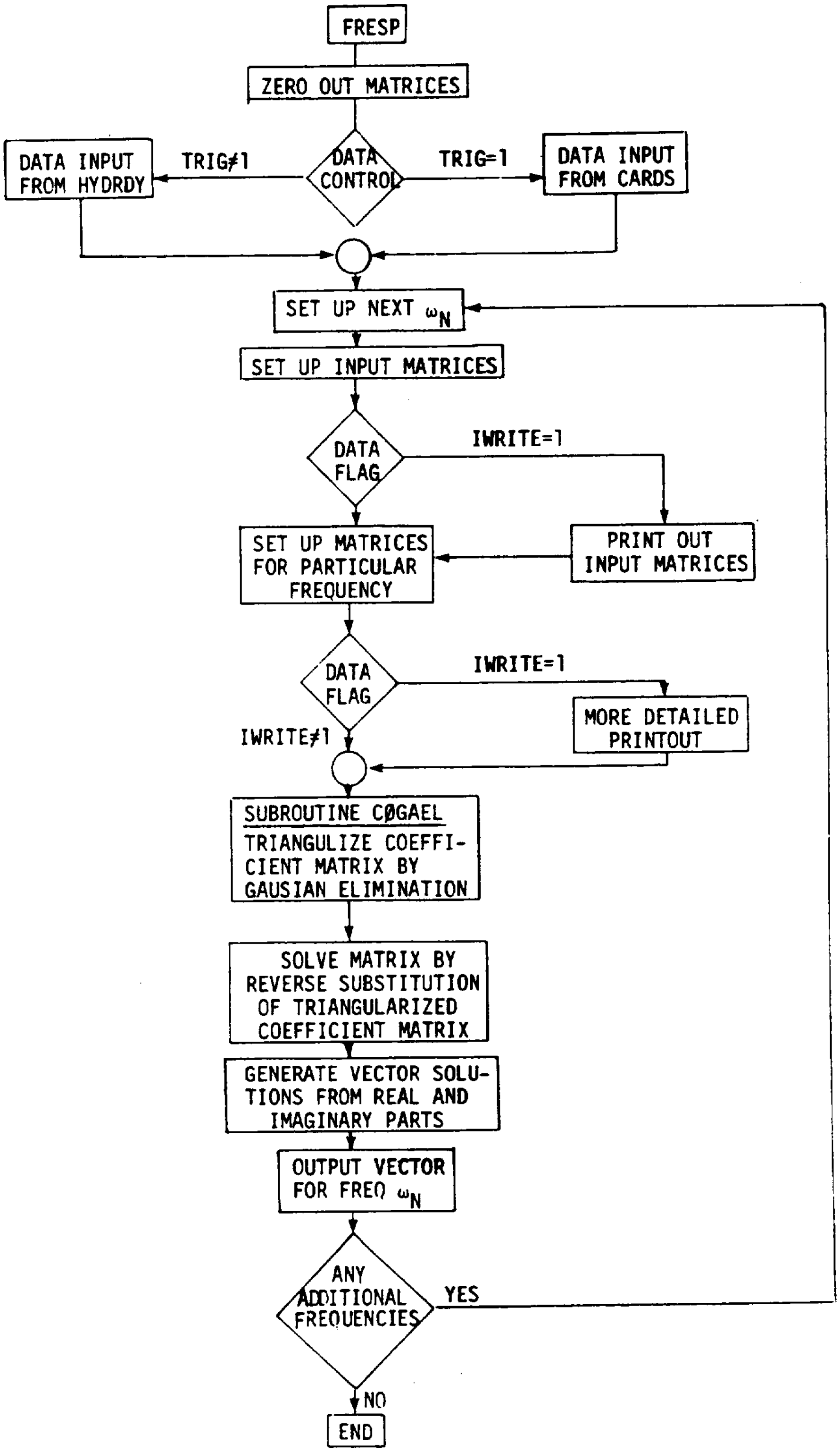

Figure 12. Logic Diagram for Subroutine FRESP

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characteristics of the feed system. (The actual input to FRESP is generated by the subroutine HYDRDY which orders the physical characteristics of the system into specific matrices of coefficients that FRESP can use as input data.)

FRESP merely solves for the variables X_i in the following relationship:

$$C \quad \{X\} = a \quad Y$$

where Y is a single input variable that represents a unit value of the injector end combustion chamber pressures. The matrix a then relates the specific pressure input to each applicable equation that contains combustion chamber pressure (a may contain both static and dynamic terms.) The matrix C is simply the coefficients of the linear differential equations that represent the physical system. The values of the coefficients for the a and C matrices are computed by the subroutine HYDRDY.

The FRESP matrices can be expressed as:

$$C_{ijk} \, S^{k-1} \cdot \{X_j\} = a_{ik} \, S^{k-1} \cdot Y$$

with the differential operator defined as $S = J\omega$, where $J = \sqrt{-1}$ and ω is the frequency. The matrices may be broken down to provide real matrices and imaginary matrices.

$$C_{ij1} - C_{ij3}\,\omega^2 + C_{ij5}\,\omega^4 - \ldots. \quad + J \quad C_{ij2}\,\omega - C_{ij4}\,\omega^3 + \ldots$$

$$\cdot \; X_j = a_{i1} - a_{i3}\,\omega^2 + \ldots. \quad + J \quad a_{i2}\,\omega - a_{i4} \quad - A_{i4}\,\omega^3 + \ldots \circ Y \qquad (213)$$

Since the time delay coefficients used in the differential equations are of the form $e^{-\tau S} \cdot X$, which is equivalent to $e^{-\tau j\omega} \cdot X$, and since $e^{-jy} = \cos(y) + j\,\sin(y)$, these terms may be added to the previously formed real and imaginary matrices to give:

$$\left\{ \left[C_{ij1} - C_{1j3}\,\omega^2 + \ldots. + \cos\,(\tau_{ij}\,\omega) \right] + \left[J\;\; C_{ij2}\,\omega - C_{ij4}\,\omega^3 + \ldots. + \sin\,(\tau_{ij}\,\omega) \right] \right\} \cdot \left[X_j \right] = \left\{ \left[a_{i1} = a_{i3}\,\omega^2 + \ldots. \_ \cos\,(\tau_i\,\omega) \right] + J \left[a_{i2}\,\omega - a_{i4}\,\omega^3 + \ldots. + \sin\,(\tau_i\,\omega) \right] \right\} Y \tag{214}$$

and solved for $\left[X_i \right]$:

$$\left[X_i \right] = \left\{ \left[C_{ij1} - C_{ij3}\,\omega^2 + \ldots. + \cos\,(\tau_{ij}\,\omega) \right] + J \left[C_{ij2}\,\omega - C_{ij4}\,\omega^3 + \ldots. + \sin\,(\tau_{ij}\,\omega) \right] \right\} \cdot \left\{ \left[a_{i1} - a_{i3}\,\omega^2 + \ldots. + \cos\,(\tau_i\,\omega) \right] + J \left[a_{i2}\,\omega - a_{i4}\,\omega^3 + \ldots. + \sin\,(\tau\omega) \right] \right\} \cdot \tag{215}$$

The matrices are multiplied and then solved for $\left[X_i \right]$ in the subroutine COGAEL which employs the standard Gaussian elimination procedure for solving linear equations. The $\left[X_i \right]$ solution is still separated into real and imaginary components, and are simply combined to form a vector for each variable. The procedure is repeated for each frequency being considered.

C0GAEL

This subroutine is called by the hydrodynamic frequency response subroutine, FRESP, to triangularize the complex matrix of feed system equations. Back substitution into the triangular system of equations is subsequently performed by subroutine FRESP to yield the real and imaginary portions of each feed system variable.

The conventional method of Gaussian elimination is employed by C0GAEL to triangularize the system of equations. The reduction process proceeds in column order from left to right. First the complex element with the largest absolute value in the current ("pivot") column at or below the diagonal is located. Then the rows are interchanged if required to move this maximum element (pivot element) to the diagonal. The row interchange serves to minimize the round-off errors from the subsequent reduction process. The pivot row (row containing the pivot element) is then divided by the pivot element yielding 1.0 from the pivot element. Finally, the elements in the pivot column below the diagonal are eliminated by subtracting the appropriate multiple of the pivot row from each row below it. The subtraction is not actually performed on the elements below the diagonal since these elements do not enter into the subsequent back substitution process performed by subroutine FRESP.

It should be noted that the above discussion refers to the complex matrix as if the elements were single numbers. The actual elements are stored as two numbers in each row, the real portion to the left of the constant term, and the imaginary portion on the right. This distinction does not alter the elimination process except that two separate numbers must be operated on at each step.

TDPL0T

If the value of ICRT is greater than 0 this subroutine is called by the frequency response routine FRESP to generate CRT plots of the gain and phase of the output variables as a function of frequency.

The input arguments to TDPLØT are, W, an array of up to 101 frequencies; Y, an array of gain or phase values; NFP, the number of data points in arrays W and Y; TL, the lowest desired frequency grid line; XR, the highest desired frequency grid line; and LL, a flag indicating a gain plot if 1 or a phase plot if 2.

Initially TDPLØT scans the Y array for the maximum and minimum values and generates values for the Y axis grid scaling. The first value of Y is not included in this scan. This allows an initial very low value of frequency to be used to approximate the system DC frequency response without upsetting the plot frequency scaling. TDPLØT uses the standard graphics package routines for the SC-4020 to generate the plot grids and plot the data points. If the value of LL is 1 the CRT frame is advanced and a plot of Y(I) versus W(I) is made on the bottom half of the page. If LL is 2, the frame is not advanced and the plot is made on the top half of the page.

In addition to the plots, TDPLØT prints the numeric value of the first Y array element immediately above the corresponding plot. This element typically corresponds to a very low frequency value (default value of .001 cps in subroutine FRESP) which is well below the frequency range desired for the plot and approximates the DC value of the output variable.

TDPLØT does not generate any titles or identificating information on the plots.

N0ZADM, (RKTDIF, RKTZ, RKZDIF, TADAMS, ZADAMS)

This routine and its support routines, is called by the main program to determine the nozzle admittance based on downstream conditions. The programs were developed and programmed by Georgia Institute of Technology and the user is referred to Ref. 23 for a complete description of these routines. The main nozzle admittance program was modified by Rocketdyne so that input data could be read if required and also the nozzle admittance saved on a tape unit ITAPN (Fig. 13).

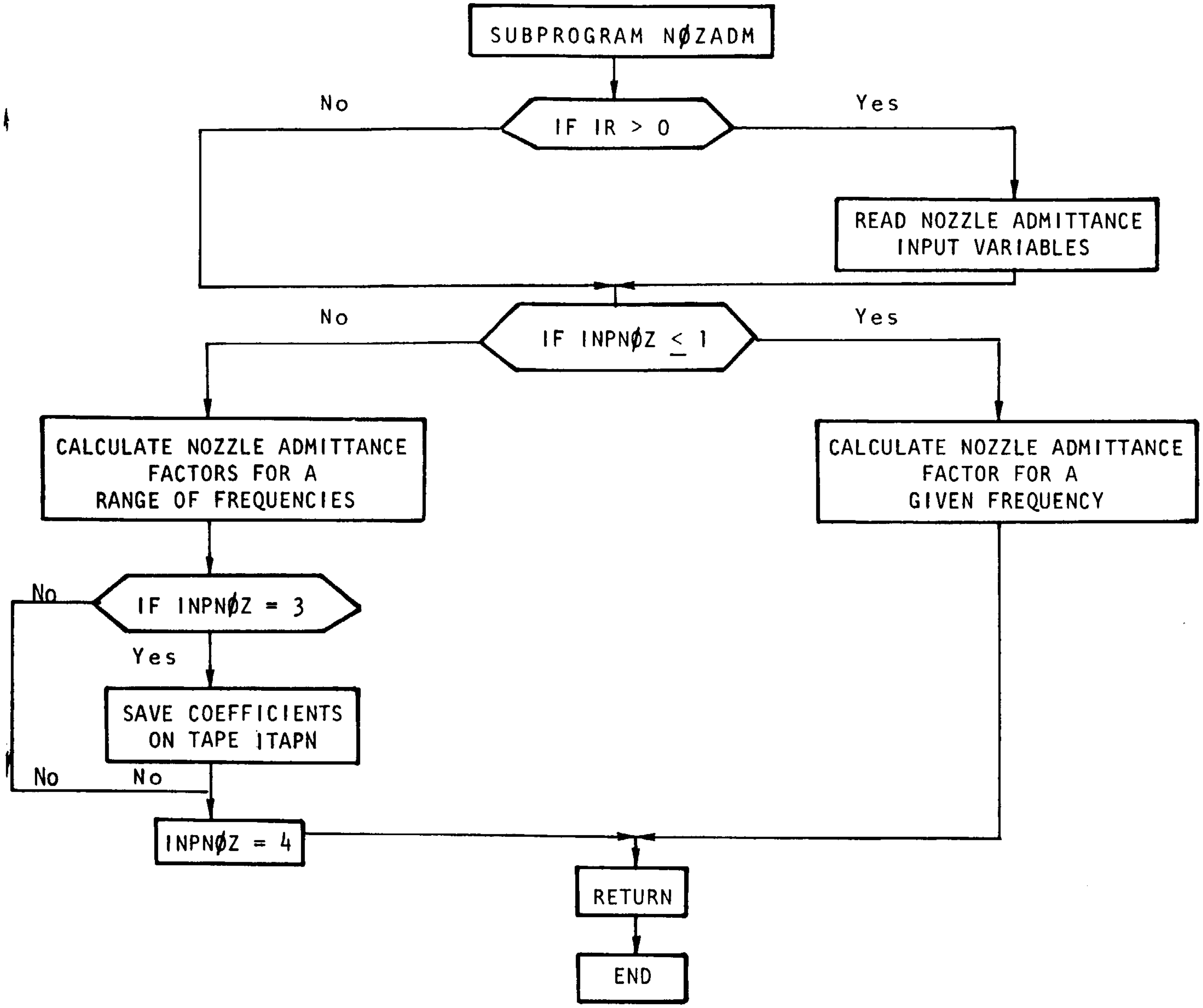


Figure 13. Logic Diagram for Subroutine NØZADM

FSCSM COMPUTER MODEL INPUT

This section, and the Hydrodynamic Input section, describes the input necessary to run the FSCSM computer model. The input is broken up into four major control sections. These are the main control section input, the nozzle admittance control section input, the hydrodynamics control section input, and the combustion dynamics control section input. Table 2 lists all the variables that are to be input for each control section. This input is in the usual 80 character card form. Listed in Table 2 for each control section are each card's number and format, the variable names appearing on each card, and a brief description of each variable appearing in the list.

The main control section requires either eight or nine cards depending upon the input value of INPN0Z. (If INPN0Z is less than or equal to three, the last card in this section should be input). The first two cards, cards 1 and 2, should contain title and case identification information. These are read in alpha numeric format and printed at the top of almost every page of output to identify the case being considered.

The third card contains control information for various run options, file numbers for the auxiliary storage of datasets used by the program, print codes, and the number of mesh points to be used in the analysis. The control flags are INPHYD, INPC0M, and INPN0Z. These flags allow the user to save the results from the current case or use the results from a previous case for the current case. It is recommended that these datasets be set up as permanent files in order to use them for subsequent job submittals.

The first of these flags, INPHYD, controls the hydrodynamics feed system dataset. If it is input as one, no action will be taken with respect to saving or reading information on or from a dataset. The hydrodynamics coupling terms will be recomputed each time the frequency changes. If INPHYD is input as two, a table of hydrodynamic coupling terms will be generated for the frequency range specified by the input variables NFREQ, FREQMI, and FREQMX. This table will be saved on file ITAPH (also input on this card) and used to linearly interpolate in each time the frequency changes. If INPHYD is input as three, the program assumes a

TABLE 2. FSCSM INPUT DATA

CONTROL SECTION	CARD NO./ FORMAT	VARIABLE NAME	DESCRIPTION
Main Program Input	THESE CARDS MUST ALWAYS BE INPUT		
	1,2 (18A4)	((TITLE(I,J), I=1,18), J=1,2)	Title information is input on the first two cards in the input dataset. These should be used to identify the case being run.
	3 (12I6)	INPHYD	Code used for hydrodynamic calculations. 1: Hydrodynamic coupling terms (HCT) will be computed each time the frequency changes. 2: A table of HCT's will be computed using frequency table, FREQT, and saved on file ITAPH. Each time the frequency changes in trying to satisfy the nozzle admittance boundary condition, the HCT will be interpolated for in that table. 3: Table of HCT's already resides on file ITAPH from an earlier run. When the frequency changes, the HCT will be interpolated for in that table.
		INPC0M	Code used for the combustion dynamics coefficients (CDC). It can take on values from one to three. It has the same meaning with respect to the CDC as INPHYD does with respect to the HCT. The tables are saved on file ITAPC.
		INPN0Z	Code used for the downstream nozzle admittance term (DNAT). 1: The DNAT is computed each time the frequency changes. 2: A table of DNT's versus frequency using frequency table, FREQT, is computed and saved internally. Each time the frequency changes in trying to satisfy the nozzle admittance boundary condition, the DNT will be interpolated for in that table.

TABLE 2. (Continued)

CONTROL SECTION	CARD NO./ FORMAT	VARIABLE NAME	DESCRIPTION
Main Program Input (Cont.)			3: Same as 2, but the table is also saved on file ITAPN. 4: A table of DNT's versus frequency already resides on file ITAPN (from a previous run). Interpolation is the same as 2 and 3.
		ITAPH	File used to save hydrodynamic coupling term table. Must be specified if INPHYD$\geq$2.
		ITAPC	File used to save combustion coefficients table. Must be specified if INPCØM$\geq$3.
		ITAPN	File used to save nozzle admittance terms table. Must be specified if INPNØZ$\geq$3.
		IPRHYD	Code used for hydrodynamics coupling term table printout. 0: Table will not be printed. 1: Table will be printed.
		IPRCØM	Code used for combustion coupling coefficients printout 0: Coefficients will not be printed. 1: Coefficients will be printed at each frequency found to satisfy the nozzle admittance boundary condition.
		IPRNØZ	Code used for the downstream nozzle admittance terms table printout. 0: Table will not be printed. 1: Table will be printed.
		IPRCHM	Code used for the oscillatory profiles printout. 0: Profiles will not be printed. 1: Profiles will be printed at each frequency found to satisfy the nozzle admittance boundary condition.

TABLE 2. (Continued)

CONTROL SECTION	CARD NO./ FORMAT	VARIABLE NAME	DESCRIPTION
Main Program Input (Cont.)		IPRSTE	Code used for the steady-state profiles printout. 0: Profiles will not be printed. 1: Profiles will be printed.
		NXP	Number of axial positions to be used between the X0 plane (start of vaporization) and the nozzle inlet plane. (Both the X0 and nozzle inlet planes must be counted.)
	4 (6E12.8)	X0	Axial coordinate of start of vaporization plane, inches.
		XN0Z	Nozzle inlet plane, inches
		RINJ	Radius of combustion chamber at injector face, inches.
		GAM0	Ratio of specific heats of combustion gas (C_p/C_v) evaluated at overall mixture ratio, unitless.
		C0	Sonic velocity evaluated at overall mixture ratio, ft/sec.
		DELP	Oscillatory non-dimensional pressure amplitude at injector face, unitless.
	5 (6I6)	NR00T	Absolute value of this variable is the number of frequency solutions that will be searched for starting at the frequency specified by the real part of 0MEGA and ending at FROMAX. This variable may be input as either positive or negative. (See input of 0MEGAR for explanation.)
		IWRT	Intermediate output dump code used to write the oscillatory profiles solved for in CHAMDY for each iteration. 0: Oscillatory profiles will not be printed out between iterations. 1: Oscillatory profiles will be printed for each iteration.

TABLE 2. (Continued)

CONTROL SECTION	CARD NO./ FORMAT	VARIABLE NAME	DESCRIPTION
Main Program Input (Cont.)		IWSKP	Intermediate output dump code used in subroutine SØLVW. 0: No intermediate output will be printed from SØLVW during iterations. 1: Limited intermediate output will be printed by SØLVW 2: Extended intermediate output will be printed by SØLVW.
		KNTMX	Maximum number of iterations allowed to minimize the error in the nozzle admittance boundary equation with respect to the imaginary part of ω.
		KNTRMX	Maximum number of times the frequency will be allowed to be changed by DELFRQ during the searching algorithm between each solution.
		KNTSMX	Maximum number of iterations allowed for the convergence of the two-dimensional secant method used in SØLVW.
	6 (6E12.8)	ØMEGAR	Starting value for the real part of complex frequency of NROOT>0. This should be input in units of Hertz times 2π. If NROOT<0, this should be input in Hertz.
		ØMEGAI	Starting value for the imaginary part of complex frequency. This should be input as the growth coefficient if NROOT>0. It should be input as the decrement if NROOT<0.
		FRQMAX	Maximum frequency above which no solutions to the nozzle admittance boundary equation will be sought, Hertz.
		DELFRQ	Increment used to adjust the frequency during the searching portion of the algorithm to solve the nozzle admittance boundary equation, Hertz.

TABLE 2. (Continued)

CONTROL SECTION	CARD NO./ FORMAT	VARIABLE NAME	DESCRIPTION
Main Program Input (Cont.)		DELMX	Maximum allowable change in the growth coefficient between two successive iterations in the portion of the program that minimizes the error in the nozzle boundary condition equation with respect to the growth coefficient, sec^{-1}.
		CTEST	Upper bound on the condition number of the transpose of the Jacobian of the difference between the upstream and downstream nozzle admittances with respect to the complex frequency. If the condition number of that matrix exceeds CTEST for a given frequency, then it is assumed the Jacobian is singular near that frequency and hence a solution will not be sought at that point. Unitless.
	7 (4E12.8)	EPSF	Relative error criterion used during the search algorithm/or the portion of the program that minimizes the eror, HN, in the nozzle admittance boundary equation with respect to the growth coefficient, ω_I. To obtain convergence, it is necessary that $\frac{\partial \lvert HN \rvert^2}{\partial \omega_I} \Big/ \lvert N_D \rvert < EPSF$. Unitless.
		EPSX	Relative error criterion used during the search algorithm for the portion of the program that minimizes the error, HN, in the nozzle admittance boundary equation with respect to the growth coefficient, ω_I. To obtain convergence, it is necessary that $\lvert \omega_{I_1} - \omega_{I_2} \rvert \Big/ \lvert \omega_{I_2} \rvert < EPSX$ where the subscripts 1 and 2 refer to two successive iterations. Unitless.

TABLE 2. (Continued)

CONTROL SECTION	CARD NO./ FORMAT	VARIABLE NAME	DESCRIPTION
Main Program Input (Cont.)		EPSFS	Tightened relative error criterion used to determine if convergence has been obtained while iterating to solve the nozzle admittance boundary equation. To obtain convergence, it is necessary that $|A_{N_U} - A_{N_D}| \big/ A_{N_D} < EPSFS$ Unitless.
		EPSXS	Tightened relative error criterion used to determine if convergence has been obtained while iterating to solve the nozzle admittance boundary equation. To obtain convergence, it is necessary that $|\omega_1 - \omega_2| \big/ |\omega_2| < EPSXS$ where the subscripts 1 and 2 refer to successive iterations. Unitless.
	8 (3E12.8)	PC	Steady-state chamber pressure, psia.
		MBØXI	Oxidizer injection flowrate, lbm/sec
		MBFUI	Fuel injection flowrate, lbm/sec
		INPUT THIS CARD ONLY IF INPNØZ≤3	
	9 (I12,2E12.8)	NFREQT	Number of points in frequency table.
		FREQMI	Minimum frequency in frequency table, Hertz.
		FREQMX	Maximum frequency in frequency table, Hertz.

TABLE 2. (Continued)

CONTROL SECTION	CARD NO./ FORMAT	VARIABLE NAME	DESCRIPTION
Nozzle Admittance Program		INPUT THE CARD IN THIS CONTROL SECTION ONLY IF INPN0Z≤3	
	1 (4E12.8)	RCCX	Ratio of the radius of curvature at the nozzle inlet to the chamber radius at nozzle inlet, unitless (see Fig.15).
		RCTX	Ratio of the radius of curvature upstream of the throat to the chamber radius at nozzle inlet, unitless (see Fig. 15).
		ANGLEX	Nozzle convergence half angle, degrees, (see Fig.15).
		CRR	Contraction ratio, cross-sectional area of chamber/throat area, unitless (see Fig. 15)
Hydrodynamics Program		THIS CONTROL SECTION READS IN ITS INPUT DATA IN NAMELIST FORMAT. THE NAMELIST NAME IS /HYD/. INPUT THIS DATA ONLY IF INPHYD≤2.	
		&HYD*	Input these characters starting in column two of the first card of the input.
		NAMELIST Variables in any order	See Table 3 for a listing of the NAMELIST data input names. The accompanying text describes the meaning of these variables.
		&END*	Character string denoting the end of the NAMELIST input block.

---

*For Univac 1110 systems, use $HYD and $END

TABLE 2. (Continued)

CONTROL SECTION	CARD NO./ FORMAT	VARIABLE NAME	DESCRIPTION
Combustion Dynamics Program			INPUT THE CARDS IN THIS CONTROL SECTION ONLY IF INPC0M≤ 2
	1 (6E12.8)	XK0X	Klystron constant for oxidizer jet, inches.
		TAUB0X	Steady-state oxidizer vaporization time delay, sec.
		VB0X	Steady-state oxidizer injection velocity, ft/sec.
		DELH0X	Pseudo energy term for oxidizer, Btu/lbm.
		TDRAG0	Steady-state oxidizer drag time delay, sec.
		ADV0X	Velocity exponent for the oxidizer atomization process, unitless.
	2 (5E12.8)	ADD0X	Oxidizer liquid jet diameter exponent, unitless.
		DELV0X	Steady-state velocity difference between oxidizer droplets and gas stream normalized to the sonic velocity at the overall mixture ratio, unitless.
		NUB0X	Steady-state oxidizer Nusselt number used in vaporization expression, unitless.
		DT0XDM	Partial derivative of oxidizer vaporization time delay with respect to mixture ratio, holding the vaporization blockage term, drop diameter, and Nusselt number constant, sec.
		XIMP0X	Oxidizer jet impingement point, inches.
	3 (6E12.8)	XKFU	Klystron constant for fuel jet, inches.
		TAUBFU	Steady-state vaporization time delay, sec
		VBFU	Steady-state fuel injection velocity, ft/sec.

C.2

TABLE 2. (Concluded)

CONTROL SECTION	CARD NO./ FORMAT	VARIABLE NAME	DESCRIPTION
Combustion Dynamics Program (Cont.)		DELHFU	Pseudo energy term for fuel, Btu/lbm.
		TDRAGF	Steady-state fuel drag time delay, sec.
		ADVFU	Velocity exponent for fuel atomization process, unitless.
	4 (5E12.8)	ADDFU	Fuel liquid jet diameter exponent, unitless.
		DELVFU	Steady-state velocity difference between fuel droplets and gas stream normalized to the sonic velocity at the overall mixture ratio, unitless.
		NUBFU	Average steady-state fuel Nusselt number used in vaporization expression, unitless.
		DTFUDM	Partial derivative of fuel vaporization time delay with respect to mixture ratio, holding the vaporization blockage term, droplet diameter, and Nusselt number constant, sec.
		XIMPFU	Fuel jet injection impingement point, inches.
	5 (5E12.8)	MWG	Steady-state molecular weight of the gas at the overall mixture ratio, lbm/lbm-mole.
		CS	Characteristic velocity at the overall mixture ratio, ft/sec.
		DRGDMR	Partial derivative of gas constant with respect to mixture ratio evaluated at the overall mixture ratio, ft-lb/lb/^{o}R.
		DCSDMR	Partial derivative of characteristic velocity with respect to mixture ratio evaluated at the overall mixture ratio, ft/sec.
		DHDMR	Partial derivative of gas reference enthalpy with respect to mixture ratio averaged over the mixture range during steady-state operation, Btu/lbm.

table of hydrodynamic coupling terms versus frequency already resides on file ITAPH in the format used during generation of such a table when INPHYD is input as two. The program will interpolate in this table in order to obtain the hydrodynamic coupling terms each time the frequency changes. The use of interpolation, once a table has been generated, substantially reduces the computer run time for each case run.

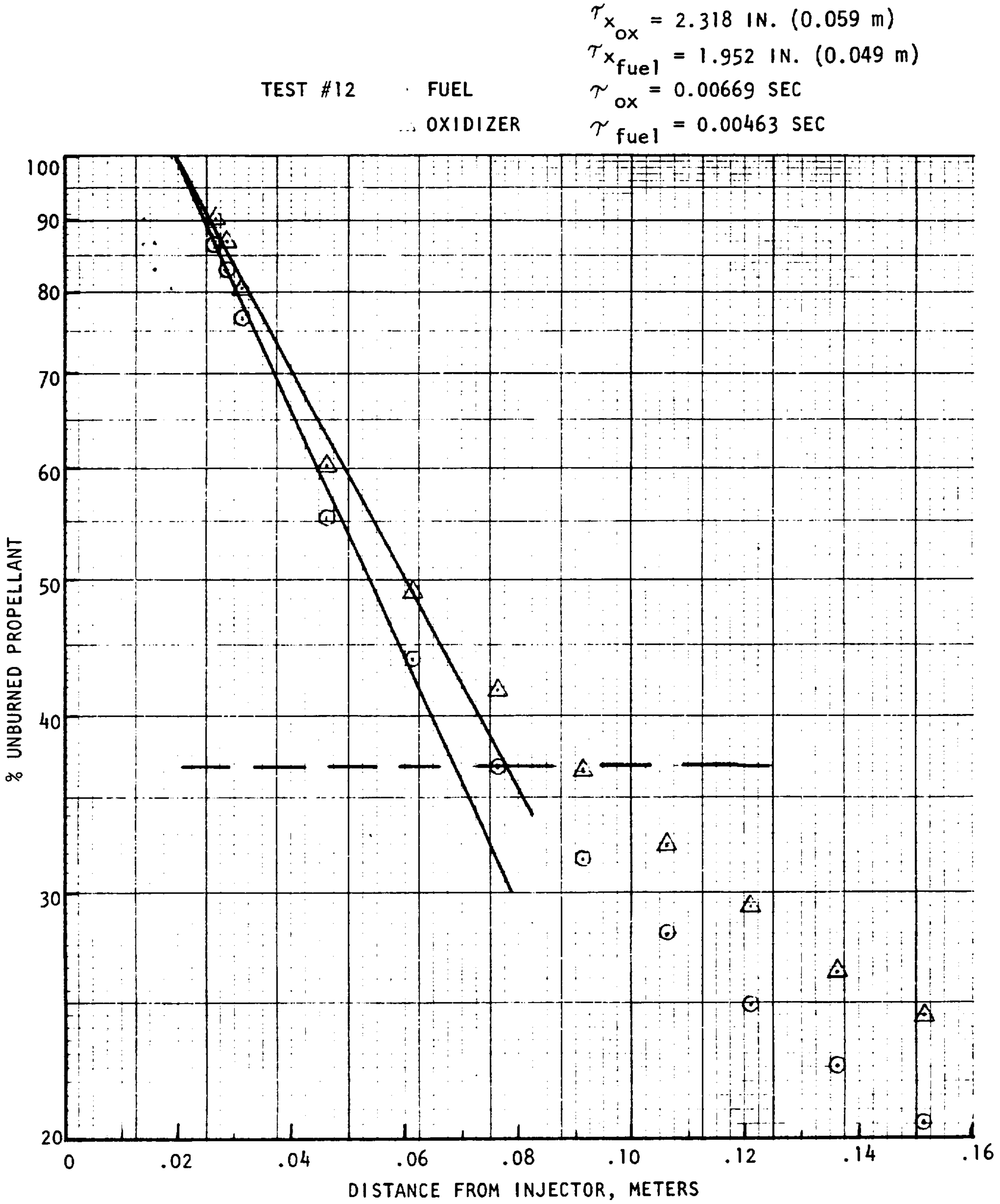
The other two control flags input on the third card control the datasets for the combustion dynamics coefficients and the nozzle admittance factors. These flags are similar to INPHYD. Their description is given in Table 2.

Also input on the third card of the main control section input are the file numbers of the datasets discussed above and print control flags for the various forms of output one can obtain. These are all self-explanatory. The user need only refer to Table 2 in order to determine the values that should be input for the case being considered.

The final entry on the third card is for the variable NXP, the number of points to be used for the axial distance and area arrays. This controls the step size that will be taken during the integration of the chamber dynamics equations; i.e., step size = (XN0Z - XO)/(NXP-1) where XO is the axial location of the start of vaporization plane and XN0Z is the axial location of the nozzle inlet plane. The values of XO and XN0Z are both input on the very next card read in (card 4 in Table 2).

The start of vaporization plane (XO) is calculated by plotting the percent unburned of both fuel and oxidizer that is calculated by the DER program (or equivalent steady-state combustion model) as a function of distance from the injector face (Fig. 14). These plots are then extrapolated back to 100% unburned and the axial location of this point is XO.

Also input on card 4 are the radius of the combustion chamber at the injector face, RINJ, the ratio of specific heats (C_p/C_v), GAM0, the sonic velocity, C0, and the oscillatory non-dimensional pressure amplitude desired at the injector face ($\Delta P/P$), DELP. The variables GAM0 and C0 should be evaluated at the overall



~~F~~igure 14. Percent Unburned Propellant as a Function of Distance from Injector Face mixture ratio. The variable DELP will scale the amplitude of the oscillatory waves solved for in subroutine CHAMDY. A value of 0.1 is recommended.

The first variable input on the fifth card of the MAIN program control section input is NR00T. The absolute value of this variable controls the maximum number of frequency solutions the program will try to find. The program begins its search at the frequency implied by the input variable 0MEGAR. It will stop looking once it has found |NR00T| solutions or if the frequency is above FRQMAX. The variables IWRT and IWSKP are the next two variables input on this card. They control the amount of intermediate output one desires. Their exact function is described in the Program Operation Section of this manual.

The last three variables input on the fifth card are KNTMX, KNTRMX, and KNTSMX. Their meaning is explained in Table 2 . Recommended values for these variables are 50, 100, and 20 respectively.

The sixth card of the MAIN program control section input contains the variables 0MEGAR, 0MEGAI, FRQMAX, DELFRQ, DELMX, and CTEST. The first two of these variables specify the starting guess in the ω plane for solution. No solutions will be sought below the frequency implied by OMEGAR. Note that 0MEGAR and 0MEGAI can be input as the frequency in Hertz times 2 π and the growth coefficient or the frequency in Hertz and the decrement depending upon whether NROOT was input as positive or negative. The variable FRQMAX, as mentioned earlier, is the maximum frequency allowed for the search algorithm to find solutions. The variable DELFRQ specifies the "stepsize" used by the search algorithm. Since there are sometimes many areas in the ω plane which contain solutions, a fairly small stepsize is recommended, e.g., 5 Hz. The variable DELMX controls the maximum allowable change in the growth coefficient during successive iterations to minimize the error in the nozzle admittance boundary condition as a function of the imaginary part of ω. A recommended value for this variable is 50 sec^{-1}. The last variable on this card, CTEST, is the upper bound on the condition number of the transposed Jacobian used to solve the nozzle admittance boundary condition. If the calculated condition number exceeds CTEST, then the search algorithm assumes that there is a singularity near the current value of ω and hence, does not proceed further in that area to try and find a solution. A value of 50 to 80 is recommended.

The seventh card of the MAIN Program Control Section input contains error tolerances used in solving the nozzle admittance boundary condition. The first two, EPSF and EPSX, are used during the search algorithm and should be fairly large, e.g. 0.01 to 0.05 (1% to 5% error). The last two, EPSFS and EPSXS, control the final stages of iteration and should be fairly tight, e.g. 0.0005 (0.05%).

The eighth card of this control section contains the variables PC, MB0XI, and MBFUI. The first is the steady state chamber pressure, in PSIA, and the next two are the oxidizer and fuel injection flowrates, respectively (lbm/sec).

The last card, card number 9, in the MAIN Program Control Section input should be input only if the variable INPN0Z is less than or equal to three. If this is the case, the program needs to know the size and range of the frequency table it will use to generate tables for linear interpolation as discussed in the section describing the input variables INPHYD, INPC0M, and INPN0Z. The input variables on this ninth card are NFREQT, FREQMI, and FREQMX. Their meaning is described in Table 2.

The next control section to read data after the MAIN program is the Nozzle Admittance Program. The data for this control section should be input only if INPN0Z ≤ 3. Otherwise, the information is not needed since the nozzle admittance information will be on tape ITAPN. Even when INPN0Z ≤ 3, there is only one card input. This card contains information describing the nozzle geometry. Refer to Table 2 to determine the meaning of the variables on this card. Figure 15 shows exactly what portion of the nozzle each variable is applicable to.

The next control section that requires data is the Hydrodynamics Program section. This control section uses namelist input. The data for this control section are only input if INPHYD ≤ 2. Otherwise, the hydrodynamics information will be on tape ITAPH. The Hydrodynamic Input section (page 102) describes the meaning of the variables to be input for the control section.

The last control section to require input data is the Combustion Dynamics Program. This input is contained on five cards. It should be omitted if INPC0M is greater than or equal to three, since then the combustion dynamics information will reside on tape ITAPC.

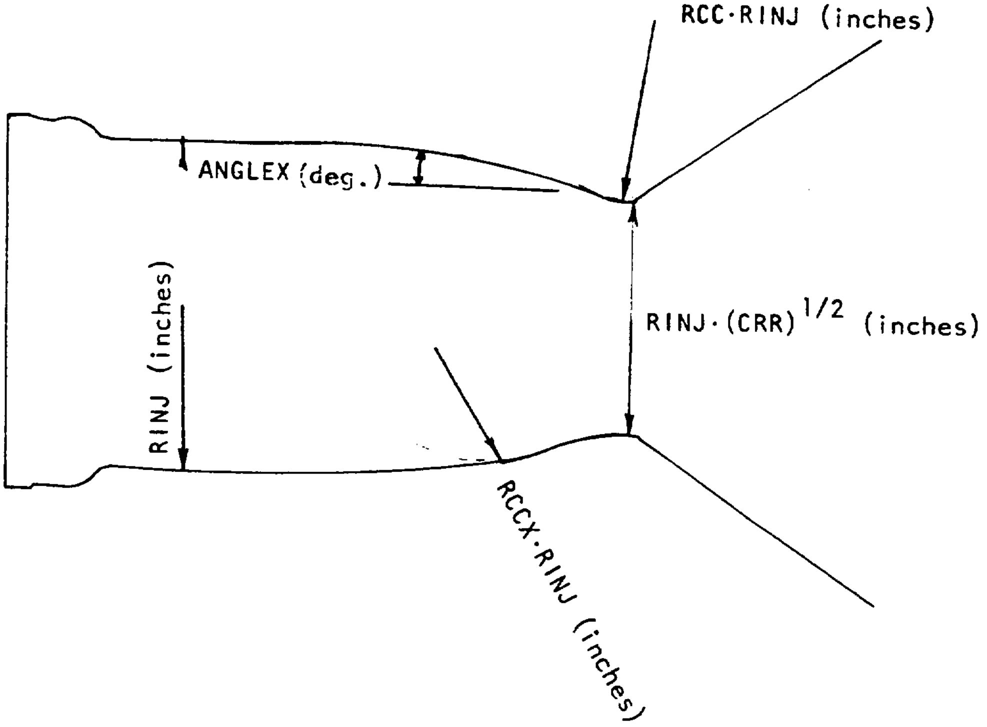


Figure 15. Chamber and Nozzle Geometry

The first two cards for this section contain information specific to the oxidizer; the next two cards contain information specific to the fuel; the last card contains information specific to the combustion gas. Much of the information required in this section is obtainable from the output of the DER program (Ref. 11). This program solves for the steady state behavior of the chamber under consideration. The single stream tube option of the DER program is sufficient for this application.

As mentioned above, the variables input on the first two cards of the Combustion Dynamics Program control section are applicable to the oxidizer. These variables are XK0X, TAUB0X, VB0X, DELH0X, TDRAG0, ADV0X, ADD0X, DELV0X, NUB0X, DT0XDM, and XIMP0X. The first variable XK0X, is the Klystron constant for the oxidizer jet. This variable controls the distance downstream from the injector face that the Klystron effect will be allowed to occur. The exact method of calculating XK0X has not been determined but it is recommended that a distance corresponding to approximately 45% of the oxidizer vaporized be used.

The next variable, TAUB0X, is the steady state oxidizer vaporization time delay. Figure 14 gives the percent unburned for the sample input case of liquid oxidizer and fuel remaining in the chamber as a function of axial distance plotted on semi log graph paper. This output was derived from a DER computer run. The reciprocal of the average slope of the oxidizer curve during the initial burning phases should be taken as the oxidizer vaporization distance delay. For Figure 14, this is 2.318 inches. The time delay is obtained by dividing this by the average injector velocity, which, for the sample case presented in Figure 14 is 28.859 ft/sec. The result is 0.00669 seconds. The next variable, VB0X, is the average oxidizer injection velocity. This is also given by the DER program from injector orifice and steady state ΔP considerations.

The variable DELH0X is the pseudo energy of the oxidizer droplets and is discussed at the end of this section. The variable TDRAG0 is the steady-state oxidizer drag time delay and a value of zero is currently recommended. If this variable is different from zero, the computed pressure and velocity profiles calculated in the chamber are unrealistic (see Conclusions and Recommendations in Ref. 1).

ADV0X and ADD0X are the velocity and orifice diameter exponents for the oxidizer atomization process, i.e.,

$$\bar{D}_{ox} \sim V^{ADV0X} D_{orif}^{ADD0X} \tag{216}$$

These variables are obtained from cold flow tests and for like-doublets -0.75 and 0.57 are recommended. It should be noted that these variables are on different input cards. The next input variable is DELV0X which is the steady-state velocity difference between the oxidizer droplets and the combustion gas stream normalized to the sonic velocity. Since the vaporization rate is highest near the injector face, this variable should be evaluated near the injector face. Because the gas and the droplet velocities are approximately equal to each other at this location, a value of 0.01 is recommended based on turbulence levels in a rocket chamber (Ref. 26).

The next variable, NUB0X, is the steady state oxidizer Nusselt number used in the vaporization expression. This variable should be computed from the relation

$$N_{u_{ox}} = 8/6 \frac{\bar{D}_{ox}^{2}}{k'_{ox} \bar{\tau}_{ox}} . \tag{217}$$

where $\bar{D}_{ox}$ is the average oxidizer droplet diameter near the injector face, k'_{ox} is the vaporization coefficient used in the k'-model evaluated at a mixture ratio near the injector face and $\bar{\tau}_{ox}$ is the oxidizer time delay. Both $\bar{D}_{ox}$ and k'_{ox} are obtainable from a DER computer run. For the sample case input, "near the injector face" was taken as the first axial step printed by the DER program.

The variable DT0XDM is the change in the oxidizer vaporization time delay with respect to mixture ratio. At the present time, a value of zero is recommended based on model verification cases (Ref. 1).

The last oxidizer variable input is XIMP0X. This is the impingement point in inches for the oxidizer jets.

The next two cards contain data for the fuel. These data are obtained the same way as they were for the oxidizer and are input in the same order.

The last card for this control section contains combustion gas data. The first variable input on this card, MWG, is the steady state molecular weight evaluated at the overall mixture ratio. This may be obtained from tables of molecular weight versus mixture ratio printed by the DER program. The next variable, CS, is the characteristic velocity evaluated at the overall mixture ratio. This is also obtainable from DER table output. The last three variables on this card are DRGDMR, DCSDMR, and DHDMR. These are the partial derivatives with respect to mixture ratio of the gas constant, the characteristic velocity, and the reference enthalpy respectively. DRGDMR and DCSDMR can be calculated from equilibrium calculations but a value of zero is recommended for DCSDMR based on model verification cases (Ref. 1).

The variable DHDMR, and also the variables DELHØX and DELHFU, is calculated by curvfitting the steady-state energy equation with stagnation temperature/mixture ratio data calculated by an equilibrium program. The steady-state energy equation can be written as

$$\left(\frac{\gamma_\phi}{\gamma_\phi-1}\right) R_\phi \left\{ T \left[1+\frac{1}{R_\phi}\left(\frac{\partial R}{\partial MR}\right)_\phi (MR-MR_\phi) \right] (1+MR) - (1+MR_\phi)\, T_\phi \right\} = (MR-MR_\phi)\,(\Delta h_{ox}) - \left[MR\,(1+MR) - MR_\phi\,(1+MR_\phi) \right] \left(\frac{\partial h}{\partial MR}\right)_\phi \tag{218}$$

where

$$(\Delta h_{fu}) = \left(\frac{\gamma_\phi}{\gamma_\phi-1}\right)(1+MR_\phi)\, R_\phi\, T_\phi - MR_\phi\,(\Delta h_{ox}) + (MR_\phi)(1+MR_\phi)\left(\frac{\partial h}{\partial MR}\right)_\phi \tag{219}$$

and the subscript ϕ indicates that the variable is to be evaluated based on the overall mixture ratio.

HYDRODYNAMIC INPUT

This section describes data needed by the hydrodynamics subroutine, HYDRDY, to simulate the various feed system components. It is assumed that the feed system being modeled has been laid out on the generalized feed system schematic of Fig. 4 with an appropriate segment number assigned to each feed system component (or combination of components).

Basic Feed-System Data

To describe the basic feed system it is necessary to know the length, area, resistance and wall compliance of each of the numbered segments of Fig. 4 which are being used. Also, the acoustic velocity and density of the fluid in each segment must be known. If there is dissolved an entrained gas in the system, then a preliminary calculation must be made for each feed system section to account for the effect of the gas on the fluid acoustic velocity.

Specific parameters required for the numbered segments are:

A - Segment cross-sectional area - in.^{2}
CW - Segment wall compliance ($\Delta V/\Delta P/V$ - in.^{2}/lb
L - Segment length - in.
R - Segment linearized hydraulic resistance ($\Delta P/\dot{W}$) - sec/in.^{2}
V - Segment fluid acoustic velocity - in./sec
RH0L - Segment fluid density - lb/in.^{3}

Valves, Fittings, Orifices, Screens, Flowmeters, etc.

These components can each be described in the model simply as lumped resistance at the end of a line segment. Rather than using all the attributes of one of the numbered segments (length, area, wall compliance, etc.) for one of these "resistance only" components, it is suggested that its resistance merely be added to that of the adjacent upstream pipe segment. The combination can then be entered as one of the numbered segments with the length, area and wall compliance values being primarily those of the pipe segment.

Accumulators

A feed system accumulator can be represented as one of the side branch lines of the Fig. 4 schematic by specifying an appropriate length, area, acoustic velocity and fluid density for the fluid volume of the accumulator and also specifying an appropriate connecting resistance. The spring rate of the accumulator piston can be specified in terms of the segment wall compliance value.

Propellant Tanks

A large tank will have the effect of constant fluid pressure at its outlet and can be represented simply as the input to segment number 1, 15, or 22. No descriptive parameters are required for these inputs. Small tanks can be represented as one of the side branch lines in a manner similar to an accumulator. Ullage volume in a small tank is represented by a reduced value for the segment acoustic velocity.

Cavitating Venturies

The steady-state effect of a cavitating venturi is to have constant flow through the venturi as a function of variations in downstream pressure. For an oscillatory system, the vapor bubble downstream of the venturi throat makes the venturi look like a constant pressure boundary for small amplitude oscillations. To simulate this effect the effective acoustic velocity for the segment downstream of the cavitating venturi should be made very small (≈10 inches/sec would be appropriate). The steady-state hydraulic resistance of the cavitating venturi can be lumped with that of the upstream pipe segment as described above for valves, fittings, etc.

Regeneratively-Cooled Thrust Chamber

Regeneratively-cooled thrust chamber jackets can be represented as one or more of the numbered Fig. 4 segments. Because in most thrust chambers the coolant flow area changes continuously with length, as many segments as possible should be devoted to the jacket so as to improve the simulation accuracy. The fluid temperature also may change significantly along the chamber length thereby necessitating the use of several segments with different acoustic velocities to achieve accurate simulation.

Lines, Ducts, Bends, Bellows, and Flex Lines

These components are described in the model in terms of the basic numbered segment input parameters of length, area, fluid acoustic velocity, fluid density, wall compliance and linearized hydraulic resistance. For a duct or line of constant diameter, D, wall thickness, h, and wall material bulk modulus, E, the program input wall compliance value, CW, is simply D/LE. For a bellows or flux line of volume, V, the wall compliance value, CW, may be calculated from $\Delta V/\Delta P/V$ where $\Delta V/\Delta P$ is the volume change per psi at the operating pressure.

Injectors

The hydrodynamics subprogram employs a separate set of equations to describe the hydrodynamic characteristics of the two injectors in the Fig. 4 generalized feed system schematic. The specific input parameters for the two injectors are the volume, linearized hydraulic resistance, orifice inertance (1/Ag), fluid acoustic velocity, and a structural parameter defining the change in injector volume per psi of injector ΔP. In terms of the program variable names the required injector parameters are:

RF - Linearized hydraulic resistance for the "F" injector, $(2\ \Delta P/\dot{W})$ - sec/in.^{2}
RØ - Linearized hydraulic resistance for the "Ø" injector, $(2\ \Delta P/\dot{W})$ - sec/in.^{2}
VOLF - Volume of the "F" injector - in.^{3}
VOLØ - Volume of the "Ø" injector - in.^{3}
VF - Fluid acoustic velocity of the "F" injector - in./sec
VØ - Fluid acoustic velocity of the "Ø" injector - in./sec
ZF - Inertance of the "F" injector orifices (1/Ag) - sec^2/in.^{2}
ZØ - Inertance of the "Ø" injector orifices, (1/Ag) - sec^2/in.^{2}
KF - "F" injector deflection constant, $(\Delta V/\Delta P)$ - in.^{5}/lb
KØ - "Ø" injector deflection constant, $(\Delta V/\Delta P)$ - in.^{5}/lb

Tees, Splitters and Capped Lines

No provision is made in the model for completely generalized input of tees and branched lines. However, a system of considerable complexity can be modeled by laying out an appropriate flow path on the generalized Fig. 4 schematic. For example, a feed system with up to seven side branch lines can be simulated by choosing the main flow path through segments 1, 3, 4, 14, 17, 21, 25, 26, 28, 29, 30 and the "F" injector in series.

Input Variables

Data input to the hydrodynamics subprogram is from three sources: (1) Via the argument list in the CALL HYDRDY statement, (2) Through labeled common block/C0MTAP/and (3) By use of the NAMELIST data read routine.

The argument list variables, in order, are:

IR - Data read flag - dimensionless
INPHYD- Program function flag - dimensionless
FRE - Single frequency for feed system frequency response calculation - Hz
GIN0 - Output value of oscillatory oxidizer injector flowrate for input frequency FRE - dimensionless
GINF - Output value of oscillatory fuel injector flowrate for input frequency FRE - dimensionless
PCIN - Injector end thrust chamber pressure - psia
W0IN - Steady-state oxidizer injector flowrate - lb/sec
WFIN - Steady-state fuel injector flowrate - lb/sec

Several HYDRDY input variables are transmitted via labeled common block/C0NTAP/. ITAPH is the logical unit number of the output device on which subroutine HYDRY tabulates output values of oscillatory injection flowrates for the specific frequencies (up to 100 separate values) given in the array FREQT in common block/CONTAP/. The value of the FREQT in common block/C0NTAP/ is the total number of frequencies stored in the array FREQT.

All other data required by HYDRDY, including all the feed system descriptive data, is read in by use of the NAMELIST routine. The local rules for using this routine should be checked to verify that the correct card or terminal format is being used. Table 3 shows a list of allowable F0RTRAN names, the maximum values of subscripts, and a definition of the names. The name of the NAMELIST block is HYD.

TABLE 3. NAME LIST/HYD/DATA INPUT NAMES

NAME	DEFINITION
A(30)	Array containing segment cross-sectional area values
CW(30)	Array containing segment wall compliance values
FREQ	Frequency at which HYDRDY will compute feed system frequency response if INPHYD $\leq$ 1
FREQT(100)	Array containing frequencies at which HYDRDY will compute feed system frequency response of INPHYD > 1.
ICRT	ICRT = 1; injector flowrate gain and phase will be plotted vs frequency. ICRT = 0; no plot (default)
ID	Dummy name to allow for data card sequence numbers
IH(126)	Array containing control flags used by subroutine FREQD. Can be used to obtain printouts and plots of feed system frequency response for other variables in addition to the injector flowrates.
IRFLAG	IRFLAG = 0; read data from unit 5 (default) IRFLAG ≠ 0; read data from unit ITERM
ITERM	ITERM = 0; no terminal data input (default) ITERM > 0; read data from terminal (unit ITERM)
ITYPE	ITYPE = 1; both oxidizer and fuel feed systems are modeled simultaneously (default) ITYPE = 2; oxidizer feed system modeled on first pass of frequency response routine; fuel feed system modeled on second pass.
IWRITE	IWRITE = 0; HYDRDY input printed on unit 6 (default) IWRITE = 2; extensive printout of all HYDRDY input, intermediate output and final output on unit 6 IWRITE = 1; printout of HYDRDY input and final output on unit 6
KF	Injector face flexibility constant for "F" injector
KØ	Injector face flexibility constant for "Ø" injector.
L(30)	Array containing segment length values

TABLE 3. (Concluded)

NAME	DEFINITION
ØMI	Lowest frequency for injector flowrate gain/phase plot; default to FREQT(1) if not entered
ØMFL	Highest frequency for injector flowrate gain/phase plot; default to FREQT(NFREQT) if not entered
R(30)	Array containing segment hydraulic resistance values
RF	Hydraulic resistance for "F" injector
RHØL(30)	Array containing segment propellant density values
RØ	Hydraulic resistance for "Ø" injector
V(30)	Array containing segment acoustic velocity values
VF	Acoustic velocity for "F" injector
VØ	Acoustic velocity for "Ø" injector
VØLF	Volume of "F" injector
VØLØ	Volume of "Ø" injector
ZF	Inertance of "F" injector
ZØ	Inertance of "Ø" injector

Required input in the NAMELIST/HYD/data is a value of A, CW, L, R, RHØL, and V (see Table 3 for descriptions) for each numbered segment being included in the feed system. Values of KF and/or KØ, RF and/or RØ, VF and/or VØ, VØLF and/or VØLØ and ZF and/or ZØ are also required. It should be noted that, when possible, both oxidizer and fuel feed systems should simultaneously be laid out on the Fig. 4 schematic with the injector labeled "Ø" being used for the oxidizer side (data values KØ, RØ, VØ, VØLØ and ZØ) and the injector labeled "F" being used for the fuel side (data values, KF, RF, VF, VØLF and ZF). If this can be done, a single call to subroutine FRESP will generate frequency response data for both oxidizer and fuel feed systems. If feed system complexity requires that the oxidizer and fuel feed systems be laid out separately on the Fig. 4 schematic, then two sets of input data must be read and subroutine HYDRDY must call FRESP twice - first for the oxidizer feed system calculations and second for the fuel feed system calculations. To specify this option, variable ITYPE must be set equal to 2.

Variable INPHYD in the HYDRDY argument list controls the HYDRDY calculation process. If INPHYD $\leq$ 1 the oscillation injection flowrates are calculated for a single frequency, specified by variable FRE in the HYDRDY argument list. If INPHYD > 1, HYDRDY calculates oscillatory injector flowrates for the number of frequencies, NFREQT, which are contained in array FREQT. Both NFREQT and the array FREQT are stored in labeled common block/CØMTAP/ prior to calling HYDRDY.

NAMELIST variable ICRT controls the option for generating CRT plots of the oscillatory injection flowrate gains and phase values as a function of frequency. If ICRT = 0 (the default value) no plots are made. If ICRT $\geq$ 1 plot output is written to the output file named SYSCRT.

NAMELIST variable, ID, is a dummy name which can be used on each input card to provide an identification number field without violating the NAMELIST restriction that the entire card is read as data. For example, ID = 00000010 could be in columns 70-80 of a HYDRDY data card and ID = 00000020 in columns 70-80 of the next card. The NAMELIST routine would then interpret each card's sequence number as a new value for the dummy variable, ID. The value of ID is not used in any way by subroutine HYDRDY.

NAMELIST variable, ITYPE, is used to indicate to HYDRDY the format of the feed system modeling. If ITYPE = 1 (the default value) it is assumed that both oxidizer and fuel feed systems are modeled simultaneously with only one set of HYDRDY input values (for the 30 segments and 2 injectors of the Fig. 4 schematic). If ITYPE = 2, HYDRDY will send two consecutive sets of input data; the first set will be assigned to the oxidizer feed system and the second set to the fuel feed system. For either value of ITYPE the program will assume that the injector labeled "O" on Fig. 4 is the oxidizer flow outlet and the injector labeled "F" is the fuel flow outlet. Therefore, this convention must be followed when laying out the feed system model.

NAMELIST variables IRFLAG and ITERM are optional HYDRDY inputs which indicate that data input will be provided from a timesharing terminal. If IRFLAG = 0 (the default value), input data will be read only from FORTRAN logic unit number, ITERM. It should be noted that the default values for IRFLAG and ITERM are set up so that the initial data input will always be card input on unit 5.

After reading the initial NAMELIST data on unit 5, HRDRDY checks the value of ITERM and, if non-zero, proceeds to read additional first case data from the terminal on unit ITERM. Thus, the first case card NAMELIST input could consist of the single item ITERM = N, where N is the terminal logical unit number. If terminal input <u>only</u> is desired, block data program/F/ can be recompiled with the IRFLAG default value changed from 0 to 1 and the ITERM default value changed from 0 to the desired unit number.

NAMELIST variable IWRITE (main program control variable IPRHYD) controls the printed output from HYDRDY. If IWRITE = 0 (the default value), only the NAMELIST input to HYDRDY is printed on logical unit 6. If IWRITE < 0 the NAMELIST input is printed and the normal HYDRDY output is printed as well as being saved on an output device in binary form. If IWRITE = 1 both HYDRY input and normal output are printed. If IWRITE > 1 extensive printouts of subroutine FRESP intermediate calculations are printed in addition to the normal HYDRDY input and output.

PROGRAM OUTPUT

The output of the FSCSM computer program is provided as the usual tabular printout. A sample case is included in Appendix E which corresponds to the input dataset listed in Appendix D. As is also mentioned in the Program Operation section of this manual, the input case listed in Appendix D consists of two cases being run back to back. The output from the first case is given in Appendix E from pages E-2 through E-14. The first page of output consists of a title page identifying the current version of the FSCSM computer program. The input data are printed out as they are read in. This permits both a full documentation of the computer run conditions for later analysis as well as a convenient method to check for input errors if unusual results are calculated. Page E-3 of the listing in Appendix E gives the two alphanumeric cards identifying the case at the top of the page right under the program title. Subsequent to these two cards, the information on the cards read in by the main control section and the nozzle admittance control section are printed out. After reading and writing these cards, and since INPN0Z = 3, the program proceeds to the nozzle admittance table calculations. Information pertinent to these calculations is printed on page E-4. The frequency table goes from 150 Hz to 400 Hz as specified by the input variables FREQMI and FREQMX.

Since INPHYD = 2, the program proceeds to the hydrodynamic subroutines right after the nozzle admittance calculations. Input for this routine is in the form of NAMELIST data. The NAMELIST is output on pages E-5 and E-6. A printout of the feed system response table computed by subroutine HYDRDY and saved on file ITAPH is given on page E-7.

The next set of input required is used in subroutine C0MBDY and STEADY. This is output on page E-8. The steady-state profiles are then computed and printed on pages E-9 and E-10.

The program then begins its search for solutions to the nozzle admittance boundary condition. The first one it finds is at 210.42 Hz. The program then outputs the combustion dynamic coefficients, the frequency and decrement, and the feed system response for this solution on page E-14. On page E-12, the oscillatory profiles correspond to this solution are given. The program then proceeds to the next case.

Since the second case does not generate the data on files ITAPN and ITAPH (it only reads this information), these tables are not printed. The first page of output, page E- 15, in Appendix E, consists entirely of the data read by the Main Control Section and the Combustion Dynamics Control Section. Since the STEADY Control Section print code is zero (IPRSTE = 0), the program skips over the steady-state output (although of course, it still computes it) and proceeds directly to the section which solves the nozzle admittance boundary condition. The first root it finds above the input frequency of 265 Hz (given by the variable 0MEGAR), is at 280.62 Hz. It prints out the frequency, decrement, nozzle admittances, and feed system response for this solution. Output of the combustion coefficients and oscillatory profiles is bypassed because the input flags IPRC0M and IPRCHM were set to zero.

The final page of output is the title page. This indicates normal termination of the job.

PROGRAM OPERATION

The FSCSM computer program is designed to read in an input case sequentially, perform the calculations for that case, and output the results. The program then transfers back to its beginning to read in the next case. In this manner, running jobs back-to-back is quite straightforward. The sample input case listed in Appendix D provides an example of two such cases run back to back. The first case, given by the first 24 cards, is run with no prior information residing on the hydrodynamic feed system, the combustion dynamics, or the nozzle admittance datasets. Since INPHYD = 2 and INPN0Z = 3, this case generates tables of the hydrodynamic feed system response and nozzle admittance versus frequency and saves them on files ITAPH and ITAPN, respectively. The subsequent case (the last 13 cards in Appendix D) will use the information stored on these datasets. Although these two cases were run back to back, this was by no means necessary. The second case is self-contained and could be submitted separately. Of course, if this were the situation, the user must be sure there are datasets on files ITAPH and ITAPN which are applicable to that second case.

For the sample dataset run, the two input cases found solutions to the nozzle admittance boundary equation at 210.42 Hz and 280.62 Hz, respectively. If there are no other solutions between these two frequencies, the same effect could have been obtained by setting the input variable NR00T equal to -2 for the first case instead of -1. The program would have then looked for the first two roots above the input frequency 190 Hz (0MEGAR) and found both solutions automatically. The second case would not be input for this situation.

Program Size, Overlay Structure, and Timing

Without overlay, the FSCSM computer program load module requires 262.4 K Bytes of computer storage on the IBM 370 Model 165 computer. This storage does not count the buffers needed for input/output. If one allocates a 1 K Byte of buffer size for each of the three date sets used to store the feed system, combustion dynamic, and nozzle admittance data (which are all unformatted input/output), uses two buffers for each data set, and adds in the buffer requirements for his card input, printed output, and CRT output, then the total buffer space should be well under 10 K bytes on a 370/165 computer. With the overlay structure specified in Fig. 16 , the total program requirement is 220 K bytes of storage on an IBM 370/165 computer, including two buffers for each of the three unformatted datasets at 1 K bytes each.

Computer run time has only been checked for an IBM 370/165 computer where the subroutines were compiled using the IBM procedure AFORTRAN with the optimizing parameter, OPT, equal to one. For this situation, each iteration during the search algorithm portion of the program (when ISCNT equals one or four) averaged 3.7 CPU seconds. When ISCNT=5, each iteration is about twice as fast. For the cases run during model verification a five Hz step size for the search algorithim was used (DELFRQ=5). For these cases, each solution to the nozzle admittance boundary equations averaged 0.85 minutes of CPU.

Program Input/Output Dataset File Information

The case input dataset file number used by the FSCSM computer program is 5. The printed output dataset file number is 6. There are three auxiliary files used by the program. These are specified by the input parameters, ITAPC, ITAPH, and ITAPN, corresponding to the combustion dynamics, hydrodynamic feed system, and nozzle admittance datasets. Control of the reading from or writing on to these respective datasets is specified by the three input flags INPCOM, INPHYD, and INPNOZ. The program uses unformatted input/output statements for transmitting information to and from these datasets. A convenient blocksize to use is 1 K bytes.

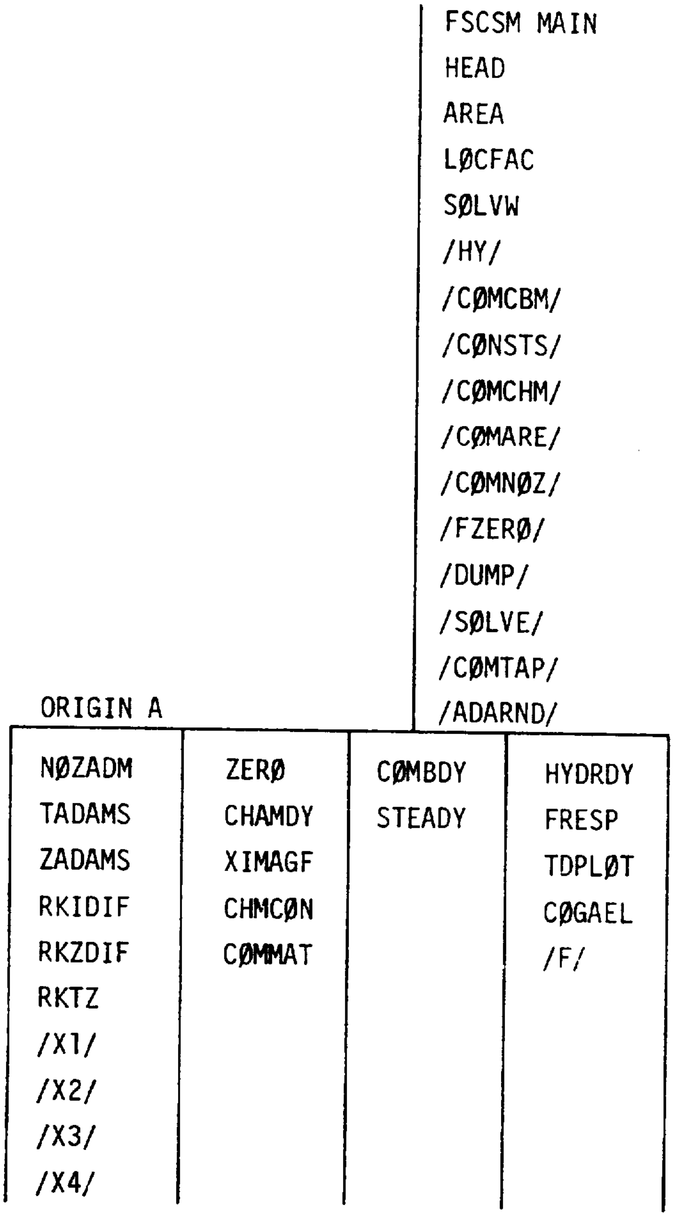


Figure 16. FSCSM Program Overlay Structure

Diagnostics

The Feed System Coupled Stability Model computer program has been designed to operate as straightforward as possible with a minimum amount of user interaction for each case being run. There may be times however, when the program's results appear questionable or the algorithm used to find solutions in the frequency space to the nozzle admittance boundary equation runs into difficulty or does not find solutions that were expected. Many diagnostic messages are coded into the program to warn the user of such problems. Also, there are certain dump codes which enable the user to obtain intermediate output in order to debug most problems that may arise.

One of these dump codes is the variable IWSKP. When this is set to zero, no intermediate output is obtained. When it equals one, a certain amount of limited output will be generated. This output comes in two forms depending upon whether or not the program is within its search algorithm portion or its two-dimensional secant portion. For the first case, the variable ISCNT has the value of one or four. In the second case it has the value 5. When ISCNT equals one or four and IWSKP equals one, subroutine SOLVW will print the following variables in the order given: the iteration counter (KNTR), the control flag (ISCNT), the counter (KSCNT4), the current values of omega (ω), the upstream and downstream nozzle admittances (CN0ZA and N0ZA), the absolute value of the error in the nozzle admittance equation (HN), the value of the test function (FTST2), and the determinant and condition number of the transposed Jacobian (DET2 and C0ND2). This printing will be performed every time the real part of ω is incremented by 2π*DELFRQ right after the imaginary part of ω has been chosen to minimize $|F|$, the absolute value of the error in the nozzle admittance boundary equation. The user can employ this output to determine if there is a region in the ω-plane where a possible solution may have existed (e.g., the error became small but the test function did not change sign). He can then rerun his case while taking smaller frequency steps through the narrowed range where he suspects a solution may exist. Also, the program may jump over a solution if there is a singularity within DELFRQ of that solution. If this is the case, the program will sense the singularity and not proceed any further in its search in that range. Rerunning the case with a smaller value of DELFRQ will solve this problem.

When ISCNT equals five and IWSKP equals one, subroutine S0LVW prints after each two-dimensional secant method, these variables in the following order: ISCNT, KNTS, 0MEGA, CN0ZA, N0ZA, and HN. Although it did not happen for any of the cases performed during the checkout of the computer model, the two-dimensional secant method may diverge. The above computer output would be useful in determining the cause of the problem.

When the variable IWSKP equals two, all the above output is printed plus the following:

1. When ISCNT equals one or four, intermediate output is obtained during the iterations to minimize |FN| with respect to Imag (ω). For this case, one obtains the variables KNT, IER, X1, X2, F1, F2, 0MEGA, FN, GN, and HN. These are all described in Appendix A. This output may be useful in seeing how the error is changing as a function of the decrement when the real part of the frequency is held fixed. Further, when ISCNT equals one or four, the variables FN, DFRDX, DFIDX, DFRDY, and DFIDY are printed along with the output obtained when IWSKP = 1.
2. When ISCNT equals five and IWSKP equals two, one obtains the output for the case IWSKP equals one for the two-dimensional secant method plus the following variables in order: XR1, XI1, FR1, FI1, XR2, XI2, FR2, FI2, XR3, XI3, FR3, FI3, XR4, XI4, FR4, FI4, and FN. These variables correspond to the current values of ω and FN being used by the two-dimensional secant method. They can be used to trace which points the algorithm is replacing as the iteration proceeds as well as how the error is behaving.

Another input variable which controls intermediate output is the F0RTRAN variable IWRT. This variable is input as zero, no intermediate output is obtained. If this variable is input as a positive number, then intermediate output from subroutine CHAMDY is obtained. This output consists of the oscillatory profiles for the variables P (pressure), RH0 (density), MR (mixture ratio), and T (temperature) along with the current value of the complex frequency, ω. This output is printed everytime subroutine CHAMDY is entered.

The diagnostic messages that are coded within the FSCSM computer program may be printed for several reasons.

Within subroutine SØLVW, there are three diagnostic messages coded which will appear when certain iteration counters are exceeded. The first is

```
**************************************************
   WARNING, POSSIBLE ROOT IN FREQUENCY RANGE: --
*************************************************
```

When this message appears, it means that a potential root was bracketed but the error did not decrease sufficiently within ten additional iterations to warrant the program proceeding further with its search in that range. Moreover, the determinant did not change sign and the condition number remained less than CTEST in that range. Rerunning the case over the specified frequency range given in the message with IWSKP equal to one or two may prove beneficial if the user suspects there may be an actual solution in that range.

The second diagnostic message printed by subroutine SØLVW is

```
**** UNABLE TØ FIND RØØT FØR IMAG PART ØF F ****
```

Along with this message, the variables X1, F1, K2, F2, X3, F3, ANS, FANS, KNT, IER, and ØMEGA are printed in the order listed. When this message appears, it means the algorithm to minimize |FN| with respect to Imag (ω) has failed. If this message appears, it usually means something is wrong with the input parameters. The only occurrence that the programmers are aware of when this is not the case is when the error attains a minimum as |Imag (ω)| → ∞. Since this happens only in the most extraordinary situations, the procedure should be to rerun the case and not include the frequency range where that anomally is occurring.

The third diagnostic produced by subroutine S0LVW is

**** EXCEEDED CONVERGENCE LIMIT ****

Along with this message, the variables IER, KNTS, KNTR, ISCNT, XRI, XI1, FR1, FI1, ..., XR4, XI4, FR4, FI4, are printed.

This message will appear if KNTR is greater than KNTRMX or KNTS is greater than KNTSMX. In the former case, the usual error is that the user input too small a DELFRQ to cover the range between solutions to the nozzle admittance boundary equation in KNTRMX steps or too small a KNTRMX to allow that range to be covered in steps of length DELFRQ.

In the case where KNTS is greater than KNTSMX, it would probably mean that the two-dimensional secant method is diverging. The job should be rerun with IWSKP equal to one or two to obtain more information concerning the problem.

There is also a diagnostic message printed from subroutine C0MMAT. This is the subroutine that solves the four by four system of linear equations for subroutine CHAMDY. If any of the diagonal elements of the associated matrix are zero, then the message

***** DIVIDE CHECK IN C0MMAT *****

will appear along with a printout of the row number of the zero diagonal as well as the complex matrix being solved. If this error message appears, then there must be something very wrong with the case being run, e.g, the input data is in error, or a dimension has been exceeded. One should recheck his input carefully and then, if necessary, rerun the case with IWRT equal to one and IWSKP equal to one or two.

Two similar messages as the one above are printed by subroutine C0GAEL. The first of these messages is

```
****ERROR IN CØGAEL SUBROUTINE, J AND JMAX EQUAL, RESPECTIVELY****
```

and the second is

```
****MATRIX IS SINGULAR, EXIT FROM CØGAEL.  THE PIVOT ELEMENTS ARE...****
```

The reasons for these errors are similar to the CØMMAT error message.

Conversion to UNIVAC

The following cards must be changed to execute the FSCSM program on a UNIVAC computer (see Appendix C for code listing):

1. Change CØMPLEX*16...to CØMPLEX....

Routine	Card Number
CHAMDY	80
CØMMAT	150

2. In subroutine CØMMAT, change CDABS to CABS on card No. 24.
3. In subroutine TDPLØT, replace card 11310 with

```
31 CØNTINUE.....0011310
```

4. In subroutine NØZADM, replace card 1730 with

```
8 NØZA = CMPLX(SYR, SYI)....00001730
```

5. In the main program, change ATAND(   ) to 57.296*ATAN(   ) on card numbers 3370, 3410, 3450, and 3490.

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APPENDIX A

FORTRAN SYMBOL TABLE

FORTRAN VARIABLE NAME	ENGINEERING VARIABLE SYMBOL	TYPE	CONTROL SECTION	DESCRIPTION
A(100)	A	R	CØMARE	Axial distance array, X(I) = XO + (X-1)* DELX, m
ADDFU	a_{fu}	R	CØMCBM	Fuel liquid jet diameter exponent, unitless
ADDØX	$a_{\emptyset x}$	R	CØMCBM	Oxidizer liquid jet diameter exponent, unitless
ADVFU	b_{fu}	R	CØMCBM	Velocity exponent for fuel atomization process, unitless
ADVØX	$b_{\emptyset x}$	R	CØMCBM	Velocity exponent for the oxidizer atomization
AINJ	A_{inj}	R	CØMARE	Cross sectional area at injector face, m^2
AMA(4,5)	--	C	CHAMDY	Array used to store coefficients of finite difference equations approximating the oscillatory differential equations
ANGLEX	--	R	CØMNØZ	Nozzle convergence half angle, degrees (see Fig. 15)
ANS	--	R	SØLVW	Solution to minimization of error in nozzle admittance boundary equations. Returned to SØLVW from subroutine ZERØ.
CFU1,..., CFU16	$c_{1_{fu}}, \ldots, c_{16_{fu}}$	C	CØMCBM	Fuel combustion coefficients, unitless
CMA(4)		C	CHAMDY	Right hand side of finite difference equation approximating the oscillatory differential equations. In equivalence with CMA(1,5).
CNØZA	A_{N_u}	C	CØMCHM	Upstream nozzle admittance
CØ	$c_{\emptyset}$	R	CØMCBM	Sonic velocity evaluated at overall mixture ratio, m/sec (ft/sec)
CØND1	--	R	SØLVW	Condition number of the transpose of the Jacobian of the difference between the upstream and downstream nozzle admittances with respect to ω.

FORTRAN VARIABLE NAME	ENGINEERING VARIABLE SYMBOL	TYPE	CONTROL SECTION	DESCRIPTION
COND2	--	R	SOLVW	Condition number of the transpose of the Jacobian of the difference between the upstream and downstream nozzle admittances with respect to ω.
COX1,..., COX16	$c_{1_{ox}}$	C	COMCBM	Oxidizer combustion coefficients, unitless
CRR		R	COMNOZ	Contraction ratio, cross-sectional area of chamber/throat area, unitless (see Fig. 15)
CS	c^*	R	COMCBM	Characteristic velocity evaluated at the overall mixture ratio, m/sec (ft/sec)
CTEST	--	R	SOLVE	Upper bound on the condition number of the transpose of the Jacobian of the difference between the upstream and downstream nozzle admittances with respect to the complex frequency. If the condition number of that matrix exceeds CTEST for a given frequency, then it is assumed that Jacobian is singular near that frequency and hence a solution will not be sought at that point, unitless.
DA(100)	$\partial A/\partial x$	R	COMARE	Slope of area of chamber at XM(I), m
DCSDMR	$\partial c^*/\partial MR$	R	COMCBM	Partial derivative of the characteristic velocity with respect to mixture ratio holding, m/sec.
DELFRQ	--	R	SOLVE	Frequency increment used during the search procedure to solve the nozzle admittance boundary equation, Hz.
DELHFU	Δh_{fu}	R	COMCBM	Pseudo energy term for fuel, J/kg (Btu/lbm)
DELHOX	Δh_{ox}	R	COMCBM	Pseudo energy term for oxidizer, J/kg (Btu/lbm)
DELMX	--	R	SOLVE	Maximum change in ω allowed between iterations
DELP	ΔP	R	COMCHM	Oscillatory pressure at injector face, dimensionless

FORTRAN VARIABLE NAME	ENGINEERING VARIABLE SYMBOL	TYPE	CONTROL SECTION	DESCRIPTION
DELVFU	--	R	CØMCBM	Steady-state velocity difference between fuel droplets and gas stream normalized to the sonic velocity at the overall mixture ratio, unitless
DELVØX	--	R	CØMCBM	Steady-state velocity difference between oxidizer droplets and gas stream normalized to the sonic velocity at the overall mixture ratio, unitless
DELX	Δx	R	CØMARE	Axial distance between successive X(I), m
DET1	--	R	SØLVW	Determinant of the Jacobian of the difference between the upstream and downstream nozzle admittances with respect to ω.
DET2	--	R	SØLVW	Determinant of the Jacobian of the difference between the upstream and downstream nozzle admittances with respect to ω.
DFIDX	--	R	SØLVW	Derivative of Imag (FN) with respect to real (ω).
DFIDY	--	R	SØLVW	Derivative of real (FN) with respect to real (ω).
DHDMR	$(\partial h/\partial MR)_\phi$	R	CØMCBM	Partial derivative of gas reference enthalpy with respect to mixture ratio averaged over the mixture ratio range during steady-state operation, J/kg (Btu/lbm).
DM1	--	C	ADARND	Used to store intermediate values needed to compute boundary conditions and coefficients of finite difference equations approximating the oscillatory differential equations.
DM2	--	R	ADARND	Used to store intermediate values needed to compute boundary conditions and coefficients of finite difference equation approximating the oscillatory differential equations.

FORTRAN VARIABLE NAME	ENGINEERING VARIABLE SYMBOL	TYPE	CONTROL SECTION	DESCRIPTION
DM3	--	C	ADARND	Used to store intermediate values needed to compute boundary conditions and coefficients of finite difference equations approximating the oscillatory differential equations.
DM4	--	C	ADARND	↓
DM5	--	C	ADARND	↓
DM6	--	C	ADARND	↓
DM7FU	--	C	ADARND	↓
DM70X	--	C	ADARND	↓
DM8FU	--	C	ADARND	↓
DM80X	--	C	ADARND	↓
DM9FU	--	C	ADARND	↓
DM90X	--	C	ADARND	↓
DM22	--	R	ADARND	↓
DMRB(100)	$\partial\overline{MR}/x$	R	C0NSTS	Derivative of steady-state mixture ratio with respect to distance, m^{-1}
DRGDMR	$\partial R/\partial x$	R	C0MCBM	Partial derivative of gas constant with respect to mixture ratio evaluated at the overall mixture ratio, J/kmole/°K (ft-lb/lb/°R)
DRHQB(100)	$\partial\bar{\rho}/\partial x$	R	C0NSTS	Derivative of steady-state density with respect to distance, $kg/m^3/m$
DTFUDM	$\partial\bar{\tau}_{fu}/\partial MR$	R	C0MCBM	Partial derivative of fuel vaporization time delay with respect to mixture ratio, holding the vaporization blockage term, droplet diameter, and Nusselt number constant, sec

FORTRAN VARIABLE NAME	ENGINEERING VARIABLE SYMBOL	TYPE	CONTROL SECTION	DESCRIPTION
DT0XDM	$\partial\bar{\tau}_{ox}/\partial MR$	R	C0MCBM	Partial derivative of oxidizer vaporization time delay with respect to mixture ratio, holding the vaporization blockage term, drop diameter, and Nusselt number constant, sec
EPSF	--	R	S0LVE	Relative error criterion used during the search algorithm for the portion of the program that minimizes the error, HN, in the nozzle admittance boundary equation with respect to the growth coefficient, ω_I. To obtain convergence, it is necessary that $\frac{\partial \lvert HN \rvert^2}{\partial \omega_I} < EPSFS$ Unitless.
EPSFS	--	R	S0LVE	Tightened relative error criterion used to determine if convergence has been obtained while iterating to solve the nozzle admittance boundary equation. To obtain convergence, it is necessary that $\lvert N_{A_U} - N_{A_D} \rvert / \lvert N_{A_D} \rvert < EPSFS.$
EPSX	--	R	S0LVE	Relative error criterion used during the search algorithm for the portion of the program that minimizes the error, HN, in the nozzle admittance boundary equation with respect to the growth coefficient, ω_I. To obtain convergence, it is necessary that $\lvert \omega_{I_1}, - \omega_{I_2} \rvert / \lvert \omega_{I_2} \rvert < EPSX$ where the subscripts 1 and 2 refer to two successive iterations, unitless.

FORTRAN VARIABLE NAME	ENGINEERING VARIABLE SYMBOL	TYPE	CONTROL SECTION	DESCRIPTION
EPSXS	--	R	S0LVE	Tightened relative error criterion used to determine if convergence has been obtained while iterating to solve the nozzle admittance boundary equation. To obtain convergence, it is necessary that $|\omega_1 - \omega_2|/|\omega_2| < \text{EPSXS}$ where the subscripts 1 and 2 refer to successive iterations, unitless.
F1	--	R	S0LVW	Derivatives of absolute value squared of the difference between the upstream and downstream nozzle admittances with respect to Imag (ω) corresponding to X1, X2, and X3.
F2	--	R	S0LVW	↓
F3		R	S0LVW	↓
FANS	--	R	S0LVW	Derivative of squared error in nozzle admittance boundary equation at ANS.
FI	--	R	MAIN	Interpolating factor used in the main program.
FI1	--	R	S0LVW	Used to store successive values of Imag (FN) during the 2-dimensional secant method.
FI2	--	R	S0LVW	↓
FI3	--	R	S0LVW	↓
FI4	--	R	S0LVW	↓
FN	--	C	FZER0	Difference between the upstream and downstream nozzle admittances.
FNF	--	R	FZER0	Imaginary (FN)
FNR	--	R	FZER0	Real (FN)
FR1	--	R	S0LVW	Used to store successive values of Real (FN) during the 2-dimensional secant method.

FORTRAN VARIABLE NAME	ENGINEERING VARIABLE SYMBOL	TYPE	CONTROL SECTION	DESCRIPTION
FR2	--	R	S0LVW	Used to store successive values of Real (FN) during the 2-dimensional secant method.
FR3	--	R	S0LVW	↓
FR4	--	R	S0LVW	↓
FREQ	$2\pi\omega_R$	R	S0LVE	Frequency, i.e., real (ω), Hz
FREQMI	--	R	C0MN0Z	Minimum frequency, used for generation of frequency table FREQT, Hz
FREQMX	--	R	C0MN0Z	Maximum frequency used for generation of frequency table FREQT, Hz
FREQT(100)	--	R	C0MTAP	Table of terms used for computation of downstream nozzle admittance.
FRQMAX	--	R	S0LVE	Maximum frequency above which no solutions to the nozzle admittance boundary equation will be sought, Hz
FTST1	--	R	S0LVW	Test function used to determine if a solution to the nozzle admittance boundary equation has been bracketed.
FTST2	--	R	S0LVW	Test function used to determine if a solution to the nozzle admittance boundary equation has been bracketed.
G1FU	--	C	ADARND	Coefficient of oscillatory pressure in fuel oscillatory vaporization expression.
G10X	--	C	ADARND	Coefficient of oscillatory pressure in oxidizer oscillating vaporization expression.
G2FU	--	C	ADARND	Coefficient of oscillatory density in fuel oscillatory vaporization expression.
G20X	--	C	ADARND	Coefficient of oscillatory density in oxidizer oscillating vaporization expression.

FORTRAN VARIABLE NAME	ENGINEERING VARIABLE SYMBOL	TYPE	CONTROL SECTION	DESCRIPTION
G3FU	--	C	ADARND	Coefficient of oscillatory mixture ratio in fuel oscillatory vaporization expression.
G3ØX	--	C	ADARND	Coefficient of oscillatory mixture ratio in oxidizer oscillating vaporization expression.
G4FU	--	C	ADARND	Coefficient of oscillatory velocity in fuel oscillatory vaporization expression.
G4ØX	--	C	ADARND	Coefficient of oscillatory velocity in oxidizer oscillating vaporization expression.
GAMØ	$\gamma_{\emptyset}$	R	CØMCBM	Specific heat ratio evaluated at the overall mixture ratio, unitless.
GINJFT(100)	$G_{inj_{fu}}$	C	CØMTAP	Fuel feed system response table. Real (GINJFT) is the amplitude of the response and Imag (GINJFT) is the phase angle of the response.
GINJOT(100)	$G_{inj_{ox}}$	C	CØMTAP	Oxidizer feed system response table. Real (GINJØT) is the amplitude of the response and Imag (GINJØT) is the phase angle of the response.
GN	--	C	FZERØ	Variable used to store the value of the derivative of CNØZA-NØZA with respect to ω_I or the value of CNØZA-NØZA itself.
HN	--	R	FZERØ	$FN*\overline{FN}$
I	--	I	-	Used throughout the program as a do loop index.
INPNØZ	--	I	CØMNØZ	Code used for the downstream nozzle admittance term calculation.
INRT	--	I	DUMP	Code used to determine whether or not intermediate output from CHAMDY is desired.
IPASS	--	I	SØLVE	Internal code no longer in use.

FORTRAN VARIABLE NAME	ENGINEERING VARIABLE SYMBOL	TYPE	CONTROL SECTION	DESCRIPTION
IPRN0Z	--	R	C0MN0Z	Code used for downstream nozzle admittance term printout
IR	--	I	MAIN	Flag set by MAIN program to indicate the first pass through it. After reading in a new case.
ISCNT	--	I	FZER0	Code used to determine logical flow in subroutine S0LVW.
ISLP	--	I	FZER0	Code used to determine whether or not the derivative of FN with respect to Imag (ω) is needed.
ISTRT	--	I	S0LVE	Code used to indicate the first iteration after a solution to the nozzle boundary equation.
II		C	ADARND	The imaginary number i.
ITAPC	--	I	C0MTAP	File number used to save combustion coefficients table.
ITAPH	--	I	C0MTAP	File number used to save hydrodynamic coupling term table.
ITAPN	--	I	C0MTAP	File number used to save nozzle admittance term table.
IWSKP	--	I	S0LVE	Intermediate output dump code used in subroutine S0LVW.
J	--	I	-	Used throughout the program as a do loop index.
KNTMX	--	I	S0LVE	Maximum number of iterations allowed to minimize the error in the nozzle admittance boundary equation with respect to the imaginary part of ω.
KNTR	--	I	S0LVE	Counter used to control the number of iterations used during the search algorithm between solutions.
KNTRMX	--	I	S0LVE	Maximum number of times the frequency will be allowed to be changed by DELFRQ during the searching algorithm between each solution.

FORTRAN VARIABLE NAME	ENGINEERING VARIABLE SYMBOL	TYPE	CONTROL SECTION	DESCRIPTION
KNTSMX	--	I	SØLVE	Maximum number of iterations allowed for the convergence of the two-dimensional secant method used in SØLVW.
KSCNT4	--	I	SØLVE	Counter used to control the number of iterations used when ISCNT = 4.
KWHERE	--	I	MAIN	Flag to control logical flow in the MAIN program after a call to subroutine SØLVW.
MBFUI	$(\bar{\dot{m}}_{fu})_{inj}$	R	CØMCBM	Fuel injection mass flowrate, kg/sec (lb/sec).
MBØXI	$(\bar{\dot{m}}_{ox})_{inj}$	R	CØMCBM	Oxidizer injection mass flowrate, kg/sec (lb/sec).
MGI	$\bar{\dot{m}}_{inj}$	R	CØNSTS	Steady-state gas flowrate at injector face, kg/sec.
MR(100)	MR'	R	CØMCHM	Oscillatory mixture ratio, dimensionless.
MRB(100)	$\overline{MR}$	R	CØNSTS	Steady-state mixture ratio, unitless.
MRGI	$\overline{MR}_{inj}$	R	CØNSTS	Steady-state gas mixture ratio at injector face, unitless.
MRNTFU	--	C	ADARND	Mixture ratio integral in fuel oscillatory vaporization expression.
MRNTØX	--	C	ADARND	Mixture ratio integral in oxidizer oscillatory vaporization expression.
MWG	$MW_{\text{Ø}}$	R	CØMCBM	Molecular weight of the gas evaluated at the overall mixture ratio, kg/kmole (lbm/lb-mole).
NFREQT	--	I	CØMTAP	Number of points in frequency table.
NØZA	A_{N_D}	C	FZERØ	Downstream nozzle admittance
NØZAMR	$A_{N_{MR=constant}}$	C	FZERØ	Term used in computation of downstream nozzle admittance
NØZAT(100)	--	C	CØMTAP	Table of terms used for computation of downstream nozzle admittance.

FORTRAN VARIABLE NAME	ENGINEERING VARIABLE SYMBOL	TYPE	CONTROL SECTION	DESCRIPTION
NR00T	--	I	MAIN	Number of solutions to the downstream nozzle admittance boundary equation being sought.
NRT	--	I	MAIN	Used as do loop index for MAIN program. Counts the number of solutions to the nozzle admittance boundary equation.
NUBFU	$\overline{N_u}_{fu}$	R	C0MCBM	Average steady-state fuel Nusselt number used in vaporization expression, unitless.
NUB0X	$\overline{N_u}_{0x}$	R	C0MCBM	Steady-state oxidizer Nusselt number used in vaporization expression, unitless.
NXP	--	I	C0MARE	Number of points in axial distance array, inclusion between X0 and the start of nozzle inlet.
NXPM1	--	I	CHAMDY	NXP-1
0MEGA	ω	C	C0MCHM	Complex frequency.
P(100)	ρ'	R	C0MCHM	Oscillatory pressure, dimensionless.
PI	π	R	-	pi (3.141593)
PC	$\bar{\rho}$	R	C0MCBM	Steady-state chamber pressure, N/in.^{2} (psia).
PINTFU	--	C	ADARND	Pressure integral in fuel oscillatory vaporization expression.
PINT0X	--	C	ADARND	Pressure integral in oxidizer oscillatory vaporization expression.
RBS0X	--	C	ADARND	Collection of terms used in oxidizer oscillatory vaporization expression.
RCCX	--	R	C0MN0Z	Ratio of the radius of curvature at the nozzle inlet to the chamber radius at nozzle inlet, unitless (see Fig. 15).
RCTX	--	R	C0MN0Z	Ratio of the radius of curvature upstream of the throat to the chamber radius at nozzle inlet, unitless (see Fig. 15).

FORTRAN VARIABLE NAME	ENGINEERING VARIABLE SYMBOL	TYPE	CONTROL SECTION	DESCRIPTION
RGØ	$R_{\emptyset}$	R	CØMCBM	Gas constant evaluated at the overall mixture ratio, J/kmole/°K (Btu/lb mole/°R).
RHNTFU	--	C	ADARND	Density integral in fuel oscillatory vaporization expression.
RHNTØX	--	C	ADARND	Density integral in oxidizer oscillatory vaporization expression.
RHØ(100)	ρ'	R	CØMCHM	Oscillatory density, dimensionless.
RHØB(100)	$\bar{\rho}$	R	CØNSTS	Steady-state density, kg/m^3.
RHØGI	$\bar{\rho}_{inj}$	R	CØNSTS	Steady-state gas density at injector face, kg/m^3
RHØINJ	ρ'_{inj}	R	ADARND	Oscillatory density at injector face, unitless.
RINJ	--	R	CØMNØZ	Radius of the chamber at the injector, in.
RPSFU	--	C	ADARND	Collection of terms used in fuel oscillatory vaporization expression.
SSV1(100)	--	R	CØNSTS	Steady-state parameters computed in subroutine STEADY for use by subroutine CHAMDY
SSV2(100)	--	R	CØNSTS	
SSV3(100)	--	R	CØNSTS	
SSV4(100)	--	R	CØNSTS	
SSV5(100)	--	R	CØNSTS	
SSV6(100)	--	R	CØNSTS	
SSV7(100)	--	R	CØNSTS	
SSV8(100)	--	R	CØNSTS	
SSV9FU(100)	--	R	CØNSTS	
SSV9ØX(100)	--	R	CØNSTS	

FORTRAN VARIABLE NAME	ENGINEERING VARIABLE SYMBOL	TYPE	CONTROL SECTION	DESCRIPTION
SSV10(100)	--	R	CØNSTS	Steady-state parameters computed in subroutine STEADY for use by subroutine CHAMDY.
SSV11(100)	--	R	CØNSTS	↓
SSV12(100)	--	R	CØNSTS	↓
SSV13(100)	--	R	CØNSTS	↓
SSV14(100)	--	R	CØNSTS	↓
SSV15(10)	--	R	CØNSTS	↓
T(100)	T'	R	CØMCHM	Oscillatory temperature, dimensionless.
TAUBFU	$\bar{\tau}_{fu}$	R	CØMCBM	Fuel vaporization time delay, sec.
TAUBØX	$\bar{\tau}_{ox}$	R	CØMCBM	Oxidizer vaporization time delay, sec.
TB(100)	$\bar{T}$	R	CØNSTS	Steady-state temperature, °K.
TDRAGF	$\tau_{drag_{fu}}$	R	CØMCBM	Steady-state oxidizer drag time delay, sec.
TDRAGØ	$\tau_{drag_{ox}}$	R	CØMCBM	Steady-state oxidizer drag time delay, sec.
TITLE(18,2)	--	R	MAIN	Array containing 2 card records of alpha-numeric title information.
V(100)	v'	R	CØMCHM	Oscillatory velocity, dimensionless.
VAPBFU(100)	$\bar{\dot{m}}_{vap_{fu}}$	R	CØNSTS	Steady-state fuel vaporization rate, kg/sec/m^3.
VAPBØX(100)	$\bar{\dot{m}}_{vap_{ox}}$	R	CØNSTS	Steady-state oxidizer vaporization rate, kg/sec/m^3
VB(100)	$\bar{v}$	R	CØNSTS	Steady-state velocity, m/sec.
VBFU	$v_{j_{fu}}$	R	CØMCBM	Steady-state fuel liquid injection velocity, m/sec (ft/sec).
VBØX	$v_{j_{ox}}$	R	CØMCBM	Steady-state oxidizer liquid injection velocity, m/sec (ft/sec).
VGI	$\bar{v}_{inj}$	R	CØNSTS	Steady-state gas velocity at injector face, m/sec.

FORTRAN VARIABLE NAME	ENGINEERING VARIABLE SYMBOL	TYPE	CONTROL SECTION	DESCRIPTION
VINTFU	--	C	ADARND	Velocity integral in oxidizer oscillatory vaporization expression.
VINTØX	--	C	ADARND	Velocity integral in oxidizer oscillatory vaporization expression.
VXØ	$v'_{x=o}$	C	CØMCHM	Oscillatory velocity at X=0, dimensionless.
X(100)	X	R	CØMARE	Axial distance array, X(I) = XO + (X-1)* DELX, m.
XO	X_o	R	CØMARE	Start of vaporization point, m
X1	--	R	SØLVW	Used to store successive values of Imag (ω) during the iteration to minimize the error in the nozzle admittance boundary equation with respect to Imag (ω).
X2	--	R	SØLVW	↓
X3	--	R	SØLVW	↓
XIMPFU	$ximp_{fu}$	R	CØMCBM	Fuel jet injection impingement point, m (in.).
XIMPØX	$ximp_{ox}$	R	CØMCBM	Oxidizer jet injection impingement point, m(in.).
XI1	--	R	SØLVW	Used to store successive values of Imag (ω) during the 2-dimensional secant method.
XI2	--	R	SØLVW	↓
XI3	--	R	SØLVW	↓
XI4	--	R	SØLVW	↓
XKFU	xk_{fu}	R	CØMCBM	Fuel Klystron distance, m(in.).
XKØX	xk_{ox}	R	CØMCBM	Oxidizer Klystron distance, m(in.).

FORTRAN VARIABLE NAME	ENGINEERING VARIABLE SYMBOL	TYPE	CONTROL SECTION	DESCRIPTION
XM(100)	--	R	COMARE	Axial distance midpoints, XM(I) = (X(I) + X(I-1))/2, m.
XNOZ	--	R	COMARE	Nozzle inlet point, m.
XR1	--	R	SOLVW	Used to store successive values of Real (ω) during the 2-dimensional secant method.
XR2	--	R	SOLVW	
XR3	--	R	SOLVW	
XR4	--	R	SOLVW	

APPENDIX B

PROGRAM FLOW CHARTS

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*Flow chart page numbers in upper right-hand corner.

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CARD ID   PAGE/BOX    NAME                            REFERENCES  (SOURCE SEQUENCE NO. AND PAGE/BOX)


FORTRAN MODULE    COMPUTER PROGRAM


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CHART TITLE - PROCEDURES

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00001920    3.15               00003570   7.14
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00002250    3.30               00002245   3.27
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00002670    5.11  82           00002600   5.06
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00002890    5.35               00002880   5.33
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00003090    6.06               00003070   6.03
00003130    6.09               00003160   6.11
00003160    6.11  1085
00003180    6.12  1090         00003090   6.06
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00003370    6.27               00003360   6.25
00003400    6.30               00003390   6.28
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00003450    7.05               00003440   7.03
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CHART TITLE - NON-PROCEDURAL STATEMENTS


CHART TITLE - SUBROUTINE  AREA

00000030   10.01  AREA         00001560   3.01-X
00000160   10.03               00000190  10.04
00000190   10.04  10
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00000220   10.06              00000230  10.07
00000230   10.07  20

CHART TITLE - NON-PROCEDURAL STATEMENTS


CHART TITLE - SUBROUTINE  CHAMDY

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00001010   12.18              00000970  12.15
00001800   13.07              00001760  13.04

CHART TITLE - NON-PROCEDURAL STATEMENTS


CHART TITLE - SUBROUTINE  CHMCON(1)

00000030   15.01  CHMCON      00001050  12.20-X
00000510   15.01  10

CHART TITLE - NON-PROCEDURAL STATEMENTS


CHART TITLE - SUBROUTINE  COGAEL(A;N)

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00012500   17.22  14
00012510   17.23  15
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00012610   18.03  8
00012670   18.05  26
00012690   18.07              00012750  18.11
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00012750   18.10  9
00012760   18.12  27          00012660  18.04

CHART TITLE - NON-PROCEDURAL STATEMENTS


CHART TITLE - SUBROUTINE  COMBDY(IR,FREQ,GINJOX,GINJFU,IPRCOM,INPCOM)

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CHART TITLE - NON-PROCEDURAL STATEMENTS


CHART TITLE - SUBROUTINE  COMMAT(A,NRA,N)

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00000290   23.19              00000290  23.20
00000490   23.21  100         00000240  23.15

CHART TITLE - NON-PROCEDURAL STATEMENTS
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CHART TITLE - SUBROUTINE  FRESP(ICRT,IWRITE,IX)

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                            00008480  32.20

CHART TITLE - NON-PROCEDURAL STATEMENTS


CHART TITLE - SUBROUTINE  HEAD

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CHART TITLE - NON-PROCEDURAL STATEMENTS


CHART TITLE - BLOCK DATA


CHART TITLE - NON-PROCEDURAL STATEMENTS


CHART TITLE - SUBROUTINE  HYDRDY(IR,INPHYD,FRE,GINO,GINF,PCIN,WOIN,WFIN)

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00001490  43.26  40
00001600  44.04  45            00001420  43.23
00001610  44.07                00001600  44.04
00001620  44.09                00001610  44.07
00001650  44.11  60            00001600  44.06
00001650  44.11                00001620  44.09
00001660  44.14                00001650  44.11
00001680  44.16                00001660  44.14
00001685  44.18  100           00001410  43.22
00001685  44.18                00001680  44.16
00009430  44.19  999           00001650  44.13
00001690  44.21                00001685  44.18
00001710  44.22  101
00001710  44.22                00001710  44.23
00005280  48.06  400
00005300  48.08  500           00005280  48.06
00005306  48.11  502           00005301  48.09
00005308  48.13  503
00005308  48.13                00005308  48.14
00005303  48.15                00005304  48.17
00005304  48.16  501
00005310  48.18  510           00005306  48.11    00005305  48.17
00005340  48.22                00005320  48.19
00009400  48.26  700           00005310  48.18

CHART TITLE - NON-PROCEDURAL STATEMENTS


CHART TITLE - SUBROUTINE  LOCFAC(JK,X,TX,NX,JX,FX)

00000030  50.01  LOCFAC        00002150   3.23-X  00002320   4.09-X
00000180  50.06                00000170  50.04
00000610  50.10  200           00000150  50.02    00000440  51.05    00000480  51.10    00000540  51.16
00000270  50.11  30            00000220  50.09
00000280  50.12                00000290  50.13
00000290  50.13  40
00000240  50.15                00000250  50.16
00000250  50.16  20
00000320  50.17  50            00000280  50.12    00000240  50.15
00000340  50.18  70            00000590  51.17
00000400  51.01  90            00000190  50.07    00000300  50.13    00000260  50.16
00000430  51.04                00000450  51.07
00000450  51.06  100
00000460  51.08  110           00000410  51.02    00000440  51.05
00000470  51.09                00000490  51.11
00000490  51.11  120
00000500  51.12  130           00000480  51.10
00000510  51.14                00000500  51.12
00000560  51.17  150           00000520  51.15    00000530  51.16

CHART TITLE - NON-PROCEDURAL STATEMENTS


CHART TITLE - SUBROUTINE  NOZADM(IR,GAMX,CO,FREQ,NOZA)

00000030  53.01  NOZADM        00002230   3.25-X
00000290  53.03                00000270  53.01
00000410  53.08  2             00000290  53.03
00000470  53.12                00000460  53.09
00000540  53.15  2000          00000490  53.13
00000570  53.16  2010          00000530  53.14
00000620  53.20  5             00000660  53.22
00000670  53.23  7             00000600  53.18
00000700  53.27                00000680  53.24
00000710  53.28  20
00000710  53.28                00001810  55.24
00000720  53.29  25
00001110  54.09                00001220  54.13
00001220  54.12  30
00001440  55.01  35            00001390  54.19
00001490  55.03  40            00001430  54.20
00001540  55.06  45
```

```
CARD ID   PAGE/BOX   NAME                REFERENCES  (SOURCE SEQUENCE NO. AND PAGE/BOX)

00001680   55.13                 00001660  55.10
00001690   55.14  50             00001530  55.05
00001730   55.18  8              00001680  55.13
00001730   55.18                 00001710  55.15
00001810   55.24  10             00001290  54.16    00001740  55.19
00001810   55.24                 00001800  55.21
00001900   55.27                 00001890  55.25
00001910   55.29                 00001900  55.27

CHART TITLE - NON-PROCEDURAL STATEMENTS


CHART TITLE - SUBROUTINE  RKTDIF(P,G,GP)

00002650   57.01  RKTDIF         00003750  59.07-X  00003860  59.20-X  00003950  59.31-X
00002820   57.04  22
00002830   57.05  25
00002920   57.06  50             00002810  57.03
00002930   57.07  55             00002910  57.15
00002850   57.12  30             00002820  57.04
00002860   57.13  35
00002880   57.14  40             00002850  57.12
00002890   57.15  45             00002840  57.05    00002870  57.13

CHART TITLE - NON-PROCEDURAL STATEMENTS


CHART TITLE - SUBROUTINE  RKTZ(NU,H,T1,U,DUM,JOPT)

00003580   59.01  RKTZ           00001110  54.09-X  00001110  75 07-X  00002410  84.07-X
00003720   59.03                 00003730  59.05
00003730   59.04  10
00003770   59.09  15             00003740  59.06
00003780   59.10  20             00003760  59.08
00003790   59.11  25
00003790   59.11                 00003790  59.12
00003810   59.14                 00003910  56.26
00003830   59.16                 00003840  59.18
00003840   59.17  35
00003880   59.22  40             00003850  59.19
00003890   59.23  45             00003870  59.21
00003900   59.24  50
00003900   59.24                 00003900  59.25
00003910   59.26  30
00003930   59.28  55
00003930   59.28                 00003930  59.29
00003950   59.31  60             00003940  59.30
00003970   59.33  65             00003940  59.30
00003980   59.34  70             00003960  59.32
00004050   59.39  75             00003980  59.34

CHART TITLE - NON-PROCEDURAL STATEMENTS


CHART TITLE - SUBROUTINE  RKZDIF(P,G,GP)

00003070   61.01  RKZDIF         00003770  59.09-X  00003880  59.22-X  00003970  59.33-X
00003210   61.03  10
00003270   61.04  15             00003200  61.02
00003320   61.07                 00003310  61.05
00003330   61.09                 00003320  61.07
00003340   61.10  22
00003350   61.11  25
00003440   61.12  50             00003330  61.09
00003450   61.13  55             00003430  61.20
00003540   61.16  20             00003260  61.03
00003370   61.17  30             00003340  61.10
00003380   61.18  35
00003400   61.19  40             00003370  61.17
00003410   61.20  45             00003360  61.11    00003390  61.18

CHART TITLE - NON-PROCEDURAL STATEMENTS


CHART TITLE - SUBROUTINE  SOLVW(KWHERE)
```

```
CARD ID   PAGE/BOX    NAME                           REFERENCES  (SOURCE SEQUENCE NO. AND PAGE/BOX)

00000030   63.01  SOLVH        00002980   5.36-X
00003940   63.06  225          00000410  63.03
00000840   64.01  117          00000780  64.10
00000910   64.04  118          00001020  65.01
00000780   64.10               00000750  64.07
00000600   64.14  110          00000970  64.06     00000830  64.11
00000670   64.15  115
00001310   64.19  145          00000720  64.17     00001050  65.04     00001210  65.09
00001010   65.01  120          00000840  64.01     00000850  64.02
00001030   65.02  125          00000670  64.15
00001050   65.03  135
00001140   65.07  137          00001070  65.05
00001220   65.10  140          00000920  64.05
00001530   65.12  146          00000520  64.12
00001760   66.01               00001730  65.18
00001780   66.04               00001760  66.01
00001940   66.13  147          00002590  66.34
00001990   66.15  150          00001800  66.06     00002950  67.25
00002140   66.19  160          00001880  66.11
00002160   66.21  170          00001810  66.07
00003780   66.25  205          00001900  66.12     00003360  68.13
00002360   66.27  180          00002140  66.19
00002470   66.29  181          00002660  67.17
00002510   66.30  182          00002740  67.09
00002560   66.33  1825         00002530  66.31
00002220   67.01  175          00002180  66.23
00002240   67.02  177          00002210  66.24
00003000   67.03  185          00002640  67.15
00003020   67.04  190          00003530  68.16     00003660  68.20     00003720  68.22     00003770  68.23
00002600   67.10  183          00001790  66.05
00002790   67.19  184          00002610  67.11     00002650  67.16
00002930   67.25               00002890  67.22
00003920   67.26  220          00002160  66.22     00002620  67.13     00003330  68.11
00003170   68.01  195          00000460  63.04

00003220   68.05               00003200  68.02
00003260   68.08               00003220  68.05
00003570   68.17  200          00003370  68.14
00003620   68.20  201
00003670   68.21  202          00003600  68.18
00003730   68.23  203          00003610  68.19     00003670  68.21
00003880   69.01  10           00002100  66.17     00002130  66.18     00002260  67.02
00003900   69.02  15           00001470  64.22     00003160  67.08
00003960   69.03  5000         00001260  65.11     00003830  66.26
00003970   69.04  6000         00003950  63.06     00003930  67.26     00003890  69.01     00003910  69.02

CHART TITLE - NON-PROCEDURAL STATEMENTS


CHART TITLE - SUBROUTINE  STEADY(IPRSTE)

00000030   71.01  STEADY       00002880   5.34-X
00000440   71.03               00000360  71.01
00000520   71.07  15           00000470  71.04
00000530   71.08  16           00000510  71.06
00000590   71.10               00001240  71.34
00001110   71.29               00001080  71.27
00001240   71.34  30           00001130  71.29

CHART TITLE - NON-PROCEDURAL STATEMENTS


CHART TITLE - SUBROUTINE  TADAMS(N,H,X,Y,DY,IQZ,IQ)

00000030   73.01  TADAMS       00002580  84.13-X
00000110   73.01  10           00000920  74.25
00000130   73.03               00000150  73.04
00000150   73.04  15
00000270   73.08  17
00000280   73.09  20
00001300   73.10  100          00000260  73.07     00000660  74.09
00001320   73.11  105          00001290  75.12
00000300   73.12  25           00000270  73.08
00000310   73.13  30
00000330   73.14  35           00000300  73.12
```

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06/25/75        TABLE OF CONTENTS AND REFERENCES        AUTOFLOW CHART SET - FSCSM                                      PAGE   9
CARD ID   PAGE/BOX    NAME                              REFERENCES  (SOURCE SEQUENCE NO. AND PAGE/BOX)

00000340   73.15  40             00000290  73.09     00000320  73.13
00000480   73.21                 00000490  73.23
00000490   73.22  45
00000560   74.02  52
00000570   74.03                 00000590  74.05
00000590   74.04  55
00000630   74.08  60
00000670   74.10  62
00000700   74.11  70             00000670  74.10
00000710   74.12  75
00000680   74.13  65
00000730   74.14  80             00000700  74.11
00000740   74.15  85             00000720  74.12     00000690  74.13
00000920   74.25  87             00000860  74.20
00000930   75.01  90             00000620  74.07
00001110   75.07                 00001220  75.11
00001220   75.10  95

CHART TITLE - NON-PROCEDURAL STATEMENTS


CHART TITLE - SUBROUTINE  TDPLOT(W,Y,NFP,TL,XR,LL)

00011002   77.01  TDPLOT         00010090  36.11-X   00010050  36.21-X   00010130  36.26-X   00010170  36.30-X
00011050   77.03                 00011070  77.04
00011070   77.04  100
00011120   77.07  5
00011150   77.08  201            00011110  77.06
00011190   77.09  200            00011140  77.07
00011220   77.11  10             00011270  77.19
00011260   77.17                 00011250  77.15
00011270   77.19                 00011260  77.17
00011280   77.20  20             00011240  77.14
00011290   77.21  30             00011230  77.12
00011310   77.23  31

00011330   77.25  50
00011350   77.27  60             00011300  77.22     00011320  77.24
00011360   77.28  61             00011340  77.26
00011380   77.30  180            00011430  78.03     00011430  78.03     00011430  78.03
00011390   77.31  181            00011380  77.30
00011410   78.01  182            00011380  77.30
00011420   78.02  40             00011400  77.32
00011440   78.04  190            00011430  78.03
00011450   78.05  191
00011470   78.07  192            00011440  78.04
00011480   78.08  193            00011460  78.06

CHART TITLE - NON-PROCEDURAL STATEMENTS


CHART TITLE - FUNCTION  XIMAGF(XIMOMG)

00000480   80.05  10             00000370  80.03     00000700  80.13
00000630   80.12  20             00000510  80.08
00000620   80.14                 00000610  80.10
00000750   80.15  30             00000620  80.14

CHART TITLE - NON-PROCEDURAL STATEMENTS


CHART TITLE - SUBROUTINE  ZADAMS(N,H,X,Y,DY,IQZ)

00001360   82.01  ZADAMS         00001280  54.15-X
00001440   82.01  10             00002210  83.33     00002590  84.14
00001460   82.03                 00001480  82.04
00001480   82.04  15
00001600   82.08  17
00001610   82.09  20
00001630   82.10  25             00001600  82.08
00001640   82.11  30
00001660   83.01  35             00001630  82.10
00001570   83.02  40             00001620  82.09     00001650  82.11
00001790   83.07                 00001800  83.09
00001800   83.08  45
00001870   83.11  52
```

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06/25/75        TABLE OF CONTENTS AND REFERENCES        AUTOFLOW CHART SET - FSCSM                                PAGE  10
CARD ID   PAGE/BOX   NAME                            REFERENCES  (SOURCE SEQUENCE NO. AND PAGE/BOX)

00001880   83.12                00001900  83.14
00001900   83.13  55
00001930   83.17  60
00001970   83.19  62
00001980   83.20  65
00002000   83.21  70            00001970  83.19
00002010   83.22  75
00002020   83.23  80            00002000  83.21
00002040   83.24  85            00001980  83.20    00002020  83.22
00002210   83.33  87            00002150  83.28
00002220   84.01  90            00001920  83.16
00002410   84.07                00002520  84.11
00002520   84.10  95
00002610   84.15  100           00001580  82.07    00001960  83.18    00002590  84.14

CHART TITLE - NON-PROCEDURAL STATEMENTS


CHART TITLE - SUBROUTINE  ZERO(FI,T11,T21,F11,F21,ANS,FANS,EPSF,EPSX,AF,ICNT,NCN

00000040   86.01  ZERO          00001190  65.08-X
00000160   86.04  5             00000240  86.07
00000200   86.05  10
00000220   86.07  15            00000130  86.02
00000250   87.01  50            00000160  86.04
00000270   87.04                00000260  87.02
00000310   87.05  220           00000850  87.29    00000710  87.34    00000900  87.35    00000760  88.01    00000820  88.06
                                00000870  88.07
00000950   87.12  500           00000330  87.06
00000910   87.14  300           00000390  87.09
00000930   87.15  400           00000670  87.32    00000780  88.04
00000980   87.23  600           00000500  87.19
00000550   87.25  230           00000520  87.21
00000600   87.26  240           00000540  87.22
00000620   87.28  245           00000480  87.17
00000660   87.30  250           00000600  87.26
00000880   87.35  270           00000620  87.28
00000720   88.01  255           00000680  87.33
00000770   88.02  260           00000610  87.27
00000830   88.07  265           00000790  88.05

CHART TITLE - NON-PROCEDURAL STATEMENTS
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```
06/25/75        TABLE OF DIAGNOSTICS                 AUTOFLOW CHART SET - FSCSM                                  PAGE   1
        LOCATION               DIAGNOSTIC
     CARD ID   PAGE/BOX
    00010100      36.12      UNDEFINED - 'PRINTV' EXTERNAL REFERENCE
    00010060      36.22      UNDEFINED - 'PRINTV' EXTERNAL REFERENCE
    00010070      36.23      UNDEFINED - 'PRINTV' EXTERNAL REFERENCE
    00010140      36.27      UNDEFINED - 'PRINTV' EXTERNAL REFERENCE
    00010150      36.28      UNDEFINED - 'PRINTV' EXTERNAL REFERENCE
    00010180      36.31      UNDEFINED - 'PRINTV' EXTERNAL REFERENCE
    00010190      36.32      UNDEFINED - 'PRINTV' EXTERNAL REFERENCE
    00010210      36.34      UNDEFINED - 'LABLV' EXTERNAL REFERENCE
    00011310      77.23      UNDEFINED - 'CAMRAV' EXTERNAL REFERENCE
    00011330      77.25      UNDEFINED - 'SETMIV' EXTERNAL REFERENCE
    00011350      77.27      UNDEFINED - 'SETMIV' EXTERNAL REFERENCE
    00011360      77.28      UNDEFINED - 'SMXYV' EXTERNAL REFERENCE
    00011370      77.29      UNDEFINED - 'GRIDIV' EXTERNAL REFERENCE
    00011390      77.31      UNDEFINED - 'APLOTV' EXTERNAL REFERENCE
    00011410      78.01      UNDEFINED - 'APLOTV' EXTERNAL REFERENCE
    00011450      78.05      UNDEFINED - 'LABLV' EXTERNAL REFERENCE
    00011470      78.07      UNDEFINED - 'LABLV' EXTERNAL REFERENCE
```

```
CHART TITLE - INTRODUCTORY COMMENTS



                    MAIN CONTROL PROGRAM FOR THE FEED SYSTEM COUPLED STABILITY MODEL
                    PROGRAM DEVELOPED BY ROCKETDYNE, A DIVISION OF ROCKWELL
                       INTERNATIONAL, CANOGA PARK, CALIF 91304
                    PROGRAMMED BY M. D. SCHUMAN, ROCKETDYNE, MAY 1975
```

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OF POOR QUALITY

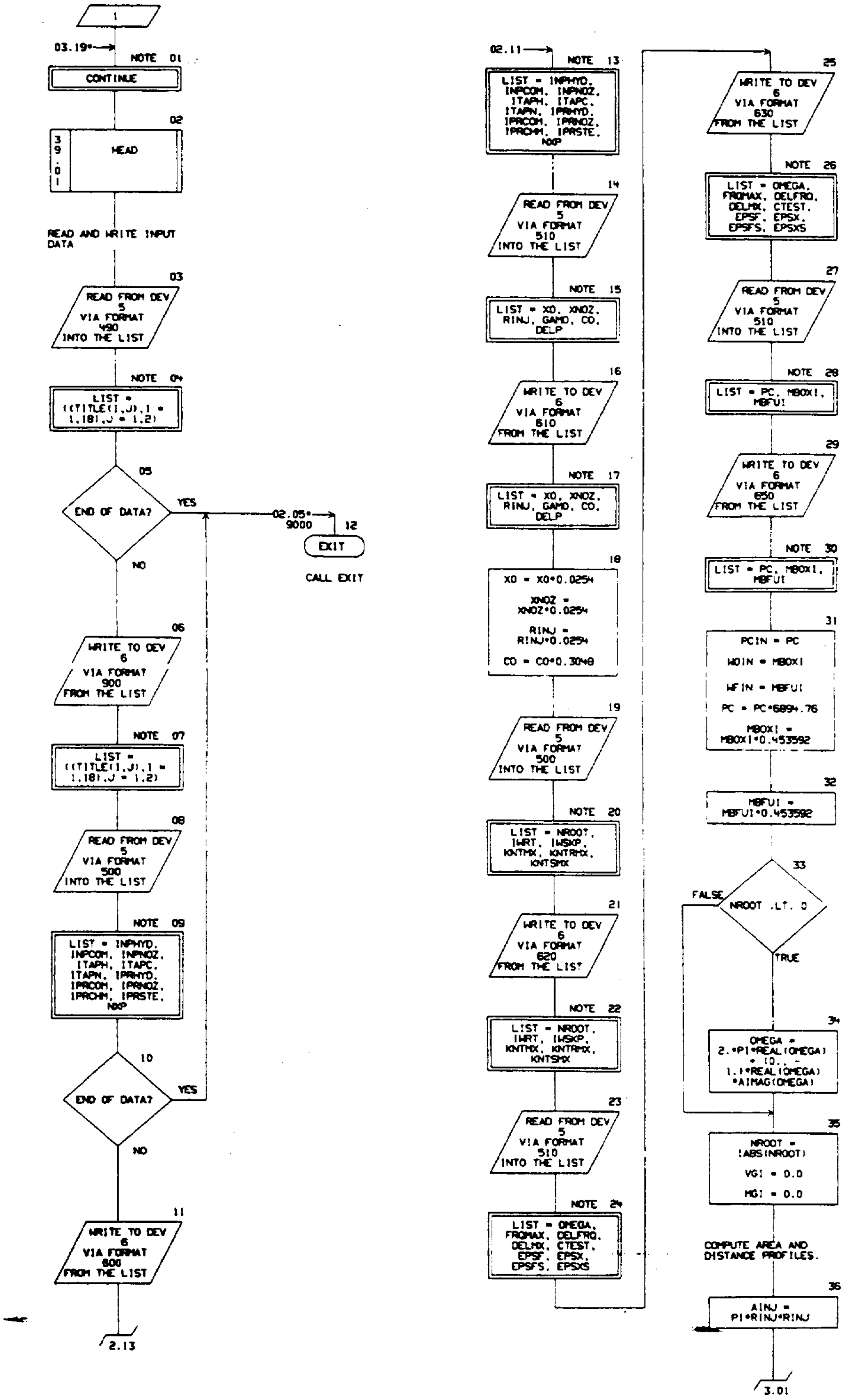
1
03.19*
NOTE 01
CONTINUE
02
3
9
.
0
1
HEAD
READ AND WRITE INPUT DATA
03
READ FROM DEV 5 VIA FORMAT 490 INTO THE LIST
NOTE 04
LIST = ((TITLE(I,J),I = 1,18),J = 1,2)
05
END OF DATA?
YES
02.05*
9000
12
EXIT
CALL EXIT
NO
06
WRITE TO DEV 6 VIA FORMAT 900 FROM THE LIST
NOTE 07
LIST = ((TITLE(I,J),I = 1,18),J = 1,2)
08
READ FROM DEV 5 VIA FORMAT 500 INTO THE LIST
NOTE 09
LIST = INPHYD, INPCOM, INPNOZ, ITAPH, ITAPC, ITAPN, IPRHYD, IPRCOM, IPRNOZ, IPRCHM, IPRSTE, NOP
10
END OF DATA?
YES
NO
11
WRITE TO DEV 6 VIA FORMAT 600 FROM THE LIST
2.13
02.11
NOTE 13
LIST = INPHYD, INPCOM, INPNOZ, ITAPH, ITAPC, ITAPN, IPRHYD, IPRCOM, IPRNOZ, IPRCHM, IPRSTE, NOP
14
READ FROM DEV 5 VIA FORMAT 510 INTO THE LIST
NOTE 15
LIST = XO, XNOZ, RINJ, GAMO, CO, DELP
16
WRITE TO DEV 6 VIA FORMAT 610 FROM THE LIST
NOTE 17
LIST = XO, XNOZ, RINJ, GAMO, CO, DELP
18
XO = XO*0.0254
XNOZ = XNOZ*0.0254
RINJ = RINJ*0.0254
CO = CO*0.3048
19
READ FROM DEV 5 VIA FORMAT 500 INTO THE LIST
NOTE 20
LIST = NROOT, IWRT, IWSKP, KNTMX, KNTRMX, KNTSMX
21
WRITE TO DEV 6 VIA FORMAT 620 FROM THE LIST
NOTE 22
LIST = NROOT, IWRT, IWSKP, KNTMX, KNTRMX, KNTSMX
23
READ FROM DEV 5 VIA FORMAT 510 INTO THE LIST
NOTE 24
LIST = OMEGA, FROMAX, DELFRQ, DELMX, CTEST, EPSF, EPSX, EPSFS, EPSXS
25
WRITE TO DEV 6 VIA FORMAT 630 FROM THE LIST
NOTE 26
LIST = OMEGA, FROMAX, DELFRQ, DELMX, CTEST, EPSF, EPSX, EPSFS, EPSXS
27
READ FROM DEV 5 VIA FORMAT 510 INTO THE LIST
NOTE 28
LIST = PC, MBOXI, MBFUI
29
WRITE TO DEV 6 VIA FORMAT 650 FROM THE LIST
NOTE 30
LIST = PC, MBOXI, MBFUI
31
PCIN = PC
WOIN = MBOXI
WFIN = MBFUI
PC = PC*6894.76
MBOXI = MBOXI*0.453592
32
MBFUI = MBFUI*0.453592
33
NROOT .LT. 0
FALSE
TRUE
34
OMEGA = 2.*PI*REAL(OMEGA) + (0., -1.)*REAL(OMEGA) *AIMAG(OMEGA)
35
NROOT = IABS(NROOT)
VGI = 0.0
MGI = 0.0
COMPUTE AREA AND DISTANCE PROFILES.
36
AINJ = PI*RINJ*RINJ
3.01

CHART TITLE - PROCEDURES

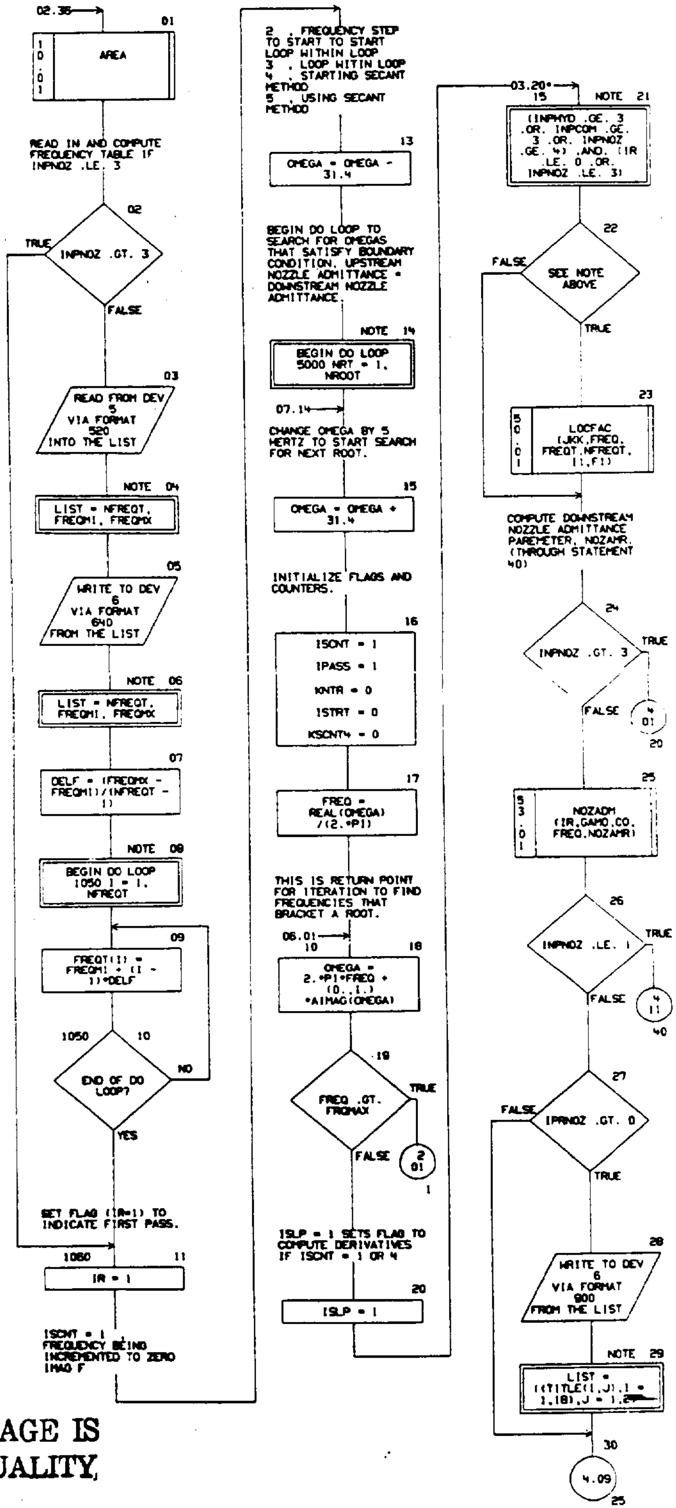

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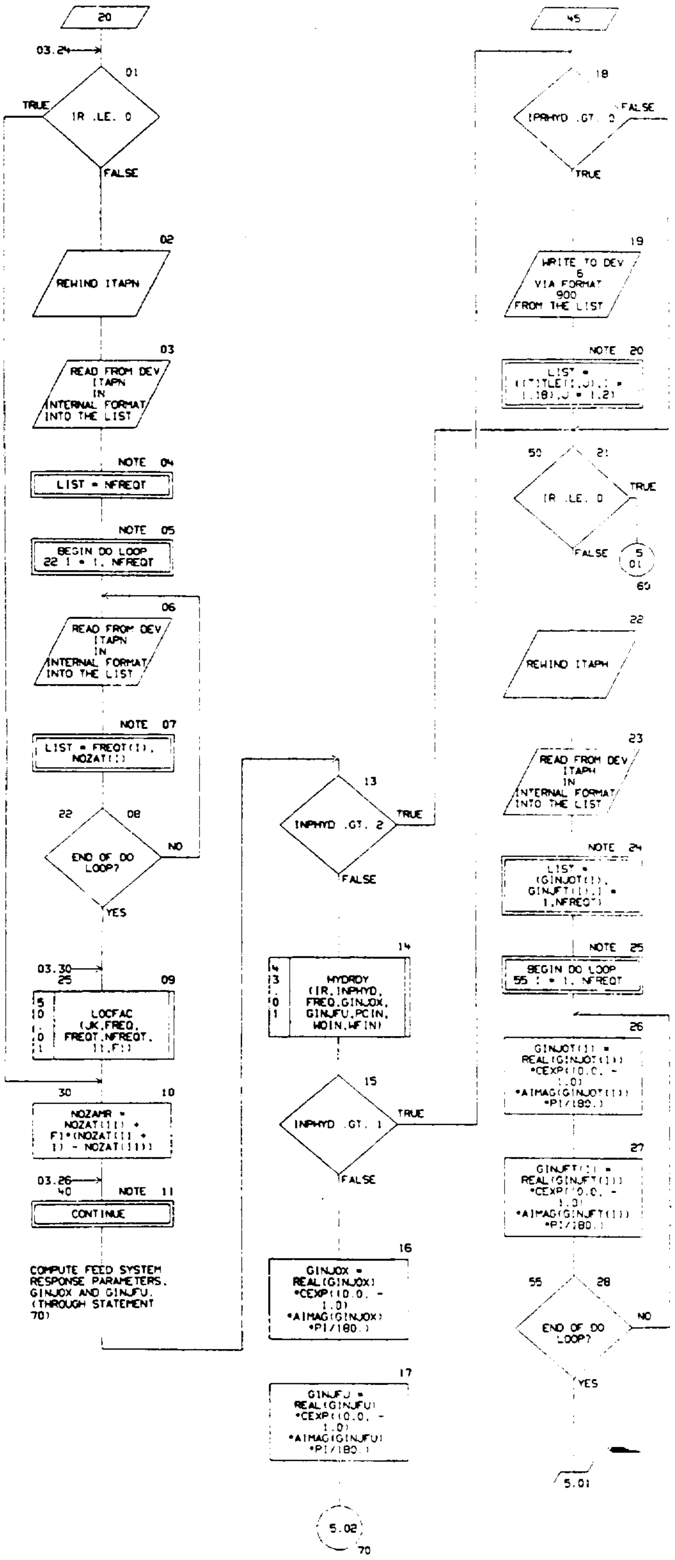
CHART TITLE - PROCEDURES



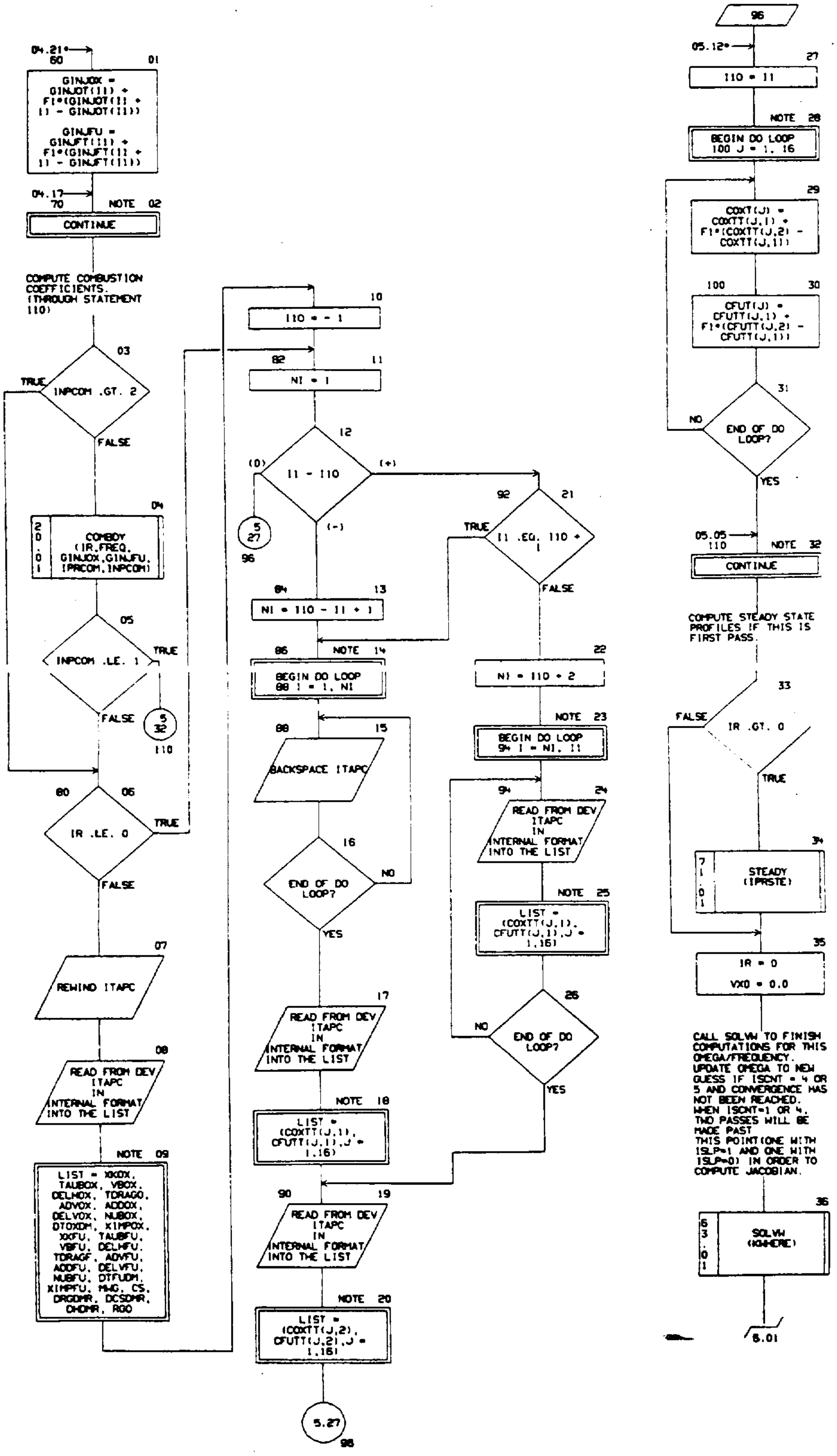
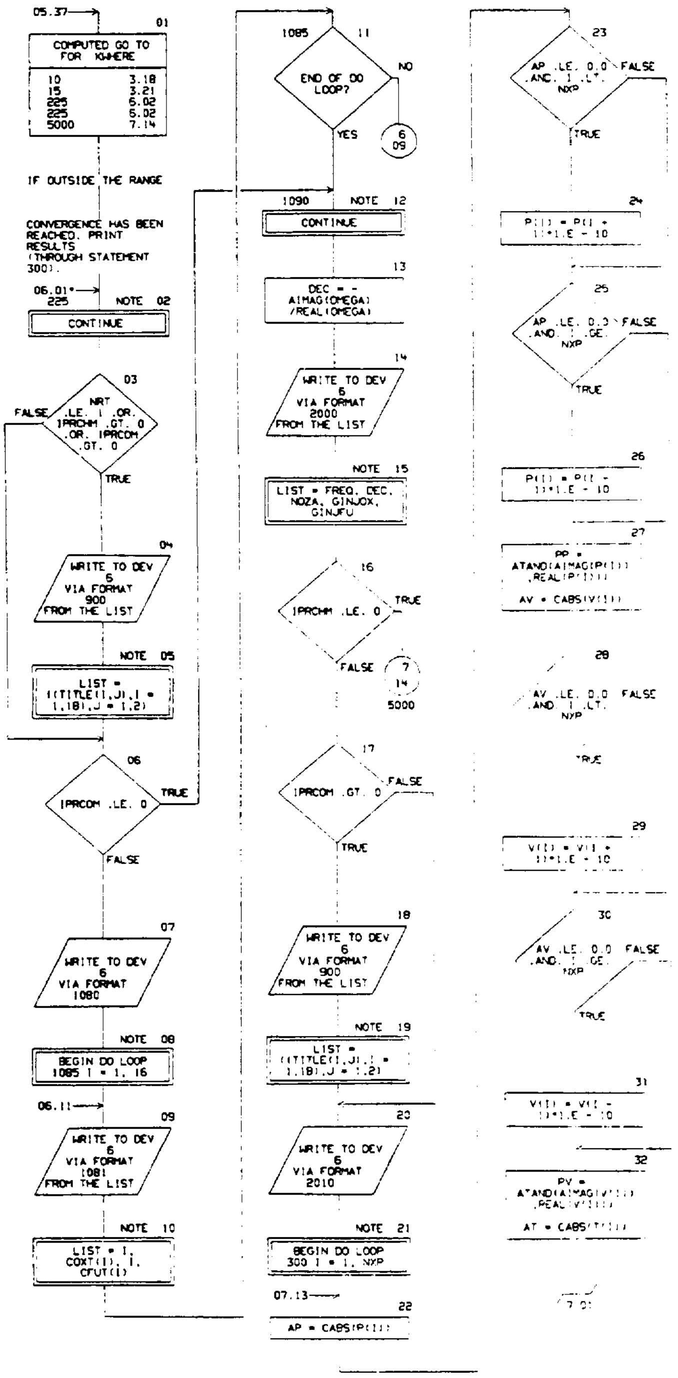
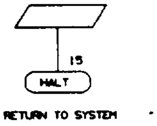

04.21*
60
01
GINJOX = GINJOT(I1) + F1*(GINJOT(I1 + 1) - GINJOT(I1))
GINJFU = GINJFT(I1) + F1*(GINJFT(I1 + 1) - GINJFT(I1))
04.17
70
NOTE 02
CONTINUE
COMPUTE COMBUSTION COEFFICIENTS. (THROUGH STATEMENT 110)
03
INPCOM .GT. 2
TRUE
FALSE
04
20.01
COMBOY (IR,FREQ, GINJOX,GINJFU, IPRCOM,INPCOM)
05
INPCOM .LE. 1
TRUE
FALSE
5 32
110
80
06
IR .LE. 0
TRUE
FALSE
07
REWIND ITAPC
08
READ FROM DEV ITAPC IN INTERNAL FORMAT INTO THE LIST
NOTE 09
LIST = XXOX, TAUBOX, VBOX, DELHOX, TDRAGO, ADVOX, ADDOX, DELVOX, NUBOX, DTOXDM, XIMPOX, XXFU, TAUBFU, VBFU, DELHFU, TDRAGF, ADVFU, ADDFU, DELVFU, NUBFU, DTFUDM, XIMPFU, MWG, CS, DRGDMR, DCSDMR, DHDMR, RGO
10
I10 = - 1
82
11
NI = 1
12
I1 - I10
(0)
(+)
(-)
5 27
96
84
13
NI = I10 - I1 + 1
86
NOTE 14
BEGIN DO LOOP 88 I = 1, NI
88
15
BACKSPACE ITAPC
16
END OF DO LOOP?
NO
YES
17
READ FROM DEV ITAPC IN INTERNAL FORMAT INTO THE LIST
NOTE 18
LIST = (COXTT(J,1), CFUTT(J,1),J = 1,16)
90
19
READ FROM DEV ITAPC IN INTERNAL FORMAT INTO THE LIST
NOTE 20
LIST = (COXTT(J,2), CFUTT(J,2),J = 1,16)
5.27
96
92
21
I1 .EQ. I10 + 1
TRUE
FALSE
22
NI = I10 + 2
NOTE 23
BEGIN DO LOOP 94 I = NI, I1
94
24
READ FROM DEV ITAPC IN INTERNAL FORMAT INTO THE LIST
NOTE 25
LIST = (COXTT(J,1), CFUTT(J,1),J = 1,16)
26
END OF DO LOOP?
NO
YES
96
05.12*
27
I10 = I1
NOTE 28
BEGIN DO LOOP 100 J = 1, 16
29
COXT(J) = COXTT(J,1) + F1*(COXTT(J,2) - COXTT(J,1))
100
30
CFUT(J) = CFUTT(J,1) + F1*(CFUTT(J,2) - CFUTT(J,1))
31
END OF DO LOOP?
NO
YES
05.05
110
NOTE 32
CONTINUE
COMPUTE STEADY STATE PROFILES IF THIS IS FIRST PASS.
33
IR .GT. 0
FALSE
TRUE
34
71.01
STEADY (IPRSTE)
35
IR = 0
VX0 = 0.0
CALL SOLVW TO FINISH COMPUTATIONS FOR THIS OMEGA/FREQUENCY. UPDATE OMEGA TO NEW GUESS IF ISCNT = 4 OR 5 AND CONVERGENCE HAS NOT BEEN REACHED. WHEN ISCNT=1 OR 4, TWO PASSES WILL BE MADE PAST THIS POINT(ONE WITH ISLP=1 AND ONE WITH ISLP=0) IN ORDER TO COMPUTE JACOBIAN.
36
63.01
SOLVW (KWHERE)
6.01

CHART TITLE - PROCEDURES





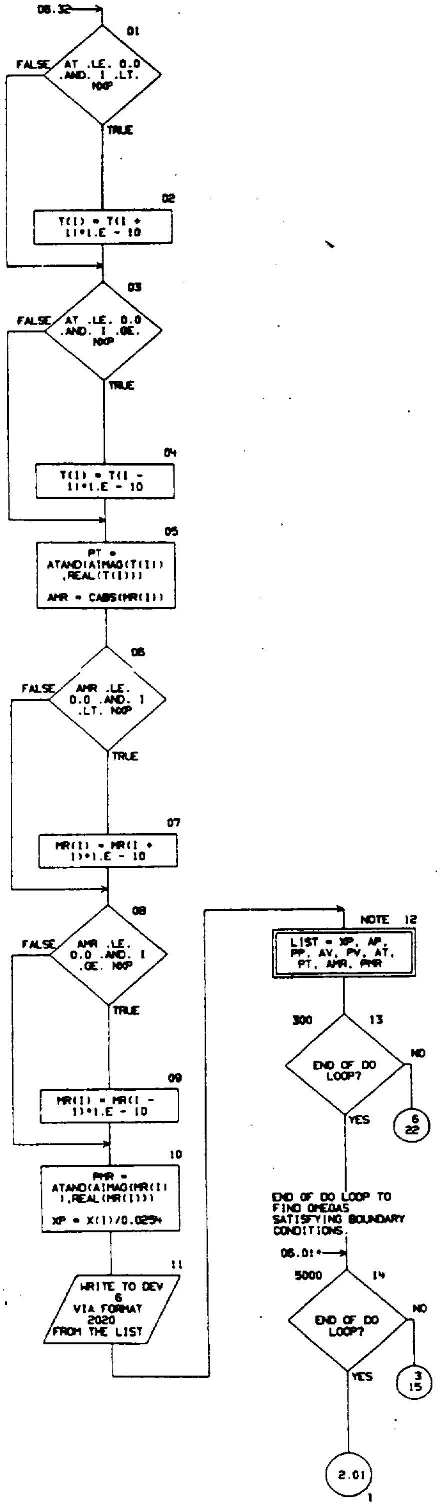


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CHART TITLE - NON-PROCEDURAL STATEMENTS

```
            DIMENSION TITLE(18,2)
            COMPLEX OMEGA, P, RHO, V, MR, T, CNOZA, VXO,
                 COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9,
                 COX10, COX11, COX12, COX13, COX14, COX15, COX16,
                 CFU1, CFU2, CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9,
                 CFU10, CFU11, CFU12, CFU13, CFU14, CFU15, CFU16,
                 NOZA, GINJOX, GINJFU,
                 NOZAT, GINJOT, GINJFT,
                 FN, NOZAMR, GN,
                 COXT(16), CFUT(16),
                 COXTT(16,2), CFUTT(16,2)
            REAL  MBOX1, MBFU1, MRB, MRG1, MG1, NUBOX, NUBFU, KF, KO, L, MWG
            COMMON  /COMCBM/  XKOX, XKFU, MBOX1, MBFU1, TAUBOX, TAUBFU, VBOX,
                 VBFU, GAMO, RGO, DELHOX, DELHFU, PC, CO,
                 COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9, COX10,
                 COX11, COX12, COX13, COX14, COX15, COX16, CFU1, CFU2,
                 CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9, CFU10, CFU11,
                 CFU12, CFU13, CFU14, CFU15, CFU16, MWG, XIMPFU, XIMPOX,
                 CS, DCSDMR, DHDMR, DRGDMR, ADVOX, ADDOX, TDRAGO, DELVOX,
                 NUBOX, DTOXDM, ADVFU, ADDFU, TDRAGF, DELVFU, NUBFU, DTFUDM
            EQUIVALENCE (COXT(1),COX1), (CFUT(1),CFU1)
            COMMON /CONSTS/  MRB(100), TB(100), RHOB(100), VB(100),
                 DMRB(100), DRHOB(100), DVB(100), VAPBOX(100), VAPBFU(100),
                 SSV1(100), SSV2(100), SSV3(100), SSV4(100),
                 SSV5(100), SSV6(100), SSV7(100), SSV8(100), SSV9OX(100),
                 SSV9FU(100), SSV10(100), SSV11(100), SSV12(100), SSV13(100),
                 SSV14(100), SSV15(100), SSV16(100),
                 RHOG1, VG1, MRG1, MG1
            COMMON /COMCHM/ P(100), RHO(100), V(100), MR(100), T(100),
                 VXO, OMEGA, CNOZA, DELP
            COMMON /COMARE/ NXP, X(100), XM(100), A(100), DA(100), DELX,
                 XO, XNOZ, AINJ
            COMMON /COMNOZ/ RCCX, RCTX, ANGLEX, CRR, RINJ, INPNOZ, FREQMX,
                 FREQMI, IPRNOZ
            COMMON /FZERO/ NOZA,NOZAMR,GN,FN,FNR,FNI,HN,ISCNT,ISLP
            COMMON /DUMP/ IWRT
            DATA JK/1/,  JKK/1/,  PI/3.141593/
            COMMON /SOLVE/ FREQ, DELFRQ, DELMX, EPSF, EPSX, EPSFS, EPSXS,
                           FRQMAX, CTEST, IPASS, KNTR, ISTRT, KSCNT4, IWSKP,
                           KNTMX, KNTSMX, KNTRMX
            COMMON /COMTAP/ NFREQT, FREQT(100), NOZAT(100), GINJOT(100),
                 GINJFT(100), ITAPN, ITAPC, ITAPH
            COMMON /HY/ ICRT,IRFLAG,ITERM,ITYPE,IPRHYD,IX,AA(30),CH(30),KF,KO,
                 L(30),R(30),RHOL(30),VV(30),VF,VO,VOLF,VOLO,ZF,ZO,OSAVE(188),
                 FSAVE(188)
490         FORMAT(18A4)
900         FORMAT(1H1,///,26X,'FEED  SYSTEM  COUPLED  STABILITY  MODEL',/,
                 9X,18A4,/,9X,18A4)
500         FORMAT(12I6)
600         FORMAT(/,5X,'INPHYD =',I2,5X,'INPCOM =',I2,5X,'INPNOZ =',I2,
                 5X,'ITAPH =',I3,5X,'ITAPC =',I3,5X,'ITAPN =',I3,/,5X,
                 'IPRHYD =',I2,5X,'IPRCOM =',I2,5X,'IPRNOZ =',I2,5X,
                 'IPRCHM =',I2,5X,'IPRSTE =',I2,5X,'NXP =',I4)
510         FORMAT(6E12.8)
610         FORMAT(/,5X,'XO =',1PE11.4,7X,'XNOZ =',E11.4,5X,'RINJ =',
                 E11.4,5X,'GAMO =',E11.4,/,27X,'CO =',E11.4,7X,'DELP =',
                 E11.4)
620         FORMAT(/,5X,'NROOT =',I3,5X,'IWRT =',I2,7X,'IWSKP =',I2,6X,
                 'KNTMX =',I4,4X,'KNTRMX =',I4,3X,'KNTSMX =',I4)
630         FORMAT(/,5X,'OMEGA(R)=',1PE11.4,2X,'OMEGA(I)=',E11.4,2X,
                 'FRQMAX =',E11.4,3X,'DELFRQ =',E11.4,/,27X,'DELMX =',
                 E11.4,4X,'CTEST =',E11.4,//,5X,'EPSF =',E11.4,5X,
                 'EPSX =',E11.4,5X,'EPSFS =',E11.4,4X,'EPSXS =',E11.4)
```

CHART TITLE - NON-PROCEDURAL STATEMENTS

```
650     FORMAT(/,5X,'PC =',1PE11.4,7X,'MBOX1 =',E11.4,4X,'MBFUI =',
             E11.4)
520     FORMAT(I12,5E12.8)
640     FORMAT(/,5X,'NFREQT =',I4,10X,'FREQMI =',1PE11.4,3X,
             'FREQMX =',E11.4)
1080    FORMAT(///,20X,'COMBUSTION DYNAMIC COEFFICIENTS',/)
1081    FORMAT(5X,'COX(',I2,') =',1PE11.4,',',E11.4,5X,'CFU(',I2,
             ') =',E11.4,',',E11.4)
2000    FORMAT(///,10X,'FREQUENCY =',F8.2,' HZ.',/,10X,
             'DECREMENT =',F8.5,//,
             10X,'NOZZLE ADMITTANCE =',F9.5,',',2X,F9.5,//,10X,
             'FEED SYSTEM RESPONSE',/,20X,'OXIDIZER =',F9.5,',',2X,F9.5,
             /,24X,'FUEL =',F9.5,',',2X,F9.5,///)
2010    FORMAT(10X,4(11X,'OSCILLATORY'),/,5X,'DISTANCE',6X,
             'PRESSURE  RATIO',7X,'VELOCITY  RATIO',6X,
             'TEMPERATURE RATIO',7X,'MIXTURE RATIO',/,5X,'(INCHES)',
             4(5X,'AMPLITUDE   PHASE'),/)
2020    FORMAT(5X,F8.4,4(5X,F8.5,2X,F7.2))
```

CHART TITLE - SUBROUTINE AREA

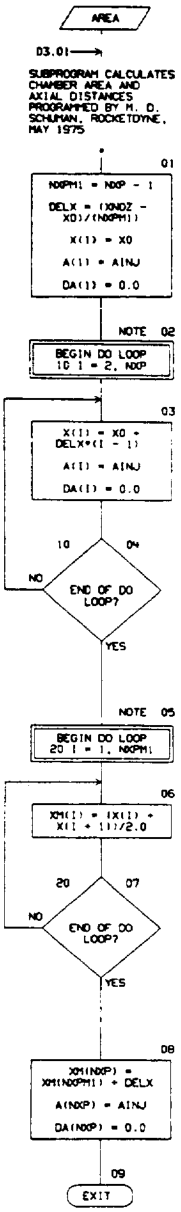

CHART TITLE - NON-PROCEDURAL STATEMENTS

```
      COMMON /COMARE/ NXP, X(100), XM(100), A(100), DA(100), DELX,
          XO, XNOZ, AINJ
```

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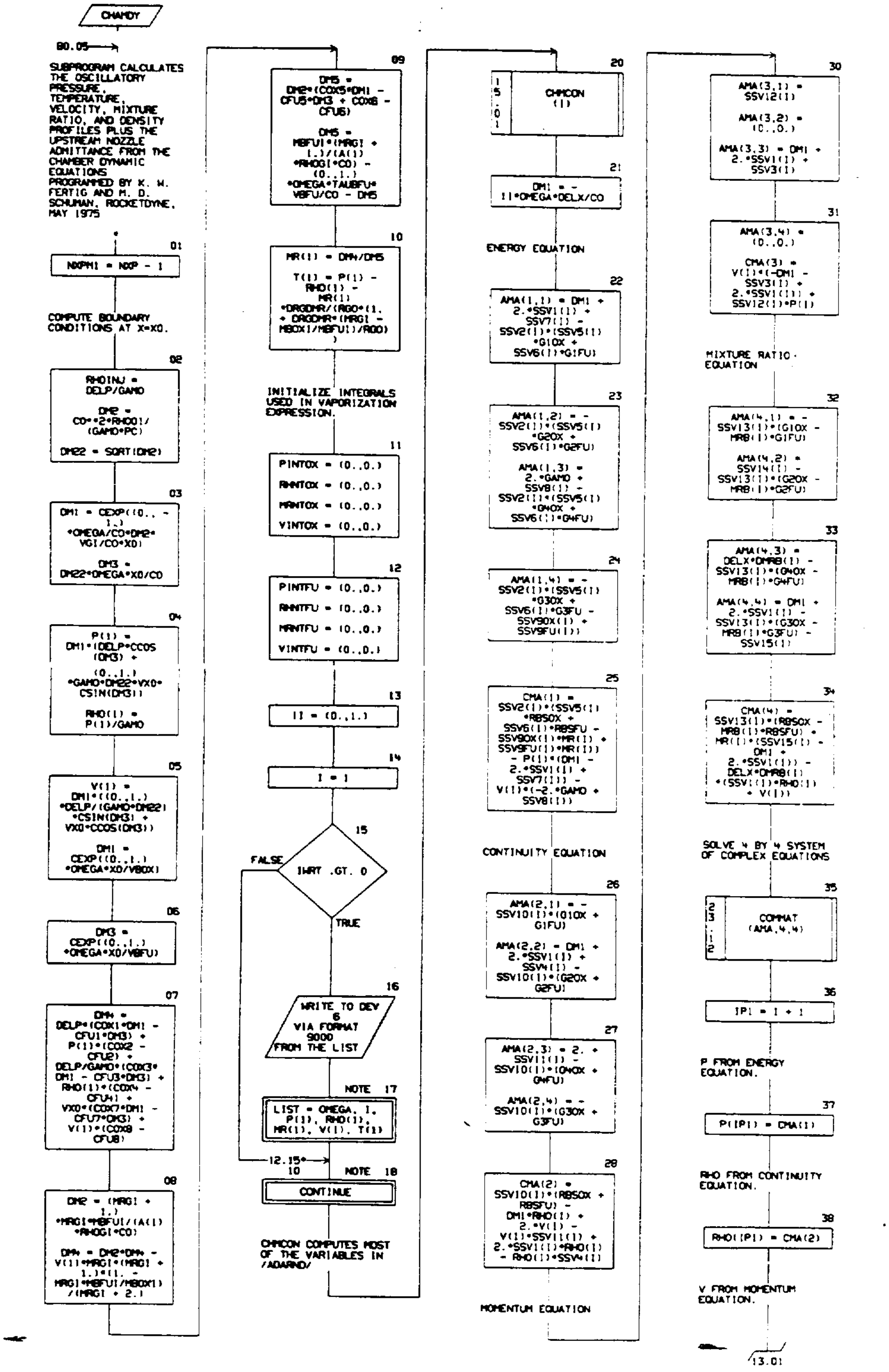

CHAMDY
B0.05
SUBPROGRAM CALCULATES THE OSCILLATORY PRESSURE, TEMPERATURE, VELOCITY, MIXTURE RATIO, AND DENSITY PROFILES PLUS THE UPSTREAM NOZZLE ADMITTANCE FROM THE CHAMBER DYNAMIC EQUATIONS
PROGRAMMED BY K. W. FERTIG AND M. D. SCHUMAN, ROCKETDYNE, MAY 1975
01
NXPM1 = NXP - 1
COMPUTE BOUNDARY CONDITIONS AT X=X0.
02
RHOINJ = DELP/GAMO
DM2 = CO**2*RHOO1/(GAMO*PC)
DM22 = SQRT(DM2)
03
DM1 = CEXP((0., -1.)*OMEGA/CO*DM2*VGI/CO*X0)
DM3 = DM22*OMEGA*X0/CO
04
P(1) = DM1*(DELP*CCOS(DM3) + (0.,1.)*GAMO*DM22*VX0*CSIN(DM3))
RHO(1) = P(1)/GAMO
05
V(1) = DM1*((0.,1.)*DELP/(GAMO*DM22)*CSIN(DM3) + VX0*CCOS(DM3))
DM1 = CEXP((0.,1.)*OMEGA*X0/VBOX)
06
DM3 = CEXP((0.,1.)*OMEGA*X0/VBFU)
07
DM4 = DELP*(COX1*DM1 - CFU1*DM3) + P(1)*(COX2 - CFU2) + DELP/GAMO*(COX3*DM1 - CFU3*DM3) + RHO(1)*(COX4 - CFU4) + VX0*(COX7*DM1 - CFU7*DM3) + V(1)*(COX8 - CFU8)
08
DM2 = (MRGI + 1.)*MRGI*MBFUI/(A(1)*RHOGI*CO)
DM4 = DM2*DM4 - V(1)*MRGI*(MRGI + 1.)*(1. - MRGI*MBFUI/MBOXI)/(MRGI + 2.)
09
DM5 = DM2*(COX5*DM1 - CFU5*DM3 + COX6 - CFU6)
DM5 = MBFUI*(MRGI + 1.)/(A(1)*RHOGI*CO) - (0.,1.)*OMEGA*TAUBFU*VBFU/CO - DM5
10
MR(1) = DM4/DM5
T(1) = P(1) - RHO(1) - MR(1)*DRGDMR/(RGO*(1. + DRGDMR*(MRGI - MBOXI/MBFUI)/RGO))
INITIALIZE INTEGRALS USED IN VAPORIZATION EXPRESSION.
11
PINTOX = (0.,0.)
RHNTOX = (0.,0.)
MRNTOX = (0.,0.)
VINTOX = (0.,0.)
12
PINTFU = (0.,0.)
RHNTFU = (0.,0.)
MRNTFU = (0.,0.)
VINTFU = (0.,0.)
13
II = (0.,1.)
14
I = 1
15
IWRT .GT. 0
FALSE
TRUE
16
WRITE TO DEV 6 VIA FORMAT 9000 FROM THE LIST
NOTE 17
LIST = OMEGA, I, P(I), RHO(I), MR(I), V(I), T(I)
12.15*
10
NOTE 18
CONTINUE
CHMCON COMPUTES MOST OF THE VARIABLES IN /ADARND/
20
15.01
CHMCON (I)
21
DM1 = - II*OMEGA*DELX/CO
ENERGY EQUATION
22
AMA(1,1) = DM1 + 2.*SSV1(I) + SSV7(I) - SSV2(I)*(SSV5(I)*G1OX + SSV6(I)*G1FU)
23
AMA(1,2) = - SSV2(I)*(SSV5(I)*G2OX + SSV6(I)*G2FU)
AMA(1,3) = 2.*GAMO + SSV8(I) - SSV2(I)*(SSV5(I)*G4OX + SSV6(I)*G4FU)
24
AMA(1,4) = - SSV2(I)*(SSV5(I)*G3OX + SSV6(I)*G3FU - SSV9OX(I) + SSV9FU(I))
25
CMA(1) = SSV2(I)*(SSV5(I)*RBSOX + SSV6(I)*RBSFU - SSV9OX(I)*MR(I) + SSV9FU(I)*MR(I)) - P(I)*(DM1 - 2.*SSV1(I) + SSV7(I)) - V(I)*(-2.*GAMO + SSV8(I))
CONTINUITY EQUATION
26
AMA(2,1) = - SSV10(I)*(G1OX + G1FU)
AMA(2,2) = DM1 + 2.*SSV1(I) + SSV4(I) - SSV10(I)*(G2OX + G2FU)
27
AMA(2,3) = 2. + SSV11(I) - SSV10(I)*(G4OX + G4FU)
AMA(2,4) = - SSV10(I)*(G3OX + G3FU)
28
CMA(2) = SSV10(I)*(RBSOX + RBSFU) - DM1*RHO(I) + 2.*V(I) - V(I)*SSV11(I) + 2.*SSV1(I)*RHO(I) - RHO(I)*SSV4(I)
MOMENTUM EQUATION
30
AMA(3,1) = SSV12(I)
AMA(3,2) = (0.,0.)
AMA(3,3) = DM1 + 2.*SSV1(I) + SSV3(I)
31
AMA(3,4) = (0.,0.)
CMA(3) = V(I)*(-DM1 - SSV3(I) + 2.*SSV1(I)) + SSV12(I)*P(I)
MIXTURE RATIO EQUATION
32
AMA(4,1) = - SSV13(I)*(G1OX - MRB(I)*G1FU)
AMA(4,2) = SSV14(I) - SSV13(I)*(G2OX - MRB(I)*G2FU)
33
AMA(4,3) = DELX*DMRB(I) - SSV13(I)*(G4OX - MRB(I)*G4FU)
AMA(4,4) = DM1 + 2.*SSV1(I) - SSV13(I)*(G3OX - MRB(I)*G3FU) - SSV15(I)
34
CMA(4) = SSV13(I)*(RBSOX - MRB(I)*RBSFU) + MR(I)*(SSV15(I) - DM1 + 2.*SSV1(I)) - DELX*DMRB(I)*(SSV1(I)*RHO(I) + V(I))
SOLVE 4 BY 4 SYSTEM OF COMPLEX EQUATIONS
35
23.12
COMMAT (AMA,4,4)
36
IP1 = I + 1
P FROM ENERGY EQUATION.
37
P(IP1) = CMA(1)
RHO FROM CONTINUITY EQUATION.
38
RHO(IP1) = CMA(2)
V FROM MOMENTUM EQUATION.
13.01

CHART TITLE - SUBROUTINE CHAMDY

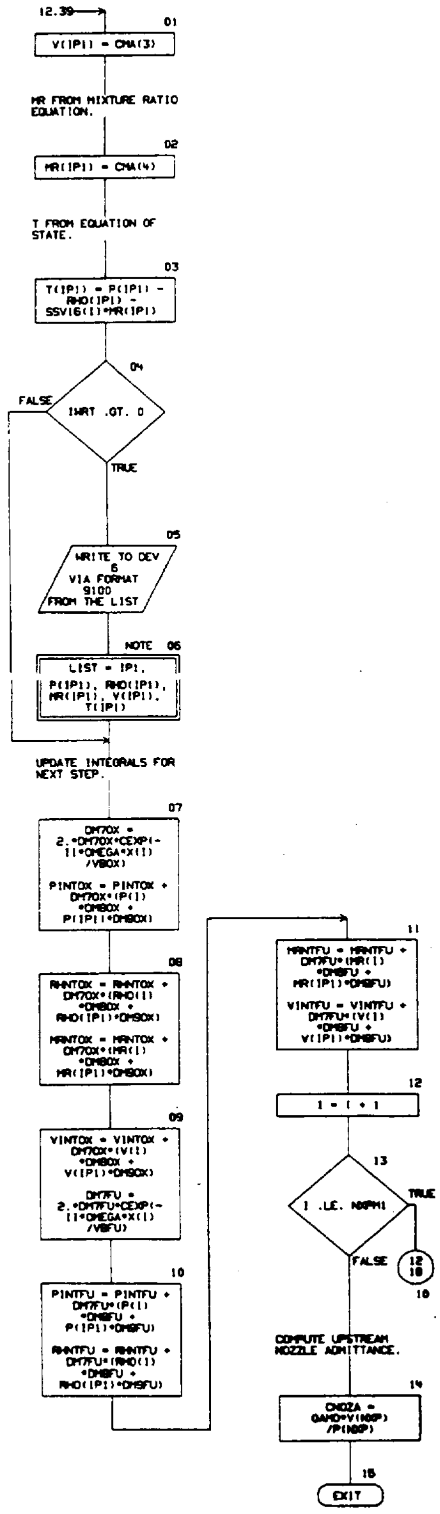


CHART TITLE - NON-PROCEDURAL STATEMENTS

```
        COMPLEX*16  AMA(4,5), CMA(4)
        COMPLEX OMEGA, P, RHO, V, MR, T, CNOZA, VX0,
             COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9,
             COX10, COX11, COX12, COX13, COX14, COX15, COX16,
             CFU1, CFU2, CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9,
             CFU10, CFU11, CFU12, CFU13, CFU14, CFU15, CFU16
        COMPLEX DM1,  DM3, DM4, DM5, DM6, DM7OX, DM7FU, DM8OX,
             DM8FU, G1OX, G1FU, G2OX, G2FU, G3OX, G3FU, G4OX, G4FU,
             RBSOX, RBSFU, PINTOX, PINTFU, RHNTOX, RHNTFU, MRNTOX,
             MRNTFU, VINTOX, VINTFU, II
             ,DM9OX,DM9FU
        REAL  MBOX1, MBFU1, MRB, MRG1, MG1, NUBOX, NUBFU, MWG
        COMMON  /COMCBM/  XKOX, XKFU, MBOX1, MBFU1, TAUBOX, TAUBFU, VBOX,
             VBFU, GAMO, RGO, DELHOX, DELHFU, PC, CO,
             COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9, COX10,
             COX11, COX12, COX13, COX14, COX15, COX16, CFU1, CFU2,
             CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9, CFU10, CFU11,
             CFU12, CFU13, CFU14, CFU15, CFU16, MWG, XIMPFU, XIMPOX,
             CS, DCSDMR, DHDMR, DRGDMR, ADVOX, ADDOX, TORAGO, DELVOX,
             NUBOX, DTOXDM, ADVFU, ADDFU, TORAGF, DELVFU, NUBFU, DTFUDM
        COMMON /CONSTS/  MRB(100), TB(100), RHOB(100), VB(100),
             DMRB(100), DRHOB(100), DVB(100), VAPBOX(100), VAPBFU(100),
             SSV1(100), SSV2(100), SSV3(100), SSV4(100),
             SSV5(100), SSV6(100), SSV7(100), SSV8(100), SSV9OX(100),
             SSV9FU(100), SSV10(100), SSV11(100), SSV12(100), SSV13(100),
             SSV14(100), SSV15(100), SSV16(100),
             RHOG1, VG1, MRG1, MG1
        COMMON /COMCHM/ P(100), RHO(100), V(100), MR(100), T(100),
             VX0, OMEGA, CNOZA, DELP
        COMMON /COMARE/ NXP, X(100), XM(100), A(100), DA(100), DELX,
             X0, XNOZ, AINJ
        COMMON /ADARND/ G1OX,G2OX,G3OX,G4OX,G1FU,G2FU,G3FU,G4FU,PINTOX,
               RHNTOX,MRNTOX,VINTOX,PINTFU,RHNTFU,MRNTFU,VINTFU,RB5OX,
               RBSFU,DM1,DM3,DM4,DM5,DM6,DM7OX,DM8OX,DM9OX,DM7FU,
               DM8FU,DM9FU,II,DM2,DM22,RHOINJ
        COMMON /DUMP/ IWRT
        EQUIVALENCE (AMA(1,5),CMA(1))
9000    FORMAT(///'  OMEGA = ',1P2E13.5//3X,'I',11X,'P',19X,'RHO',
            20X,'MR',20X,'V',21X,'T'//1X,I3,1P10E11.4)
9100    FORMAT(1X,I3,1P10E11.4)
```

CHART TITLE - SUBROUTINE CHMCON(I)

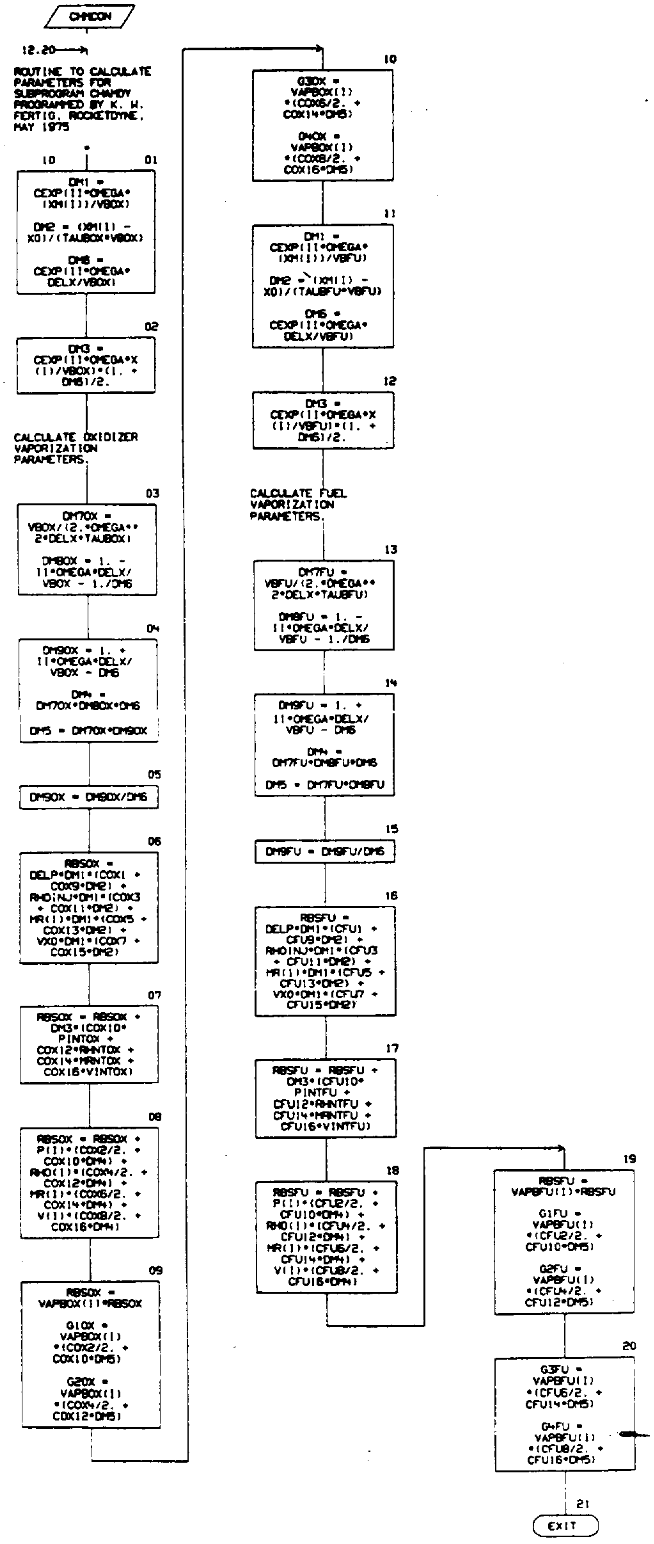
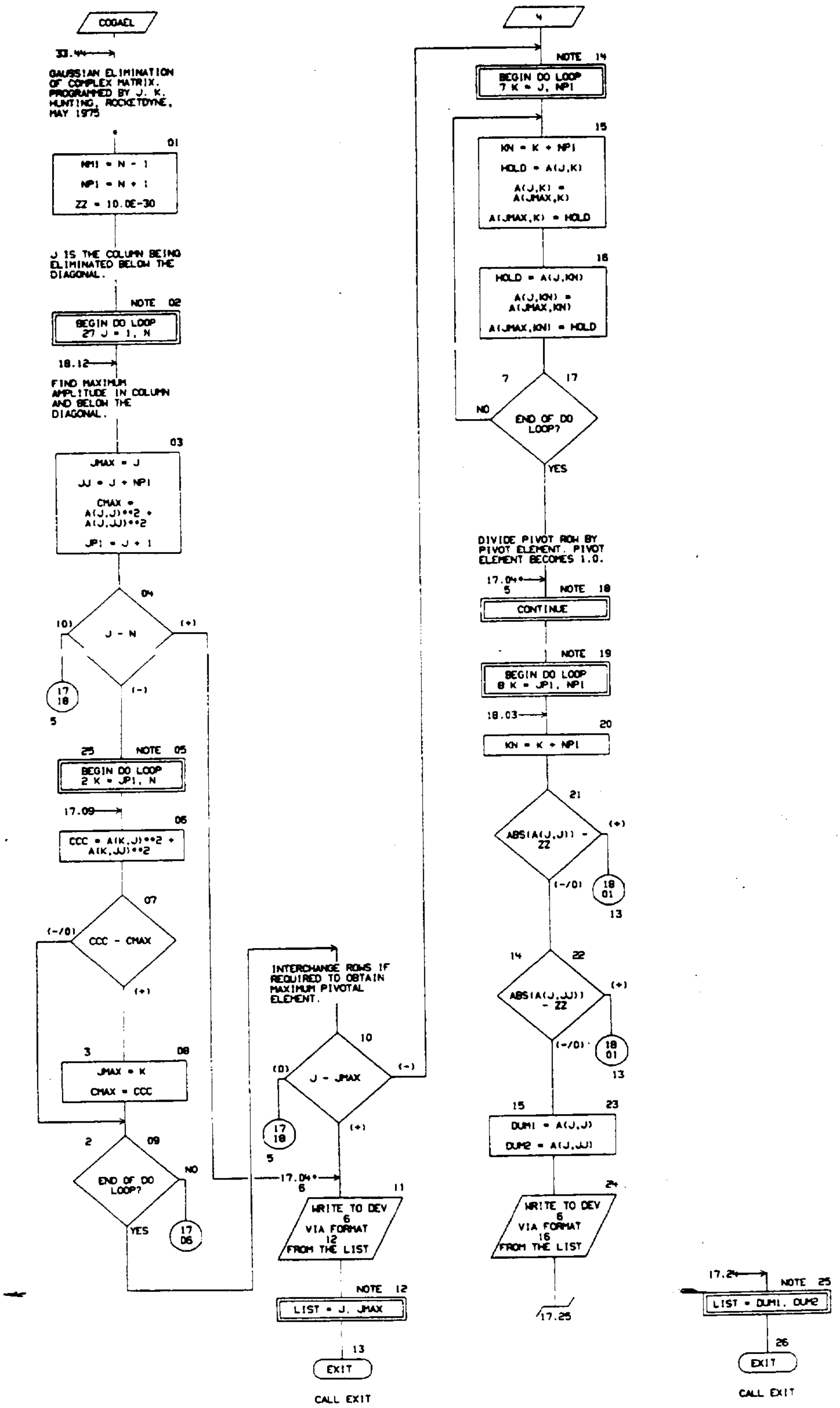
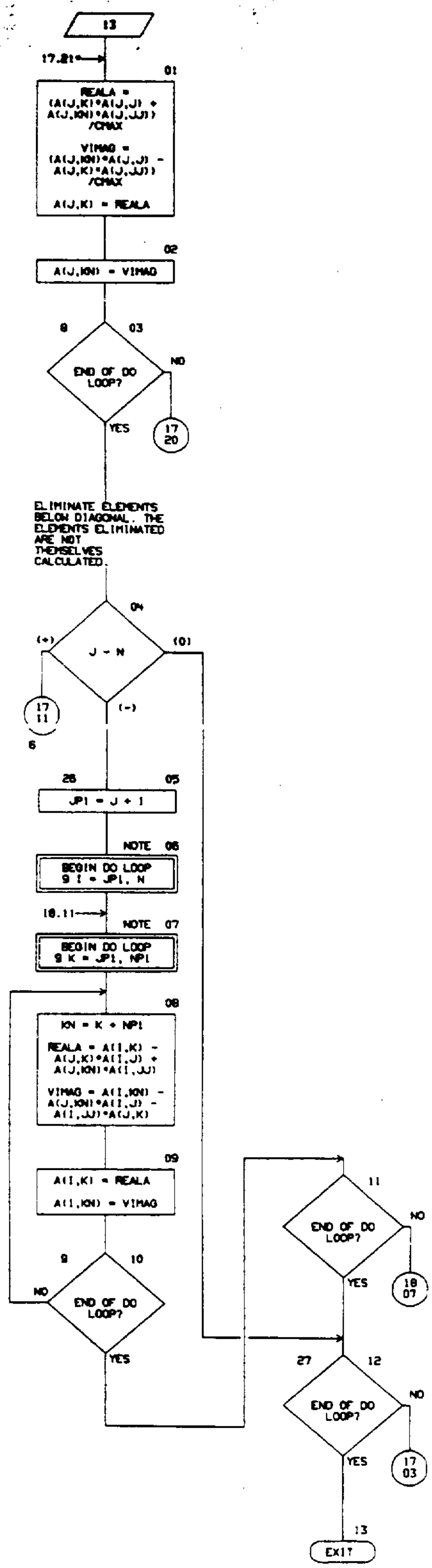


CHART TITLE - NON-PROCEDURAL STATEMENTS

```
COMPLEX OMEGA, P, RHO, V, MR, T, CNOZA, VXO,
     COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9,
     COX10, COX11, COX12, COX13, COX14, COX15, COX16,
     CFU1, CFU2, CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9,
     CFU10, CFU11, CFU12, CFU13, CFU14, CFU15, CFU16
COMPLEX DM1,  DM3, DM4, DM5, DM6, DM7OX, DM7FU, DM8OX,
     DM8FU, G1OX, G1FU, G2OX, G2FU, G3OX, G3FU, G4OX, G4FU,
     RBSOX, RBSFU, PINTOX, PINTFU, RHNTOX, RHNTFU, MRNTOX,
     MRNTFU, VINTOX, VINTFU, I1
     ,DM9OX,DM9FU
REAL  MBOXI, MBFUI, MRB, MRGI, MGI, NUBOX, NUBFU, MWG
COMMON  /COMCBM/  XKOX, XKFU, MBOXI, MBFUI, TAUBOX, TAUBFU, VBOX,
     VBFU, GAMO, RGO, DELHOX, DELHFU, PC, CO,
     COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9, COX10,
     COX11, COX12, COX13, COX14, COX15, COX16, CFU1, CFU2,
     CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9, CFU10, CFU11,
     CFU12, CFU13, CFU14, CFU15, CFU16, MWG, XIMPFU, XIMPOX,
     CS, DCSDMR, DHDMR, DRGDMR, ADVOX, ADDOX, TORAGO, DELVOX,
     NUBOX, DTOXDM, ADVFU, ADDFU, TORAGF, DELVFU, NUBFU, DTFUDM
COMMON /CONSTS/  MRB(100), TB(100), RHOB(100), VB(100),
     DMRB(100), DRHOB(100), DVB(100), VAPBOX(100), VAPBFU(100),
     SSV1(100), SSV2(100), SSV3(100), SSV4(100),
     SSV5(100), SSV6(100), SSV7(100), SSV8(100), SSV9OX(100),
     SSV9FU(100), SSV10(100), SSV11(100), SSV12(100), SSV13(100),
     SSV14(100), SSV15(100), SSV16(100),
     RHOGI, VGI, MRGI, MGI
COMMON /COMCHM/ P(100), RHO(100), V(100), MR(100), T(100),
     VXO, OMEGA, CNOZA, DELP
COMMON /COMARE/ NXP, X(100), XM(100), A(100), DA(100), DELX,
     XO, XNOZ, AINJ
COMMON /ADARND/ G1OX,G2OX,G3OX,G4OX,G1FU,G2FU,G3FU,G4FU,PINTOX,
         RHNTOX,MRNTOX,VINTOX,PINTFU,RHNTFU,MRNTFU,VINTFU,RBSOX,
         RBSFU,DM1,DM3,DM4,DM5,DM6,DM7OX,DM8OX,DM9OX,DM7FU,
         DM8FU,DM9FU,I1,DM2,DM22,RHOINJ
```

CHART TITLE - SUBROUTINE COGAEL(A,N)




13
17.21
01
REALA = (A(J,K)*A(J,J) + A(J,KN)*A(J,JJ)) /CMAX
VIMAG = (A(J,KN)*A(J,J) - A(J,K)*A(J,JJ)) /CMAX
A(J,K) = REALA
02
A(J,KN) = VIMAG
8
03
END OF DO LOOP?
NO
17 20
YES
ELIMINATE ELEMENTS BELOW DIAGONAL. THE ELEMENTS ELIMINATED ARE NOT THEMSELVES CALCULATED.
04
(+)
J - N
(0)
(-)
17 11
6
26
05
JP1 = J + 1
NOTE 06
BEGIN DO LOOP 9 I = JP1, N
18.11
NOTE 07
BEGIN DO LOOP 9 K = JP1, NP1
08
KN = K + NP1
REALA = A(I,K) - A(J,K)*A(I,J) + A(J,KN)*A(I,JJ)
VIMAG = A(I,KN) - A(J,KN)*A(I,J) - A(I,JJ)*A(J,K)
09
A(I,K) = REALA
A(I,KN) = VIMAG
9
10
NO
END OF DO LOOP?
YES
11
END OF DO LOOP?
NO
YES
18 07
27
12
END OF DO LOOP?
NO
YES
17 03
13
EXIT

```
          DIMENSION A(82,126)
12        FORMAT (61H1ERROR IN COGAEL SUBROUTINE, J AND JMAX EQUAL, RESPECTI
          VELY, ,2I12)
16        FORMAT (61H1MATRIX IS SINGULAR. EXIT FROM COGAEL. THE PIVOT ELEMEN
          TS ARE,2E14.6)
```

CHART TITLE - SUBROUTINE COMBDY(IR,FREQ,GINJOX,GINJFU,IPRCOM,INPCOM)

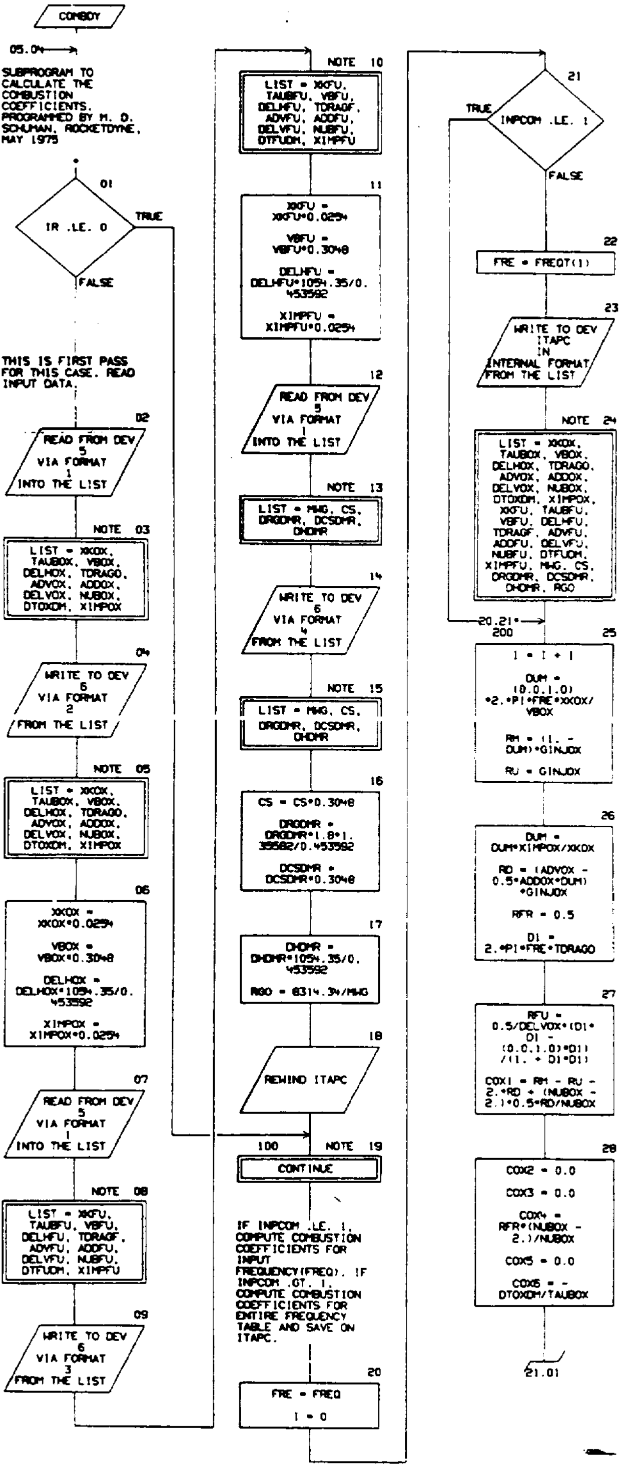


CHART TITLE - SUBROUTINE COMBOY(IR,FREQ,GINJOX,GINJFU,IPRCOM,INPCOM)

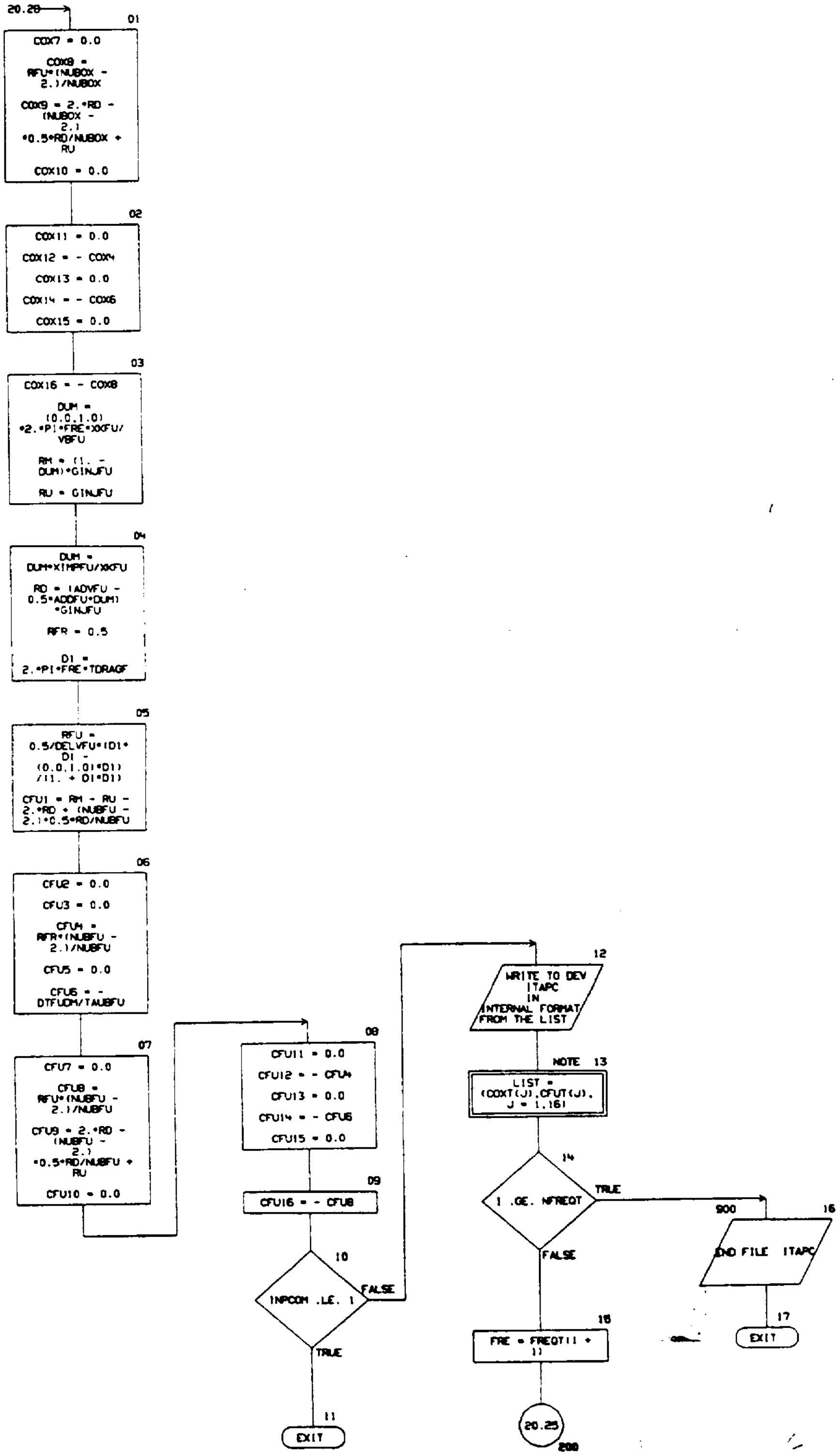
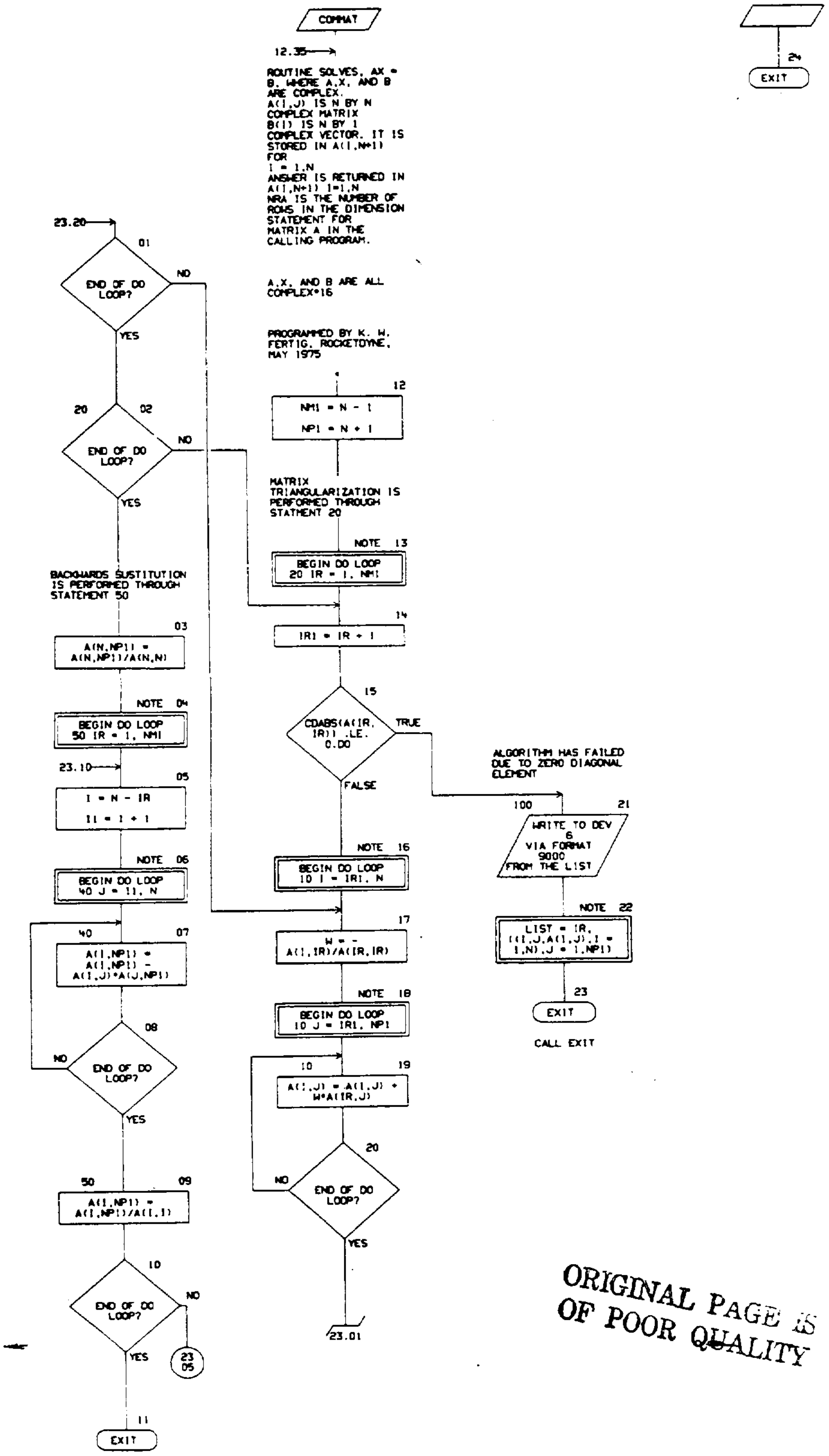


CHART TITLE - NON-PROCEDURAL STATEMENTS

```
          COMPLEX GINJOX, GINJFU, DUM, NOZAT, GINJOT, GINJFT,
               COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9,
               COX10, COX11, COX12, COX13, COX14, COX15, COX16,
               CFU1, CFU2, CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9,
               CFU10, CFU11, CFU12, CFU13, CFU14, CFU15, CFU16,
               COXT(16), CFUT(16), RM, RU, RO, RFU
          REAL  MBOX1, MBFU1, MWG, NUBOX, NUBFU
          COMMON /COMTAP/  NFREQT, FREQT(100), NOZAT(100), GINJOT(100),
               GINJFT(100), ITAPN, ITAPC, ITAPH
          COMMON  /COMCBM/  XKOX, XKFU, MBOX1, MBFU1, TAUBOX, TAUBFU, VBOX,
               VBFU, GAMO, RGO, DELHOX, DELHFU, PC, CO,
               COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9, COX10,
               COX11, COX12, COX13, COX14, COX15, COX16, CFU1, CFU2,
               CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9, CFU10, CFU11,
               CFU12, CFU13, CFU14, CFU15, CFU16, MWG, XIMPFU, XIMPOX,
               CS, DCSDMR, DHOMR, DRGOMR, ADVOX, ADDOX, TDRAGO, DELVOX,
               NUBOX, DTOXOM, ADVFU, ADDFU, TDRAGF, DELVFU, NUBFU, DTFUOM
          EQUIVALENCE (COXT(1),COX1), (CFUT(1),CFU1)
          DATA PI/3.14159/
1         FORMAT(8E12.8)
2         FORMAT(/5X,'XKOX =',1PE11.4,5X,'TAUBOX =',
               E11.4,3X,'VBOX =',E11.4,5X,'DELHOX =',E11.4,/,27X,
               'TDRAGO =',E11.4,3X,'ADVOX =',E11.4,//,5X,'ADDOX =',E11.4,
               4X,'DELVOX =',E11.4,3X,'NUBOX =',E11.4,4X,'DTOXOM =',
               E11.4,/,27X,'XIMPOX =',E11.4)
3         FORMAT(/,5X,'XKFU =',1PE11.4,5X,'TAUBFU =',
               E11.4,3X,'VBFU =',E11.4,5X,'DELHFU =',E11.4,/,27X,
               'TDRAGF =',E11.4,3X,'ADVFU =',E11.4,//,5X,'ADDFU =',E11.4,
               4X,'DELVFU =',E11.4,3X,'NUBFU =',E11.4,4X,'DTFUOM =',
               E11.4,/,27X,'XIMPFU =',E11.4)
4         FORMAT(/,5X,'MWG =',1PE11.4,6X,'CS =',E11.4,
               7X,'DRGOMR =',E11.4,3X,'DCSDMR =',E11.4,/,27X,'DHOMR =',
               E11.4)
```

CHART TITLE - SUBROUTINE COMMAT(A,NRA,N)



```
              COMPLEX*16 A(NRA,1),W
 9000         FORMAT(// '  ***** DIVIDE CHECK IN COMMAT *****'/
                 '      IR = ',I10/'   MATRIX A(I,J) = '/
                 (5X,2I6,1PE15.6,' ,',1PE13.6))
```

CHART TITLE - SUBROUTINE FRESP(ICRT,IWRITE,IX)

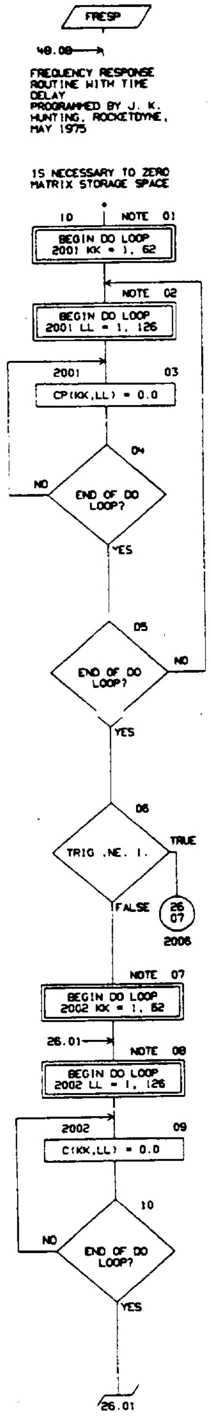


CHART TITLE - SUBROUTINE FRESP(ICRT,IWRITE,IX)

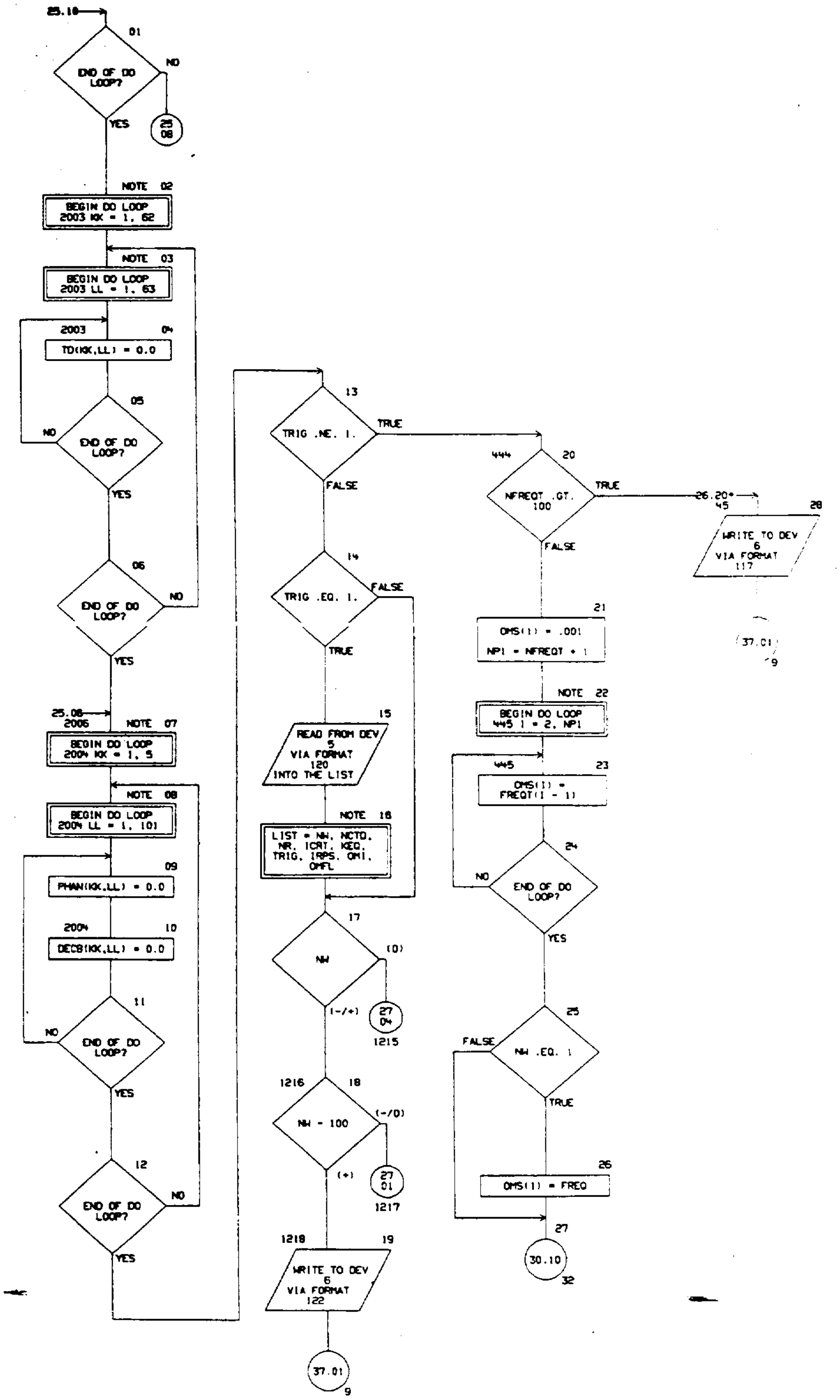


CHART TITLE - SUBROUTINE FRESP(ICRT,IWRITE,IX)

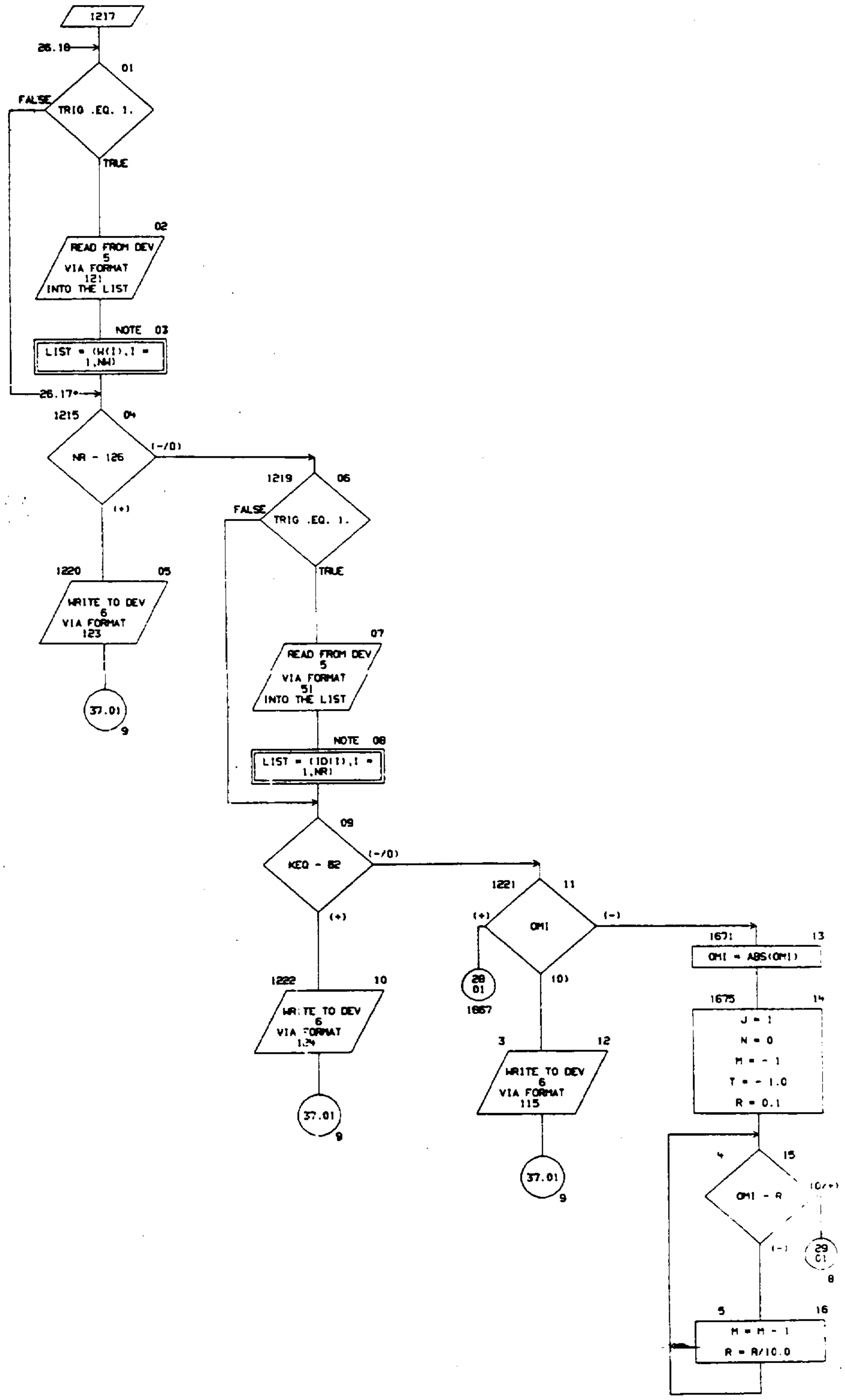


CHART TITLE - SUBROUTINE FRESP(ICRT,IWRITE,IX)

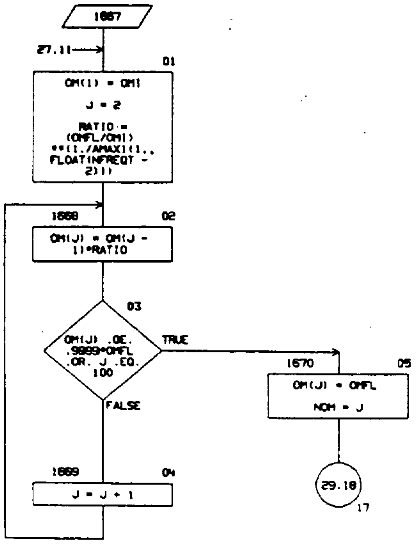


CHART TITLE - SUBROUTINE FRESP(ICRT,IWRITE,IX)

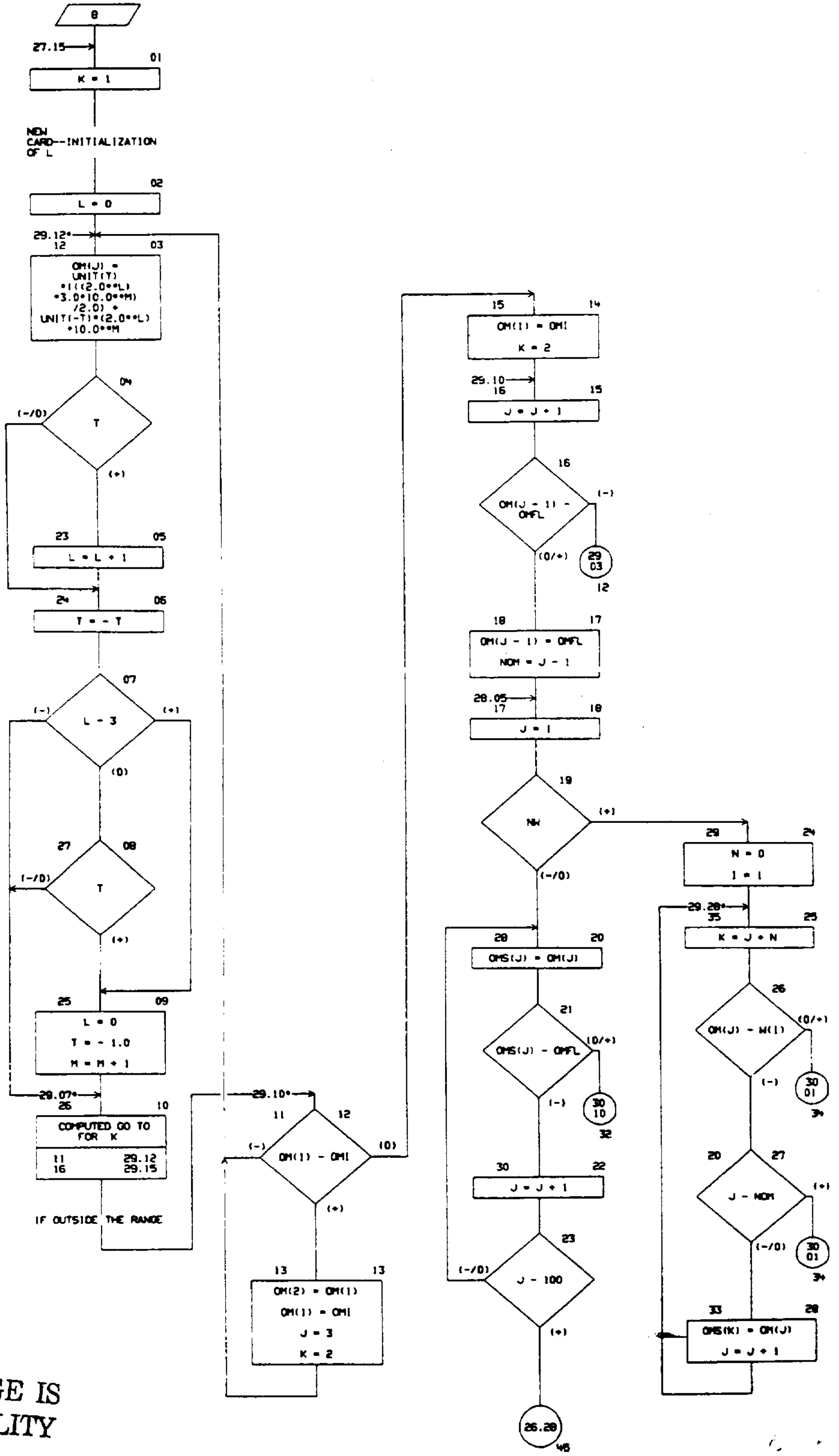


CHART TITLE - SUBROUTINE FRESP(ICRT,IWRITE,IX)

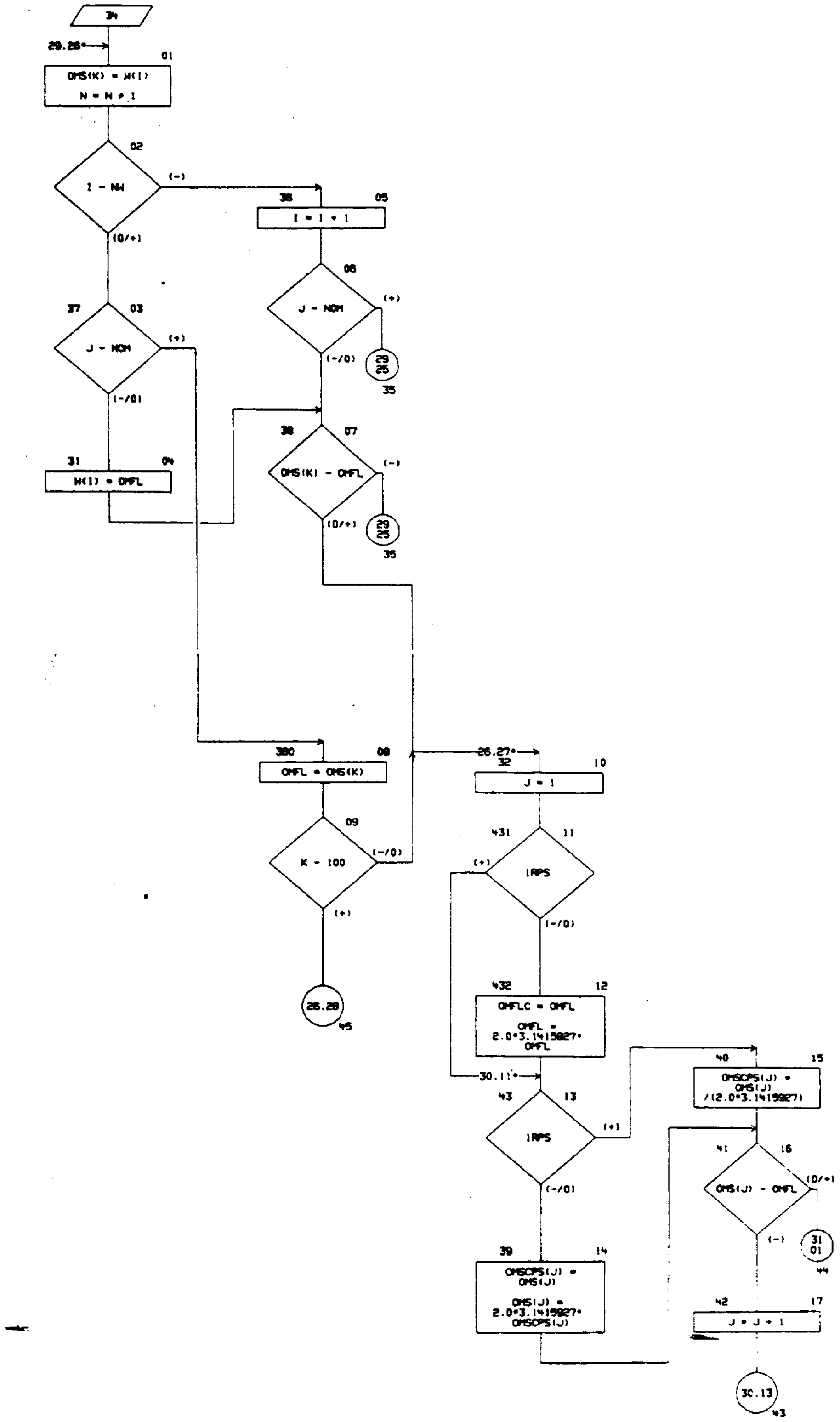


CHART TITLE - SUBROUTINE FRESP(ICRT,IWRITE,IX)

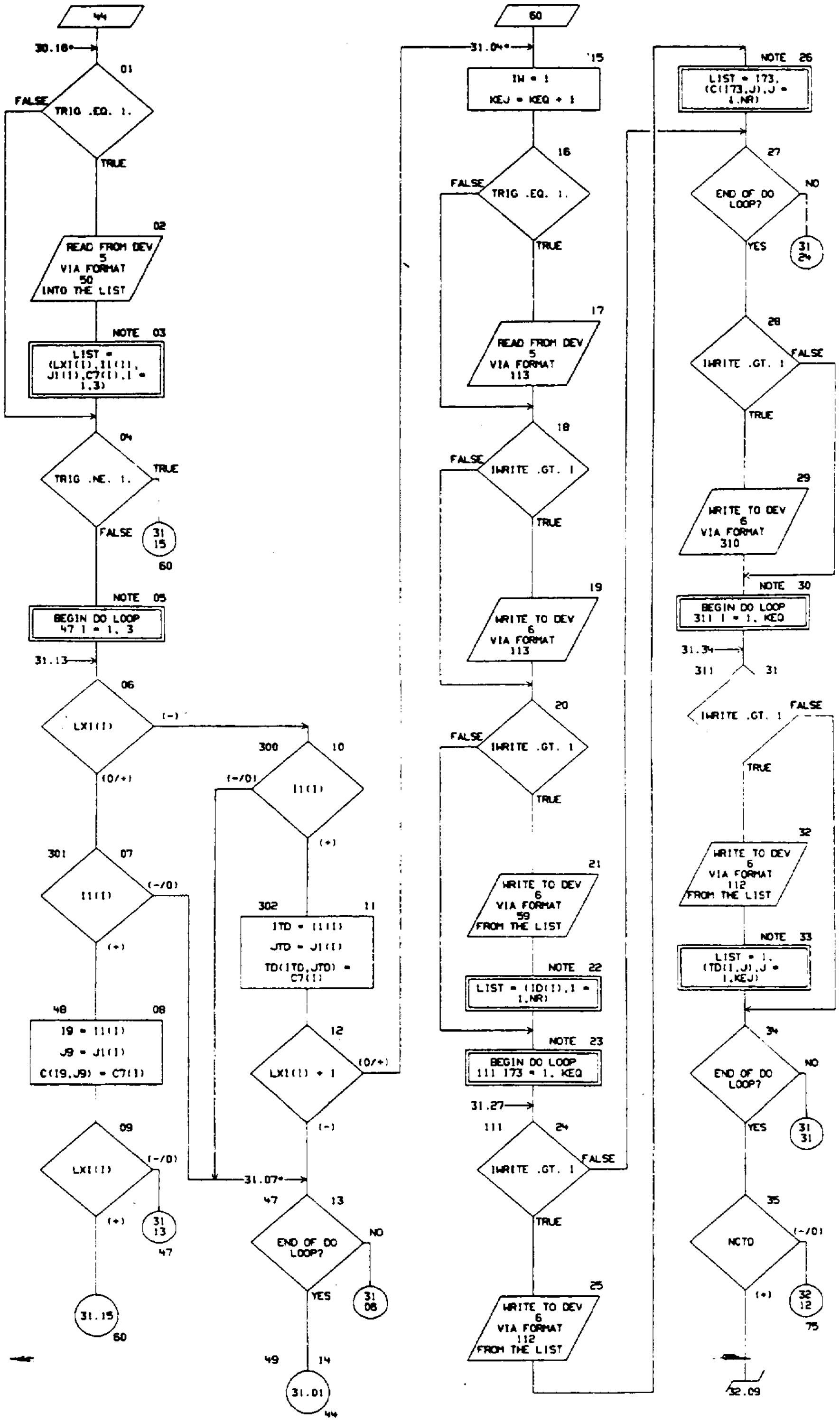


CHART TITLE - SUBROUTINE FRESP(ICRT,IWRITE,IX)

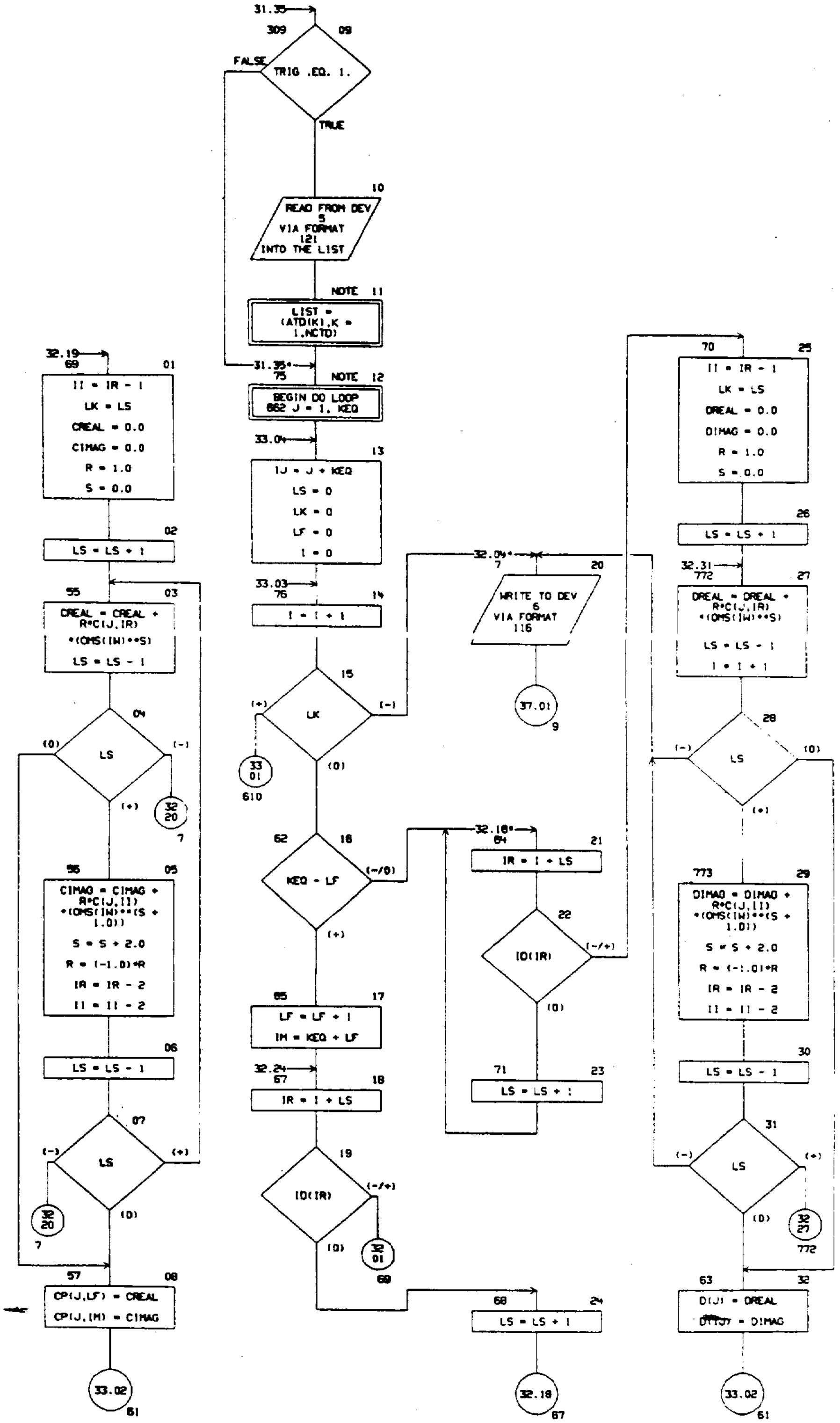


CHART TITLE - SUBROUTINE FRESP(ICRT,IWRITE,IX)

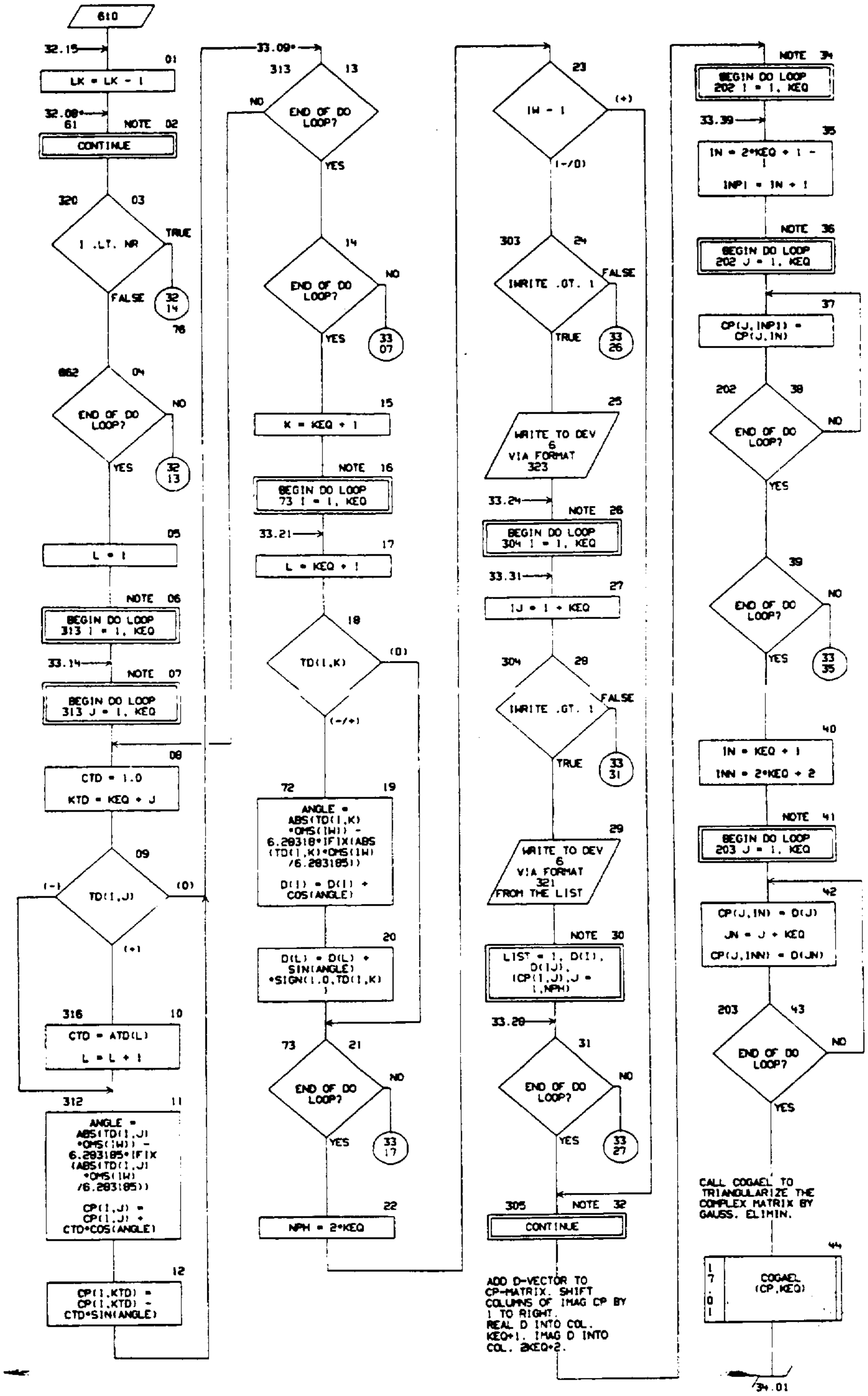


CHART TITLE - SUBROUTINE FRESP(ICRT,IWRITE,IX)

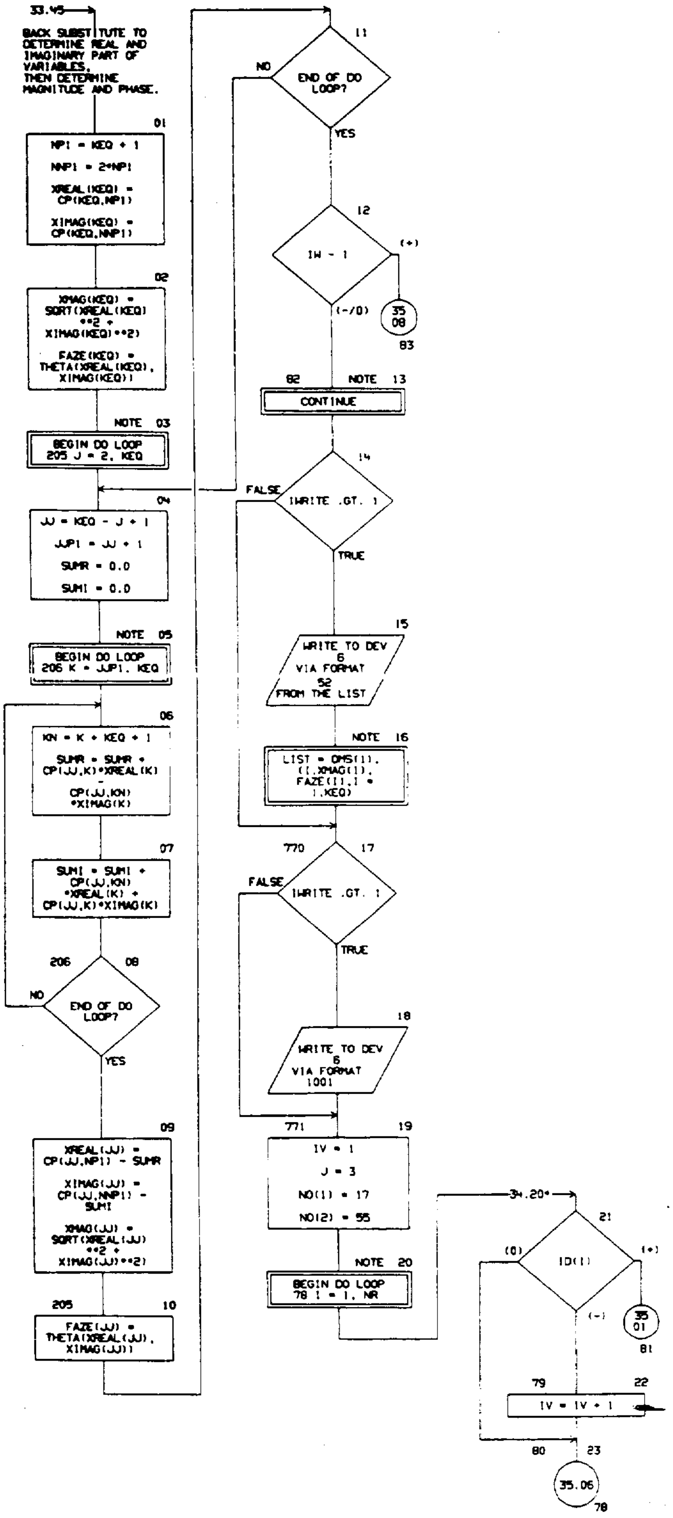


CHART TITLE - SUBROUTINE FRESP(ICRT,IWRITE,IX)

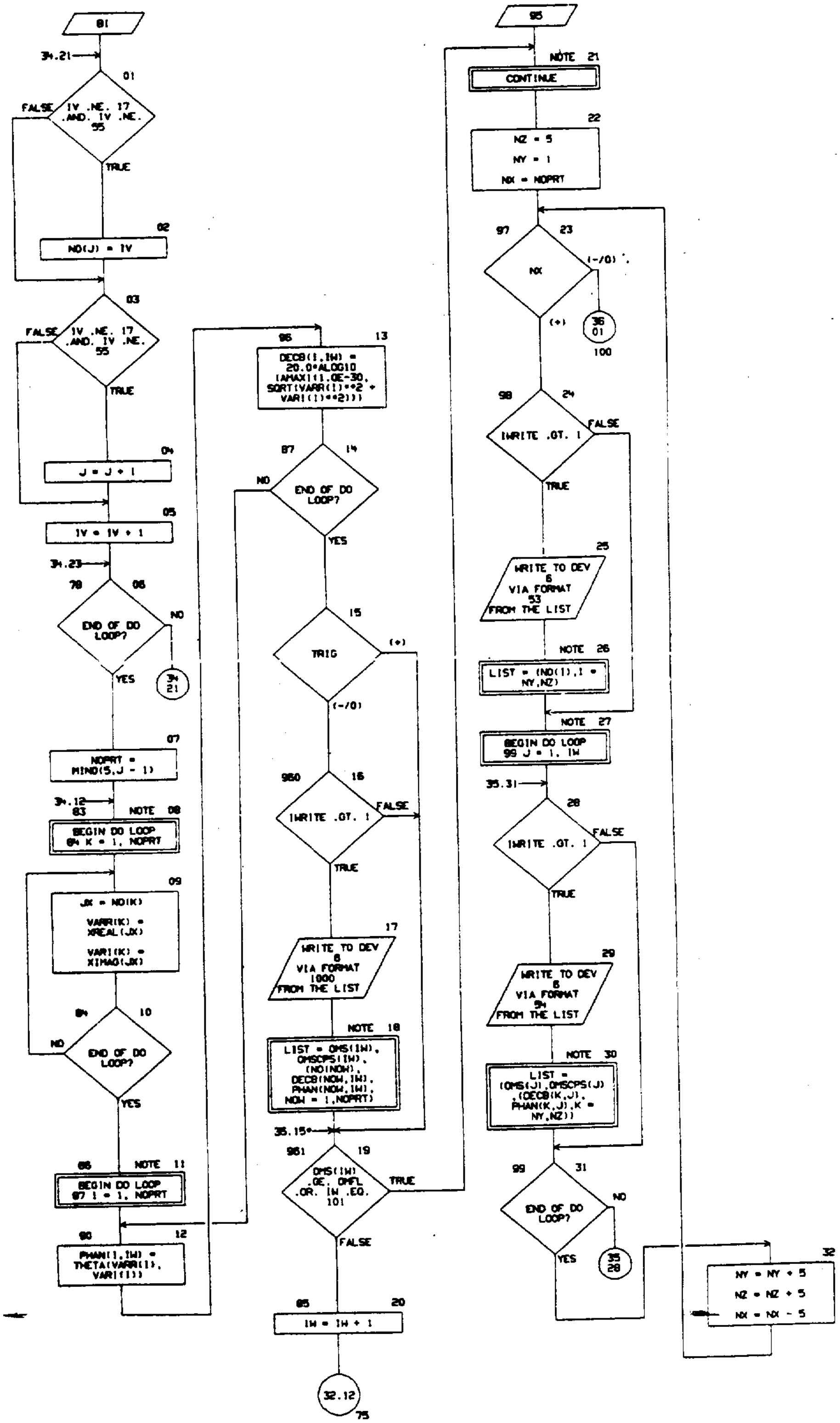


CHART TITLE - SUBROUTINE FRESP(ICRT,IWRITE,IX)

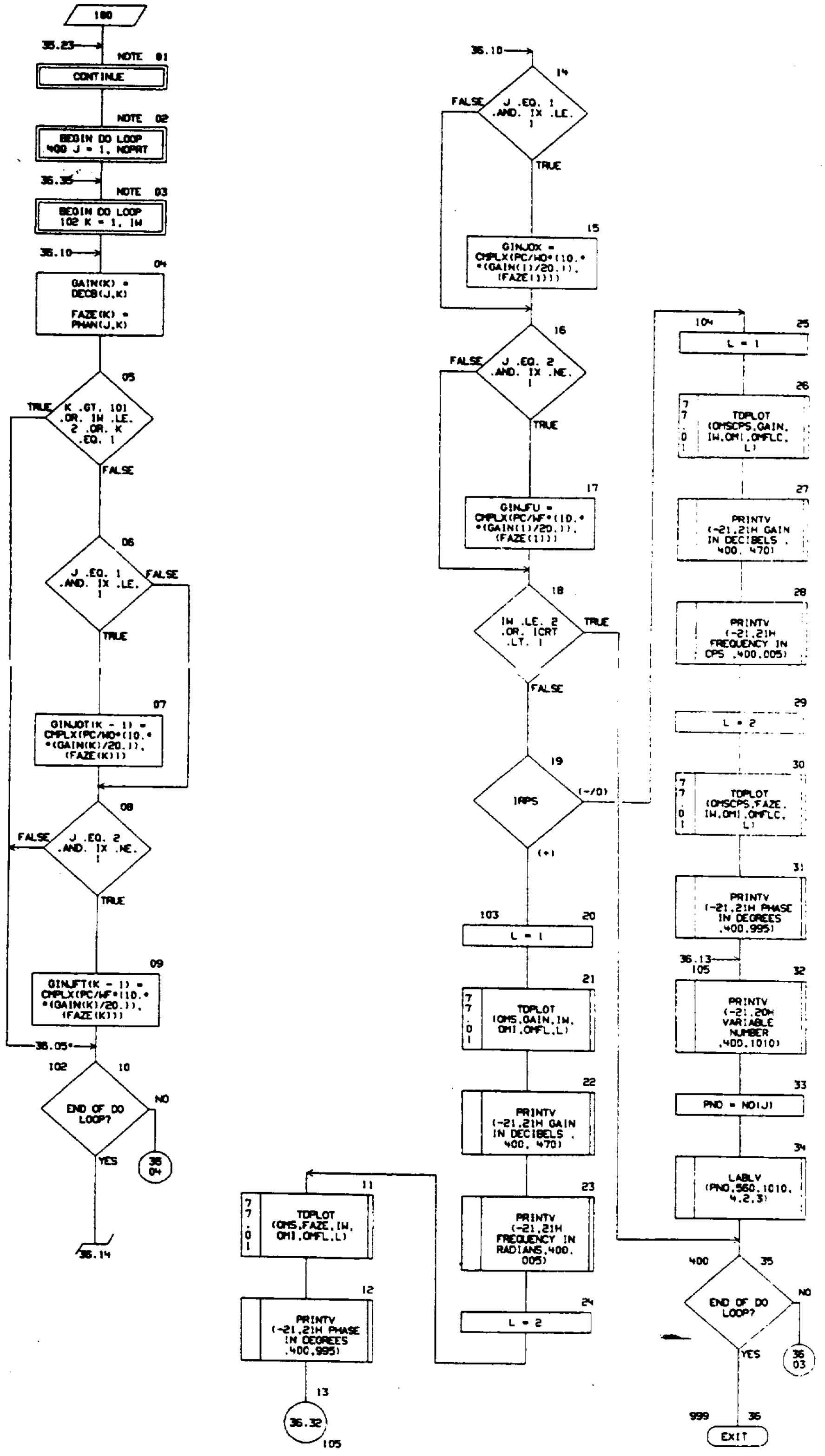
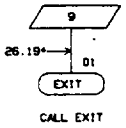
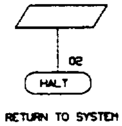


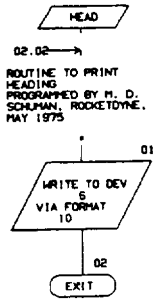
CHART TITLE - SUBROUTINE FRESP(ICRT,IWRITE,IX)





```
        DIMENSION OM(101),OMSCPS(101),W(101),OMS(101),IO(126),CP(62,126)
        DIMENSION LXI(3),II(3),JI(3),C7(3),C(62,126),TD(62,63),D(126)
        DIMENSION XMAG(62),NO(62),XREAL(62),XIMAG(62),GAIN(101),FAZE(101)
        DIMENSION VARR(62),VARI(62),PHAN(5,101),DECB(5,101)
        DIMENSION ATD(126),IOF(18)
        COMMON/F/NH,NCTD,NR,NEQ,TRIG,IRPS,OM1,OMFL,W,ID,C,TD,ATD,
        FREQ,GINJOX,GINJFU,PC,WO,WF
        COMPLEX   NOZAT(100),GINJOT(100),GINJFT(100),GINJOX,GINJFU
        COMMON/COMTAP/NFREQT,FREQT(100),NOZAT,GINJOT,GINJFT,ITAPN,ITAPC,
        ITAPH
        STATEMENT FUNCTION DEFINITION,  DELTA(Q001FL) =1.0 -ABS(Q001FL)/AMAX1(ABS(Q001FL),.14693679E-38)
        STATEMENT FUNCTION DEFINITION,  UNIT(Q002FL) =0.5 + SIGN( 0.5,DELTA(Q002FL) +
        02FL)))
        STATEMENT FUNCTION DEFINITION,  THETA(Q003FL,Q004FL)
        L)))+ SIGN(1.0,Q003FL*Q004FL)*  ATAN(((ABS(Q004FL)*(1.0-DELTA(Q003
        FL))))/(ABS(Q003FL)+DELTA(Q003FL)))*(180.0/3.141593)) * (1.0-DELTA
        (Q003FL))+ 180.0*DELTA(Q003FL)*(1.0-DELTA(Q004FL))*(.5 +UNIT(-Q004
        FL))
120     FORMAT((I2,I3,I9,I3,I9,F2.0,I10,2F12.0)
122     FORMAT(48H-NUMBER OF SHUFFLED IN FREQUENCIES EXCEEDS 100)
121     FORMAT(6F12.0)
123     FORMAT(30H-NUMBER OF COLUMNS EXCEEDS 126)
51      FORMAT(6I12)
124     FORMAT(31H-NUMBER OF EQUATIONS EXCEEDS 62)
115     FORMAT(26H INITIAL FREQUENCY IS ZERO)
117     FORMAT(38H1THE NUMBER OF FREQUENCIES EXCEEDS 100)
50      FORMAT(3(I2,I4,I6,F12.0))
113     FORMAT(72H1
                          )
59      FORMAT(18H    I.D. VECTOR   /(1H0,24I4))
112     FORMAT(13H0   EQUATION  ,I3  /(4H0     ,1P7E14.6))
310     FORMAT(27H1MATRIX OF TIME DELAY TERMS)
116     FORMAT(24H LS HAS A NEGATIVE VALUE)
52      FORMAT(67H1                          VARIABLE MAGNITUDES USING A FRE
        QUENCY OF     ,1PE14.6,5H RPS./  1H0 ,84H                    VARIAB
        LE NUMBER            MAGNITUDE                           PHASE /(1H0 ,
        I27,1P2E30.6))
1001    FORMAT(70 H1 THESE ARE INTERMEDIATE RESULTS PRODUCED AFTER EACH MA
        TRIX INVERSION./53H0INPUT FREQUENCY IN RADIANS/SECOND AND CYCLES/S
        ECOND./59H0       VARIABLE,GAIN(DB),PHASE(DEGREES)       VARIABLE,E
        TC. )
323     FORMAT(37H1INITIAL VALUES OF COEFFICIENT MATRIX)
321     FORMAT(//I3,5X,1P2E20.6/(4H0   ,1P7E14.6))
1000    FORMAT(//F20.4,F20.5//(I4,F8.2,F7.1,I4,F8.2,F7.1,I4,F8.2,F7.1,I4,F
        8.2,F7.1,I4,F8.2,F7.1))
53      FORMAT(21H1      FREQUENCY      ,5(13H   VARIABLE  ,I2,3H   )/21H0
          RPS      CPS     ,5(18H  DECIBELS  PHASE )/)
54      FORMAT(1P2E10.2,5(2H /, 0P2F8.2))
```

CHART TITLE - SUBROUTINE HEAD



```
10      FORMAT(1H1,/////,43X,'ANALYTICAL  DESCRIPTION',//,
         44X,'FEED  SYSTEM  COUPLED',//,47X,'STABILITY  MODEL',//////,
         47X,'COMPUTER  MODEL',///,25X,'PROGRAM NAME,    FSCSM,  FIV VER',
         'SION,   MAY 1975',///,25X,'DEVELOPED BY,    M. D. SCHUMAN,',
         ' J. K. HUNTING, AND K. W. FERTIG',/,42X,'ADVANCED PROGRAMS,',
         ' ROCKETDYNE',/,42X,'DIVISION OF ROCKWELL INTERNATIONAL',/,
         42X,'CANOGA PARK, CALIF  91304',///,
         25X,'SPONSERED BY,    NASA/LYNDON B. JOHNSON SPACE CENTER',/,
         42X,'HOUSTON, TEXAS  77058',/,42X,'UNDER CONTRACT NAS9-14315')
```

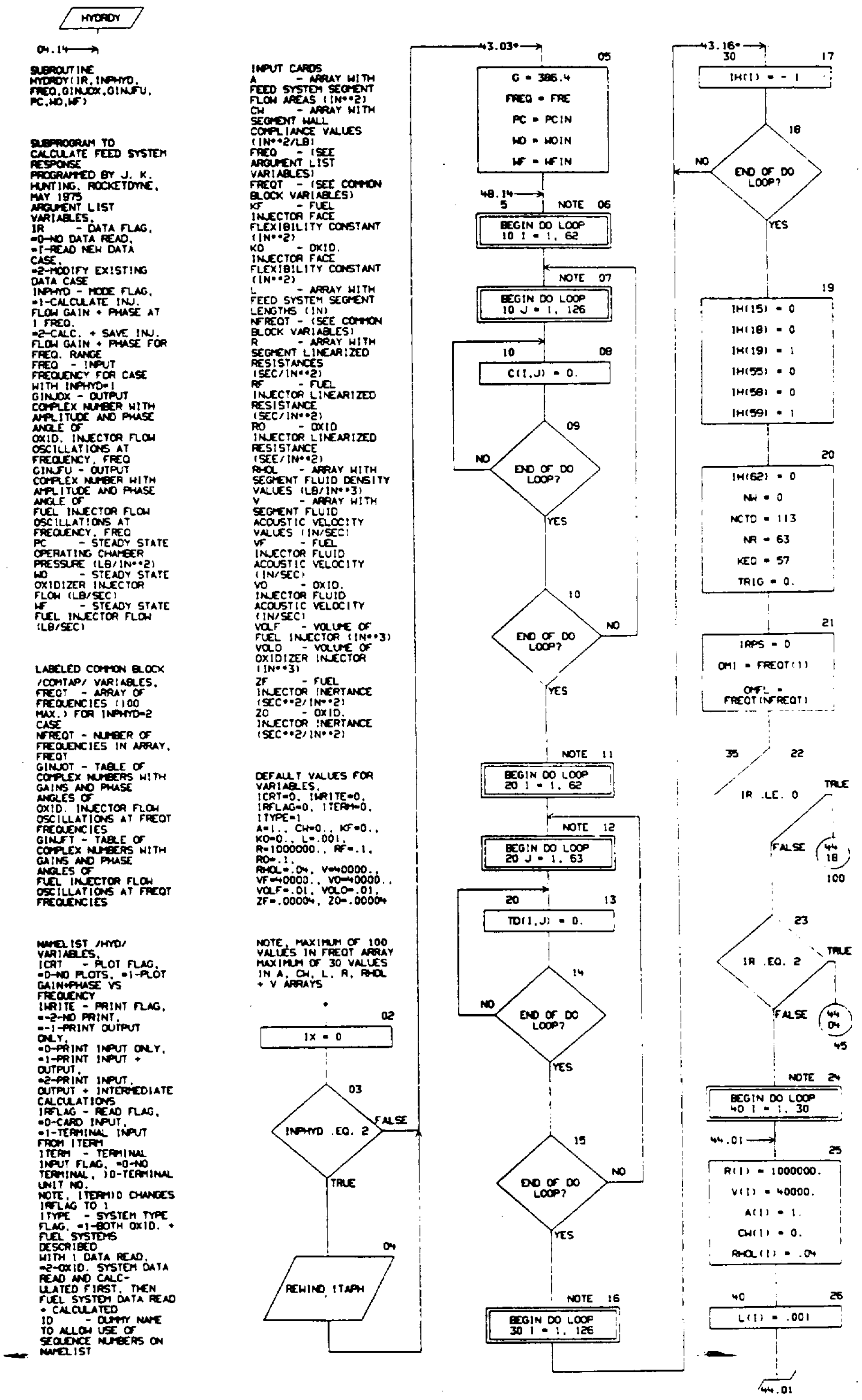
C-3

CHART TITLE - BLOCK DATA

CHART TITLE - NON-PROCEDURAL STATEMENTS

```
COMMON/HY/ICRT,IRFLAG,ITERM,ITYPE,IWRITE,IX,A,CW,KF,KO,L,R,RHOL,V,
VF,VO,VOLF,VOLO,ZF,ZO,OSAVE(100),FSAVE(100)
REAL   A(30),CW(30),KF,KO,L(30),R(30),RHOL(30),V(30)
DATA ICRT/0/,IRFLAG/0/,ITERM/0/,ITYPE/1/,IWRITE/0/
```

CHART TITLE - SUBROUTINE HYDRDY(IR,INPHYD,FRE,GINO,GINF,PCIN,WOIN,WFIN)



```
SUBROUTINE
HYDRDY(IR,INPHYD,
FREQ,GINJOX,GINJFU,
PC,WO,WF)

SUBPROGRAM TO
CALCULATE FEED SYSTEM
RESPONSE
PROGRAMMED BY J. K.
HUNTING, ROCKETDYNE,
MAY 1975
ARGUMENT LIST
VARIABLES,
IR      - DATA FLAG,
=0-NO DATA READ,
=1-READ NEW DATA
CASE,
=2-MODIFY EXISTING
DATA CASE
INPHYD - MODE FLAG,
=1-CALCULATE INJ.
FLOW GAIN + PHASE AT
1 FREQ.
=2-CALC. + SAVE INJ.
FLOW GAIN + PHASE FOR
FREQ. RANGE
FREQ  - INPUT
FREQUENCY FOR CASE
WITH INPHYD=1
GINJOX - OUTPUT
COMPLEX NUMBER WITH
AMPLITUDE AND PHASE
ANGLE OF
OXID. INJECTOR FLOW
OSCILLATIONS AT
FREQUENCY, FREQ
GINJFU - OUTPUT
COMPLEX NUMBER WITH
AMPLITUDE AND PHASE
ANGLE OF
FUEL INJECTOR FLOW
OSCILLATIONS AT
FREQUENCY, FREQ
PC      - STEADY STATE
OPERATING CHAMBER
PRESSURE (LB/IN**2)
WO      - STEADY STATE
OXIDIZER INJECTOR
FLOW (LB/SEC)
WF      - STEADY STATE
FUEL INJECTOR FLOW
(LB/SEC)

LABELED COMMON BLOCK
/COMTAP/ VARIABLES,
FREQT  - ARRAY OF
FREQUENCIES (100
MAX.) FOR INPHYD=2
CASE
NFREQT - NUMBER OF
FREQUENCIES IN ARRAY,
FREQT
GINJOT - TABLE OF
COMPLEX NUMBERS WITH
GAINS AND PHASE
ANGLES OF
OXID. INJECTOR FLOW
OSCILLATIONS AT FREQT
FREQUENCIES
GINJFT - TABLE OF
COMPLEX NUMBERS WITH
GAINS AND PHASE
ANGLES OF
FUEL INJECTOR FLOW
OSCILLATIONS AT FREQT
FREQUENCIES

NAMELIST /HYD/
VARIABLES,
ICRT    - PLOT FLAG,
=0-NO PLOTS, =1-PLOT
GAIN+PHASE VS
FREQUENCY
IWRITE - PRINT FLAG,
=-2-NO PRINT,
=-1-PRINT OUTPUT
ONLY,
=0-PRINT INPUT ONLY,
=1-PRINT INPUT +
OUTPUT,
=2-PRINT INPUT,
OUTPUT + INTERMEDIATE
CALCULATIONS
IRFLAG - READ FLAG,
=0-CARD INPUT,
=1-TERMINAL INPUT
FROM ITERM
ITERM   - TERMINAL
INPUT FLAG, =0-NO
TERMINAL, )0-TERMINAL
UNIT NO.
NOTE, ITERM)0 CHANGES
IRFLAG TO 1
ITYPE   - SYSTEM TYPE
FLAG, =1-BOTH OXID. +
FUEL SYSTEMS
DESCRIBED
WITH 1 DATA READ,
=2-OXID. SYSTEM DATA
READ AND CALC-
ULATED FIRST, THEN
FUEL SYSTEM DATA READ
+ CALCULATED
ID      - DUMMY NAME
TO ALLOW USE OF
SEQUENCE NUMBERS ON
NAMELIST
```

```
INPUT CARDS
A       - ARRAY WITH
FEED SYSTEM SEGMENT
FLOW AREAS (IN**2)
CW      - ARRAY WITH
SEGMENT WALL
COMPLIANCE VALUES
(IN**2/LB)
FREQ    - (SEE
ARGUMENT LIST
VARIABLES)
FREQT   - (SEE COMMON
BLOCK VARIABLES)
KF      - FUEL
INJECTOR FACE
FLEXIBILITY CONSTANT
(IN**2)
KO      - OXID.
INJECTOR FACE
FLEXIBILITY CONSTANT
(IN**2)
L       - ARRAY WITH
FEED SYSTEM SEGMENT
LENGTHS (IN)
NFREQT - (SEE COMMON
BLOCK VARIABLES)
R       - ARRAY WITH
SEGMENT LINEARIZED
RESISTANCES
(SEC/IN**2)
RF      - FUEL
INJECTOR LINEARIZED
RESISTANCE
(SEC/IN**2)
RO      - OXID
INJECTOR LINEARIZED
RESISTANCE
(SEE/IN**2)
RHOL    - ARRAY WITH
SEGMENT FLUID DENSITY
VALUES (LB/IN**3)
V       - ARRAY WITH
SEGMENT FLUID
ACOUSTIC VELOCITY
VALUES (IN/SEC)
VF      - FUEL
INJECTOR FLUID
ACOUSTIC VELOCITY
(IN/SEC)
VO      - OXID.
INJECTOR FLUID
ACOUSTIC VELOCITY
(IN/SEC)
VOLF    - VOLUME OF
FUEL INJECTOR (IN**3)
VOLO    - VOLUME OF
OXIDIZER INJECTOR
(IN**3)
ZF      - FUEL
INJECTOR INERTANCE
(SEC**2/IN**2)
ZO      - OXID.
INJECTOR INERTANCE
(SEC**2/IN**2)

DEFAULT VALUES FOR
VARIABLES,
ICRT=0, IWRITE=0,
IRFLAG=0, ITERM=0,
ITYPE=1
A=1., CW=0., KF=0.,
KO=0., L=.001,
R=1000000., RF=.1,
RO=.1,
RHOL=.04, V=40000.,
VF=40000., VO=40000.,
VOLF=.01, VOLO=.01,
ZF=.00004, ZO=.00004

NOTE, MAXIMUM OF 100
VALUES IN FREQT ARRAY
MAXIMUM OF 30 VALUES
IN A, CW, L, R, RHOL
+ V ARRAYS
```

CHART TITLE - SUBROUTINE HYDRDY(IR,INPHYD,FRE,GINO,GINF,PCIN,WOIN,WFIN)

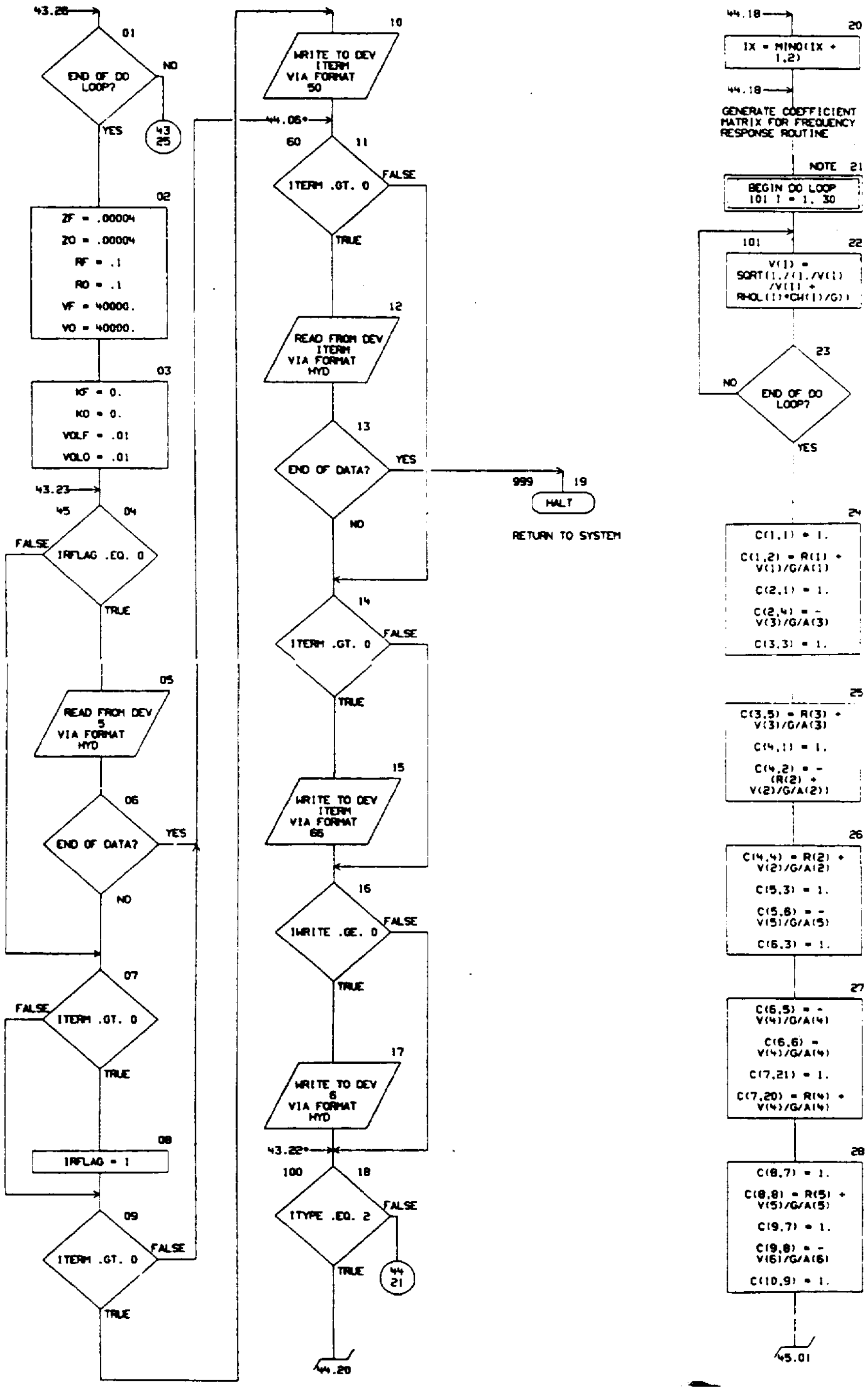


CHART TITLE - SUBROUTINE HYDRDY(IR,INPHYD,FRE,GINO,GINF,PCIN,WOIN,WFIN)

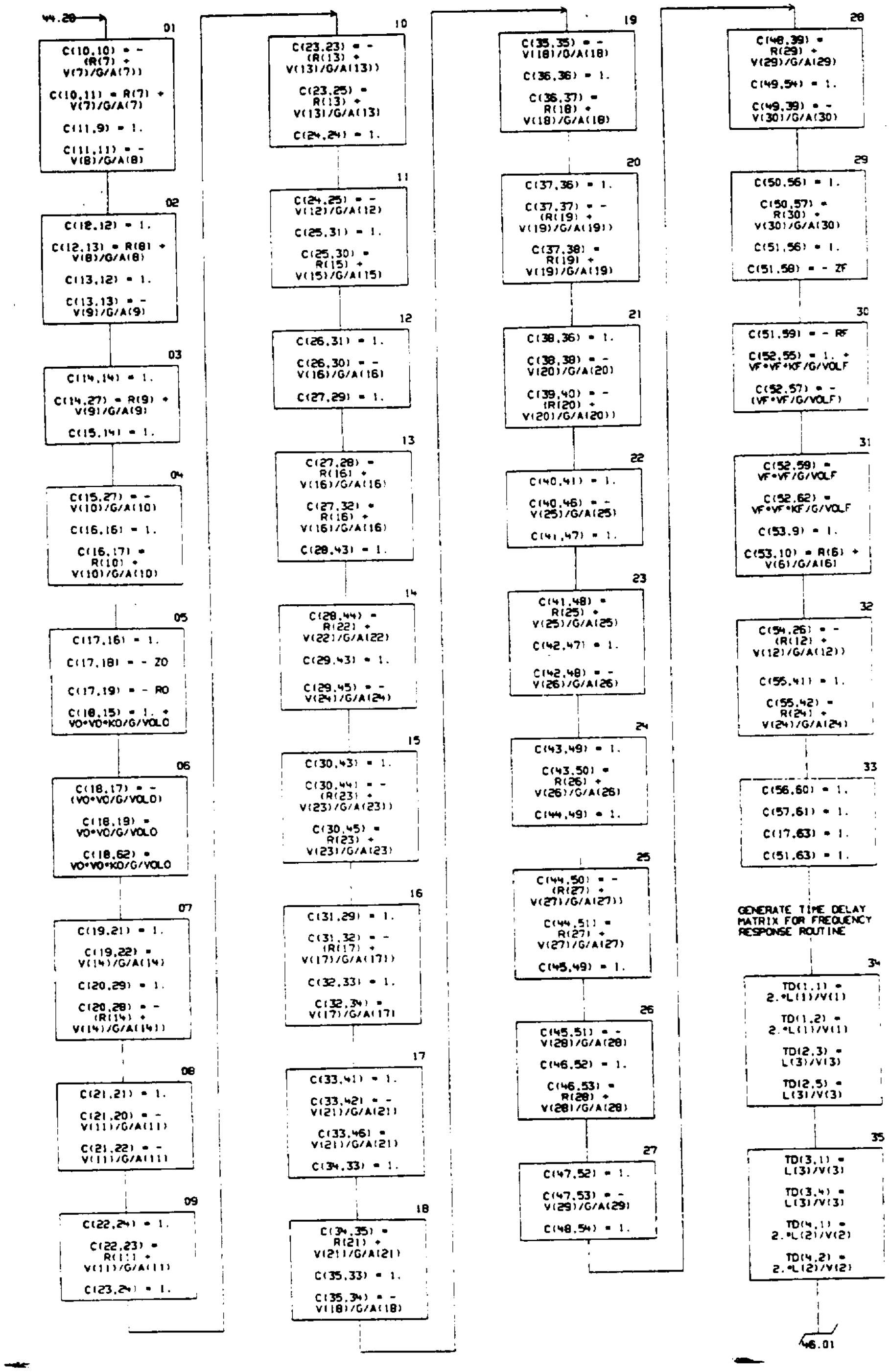


CHART TITLE - SUBROUTINE HYDRDY(IR,INPHYD,FRE,GINO,GINF,PCIN,WOIN,WFIN)

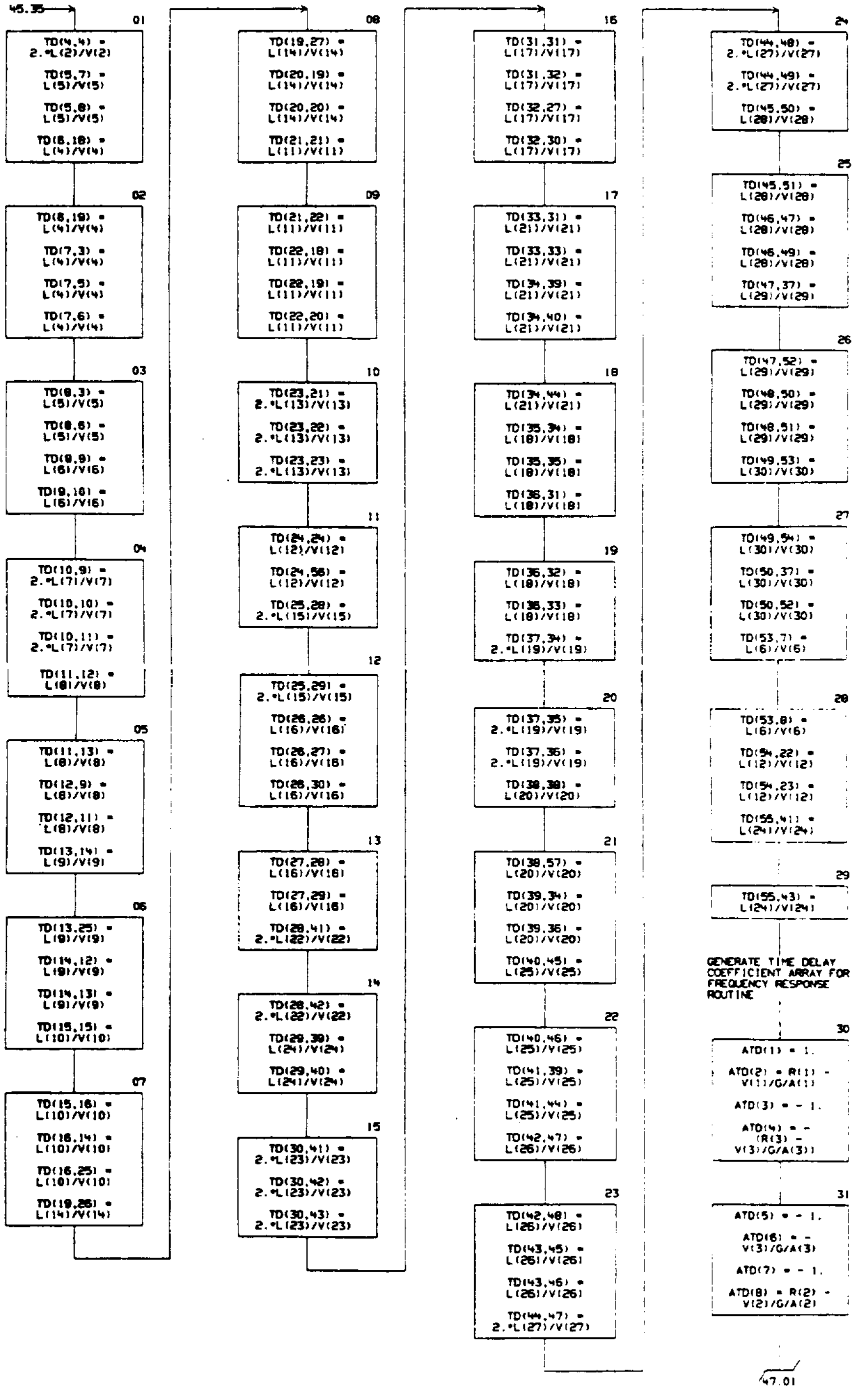


CHART TITLE - SUBROUTINE HYDROY(IR,INPHYD,FRE,GINO,GINF,PCIN,WOIN,WFIN)

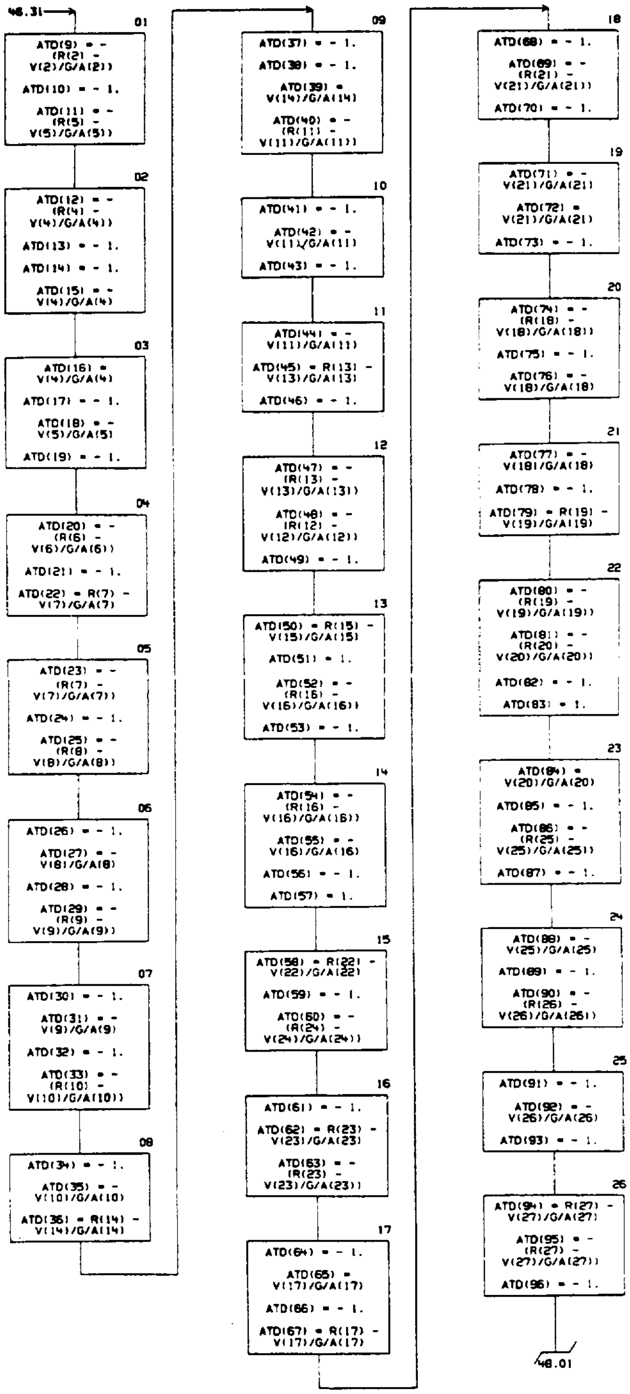
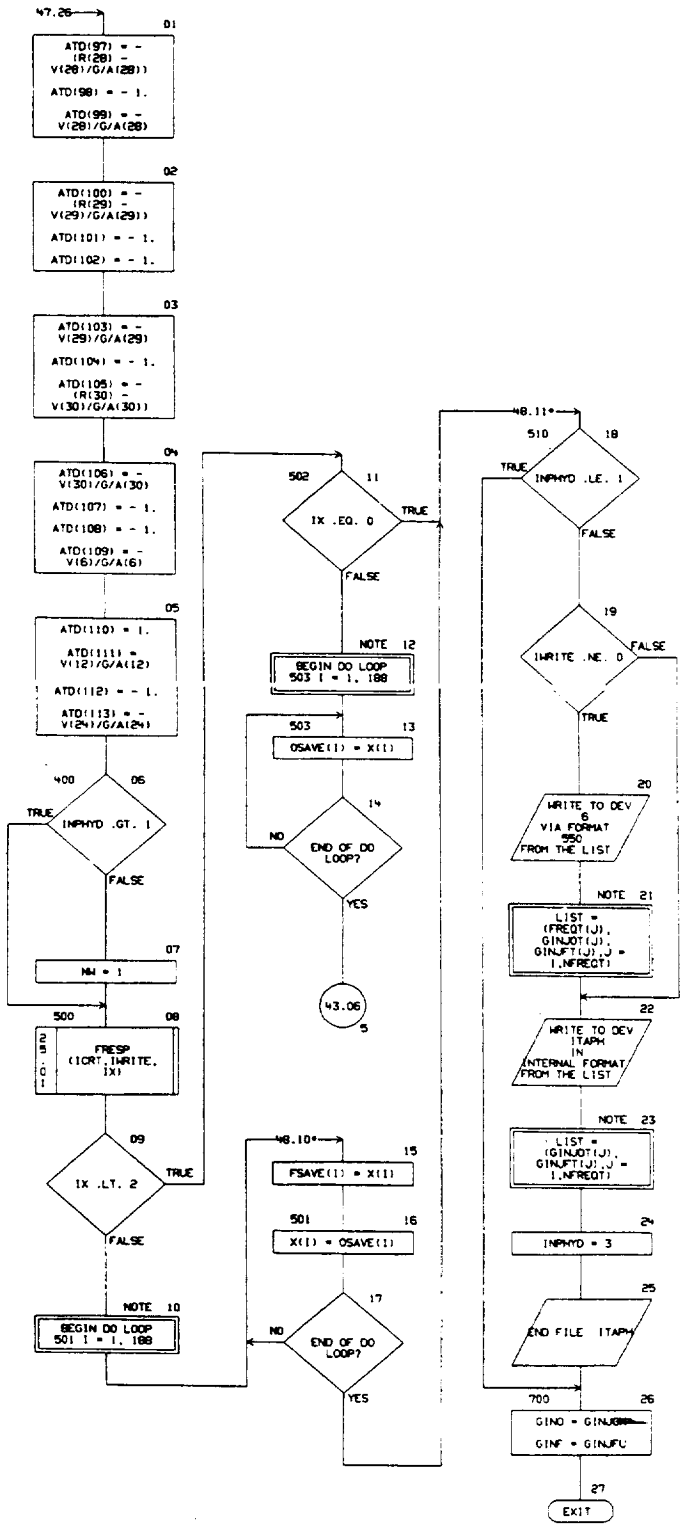


CHART TITLE - SUBROUTINE HYDRDY(IR,INPHYD,FRE,GINO,GINF,PCIN,WDIN,WFIN)



```
            COMMON/HY/ICRT,IRFLAG,ITERM,ITYPE,IWRITE,IX,A,CH,KF,KO,L,R,RHOL,V,
            VF,VO,VOLF,VOLO,ZF,ZO,OSAVE(188),FSAVE(188)
            REAL   X(188)
            EQUIVALENCE (X(1),A(1))
            COMMON/F/NH,NCTD,NR,KEQ,TRIG,IRPS,OMI,OMFL,W,IH,C,TD,ATD,
            FREQ,GINJOX,GINJFU,PC,WO,WF
            COMPLEX   NOZAT(100),GINJOT(100),GINJFT(100),GINJOX,GINJFU,
            GINO,GINF
            COMMON/COMTAP/NFREQT,FREQT(100),NOZAT,GINJOT,GINJFT,ITAPN,ITAPC,
            ITAPH
            REAL   L(30),R(30),A(30),V(30),C(62,126),TD(62,63),ATD(126),W(101)
            ,CH(30),RHOL(30),KO,KF
            INTEGER*4 IH(126)
            NAMELIST/HYD/L,R,A,V,OMI,OMFL,FREQ,NFREQT,IWRITE,ICRT,ZF,RF,VOLF,
            VF,ZO,RO,VOLO,VO,FREQT,IH,ITERM,IRFLAG,KO,KF,CH,RHOL,ID,ITYPE,IX
  50        FORMAT(' INPUT NAMELIST +HYD DATA'/' VARIABLES ARE, L,R,A,V,CH,RHO
            L,NFREQT,FREQT,IWRITE,ITERM'/' ICRT,ZF,RF,VO,KOLF,VF,KF,ZO,RO,VOLO
            ,VO,ID,ITYPE,IRFLAG')
  66        FORMAT(' END OF +HYD INPUT')
  550       FORMAT(1H1,///,18X,'FEED  SYSTEM  RESPONSE  PARAMETERS',//,
                 5X,'FREQUENCY',4X,'OXIDIZER INJECTION RATE',4X,
                 'FUEL INJECTION RATE',/,20X,'AMPLITUDE',5X,'PHASE',
                 6X,'AMPLITUDE',5X,'PHASE',/,(5X,0PF9.3,5X,1PE11.4,
                 0PF9.2,5X,1PE11.4,0PF9.2))
```

CHART TITLE - SUBROUTINE LOCFAC(JK,X,TX,NX,JX,FX)

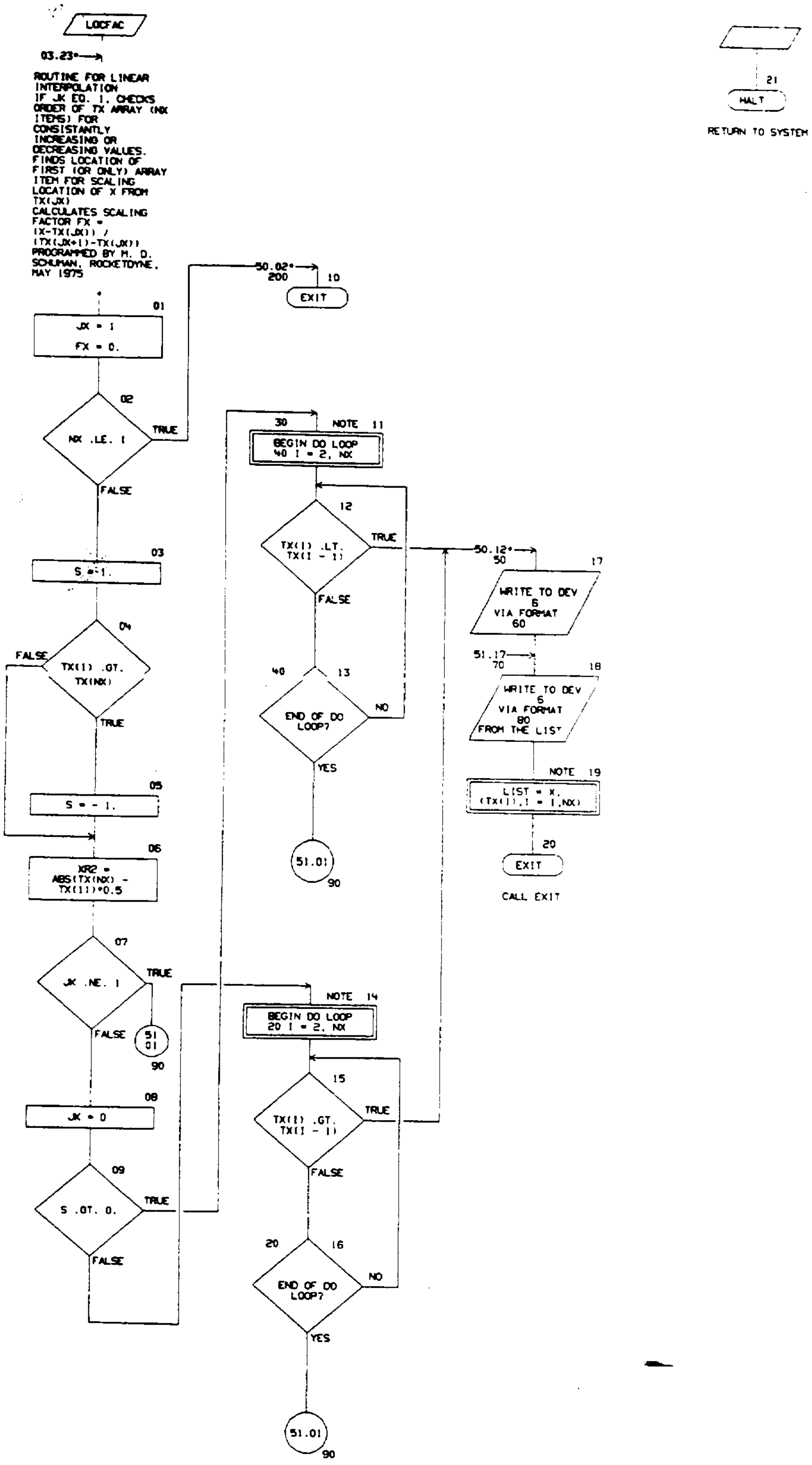


CHART TITLE - SUBROUTINE LOCFAC(JK,X,TX,NX,JX,FX)

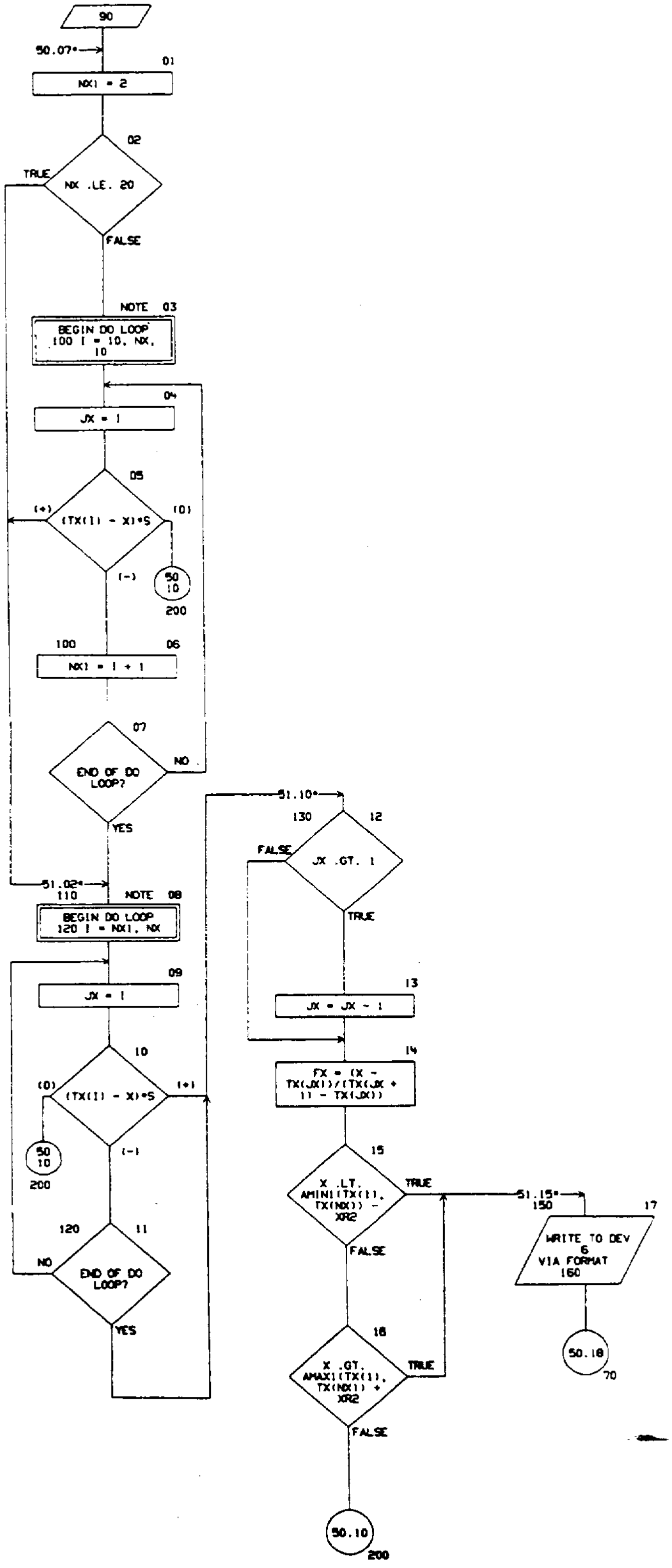


CHART TITLE - NON-PROCEDURAL STATEMENTS

```
           DIMENSION  TX(1)
 60        FORMAT(1H1 41X 27HE R R O R   I N   T A B L E )
 80          FORMAT(1H0 41X 27HREFER TO SUBROUTINE  LOCFAC  //
                     5X 3HX = 1PE15.4 / 4X 4HTX = 6E15.4 / (8X 6E15.4) )
 160       FORMAT(1H1 22X 84HE R R O R  -  EXTRAPOLATION OF TABLE IS BEYOND R
           EASONABLE LIMITS )
```

CHART TITLE - SUBROUTINE NOZADM(IR,GAMX,CO,FREQ,NOZA)

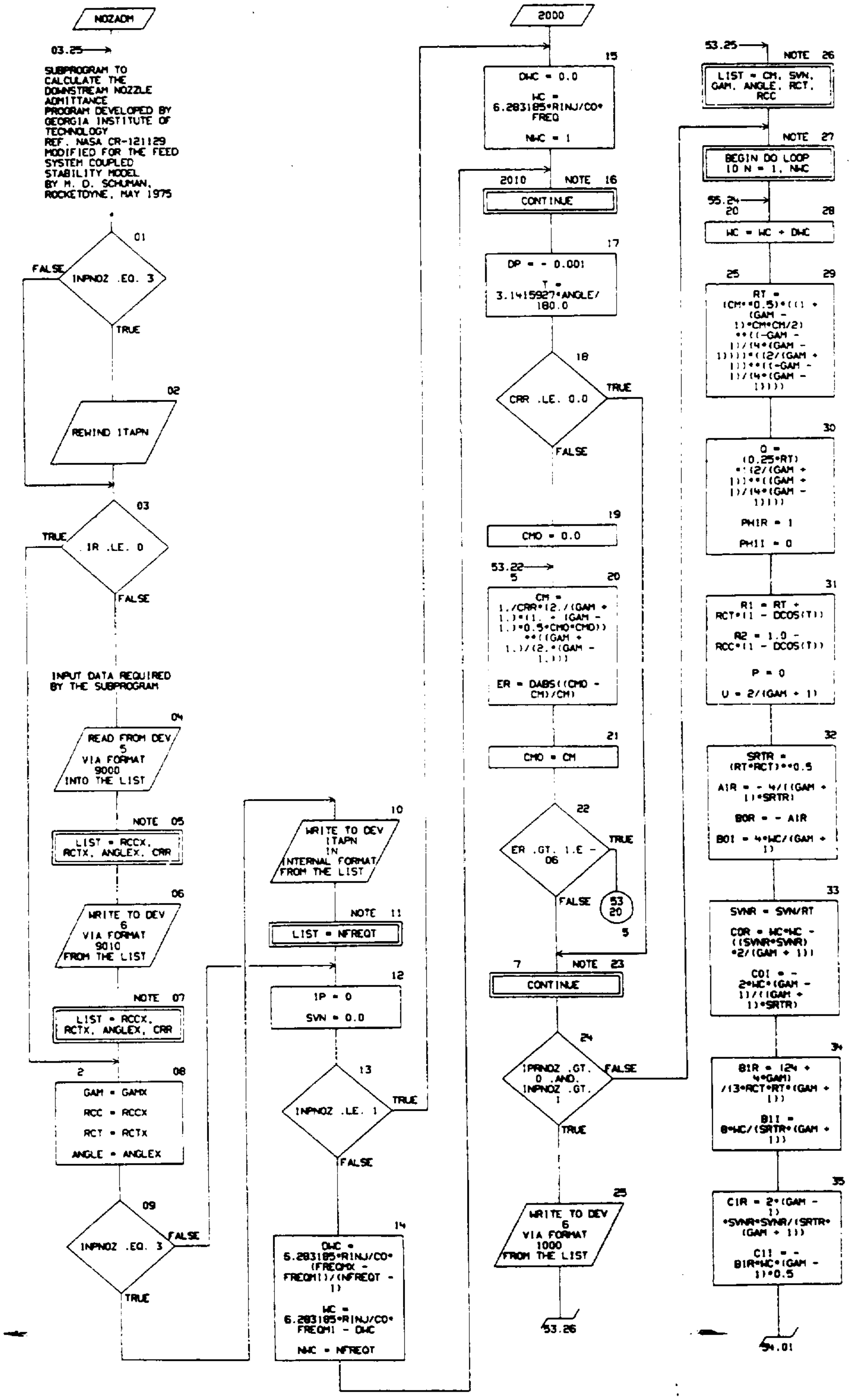


CHART TITLE - SUBROUTINE NOZADM(IR,GAMX,CO,FREQ,NOZA)

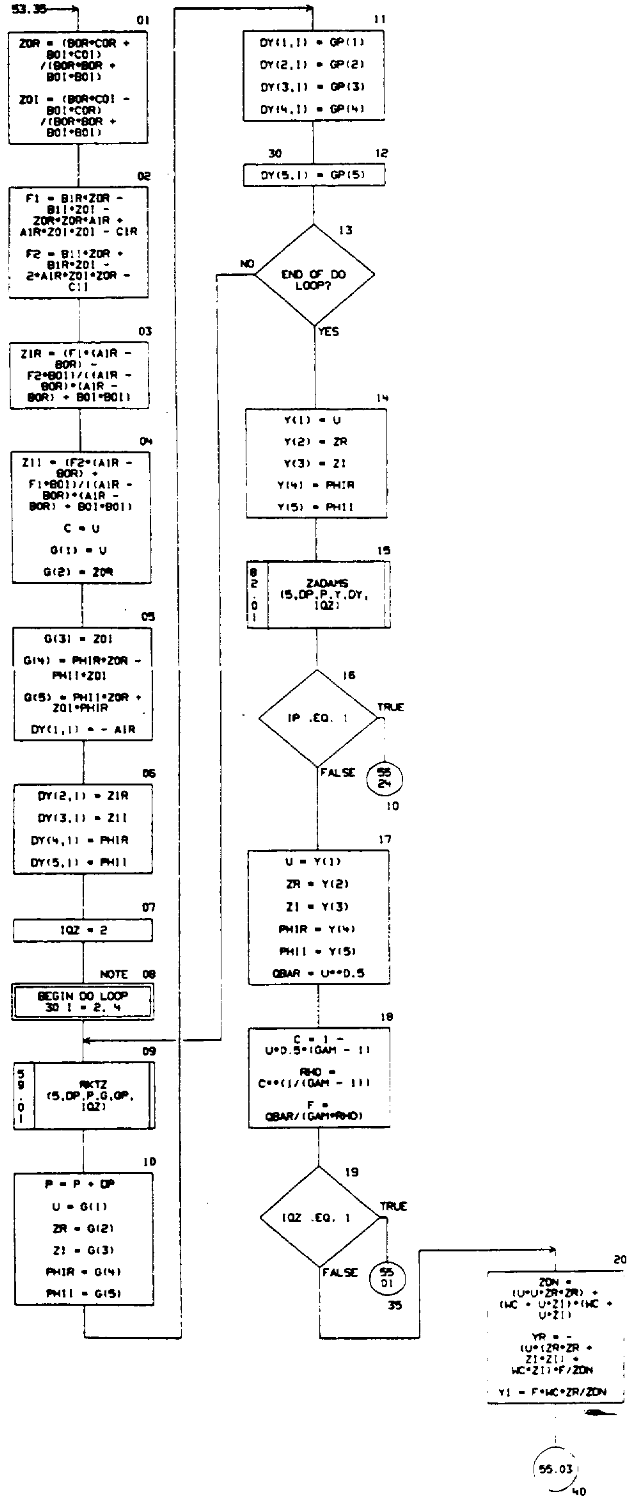
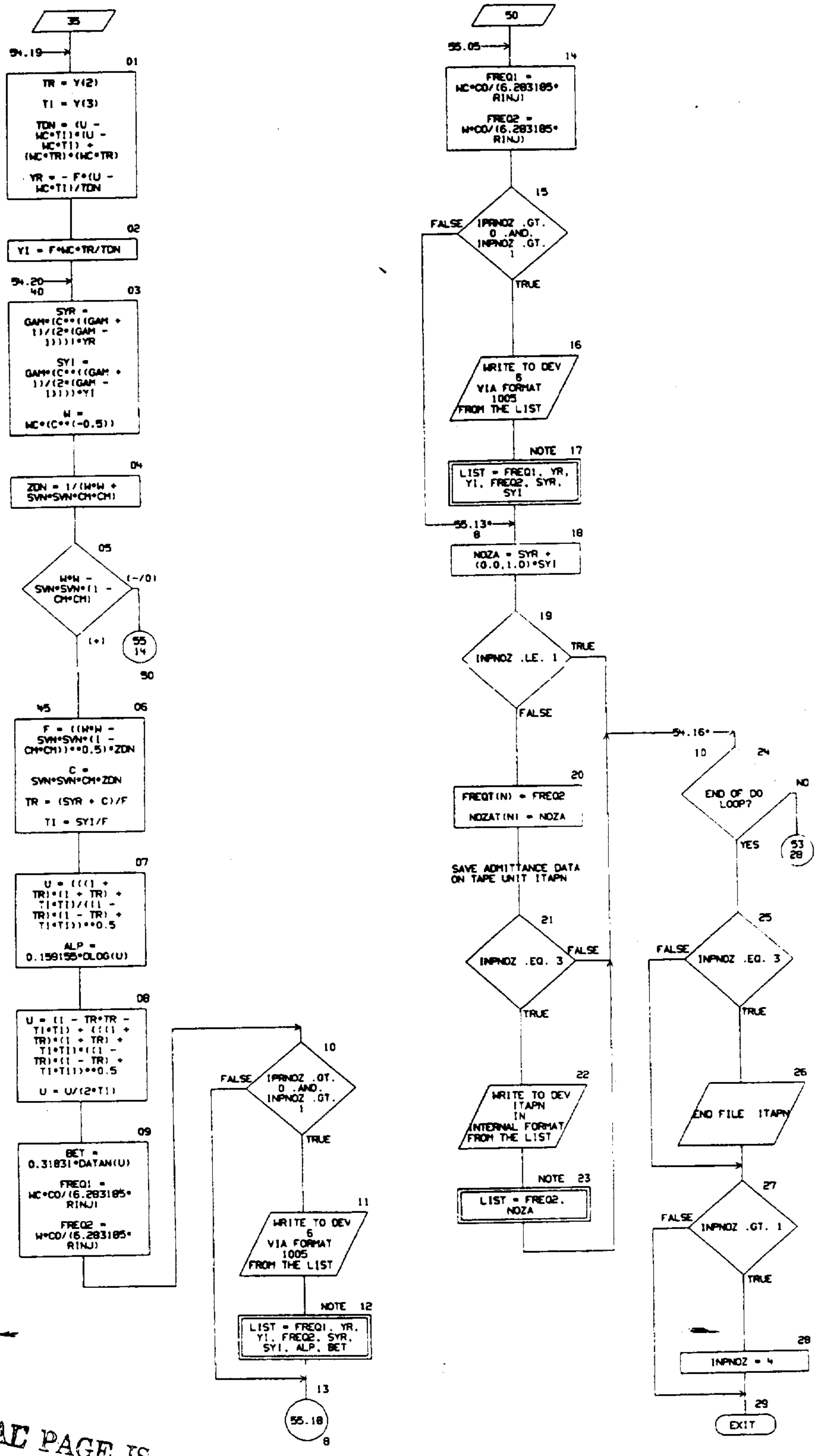


CHART TITLE - SUBROUTINE NOZADM(IR,GAMX,CO,FREQ,NOZA)



```
              IMPLICIT REAL*8(A-H,O-Z)
              COMPLEX    NOZA, NOZAT, GINJOT, GINJFT
              REAL    FREQ, GAMX, RCCX, RCTX, ANGLEX, CRR, RINJ, CO, FREQMX,
                   FREQMI, FREQT, FREQ1, FREQ2
              DIMENSION DY(5,4), G(5), GP(5), Y(5)
              COMMON /X1/GAM,SVN,ANGLE,RCT,RCC /X2/T,RT,Q,R1,R2,HC,IP
                     /X3/Z1R,Z1I  /X4/CM
              COMMON /COMTAP/ NFREQT, FREQT(100), NOZAT(100), GINJOT(100),
                   GINJFT(100), ITAPN, ITAPC, ITAPH
              COMMON /COMNOZ/ RCCX, RCTX, ANGLEX, CRR, RINJ, INPNOZ, FREQMX,
                   FREQMI, IPRNOZ
9000          FORMAT(6E12.8)
9010          FORMAT(/,5X,'RCCX =',1PE11.4,5X,'RCTX =',E11.4,5X,'ANGLEX =',
                   E11.4,3X,'CRR =',E11.4)
1000          FORMAT(1H1,////,30X,30HTHEORETICAL NOZZLE ADMITTANCES,//,23X,
                14HMACH NUMBER = ,F3.2,7H SVN = ,F6.4,9H GAMMA = ,F5.3,//,
                7X,15HNOZZLE ANGLE = ,F4.1,2X,21HRADII OF CURVATURE,
                ,9HTHROAT = ,F6.4,12H ENTRANCE = ,F6.4,//,9X,2HFC,
                7X,2HYR,8X,2HYI,8X,1HF,8X,3HSYR,8X,3HSYI,
                6X,5HALPHA,5X,4HBETA,/)
1005          FORMAT(6X,F6.1,2F10.5,F10.2,4F10.5)
```

CHART TITLE - SUBROUTINE RKTDIF(P,Q,GP)

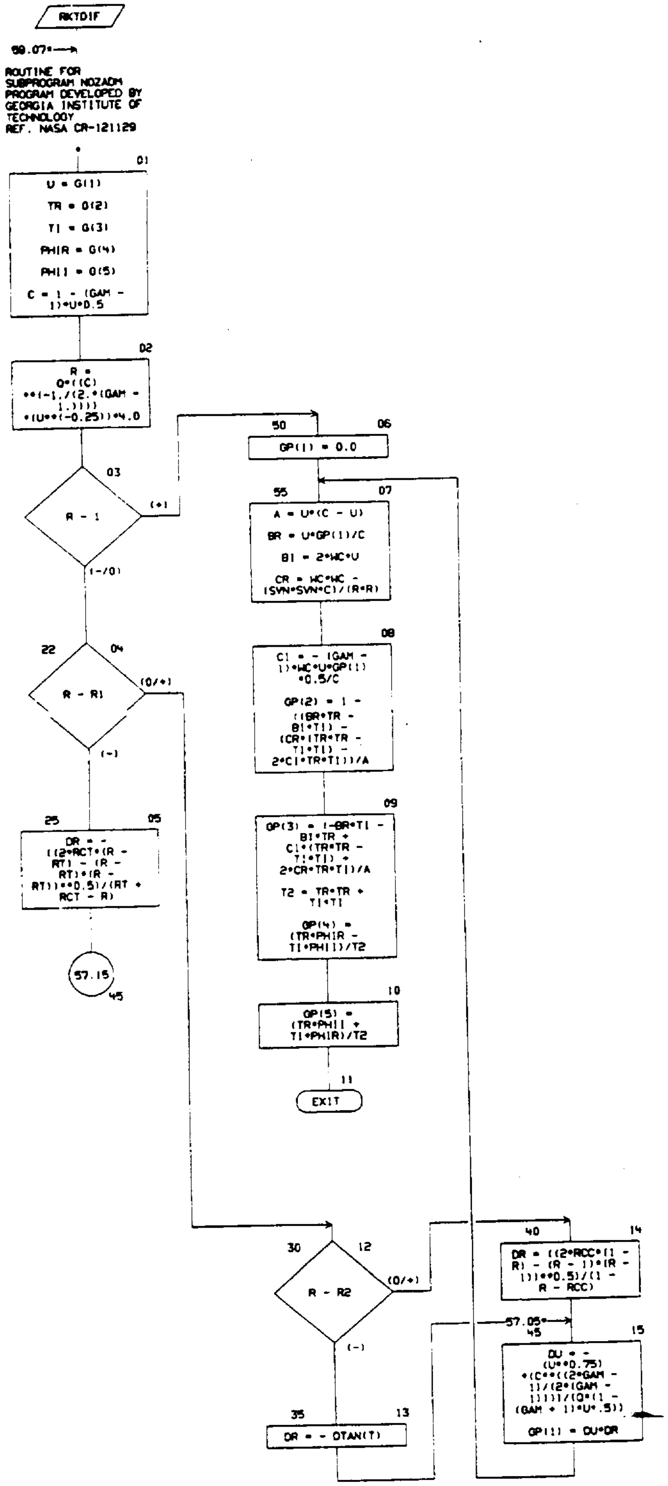


CHART TITLE - NON-PROCEDURAL STATEMENTS

```
              IMPLICIT REAL*8(A-H,O-Z)
              COMMON /X1/GAM,SVN,ANGLE,RCT,RCC /X2/T,RT,Q,R1,R2,WC,IP
              DIMENSION G(5), GP(5)
        9     FORMAT(3X,'PRINTING FROM CARD 4570',/,3X,'R=',E15.8,
                 3X,'R1=',E15.8,3X,'RT=',E15.8)
```

CHART TITLE - SUBROUTINE RKTZ(NU,H,T1,U,DUM,JOPT)

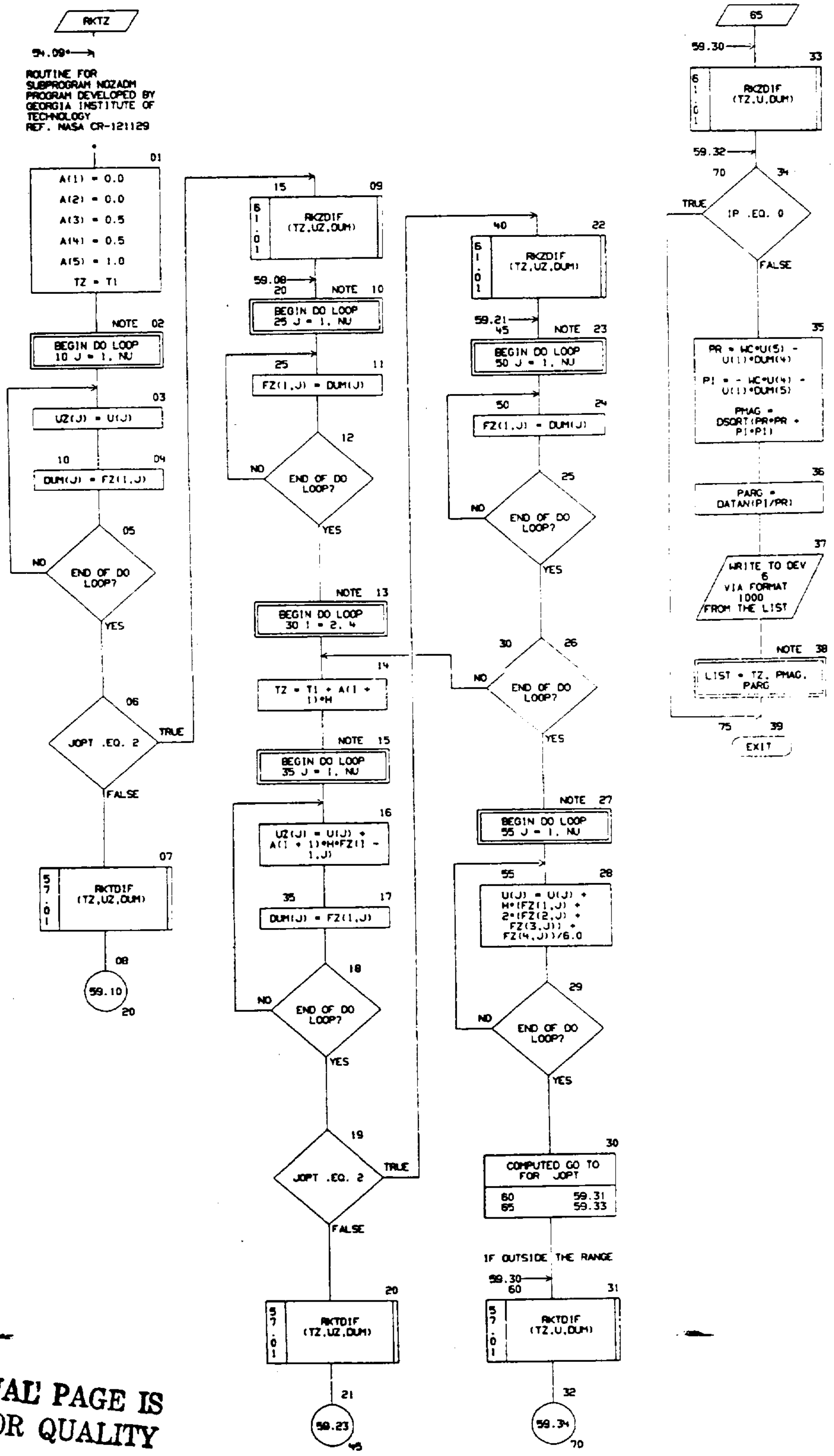


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CHART TITLE - NON-PROCEDURAL STATEMENTS

```
              IMPLICIT REAL*8(A-H,O-Z)
              COMMON /X2/T,RT,Q,R1,R2,MC,IP
              DIMENSION U(5), A(5), UZ(5), FZ(4,5), DUM(5)
      1000    FORMAT(46X,F6.4,1X,F10.5,3X,F10.5)
```

CHART TITLE - SUBROUTINE RKZDIF(P,G,GP)

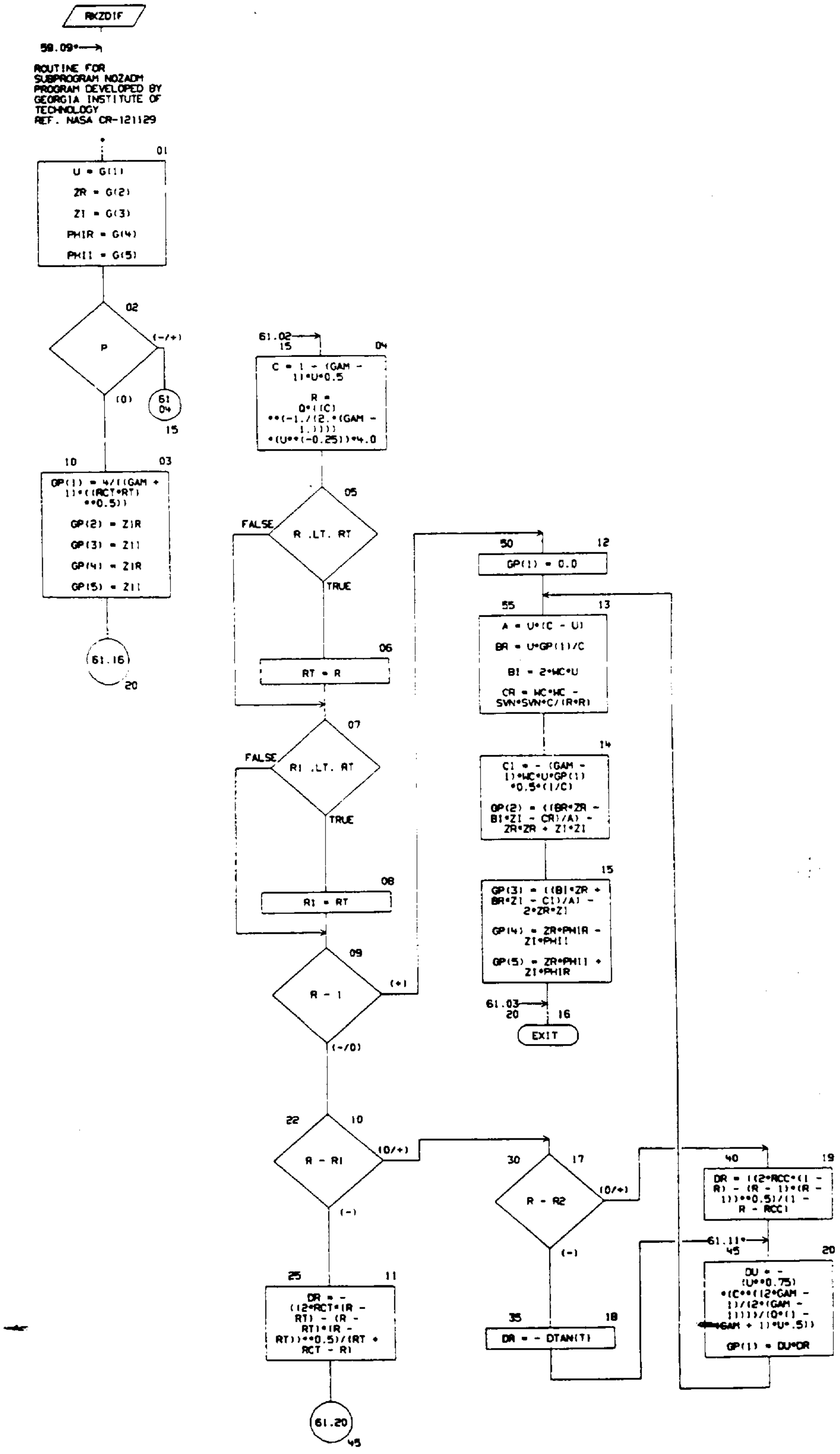
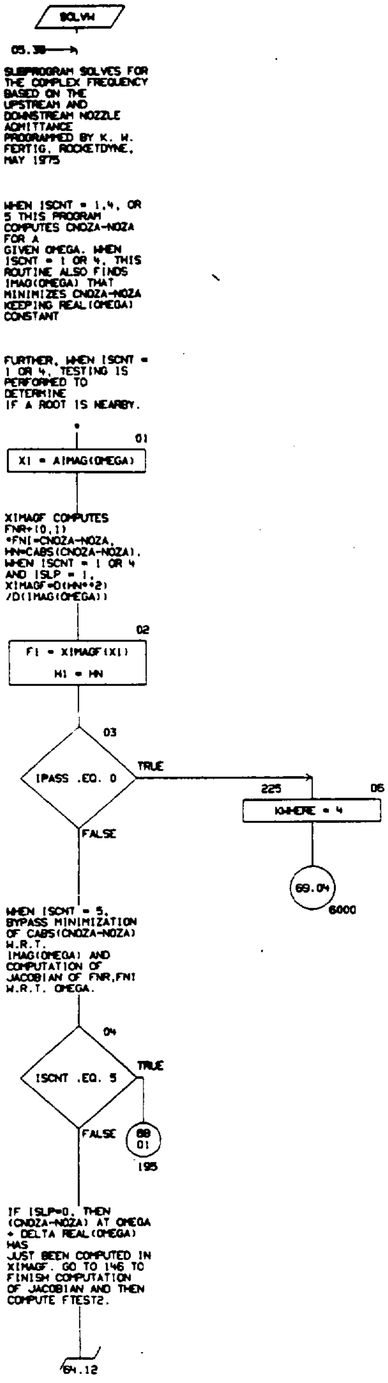


CHART TITLE - NON-PROCEDURAL STATEMENTS

```
            IMPLICIT REAL*8(A-H,O-Z)
            COMMON /X1/GAM,SVN,ANGLE,RCT,RCC /X2/T,RT,Q,R1,R2,WC,IP
                 /X3/Z1R,Z1I
            DIMENSION G(5), GP(5)
 16         FORMAT(3X,'PRINTING FROM CARD 5000',/,3X,'R=',E15.8,
              3X,'R1=',E15.8,3X,'RT=',E15.8)
```

CHART TITLE - SUBROUTINE SOLVH(KWHERE)



SUBPROGRAM SOLVES FOR THE COMPLEX FREQUENCY BASED ON THE UPSTREAM AND DOWNSTREAM NOZZLE ADMITTANCE PROGRAMMED BY K. W. FERTIG, ROCKETDYNE, MAY 1975

WHEN ISCNT = 1,4, OR 5 THIS PROGRAM COMPUTES CNOZA-NOZA FOR A GIVEN OMEGA. WHEN ISCNT = 1 OR 4, THIS ROUTINE ALSO FINDS IMAG(OMEGA) THAT MINIMIZES CNOZA-NOZA KEEPING REAL(OMEGA) CONSTANT

FURTHER, WHEN ISCNT = 1 OR 4, TESTING IS PERFORMED TO DETERMINE IF A ROOT IS NEARBY.

XIMAGF COMPUTES FNR+(0,1) *FNI=CNOZA-NOZA, HN=CABS(CNOZA-NOZA). WHEN ISCNT = 1 OR 4 AND ISLP = 1, XIMAGF=D(HN**2) /D(IMAG(OMEGA))

WHEN ISCNT = 5, BYPASS MINIMIZATION OF CABS(CNOZA-NOZA) W.R.T. IMAG(OMEGA) AND COMPUTATION OF JACOBIAN OF FNR,FNI W.R.T. OMEGA.

IF ISLP=0, THEN (CNOZA-NOZA) AT OMEGA + DELTA REAL(OMEGA) HAS JUST BEEN COMPUTED IN XIMAGF. GO TO 146 TO FINISH COMPUTATION OF JACOBIAN AND THEN COMPUTE FTEST2.

CHART TITLE - SUBROUTINE SOLVW(NOWHERE)

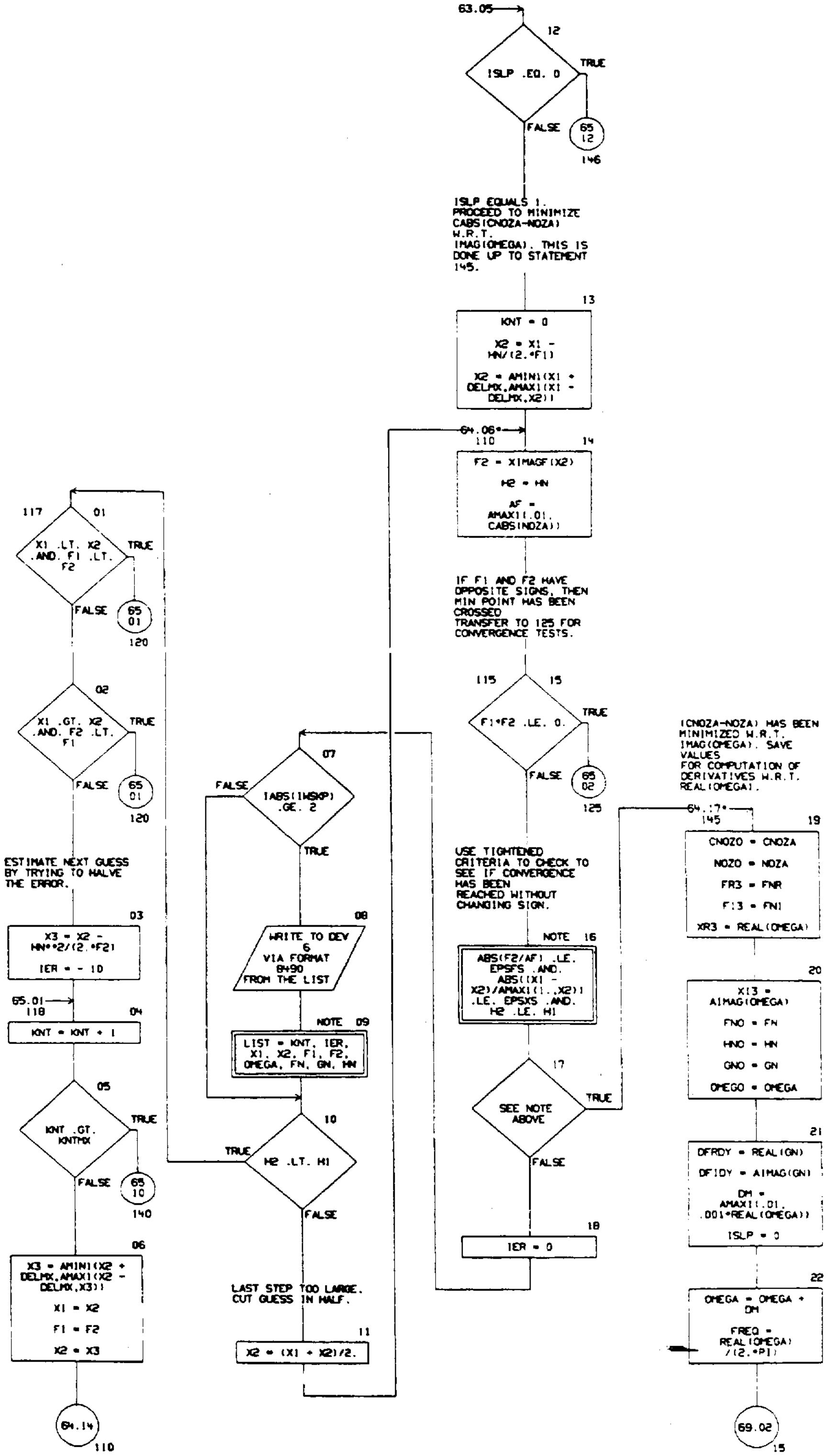


CHART TITLE - SUBROUTINE SOLVH(KWHERE)

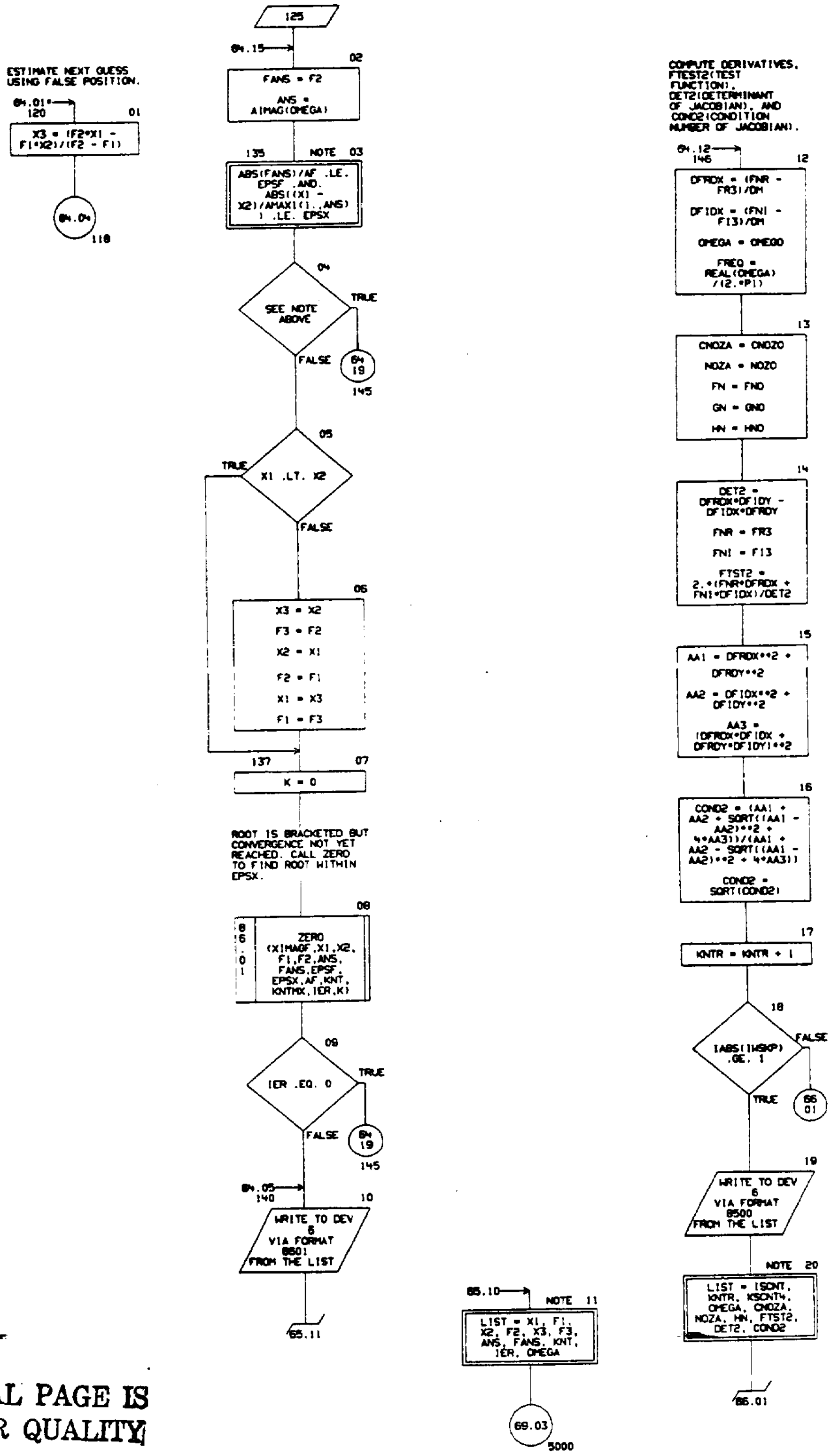


CHART TITLE - SUBROUTINE SOLVH(NWHERE)

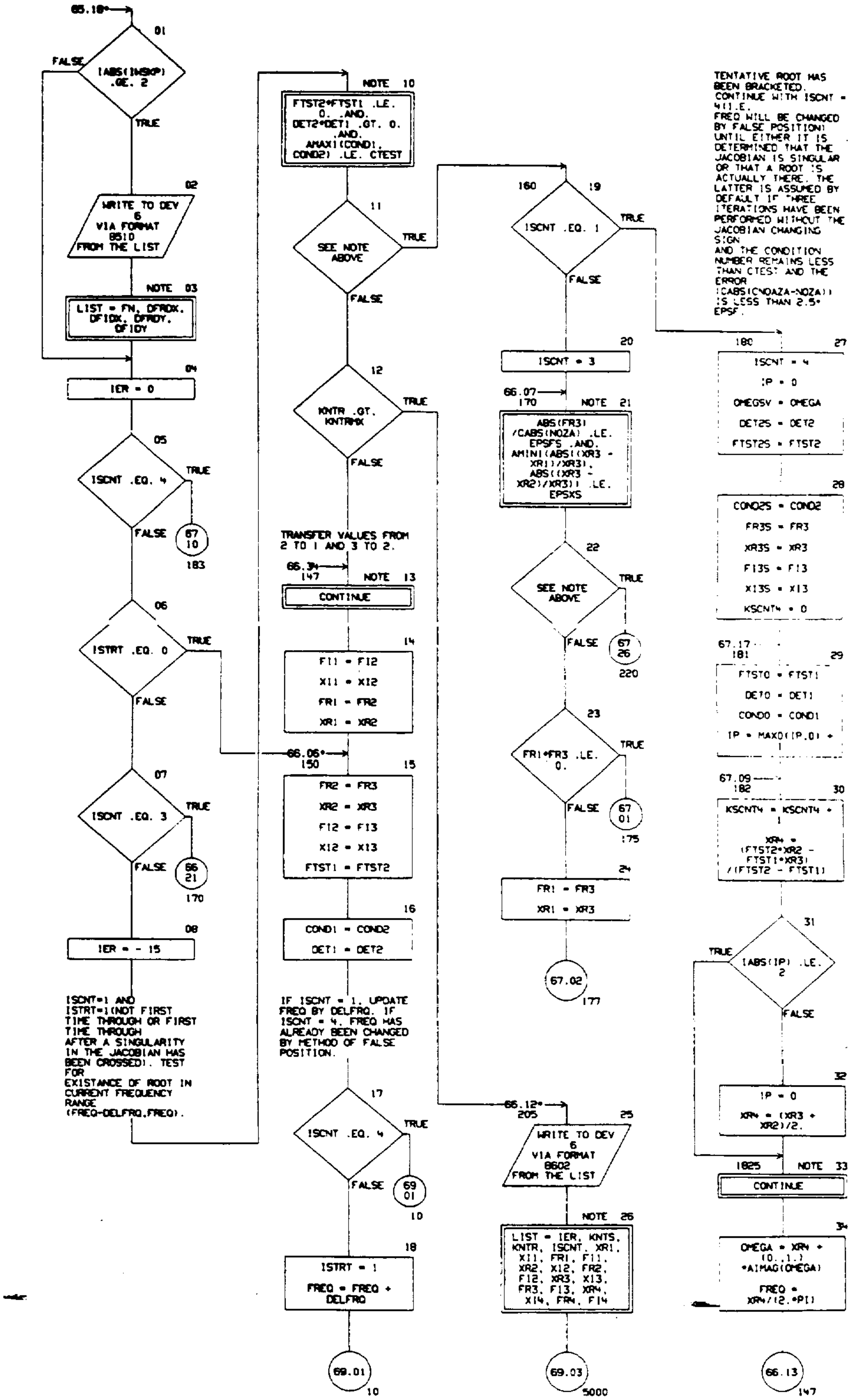
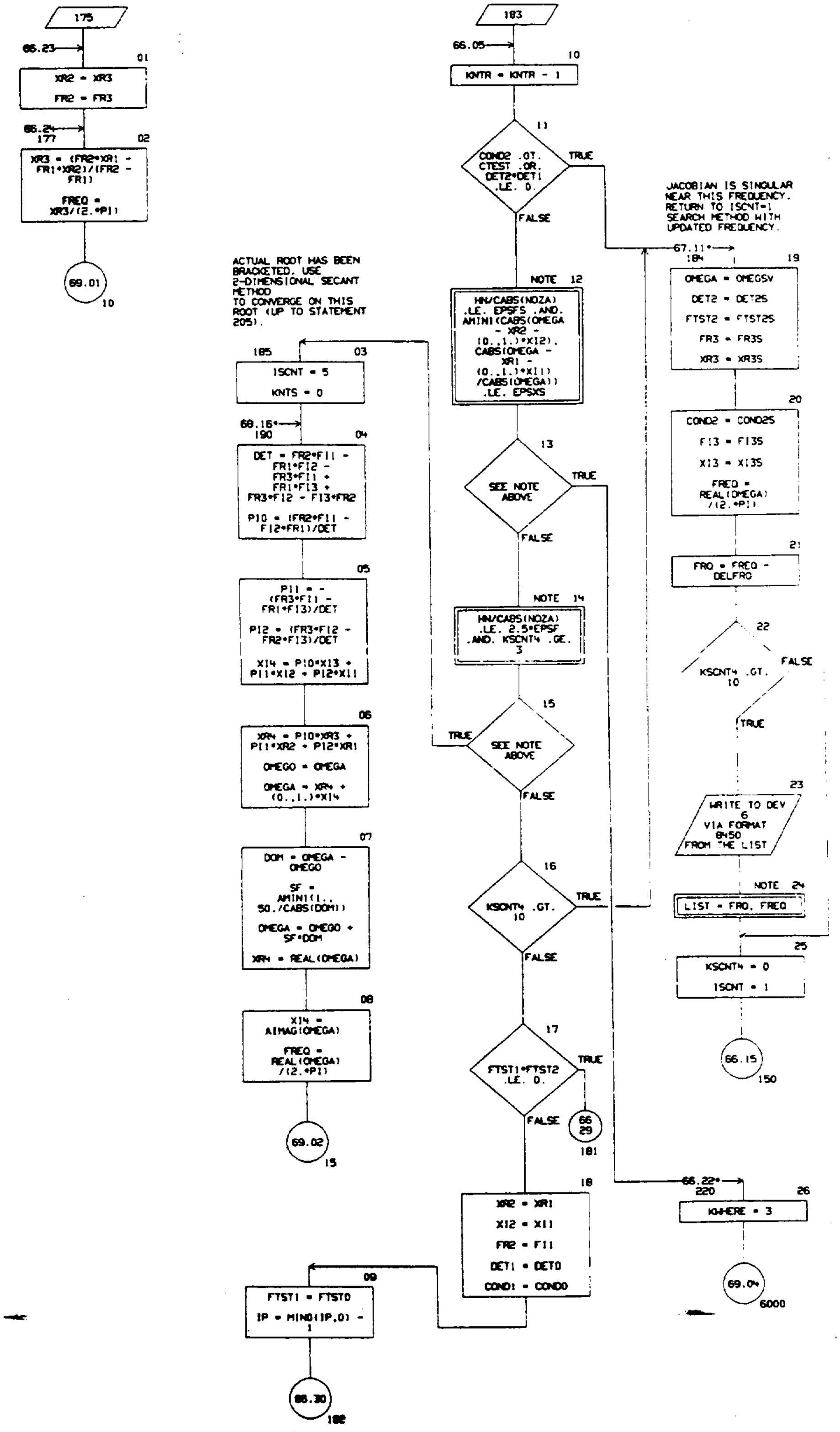


CHART TITLE - SUBROUTINE SOLVW(KWHERE)


ACTUAL ROOT HAS BEEN BRACKETED. USE 2-DIMENSIONAL SECANT METHOD TO CONVERGE ON THIS ROOT (UP TO STATEMENT 205).

JACOBIAN IS SINGULAR NEAR THIS FREQUENCY. RETURN TO ISCNT=1 SEARCH METHOD WITH UPDATED FREQUENCY.

CHART TITLE - SUBROUTINE SOLVH(KWHERE)

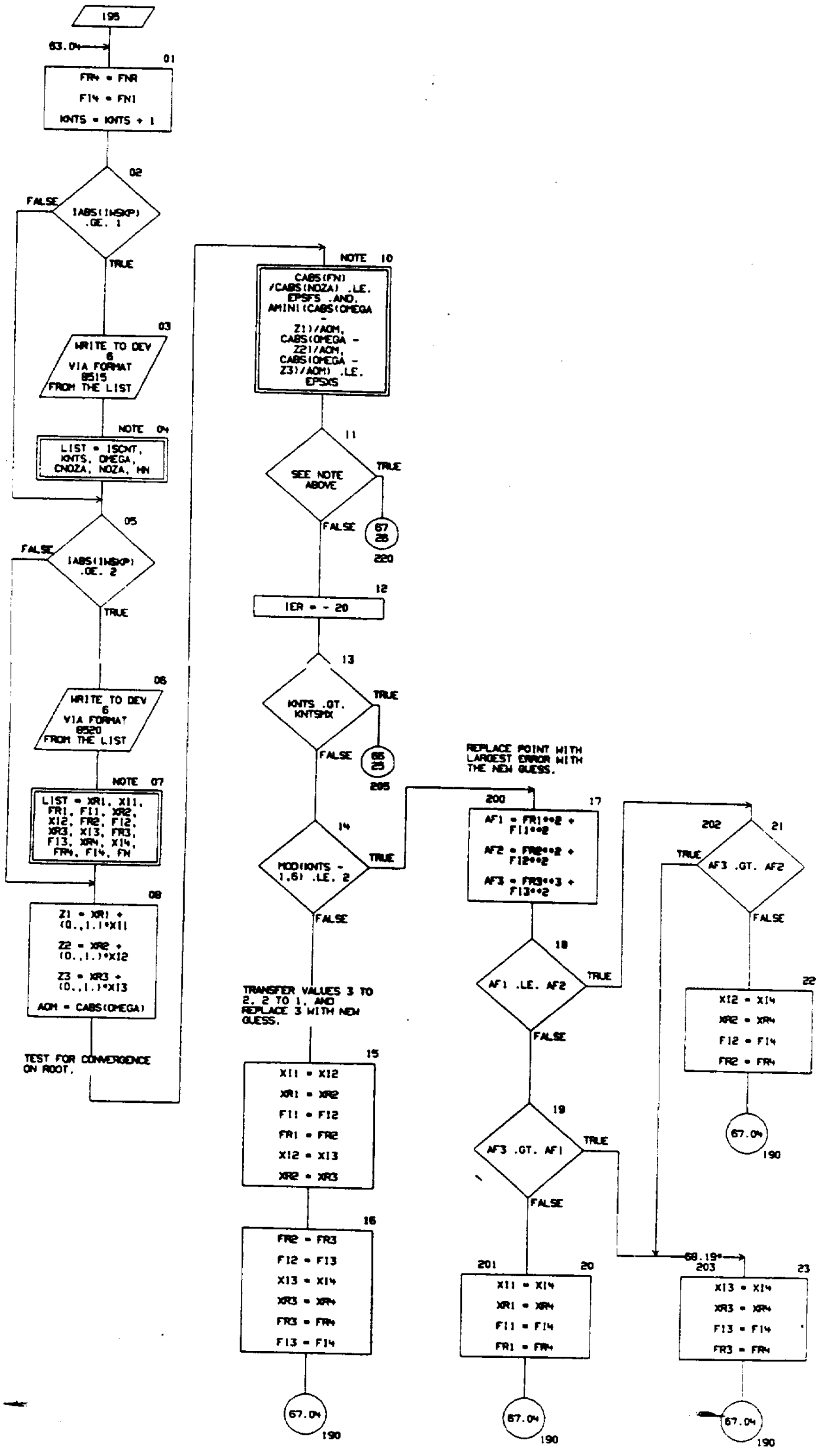
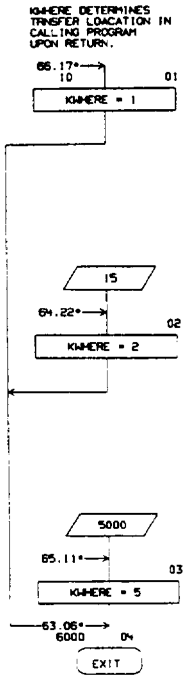


CHART TITLE - SUBROUTINE SOLVW(KWHERE)



```
         COMPLEX OMEGA, P, RHO, V, MR, T, CNOZA, VXO,
              NOZA, OMEGO,
              DOM, Z1, Z2, Z3, FN, NOZAMR, GN,
              CNOZO, NOZO, FNO, GNO, OMEGSV
         COMMON /COMCHM/ P(100), RHO(100), V(100), MR(100), T(100),
              VXO, OMEGA, CNOZA, DELP
         COMMON /FZERO/ NOZA,NOZAMR,GN,FN,FNR,FNI,HN,ISCNT,ISLP
         EXTERNAL XIMAGF
         DATA PI/3.141593/
         COMMON /SOLVE/ FREQ, DELFRQ, DELMX, EPSF, EPSX, EPSFS, EPSXS,
                        FRQMAX, CTEST, IPASS, KNTR, ISTRT, KSCNT4, IWSKP,
                        KNTMX, KNTSMX, KNTRMX
8490     FORMAT(/2I5,1P4E13.5/2X,3(1PE13.5,' ,',1PE12.5),1PE15.5)
8601     FORMAT(//'   **** UNABLE TO FIND ROOT FOR IMAG PART OF F ****'
          //'   X1,F1,X2,F2,X3,F3,ANS,FANS,KNT,IER,OMEGA = '/
           3X,1P8E13.5/3X,2I10/3X,1PE13.5,' , ',1PE13.5)
8500     FORMAT(/3I5,3(1PE14.5,' ,',1PE12.5)/2X,1P4E13.5)
8510     FORMAT(2X,1PE14.5,' ,',1PE12.5,2X,1P4E13.5)
8450     FORMAT(//'   **************************'//
             '       WARNING, POSSIBLE ROOT IN FREQUENCY RANGE. ',
               1P2E15.6//'   **************************'//)
8515     FORMAT(/2I5,3(1PE14.5,' ,',1PE12.5),1PE14.5)
8520     FORMAT(2X,4(1PE14.5,' ,',1PE12.5)/2X,4(1PE14.5,' ,',
               1PE12.5)/2X,1PE14.5,' ,',1PE12.5)
8602     FORMAT(//'  **** EXCEED CONVERGENCE LIMIT  ****'/
           '  IER,KNTS,KNTR,ISCNT = ',4I10/'   X,F FROM 1-4 = '/
            (3X,1PE15.5,' , ',1PE15.5,1PE18.5,' , ',1PE15.5))
```

CHART TITLE - SUBROUTINE STEADY(IPRSTE)

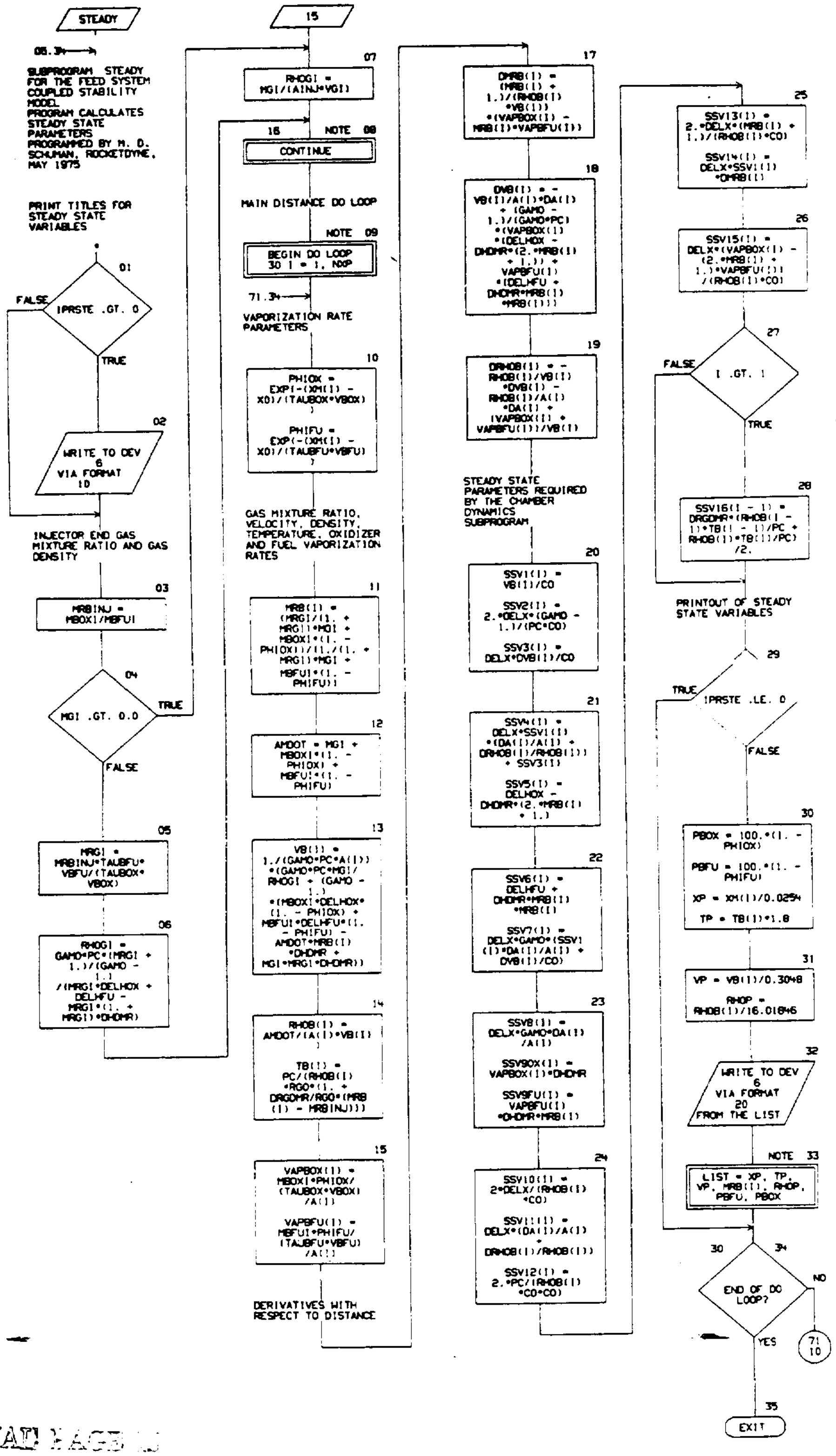


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CHART TITLE - NON-PROCEDURAL STATEMENTS

```
          COMPLEX  COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9,
               COX10, COX11, COX12, COX13, COX14, COX15, COX16,
               CFU1, CFU2, CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9,
               CFU10, CFU11, CFU12, CFU13, CFU14, CFU15, CFU16
          REAL  MRBINJ, MBOX1, MBFU1, MRB, MRGI, MGI, NUBOX, NUBFU, MWG
          COMMON  /COMCBM/  XKOX, XKFU, MBOX1, MBFU1, TAUBOX, TAUBFU, VBOX,
               VBFU, GAMO, RGO, DELHOX, DELHFU, PC, CO,
               COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9, COX10,
               COX11, COX12, COX13, COX14, COX15, COX16, CFU1, CFU2,
               CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9, CFU10, CFU11,
               CFU12, CFU13, CFU14, CFU15, CFU16, MWG, XIMPFU, XIMPOX,
               CS, DCSDMR, DHDMR, DRGDMR, ADVOX, ADDOX, TORAGO, DELVOX,
               NUBOX, DTOXDM, ADVFU, ADDFU, TORAGF, DELVFU, NUBFU, DTFUDM
          COMMON /CONSTS/  MRB(100), TB(100), RHOB(100), VB(100),
               DMRB(100), DRHOB(100), DVB(100), VAPBOX(100), VAPBFU(100),
               SSV1(100), SSV2(100), SSV3(100), SSV4(100),
               SSV5(100), SSV6(100), SSV7(100), SSV8(100), SSV9OX(100),
               SSV9FU(100), SSV10(100), SSV11(100), SSV12(100), SSV13(100),
               SSV14(100), SSV15(100), SSV16(100),
               RHOGI, VGI, MRGI, MGI
          COMMON /COMARE/ NXP, X(100), XM(100), A(100), DA(100), DELX,
               XO, XNOZ, AINJ
10        FORMAT(1H1,///,31X,'STEADY   STATE   SOLUTION',//,
               7X,'DISTANCE',
               4X,'TEMPERATURE',2X,'VELOCITY',3X,'MIXTURE',
               6X,'DENSITY',7X,'PERCENT VAPORIZED',/,7X,'(INCHES)',5X,
               '(RANKINE)',4X,'(FT/S)',5X,'RATIO',5X,
               '(LBM/FT**3)',6X,'FUEL',3X,'OXIDIZER',/)
20        FORMAT(6X,F9.4,2X,2F11.2,F11.4,1PE15.5,0PF11.2,F9.2)
```

CHART TITLE - SUBROUTINE TADAMS(N,H,X,Y,DY,IQZ,IQ)

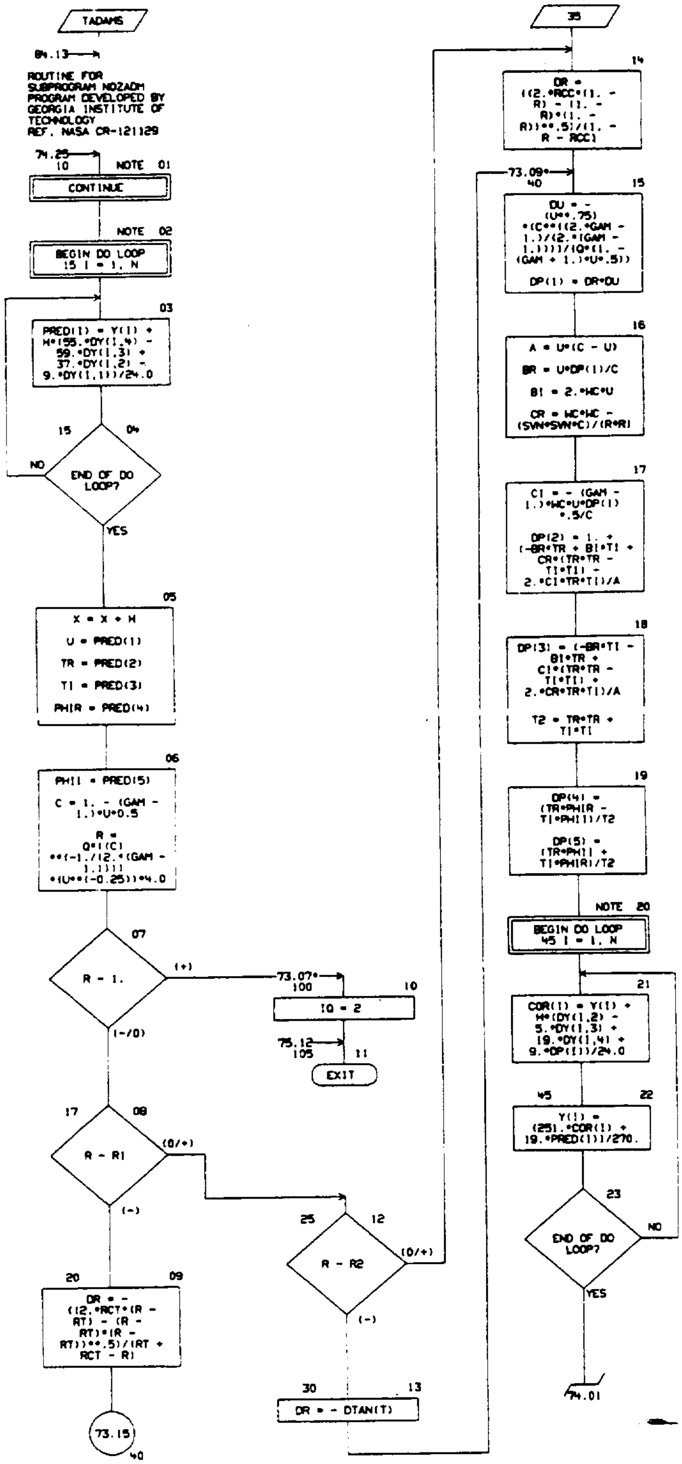


CHART TITLE - SUBROUTINE TADAMS(N,M,X,Y,DY,102,10)

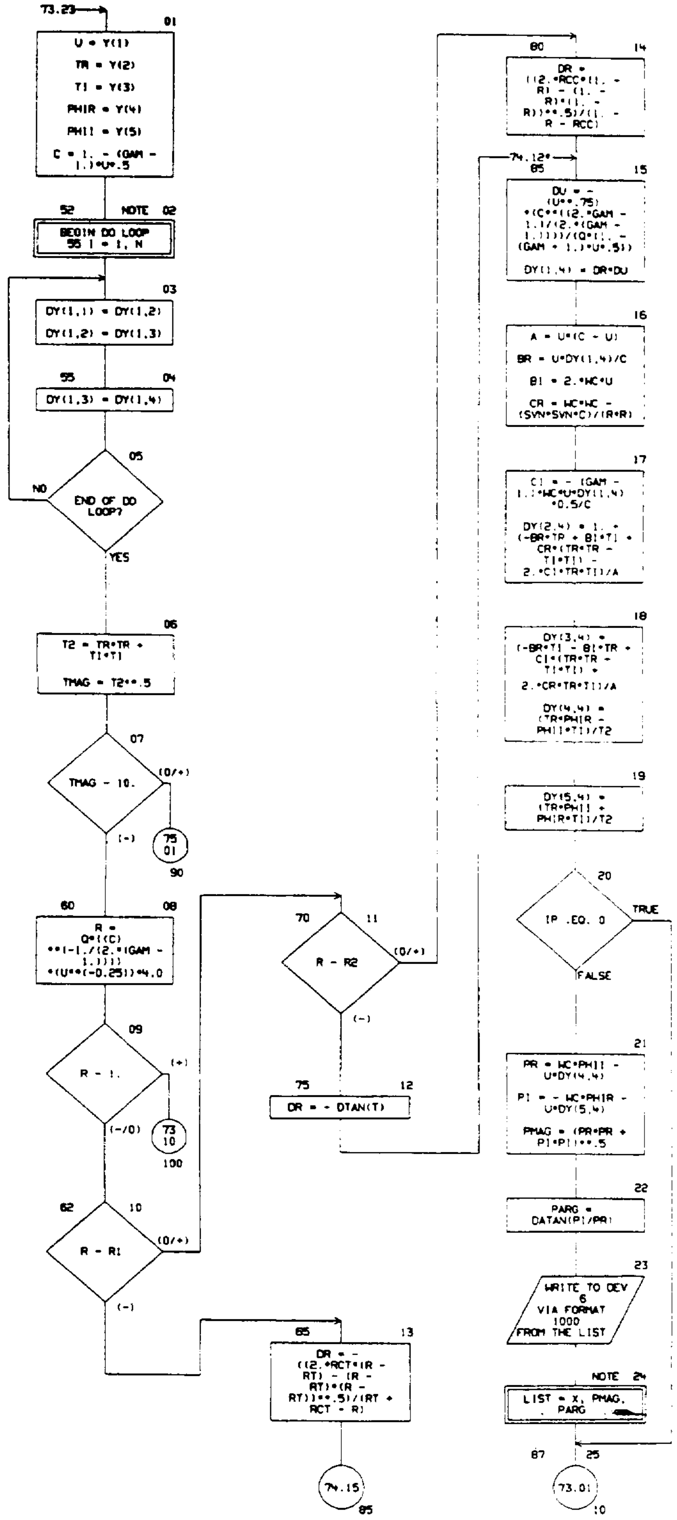
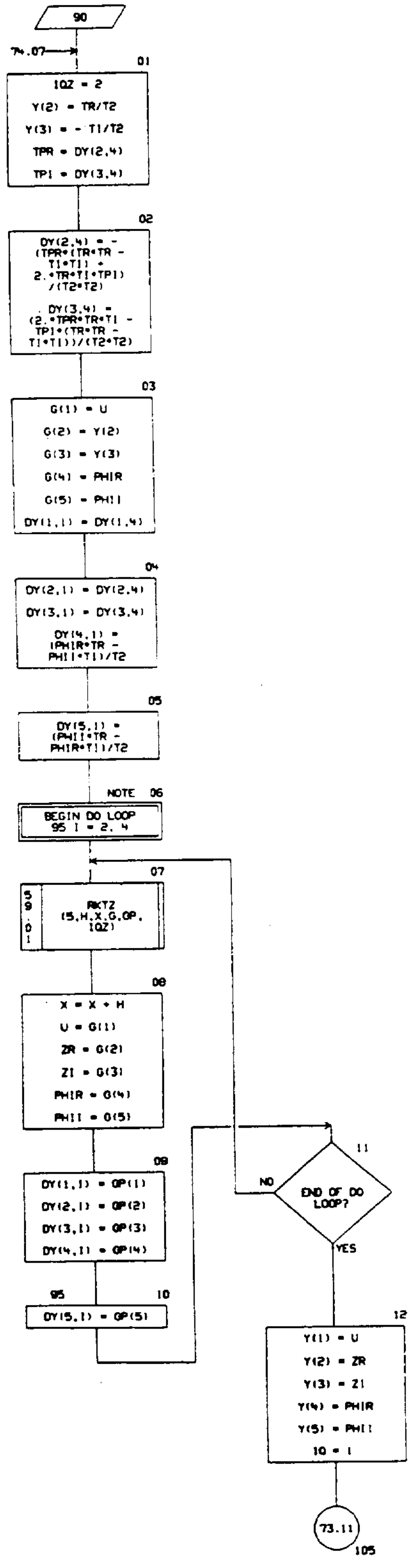


CHART TITLE - SUBROUTINE TADAMS(N,H,X,Y,DY,IQZ,IQ)



```
                IMPLICIT REAL*8(A-H,O-Z)
                COMMON /X1/GAM,SVN,ANGLE,RCT,RCC /X2/T,RT,Q,R1,R2,WC,IP
                COMMON /X4/CM
                DIMENSION COR(5), DP(5), DY(5,4), PRED(5), Y(5), G(5), GP(5)
 16             FORMAT(3X,'PRINTING FROM CARD 2180',/,3X,'R=',E15.8,
                   3X,'R1=',E15.8,3X,'RT=',E15.8)
 61             FORMAT(3X,'PRINTING FROM CARD 2570',/,3X,'R=',E15.8,
                   3X,'R1=',E15.8,3X,'RT=',E15.8)
 1000           FORMAT(46X,F6.4,1X,F10.6,3X,F10.5)
```

CHART TITLE - SUBROUTINE TOPLOT(W,Y,NFP,TL,XR,LL)

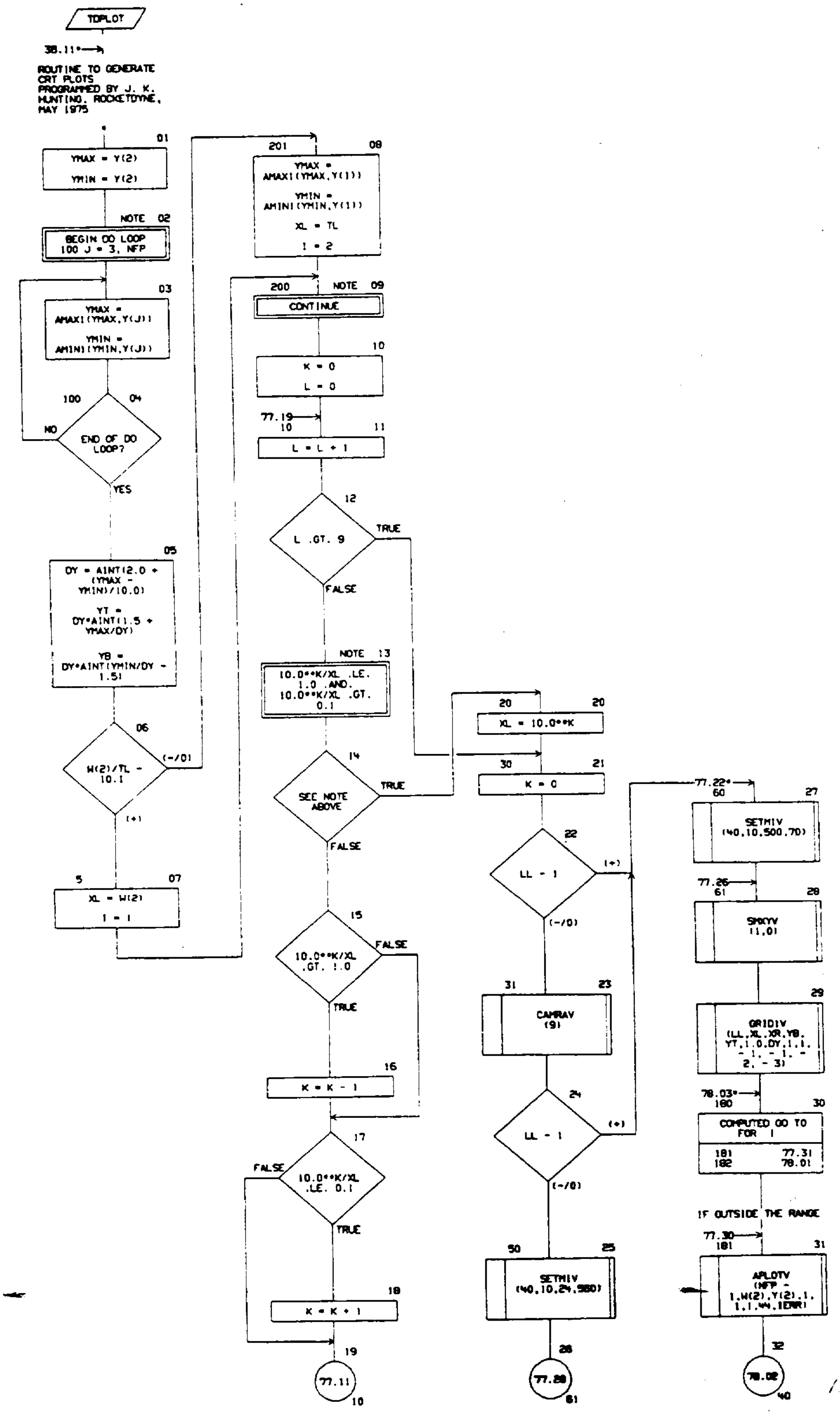


CHART TITLE - SUBROUTINE TOPLOT(W,Y,NFP,TL,XR,LL)

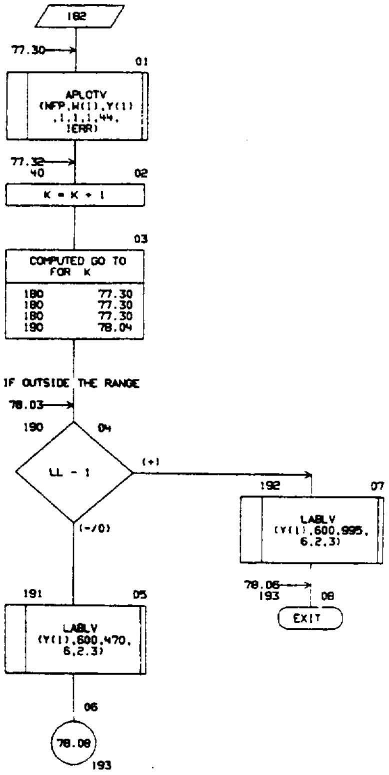


CHART TITLE - NON-PROCEDURAL STATEMENTS

```
DIMENSION W(101),Y(101)
```

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CHART TITLE - FUNCTION XIMAGF(XIMOMG)

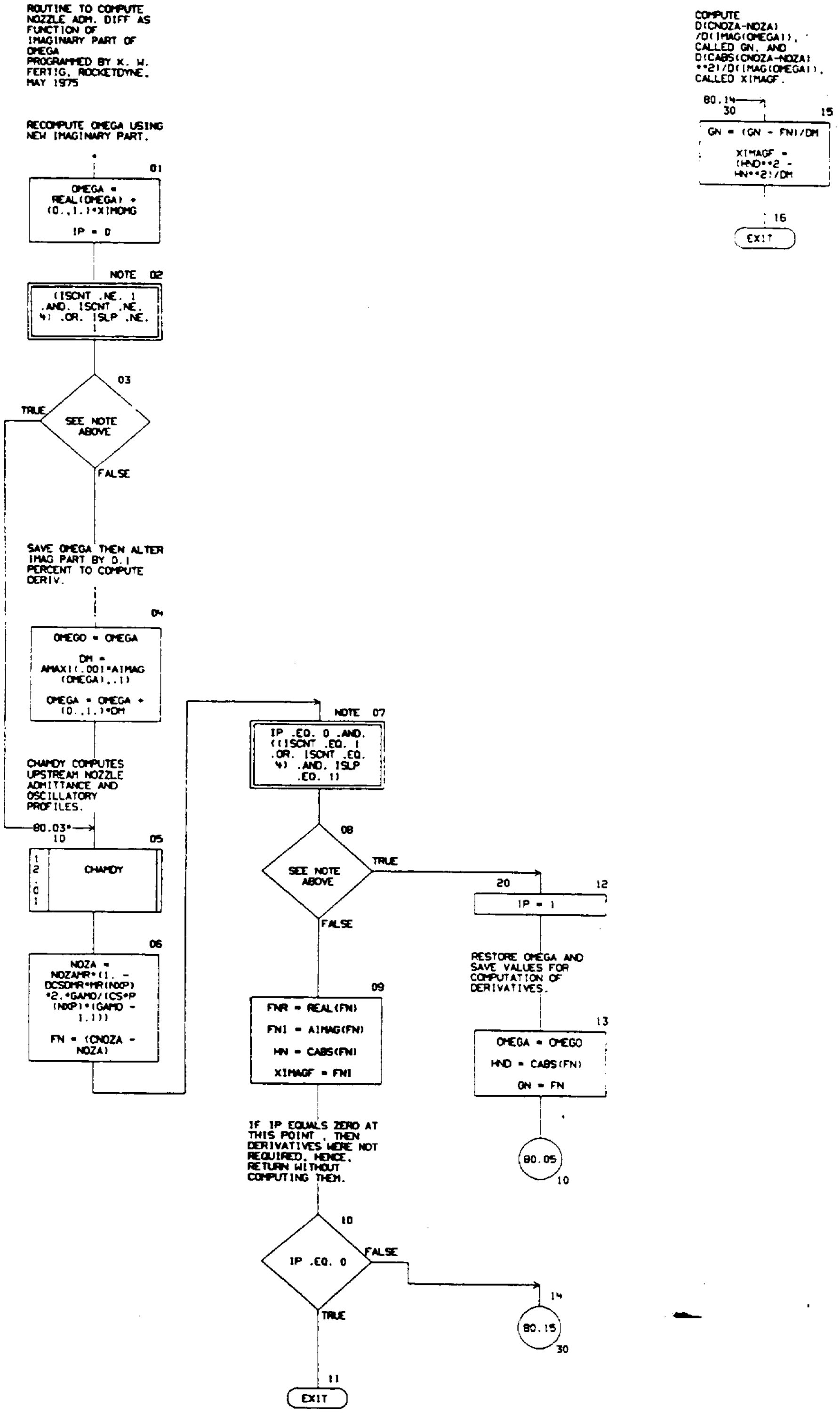


CHART TITLE - NON-PROCEDURAL STATEMENTS

```
COMPLEX OMEGA,NOZA,CNOZA,P,RHO,V,MR,T,VX0,FN,NOZAMR,GN,
     COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9,
     COX10, COX11, COX12, COX13, COX14, COX15, COX16,
     CFU1, CFU2, CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9,
     CFU10, CFU11, CFU12, CFU13, CFU14, CFU15, CFU16
    ,OMEGO
REAL  MBOX1, MBFU1, NUBOX, NUBFU, MWG
COMMON  /COMCBM/  XXOX, XXFU, MBOX1, MBFU1, TAUBOX, TAUBFU, VBOX,
     VBFU, GAMO, RGO, DELHOX, DELHFU, PC, CO,
     COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9, COX10,
     COX11, COX12, COX13, COX14, COX15, COX16, CFU1, CFU2,
     CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9, CFU10, CFU11,
     CFU12, CFU13, CFU14, CFU15, CFU16, MWG, XIMPFU, XIMPOX,
     CS, DCSDMR, DHDMR, DRGDMR, ADVOX, ADDOX, TDRAGO, DELVOX,
     NUBOX, DTOXDM, ADVFU, ADDFU, TDRAGF, DELVFU, NUBFU, DTFUDM
COMMON /FZERO/ NOZA,NOZAMR,GN,FN,FNR,FN1,HN,ISCNT,ISLP
COMMON /COMCHM/ P(100),RHO(100),V(100),MR(100),T(100),
               VX0,OMEGA,CNOZA,DELP
COMMON /COMARE/ NXP,X(100),XM(100),A(100),DA(100),DELX,
               X0,XNOZ,AINJ
```

CHART TITLE - SUBROUTINE ZADAMS(N,H,X,Y,DY,IQ2)

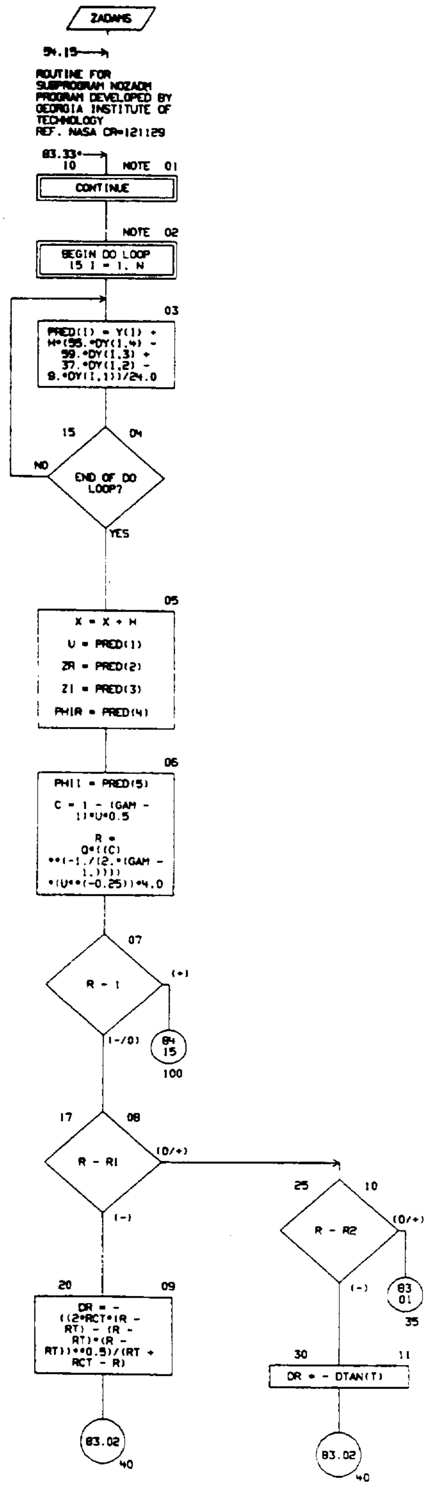


CHART TITLE - SUBROUTINE ZADAMS(N,H,X,Y,DY,IQZ)

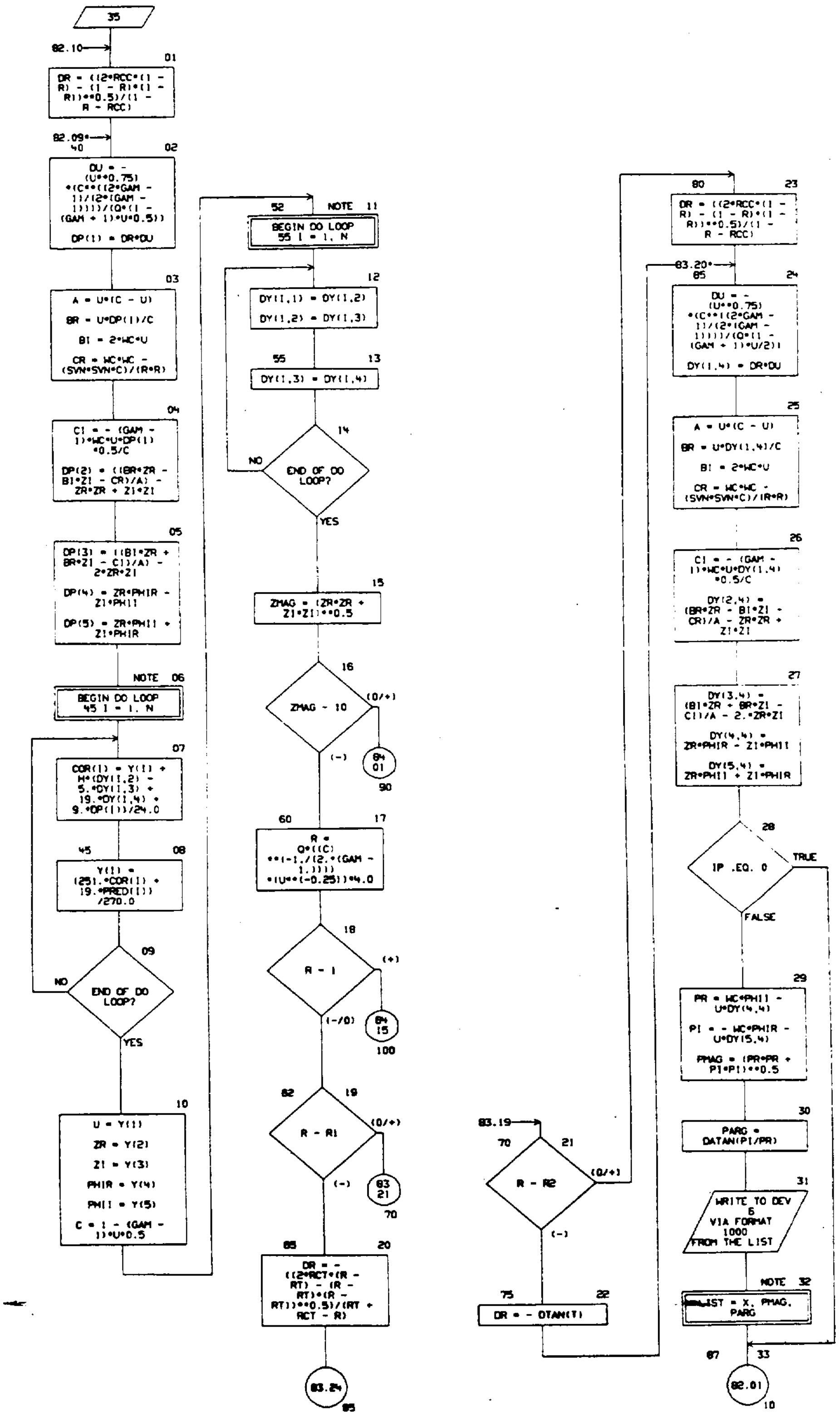


CHART TITLE - SUBROUTINE ZADAMS(N,H,X,Y,DY,IQZ)

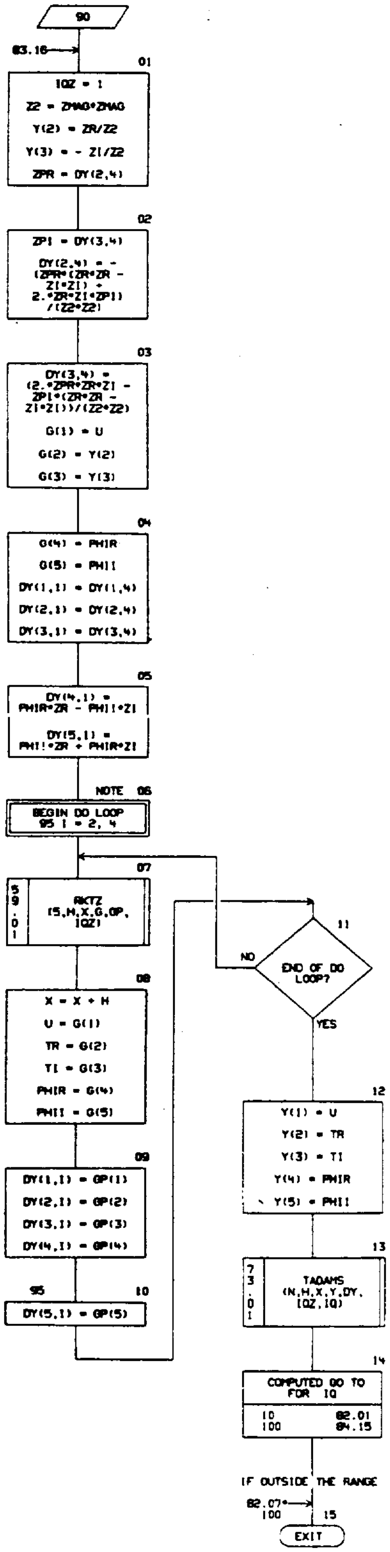


CHART TITLE - NON-PROCEDURAL STATEMENTS

```
         IMPLICIT REAL*8(A-H,O-Z)
         COMMON /X1/GAM,SVN,ANGLE,RCT,RCC /X2/T,RT,Q,R1,R2,HC,IP
               /X4/CM
         DIMENSION COR(5), DP(5), DY(5,4), PRED(5), Y(5), Q(5), GP(5)
16       FORMAT(3X,'PRINTING FROM CARD 3430',/,3X,'R=',E15.8,
            3X,'R1=',E15.8,3X,'RT=',E15.8)
61       FORMAT(3X,'PRINTING FROM CARD 3790',/,3X,'R=',E15.8,
            3X,'R1=',E15.8,3X,'RT=',E15.8)
1000     FORMAT(46X,F6.4,1X,F10.5,3X,F10.5)
```

CHART TITLE - SUBROUTINE ZERO(F1,T11,T21,F11,F21,ANS,FANS,EPSF,EPSX,AF,ICNT,NCN

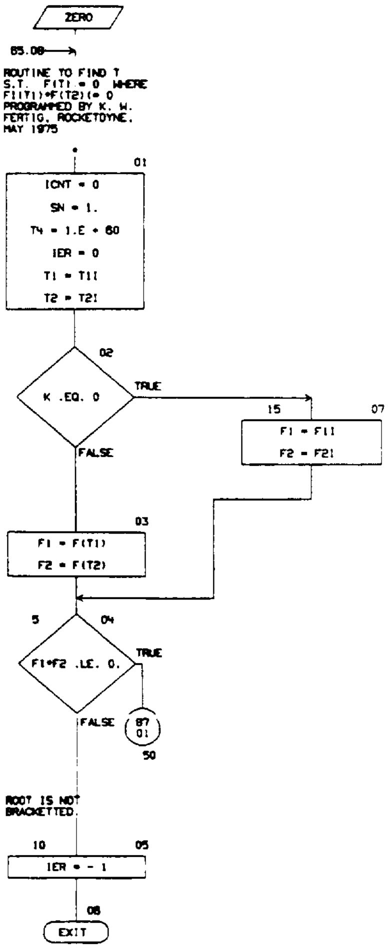


CHART TITLE - SUBROUTINE ZERO(F1,T1I,T2I,F1I,F2I,ANS,FANS,EPSF,EPSX,AF,ICNT,NCN

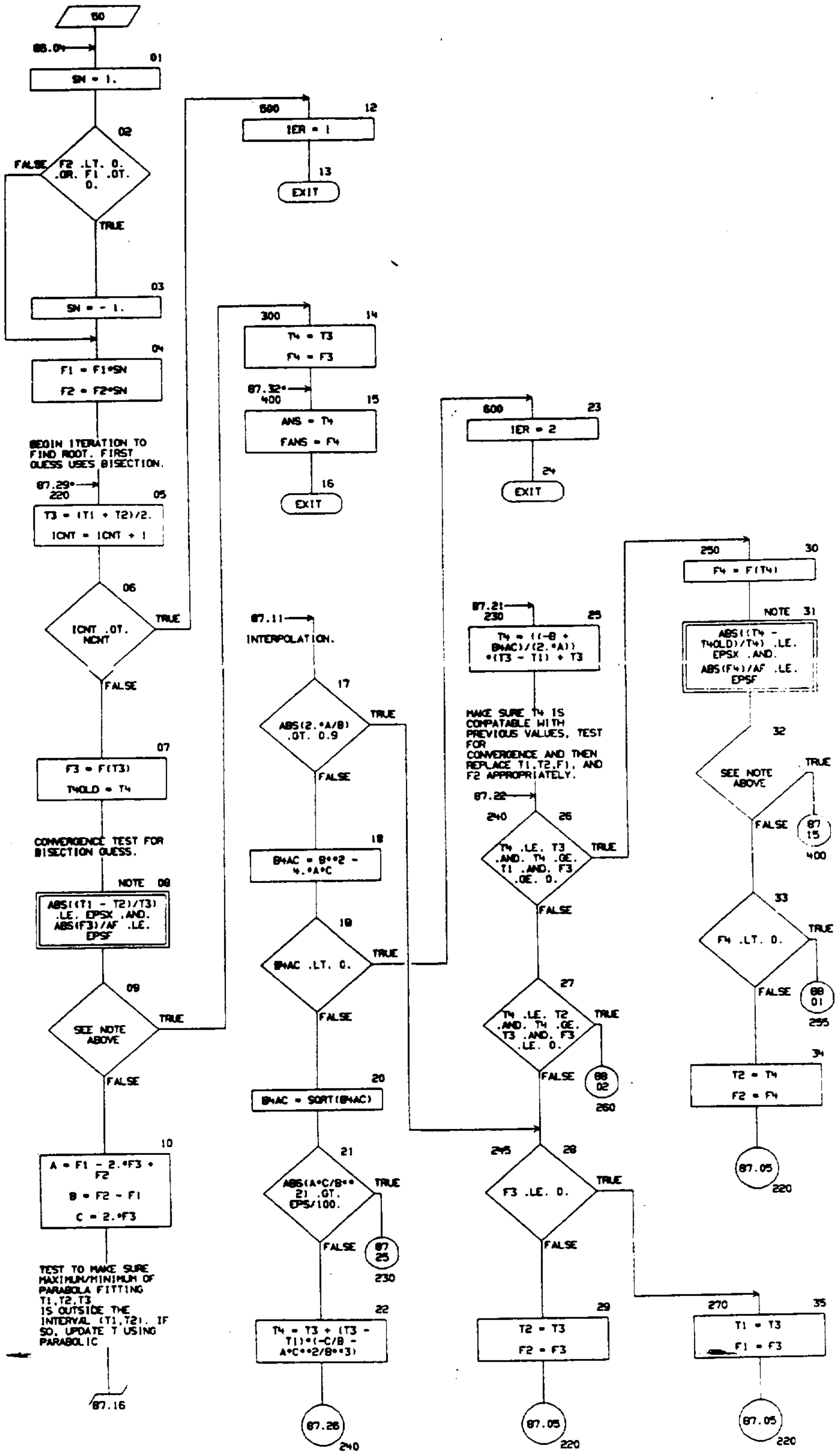
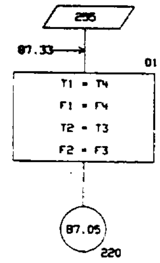
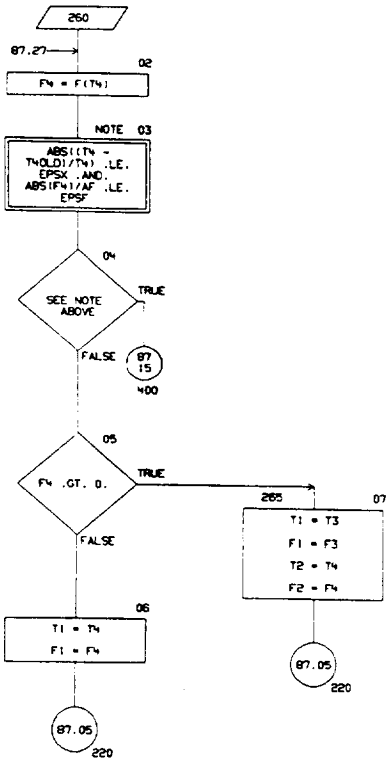


CHART TITLE - SUBROUTINE ZERO(F1,T11,T21,F11,F21,ANS,FANS,EPSF,EPSX,AF,ICNT,NCN





```
CHART TITLE - NON-PROCEDURAL STATEMENTS


                    STATEMENT FUNCTION DEFINITION.  F(X) = SN*F1(X)
```

```
END OF AUTOFLOW CHART SET          3,387 INPUT STATEMENTS PROCESSED          EXECUTION TIME -        4 MIN  21 SEC
```

APPENDIX C

COMPUTER CODE LISTINGS

F S C S M MAIN PROGRAM

```
C
C
C     MAIN CONTROL PROGRAM FOR THE FEED SYSTEM COUPLED STABILITY MODEL
C     PROGRAM DEVELOPED BY ROCKETDYNE, A DIVISION OF ROCKWELL
C        INTERNATIONAL, CANOGA PARK, CALIF 91304
C     PROGRAMMED BY M. D. SCHUMAN, ROCKETDYNE, MAY 1975
C
C
      DIMENSION TITLE(18,2)
C
      COMPLEX OMEGA, P, RHO, V, MR, T, CNOZA, VXO,
     1     COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9,
     2     COX10, COX11, COX12, COX13, COX14, COX15, COX16,
     3     CFU1, CFU2, CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9,
     4     CFU10, CFU11, CFU12, CFU13, CFU14, CFU15, CFU16,
     5     NOZA, GINJOX, GINJFU,
     6     NOZAT, GINJOT, GINJFT,
     7     FN, NOZAMR, GN,
     8     COXT(16), CFUT(16),
     9     COXTT(16,2), CFUTT(16,2)
C
      REAL  MBOXI, MBFUI, MRB, MRGI, MGI, NUBOX, NUBFU, KF, KO, L, MWG
C
      COMMON  /COMCBM/  XKOX, XKFU, MBOXI, MBFUI, TAUBOX, TAUBFU, VBOX,
     1     VBFU, GAMU, RGO, DELHOX, DELHFU, PC, CO,
     2     COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9, COX10,
     3     COX11, COX12, COX13, COX14, COX15, COX16, CFU1, CFU2,
     4     CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9, CFU10, CFU11,
     5     CFU12, CFU13, CFU14, CFU15, CFU16, MWG, XIMPFU, XIMPOX,
     6     CS, DCSDMR, DHDMR, DRGDMR, ADVOX, ADDOX, TDRAGO, DELVOX,
     7     NUBOX, DTOXDM, ADVFU, ADDFU, TDRAGF, DELVFU, NUBFU, DTFUDM
C
      EQUIVALENCE (COXT(1),COX1), (CFUT(1),CFU1)
```

FSCSM MAIN PROGRAM

```
C                                                                       00000340
      COMMON /CONSTS/  MRB(100), TB(100), RHOB(100), VB(100),           00000350
     1     DMRB(100), DRHOB(100), DVB(100), VAPBOX(100), VAPBFU(100),   00000360
     2     SSV1(100), SSV2(100), SSV3(100), SSV4(100),                  00000370
     3     SSV5(100), SSV6(100), SSV7(100), SSV8(100), SSV9OX(100),     00000380
     4     SSV9FU(100), SSV10(100), SSV11(100), SSV12(100), SSV13(100), 00000390
     5     SSV14(100), SSV15(100), SSV16(100),                          00000400
     6     RHOGI, VGI, MRGI, MGI                                        00000410
C                                                                       00000420
      COMMON /COMCHM/ P(100), RHO(100), V(100), MR(100), T(100),        00000430
     1     VX0, OMEGA, CNOZA, DELP                                      00000440
C                                                                       00000450
      COMMON /COMARE/ NXP, X(100), XM(100), A(100), DA(100), DELX,      00000460
     1     X0, XNOZ, AINJ                                               00000470
C                                                                       00000480
      COMMON /COMNOZ/ RCCX, RCTX, ANGLEX, CRR, RINJ, INPNOZ, FREQMX,    00000490
     1     FREQMI, IPRNOZ                                               00000500
C                                                                       00000510
      COMMON /FZERO/ NOZA,NOZAMR,GN,FN,FNR,FNI,HN,ISCNT,ISLP            00000520
C                                                                       00000530
      COMMON /DUMP/ IWRT                                                00000540
C                                                                       00000550
      DATA JK/1/,  JKK/1/,  PI/3.141593/                                00000560
C                                                                       00000570
      COMMON /SOLVE/ FREQ, DELFRQ, DELMX, EPSF, EPSX, EPSFS, EPSXS,     00000580
     1               FRQMAX, CTEST, IPASS, KNTR, ISTRT, KSCNT4, IWSKP,  00000590
     1               KNTMX, KNTSMX, KNTRMX                              00000600
C                                                                       00000610
      COMMON /COMTAP/ NFREQT, FREQT(100), NOZAT(100), GINJOT(100),      00000620
     1     GINJFT(100), ITAPN, ITAPC, ITAPH                             00000630
C                                                                       00000640
      COMMON /HY/ ICRT,IRFLAG,ITERM,ITYPE,IPRHYD,IX,AA(30),CW(30),KF,KO,00000650
     1     L(30),R(30),RHOL(30),VV(30),VF,VO,VOLF,VOLO,ZF,ZO,OSAVE(188),00000660
```

```
    2     FSAVE(166)                                                    00000670
C                                                                       00000680
    1 CONTINUE                                                          00000690
C                                                                       00000700
      CALL HEAD                                                         00000710
C                                                                       00000720
C      READ AND WRITE INPUT DATA                                        00000730
C                                                                       00000740
      READ(5,490,END=9000) ((TITLE(I,J),I=1,18),J=1,2)                  00000750
  490 FORMAT(18A4)                                                      00000760
      WRITE(6,900) ((TITLE(I,J),I=1,18),J=1,2)                          00000770
  900 FORMAT(1H1,///,26X,'FEED  SYSTEM  COUPLED  STABILITY  MODEL',/,   00000780
     1     9X,18A4,/,9X,18A4)                                           00000790
      READ(5,500,END=9000) INPHYD, INPCOM, INPNOZ, ITAPH, ITAPC, ITAPN, 00000860
     1     IPRHYD, IPRCOM, IPRNOZ, IPRCHM, IPRSTE, NXP                  00000870
  500 FORMAT(12I6)                                                      00000880
      WRITE(6,600) INPHYD, INPCOM, INPNOZ, ITAPH, ITAPC, ITAPN,         00000890
     1     IPRHYD, IPRCOM, IPRNOZ, IPRCHM, IPRSTE, NXP                  00000900
  600 FORMAT(/,5X,'INPHYD =',I2,5X,'INPCOM =',I2,5X,'INPNOZ =',I2,      00000910
     1     5X,'ITAPH =',I3,5X,'ITAPC =',I3,5X,'ITAPN =',I3,/,5X,        00000920
     2     'IPRHYD =',I2,5X,'IPRCOM =',I2,5X,'IPRNOZ =',I2,5X,          00000930
     3     'IPRCHM =',I2,5X,'IPRSTE =',I2,5X,'NXP =',I4)                00000940
C                                                                       00000950
      READ(5,510) X0, XNOZ, RINJ, GAMO, CO, DELP                        00000990
  510 FORMAT(6E12.8)                                                    00001000
      WRITE(6,610) X0, XNOZ, RINJ, GAMO, CO, DELP                       00001010
  610 FORMAT(/,5X,'X0 =',1PE11.4,7X,'XNOZ =',E11.4,5X,'RINJ =',         00001020
     1     E11.4,5X,'GAMO =',E11.4,/,27X,'CO =',E11.4,7X,'DELP =',      00001030
     2     E11.4)                                                       00001040
      X0 = X0*0.0254                                                    00001050
      XNOZ = XNOZ*0.0254                                                00001060
      RINJ = RINJ*0.0254                                                00001070
      CO = CO*0.3048                                                    00001080
```

```
C
      READ(5,500) NROOT, IWRT, IWSKP, KNTMX, KNTRMX, KNTSMX
      WRITE(6,620) NROOT, IWRT, IWSKP, KNTMX, KNTRMX, KNTSMX
  620 FORMAT(/,5X,'NROOT =',I3,5X,'IWRT =',I2,7X,'IWSKP =',I2,6X,
     1      'KNTMX =',I4,4X,'KNTRMX =',I4,3X,'KNTSMX =',I4)
C
      READ(5,510) OMEGA, FRQMAX, DELFRQ, DELMX, CTEST,
     1      EPSF, EPSX, EPSFS, EPSXS
      WRITE(6,630) OMEGA, FRQMAX, DELFRQ, DELMX, CTEST, EPSF, EPSX,
     1      EPSFS, EPSXS
  630 FORMAT(/,5X,'OMEGA(R)=',1PE11.4,2X,'OMEGA(I)=',E11.4,2X,
     1      'FRQMAX =',E11.4,3X,'DELFRQ =',E11.4,/,27X,'DELMX =',
     2      E11.4,4X,'CTEST =',E11.4,//,5X,'EPSF =',E11.4,5X,
     3      'EPSX =',E11.4,5X,'EPSFS =',E11.4,4X,'EPSXS =',E11.4)
C
      READ(5,510) PC, MBOXI, MBFUI
      WRITE(6,650) PC, MBOXI, MBFUI
  650 FORMAT(/,5X,'PC =',1PE11.4,7X,'MBOXI =',E11.4,4X,'MBFUI =',
     1      E11.4)
      PCIN = PC
      WOIN = MBOXI
      WFIN = MBFUI
      PC = PC*6894.76
      MBOXI = MBOXI*0.453592
      MBFUI = MBFUI*0.453592
C
      IF(NROOT.LT.0) OMEGA = 2.*PI*REAL(OMEGA) + (0.,-1.)*
     1                         REAL(OMEGA)*AIMAG(OMEGA)
      NROOT = IABS(NROOT)
      VGI = 0.0
      MGI = 0.0
C
C
```

F S C S M MAIN PROGRAM

```
C       COMPUTE AREA AND DISTANCE PROFILES.                             00001530
C                                                                       00001540
      AINJ = PI*RINJ*RINJ                                               00001550
      CALL AREA                                                         00001560
C                                                                       00001570
C       READ IN AND COMPUTE FREQUENCY TABLE IF INPNOZ .LE. 3            00001580
C                                                                       00001590
      IF(INPNOZ.GT.3) GO TO 1060                                        00001600
      READ(5,520) NFREQT, FREQMI, FREQMX                                00001640
  520 FORMAT(I12,5E12.8)                                                00001650
      WRITE(6,640) NFREQT, FREQMI, FREQMX                               00001660
  640 FORMAT(/,5X,'NFREQT =',I4,10X,'FREQMI =',1PE11.4,3X,              00001670
     1      'FREQMX =',E11.4)                                           00001680
      DELF = (FREQMX-FREQMI)/(NFREQT-1)                                 00001690
      DO 1050 I=1,NFREQT                                                00001700
      FREQT(I) = FREQMI+(I-1)*DELF                                      00001710
 1050 CONTINUE                                                          00001720
C                                                                       00001730
C       SET FLAG (IR=1) TO INDICATE FIRST PASS.                         00001740
C                                                                       00001750
 1060 IR = 1                                                            00001760
C                                                                       00001770
C       ISCNT = 1  : FREQUENCY BEING INCREMENTED TO ZERO IMAG F         00001780
C               2  : FREQUENCY STEP TO START TO START LOOP WITHIN LOOP  00001790
C               3  : LOOP WITIN LOOP                                    00001800
C               4  : STARTING SECANT METHOD                             00001810
C               5  : USING SECANT METHOD                                00001820
C                                                                       00001830
      OMEGA = OMEGA - 31.4                                              00001840
C                                                                       00001850
C       BEGIN DO LOOP TO SEARCH FOR OMEGAS THAT SATISFY BOUNDARY        00001860
C       CONDITION: UPSTREAM NOZZLE ADMITTANCE = DOWNSTREAM NOZZLE       00001870
C       ADMITTANCE.                                                     00001880
```

F S C S M MAIN PROGRAM

```
C
      DO 5000 NRT = 1,NROOT
C
C      CHANGE OMEGA BY 5 HERTZ TO START SEARCH FOR NEXT ROOT.
C
      OMEGA = OMEGA + 31.4
C
C      INITIALIZE FLAGS AND COUNTERS.
C
      ISCNT = 1
      IPASS = 1
      KNTR = 0
      ISTRT = 0
      KSCNT4 = 0
      FREQ = REAL(OMEGA)/(2.*PI)
C
C      THIS IS RETURN POINT FOR ITERATION TO FIND FREQUENCIES THAT
C      BRACKET A ROOT.
C
   10 OMEGA = 2.*PI*FREQ + (0.,1.)*AIMAG(OMEGA)
      IF(FREQ.GT.FRQMAX) GO TO 1
C
C      ISLP = 1 SETS FLAG TO COMPUTE DERIVATIVES IF ISCNT = 1 OR 4
C
      ISLP = 1
C
   15 IF((INPHYD.GE.3.OR.INPCOM.GE.3.OR.INPNOZ.GE.4)
     1          .AND.(IR.LE.0.OR.INPNOZ.LE.3))
     2    CALL LOCFAC(JKK,FREQ,FREQT,NFREQT,I1,F1)
C
C      COMPUTE DOWNSTREAM NOZZLE ADMITTANCE PAREMETER, NOZAMR.
C      (THROUGH STATEMENT 40)
C
```

F S C S M MAIN PROGRAM

```
      IF(INPNOZ.GT.3) GO TO 20                                          00002220
      CALL NOZADM(IR,CAMO,CO,FREQ,NOZAMR)                               00002230
      IF(INPNOZ.LE.1) GO TO 40                                          00002240
      IF(IPRNOZ.GT.0)  WRITE(6,900) ((TITLE(I,J),I=1,18),J=1,2)         00002245
      GO TO 25                                                          00002250
   20 IF(IR.LE.0) GO TO 30                                              00002260
      REWIND ITAPN                                                      00002270
      READ(ITAPN) NFREQT                                                00002280
      DO 22 I=1,NFREQT                                                  00002290
      READ(ITAPN) FREQT(I), NOZAT(I)                                    00002300
   22 CONTINUE                                                          00002310
   25 CALL LOCFAC(JK,FREQ,FREQT,NFREQT,I1,F1)                           00002320
   30 NOZAMR = NOZAT(I1)+F1*(NOZAT(I1+1)-NOZAT(I1))                     00002330
   40 CONTINUE                                                          00002340
C                                                                       00002350
C       COMPUTE FEED SYSTEM RESPONSE PARAMETERS, GINJOX AND GINJFU.     00002360
C       (THROUGH STATEMENT 70)                                          00002370
C                                                                       00002380
      IF(INPHYD.GT.2) GO TO 50                                          00002390
      CALL HYDRDY(IR,INPHYD,FREQ,GINJOX,GINJFU,PCIN,WOIN,WFIN)          00002400
      IF(INPHYD.GT.1) GO TO 45                                          00002405
      GINJOX = REAL(GINJOX)*CEXP((0.0,-1.0)*AIMAG(GINJOX)*PI/180.)      00002406
      GINJFU = REAL(GINJFU)*CEXP((0.0,-1.0)*AIMAG(GINJFU)*PI/180.)      00002407
      GO TO 70                                                          00002408
   45 IF(IPRHYD.GT.0)  WRITE(6,900) ((TITLE(I,J),I=1,18),J=1,2)         00002410
   50 IF(IR.LE.0) GO TO 60                                              00002420
      REWIND ITAPH                                                      00002430
      READ(ITAPH) (GINJOT(I),GINJFT(I),I=1,NFREQT)                      00002440
      DO 55 I=1,NFREQT                                                  00002450
      GINJOT(I) = REAL(GINJOT(I))*CEXP((0.0,-1.0)*                      00002460
     1     AIMAG(GINJOT(I))*PI/180.)                                    00002470
      GINJFT(I) = REAL(GINJFT(I))*CEXP((0.0,-1.0)*                      00002480
     1     AIMAG(GINJFT(I))*PI/180.)                                    00002490
```

```
   55 CONTINUE
   60 GINJOX = GINJOT(I1)+F1*(GINJOT(I1+1)-GINJOT(I1))
      GINJFU = GINJFT(I1)+F1*(GINJFT(I1+1)-GINJFT(I1))
   70 CONTINUE
C
C       COMPUTE COMBUSTION COEFFICIENTS. (THROUGH STATEMENT 110)
C
      IF(INPCOM.GT.2) GO TO 80
      CALL COMBDY(IR,FREQ,GINJOX,GINJFU,IPRCOM,INPCOM)
      IF(INPCOM.LE.1) GO TO 110
   80 IF(IR.LE.0) GO TO 82
      REWIND ITAPC
      READ(ITAPC) XKOX, TAUBOX, VBOX, DELHOX, TDRAGO, ADVOX,
     1     ADDOX, DELVOX, NUBOX, DTOXDM, XIMPOX, XKFU, TAUBFU,
     2     VBFU, DELHFU, TDRAGF, ADVFU, ADDFU, DELVFU, NUBFU,
     3     DTFUDM, XIMPFU, MWG, CS, DRGDMR, DCSDMR, DHDMR, RGO
      I10 = -1
   82 NI = 1
      IF(I1-I10) 84, 96, 92
   84 NI = I10-I1+1
   86 DO 88 I=1,NI
   88 BACKSPACE ITAPC
      READ(ITAPC) (COXTT(J,1),CFUTT(J,1),J=1,16)
   90 READ(ITAPC) (COXTT(J,2),CFUTT(J,2),J=1,16)
      GO TO 96
   92 IF(I1.EQ.I10+1) GO TO 86
      NI = I10+2
      DO 94 I=NI,I1
   94 READ(ITAPC) (COXTT(J,1),CFUTT(J,1),J=1,16)
      GO TO 90
   96 I10 = I1
      DO 100 J=1,16
      COXT(J) = COXTT(J,1)+F1*(COXTT(J,2)-COXTT(J,1))
```

```
  100 CFUT(J) = CFUTT(J,1)+F1*(CFUTT(J,2)-CFUTT(J,1))
  110 CONTINUE
C
C        COMPUTE STEADY STATE PROFILES IF THIS IS FIRST PASS.
C
      IF(IR.GT.0) CALL STEADY(IPRSTE)
      IR = 0
      VX0 = 0.0
C
C      CALL SOLVW TO FINISH COMPUTATIONS FOR THIS OMEGA/FREQUENCY.
C      UPDATE OMEGA TO NEW GUESS IF ISCNT = 4 OR 5 AND CONVERGENCE HAS
C      NOT BEEN REACHED. WHEN ISCNT=1 OR 4, TWO PASSES WILL BE MADE PAST
C      THIS POINT(ONE WITH ISLP=1 AND ONE WITH ISLP=0) IN ORDER TO
C      COMPUTE JACOBIAN.
C
      CALL SOLVW(KWHERE)
      GO TO (10,15,225,225,5000), KWHERE
C
C
C      CONVERGENCE HAS BEEN REACHED. PRINT RESULTS
C      (THROUGH STATEMENT 300).
C
  225 CONTINUE
C
      IF(NRT.LE.1.OR.IPRCHM.GT.0.OR.IPRCOM.GT.0)
     1     WRITE(6,900) ((TITLE(I,J),I=1,18),J=1,2)
      IF(IPRCOM.LE.0) GO TO 1090
      WRITE(6,1080)
 1080 FORMAT(///,20X,'COMBUSTION DYNAMIC COEFFICIENTS',/)
      DO 1085 I=1,16
      WRITE(6,1081) I, COXT(I), I, CFUT(I)
 1081 FORMAT(5X,'COX(',I2,') =',1PE11.4,':',E11.4,5X,'CFU(',I2,
     1     ') =',E11.4,':',E11.4)
```

```
 1085 CONTINUE                                                          00003160
C                                                                       00003170
 1090 CONTINUE                                                          00003180
      DEC = -AIMAG(OMEGA)/REAL(OMEGA)                                   00003190
      WRITE(6,2000) FREQ, DEC, NOZA, GINJOX, GINJFU                     00003200
 2000 FORMAT(///,10X,'FREQUENCY =',F8.2,' HZ,',/,10X,                   00003210
     1     'DECREMENT =',F8.5,//,                                       00003220
     2     10X,'NOZZLE ADMITTANCE =',F9.5,':',2X,F9.5,//,10X,           00003230
     3     'FEED SYSTEM RESPONSE',/,20X,'OXIDIZER =',F9.5,':',2X,F9.5,  00003240
     4     /,24X,'FUEL =',F9.5,':',2X,F9.5,///)                         00003250
C                                                                       00003260
      IF(IPRCHM.LE.0) GO TO 5000                                        00003270
      IF(IPRCOM.GT.0)  WRITE(6,900) ((TITLE(I,J),I=1,18),J=1,2)         00003275
      WRITE(6,2010)                                                     00003280
 2010 FORMAT(10X,4(11X,'OSCILLATORY'),/,5X,'DISTANCE',6X,               00003290
     1     'PRESSURE  RATIO',7X,'VELOCITY  RATIO',6X,                   00003300
     2     'TEMPERATURE RATIO',7X,'MIXTURE RATIO',/,5X,'(INCHES)',      00003310
     3     4(5X,'AMPLITUDE   PHASE'),/)                                 00003320
      DO 300 I=1,NXP                                                    00003330
      AP = CABS(P(I))                                                   00003340
      IF(AP.LE.0.0.AND.I.LT.NXP) P(I)=P(I+1)*1.E-10                     00003350
      IF(AP.LE.0.0.AND.I.GE.NXP) P(I)=P(I-1)*1.E-10                     00003360
      PP = ATAND(AIMAG(P(I)),REAL(P(I)))                                00003370
      AV = CABS(V(I))                                                   00003380
      IF(AV.LE.0.0.AND.I.LT.NXP) V(I)=V(I+1)*1.E-10                     00003390
      IF(AV.LE.0.0.AND.I.GE.NXP) V(I)=V(I-1)*1.E-10                     00003400
      PV = ATAND(AIMAG(V(I)),REAL(V(I)))                                00003410
      AT = CABS(T(I))                                                   00003420
      IF(AT.LE.0.0.AND.I.LT.NXP) T(I)=T(I+1)*1.E-10                     00003430
      IF(AT.LE.0.0.AND.I.GE.NXP) T(I)=T(I-1)*1.E-10                     00003440
      PT = ATAND(AIMAG(T(I)),REAL(T(I)))                                00003450
      AMR = CABS(MR(I))                                                 00003460
      IF(AMR.LE.0.0.AND.I.LT.NXP) MR(I)=MR(I+1)*1.E-10                  00003470
```

```
      IF(AMR.LE.0.0.AND.I.GE.NXP) MR(I)=MR(I-1)*1.E-10
      PMR = ATAND(AIMAG(MR(I)),REAL(MR(I)))
      XP = X(I)/0.0254
      WRITE(6,2020) XP, AP, PP, AV, PV, AT, PT, AMR, PMR
 2020 FORMAT(5X,F8.4,4(5X,F8.5,2X,F7.2))
  300 CONTINUE
C
C       END OF DO LOOP TO FIND OMEGAS SATISFYING BOUNDARY CONDITIONS.
C
 5000 CONTINUE
      GO TO 1
C
 9000 CALL EXIT
      STOP
      END
```

```
      SUBROUTINE AREA                                                   00000010
C                                                                       00000020
C     SUBPROGRAM CALCULATES CHAMBER AREA AND AXIAL DISTANCES            00000030
C     PROGRAMMED BY M. D. SCHUMAN, ROCKETDYNE, MAY 1975                 00000040
C                                                                       00000050
      COMMON /COMARE/ NXP, X(100), XM(100), A(100), DA(100), DELX,      00000060
     1     XO, XNOZ, AINJ                                               00000070
C                                                                       00000080
      NXPM1 = NXP-1                                                     00000090
      DELX = (XNOZ-XO)/(NXPM1)                                          00000100
      X(1) = XO                                                         00000110
      A(1) = AINJ                                                       00000120
      DA(1) = 0.0                                                       00000130
C                                                                       00000140
      DO 10 I=2,NXP                                                     00000150
      X(I) = XO+DELX*(I-1)                                              00000160
      A(I) = AINJ                                                       00000170
      DA(I) = 0.0                                                       00000180
   10 CONTINUE                                                          00000190
C                                                                       00000200
      DO 20 I=1,NXPM1                                                   00000210
      XM(I) = (X(1)+X(I+1))/2.0                                         00000220
   20 CONTINUE                                                          00000230
      XM(NXP) = XM(NXPM1)+DELX                                          00000240
      A(NXP) = AINJ                                                     00000250
      DA(NXP) = 0.0                                                     00000260
C                                                                       00000270
      RETURN                                                            00000280
      END                                                               00000290
```

```
      SUBROUTINE  CHAMDY
C
C     SUBPROGRAM CALCULATES THE OSCILLATORY PRESSURE, TEMPERATURE,
C        VELOCITY, MIXTURE RATIO, AND DENSITY PROFILES PLUS THE
C        UPSTREAM NOZZLE ADMITTANCE FROM THE CHAMBER DYNAMIC EQUATIONS
C     PROGRAMMED BY K. W. FERTIG AND M. D. SCHUMAN, ROCKETDYNE, MAY 1975
C
      COMPLEX*16  AMA(4,5), CMA(4)
C
      COMPLEX OMEGA, P, RHO, V, MR, T, CNOZA, VXO,
     1     COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9,
     2     COX10, COX11, COX12, COX13, COX14, COX15, COX16,
     3     CFU1, CFU2, CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9,
     4     CFU10, CFU11, CFU12, CFU13, CFU14, CFU15, CFU16
C
      COMPLEX DM1,  DM3, DM4, DM5, DM6, DM7OX, DM7FU, DM8OX,
     1     DM8FU, G1OX, G1FU, G2OX, G2FU, G3OX, G3FU, G4OX, G4FU,
     2     RBSOX, RBSFU, PINTOX, PINTFU, RHNTOX, RHNTFU, MRNTOX,
     3     MRNTFU, VINTOX, VINTFU, II
     4     ,DM9OX,DM9FU
C
      REAL  MBOXI, MBFUI, MRB, MRGI, MGI, NUBOX, NUBFU, MWG
C
      COMMON  /COMCBM/  XKOX, XKFU, MBOXI, MBFUI, TAUBOX, TAUBFU, VBOX,
     1     VBFU, GAMO, RGO, DELHOX, DELHFU, PC, CO,
     2     COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9, COX10,
     3     COX11, COX12, COX13, COX14, COX15, COX16, CFU1, CFU2,
     4     CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9, CFU10, CFU11,
     5     CFU12, CFU13, CFU14, CFU15, CFU16, MWG, XIMPFU, XIMPOX,
     6     CS, DCSDMR, DHDMR, DRGDMR, ADVOX, ADDOX, TDRAGO, DELVOX,
     7     NUBOX, DTOXDM, ADVFU, ADDFU, TDRAGF, DELVFU, NUBFU, DTFUDM
C
      COMMON /CONSTS/  MRB(100), TB(100), RHOB(100), VB(100),
```

F S C S M SUBROUTINES

```
     1      DMRB(100), DRHOB(100), DVB(100), VAPBOX(100), VAPBFU(100),   00000340
     2      SSV1(100), SSV2(100), SSV3(100), SSV4(100),                  00000350
     3      SSV5(100), SSV6(100), SSV7(100), SSV8(100), SSV9OX(100),     00000360
     4      SSV9FU(100), SSV10(100), SSV11(100), SSV12(100), SSV13(100), 00000370
     5      SSV14(100), SSV15(100), SSV16(100),                          00000380
     6      RHOGI, VGI, MRGI, MGI                                        00000390
C                                                                        00000400
      COMMON /COMCHM/ P(100), RHO(100), V(100), MR(100), T(100),         00000410
     1      VXO, OMEGA, CNOZA, DELP                                      00000420
C                                                                        00000430
      COMMON /COMARE/ NXP, X(100), XM(100), A(100), DA(100), DELX,       00000440
     1      XO, XNOZ, AINJ                                               00000450
C                                                                        00000460
      COMMON /ADARND/ G1OX,G2OX,G3OX,G4OX,G1FU,G2FU,G3FU,G4FU,PINTOX,    00000470
     1         RHNTOX,MRNTOX,VINTOX,PINTFU,RHNTFU,MRNTFU,VINTFU,RBSOX,   00000480
     2         RBSFU,DM1,DM3,DM4,DM5,DM6,DM7OX,DM8OX,DM9OX,DM7FU,        00000490
     3         DM8FU,DM9FU,II,DM2,DM22,RHOINJ                            00000500
C                                                                        00000510
      COMMON /DUMP/ IWRT                                                 00000520
C                                                                        00000530
      EQUIVALENCE (AMA(1,5),CMA(1))                                      00000540
C                                                                        00000550
      NXPM1 = NXP-1                                                      00000560
C                                                                        00000570
C       COMPUTE BOUNDARY CONDITIONS AT X=XO.                             00000580
C                                                                        00000590
      RHOINJ = DELP/GAMO                                                 00000600
      DM2 = CO**2*RHOGI/(GAMO*PC)                                        00000610
      DM22 = SQRT(DM2)                                                   00000620
      DM1 = CEXP((0.,-1.)*OMEGA/CO*DM2*VGI/CO*XO)                        00000630
      DM3 = DM22*OMEGA*XO/CO                                             00000640
      P(1) = DM1*(DELP*CCOS(DM3)+(0.,1.)*GAMO*DM22*VXO*CSIN(DM3))        00000650
      RHO(1) = P(1)/GAMO                                                 00000660
```

```
      V(1) = DM1*((0.,1.)*DELP/(GAMO*DM22)*CSIN(DM3)+VXO*CCOS(DM3))
      DM1 = CEXP((0.,1.)*OMEGA*XO/VBOX)
      DM3 = CEXP((0.,1.)*OMEGA*XO/VBFU)
      DM4 = DELP*(COX1*DM1-CFU1*DM3) + P(1)*(COX2-CFU2)
     1      + DELP/GAMO*(COX3*DM1-CFU3*DM3) + RHO(1)*(COX4-CFU4)
     2      + VXO*(COX7*DM1-CFU7*DM3) + V(1)*(COX8-CFU8)
      DM2 = (MRGI+1.)*MRGI*MBFUI/(A(1)*RHOGI*CO)
      DM4 = DM2*DM4 - V(1)*MRGI*(MRGI+1.)*(1.-MRGI*MBFUI/MBOXI)/
     1                                       (MRGI+2.)
      DM5 = DM2*(COX5*DM1-CFU5*DM3 + COX6-CFU6)
      DM5 = MBFUI*(MRGI+1.)/(A(1)*RHOGI*CO) - (0.,1.)*OMEGA*TAUBFU
     1                     *VBFU/CO  -  DM5
      MR(1) = DM4/DM5
      T(1) = P(1) - RHO(1) - MR(1)*DRGDMR/(RGO*(1.
     1            + DRGDMR*(MRGI-MBOXI/MBFUI)/RGO))
C
C       INITIALIZE INTEGRALS USED IN VAPORIZATION EXPRESSION.
C
      PINTOX = (0.,0.)
      RHNTOX = (0.,0.)
      MRNTOX = (0.,0.)
      VINTOX = (0.,0.)
      PINTFU = (0.,0.)
      RHNTFU = (0.,0.)
      MRNTFU = (0.,0.)
      VINTFU = (0.,0.)
      II = (0.,1.)
C
      I = 1
C
      IF(IWRT.GT.0) WRITE(6,9000) OMEGA,I,P(1),RHO(1),MR(1),V(1),T(1)
 9000 FORMAT(///'  OMEGA = ',1P2E13.5//3X,'I',11X,'P',19X,'RHO',
     1    20X,'MR',20X,'V',21X,'T'//1X,I3,1P1(E11.4)
```

```
C
   10 CONTINUE
C
C        CHMCON COMPUTES MOST OF THE VARIABLES IN /ADARND/
C
      CALL CHMCON(I)
C
      DM1 = -II*OMEGA*DELX/CO
C
C        ENERGY EQUATION
C
      AMA(1,1) = DM1 + 2.*SSV1(I)+SSV7(I)-SSV2(I)*(SSV5(I)*G1OX
     1           +SSV6(I)*G1FU)
      AMA(1,2) = -SSV2(I)*(SSV5(I)*G2OX+SSV6(I)*G2FU)
      AMA(1,3) = 2.*GAMO + SSV8(I) - SSV2(I)*(SSV5(I)*G4OX
     1           +SSV6(I)*G4FU)
      AMA(1,4) = -SSV2(I)*(SSV5(I)*G3OX+SSV6(I)*G3FU - SSV9OX(I)
     1            + SSV9FU(I))
      CMA(1) = SSV2(I)*(SSV5(I)*RBSOX + SSV6(I)*RBSFU - SSV9OX(I)*
     1            MR(I) + SSV9FU(I)*MR(I))
     2         - P(I)*(DM1-2.*SSV1(I)+SSV7(I))
     3         - V(I)*(-2.*GAMO + SSV8(I))
C
C        CONTINUITY EQUATION
C
      AMA(2,1) = -SSV10(I)*(G1OX+G1FU)
      AMA(2,2) = DM1 + 2.*SSV1(I) + SSV4(I) - SSV10(I)*(G2OX+G2FU)
      AMA(2,3) = 2. + SSV11(I) - SSV10(I)*(G4OX+G4FU)
      AMA(2,4) = -SSV10(I)*(G3OX+G3FU)
      CMA(2) = SSV10(I)*(RBSOX+RBSFU) - DM1*RHO(I) + 2.*V(I)
     1         - V(I)*SSV11(I) + 2.*SSV1(I)*RHO(I) - RHO(I)*SSV4(I)
C
C        MOMENTUM EQUATION
```

```
C                                                                       00001330
      AMA(3,1) = SSV12(I)                                               00001340
      AMA(3,2) = (0.,0.)                                                00001350
      AMA(3,3) = DM1 + 2.*SSV1(I) + SSV3(I)                             00001360
      AMA(3,4) = (0.,0.)                                                00001370
      CMA(3) = V(I)*(-DM1-SSV3(I)+2.*SSV1(I)) + SSV12(I)*P(I)           00001380
C                                                                       00001390
C      MIXTURE RATIO EQUATION                                           00001400
C                                                                       00001410
      AMA(4,1) = -SSV13(I)*(G1OX-MRB(I)*G1FU)                           00001420
      AMA(4,2) = SSV14(I) - SSV13(I)*(G2OX-MRB(I)*G2FU)                 00001430
      AMA(4,3) = DELX*DMRB(I) - SSV13(I)*(G4OX-MRB(I)*G4FU)             00001440
      AMA(4,4) = DM1 + 2.*SSV1(I) - SSV13(I)*(G3OX-MRB(I)*G3FU)         00001450
     1           - SSV15(I)                                             00001460
      CMA(4) = SSV15(I)*(RBSOX-MRB(I)*RBSFU) + MR(I)*(SSV15(I)          00001470
     1        -DM1 + 2.*SSV1(I)) - DELX*DMRB(I)*(SSV1(I)*RHO(I)         00001480
     2                + V(I))                                           00001490
C                                                                       00001500
C      SOLVE 4 BY 4 SYSTEM OF COMPLEX EQUATIONS                         00001510
C                                                                       00001520
      CALL COMMAT(AMA,4,4)                                              00001530
C                                                                       00001540
      IP1 = I+1                                                         00001550
C                                                                       00001560
C      P FROM ENERGY EQUATION.                                          00001570
C                                                                       00001580
      P(IP1) = CMA(1)                                                   00001590
C                                                                       00001600
C      RHO FROM CONTINUITY EQUATION.                                    00001610
C                                                                       00001620
      RHO(IP1) = CMA(2)                                                 00001630
C                                                                       00001640
C      V FROM MOMENTUM EQUATION.                                        00001650
```

```
C
      V(IP1) = CMA(3)
C
C      MR FROM MIXTURE RATIO EQUATION.
C
      MR(IP1) = CMA(4)
C
C      T FROM EQUATION OF STATE.
C
      T(IP1) = P(IP1)-RHO(IP1)-SSV16(I)*MR(IP1)
      IF(IWRT.GT.0) WRITE(6,9100) IP1,P(IP1),RHO(IP1),MR(IP1),
     1                 V(IP1),T(IP1)
 9100 FORMAT(1X,I3,1P10E11.4)
C
C      UPDATE INTEGRALS FOR NEXT STEP.
C
      DM7OX = 2.*DM7OX*CEXP(-II*OMEGA*X(I)/VBOX)
      PINTOX = PINTOX + DM7OX*(P(I)*DM8OX+P(IP1)*DM9OX)
      RHNTOX = RHNTOX + DM7OX*(RHO(I)*DM8OX+RHO(IP1)*DM9OX)
      MRNTOX = MRNTOX + DM7OX*(MR(I)*DM8OX+MR(IP1)*DM9OX)
      VINTOX = VINTOX + DM7OX*(V(I)*DM8OX+V(IP1)*DM9OX)
      DM7FU = 2.*DM7FU*CEXP(-II*OMEGA*X(I)/VBFU)
      PINTFU = PINTFU + DM7FU*(P(I)*DM8FU+P(IP1)*DM9FU)
      RHNTFU = RHNTFU + DM7FU*(RHO(I)*DM8FU+RHO(IP1)*DM9FU)
      MRNTFU = MRNTFU + DM7FU*(MR(I)*DM8FU+MR(IP1)*DM9FU)
      VINTFU = VINTFU + DM7FU*(V(I)*DM8FU+V(IP1)*DM9FU)
C
      I = I+1
      IF(I.LE.NXPM1) GO TO 10
C
C      COMPUTE UPSTREAM NOZZLE ADMITTANCE.
C
      CNOZA = GAMO*V(NXP)/P(NXP)
```

```
C
      RETURN
      END
```

F S C S M SUBROUTINES

```
      SUBROUTINE  CHMCON(I)                                             00000010
C                                                                       00000020
C     ROUTINE TO CALCULATE PARAMETERS FOR SUBPROGRAM CHAMDY             00000030
C     PROGRAMMED BY K. W. FERTIG, ROCKETDYNE, MAY 1975                  00000040
C                                                                       00000050
      COMPLEX OMEGA, P, RHO, V, MR, T, CNOZA, VXO,                      00000080
     1     COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9,        00000090
     2     COX10, COX11, COX12, COX13, COX14, COX15, COX16,             00000100
     3     CFU1, CFU2, CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9,        00000110
     4     CFU10, CFU11, CFU12, CFU13, CFU14, CFU15, CFU16              00000120
      COMPLEX DM1,  DM3, DM4, DM5, DM6, DM7OX, DM7FU, DM8OX,            00000130
     1     DM8FU, G1OX, G1FU, G2OX, G2FU, G3OX, G3FU, G4OX, G4FU,       00000140
     2     RBSOX, RBSFU, PINTOX, PINTFU, RHNTOX, RHNTFU, MRNTOX,        00000150
     3     MRNTFU, VINTOX, VINTFU, II                                   00000160
     4     ,DM9OX,DM9FU                                                 00000170
C                                                                       00000180
      REAL  MBOXI, MBFUI, MRB, MRGI, MGI, NUBOX, NUBFU, MWG             00000190
C                                                                       00000200
      COMMON  /COMCBM/  XKOX, XKFU, MBOXI, MBFUI, TAUBOX, TAUBFU, VBOX, 00000210
     1     VBFU, GAMO, RGO, DELHOX, DELHFU, PC, CO,                     00000220
     2     COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9, COX10, 00000230
     3     COX11, COX12, COX13, COX14, COX15, COX16, CFU1, CFU2,        00000240
     4     CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9, CFU10, CFU11,      00000250
     5     CFU12, CFU13, CFU14, CFU15, CFU16, MWG, XIMPFU, XIMPOX,      00000260
     6     CS, DCSDMR, DHDMR, DRGDMR, ADVOX, ADDOX, TDRAGO, DELVOX,     00000270
     7     NUBOX, DTOXDM, ADVFU, ADDFU, TDRAGF, DELVFU, NUBFU, DTFUDM   00000280
C                                                                       00000290
      COMMON /CONSTS/  MRB(100), TB(100), RHOB(100), VB(100),           00000300
     1     DMRB(100), DRHOB(100), DVB(100), VAPBOX(100), VAPBFU(100),   00000310
     2     SSV1(100), SSV2(100), SSV3(100), SSV4(100),                  00000320
     3     SSV5(100), SSV6(100), SSV7(100), SSV8(100), SSV9OX(100),     00000330
     4     SSV9FU(100), SSV10(100), SSV11(100), SSV12(100), SSV13(100), 00000340
     5     SSV14(100), SSV15(100), SSV16(100),                          00000350
```

```
     6     RHOGI, VGI, MRGI, MGI
C
      COMMON /COMCHM/ P(100), RHO(100), V(100), MR(100), T(100),
     1     VXC, OMEGA, CNOZA, DELP
C
      COMMON /COMARE/ NXP, X(100), XM(100), A(100), DA(100), DELX,
     1     XO, XNOZ, AINJ
C
      COMMON /ADARND/ G1OX,G2OX,G3OX,G4OX,G1FU,G2FU,G3FU,G4FU,PINTOX,
     1        RHNTOX,MRNTOX,VINTOX,PINTFU,RHNTFU,MRNTFU,VINTFU,RBSOX,
     2        RBSFU,DM1,DM3,DM4,DM5,DM6,DM7OX,DM8OX,DM9OX,DM7FU,
     3        DM8FU,DM9FU,II,DM2,DM22,RHOINJ
C
   10 DM1 = CEXP(II*OMEGA*(XM(I))/VBOX)
      DM2 = (XM(I)-XO)/(TAUBOX*VBOX)
      DM6 = CEXP(II*OMEGA*DELX/VBOX)
      DM3 = CEXP(II*OMEGA*X(I)/VBOX)*(1.+DM6)/2.
C
C      CALCULATE OXIDIZER VAPORIZATION PARAMETERS.
C
      DM7OX  = VBOX/(2.*OMEGA**2*DELX*TAUBOX)
      DM8OX  = 1. - II*OMEGA*DELX/VBOX - 1./DM6
      DM9OX  = 1. + II*OMEGA*DELX/VBOX - DM6
      DM4  = DM7OX*DM8OX*DM6
      DM5  = DM7OX*DM9OX
      DM9OX  = DM9OX/DM6
      RBSOX  = DELP*DM1*(COX1+COX9*DM2)
     1       +RHOINJ*DM1*(COX3+COX11*DM2)+MR(1)*DM1*(COX5+COX13*DM2)
     2       +VXO*DM1*(COX7+COX15*DM2)
      RBSOX  = RBSOX+DM3*(COX10*PINTOX+COX12*RHNTOX+COX14*MRNTOX
     1                    +COX16*VINTOX)
      RBSOX  = RBSOX+P(I)*(COX2/2.+COX10*DM4) + RHO(I)*(COX4/2.
     1       +COX12*DM4) + MR(I)*(COX6/2.+COX14*DM4)
```

```
     2      + V(I)*(COX8/2.+COX16*DM4)                                  00000710
      RBSOX = VAPBOX(I)*RBSOX                                           00000720
      G1OX = VAPBOX(I)*(COX2/2.+COX10*DM5)                              00000730
      G2OX = VAPBOX(I)*(COX4/2.+COX12*DM5)                              00000740
      G3OX = VAPBOX(I)*(COX6/2.+COX14*DM5)                              00000750
      G4OX = VAPBOX(I)*(COX8/2.+COX16*DM5)                              00000760
C                                                                       00000770
      DM1 = CEXP(II*OMEGA*(XM(I))/VBFU)                                 00000780
      DM2 = (XM(I)-XO)/(TAUBFU*VBFU)                                    00000790
      DM6 = CEXP(II*OMEGA*DELX/VBFU)                                    00000800
      DM3 = CEXP(II*OMEGA*X(I)/VBFU)*(1.+DM6)/2.                        00000810
C                                                                       00000820
C      CALCULATE FUEL VAPORIZATION PARAMETERS.                          00000830
C                                                                       00000840
      DM7FU = VBFU/(2.*OMEGA**2*DELX*TAUBFU)                            00000850
      DM8FU = 1. - II*OMEGA*DELX/VBFU - 1./DM6                          00000860
      DM9FU = 1. + II*OMEGA*DELX/VBFU - DM6                             00000870
      DM4 = DM7FU*DM8FU*DM6                                             00000880
      DM5 = DM7FU*DM9FU                                                 00000890
      DM9FU = DM9FU/DM6                                                 00000900
      RBSFU = DELP*DM1*(CFU1+CFU9*DM2)                                  00000910
     1       +RHOINJ*DM1*(CFU3+CFU11*DM2)+MR(1)*DM1*(CFU5+CFU13*DM2)    00000920
     2       +VXO*DM1*(CFU7+CFU15*DM2)                                  00000930
      RBSFU = RBSFU+DM3*(CFU10*PINTFU+CFU12*RHNTFU+CFU14*MRNTFU         00000940
     1                 +CFU16*VINTFU)                                   00000950
      RBSFU = RBSFU+P(I)*(CFU2/2.+CFU10*DM4) + RHO(I)*(CFU4/2.          00000960
     1      +CFU12*DM4) + MR(I)*(CFU6/2.+CFU14*DM4)                     00000970
     2      + V(I)*(CFU8/2.+CFU16*DM4)                                  00000980
      RBSFU = VAPBFU(I)*RBSFU                                           00000990
      G1FU = VAPBFU(I)*(CFU2/2.+CFU10*DM5)                              00001000
      G2FU = VAPBFU(I)*(CFU4/2.+CFU12*DM5)                              00001010
      G3FU = VAPBFU(I)*(CFU6/2.+CFU14*DM5)                              00001020
      G4FU = VAPBFU(I)*(CFU8/2.+CFU16*DM5)                              00001030
```

```
      RETURN                                                            00001040
      END                                                               00001050
```

```
      SUBROUTINE COGAEL(A,N)                                            00012000
      DIMENSION A(62,126)                                               00012010
C                                                                       00012020
C     GAUSSIAN ELIMINATION OF COMPLEX MATRIX.                           00012030
C     PROGRAMMED BY J. K. HUNTING, ROCKETDYNE, MAY 1975                  00012031
C                                                                       00012040
      NM1 = N - 1                                                       00012050
      NP1 = N + 1                                                       00012060
      ZZ = 10.0E-30                                                     00012070
C                                                                       00012080
C     J IS THE COLUMN BEING ELIMINATED BELOW THE DIAGONAL.              00012090
C                                                                       00012100
      DO 27 J = 1,N                                                     00012110
C                                                                       00012120
C     FIND MAXIMUM AMPLITUDE IN COLUMN AND BELOW THE DIAGONAL.          00012130
C                                                                       00012140
      JMAX = J                                                          00012150
      JJ = J + NP1                                                      00012160
      CMAX = A(J,J)**2 + A(J,JJ)**2                                     00012170
      JP1 = J + 1                                                       00012180
      IF (J - N) 25,5,6                                                 00012190
   25 DO 2 K = JP1,N                                                    00012200
      CCC = A(K,J)**2 + A(K,JJ)**2                                      00012210
      IF (CCC - CMAX) 2,2,3                                             00012220
    3 JMAX = K                                                          00012230
      CMAX = CCC                                                        00012240
    2 CONTINUE                                                          00012250
C                                                                       00012260
C     INTERCHANGE ROWS IF REQUIRED TO OBTAIN MAXIMUM PIVOTAL ELEMENT.   00012270
C                                                                       00012280
      IF (J - JMAX) 4,5,6                                               00012290
    6 WRITE (6,12) J,JMAX                                               00012300
   12 FORMAT (61H1ERROR IN COGAEL SUBROUTINE, J AND JMAX EQUAL, RESPECTI00012310
```

```
     1VELY, ,2I12)                                                      00012320
      CALL EXIT                                                         00012330
    4 DO 7 K = J,NP1                                                    00012340
      KN = K + NP1                                                      00012350
      HOLD = A(J,K)                                                     00012360
      A(J,K) = A(JMAX,K)                                                00012370
      A(JMAX,K) = HOLD                                                  00012380
      HOLD = A(J,KN)                                                    00012390
      A(J,KN) = A(JMAX,KN)                                              00012400
      A(JMAX,KN) = HOLD                                                 00012410
    7 CONTINUE                                                          00012420
C                                                                       00012430
C     DIVIDE PIVOT ROW BY PIVOT ELEMENT. PIVOT ELEMENT BECOMES 1.0.     00012440
C                                                                       00012450
    5 CONTINUE                                                          00012460
      DO 8 K = JP1,NP1                                                  00012470
      KN = K + NP1                                                      00012480
      IF (ABS(A(J,J)) - ZZ) 14,14,13                                    00012490
   14 IF (ABS(A(J,JJ)) - ZZ) 15,15,13                                   00012500
   15 DUM1 = A(J,J)                                                     00012510
      DUM2 = A(J,JJ)                                                    00012520
      WRITE (6,16) DUM1,DUM2                                            00012530
   16 FORMAT (61H1MATRIX IS SINGULAR. EXIT FROM COGAEL. THE PIVOT ELEMEN00012540
     1TS ARE,2E14.6)                                                    00012550
      CALL EXIT                                                         00012560
   13 REALA = (A(J,K)*A(J,J) + A(J,KN)*A(J,JJ))/CMAX                    00012570
      VIMAG = (A(J,KN)*A(J,J) - A(J,K)*A(J,JJ))/CMAX                    00012580
      A(J,K) = REALA                                                    00012590
      A(J,KN) = VIMAG                                                   00012600
    8 CONTINUE                                                          00012610
C                                                                       00012620
C     ELIMINATE ELEMENTS BELOW DIAGONAL. THE ELEMENTS ELIMINATED ARE NOT00012630
C     THEMSELVES CALCULATED.                                            00012640
```

```
C                                                                       00012650
      IF (J - N) 26,27,6                                                00012660
   26 JP1 = J + 1                                                       00012670
      DO 9 I = JP1,N                                                    00012680
      DO 9 K = JP1,NP1                                                  00012690
      KN = K + NP1                                                      00012700
      REALA = A(I,K) - A(J,K)*A(I,J) + A(J,KN)*A(I,JJ)                  00012710
      VIMAG = A(I,KN) - A(J,KN)*A(I,J) - A(I,JJ)*A(J,K)                 00012720
      A(I,K) = REALA                                                    00012730
      A(I,KN) = VIMAG                                                   00012740
    9 CONTINUE                                                          00012750
   27 CONTINUE                                                          00012760
      RETURN                                                            00012770
      END                                                               00012780
```

```
      SUBROUTINE COMBDY(IR,FREQ,GINJOX,GINJFU,IPRCOM,INPCOM)
C
C     SUBPROGRAM TO CALCULATE THE COMBUSTION COEFFICIENTS.
C     PROGRAMMED BY M. D. SCHUMAN, ROCKETDYNE, MAY 1975
C
      COMPLEX GINJOX, GINJFU, DUM, NOZAT, GINJOT, GINJFT,
     1     COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9,
     2     COX10, COX11, COX12, COX13, COX14, COX15, COX16,
     3     CFU1, CFU2, CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9,
     4     CFU10, CFU11, CFU12, CFU13, CFU14, CFU15, CFU16,
     5     COXT(16), CFUT(16), RM, RU, RD, RFU
C
      REAL  MBOXI, MBFUI, MWG, NUBOX, NUBFU
C
      COMMON /COMTAP/  NFREQT, FREQT(100), NOZAT(100), GINJOT(100),
     1     GINJFT(100), ITAPN, ITAPC, ITAPH
C
      COMMON  /COMCBM/  XKOX, XKFU, MBOXI, MBFUI, TAUBOX, TAUBFU, VBOX,
     1     VBFU, GAMD, RGO, DELHOX, DELHFU, PC, CO,
     2     COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9, COX10,
     3     COX11, COX12, COX13, COX14, COX15, COX16, CFU1, CFU2,
     4     CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9, CFU10, CFU11,
     5     CFU12, CFU13, CFU14, CFU15, CFU16, MWG, XIMPFU, XIMPOX,
     6     CS, DCSDMR, DHDMR, DRGDMR, ADVOX, ADDOX, TDRAGO, DELVOX,
     7     NUBOX, DTOXDM, ADVFU, ADDFU, TDRAGF, DELVFU, NUBFU, DTFUDM
C
      EQUIVALENCE (COXT(1),COX1), (CFUT(1),CFU1)
C
      DATA PI/3.14159/
C
C
      IF(IR.LE.0) GO TO 100
```

```
C
C      THIS IS FIRST PASS FOR THIS CASE. READ INPUT DATA.
C
C
      READ(5,1) XKOX, TAUBOX, VBOX, DELHOX, TDRAGU, ADVOX,
     1     ADDOX, DELVOX, NUBOX, DTOXDM, XIMPOX
    1 FORMAT(6E12.8)
      WRITE(6,2) XKOX, TAUBOX, VBOX, DELHOX, TDRAGO,
     1     ADVOX, ADDOX, DELVOX, NUBOX, DTOXDM, XIMPOX
    2 FORMAT(/5X,'XKOX =',1PE11.4,5X,'TAUBOX =',
     1     E11.4,3X,'VBOX =',E11.4,5X,'DELHOX =',E11.4,/,27X,
     2     'TDRAGO =',E11.4,3X,'ADVOX =',E11.4,//,5X,'ADDOX =',E11.4,
     3     4X,'DELVOX =',E11.4,3X,'NUBOX =',E11.4,4X,'DTOXDM =',
     4     E11.4,/,27X,'XIMPOX =',E11.4)
      XKOX = XKOX*0.0254
      VBOX = VBOX*0.3048
      DELHOX = DELHOX*1054.35/0.453592
      XIMPOX = XIMPOX*0.0254
C
      READ(5,1) XKFU, TAUBFU, VBFU, DELHFU, TDRAGF, ADVFU,
     1     ADDFU, DELVFU, NUBFU, DTFUDM, XIMPFU
      WRITE(6,3) XKFU, TAUBFU, VBFU, DELHFU, TDRAGF,
     1     ADVFU, ADDFU, DELVFU, NUBFU, DTFUDM, XIMPFU
    3 FORMAT(/,5X,'XKFU =',1PE11.4,5X,'TAUBFU =',
     1     E11.4,3X,'VBFU =',E11.4,5X,'DELHFU =',E11.4,/,27X,
     2     'TDRAGF =',E11.4,3X,'ADVFU =',E11.4,//,5X,'ADDFU =',E11.4,
     3     4X,'DELVFU =',E11.4,3X,'NUBFU =',E11.4,4X,'DTFUDM =',
     4     E11.4,/,27X,'XIMPFU =',E11.4)
      XKFU = XKFU*0.0254
      VBFU = VBFU*0.3048
      DELHFU = DELHFU*1054.35/0.453592
      XIMPFU = XIMPFU*0.0254
      READ(5,1) MWG, CS, DRGDMR, DCSDMR, DHDMR
```

```
      WRITE(6,4) MWG, CS, DRGDMR, DCSDMR, DHDMR
    4 FORMAT(/,5X,'MWG =',1PE11.4,6X,'CS =',E11.4,
     1      7X,'DRGDMR =',E11.4,3X,'DCSDMR =',F11.4,/,27X,'DHDMR =',
     2      E11.4)
      CS = CS*0.3048
      DRGDMR = DRGDMR*1.8*1.35582/0.453592
      DCSDMR = DCSDMR*0.3048
      DHDMR = DHDMR*1054.35/0.453592
      RGO = 8314.34/MWG
      REWIND ITAPC
C
  100 CONTINUE
C
C       IF INPCOM .LE. 1, COMPUTE COMBUSTION COEFFICIENTS FOR INPUT
C       FREQUENCY(FREQ). IF INPCOM .GT. 1, COMPUTE COMBUSTION
C       COEFFICIENTS FOR ENTIRE FREQUENCY TABLE AND SAVE ON ITAPC.
C
      FRE = FREQ
      I = 0
      IF(INPCOM.LE.1) GO TO 200
      FRE = FREQT(1)
      WRITE(ITAPC) XKOX, TAUBOX, VBOX, DELHOX, TDRAGO, ADVOX,
     1      ADDOX, DELVOX, NUBOX, DTOXDM, XIMPOX, XKFU, TAUBFU,
     2      VBFU, DELHFU, TDRAGF, ADVFU, ADDFU, DELVFU, NUBFU,
     3      DTFUDM, XIMPFU, MWG, CS, DRGDMR, DCSDMR, DHDMR, RGO
  200 I = I+1
      DUM = (0.0,1.0)*2.*PI*FRE*XKOX/VBOX
      RM = (1.-DUM)*GINJOX
      PJ = GINJOX
      DUM = DUM*XIMPOX/XKOX
      RD = (ADVOX-0.5*ADDOX*DUM)*GINJOX
      RFR = 0.5
      D1 = 2.*PI*FRE*TDRAGO
```

```
      RFU = 0.5/DELVOX*(D1*D1-(0.0,1.0)*D1)/(1.+D1*D1)                  00001130
      COX1 = RM-RU-2.*RD+(NUBOX-2.)*0.5*RD/NUBOX                        00001140
      COX2 = 0.0                                                        00001150
      COX3 = 0.0                                                        00001160
      COX4 = RFR*(NUBOX-2.)/NUBOX                                       00001170
      COX5 = 0.0                                                        00001180
      COX6 = -DTOXDM/TAUBOX                                             00001190
      COX7 = 0.0                                                        00001200
      COX8 = RFU*(NUBOX-2.)/NUBOX                                       00001210
      COX9 = 2.*RD-(NUBOX-2.)*0.5*RD/NUBOX+RU                           00001220
      COX10 = 0.0                                                       00001230
      COX11 = 0.0                                                       00001240
      COX12 = -COX4                                                     00001250
      COX13 = 0.0                                                       00001260
      COX14 = -COX6                                                     00001270
      COX15 = 0.0                                                       00001280
      COX16 = -COX8                                                     00001290
      DUM = (0.0,1.0)*2.*PI*FRE*XKFU/VBFU                               00001300
      RM = (1.-DUM)*GINJFU                                              00001310
      RU = GINJFU                                                       00001320
      DUM = DUM*XIMPFU/XKFU                                             00001330
      RD = (ADVFU-0.5*ADDFU*DUM)*GINJFU                                 00001340
      RFR = 0.5                                                         00001350
      D1 = 2.*PI*FRE*TDRAGF                                             00001360
      RFU = 0.5/DELVFU*(D1*D1-(0.0,1.0)*D1)/(1.+D1*D1)                  00001370
      CFU1 = RM-RU-2.*RD+(NUBFU-2.)*0.5*RD/NUBFU                        00001380
      CFU2 = 0.0                                                        00001390
      CFU3 = 0.0                                                        00001400
      CFU4 = RFR*(NUBFU-2.)/NUBFU                                       00001410
      CFU5 = 0.0                                                        00001420
      CFU6 = -DTFUDM/TAUBFU                                             00001430
      CFU7 = 0.0                                                        00001440
      CFU8 = RFU*(NUBFU-2.)/NUBFU                                       00001450
```

```
      CFU9 = 2.*RD-(NUBFU-2.)*0.5*RD/NUBFU+RU
      CFU10 = 0.0
      CFU11 = 0.0
      CFU12 = -CFU4
      CFU13 = 0.0
      CFU14 = -CFU6
      CFU15 = 0.0
      CFU16 = -CFU8
C
      IF(INPCOM.LE.1) RETURN
C
      WRITE(ITAPC) (COXT(J),CFUT(J),J=1,16)
      IF(I.GE.NFREQT) GO TO 900
      FRE = FREQT(I+1)
      GO TO 200
  900 END FILE ITAPC
C
      RETURN
      END
```

```
      SUBROUTINE COMMAT(A,NRA,N)
C
C     ROUTINE SOLVES: AX = B, WHERE A,X, AND B ARE COMPLEX.
C      A(I,J) IS N BY N COMPLEX MATRIX
C      B(I) IS N BY 1 COMPLEX VECTOR. IT IS STORED IN A(I,N+1) FOR
C           I = 1,N
C      ANSWER IS RETURNED IN A(I,N+1) I=1,N
C      NRA IS THE NUMBER OF ROWS IN THE DIMENSION STATEMENT FOR
C        MATRIX A IN THE CALLING PROGRAM.
C
C      A,X, AND B ARE ALL COMPLEX*16
C
C     PROGRAMMED BY K. W. FERTIG, ROCKETDYNE, MAY 1975
C
      COMPLEX*16 A(NRA,1),W
C
      NM1 = N-1
      NP1 = N+1
C
C      MATRIX TRIANGULARIZATION IS PERFORMED THROUGH STATMENT 20
C
      DO 20 IR = 1,NM1
      IR1 = IR+1
      IF(CDABS(A(IR,IR)).LE.0.D0) GO TO 100
C
      DO 10 I = IR1,N
      W = -A(I,IR)/A(IR,IR)
      DO 10 J = IR1,NP1
   10 A(I,J) = A(I,J) + W*A(IR,J)
C
   20 CONTINUE
C
C
```

```
C        BACKWARDS SUSTITUTION IS PERFORMED THROUGH STATEMENT 50
C
      A(N,NP1) = A(N,NP1)/A(N,N)
C
      DO 50 IR = 1,NM1
      I = N-IR
      I1 = I+1
      DO 40 J = I1,N
   40 A(I,NP1) = A(I,NP1) - A(I,J)*A(J,NP1)
   50 A(I,NP1) = A(I,NP1)/A(I,I)
C
      RETURN
C
C        ALGORITHM HAS FAILED DUE TO ZERO DIAGONAL ELEMENT
C
  100 WRITE(6,9000) IR,((I,J,A(I,J),I=1,N),J=1,NP1)
 9000 FORMAT(// '  ***** DIVIDE CHECK IN COMMAT *****'/
     1    '     IR = ',I10/'   MATRIX A(I,J) = '/
     2     (5X,2I6,1PE15.6,' :',1PE13.6))
      CALL EXIT
      RETURN
      END
```

```
      SUBROUTINE FRESP(ICRT,IWRITE,IX)                                  00006000
C                                                                       00006001
C     FREQUENCY RESPONSE ROUTINE WITH TIME DELAY                        00006010
C     PROGRAMMED BY J. K. HUNTING, ROCKETDYNE, MAY 1975                 00006011
C                                                                       00006012
      DIMENSION OM(101),OMSCPS(101),W(101),OMS(101),ID(126),CP(62,126)  00006020
      DIMENSION LXI(3),I1(3),J1(3),C7(3),C(62,126),TD(62,63),D(126)     00006030
      DIMENSION XMAG(62),NO(62),XREAL(62),XIMAG(62),GAIN(101),FAZE(101) 00006040
      DIMENSION VARR(62),VARI(62),PHAN(5,101),DECB(5,101)               00006050
      DIMENSION ATD(126),IDF(18)                                        00006060
      COMMON/F/NW,NCTD,NR,KEQ,TRIG,IRPS,OMI,OMFL,W,ID,C,TD,ATD,         00006070
     1FREQ,GINJOX,GINJFU,PC,WO,WF                                       00006080
      COMPLEX   NOZAT(100),GINJOT(100),GINJFT(100),GINJOX,GINJFU        00006090
      COMMON/COMTAP/NFREQT,FREQT(100),NOZAT,GINJOT,GINJFT,ITAPN,ITAPC,  00006100
     1ITAPH                                                             00006110
      DELTA(Q001FL) =1.0 -ABS(Q001FL)/AMAX1(ABS(Q001FL),.146936794E-38) 00006120
      UNIT(Q002FL) =0.5 + SIGN( 0.5,DELTA(Q002FL) + Q002FL*(1.0-DELTA(Q000006130
     102FL)))                                                           00006140
      THETA(Q003FL,Q004FL) =(180.0*(1.0+UNIT(Q003FL)*(1.0-2.0*UNIT(Q004F00006150
     1L)))+ SIGN(1.0,Q003FL*Q004FL)*  ATAN(((ABS(Q004FL)*(1.0-DELTA(Q00300006160
     2FL))))/(ABS(Q003FL)+DELTA(Q003FL)))*(180.0/3.141593)) * (1.0-DELTA00006170
     3(Q003FL))+ 180.0*DELTA(Q003FL)*(1.0-DELTA(Q004FL))*(.5 +UNIT(-Q00400006180
     4FL))                                                              00006190
C     IS NECESSARY TO ZERO MATRIX STORAGE SPACE                         00006200
   10 DO 2001 KK = 1,62                                                 00006210
      DO 2001 LL = 1,126                                                00006220
 2001 CP(KK,LL)=0.0                                                     00006230
      IF(TRIG.NE.1.) GO TO 2006                                         00006240
      DO 2002 KK=1,62                                                   00006250
      DO 2002 LL=1,126                                                  00006260
 2002 C(KK,LL)=0.0                                                      00006270
      DO 2003 KK=1,62                                                   00006280
      DO 2003 LL=1,63                                                   00006290
```

```
2003 TD(KK,LL)=0.0
2006 DO 2004 KK=1,5
     DO 2004 LL=1,101
     PHAN(KK,LL)=0.0
2004 DECB(KK,LL)=0.0
     IF(TRIG.NE.1.) GO TO 444
     IF(TRIG.EQ.1.)READ(5,120)NW,NCTD,NR,ICRT,KEQ,TRIG,IRPS,OMI,OMFL
 120 FORMAT(I12,I3,I9,I3,I9,F2.0,I10,2F12.0)
     IF(NW)1216,1215,1216
1216 IF(NW-100)1217,1217,1218
1218 WRITE (6,122)
 122 FORMAT(46H-NUMBER OF SHUFFLED IN FREQUENCIES EXCEEDS 100)
     GO TO 9
1217 IF(TRIG.EQ.1.)READ (5,121)(W(I),I=1,NW)
 121 FORMAT(6F12.0)
1215 IF(NR-126)1219,1219,1220
1220 WRITE (6,123)
 123 FORMAT(30H-NUMBER OF COLUMNS EXCEEDS 126)
     GO TO 9
1219 IF(TRIG.EQ.1.)READ (5,51)(ID(I),I=1,NR)
  51 FORMAT(6I12)
     IF(KEQ-62)1221,1221,1222
1222 WRITE (6,124)
 124 FORMAT(31H-NUMBER OF EQUATIONS EXCEEDS 62)
     GO TO 9
1221 IF(OMI)1671,3,1667
   3 WRITE (6,115)
     GO TO 9
1667 OM(1)=OMI
     J=2
     RATIO=(OMFL/OMI)**(1./AMAX1(1.,FLOAT(NFREQT-2)))
1668 OM(J)=OM(J-1)*RATIO
     IF(OM(J).GE..9999*OMFL.OR.J.EQ.100) GO TO 1670
```

```
 1669 J=J+1                                                               00006630
      GO TO 1668                                                          00006640
 1670 OM(J)=OMFL                                                          00006650
      NOM=J                                                               00006660
      GO TO 17                                                            00006670
 1671 OMI=ABS(OMI)                                                        00006680
 1675 J=1                                                                 00006690
      N=0                                                                 00006700
      M=-1                                                                00006710
      T=-1.0                                                              00006720
      R=0.1                                                               00006730
  115 FORMAT(26H INITIAL FREQUENCY IS ZERO)                               00006740
    4 IF(OMI-R)5,8,8                                                      00006750
    5 M=M-1                                                               00006760
      R=R/10.0                                                            00006770
      GO TO 4                                                             00006780
    8 K=1                                                                 00006790
C     NEW CARD--INITIALIZATION OF L                                       00006800
      L=0                                                                 00006810
   12 OM(J)=UNIT(T)*(((2.0**L)*3.0*10.0**M)/2.0)+UNIT(-T)*(2.0**L)*10.0*00006820
     1*M                                                                  00006830
      IF(T)24,24,23                                                       00006840
   23 L=L+1                                                               00006850
   24 T=-T                                                                00006860
      IF(L-3)26,27,25                                                     00006870
   27 IF(T)26,26,25                                                       00006880
   25 L=0                                                                 00006890
      T=-1.0                                                              00006900
      M=M+1                                                               00006910
   26 GO TO(11,16),K                                                      00006920
   11 IF(OM(1)-OMI)12,15,13                                               00006930
   13 OM(2)=OM(1)                                                         00006940
      OM(1)=OMI                                                           00006950
```

```
      J=3                                                               00006960
      K=2                                                               00006970
      GO TO 12                                                          00006980
   15 OM(1)=OM1                                                         00006990
      K=2                                                               00007000
   16 J=J+1                                                             00007010
      IF(OM(J-1)-OMFL)12,18,13                                          00007020
   18 OM(J-1)=OMFL                                                      00007030
      NOM=J-1                                                           00007040
   17 J=1                                                               00007050
      IF(NW)28,28,29                                                    00007060
   28 OMS(J)=OM(J)                                                      00007070
      IF(OMS(J)-OMFL)30,32,32                                           00007080
   30 J=J+1                                                             00007090
      IF(J-100)28,28,45                                                 00007100
   29 N=0                                                               00007110
      I=1                                                               00007120
   35 K=J+N                                                             00007130
      IF(OM(J)-W(I))20,34,34                                            00007140
   20 IF(J-NOM)33,33,34                                                 00007150
   33 OMS(K)=OM(J)                                                      00007160
      J=J+1                                                             00007170
      GO TO 35                                                          00007180
   34 OMS(K)=W(I)                                                       00007190
      N=N+1                                                             00007200
      IF(I-NW)36,37,37                                                  00007210
   37 IF(J-NOM)31,31,380                                                00007220
   31 W(I)=OMFL                                                         00007230
      GO TO 38                                                          00007240
   36 I=I+1                                                             00007250
      IF(J-NOM)38,38,35                                                 00007260
   38 IF(OMS(K)-OMFL)35,32,32                                           00007270
  380 OMFL=OMS(K)                                                       00007280
```

```
      IF(K-100)32,32,45                                                 00007290
 444  IF(NFREQT.GT.100) GO TO 45                                        00007300
      OMS(1)=.001                                                       00007310
      NP1=NFREQT+1                                                      00007320
      DO 445 I=2,NP1                                                    00007330
 445  OMS(I)=FREQT(I-1)                                                 00007340
      IF(NW.EQ.1) OMS(1)=FREQ                                           00007350
      GO TO 32                                                          00007360
  45  WRITE (6,117)                                                     00007370
 117  FORMAT(38H1THE NUMBER OF FREQUENCIES EXCEEDS 100)                 00007380
      GO TO 9                                                           00007390
  32  J=1                                                               00007400
 431  IF(IRPS)432,432,43                                                00007410
 432  OMFLC=OMFL                                                        00007420
      OMFL=2.0*3.1415927*OMFL                                           00007430
  43  IF(IRPS)39,39,40                                                  00007440
  39  OMSCPS(J)=OMS(J)                                                  00007450
      OMS(J)=2.0*3.1415927*OMSCPS(J)                                    00007460
      GO TO 41                                                          00007470
  40  OMSCPS(J)=OMS(J)/(2.0*3.1415927)                                  00007480
  41  IF(OMS(J)-OMFL)42,44,44                                           00007490
  42  J=J+1                                                             00007500
      GO TO 43                                                          00007510
  44  IF(TRIG.EQ.1.)READ (5,50)(LXI(I),I1(I),J1(I),C7(I),I=1,3)         00007520
  50  FORMAT(3(I2,I4,I6,F12.0))                                         00007530
      IF(TRIG.NE.1.) GO TO 60                                           00007540
      DO47 I=1,3                                                        00007550
      IF(LXI(I))300,301,301                                             00007560
 301  IF(I1(I))47,47,48                                                 00007570
  48  I9=I1(I)                                                          00007580
      J9=J1(I)                                                          00007590
      C(I9,J9)=C7(I)                                                    00007600
      IF(LXI(1))47,47,60                                                00007610
```

```
 300 IF(I1(I))47,47,302                                                00007620
 302 ITD=I1(I)                                                         00007630
     JTD=J1(I)                                                         00007640
     TD(ITD,JTD)=C7(I)                                                 00007650
     IF(LXI(I)+1)47,60,60                                              00007660
  47 CONTINUE                                                          00007670
  49 GO TO 44                                                          00007680
  60 IW=1                                                              00007690
     KEJ=KEQ+1                                                         00007700
     IF(TRIG.EQ.1.)READ (5,113)                                        00007710
 113 FORMAT(72H1                                                       00007720
    1                    )                                             00007730
     IF(IWRITE.GT.1)WRITE (6,113)                                      00007740
     IF(IWRITE.GT.1)WRITE (6,59)(ID(I),I=1,NR)                         00007750
  59 FORMAT(16H    I.D. VECTOR   /(1H0,24I4))                          00007760
     DO 111 I73=1,KEQ                                                  00007770
 111 IF(IWRITE.GT.1)WRITE (6,112)I73,(C(I73,J),J=1,NR)                 00007780
 112 FORMAT(13H0   EQUATION  ,I3  /(4H0      ,1P7E14.6))               00007790
     IF(IWRITE.GT.1)WRITE (6,310)                                      00007800
 310 FORMAT(27H1MATRIX OF TIME DELAY TERMS)                            00007810
     DO311 I=1,KEQ                                                     00007820
 311 IF(IWRITE.GT.1)WRITE (6,112)I,(TD(I,J),J=1,KEJ )                  00007830
     IF(NCTD) 75,75,309                                                00007840
 309 IF(TRIG.EQ.1.)READ (5,121)(ATD(K),K=1,NCTD)                       00007850
  75 DO 662 J=1,KEQ                                                    00007860
     IJ=J+KEQ                                                          00007870
     LS=0                                                              00007880
     LK=0                                                              00007890
     LF=0                                                              00007900
     I=0                                                               00007910
  76 I=I+1                                                             00007920
     IF(LK)7,62,610                                                    00007930
  62 IF(KEQ-LF)64,64,65                                                00007940
```

F S C S M SUBROUTINES

```
   65 LF=LF+1                                                           00007950
      IM=KEQ+LF                                                         00007960
   67 IR=I+LS                                                           00007970
      IF(ID(IR))69,68,69                                                00007980
   68 LS=LS+1                                                           00007990
      GO TO 67                                                          00008000
   69 II=IR-1                                                           00008010
      LK=LS                                                             00008020
      CREAL=0.0                                                         00008030
      CIMAG=0.0                                                         00008040
      R=1.0                                                             00008050
      S=0.0                                                             00008060
      LS=LS+1                                                           00008070
   55 CREAL=CREAL + R*C(J,IR)*(OMS(IW)**S)                              00008080
      LS=LS-1                                                           00008090
      IF(LS)7,57,56                                                     00008100
   56 CIMAG=CIMAG+R*C(J,II)*(OMS(IW)**(S+1.0))                          00008110
      S=S+2.0                                                           00008120
      R=(-1.0)*R                                                        00008130
      IR=IR-2                                                           00008140
      II=II-2                                                           00008150
      LS=LS-1                                                           00008160
      IF(LS)7,57,55                                                     00008170
   57 CP(J,LF)=CREAL                                                    00008180
      CP(J,IM)=CIMAG                                                    00008190
      GO TO 61                                                          00008200
   64 IR=I+LS                                                           00008210
      IF(ID(IR))70,71,70                                                00008220
   71 LS=LS+1                                                           00008230
      GO TO 64                                                          00008240
   70 II=IR-1                                                           00008250
      LK=LS                                                             00008260
      DREAL=0.0                                                         00008270
```

```
     DIMAG=0.0                                                          00008280
     R=1.0                                                              00008290
     S=0.0                                                              00008300
     LS=LS+1                                                            00008310
 772 DREAL=DREAL+R*C(J,IR)*(OMS(IW)**S)                                 00008320
     LS=LS-1                                                            00008330
     I=I+1                                                              00008340
     IF(LS)7,63,773                                                     00008350
 773 DIMAG=DIMAG+R*C(J,II)*(OMS(IW)**(S+1.0))                           00008360
     S=S+2.0                                                            00008370
     R=(-1.0)*R                                                         00008380
     IR=IR-2                                                            00008390
     II=II-2                                                            00008400
     LS=LS-1                                                            00008410
     IF(LS)7,63,772                                                     00008420
  63 D(J)=DREAL                                                         00008430
     D(IJ)=DIMAG                                                        00008440
     GO TO 61                                                           00008450
   7 WRITE (6,116)                                                      00008460
 116 FORMAT(24H LS HAS A NEGATIVE VALUE)                                00008470
     GO TO 9                                                            00008480
 610 LK=LK-1                                                            00008490
  61 CONTINUE                                                           00008500
 320 IF(I.LT.NR) GO TO 76                                               00008510
 662 CONTINUE                                                           00008520
     L=1                                                                00008530
     DO 313 I=1,KEQ                                                     00008540
     DO 313 J=1,KEQ                                                     00008550
     CTD=1.0                                                            00008560
     KTD=KEQ+J                                                          00008570
     IF(TD(I,J))312,313,316                                             00008580
 316 CTD=ATD(L)                                                         00008590
     L=L+1                                                              00008600
```

```
  312 ANGLE=ABS(TD(I,J)*OMS(IW))-6.283185*IFIX(ABS(TD(I,J)*OMS(IW)/6.28300008610
     1185))                                                             00008620
      CP(I,J)=CP(I,J)+CTD*COS(ANGLE)                                    00008630
      CP(I,KTD)=CP(I,KTD)-CTD*SIN(ANGLE)                                00008640
  313 CONTINUE                                                          00008650
      K=KEQ+1                                                           00008660
      DO 73 I=1,KEQ                                                     00008670
      L=KEQ+I                                                           00008680
      IF(TD(I,K))72,73,72                                               00008690
   72 ANGLE=ABS(TD(I,K)*OMS(IW))-6.28318*IFIX(ABS(TD(I,K)*OMS(IW)/6.283100008700
     185))                                                              00008710
      D(I)=D(I)+COS(ANGLE)                                              00008720
      D(L)=D(L)+SIN(ANGLE)*SIGN(1.0,TD(I,K))                            00008730
   73 CONTINUE                                                          00008740
      NPH=2*KEQ                                                         00008750
      IF(IW-1)303,303,305                                               00008760
  303 IF(IWRITE.GT.1)WRITE (6,323)                                      00008770
      DO 304 I=1,KEQ                                                    00008780
      IJ=I+KEQ                                                          00008790
  304 IF(IWRITE.GT.1)WRITE (6,321)I,D(I),D(IJ),(CP(I,J),J=1,NPH)        00008800
  305 CONTINUE                                                          00008810
C                                                                       00008820
C     ADD D-VECTOR TO CP-MATRIX. SHIFT COLUMNS OF IMAG CP BY 1 TO RIGHT.00008830
C     REAL D INTO COL. KEQ+1. IMAG D INTO COL. 2KEQ+2.                  00008840
C                                                                       00008850
      DO 202 I = 1,KEQ                                                  00008860
      IN = 2*KEQ + 1 - I                                                00008870
      INP1 = IN + 1                                                     00008880
      DO 202 J = 1,KEQ                                                  00008890
      CP(J,INP1) = CP(J,IN)                                             00008900
  202 CONTINUE                                                          00008910
      IN = KEQ + 1                                                      00008920
      INN = 2*KEQ + 2                                                   00008930
```

```
      DO 203 J = 1,KEQ                                                  00008940
      CP(J,IN) = D(J)                                                   00008950
      JN = J + KEQ                                                      00008960
      CP(J,INN) = D(JN)                                                 00008970
  203 CONTINUE                                                          00008980
C                                                                       00008990
C     CALL COGAEL TO TRIANGULARIZE THE COMPLEX MATRIX BY GAUSS. ELIMIN. 00009000
C                                                                       00009010
      CALL COGAEL(CP,KEQ)                                               00009020
C                                                                       00009030
C     BACK SUBSTITUTE TO DETERMINE REAL AND IMAGINARY PART OF VARIABLES,00009040
C     THEN DETERMINE MAGNITUDE AND PHASE.                               00009050
C                                                                       00009060
      NP1 = KEQ + 1                                                     00009070
      NNP1 = 2*NP1                                                      00009080
      XREAL(KEQ) = CP(KEQ,NP1)                                          00009090
      XIMAG(KEQ) = CP(KEQ,NNP1)                                         00009100
      XMAG(KEQ) = SQRT(XREAL(KEQ)**2 + XIMAG(KEQ)**2)                   00009110
      FAZE(KEQ) = THETA(XREAL(KEQ),XIMAG(KEQ))                          00009120
      DO 205 J = 2,KEQ                                                  00009130
      JJ = KEQ - J + 1                                                  00009140
      JJP1 = JJ + 1                                                     00009150
      SUMR = 0.0                                                        00009160
      SUMI = 0.0                                                        00009170
      DO 206 K = JJP1,KEQ                                               00009180
      KN = K + KEQ + 1                                                  00009190
      SUMR = SUMR + CP(JJ,K)*XREAL(K) - CP(JJ,KN)*XIMAG(K)              00009200
      SUMI = SUMI + CP(JJ,KN)*XREAL(K) + CP(JJ,K)*XIMAG(K)              00009210
  206 CONTINUE                                                          00009220
      XREAL(JJ) = CP(JJ,NP1) - SUMR                                     00009230
      XIMAG(JJ) = CP(JJ,NNP1) - SUMI                                    00009240
      XMAG(JJ) = SQRT(XREAL(JJ)**2 + XIMAG(JJ)**2)                      00009250
  205 FAZE(JJ) = THETA(XREAL(JJ),XIMAG(JJ))                             00009260
```

```
      IF (IW - 1) 82,82,83                                              00009270
   82 CONTINUE                                                          00009280
      IF(IWRITE.GT.1)WRITE (6,52)OMS(1),(I,XMAG(I),FAZE(I),I=1,KEQ)     00009290
   52 FORMAT(67H1                        VARIABLE MAGNITUDES USING A FREQ00009300
     1QUENCY OF     ,1PE14.6,5H RPS./  1H0 ,84H                   VARIAB00009310
     2LE NUMBER           MAGNITUDE                       PHASE /(1H0 ,00009320
     3I27,1P2E30.6))                                                    00009330
  770 IF(IWRITE.GT.1)WRITE (6,1001)                                     00009350
 1001 FORMAT(70 H1 THESE ARE INTERMEDIATE RESULTS PRODUCED AFTER EACH MA00009360
     1TRIX INVERSION./53H0INPUT FREQUENCY IN RADIANS/SECOND AND CYCLES/S00009370
     2ECOND./59H0       VARIABLE,GAIN(DB),PHASE(DEGREES)     VARIABLE,E00009380
     3TC. )                                                             00009390
  323 FORMAT(37H1INITIAL VALUES OF COEFFICIENT MATRIX)                  00009400
  321 FORMAT(//I3,5X,1P2E20.6/(4H0   ,1P7E14.6))                        00009410
  771 IV=1                                                              00009420
      J=3                                                               00009430
      NO(1)=17                                                          00009432
      NO(2)=55                                                          00009434
      DO 78 I=1,NR                                                      00009440
      IF(ID(I))79,80,81                                                 00009450
   79 IV=IV+1                                                           00009460
   80 GO TO 78                                                          00009470
   81 IF(IV.NE.17.AND.IV.NE.55) NO(J)=IV                                00009480
      IF(IV.NE.17.AND.IV.NE.55) J=J+1                                   00009490
      IV=IV+1                                                           00009500
   78 CONTINUE                                                          00009510
      NOPRT=MINO(5,J-1)                                                 00009520
   83 DO 84 K=1,NOPRT                                                   00009530
      JX=NO(K)                                                          00009540
      VARR(K) = XREAL(JX)                                               00009550
      VARI(K) = XIMAG(JX)                                               00009560
   84 CONTINUE                                                          00009570
   86 DO 87 I=1,NOPRT                                                   00009580
```

```
  90 PHAN(I,IW)=THETA(VARR(I),VARI(I))                                   00009590
  96 DECB(I,IW)=20.0*ALOG10(AMAX1(1.0E-30,SQRT(VARR(I)**2+VARI(I)**2)))00009600
  87 CONTINUE                                                            00009610
     IF(TRIG)960,960,961                                                 00009620
 960 IF(IWRITE.GT.1)WRITE (6,1000)OMS(IW),OMSCPS(IW),(NO(NOW),DECB(NOW 00009630
    1,IW),PHAN(NOW,IW),NOW=1,NOPRT)                                      00009640
1000 FORMAT(//F20.4,F20.5//(I4,F8.2,F7.1,I4,F8.2,F7.1,I4,F8.2,F7.1,I4,F00009650
    18.2,F7.1,I4,F8.2,F7.1))                                             00009660
 961 IF(OMS(IW).GE.OMFL.OR.IW.EQ.101) GO TO 95                           00009670
  85 IW=IW+1                                                             00009680
     GO TO 75                                                            00009690
  95 CONTINUE                                                            00009700
  53 FORMAT(21H1      FREQUENCY       ,5(13H   VARIABLE   ,I2,3H    )/21H0 00009710
    1  RPS       CPS      ,5(18H  DECIBELS  PHASE )/)                    00009720
  54 FORMAT(1P2E10.2,5(2H /, 0P2F8.2))                                   00009730
     NZ=5                                                                00009740
     NY=1                                                                00009750
     NX=NOPRT                                                            00009760
  97 IF(NX)100,100,98                                                    00009770
  98 IF(IWRITE.GT.1)WRITE (6,53)(NO(I),I=NY,NZ)                          00009780
     DO 99 J=1,IW                                                        00009790
     IF(IWRITE.GT.1)WRITE (6,54)(OMS(J),OMSCPS(J),(DECB(K,J),PHAN(K,J) 00009800
    1,K=NY,NZ))                                                          00009810
  99 CONTINUE                                                            00009820
     NY=NY+5                                                             00009830
     NZ=NZ+5                                                             00009840
     NX=NX-5                                                             00009850
     GO TO 97                                                            00009860
 100 CONTINUE                                                            00009870
     DO 400 J=1,NOPRT                                                    00009900
     DO 102 K=1,IW                                                       00009910
     GAIN(K)=DECB(J,K)                                                   00009920
     FAZE(K)=PHAN(J,K)                                                   00009930
```

```
      IF(K.GT.101.OR.IW.LE.2.OR.K.EQ.1) GO TO 102                       00009940
      IF(J.EQ.1.AND.IX.LE.1)GINJOT(K-1)=CMPLX(PC/WO*(10.**(GAIN(K)/20.))00009950
     &,(FAZE(K)))                                                       00009960
      IF(J.EQ.2.AND.IX.NE.1)GINJFT(K-1)=CMPLX(PC/WF*(10.**(GAIN(K)/20.))00009970
     &,(FAZE(K)))                                                       00009980
  102 CONTINUE                                                          00009990
      IF(J.EQ.1.AND.IX.LE.1)GINJOX=CMPLX(PC/WO*(10.**(GAIN(1)/20.)),(FAZ00010000
     &E(1)))                                                            00010001
      IF(J.EQ.2.AND.IX.NE.1)GINJFU=CMPLX(PC/WF*(10.**(GAIN(1)/20.)),(FAZ00010010
     &E(1)))                                                            00010011
      IF(IW.LE.2.OR.ICRT.LT.1) GO TO 400                                00010020
      IF(IRPS)104,104,103                                               00010030
  103 L=1                                                               00010040
      CALL TDPLOT(OMS,GAIN,IW,OMI,OMFL,L )                              00010050
      CALL PRINTV(-21,21H GAIN IN DECIBELS    , 400, 470)               00010060
      CALL PRINTV(-21,21H FREQUENCY IN RADIANS,400,005)                 00010070
      L=2                                                               00010080
      CALL TDPLOT(OMS,FAZE,IW,OMI,OMFL,L )                              00010090
      CALL PRINTV(-21,21H PHASE IN DEGREES    ,400,995)                 00010100
      GO TO 105                                                         00010110
  104 L=1                                                               00010120
      CALL TDPLOT(OMSCPS,GAIN,IW,OMI,OMFLC,L )                          00010130
      CALL PRINTV(-21,21H GAIN IN DECIBELS    , 400, 470)               00010140
      CALL PRINTV(-21,21H FREQUENCY IN CPS    ,400,005)                 00010150
      L=2                                                               00010160
      CALL TDPLOT(OMSCPS,FAZE,IW,OMI,OMFLC, L )                         00010170
      CALL PRINTV(-21,21H PHASE IN DEGREES    ,400,995)                 00010180
  105 CALL PRINTV(-21,20H VARIABLE NUMBER    ,400,1010)                 00010190
      PNO=NO(J)                                                         00010200
      CALL LABLV (PNO,560,1010,4,2,3)                                   00010210
  400 CONTINUE                                                          00010220
  999 RETURN                                                            00010230
    9 CALL EXIT                                                         00010240
```

```
      STOP                                                              00010250
      END                                                               00010260
```

F S C S M SUBROUTINES

```
      SUBROUTINE HEAD
C
C     ROUTINE TO PRINT HEADING
C     PROGRAMMED BY M. D. SCHUMAN, ROCKETDYNE, MAY 1975
C
      WRITE(6,10)
   10 FORMAT(1H1,/////,43X,'ANALYTICAL  DESCRIPTION',//,
     1 44X,'FEED  SYSTEM  COUPLED',//,47X,'STABILITY  MODEL',//////,
     2 47X,'COMPUTER  MODEL',///,25X,'PROGRAM NAME:    FSCSM,  FIV VER',
     3 'SION,    MAY 1975',///,25X,'DEVELOPED BY:    M. D. SCHUMAN,',
     4 ' J. K. HUNTING, AND K. W. FERTIG',/,42X,'ADVANCED PROGRAMS,',
     5 ' ROCKETDYNE',/,42X,'DIVISION OF ROCKWELL INTERNATIONAL',/,
     6 42X,'CANOGA PARK, CALIF  91304',///,
     7 25X,'SPONSERED BY:    NASA/LYNDON B. JOHNSON SPACE CENTER',/,
     8 42X,'HOUSTON, TEXAS  77058',/,42X,'UNDER CONTRACT NAS9-14315')
C
      RETURN
      END
```

```
      BLOCK DATA                                                        00013000
      COMMON/HY/ICRT,IRFLAG,ITERM,ITYPE,IWRITE,IX,A,CW,KF,KO,L,R,RHOL,V,00013010
     &VF,VO,VOLF,VOLO,ZF,ZO,OSAVE(188),FSAVE(188)                       00013020
      REAL   A(30),CW(30),KF,KO,L(30),R(30),RHOL(30),V(30)              00013030
      DATA ICRT/0/,IRFLAG/0/,ITERM/0/,ITYPE/1/,IWRITE/0/                00013040
      END                                                               00013050
```

```
      SUBROUTINE HYDRDY(IR,INPHYD,FRE,GINO,GINF,PCIN,WOIN,WFIN)         00000005
C     SUBROUTINE HYDRDY(IR,INPHYD,FREQ,GINJOX,GINJFU,PC,WO,WF)          00000010
C                                                                       00000020
C      SUBPROGRAM TO CALCULATE FEED SYSTEM RESPONSE                     00000021
C      PROGRAMMED BY J. K. HUNTING, ROCKETDYNE, MAY 1975                00000022
C  ARGUMENT LIST VARIABLES:                                             00000030
C    IR     - DATA FLAG:  =0-NO DATA READ; =1-READ NEW DATA CASE;       00000040
C                  =2-MODIFY EXISTING DATA CASE                         00000050
C    INPHYD - MODE FLAG:  =1-CALCULATE INJ. FLOW GAIN & PHASE AT 1 FREQ.00000060
C                  =2-CALC. & SAVE INJ. FLOW GAIN & PHASE FOR FREQ. RANGE 00000070
C    FREQ  - INPUT FREQUENCY FOR CASE WITH INPHYD=1                     00000080
C    GINJOX - OUTPUT COMPLEX NUMBER WITH AMPLITUDE AND PHASE ANGLE OF   00000090
C                  OXID. INJECTOR FLOW OSCILLATIONS AT FREQUENCY, FREQ  00000100
C    GINJFU - OUTPUT COMPLEX NUMBER WITH AMPLITUDE AND PHASE ANGLE OF   00000110
C                  FUEL INJECTOR FLOW OSCILLATIONS AT FREQUENCY, FREQ   00000120
C    PC     - STEADY STATE OPERATING CHAMBER PRESSURE (LB/IN**2)        00000130
C    WO     - STEADY STATE OXIDIZER INJECTOR FLOW (LB/SEC)              00000140
C    WF     - STEADY STATE FUEL INJECTOR FLOW (LB/SEC)                  00000150
C                                                                       00000160
C  LABELED COMMON BLOCK /COMTAP/ VARIABLES:                             00000170
C    FREQT  - ARRAY OF FREQUENCIES (100 MAX.) FOR INPHYD=2 CASE         00000180
C    NFREQT - NUMBER OF FREQUENCIES IN ARRAY, FREQT                     00000190
C    GINJOT - TABLE OF COMPLEX NUMBERS WITH GAINS AND PHASE ANGLES OF   00000200
C                  OXID. INJECTOR FLOW OSCILLATIONS AT FREQT FREQUENCIES 00000210
C    GINJFT - TABLE OF COMPLEX NUMBERS WITH GAINS AND PHASE ANGLES OF   00000220
C                  FUEL INJECTOR FLOW OSCILLATIONS AT FREQT FREQUENCIES 00000230
C                                                                       00000240
C NAMELIST /HYD/ VARIABLES:                                             00000250
C    ICRT   - PLOT FLAG:  =0-NO PLOTS; =1-PLOT GAIN&PHASE VS FREQUENCY  00000260
C    IWRITE - PRINT FLAG: =-2-NO PRINT; =-1-PRINT OUTPUT ONLY;          00000270
C                  =0-PRINT INPUT ONLY; =1-PRINT INPUT & OUTPUT;        00000280
C                  =2-PRINT INPUT, OUTPUT & INTERMEDIATE CALCULATIONS   00000290
C    IRFLAG - READ FLAG:  =0-CARD INPUT; =1-TERMINAL INPUT FROM ITERM   00000300
```

F S C S M SUBROUTINES

```
C     ITERM  - TERMINAL INPUT FLAG: =0-NO TERMINAL; >0-TERMINAL UNIT NO. 00000310
C                 NOTE: ITERM>0 CHANGES IRFLAG TO 1                       00000320
C     ITYPE  - SYSTEM TYPE FLAG: =1-BOTH OXID. & FUEL SYSTEMS DESCRIBED   00000330
C                 WITH 1 DATA READ; =2-OXID. SYSTEM DATA READ AND CALC-   00000340
C                 ULATED FIRST, THEN FUEL SYSTEM DATA READ & CALCULATED   00000350
C     ID     - DUMMY NAME TO ALLOW USE OF SEQUENCE NUMBERS ON NAMELIST    00000360
C                 INPUT CARDS                                             00000370
C     A      - ARRAY WITH FEED SYSTEM SEGMENT FLOW AREAS (IN**2)          00000380
C     CW     - ARRAY WITH SEGMENT WALL COMPLIANCE VALUES (IN**2/LB)       00000390
C     FREQ   - (SEE ARGUMENT LIST VARIABLES)                              00000400
C     FREQT  - (SEE COMMON BLOCK VARIABLES)                               00000410
C     KF     - FUEL INJECTOR FACE FLEXIBILITY CONSTANT  (IN**2)           00000420
C     KO     - OXID. INJECTOR FACE FLEXIBILITY CONSTANT (IN**2)           00000430
C     L      - ARRAY WITH FEED SYSTEM SEGMENT LENGTHS (IN)                00000440
C     NFREQT - (SEE COMMON BLOCK VARIABLES)                               00000450
C     R      - ARRAY WITH SEGMENT LINEARIZED RESISTANCES (SEC/IN**2)      00000460
C     RF     - FUEL INJECTOR LINEARIZED RESISTANCE (SEC/IN**2)            00000470
C     RO     - OXID  INJECTOR LINEARIZED RESISTANCE  (SEE/IN**2)          00000480
C     RHOL   - ARRAY WITH SEGMENT FLUID DENSITY VALUES (LB/IN**3)         00000490
C     V      - ARRAY WITH SEGMENT FLUID ACOUSTIC VELOCITY VALUES (IN/SEC)00000500
C     VF     - FUEL INJECTOR FLUID ACOUSTIC VELOCITY (IN/SEC)             00000510
C     VO     - OXID. INJECTOR FLUID ACOUSTIC VELOCITY (IN/SEC)            00000520
C     VOLF   - VOLUME OF FUEL INJECTOR (IN**3)                            00000530
C     VOLO   - VOLUME OF OXIDIZER INJECTOR (IN**3)                        00000540
C     ZF     - FUEL INJECTOR INERTANCE (SEC**2/IN**2)                     00000550
C     ZO     - OXID. INJECTOR INERTANCE (SEC**2/IN**2)                    00000560
C                                                                         00000570
C   DEFAULT VALUES FOR VARIABLES:                                         00000580
C     ICRT=0, IWRITE=0, IRFLAG=0, ITERM=0, ITYPE=1                        00000590
C     A=1., CW=0., KF=0., KO=0., L=.001, R=1000000., RF=.1, RO=.1,        00000600
C     RHOL=.04, V=40000., VF=40000., VO=40000., VOLF=.01, VOLO=.01,       00000610
C     ZF=.00004, ZO=.00004                                                00000620
C                                                                         00000630
```

F S C S M SUBROUTINES

```
C  NOTE: MAXIMUM OF 100 VALUES IN FREQT ARRAY                               00000640
C         MAXIMUM OF 30 VALUES IN A, CW, L, R, RHOL & V ARRAYS              00000650
C                                                                           00000660
C                                                                           00000670
C                                                                           00000680
      COMMON/HY/ICRT,IRFLAG,ITERM,ITYPE,IWRITE,IX,A,CW,KF,KO,L,R,RHOL,V,00001005
     &VF,VO,VOLF,VOLO,ZF,ZO,OSAVE(188),FSAVE(188)                           00001006
      REAL   X(188)                                                         00001007
      EQUIVALENCE (X(1),A(1))                                               00001008
      COMMON/F/NW,NCTD,NR,KEQ,TRIG,IRPS,OMI,OMFL,W,IH,C,TD,ATD,             00001010
     1FREQ,GINJOX,GINJFU,PC,WO,WF                                           00001020
      COMPLEX   NOZAT(100),GINJOT(100),GINJFT(100),GINJOX,GINJFU,           00001030
     &GINO,GINF                                                             00001040
      COMMON/COMTAP/NFREQT,FREQT(100),NOZAT,GINJOT,GINJFT,ITAPN,ITAPC,      00001050
     1ITAPH                                                                 00001060
      REAL   L(30),R(30),A(30),V(30),C(62,126),TD(62,63),ATD(126),W(101)00001070
     6,CW(30),RHOL(30),KO,KF                                                00001080
      INTEGER*4 IH(126)                                                     00001090
      NAMELIST/HYD/L,R,A,V,OMI,OMFL,FREQ,NFREQT,IWRITE,ICRT,ZF,RF,VOLF,     00001100
     &VF,ZO,RO,VOLO,VO,FREQT,IH,ITERM,IRFLAG,KO,KF,CW,RHOL,ID,ITYPE,IX      00001110
      IX=0                                                                  00001115
      IF(INPHYD.EQ.2) REWIND ITAPH                                          00001111
      G=386.4                                                               00001120
      FREQ=FRE                                                              00001130
      PC=PCIN                                                               00001140
      WO=WOIN                                                               00001150
      WF=WFIN                                                               00001160
    5 DO 10 I=1,62                                                          00001170
      DO 10 J=1,126                                                         00001180
   10 C(I,J)=0.                                                             00001190
      DO 20 I=1,62                                                          00001200
      DO 20 J=1,63                                                          00001210
   20 TD(I,J)=0.                                                            00001220
```

```
      DO 30 I=1,126                                                     00001230
   30 IH(I)=-1                                                          00001240
      IH(15)=0                                                          00001250
      IH(18)=0                                                          00001260
      IH(19)=1                                                          00001270
      IH(55)=0                                                          00001280
      IH(58)=0                                                          00001290
      IH(59)=1                                                          00001300
      IH(62)=0                                                          00001310
      NW=0                                                              00001320
      NCTD=113                                                          00001330
      NR=63                                                             00001340
      KEQ=57                                                            00001360
      TRIG=0.                                                           00001370
      IRPS=0                                                            00001380
      OMI=FREQT(1)                                                      00001390
      OMFL=FREQT(NFKEQT)                                                00001400
   35 IF(IR.LE.0) GO TO 100                                             00001410
      IF(IR.EQ.2) GO TO 45                                              00001420
      DO 40 I=1,30                                                      00001430
      R(I)=1000000.                                                     00001440
      V(I)=40000.                                                       00001450
      A(I)=1.                                                           00001460
      CW(I)=0.                                                          00001470
      RHOL(I)=.04                                                       00001480
   40 L(I)=.001                                                         00001490
      ZF=.00004                                                         00001500
      ZO=.00004                                                         00001510
      RF=.1                                                             00001520
      RO=.1                                                             00001530
      VF=40000.                                                         00001540
      VO=40000.                                                         00001550
      KF=0.                                                             00001560
```

```
      KO=0.
      VOLF=.01
      VOLO=.01
   45 IF(IRFLAG.EQ.0) READ(5,HYD,END=60)
      IF(ITERM.GT.0) IRFLAG=1
      IF(ITERM.GT.0) WRITE(ITERM,50)
   50 FORMAT(' INPUT NAMELIST &HYD DATA'/' VARIABLES ARE: L,R,A,V,CW,RHO
     &L,NFREQT,FREQT,IWRITE,ITERM'/' ICRT,ZF,RF,VO,KOLF,VF,KF,ZO,RO,VOL
     &,VO,ID,ITYPE,IRFLAG')
   60 IF(ITERM.GT.0) READ(ITERM,HYD,END=999)
      IF(ITERM.GT.0) WRITE(ITERM,66)
   66 FORMAT(' END OF &HYD INPUT')
      IF(IWRITE.GE.0) WRITE(6,HYD)
  100 IF(ITYPE.EQ.2) IX=MIN0(IX+1,2)
C  GENERATE COEFFICIENT MATRIX FOR FREQUENCY RESPONSE ROUTINE
      DO 101 I=1,30
  101 V(I)=SQRT(1./(1./V(I)/V(I)+RHOL(I)*CW(I)/G))
      C(1,1)=1.
      C(1,2)=R(1)+V(1)/G/A(1)
      C(2,1)=1.
      C(2,4)=-V(3)/G/A(3)
      C(3,3)=1.
      C(3,5)=R(3)+V(3)/G/A(3)
      C(4,1)=1.
      C(4,2)=-(R(2)+V(2)/G/A(2))
      C(4,4)=R(2)+V(2)/G/A(2)
      C(5,3)=1.
      C(5,6)=-V(5)/G/A(5)
      C(6,3)=1.
      C(6,5)=-V(4)/G/A(4)
      C(6,6)=V(4)/G/A(4)
      C(7,21)=1.
      C(7,20)=R(4)+V(4)/G/A(4)
```

```
      C(8,7)=1.                                                         00001880
      C(8,8)=R(5)+V(5)/G/A(5)                                           00001890
      C(9,7)=1.                                                         00001900
      C(9,8)=-V(6)/G/A(6)                                               00001910
      C(10,9)=1.                                                        00001920
      C(10,10)=-(R(7)+V(7)/G/A(7))                                      00001930
      C(10,11)=R(7)+V(7)/G/A(7)                                         00001940
      C(11,9)=1.                                                        00001950
      C(11,11)=-V(8)/G/A(8)                                             00001960
      C(12,12)=1.                                                       00001970
      C(12,13)=R(8)+V(8)/G/A(8)                                         00001980
      C(13,12)=1.                                                       00001990
      C(13,13)=-V(9)/G/A(9)                                             00002000
      C(14,14)=1.                                                       00002010
      C(14,27)=R(9)+V(9)/G/A(9)                                         00002020
      C(15,14)=1.                                                       00002030
      C(15,27)=-V(10)/G/A(10)                                           00002040
      C(16,16)=1.                                                       00002050
      C(16,17)=R(10)+V(10)/G/A(10)                                      00002060
      C(17,16)=1.                                                       00002070
      C(17,18)=-ZO                                                      00002080
      C(17,19)=-RO                                                      00002090
      C(18,15)=1.+VO*VO*KO/G/VOLO                                       00002100
      C(18,17)=-(VO*VO/G/VOLO)                                          00002110
      C(18,19)=VO*VO/G/VOLO                                             00002120
      C(18,62)=VO*VO*KO/G/VOLO                                          00002130
      C(19,21)=1.                                                       00002140
      C(19,22)=V(14)/G/A(14)                                            00002150
      C(20,29)=1.                                                       00002160
      C(20,28)=-(R(14)+V(14)/G/A(14))                                   00002170
      C(21,21)=1.                                                       00002180
      C(21,20)=-V(11)/G/A(11)                                           00002190
      C(21,22)=-V(11)/G/A(11)                                           00002200
```

```
      C(22,24)=1.                                                       00002210
      C(22,23)=R(11)+V(11)/G/A(11)                                      00002220
      C(23,24)=1.                                                       00002230
      C(23,23)=-(R(13)+V(13)/G/A(13))                                   00002240
      C(23,25)=R(13)+V(13)/G/A(13)                                      00002250
      C(24,24)=1.                                                       00002260
      C(24,25)=-V(12)/G/A(12)                                           00002270
      C(25,31)=1.                                                       00002280
      C(25,30)=R(15)+V(15)/G/A(15)                                      00002290
      C(26,31)=1.                                                       00002300
      C(26,30)=-V(16)/G/A(16)                                           00002310
      C(27,29)=1.                                                       00002320
      C(27,28)=R(16)+V(16)/G/A(16)                                      00002330
      C(27,32)=R(16)+V(16)/G/A(16)                                      00002340
      C(28,43)=1.                                                       00002350
      C(28,44)=R(22)+V(22)/G/A(22)                                      00002360
      C(29,43)=1.                                                       00002370
      C(29,45)=-V(24)/G/A(24)                                           00002380
      C(30,43)=1.                                                       00002390
      C(30,44)=-(R(23)+V(23)/G/A(23))                                   00002400
      C(30,45)=R(23)+V(23)/G/A(23)                                      00002410
      C(31,29)=1.                                                       00002420
      C(31,32)=-(R(17)+V(17)/G/A(17))                                   00002430
      C(32,33)=1.                                                       00002440
      C(32,34)=V(17)/G/A(17)                                            00002450
      C(33,41)=1.                                                       00002460
      C(33,42)=-V(21)/G/A(21)                                           00002470
      C(33,46)=V(21)/G/A(21)                                            00002480
      C(34,33)=1.                                                       00002490
      C(34,35)=R(21)+V(21)/G/A(21)                                      00002500
      C(35,33)=1.                                                       00002510
      C(35,34)=-V(18)/G/A(18)                                           00002520
      C(35,35)=-V(18)/G/A(18)                                           00002530
```

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      C(36,36)=1.                                                       00002540
      C(36,37)=R(18)+V(18)/G/A(18)                                      00002550
      C(37,36)=1.                                                       00002560
      C(37,37)=-(R(19)+V(19)/G/A(19))                                   00002570
      C(37,38)=R(19)+V(19)/G/A(19)                                      00002580
      C(38,36)=1.                                                       00002590
      C(38,38)=-V(20)/G/A(20)                                           00002600
      C(39,40)=-(R(20)+V(20)/G/A(20))                                   00002610
      C(40,41)=1.                                                       00002620
      C(40,46)=-V(25)/G/A(25)                                           00002630
      C(41,47)=1.                                                       00002640
      C(41,48)=R(25)+V(25)/G/A(25)                                      00002650
      C(42,47)=1.                                                       00002660
      C(42,48)=-V(26)/G/A(26)                                           00002670
      C(43,49)=1.                                                       00002680
      C(43,50)=R(26)+V(26)/G/A(26)                                      00002690
      C(44,49)=1.                                                       00002700
      C(44,50)=-(R(27)+V(27)/G/A(27))                                   00002710
      C(44,51)=R(27)+V(27)/G/A(27)                                      00002720
      C(45,49)=1.                                                       00002730
      C(45,51)=-V(28)/G/A(28)                                           00002740
      C(46,52)=1.                                                       00002750
      C(46,53)=R(28)+V(28)/G/A(28)                                      00002760
      C(47,52)=1.                                                       00002770
      C(47,53)=-V(29)/G/A(29)                                           00002780
      C(48,54)=1.                                                       00002790
      C(48,39)=R(29)+V(29)/G/A(29)                                      00002800
      C(49,54)=1.                                                       00002810
      C(49,39)=-V(30)/G/A(30)                                           00002820
      C(50,56)=1.                                                       00002830
      C(50,57)=R(30)+V(30)/G/A(30)                                      00002840
      C(51,56)=1.                                                       00002850
      C(51,58)=-ZF                                                      00002860
```

```
      C(51,59)=-RF                                                      00002870
      C(52,55)=1.+VF*VF*KF/G/VOLF                                       00002880
      C(52,57)=-(VF*VF/G/VOLF)                                          00002890
      C(52,59)=VF*VF/G/VOLF                                             00002900
      C(52,62)=VF*VF*KF/G/VOLF                                          00002910
      C(53,9)=1.                                                        00002920
      C(53,10)=R(6)+V(6)/G/A(6)                                         00002930
      C(54,26)=-(R(12)+V(12)/G/A(12))                                   00002940
      C(55,41)=1.                                                       00002950
      C(55,42)=R(24)+V(24)/G/A(24)                                      00002960
      C(56,60)=1.                                                       00002970
      C(57,61)=1.                                                       00002980
      C(17,63)=1.                                                       00002990
      C(51,63)=1.                                                       00003000
C   GENERATE TIME DELAY MATRIX FOR FREQUENCY RESPONSE ROUTINE           00003010
      TD(1,1)=2.*L(1)/V(1)                                              00003020
      TD(1,2)=2.*L(1)/V(1)                                              00003030
      TD(2,3)=L(3)/V(3)                                                 00003040
      TD(2,5)=L(3)/V(3)                                                 00003050
      TD(3,1)=L(3)/V(3)                                                 00003060
      TD(3,4)=L(3)/V(3)                                                 00003070
      TD(4,1)=2.*L(2)/V(2)                                              00003080
      TD(4,2)=2.*L(2)/V(2)                                              00003090
      TD(4,4)=2.*L(2)/V(2)                                              00003100
      TD(5,7)=L(5)/V(5)                                                 00003110
      TD(5,8)=L(5)/V(5)                                                 00003120
      TD(6,18)=L(4)/V(4)                                                00003130
      TD(6,19)=L(4)/V(4)                                                00003140
      TD(7,3)=L(4)/V(4)                                                 00003150
      TD(7,5)=L(4)/V(4)                                                 00003160
      TD(7,6)=L(4)/V(4)                                                 00003170
      TD(8,3)=L(5)/V(5)                                                 00003180
      TD(8,6)=L(5)/V(5)                                                 00003190
```

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      TD(9,9)=L(6)/V(6)                                                 00003200
      TD(9,10)=L(6)/V(6)                                                00003210
      TD(10,9)=2.*L(7)/V(7)                                             00003220
      TD(10,10)=2.*L(7)/V(7)                                            00003230
      TD(10,11)=2.*L(7)/V(7)                                            00003240
      TD(11,12)=L(8)/V(8)                                               00003250
      TD(11,13)=L(8)/V(8)                                               00003260
      TD(12,9)=L(8)/V(8)                                                00003270
      TD(12,11)=L(8)/V(8)                                               00003280
      TD(13,14)=L(9)/V(9)                                               00003290
      TD(13,25)=L(9)/V(9)                                               00003300
      TD(14,12)=L(9)/V(9)                                               00003310
      TD(14,13)=L(9)/V(9)                                               00003320
      TD(15,15)=L(10)/V(10)                                             00003330
      TD(15,16)=L(10)/V(10)                                             00003340
      TD(16,14)=L(10)/V(10)                                             00003350
      TD(16,25)=L(10)/V(10)                                             00003360
      TD(19,26)=L(14)/V(14)                                             00003370
      TD(19,27)=L(14)/V(14)                                             00003380
      TD(20,19)=L(14)/V(14)                                             00003390
      TD(20,20)=L(14)/V(14)                                             00003400
      TD(21,21)=L(11)/V(11)                                             00003410
      TD(21,22)=L(11)/V(11)                                             00003420
      TD(22,18)=L(11)/V(11)                                             00003430
      TD(22,19)=L(11)/V(11)                                             00003440
      TD(22,20)=L(11)/V(11)                                             00003450
      TD(23,21)=2.*L(13)/V(13)                                          00003460
      TD(23,22)=2.*L(13)/V(13)                                          00003470
      TD(23,23)=2.*L(13)/V(13)                                          00003480
      TD(24,24)=L(12)/V(12)                                             00003490
      TD(24,56)=L(12)/V(12)                                             00003500
      TD(25,28)=2.*L(15)/V(15)                                          00003510
      TD(25,29)=2.*L(15)/V(15)                                          00003520
```

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      TD(26,26)=L(16)/V(16)                                             00003530
      TD(26,27)=L(16)/V(16)                                             00003540
      TD(26,30)=L(16)/V(16)                                             00003550
      TD(27,28)=L(16)/V(16)                                             00003560
      TD(27,29)=L(16)/V(16)                                             00003570
      TD(28,41)=2.*L(22)/V(22)                                          00003580
      TD(28,42)=2.*L(22)/V(22)                                          00003590
      TD(29,39)=L(24)/V(24)                                             00003600
      TD(29,40)=L(24)/V(24)                                             00003610
      TD(30,41)=2.*L(23)/V(23)                                          00003620
      TD(30,42)=2.*L(23)/V(23)                                          00003630
      TD(30,43)=2.*L(23)/V(23)                                          00003640
      TD(31,31)=L(17)/V(17)                                             00003650
      TD(31,32)=L(17)/V(17)                                             00003660
      TD(32,27)=L(17)/V(17)                                             00003670
      TD(32,30)=L(17)/V(17)                                             00003680
      TD(33,31)=L(21)/V(21)                                             00003690
      TD(33,33)=L(21)/V(21)                                             00003700
      TD(34,39)=L(21)/V(21)                                             00003710
      TD(34,40)=L(21)/V(21)                                             00003720
      TD(34,44)=L(21)/V(21)                                             00003730
      TD(35,34)=L(18)/V(18)                                             00003740
      TD(35,35)=L(18)/V(18)                                             00003750
      TD(36,31)=L(18)/V(18)                                             00003760
      TD(36,32)=L(18)/V(18)                                             00003770
      TD(36,33)=L(18)/V(18)                                             00003780
      TD(37,34)=2.*L(19)/V(19)                                          00003790
      TD(37,35)=2.*L(19)/V(19)                                          00003800
      TD(37,36)=2.*L(19)/V(19)                                          00003810
      TD(38,38)=L(20)/V(20)                                             00003820
      TD(38,57)=L(20)/V(20)                                             00003830
      TD(39,34)=L(20)/V(20)                                             00003840
      TD(39,36)=L(20)/V(20)                                             00003850
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      TD(40,45)=L(25)/V(25)                                             00003860
      TD(40,46)=L(25)/V(25)                                             00003870
      TD(41,39)=L(25)/V(25)                                             00003880
      TD(41,44)=L(25)/V(25)                                             00003890
      TD(42,47)=L(26)/V(26)                                             00003900
      TD(42,48)=L(26)/V(26)                                             00003910
      TD(43,45)=L(26)/V(26)                                             00003920
      TD(43,46)=L(26)/V(26)                                             00003930
      TD(44,47)=2.*L(27)/V(27)                                          00003940
      TD(44,48)=2.*L(27)/V(27)                                          00003950
      TD(44,49)=2.*L(27)/V(27)                                          00003960
      TD(45,50)=L(28)/V(28)                                             00003970
      TD(45,51)=L(28)/V(28)                                             00003980
      TD(46,47)=L(28)/V(28)                                             00003990
      TD(46,49)=L(28)/V(28)                                             00004000
      TD(47,37)=L(29)/V(29)                                             00004010
      TD(47,52)=L(29)/V(29)                                             00004020
      TD(48,50)=L(29)/V(29)                                             00004030
      TD(48,51)=L(29)/V(29)                                             00004040
      TD(49,53)=L(30)/V(30)                                             00004050
      TD(49,54)=L(30)/V(30)                                             00004060
      TD(50,37)=L(30)/V(30)                                             00004070
      TD(50,52)=L(30)/V(30)                                             00004080
      TD(53,7)=L(6)/V(6)                                                00004090
      TD(53,8)=L(6)/V(6)                                                00004100
      TD(54,22)=L(12)/V(12)                                             00004110
      TD(54,23)=L(12)/V(12)                                             00004120
      TD(55,41)=L(24)/V(24)                                             00004130
      TD(55,43)=L(24)/V(24)                                             00004140
C  GENERATE TIME DELAY COEFFICIENT ARRAY FOR FREQUENCY RESPONSE ROUTINE 00004145
      ATD(1)=1.                                                         00004150
      ATD(2)=R(1)-V(1)/G/A(1)                                           00004160
      ATD(3)=-1.                                                        00004170
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```
      ATD(4)=-(R(3)-V(3)/G/A(3))                                        00004180
      ATD(5)=-1.                                                        00004190
      ATD(6)=-V(3)/G/A(3)                                               00004200
      ATD(7)=-1.                                                        00004210
      ATD(8)=R(2)-V(2)/G/A(2)                                           00004220
      ATD(9)=-(R(2)-V(2)/G/A(2))                                        00004230
      ATD(10)=-1.                                                       00004240
      ATD(11)=-(R(5)-V(5)/G/A(5))                                       00004250
      ATD(12)=-(R(4)-V(4)/G/A(4))                                       00004260
      ATD(13)=-1.                                                       00004270
      ATD(14)=-1.                                                       00004280
      ATD(15)=-V(4)/G/A(4)                                              00004290
      ATD(16)=V(4)/G/A(4)                                               00004300
      ATD(17)=-1.                                                       00004310
      ATD(18)=-V(5)/G/A(5)                                              00004320
      ATD(19)=-1.                                                       00004330
      ATD(20)=-(R(6)-V(6)/G/A(6))                                       00004340
      ATD(21)=-1.                                                       00004350
      ATD(22)=R(7)-V(7)/G/A(7)                                          00004360
      ATD(23)=-(R(7)-V(7)/G/A(7))                                       00004370
      ATD(24)=-1.                                                       00004380
      ATD(25)=-(R(8)-V(8)/G/A(8))                                       00004390
      ATD(26)=-1.                                                       00004400
      ATD(27)=-V(8)/G/A(8)                                              00004410
      ATD(28)=-1.                                                       00004420
      ATD(29)=-(R(9)-V(9)/G/A(9))                                       00004430
      ATD(30)=-1.                                                       00004440
      ATD(31)=-V(9)/G/A(9)                                              00004450
      ATD(32)=-1.                                                       00004460
      ATD(33)=-(R(10)-V(10)/G/A(10))                                    00004470
      ATD(34)=-1.                                                       00004480
      ATD(35)=-V(10)/G/A(10)                                            00004490
      ATD(36)=R(14)-V(14)/G/A(14)                                       00004500
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      ATD(37)=-1.                                                       00004510
      ATD(38)=-1.                                                       00004520
      ATD(39)=V(14)/G/A(14)                                             00004530
      ATD(40)=-(R(11)-V(11)/G/A(11))                                    00004540
      ATD(41)=-1.                                                       00004550
      ATD(42)=-V(11)/G/A(11)                                            00004560
      ATD(43)=-1.                                                       00004570
      ATD(44)=-V(11)/G/A(11)                                            00004580
      ATD(45)=R(13)-V(13)/G/A(13)                                       00004590
      ATD(46)=-1.                                                       00004600
      ATD(47)=-(R(13)-V(13)/G/A(13))                                    00004610
      ATD(48)=-(R(12)-V(12)/G/A(12))                                    00004620
      ATD(49)=-1.                                                       00004630
      ATD(50)=R(15)-V(15)/G/A(15)                                       00004640
      ATD(51)=1.                                                        00004650
      ATD(52)=-(R(16)-V(16)/G/A(16))                                    00004660
      ATD(53)=-1.                                                       00004670
      ATD(54)=-(R(16)-V(16)/G/A(16))                                    00004680
      ATD(55)=-V(16)/G/A(16)                                            00004690
      ATD(56)=-1.                                                       00004700
      ATD(57)=1.                                                        00004710
      ATD(58)=R(22)-V(22)/G/A(22)                                       00004720
      ATD(59)=-1.                                                       00004730
      ATD(60)=-(R(24)-V(24)/G/A(24))                                    00004740
      ATD(61)=-1.                                                       00004750
      ATD(62)=R(23)-V(23)/G/A(23)                                       00004760
      ATD(63)=-(R(23)-V(23)/G/A(23))                                    00004770
      ATD(64)=-1.                                                       00004780
      ATD(65)=V(17)/G/A(17)                                             00004790
      ATD(66)=-1.                                                       00004800
      ATD(67)=R(17)-V(17)/G/A(17)                                       00004810
      ATD(68)=-1.                                                       00004820
      ATD(69)=-(R(21)-V(21)/G/A(21))                                    00004830
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      ATD(70)=-1.                                                       00004840
      ATD(71)=-V(21)/G/A(21)                                            00004850
      ATD(72)=V(21)/G/A(21)                                             00004860
      ATD(73)=-1.                                                       00004870
      ATD(74)=-(R(18)-V(18)/G/A(18))                                    00004880
      ATD(75)=-1.                                                       00004890
      ATD(76)=-V(18)/G/A(18)                                            00004900
      ATD(77)=-V(18)/G/A(18)                                            00004910
      ATD(78)=-1.                                                       00004920
      ATD(79)=R(19)-V(19)/G/A(19)                                       00004930
      ATD(80)=-(R(19)-V(19)/G/A(19))                                    00004940
      ATD(81)=-(R(20)-V(20)/G/A(20))                                    00004950
      ATD(82)=-1.                                                       00004960
      ATD(83)=1.                                                        00004970
      ATD(84)=V(20)/G/A(20)                                             00004980
      ATD(85)=-1.                                                       00004990
      ATD(86)=-(R(25)-V(25)/G/A(25))                                    00005000
      ATD(87)=-1.                                                       00005010
      ATD(88)=-V(25)/G/A(25)                                            00005020
      ATD(89)=-1.                                                       00005030
      ATD(90)=-(R(26)-V(26)/G/A(26))                                    00005040
      ATD(91)=-1.                                                       00005050
      ATD(92)=-V(26)/G/A(26)                                            00005060
      ATD(93)=-1.                                                       00005070
      ATD(94)=R(27)-V(27)/G/A(27)                                       00005080
      ATD(95)=-(R(27)-V(27)/G/A(27))                                    00005090
      ATD(96)=-1.                                                       00005100
      ATD(97)=-(R(28)-V(28)/G/A(28))                                    00005110
      ATD(98)=-1.                                                       00005120
      ATD(99)=-V(28)/G/A(28)                                            00005130
      ATD(100)=-(R(29)-V(29)/G/A(29))                                   00005140
      ATD(101)=-1.                                                      00005150
      ATD(102)=-1.                                                      00005160
```

```
      ATD(103)=-V(29)/G/A(29)
      ATD(104)=-1.
      ATD(105)=-(R(30)-V(30)/G/A(30))
      ATD(106)=-V(30)/G/A(30)
      ATD(107)=-1.
      ATD(108)=-1.
      ATD(109)=-V(6)/G/A(6)
      ATD(110)=1.
      ATD(111)=V(12)/G/A(12)
      ATD(112)=-1.
      ATD(113)=-V(24)/G/A(24)
  400 IF(INPHYD.GT.1) GO TO 500
      NW=1
  500 CALL FRESP(ICPT,IWRITE,IX)
      IF(IX.LT.2) GO TO 502
      DO 501 I=1,188
      FSAVE(I)=X(I)
  501 X(I)=OSAVE(I)
      GO TO 510
  502 IF(IX.EQ.0) GO TO 510
      DO 503 I=1,188
  503 OSAVE(I)=X(I)
      GO TO 5
  510 IF(INPHYD.LE.1) GO TO 700
      IF(IWRITE.NE.0)WRITE(6,550)(FREQT(J),GINJOT(J),GINJFT(J),J=1,NFREQ
     &T)
      WRITE(ITAPH) (GINJOT(J),GINJFT(J),J=1,NFREQT)
  550 FORMAT(1H1,///,18X,'FEED  SYSTEM  RESPONSE  PARAMETERS',//,
     1      5X,'FREQUENCY',4X,'OXIDIZER INJECTION RATE',4X,
     2      'FUEL INJECTION RATE',/,20X,'AMPLITUDE',5X,'PHASE',
     3      6X,'AMPLITUDE',5X,'PHASE',/,(5X,0PF9.3,5X,1PE11.4,
     4      0PF9.2,5X,1PE11.4,0PF9.2))
      INPHYD=3
```

```
      END FILE ITAPH                                                    00005380
  700 GINO=GINJUX                                                       00005400
      GINF=GINJFU                                                       00005410
      RETURN                                                            00005420
  999 STOP                                                              00005430
      END                                                               00005440
```

F S C S M SUBROUTINES

```
      SUBROUTINE  LOCFAC(JK, X,TX,NX, JX,FX)
C
C     ROUTINE FOR LINEAR INTERPOLATION
C       IF JK EQ. 1, CHECKS ORDER OF TX ARRAY (NX ITEMS) FOR
C         CONSISTANTLY INCREASING OR DECREASING VALUES.
C       FINDS LOCATION OF FIRST (OR ONLY) ARRAY ITEM FOR SCALING
C         LOCATION OF X FROM TX(JX)
C       CALCULATES SCALING FACTOR FX = (X-TX(JX)) / (TX(JX+1)-TX(JX))
C     PROGRAMMED BY M. D. SCHUMAN, ROCKETDYNE, MAY 1975
C
      DIMENSION  TX(1)
C
      JX = 1
      FX = 0.
      IF(NX.LE.1)  GO TO 200
      S = 1.
      IF(TX(1).GT.TX(NX))  S = -1.
      XR2 = ABS(TX(NX)-TX(1))*0.5
      IF(JK.NE.1)  GO TO 90
C
      JK = 0
      IF(S.GT.0.)  GO TO 30
        DO 20 I=2,NX
        IF(TX(I).GT.TX(I-1))  GO TO 50
   20   CONTINUE
      GO TO 90
   30   DO 40 I=2,NX
        IF(TX(I).LT.TX(I-1))  GO TO 50
   40   CONTINUE
      GO TO 90
C
   50 WRITE(6,60)
   60 FORMAT(1H1 41X 27HE R R O R   I N   T A B L E )
```

```
   70  WRITE(6,80)   X,(TX(I),I=1,NX)                                      00000340
   80   FORMAT(1H0 41X 27HREFER TO SUBROUTINE  LOCFAC  //                  00000350
     1            5X 3HX = 1PE15.4 / 4X 4HTX = 6E15.4 / (8X 6E15.4) )       00000360
        CALL  EXIT                                                         00000370
        STOP                                                               00000380
C                                                                          00000390
   90 NX1 = 2                                                              00000400
      IF(NX.LE.20)  GO TO 110                                              00000410
        DO 100 I=10,NX,10                                                  00000420
        JX = I                                                             00000430
        IF((TX(I)-X)*S) 100,200,110                                        00000440
  100   NX1 = 1 + 1                                                        00000450
  110     DO 120 I=NX1,NX                                                  00000460
          JX = 1                                                           00000470
          IF((TX(I)-X)*S) 120,200,130                                      00000480
  120     CONTINUE                                                         00000490
  130 IF(JX.GT.1)  JX = JX-1                                               00000500
      FX = (X-TX(JX)) / (TX(JX+1)-TX(JX))                                  00000510
        IF(X.LT.AMIN1(TX(1),TX(NX))-XR2)  GO TO 150                        00000520
        IF(X.GT.AMAX1(TX(1),TX(NX))+XR2)  GO TO 150                        00000530
          GO TO 200                                                        00000540
C                                                                          00000550
  150 WRITE(6,160)                                                         00000560
  160 FORMAT(1H1 22X 64HE R R O R  -  EXTRAPOLATION OF TABLE IS BEYOND R00000570
     1EASONABLE LIMITS )                                                   00000580
      GO TO 70                                                             00000590
C                                                                          00000600
  200     RETURN                                                           00000610
          END                                                              00000620
      SUBROUTINE NUZADM(IR,GAMX,CO,FREQ,NOZA)                              00000010
C                                                                          00000020
C     SUBPROGRAM TO CALCULATE THE DOWNSTREAM NOZZLE ADMITTANCE             00000030
C     PROGRAM DEVELOPED BY GEORGIA INSTITUTE OF TECHNOLOGY                 00000040
```

F S C S M SUBROUTINES

```
C         REF. NASA CR-121129
C      MODIFIED FOR THE FEED SYSTEM COUPLED STABILITY MODEL
C         BY M. D. SCHUMAN, ROCKETDYNE, MAY 1975
C
       IMPLICIT REAL*8(A-H,O-Z)
C
       COMPLEX    NOZA, NOZAT, GINJOT, GINJFT
C
       REAL    FREQ, GAMX, RCCX, RCTX, ANGLEX, CRR, RINJ, CO, FREQMX,
      1    FREQMI, FREQT, FREQ1, FREQ2
C
       DIMENSION DY(5,4), G(5), GP(5), Y(5)
C
       COMMON /X1/GAM,SVN,ANGLE,RCT,RCC /X2/T,RT,Q,R1,R2,WC,IP
      1       /X3/Z1R,Z11  /X4/CM
C
       COMMON /COMTAP/ NFREQT, FREQT(100), NOZAT(100), GINJOT(100),
      1    GINJFT(100), ITAPN, ITAPC, ITAPH
C
       COMMON /COMNOZ/ RCCX, RCTX, ANGLEX, CRR, RINJ, INPNOZ, FREQMX,
      1    FREQMI, IPRNOZ
C
       IF(INPNOZ.EQ.3) REWIND ITAPN
C
       IF(IR.LE.0) GO TO 2
C
C      INPUT DATA REQUIRED BY THE SUBPROGRAM
C
       READ(5,9000) RCCX, RCTX, ANGLEX, CRR
 9000  FORMAT(6E12.8)
       WRITE(6,9010) RCCX, RCTX, ANGLEX, CRR
 9010  FORMAT(/,5X,'RCCX =',1PE11.4,5X,'RCTX =',E11.4,5X,'ANGLEX =',
      1    E11.4,3X,'CRR =',E11.4)
```

F S C S M SUBROUTINES

```
    2 GAM = GAMX
      RCC = RCCX
      RCT = RCTX
      ANGLE = ANGLEX
C
      IF(INPNOZ.EQ.3)  WRITE(ITAPN) NFREQT
      IP = 0
      SVN = 0.0
      IF(INPNOZ.LE.1) GO TO 2000
      DWC = 6.283185*RINJ/CO*(FREQMX-FREQMI)/(NFREQT-1)
      WC = 6.283185*RINJ/CO*FREQMI-DWC
      NWC = NFREQT
      GO TO 2010
 2000 DWC = 0.0
      WC = 6.283185*RINJ/CO*FREQ
      NWC = 1
 2010 CONTINUE
      DP = -0.001
      T = 3.1415927*ANGLE/180.0
      IF(CRR.LE.0.0) GO TO 7
      CMO=0.0
5     CM=1./CRR*(2./(GAM+1.)*(1.+(GAM-1.)*0.5*CMO*CMO))
     1   **((GAM+1.)/(2.*(GAM-1.)))
      ER=DABS((CMO-CM)/CM)
      CMO=CM
      IF(ER.GT.1.E-06) GO TO 5
    7 CONTINUE
      IF(IPRNOZ.GT.0.AND.INPNOZ.GT.1)
     1     WRITE(6,1000) CM, SVN, GAM, ANGLE, RCT, RCC
      DO 10 N=1,NWC
   20 WC = WC + DWC
   25 RT = (CM**0.5)*((1+(GAM-1)*CM*CM/2)**((-GAM-1)/(4*(GAM-1))))
     1     *((2/(GAM+1))**((-GAM-1)/(4*(GAM-1))))
```

F S C S M   SUBROUTINES

```
      Q = (0.25*RT)*((2/(GAM+1))**((GAM+1)/(4*(GAM-1))))
      PHIR = 1
      PHII = 0
      R1 = RT+RCT*(1-DCOS(T))
      R2 = 1.0-RCC*(1-DCOS(T))
      P = 0
      U = 2/(GAM+1)
      SRTR = (RT*RCT)**0.5
      A1R = -4/((GAM+1)*SRTR)
      B0R = -A1R
      B0I = 4*WC/(GAM+1)
      SVNR = SVN/RT
      C0R = WC*WC-((SVNR*SVNR)*2/(GAM+1))
      C0I = -2*WC*(GAM-1)/((GAM+1)*SRTR)
      B1R = (24+4*GAM)/(3*RCT*RT*(GAM+1))
      B1I = 8*WC/(SRTR*(GAM+1))
      C1R = 2*(GAM-1)*SVNR*SVNR/(SRTR*(GAM+1))
      C1I = -B1R*WC*(GAM-1)*0.5
      Z0R = (B0R*C0R+B0I*C0I)/(B0R*B0R+B0I*B0I)
      Z0I = (B0R*C0I-B0I*C0R)/(B0R*B0R+B0I*B0I)
      F1 = B1R*Z0R-B1I*Z0I-Z0R*Z0R*A1R+A1R*Z0I*Z0I-C1R
      F2 = B1I*Z0R+B1R*Z0I-2*A1R*Z0I*Z0R-C1I
      Z1R = (F1*(A1R-B0R)-F2*B0I)/((A1R-B0R)*(A1R-B0R)+B0I*B0I)
      Z1I = (F2*(A1P-B0R)+F1*B0I)/((A1R-B0R)*(A1R-B0R)+B0I*B0I)
      C = U
      G(1) = U
      G(2) = Z0R
      G(3) = Z0I
      G(4) = PHIR*Z0R-PHII*Z0I
      G(5) = PHII*Z0R+Z0I*PHIR
      DY(1,1) = -A1R
      DY(2,1) = Z1R
      DY(3,1) = Z1I
```

```
      DY(4,1) = PHIR
      DY(5,1) = PHII
      IQZ = 2
      DO 30 I=2,4
      CALL RKTZ(5,DP,P,G,GP,IQZ)
      P = P+DP
      U = G(1)
      ZR = G(2)
      ZI = G(3)
      PHIR = G(4)
      PHII = G(5)
      DY(1,I) = GP(1)
      DY(2,I) = GP(2)
      DY(3,I) = GP(3)
      DY(4,I) = GP(4)
   30 DY(5,I) = GP(5)
      Y(1) = U
      Y(2) = ZR
      Y(3) = ZI
      Y(4) = PHIR
      Y(5) = PHII
      CALL ZADAMS(5,DP,P,Y,DY,IQZ)
      IF(IP.EQ.1) GO TO 10
      U = Y(1)
      ZR = Y(2)
      ZI = Y(3)
      PHIR = Y(4)
      PHII = Y(5)
      QBAR = U**0.5
      C = 1-U*0.5*(GAM-1)
      RHO = C**(1/(GAM-1))
      F = QBAR/(GAM*RHO)
      IF(IQZ.EQ.1) GO TO 35
```

```
      ZDN = (U*U*ZR*ZR)+(WC+U*ZI)*(WC+U*ZI)                             00001400
      YR = -(U*(ZR*ZR+ZI*ZI)+WC*ZI)*F/ZDN                               00001410
      YI = F*WC*ZR/ZDN                                                  00001420
      GO TO 40                                                          00001430
   35 TR = Y(2)                                                         00001440
      TI = Y(3)                                                         00001450
      TDN = (U-WC*TI)*(U-WC*TI)+(WC*TR)*(WC*TR)                         00001460
      YR = -F*(U-WC*TI)/TDN                                             00001470
      YI = F*WC*TR/TDN                                                  00001480
   40 SYR = GAM*(C**((GAM+1)/(2*(GAM-1))))*YR                           00001490
      SYI = GAM*(C**((GAM+1)/(2*(GAM-1))))*YI                           00001500
      W = WC*(C**(-0.5))                                                00001510
      ZDN = 1/(W*W+SVN*SVN*CM*CM)                                       00001520
      IF(W*W-SVN*SVN*(1-CM*CM)) 50, 50,45                               00001530
   45 F = ((W*W-SVN*SVN*(1-CM*CM))**0.5)*ZDN                            00001540
      C = SVN*SVN*CM*ZDN                                                00001550
      TR = (SYR+C)/F                                                    00001560
      TI = SYI/F                                                        00001570
      U = (((1+TR)*(1+TR)+TI*TI)/((1-TR)*(1-TR)+TI*TI))**0.5            00001580
      ALP = 0.159155*DLOG(U)                                            00001590
      U = (1-TR*TR-TI*TI)+(((1+TR)*(1+TR)+TI*TI)*((1-TR)*(1-TR)+TI*TI)) 00001600
     1     **0.5                                                        00001610
      U = U/(2*TI)                                                      00001620
      BET = 0.31831*DATAN(U)                                            00001630
      FREQ1 = WC*CO/(6.283185*RINJ)                                     00001640
      FREQ2 = W*CO/(6.283185*RINJ)                                      00001650
      IF(IPRNOZ.GT.0.AND.INPNOZ.GT.1)                                   00001660
     1     WRITE(6,1005) FREQ1,YR,YI,FREQ2,SYR,SYI,ALP,BET              00001670
      GO TO 8                                                           00001680
   50 FREQ1 = WC*CO/(6.283185*RINJ)                                     00001690
      FREQ2 = W*CO/(6.283185*RINJ)                                      00001700
      IF(IPRNOZ.GT.0.AND.INPNOZ.GT.1)                                   00001710
     1     WRITE(6,1005) FREQ1,YR,YI,FREQ2,SYR,SYI                      00001720
```

```
    8 NOZA = SYR+(0.0,1.0)*SYI
      IF(INPNOZ.LE.1) GO TO 10
      FREQT(N) = FREQ2
      NOZAT(N) = NOZA
C
C     SAVE ADMITTANCE DATA ON TAPE UNIT ITAPN
C
      IF(INPNOZ.EQ.3)  WRITE(ITAPN) FREQ2,NOZA
   10 CONTINUE
 1000 FORMAT(1H1,////,30X,30HTHEORETICAL NOZZLE ADMITTANCES,//,23X,
     1  14HMACH NUMBER = ,F3.2,7H SVN = ,F6.4,9H GAMMA = ,F5.3,//,
     2  7X,15HNOZZLE ANGLE = ,F4.1,2X,21HRADII OF CURVATURE:
     3  ,9HTHROAT = ,F6.4,12H ENTRANCE = ,F6.4,//,9X,2HFC,
     4  7X,2HYR,8X,2HYI,8X,1HF,8X,3HSYR,8X,3HSYI,
     5  6X,5HALPHA,5X,4HBETA,/)
 1005 FORMAT(6X,F6.1,2F10.5,F10.2,4F10.5)
      IF(INPNOZ.EQ.3)  END FILE ITAPN
      IF(INPNOZ.GT.1)  INPNOZ=4
      RETURN
      END
```

```
      SUBROUTINE RKTDIF(P,G,GP)                                         00002630
C                                                                       00002640
C     ROUTINE FOR SUBPROGRAM NOZADM                                     00002650
C     PROGRAM DEVELOPED BY GEORGIA INSTITUTE OF TECHNOLOGY              00002660
C        REF. NASA CR-121129                                            00002670
C                                                                       00002680
      IMPLICIT REAL*8(A-H,O-Z)                                          00002690
      COMMON /X1/GAM,SVN,ANGLE,RCT,RCC /X2/T,RT,Q,R1,R2,WC,IP           00002700
      DIMENSION G(5), GP(5)                                             00002710
      U = G(1)                                                          00002720
      TR = G(2)                                                         00002730
      TI = G(3)                                                         00002740
      PHIR = G(4)                                                       00002750
      PHII = G(5)                                                       00002760
      C = 1-(GAM-1)*U*0.5                                               00002770
      R = Q*((C)**(-1./(2.*(GAM-1.))))*(U**(-0.25))*4.0                 00002780
    9 FORMAT(3X,'PRINTING FROM CARD 4570',/,3X,'R=',E15.8,              00002790
     1   3X,'R1=',E15.8,3X,'RT=',E15.8)                                 00002800
      IF(R-1) 22,22,50                                                  00002810
   22 IF(R-R1) 25,30,30                                                 00002820
   25 DR = -((2*RCT*(R-RT)-(R-RT)*(R-RT))**0.5)/(RT+RCT-R)              00002830
      GO TO 45                                                          00002840
   30 IF(R-R2) 35,40,40                                                 00002850
   35 DR = -DTAN(T)                                                     00002860
      GO TO 45                                                          00002870
   40 DR = ((2*RCC*(1-R)-(R-1)*(R-1))**0.5)/(1-R-RCC)                   00002880
   45 DU = -(U**0.75)*(C**((2*GAM-1)/(2*(GAM-1))))/(Q*(1-(GAM+1)*U*.5)) 00002890
      GP(1) = DU*DR                                                     00002900
      GO TO 55                                                          00002910
   50 GP(1) = 0.0                                                       00002920
   55 A = U*(C-U)                                                       00002930
      BR = U*GP(1)/C                                                    00002940
      BI = 2*WC*U                                                       00002950
```

```
CR = WC*WC-(SVN*SVN*C)/(R*R)
CI = -(GAM-1)*WC*U*GP(1)*0.5/C
GP(2) = 1-((BR*TR-BI*TI)-(CR*(TR*TR-TI*TI)-2*CI*TR*TI))/A
GP(3) = (-BR*TI-BI*TR+CI*(TR*TR-TI*TI)+2*CR*TR*TI)/A
T2 = TR*TR+TI*TI
GP(4) = (TR*PHIR-TI*PHII)/T2
GP(5) = (TR*PHII+TI*PHIR)/T2
RETURN
END
```

```
      SUBROUTINE RKTZ(NU,H,T1,U,DUM,JOPT)                                00003560
C                                                                        00003570
C     ROUTINE FOR SUBPROGRAM NOZADM                                      00003580
C     PROGRAM DEVELOPED BY GEORGIA INSTITUTE OF TECHNOLOGY               00003590
C        REF. NASA CR-121129                                             00003600
C                                                                        00003610
      IMPLICIT REAL*8(A-H,O-Z)                                           00003620
      COMMON /X2/T,RT,Q,R1,R2,WC,IP                                      00003630
      DIMENSION U(5), A(5), UZ(5), FZ(4,5), DUM(5)                       00003640
      A(1) = 0.0                                                         00003650
      A(2) = 0.0                                                         00003660
      A(3) = 0.5                                                         00003670
      A(4) = 0.5                                                         00003680
      A(5) = 1.0                                                         00003690
      TZ = T1                                                            00003700
      DO 10 J=1,NU                                                       00003710
      UZ(J) = U(J)                                                       00003720
   10 DUM(J) = FZ(1,J)                                                   00003730
      IF(JOPT.EQ.2) GO TO 15                                             00003740
      CALL RK1DIF(TZ,UZ,DUM)                                             00003750
      GO TO 20                                                           00003760
   15 CALL RKZDIF(TZ,UZ,DUM)                                             00003770
   20 DO 25 J=1,NU                                                       00003780
   25 FZ(1,J) = DUM(J)                                                   00003790
      DO 30 I=2,4                                                        00003800
      TZ = T1+A(I+1)*H                                                   00003810
      DO 35 J=1,NU                                                       00003820
      UZ(J) = U(J)+A(I+1)*H*FZ(I-1,J)                                    00003830
   35 DUM(J) = FZ(I,J)                                                   00003840
      IF(JOPT.EQ.2) GO TO 40                                             00003850
      CALL RKTDIF(TZ,UZ,DUM)                                             00003860
      GO TO 45                                                           00003870
   40 CALL RKZDIF(TZ,UZ,DUM)                                             00003880
```

```
   45 DO 50 J=1,NU                                                    00003890
   50 FZ(I,J) = DUM(J)                                                00003900
   30 CONTINUE                                                        00003910
      DO 55 J=1,NU                                                    00003920
   55 U(J) = U(J)+H*(FZ(1,J)+2*(FZ(2,J)+FZ(3,J))+FZ(4,J))/6.0         00003930
      GO TO (60,65),JOPT                                              00003940
   60 CALL RKTDIF(TZ,U,DUM)                                           00003950
      GO TO 70                                                        00003960
   65 CALL RKZDIF(TZ,U,DUM)                                           00003970
   70 IF(IP.EQ.0) GO TO 75                                            00003980
      PR = WC*U(5)-U(1)*DUM(4)                                        00003990
      PI = -WC*U(4)-U(1)*DUM(5)                                       00004000
      PMAG = DSORT(PR*PR+PI*PI)                                       00004010
      PARG = DATAN(PI/PR)                                             00004020
      WRITE(6,1000) TZ,PMAG,PARG                                      00004030
 1000 FORMAT(46X,F6.4,1X,F10.5,3X,F10.5)                              00004040
   75 RETURN                                                          00004050
      END                                                             00004060
```

```
      SUBROUTINE RKZDIF(P,G,GP)
C
C     ROUTINE FOR SUBPROGRAM NOZADM
C     PROGRAM DEVELOPED BY GEORGIA INSTITUTE OF TECHNOLOGY
C        REF. NASA CR-121129
C
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON /X1/GAM,SVN,ANGLE,RCT,RCC /X2/T,RT,Q,R1,R2,WC,IP
     1        /X3/Z1R,Z1I
      DIMENSION G(5), GP(5)
      U = G(1)
      ZR = G(2)
      ZI = G(3)
      PHIR = G(4)
      PHII = G(5)
      IF(P) 15,10,15
   10 GP(1) = 4/((GAM+1)*((RCT*RT)**0.5))
      GP(2) = Z1R
      GP(3) = Z1I
      GP(4) = Z1R
      GP(5) = Z1I
      GO TO 20
   15 C = 1-(GAM-1)*U*0.5
      R = Q*((C)**(-1./(2.*(GAM-1.))))*(U**(-0.25))*4.0
   16 FORMAT(3X,'PRINTING FROM CARD 5000',/,3X,'R=',E15.8,
     1   3X,'R1=',E15.8,3X,'RT=',E15.8)
            IF(R.LT.RT)  RT=R
            IF(R1.LT.RT) R1=RT
      IF(R-1) 22,22,50
   22 IF(R-R1) 25,30,30
   25 DR = -((2*RCT*(R-RT)-(R-RT)*(R-RT))**0.5)/(RT+RCT-R)
      GO TO 45
   30 IF(R-R2) 35,40,40
```

```
35 DR = -DTAN(T)                                                         00003380
   GO TO 45                                                              00003390
40 DR = ((2*RCC*(1-R)-(R-1)*(R-1))**0.5)/(1-R-RCC)                       00003400
45 DU = -(U**0.75)*(C**((2*GAM-1)/(2*(GAM-1))))/(Q*(1-(GAM+1)*U*.5)) 00003410
   GP(1) = DU*DR                                                         00003420
   GO TO 55                                                              00003430
50 GP(1) = 0.0                                                           00003440
55 A = U*(C-U)                                                           00003450
   BR = U*GP(1)/C                                                        00003460
   BI = 2*WC*U                                                           00003470
   CR = WC*WC-SVN*SVN*C/(R*R)                                            00003480
   CI = -(GAM-1)*WC*U*GP(1)*0.5*(1/C)                                    00003490
   GP(2) = ((BR*ZR-BI*ZI-CR)/A)-ZR*ZR+ZI*ZI                              00003500
   GP(3) = ((BI*ZR+BR*ZI-CI)/A)-2*ZR*ZI                                  00003510
   GP(4) = ZR*PHIR-ZI*PHII                                               00003520
   GP(5) = ZR*PHII+ZI*PHIR                                               00003530
20 RETURN                                                                00003540
   END                                                                   00003550
```

```
      SUBROUTINE SOLVW(KWHERE)
C
C     SUBPROGRAM SOLVES FOR THE COMPLEX FREQUENCY BASED ON THE
C        UPSTREAM AND DOWNSTREAM NOZZLE ADMITTANCE
C     PROGRAMMED BY K. W. FERTIG, ROCKETDYNE, MAY 1975
C
C     WHEN ISCNT = 1,4, OR 5 THIS PROGRAM COMPUTES CNOZA-NOZA FOR A
C     GIVEN OMEGA. WHEN ISCNT = 1 OR 4, THIS ROUTINE ALSO FINDS
C     IMAG(OMEGA) THAT MINIMIZES CNOZA-NOZA KEEPING REAL(OMEGA) CONSTANT
C
C     FURTHER, WHEN ISCNT = 1 OR 4, TESTING IS PERFORMED TO DETERMINE
C     IF A ROOT IS NEARBY.
C
C
      COMPLEX OMEGA, P, RHO, V, MR, T, CNOZA, VXO,
     1     NOZA, OMEGO,
     2     DOM, Z1, Z2, Z3, FN, NOZAMR, GN,
     3     CNOZO, NOZO, FNO, GNO, OMEGSV
C
C
      COMMON /COMCHM/ P(100), RHO(100), V(100), MR(100), T(100),
     1     VXO, OMEGA, CNOZA, DELP
C
      COMMON /FZERO/ NOZA,NOZAMR,GN,FN,FNR,FNI,HN,ISCNT,ISLP
C
      EXTERNAL XIMAGF
C
      DATA PI/3.141593/
C
      COMMON /SOLVE/ FREQ, DELFRQ, DELMX, EPSF, EPSX, EPSFS, EPSXS,
     1               FRQMAX, CTEST, IPASS, KNTR, ISTR1, KSCNT4, IWSKP,
     2               KNTMX, KNTSMX, KNTRMX
C
```

```
      X1 = AIMAG(OMEGA)
C
C       XIMAGF COMPUTES FNR+(0,1)*FNI=CNOZA-NOZA, HN=CABS(CNOZA-NOZA).
C       WHEN ISCNT = 1 OR 4 AND ISLP = 1, XIMAGF=D(HN**2)/D(IMAG(OMEGA))
C
      F1 = XIMAGF(X1)
      H1 = HN
      IF(IPASS.EQ.0) GO TO 225
C
C       WHEN ISCNT = 5, BYPASS MINIMIZATION OF CABS(CNOZA-NOZA) W.R.T.
C       IMAG(OMEGA) AND COMPUTATION OF JACOBIAN OF FNR,FNI W.R.T. OMEGA.
C
      IF(ISCNT.EQ.5) GO TO 195
C
C       IF ISLP=0, THEN (CNOZA-NOZA) AT OMEGA + DELTA REAL(OMEGA) HAS
C       JUST BEEN COMPUTED IN XIMAGF. GO TO 146 TO FINISH COMPUTATION
C       OF JACOBIAN AND THEN COMPUTE FTEST2.
C
      IF(ISLP.EQ.0) GO TO 146
C
C       ISLP EQUALS 1. PROCEED TO MINIMIZE CABS(CNOZA-NOZA) W.R.T.
C       IMAG(OMEGA). THIS IS DONE UP TO STATEMENT 145.
C
      KNT = 0
      X2 = X1 - HN/(2.*F1)
      X2 = AMIN1(X1+DELMX,AMAX1(X1-DELMX,X2))
  110 F2 = XIMAGF(X2)
      H2 = HN
      AF = AMAX1(.01,CABS(NOZA))
C
C       IF F1 AND F2 HAVE OPPOSITE SIGNS, THEN MIN POINT HAS BEEN CROSSED
C       TRANSFEK TO 125 FOR CONVERGENCE TESTS.
C
```

```
  115 IF(F1*F2.LE.0.) GO TO 125
C
C       USE TIGHTENED CRITERIA TO CHECK TO SEE IF CONVERGENCE HAS BEEN
C       REACHED WITHOUT CHANGING SIGN.
C
      IF(ABS(F2/AF).LE.EPSFS.AND.ABS((X1-X2)/AMAX1(1.,X2)).LE.EPSXS
     1      .AND.H2.LE.H1) GO TO 145
      IER = 0
      IF(IABS(IWSKP).GE.2) WRITE(6,8490) KNT,IER,X1,X2,F1,F2,OMEGA,
     1                          FN,GN,HN
 8490 FORMAT(/2I5,1P4E13.5/2X,3(1PE13.5,' :',1PE12.5),1PE15.5)
      IF(H2.LT.H1) GO TO 117
C
C       LAST STEP TOO LARGE. CUT GUESS IN HALF.
C
      X2 = (X1+X2)/2.
      GO TO 110
  117 IF(X1.LT.X2.AND.F1.LT.F2) GO TO 120
      IF(X1.GT.X2.AND.F2.LT.F1) GO TO 120
C
C       ESTIMATE NEXT GUESS BY TRYING TO HALVE THE ERROR.
C
      X3 = X2 - HN**2/(2.*F2)
      IER = -10
  118 KNT = KNT+1
      IF(KNT.GT.KNTMX) GO TO 140
      X3 = AMIN1(X2+DELMX,AMAX1(X2-DELMX,X3))
      X1 = X2
      F1 = F2
      X2 = X3
      GO TO 110
C
C       ESTIMATE NEXT GUESS USING FALSE POSITION.
```

```
C
  120 X3 = (F2*X1-F1*X2)/(F2-F1)
      GO TO 118
  125 FANS = F2
      ANS = AIMAG(OMEGA)
  135 IF(ABS(FANS)/AF.LE.EPSF.AND.ABS((X1-X2)/AMAX1(1.,ANS)).LE.
     1            EPSX) GO TO 145
      IF(X1 .LT.X2) GO TO 137
      X3 = X2
      F3 = F2
      X2 = X1
      F2 = F1
      X1 = X3
      F1 = F3
  137 K = 0
C
C       ROOT IS BRACKETED BUT CONVERGENCE NOT YET REACHED. CALL ZERO
C       TO FIND ROOT WITHIN EPSX.
C
      CALL ZERO(XIMAGF,X1,X2,F1,F2,ANS,FANS,EPSF,EPSX,AF,KNT,KNTMX,IER,K
     1    )
      IF(IER.EQ.0) GO TO 145
  140 WRITE(6,8601) X1,F1,X2,F2,X3,F3,ANS,FANS,KNT,IER,OMEGA
 8601 FORMAT(//'   **** UNABLE TO FIND ROOT FOR IMAG PART OF F ****'
     1 //'   X1,F1,X2,F2,X3,F3,ANS,FANS,KNT,IER,OMEGA = '/
     2   3X,1P8E13.5/3X,2I10/3X,1PE13.5,' : ',1PE13.5)
      GO TO 5000
C
C       (CNOZA-NOZA) HAS BEEN MINIMIZED W.R.T. IMAG(OMEGA). SAVE VALUES
C       FOR COMPUTATION OF DERIVATIVES W.R.T. REAL(OMEGA).
C
  145 CNOZO = CNOZA
      NOZO = NOZA
```

```
      FR3 = FNR
      FI3 = FNI
      XR3 = REAL(OMEGA)
      XI3 = AIMAG(OMEGA)
      FNO = FN
      HNO = HN
      GNO = GN
      OMEGO = OMEGA
      DFRDY = REAL(GN)
      DFIDY = AIMAG(GN)
      DM = AMAX1(.01,.001*REAL(OMEGA))
      ISLP = 0
      OMEGA = OMEGA+DM
      FREQ = REAL(OMEGA)/(2.*PI)
      GO TO 15
C
C
C      COMPUTE DERIVATIVES, FTEST2(TEST FUNCTION), DET2(DETERMINANT
C      OF JACOBIAN), AND COND2(CONDITION NUMBER OF JACOBIAN).
C
  146 DFRDX = (FNR-FR3)/DM
      DFIDX = (FNI-FI3)/DM
      OMEGA = OMEGO
      FREQ = REAL(OMEGA)/(2.*PI)
      CNOZA = CNOZO
      NOZA = NOZO
      FN = FNO
      GN = GNO
      HN = HNO
      DET2 = DFRDX*DFIDY - DFIDX*DFRDY
      FNR = FR3
      FNI = FI3
      FTST2 = 2.*(FNR*DFRDX + FNI*DFIDX)/DET2
```

```
      AA1 = DFRDX**2+DFRDY**2                                           00001660
      AA2 = DFIDX**2+DFIDY**2                                           00001670
      AA3 = (DFRDX*DFIDX+DFRDY*DFIDY)**2                                00001680
      COND2 = (AA1+AA2+SQRT((AA1-AA2)**2+4*AA3))/                       00001690
     1        (AA1+AA2-SQRT((AA1-AA2)**2+4*AA3))                        00001700
      COND2 = SQRT(COND2)                                               00001710
      KNTR = KNTR + 1                                                   00001720
      IF(IABS(IWSKP).GE.1) WRITE(6,8500) ISCNT,KNTR,KSCNT4,OMEGA,CNOZA, 00001730
     1                       NOZA,HN,FTST2,DET2,COND2                   00001740
 8500 FORMAT(/3I5,3(1PE14.5,' :',1PE12.5)/2X,1P4E13.5)                  00001750
      IF(IABS(IWSKP).GE.2) WRITE(6,8510) FN,DFRDX,DFIDX,DFRDY,DFIDY     00001760
 8510 FORMAT(2X,1PE14.5,' :',1PE12.5,2X,1P4E13.5)                       00001770
      IER = 0                                                           00001780
      IF(ISCNT.EQ.4) GO TO 183                                          00001790
      IF(ISTRT.EQ.0) GO TO 150                                          00001800
      IF(ISCNT.EQ.3) GO TO 170                                          00001810
      IER = -15                                                         00001820
C                                                                       00001830
C      ISCNT=1 AND ISTRT=1(NOT FIRST TIME THROUGH OR FIRST TIME THROUGH 00001840
C      AFTER A SINGULARITY IN THE JACOBIAN HAS BEEN CROSSED). TEST FOR  00001850
C      EXISTANCE OF ROOT IN CURRENT FREQUENCY RANGE (FREQ-DELFRQ,FREQ). 00001860
C                                                                       00001870
      IF(FTST2*FTST1.LE.0..AND.DET2*DET1.GT.0..AND.                     00001880
     1      AMAX1(COND1,COND2).LE.CTEST) GO TO 160                      00001890
      IF(KNTR.GT.KNTRMX) GO TO 205                                      00001900
C                                                                       00001910
C      TRANSFER VALUES FROM 2 TO 1 AND 3 TO 2.                          00001920
C                                                                       00001930
  147 CONTINUE                                                          00001940
      FI1 = FI2                                                         00001950
      XI1 = XI2                                                         00001960
      FR1 = FR2                                                         00001970
      XR1 = XR2                                                         00001980
```

```
  150 FR2 = FR3
      XR2 = XR3
      FI2 = FI3
      XI2 = XI3
      FTST1 = FTST2
      COND1 = COND2
      DET1 = DET2
C
C      IF ISCNT = 1, UPDATE FREQ BY DELFRQ. IF ISCNT = 4, FREQ HAS
C      ALREADY BEEN CHANGED BY METHOD OF FALSE POSITION.
C
      IF(ISCNT.EQ.4) GO TO 10
      ISTRT = 1
      FREQ = FREQ + DELFRQ
      GO TO 10
  160 IF(ISCNT.EQ.1) GO TO 180
      ISCNT = 3
  170 IF(ABS(FR3)/CABS(NOZA).LE.EPSFS.AND. AMIN1(ABS((XR3-XR1)/XR3),
     1     ABS((XR3-XR2)/XR3)).LE.EPSXS) GO TO 220
      IF(FR1*FR3.LE.0.) GO TO 175
      FR1 = FR3
      XR1 = XR3
      GO TO 177
  175 XR2 = XR3
      FR2 = FR3
  177 XR3 = (FR2*XR1-FR1*XR2)/(FR2-FR1)
      FREQ = XR3/(2.*PI)
      GO TO 10
C
C      TENTATIVE ROOT HAS BEEN BRACKETED. CONTINUE WITH ISCNT = 4(I.E.
C      FREQ WILL BE CHANGED BY FALSE POSITION) UNTIL EITHER IT IS
C      DETERMINED THAT THE JACOBIAN IS SINGULAR OR THAT A ROOT IS
C      ACTUALLY THERE. THE LATTER IS ASSUMED BY DEFAULT IF THREE
```

```
C       ITERATIONS HAVE BEEN PERFORMED WITHOUT THE JACOBIAN CHANGING SIGN
C       AND THE CONDITION NUMBER REMAINS LESS THAN CTEST AND THE ERROR
C       (CABS(CNOAZA-NOZA)) IS LESS THAN 2.5* EPSF.
C
  180 ISCNT = 4
      IP = 0
      OMEGSV = OMEGA
      DET2S = DET2
      FTST2S = FTST2
      COND2S = COND2
      FR3S = FR3
      XR3S = XR3
      FI3S = FI3
      XI3S = XI3
      KSCNT4 = 0
  181 FTST0 = FTST1
      DET0 = DET1
      COND0 = COND1
      IP = MAX0(IP,0) + 1
  182 KSCNT4 = KSCNT4 + 1
      XR4 = (FTST2*XR2-FTST1*XR3)/(FTST2-FTST1)
      IF(IABS(IP).LE.2) GO TO 1825
      IP = 0
      XR4 = (XR3+XR2)/2.
 1825 CONTINUE
      OMEGA = XR4 + (0.,1.)*AIMAG(OMEGA)
      FREQ = XR4/(2.*PI)
      GO TO 147
  183 KNTR = KNTR - 1
      IF(COND2.GT.CTEST.OR.DET2*DET1.LE.0.) GO TO 184
      IF(HN/CABS(NOZA).LE.EPSFS.AND.AMIN1(CABS(OMEGA-XR2-(0.,1.)*XI2)
     1   ,CABS(OMEGA-XR1-(0.,1.)*XI1)/CABS(OMEGA)).LE.EPSXS) GO TO 220
      IF(HN/CABS(NOZA).LE.2.5*EPSF.AND.KSCNT4.GE.3) GO TO 185
```

```
      IF(KSCNT4.GT.10) GO TO 184
      IF(FTST1*FTST2.LE.0.) GO TO 181
      XR2 = XR1
      XI2 = XI1
      FR2 = FI1
      DET1 = DET0
      COND1 = COND0
      FTST1 = FTST0
      IP = MIN0(IP,C) - 1
      GO TO 182
C
C      JACOBIAN IS SINGULAR NEAR THIS FREQUENCY. RETURN TO ISCNT=1
C      SEARCH METHOD WITH UPDATED FREQUENCY.
C
  184 OMEGA = OMEGSV
      DET2 = DET2S
      FTST2 = FTST2S
      FR3 = FR3S
      XR3 = XR3S
      COND2 = COND2S
      FI3 = FI3S
      XI3 = XI3S
      FREQ = REAL(OMEGA)/(2.*PI)
      FRQ = FREQ-DELFRQ
      IF(KSCNT4.GT.10) WRITE(6,8450) FRQ,FREQ
 8450 FORMAT(//'    ***************************'//
     1    '         WARNING, POSSIBLE ROOT IN FREQUENCY RANGE: ',
     2       1P2E15.6//'    ***************************'//)
      KSCNT4 = 0
      ISCNT = 1
      GO TO 150
C
C      ACTUAL ROOT HAS BEEN BRACKETED. USE 2-DIMENSIONAL SECANT METHOD
```

```
C        TO CONVERGE ON THIS ROOT (UP TO STATEMENT 205).                00002980
C                                                                       00002990
  185 ISCNT = 5                                                         00003000
      KNTS = 0                                                          00003010
  190 DET = FR2*FI1-FR1*FI2-FR3*FI1+FR1*FI3+FR3*FI2-FI3*FR2             00003020
      PI0 = (FR2*FI1-FI2*FR1)/DET                                       00003030
      PI1 = -(FR3*FI1-FR1*FI3)/DET                                      00003040
      PI2 = (FR3*FI2-FR2*FI3)/DET                                       00003050
      XI4 = PI0*XI3 + PI1*XI2 + PI2*XI1                                 00003060
      XR4 = PI0*XR3 + PI1*XR2 + PI2*XR1                                 00003070
      OMEGO = OMEGA                                                     00003080
      OMEGA = XR4 + (0.,1.)*XI4                                         00003090
      DOM = OMEGA - OMEGO                                               00003100
      SF = AMIN1(1.,50./CABS(DOM))                                      00003110
      OMEGA = OMEGO + SF*DOM                                            00003120
      XR4 = REAL(OMEGA)                                                 00003130
      XI4 = AIMAG(OMEGA)                                                00003140
      FREQ = REAL(OMEGA)/(2.*PI)                                        00003150
      GO TO 15                                                          00003160
  195 FR4 = FNR                                                         00003170
      FI4 = FNI                                                         00003180
      KNTS = KNTS + 1                                                   00003190
      IF(IABS(IWSKP).GE.1) WRITE(6,8515) ISCNT,KNTS,OMEGA,CNOZA,NOZA,HN 00003200
 8515 FORMAT(/2I5,3(1PE14.5,' :',1PE12.5),1PE14.5)                      00003210
      IF(IABS(IWSKP).GE.2) WRITE(6,8520) XR1,XI1,FR1,FI1,XR2,XI2,FR2,FI200003220
     1             ,XR3,XI3,FR3,FI3,XR4,XI4,FR4,FI4,FN                  00003230
 8520 FORMAT(2X,4(1PE14.5,' :',1PE12.5)/2X,4(1PE14.5,' :',              00003240
     1       1PE12.5)/2X,1PE14.5,' :',1PE12.5)                          00003250
      Z1 = XR1 + (0.,1.)*XI1                                            00003260
      Z2 = XR2 + (0.,1.)*XI2                                            00003270
      Z3 = XR3 + (0.,1.)*XI3                                            00003280
      ADM = CABS(OMEGA)                                                 00003290
C                                                                       00003300
```

```
C       TEST FOR CONVERGENCE ON ROOT.                                   00003310
C                                                                       00003320
       IF(CABS(FN)/CABS(NOZA).LE.EPSFS.AND.AMIN1(CABS(OMEGA-Z1)/AOM,    00003330
      1        CABS(OMEGA-Z2)/AOM,CABS(OMEGA-Z3)/AOM).LE.EPSXS) GO TO 22000003340
       IER = -20                                                        00003350
       IF(KNTS.GT.KNTSMX) GO TO 205                                     00003360
       IF(MOD(KNTS-1,6).LE.2) GO TO 200                                 00003270
C                                                                       00003380
C       TRANSFER VALUES 3 TO 2, 2 TO 1, AND REPLACE 3 WITH NEW GUESS.   00003390
C                                                                       00003400
       XI1 = XI2                                                        00003410
       XR1 = XR2                                                        00003420
       FI1 = FI2                                                        00003430
       FR1 = FR2                                                        00003440
       XI2 = XI3                                                        00003450
       XR2 = XR3                                                        00003460
       FR2 = FR3                                                        00003470
       FI2 = FI3                                                        00003480
       XI3 = XI4                                                        00003490
       XR3 = XR4                                                        00003500
       FR3 = FR4                                                        00003510
       FI3 = FI4                                                        00003520
       GO TO 190                                                        00003530
C                                                                       00003540
C       REPLACE POINT WITH LARGEST ERROR WITH THE NEW GUESS.            00003550
C                                                                       00003560
  200  AF1 = FR1**2 + FI1**2                                            00003570
       AF2 = FR2**2 + FI2**2                                            00003580
       AF3 = FR3**3 + FI3**2                                            00003590
       IF(AF1.LE.AF2) GO TO 202                                         00003600
       IF(AF3.GT.AF1) GO TO 203                                         00003610
  201  XI1 = XI4                                                        00003620
       XR1 = XR4                                                        00003630
```

```
      FI1 = FI4
      FR1 = FR4
      GO TO 190
  202 IF(AF3.GT.AF2) GO TO 203
      XI2 = XI4
      XR2 = XR4
      FI2 = FI4
      FR2 = FR4
      GO TO 190
  203 XI3 = XI4
      XR3 = XR4
      FI3 = FI4
      FR3 = FR4
      GO TO 190
  205 WRITE(6,8602) IER,KNTS,KNTR,ISCNT,XR1,XI1,FR1,FI1,XR2,XI2,FR2,FI2
     1      ,XR3,XI3,FR3,FI3,XR4,XI4,FR4,FI4
 8602 FORMAT(//'  **** EXCEED CONVERGENCE LIMIT  ****'/
     1 '  IER,KNTS,KNTR,ISCNT = ',4I10/'    X,F FROM 1-4 = '/
     2    (3X,1PE15.5,' : ',1PE15.5,1PE18.5,' : ',1PE15.5))
      GO TO 5000
C
C            KWHERE DETERMINES TRNSFER LOACATION IN CALLING PROGRAM
C             UPON RETURN.
C
   10 KWHERE = 1
      GO TO 6000
   15 KWHERE = 2
      GO TO 6000
  220 KWHERE = 3
      GO TO 6000
  225 KWHERE = 4
      GO TO 6000
 5000 KWHERE = 5
```

```
 6000 RETURN                                                                    00003970
      END                                                                       00003980
```

F S C S M SUBROUTINES

```
      SUBROUTINE  STEADY(IPRSTE)                                        00000010
C                                                                       00000020
C     SUBPROGRAM  STEADY  FOR THE FEED SYSTEM COUPLED STABILITY MODEL   00000030
C     PROGRAM CALCULATES STEADY STATE PARAMETERS                        00000040
C     PROGRAMMED BY M. D. SCHUMAN, ROCKETDYNE, MAY 1975                 00000050
C                                                                       00000060
      COMPLEX  COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9,    00000070
     1     COX10, COX11, COX12, COX13, COX14, COX15, COX16,             00000080
     2     CFU1, CFU2, CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9,        00000090
     3     CFU10, CFU11, CFU12, CFU13, CFU14, CFU15, CFU16              00000100
C                                                                       00000110
      REAL  MRBINJ, MBOXI, MBFUI, MRB, MRGI, MGI, NUBOX, NUBFU, MWG     00000120
C                                                                       00000130
      COMMON  /COMCBM/  XKOX, XKFU, MBOXI, MBFUI, TAUBOX, TAUBFU, VBOX, 00000140
     1     VBFU, GAMO, RGO, DELHOX, DELHFU, PC, CO,                     00000150
     2     COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9, COX10, 00000160
     3     COX11, COX12, COX13, COX14, COX15, COX16, CFU1, CFU2,        00000170
     4     CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9, CFU10, CFU11,      00000180
     5     CFU12, CFU13, CFU14, CFU15, CFU16, MWG, XIMPFU, XIMPOX,      00000190
     6     CS, DCSDMR, DHDMR, DRGDMR, ADVOX, ADDOX, TDRAGO, DELVOX,     00000200
     7     NUBOX, DTOXDM, ADVFU, ADDFU, TDRAGF, DELVFU, NUBFU, DTFUDM   00000210
C                                                                       00000220
      COMMON /CONSTS/  MRB(100), TB(100), RHOB(100), VB(100),           00000230
     1     DMRB(100), DRHOB(100), DVB(100), VAPBOX(100), VAPBFU(100),   00000240
     2     SSV1(100), SSV2(100), SSV3(100), SSV4(100),                  00000250
     3     SSV5(100), SSV6(100), SSV7(100), SSV8(100), SSV9OX(100),     00000260
     4     SSV9FU(100), SSV10(100), SSV11(100), SSV12(100), SSV13(100), 00000270
     5     SSV14(100), SSV15(100), SSV16(100),                          00000280
     6     RHOGI, VGI, MRGI, MGI                                        00000290
C                                                                       00000300
      COMMON /COMARE/ NXP, X(100), XM(100), A(100), DA(100), DELX,      00000310
     1     XO, XNOZ, AINJ                                               00000320
C                                                                       00000330
```

```
C     PRINT TITLES FOR STEADY STATE VARIABLES
C
      IF(IPRSTE.GT.0) WRITE(6,10)
   10 FORMAT(1H1,///,31X,'STEADY   STATE   SOLUTION',//,
     1       7X,'DISTANCE',
     2       4X,'TEMPERATURE',2X,'VELOCITY',3X,'MIXTURE',
     3       6X,'DENSITY',7X,'PERCENT VAPORIZED',/,7X,'(INCHES)',5X,
     4       '(RANKINE)',4X,'(FT/S)',5X,'RATIO',5X,
     5       '(LBM/FT**3)',6X,'FUEL',3X,'OXIDIZER',/)
C
C     INJECTOR END GAS MIXTURE RATIO AND GAS DENSITY
C
      MRBINJ = MBOXI/MBFUI
      IF(MGI.GT.0.0) GO TO 15
      MRGI = MRBINJ*TAUBFU*VBFU/(TAUBOX*VBOX)
      RHOGI = GAMC*PC*(MRGI+1.)/(GAMC-1.)/(MRGI*DELHOX+DELHFU
     1      -MRGI*(1.+MRGI)*DHDMR)
      GO TO 16
   15 RHOGI = MGI/(AINJ*VGI)
   16 CONTINUE
C
C     MAIN DISTANCE DO LOOP
C
      DO 30 I=1,NXP
C
C     VAPORIZATION RATE PARAMETERS
C
      PHIOX = EXP(-(XM(I)-XO)/(TAUBOX*VBOX))
      PHIFU = EXP(-(XM(I)-XO)/(TAUBFU*VBFU))
C
C     GAS MIXTURE RATIO, VELOCITY, DENSITY, TEMPERATURE, OXIDIZER
C     AND FUEL VAPORIZATION RATES
C
```

```
      MRB(I) = (MRGI/(1.+MRGI)*MGI+MBOXI*(1.-PHIOX))/(1./(1.+MRGI)*     00000670
     1    MGI+MBFUI*(1.-PHIFU))                                         00000680
      AMDOT = MGI+MBOXI*(1.-PHIOX)+MBFUI*(1.-PHIFU)                     00000690
      VB(I) = 1./(GAMO*PC*A(I))*(GAMO*PC*MGI/RHOGI+(GAMO-1.)*(          00000700
     1    MBOXI*DELHOX*(1.-PHIOX)+MBFUI*DELHFU*(1.-PHIFU)-AMDOT*        00000710
     2    MRB(I)*DHDMR+MGI*MRGI*DHDMR))                                 00000720
      RHOB(I) = AMDOT/(A(I)*VB(I))                                      00000730
      TB(I) = PC/(RHOB(I)*RGO*(1.+DRGDMR/RGO*(MRB(I)-MRBINJ)))          00000740
      VAPBOX(I) = MBOXI*PHIOX/(TAUBOX*VBOX)/A(I)                        00000750
      VAPBFU(I) = MBFUI*PHIFU/(TAUBFU*VBFU)/A(I)                        00000760
C                                                                       00000770
C     DERIVATIVES WITH RESPECT TO DISTANCE                              00000780
C                                                                       00000790
      DMRB(I) = (MRB(I)+1.)/(RHOB(I)*VB(I))*(VAPBOX(I)-MRB(I)*          00000800
     1    VAPBFU(I))                                                    00000810
      DVB(I) = -VB(I)/A(I)*DA(I)+(GAMO-1.)/(GAMO*PC)*(VAPBOX(I)*        00000820
     1    (DELHOX-DHDMR*(2.*MRB(I)+1.))+VAPBFU(I)*(DELHFU+              00000830
     2    DHDMR*MRB(I)*MRB(I)))                                         00000840
      DRHOB(I) = -RHOB(I)/VB(I)*DVB(I)-RHOB(I)/A(I)*DA(I)+              00000850
     1     (VAPBOX(I)+VAPBFU(I))/VB(I)                                  00000860
C                                                                       00000870
C     STEADY STATE PARAMETERS REQUIRED BY THE CHAMBER DYNAMICS          00000880
C     SUBPROGRAM                                                        00000890
C                                                                       00000900
      SSV1(I) = VB(I)/CO                                                00000910
      SSV2(I) = 2.*DELX*(GAMO-1.)/(PC*CO)                               00000920
      SSV3(I) = DELX*DVB(I)/CO                                          00000930
      SSV4(I) = DELX*SSV1(I)*(DA(I)/A(I)+DRHOB(I)/RHOB(I))+SSV3(I)      00000940
      SSV5(I) = DELHOX-DHDMR*(2.*MRB(I)+1.)                             00000950
      SSV6(I) = DELHFU+DHDMR*MRB(I)*MRB(I)                              00000960
      SSV7(I) = DELX*GAMO*(SSV1(I)*DA(I)/A(I)+DVB(I)/CO)                00000970
      SSV8(I) = DELX*GAMO*DA(I)/A(I)                                    00000980
      SSV9OX(I) = VAPBOX(I)*DHDMR                                       00000990
```

```
      SSV9FU(I) = VAPBFU(I)*DHDMR*MRB(I)
      SSV10(I) = 2*DELX/(RHOB(I)*CO)
      SSV11(I) = DELX*(DA(I)/A(I)+DRHOB(I)/RHOB(I))
      SSV12(I) = 2.*PC/(RHOB(I)*CO*CO)
      SSV13(I) = 2.*DELX*(MRB(I)+1.)/(RHOB(I)*CO)
      SSV14(I) = DELX*SSV1(I)*DMRB(I)
      SSV15(I) = DELX*(VAPBOX(I)-(2.*MRB(I)+1.)*VAPBFU(I))/
     1     (RHOB(I)*CO)
      IF(I.GT.1) SSV16(I-1) = DRGDMR*(RHOB(I-1)*TB(I-1)/PC+RHOB(I)*
     1     TB(I)/PC)/2.
C
C     PRINTOUT OF STEADY STATE VARIABLES
C
      IF(IPRSTE.LE.0) GO TO 30
      PBOX = 100.*(1.-PHIOX)
      PBFU = 100.*(1.-PHIFU)
      XP = XM(I)/0.0254
      TP = TB(I)*1.8
      VP = VB(I)/0.3048
      RHOP = RHOB(I)/16.01846
      WRITE(6,20) XP, TP, VP, MRB(I), RHOP,
     1     PBFU, PBOX
   20 FORMAT(6X,F9.4,2X,2F11.2,F11.4,1PE15.5,0PF11.2,F9.2)
C
   30 CONTINUE
C
      RETURN
      END
```

F S C S M SUBROUTINES

```
      SUBROUTINE TADAMS(N,H,X,Y,DY,IQZ,IQ)
C
C     ROUTINE FOR SUBPROGRAM NOZADM
C     PROGRAM DEVELOPED BY GEORGIA INSTITUTE OF TECHNOLOGY
C        REF. NASA CR-121129
C
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON /X1/GAM,SVN,ANGLE,RCT,RCC /X2/T,RT,Q,R1,R2,WC,IP
      COMMON /X4/CM
      DIMENSION COR(5), DP(5), DY(5,4), PRED(5), Y(5), G(5), GP(5)
   10 CONTINUE
      DO 15 I=1,N
      PRED(I) = Y(I)+H*(55.*DY(I,4)-59.*DY(I,3)+37.*DY(I,2)-9.*DY(I,1))
     1   /24.0
   15 CONTINUE
      X = X+H
      U = PRED(1)
      TR = PRED(2)
      TI = PRED(3)
      PHIR = PRED(4)
      PHII = PRED(5)
      C = 1.-(GAM-1.)*U*0.5
      R = Q*((C)**(-1./(2.*(GAM-1.))))*(U**(-0.25))*4.0
   16 FORMAT(3X,'PRINTING FROM CARD 2180',/,3X,'R=',E15.8,
     1   3X,'R1=',E15.8,3X,'RT=',E15.8)
      IF(R-1.) 17,17,100
   17 IF(R-R1) 20,25,25
   20 DR = -((2.*RCT*(R-RT)-(R-RT)*(R-RT))**.5)/(RT+RCT-R)
      GO TO 40
   25 IF(R-R2) 30,35,35
   30 DR = -DTAN(T)
      GO TO 40
   35 DR = ((2.*RCC*(1.-R)-(1.-R)*(1.-R))**.5)/(1.-R-RCC)
```

```
 40 DU = -(U**.75)*(C**((2.*GAM-1.)/(2.*(GAM-1.))))/(Q*(1.-(GAM+1.)
   1    *U*.5))
    DP(1) = DR*DU
    A = U*(C-U)
    BR = U*DP(1)/C
    BI = 2.*WC*U
    CR = WC*WC-(SVN*SVN*C)/(R*R)
    CI = -(GAM-1.)*WC*U*DP(1)*.5/C
    DP(2) = 1.+(-BR*TR+BI*TI+CR*(TR*TR-TI*TI)-2.*CI*TR*TI)/A
    DP(3) = (-BR*TI-BI*TR+CI*(TR*TR-TI*TI)+2.*CR*TR*TI)/A
    T2 = TR*TR+TI*TI
    DP(4) = (TR*PHIR-TI*PHII)/T2
    DP(5) = (TR*PHII+TI*PHIR)/T2
    DO 45 I=1,N
    COR(I) = Y(I)+H*(DY(I,2)-5.*DY(I,3)+19.*DY(I,4)+9.*DP(I))/24.0
 45 Y(I) = (251.*COR(I)+19.*PRED(I))/270.
    U = Y(1)
    TR = Y(2)
    TI = Y(3)
    PHIR = Y(4)
    PHII = Y(5)
    C = 1.-(GAM-1.)*U*.5
 52 DO 55 I=1,N
    DY(I,1) = DY(I,2)
    DY(I,2) = DY(I,3)
 55 DY(I,3) = DY(I,4)
    T2 = TR*TR+TI*TI
    TMAG = T2**.5
    IF(TMAG-10.) 60,90,90
 60 R = Q*((C)**(-1./(2.*(GAM-1.))))*(U**(-0.25))*4.0
 61 FORMAT(3X,'PRINTING FROM CARD 2570',/,3X,'R=',E15.8,
   1    3X,'R1=',E15.8,3X,'RT=',E15.8)
    IF(R-1.) 62,62,100
```

```
 62 IF(R-R1) 65,70,70
 65 DR = -((2.*RCT*(R-RT)-(R-RT)*(R-RT))**.5)/(RT+RCT-R)
    GO TO 85
 70 IF(R-R2) 75,80,80
 75 DR = -DTAN(T)
    GO TO 85
 80 DR = ((2.*RCC*(1.-R)-(1.-R)*(1.-R))**.5)/(1.-R-RCC)
 85 DU = -(U**.75)*(C**((2.*GAM-1.)/(2.*(GAM-1.))))/(Q*(1.-(GAM+1.)
   1     *U*.5))
    DY(1,4) = DR*DU
    A = U*(C-U)
    BR = U*DY(1,4)/C
    BI = 2.*WC*U
    CR = WC*WC-(SVN*SVN*C)/(R*R)
    CI = -(GAM-1.)*WC*U*DY(1,4)*0.5/C
    DY(2,4) = 1.+(-BR*TR+BI*TI+CR*(TR*TR-TI*TI)-2.*CI*TR*TI)/A
    DY(3,4) = (-BR*TI-BI*TR+CI*(TR*TR-TI*TI)+2.*CR*TR*TI)/A
    DY(4,4) = (TR*PHIR-PHII*TI)/T2
    DY(5,4) = (TR*PHII+PHIR*TI)/T2
    IF(IP.EQ.0) GO TO 87
    PR = WC*PHII-U*DY(4,4)
    PI = -WC*PHIR-U*DY(5,4)
    PMAG = (PR*PR+PI*PI)**.5
    PARG = DATAN(PI/PR)
    WRITE(6,1000) X,PMAG,PARG
 87 GO TO 10
 90 IQZ = 2
    Y(2) = TR/T2
    Y(3) = -TI/T2
    TPR = DY(2,4)
    TPI = DY(3,4)
    DY(2,4) = -(TPR*(TR*TR-TI*TI)+2.*TR*TI*TPI)/(T2*T2)
    DY(3,4) = (2.*TPR*TR*TI-TPI*(TR*TR-TI*TI))/(T2*T2)
```

F S C S M SUBROUTINES

```
      G(1) = U
      G(2) = Y(2)
      G(3) = Y(3)
      G(4) = PHIR
      G(5) = PHII
      DY(1,1) = DY(1,4)
      DY(2,1) = DY(2,4)
      DY(3,1) = DY(3,4)
      DY(4,1) = (PHIR*TR-PHII*TI)/T2
      DY(5,1) = (PHII*TR-PHIR*TI)/T2
      DO 95 I=2,4
      CALL RKTZ(5,H,X,G,GP,IOZ)
      X = X+H
      U = G(1)
      ZR = G(2)
      ZI = G(3)
      PHIR = G(4)
      PHII = G(5)
      DY(1,I) = GP(1)
      DY(2,I) = GP(2)
      DY(3,I) = GP(3)
      DY(4,I) = GP(4)
   95 DY(5,I) = GP(5)
      Y(1) = U
      Y(2) = ZR
      Y(3) = ZI
      Y(4) = PHIR
      Y(5) = PHII
      IQ = 1
      GO TO 105
  100 IQ = 2
 1000 FORMAT(46X,F6.4,1X,F10.5,3X,F10.5)
  105 RETURN
```

```
      END                                                               00001330
```

```
      SUBROUTINE  TDPLOT(W,Y,NFP,TL,XR,LL )
C
C     ROUTINE TO GENERATE CRT PLOTS
C     PROGRAMMED BY J. K. HUNTING, ROCKETDYNE, MAY 1975
C
      DIMENSION W(101),Y(101)
      YMAX=Y(2)
      YMIN=Y(2)
      DO100J=3,NFP
      YMAX=AMAX1(YMAX,Y(J))
      YMIN=AMIN1(YMIN,Y(J))
  100 CONTINUE
      DY=AINT(2.0+(YMAX-YMIN)/10.0)
      YT=DY*AINT(1.5+YMAX/DY)
      YB=DY*AINT(YMIN/DY-1.5)
      IF(W(2)/TL-10.1)201,201,5
    5 XL=W(2)
      I=1
      GO TO 200
  201 YMAX=AMAX1(YMAX,Y(1))
      YMIN=AMIN1(YMIN,Y(1))
      XL=TL
      I=2
  200 CONTINUE
      K=0
      L=0
   10 L=L+1
      IF(L.GT.9)GO TO 30
      IF(10.0**K/XL.LE.1.0.AND.10.0**K/XL.GT.0.1)GO TO 20
      IF(10.0**K/XL.GT.1.0)K=K-1
      IF(10.0**K/XL.LE.0.1)K=K+1
      GO TO 10
   20 XL=10.0**K
```

```
 30 K=0                                                               00011290
    IF(LL-1) 31,31,60                                                 00011300
 31 CALL CAMRAV(9)                                                    00011310
    IF(LL-1) 50,50,60                                                 00011320
 50 CALL SETMIV(40,10,24,560)                                         00011330
    GO TO 61                                                          00011340
 60 CALL SETMIV(40,10,500, 70)                                        00011350
 61 CALL SMXYV(1,0)                                                   00011360
    CALL GRIDIV(LL,XL,XR,YB,YT,1.0,DY,1,1,-1,-1, -2, -3)             00011370
180 GO TO(181,182),I                                                  00011380
181 CALL APLOTV(NFP-1,W(2),Y(2),1,1,1,44,IERR)                        00011390
    GO TO 40                                                          00011400
182 CALL APLOTV(NFP,W(1),Y(1),1,1,1,44,IERR)                          00011410
 40 K=K+1                                                             00011420
    GO TO (180,180,180,190),K                                         00011430
190 IF(LL-1) 191,191,192                                              00011440
191 CALL LABLV(Y(1),600,470, 6, 2, 3)                                 00011450
    GO TO 193                                                         00011460
192 CALL LABLV(Y(1),600,995,6,2,3)                                    00011470
193 RETURN                                                            00011480
    END                                                               00011490
```

```
      FUNCTION XIMAGF(XIMOMG)
C
C     ROUTINE TO COMPUTE NOZZLE ADM. DIFF AS FUNCTION OF
C        IMAGINARY PART OF OMEGA
C     PROGRAMMED BY K. W. FERTIG, ROCKETDYNE, MAY 1975
C
      COMPLEX OMEGA,NOZA,CNOZA,P,RHO,V,MR,T,VXO,FN,NOZAMR,GN,
     1     COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9,
     2     COX10, COX11, COX12, COX13, COX14, COX15, COX16,
     3     CFU1, CFU2, CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9,
     4     CFU10, CFU11, CFU12, CFU13, CFU14, CFU15, CFU16
     5    ,OMEGO
C
      REAL  MBOXI, MBFUI, NUBOX, NUBFU, MWG
C
      COMMON  /COMCBM/  XKOX, XKFU, MBOXI, MBFUI, TAUBOX, TAUBFU, VBOX,
     1     VBFU, GAMO, RGO, DELHOX, DELHFU, PC, CO,
     2     COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9, COX10,
     3     COX11, COX12, COX13, COX14, COX15, COX16, CFU1, CFU2,
     4     CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9, CFU10, CFU11,
     5     CFU12, CFU13, CFU14, CFU15, CFU16, MWG, XIMPFU, XIMPOX,
     6     CS, DCSDMR, DHDMR, DRGDMR, ADVOX, ADDOX, TDRAGO, DELVOX,
     7     NUBOX, DTOXDM, ADVFU, ADDFU, TDRAGF, DELVFU, NUBFU, DTFUDM
C
      COMMON /FZERO/ NOZA,NOZAMR,GN,FN,FNR,FNI,HN,ISCNT,ISLP
C
      COMMON /COMCHM/ P(100),RHO(100),V(100),MR(100),T(100),
     1                VXO,OMEGA,CNOZA,DELP
C
      COMMON /COMARE/ NXP,X(100),XM(100),A(100),DA(100),DELX,
     1               XO,XNOZ,AINJ
C
C      RECOMPUTE OMEGA USING NEW IMAGINARY PART.
```

```
C
      OMEGA = REAL(OMEGA) + (0.,1.)*XIMOMG
      IP = 0
      IF((ISCNT.NE.1.AND.ISCNT.NE.4).OR.ISLP.NE.1) GO TO 10
C
C      SAVE OMEGA THEN ALTER IMAG PART BY 0.1 PERCENT TO COMPUTE DERIV.
C
      OMEGO = OMEGA
      DM = AMAX1(.001*AIMAG(OMEGA),.1)
      OMEGA = OMEGA + (0.,1.)*DM
C
C      CHAMDY COMPUTES UPSTREAM NOZZLE ADMITTANCE AND OSCILLATORY
C      PROFILES.
C
   10 CALL CHAMDY
      NOZA = NOZAMR*(1.-DCSDMR*MR(NXP)*2.*GAMO/(CS*P(NXP)*(GAMO-1.)))
      FN = (CNOZA - NOZA)
      IF(IP.EQ.0 .AND.((ISCNT.EQ.1.OR.ISCNT.EQ.4).AND.ISLP.EQ.1))
     1          GO TO 20
      FNR = REAL(FN)
      FNI = AIMAG(FN)
      HN = CABS(FN)
      XIMAGF = FNI
C
C      IF IP EQUALS ZERO AT THIS POINT , THEN DERIVATIVES WERE NOT
C      REQUIRED; HENCE, RETURN WITHOUT COMPUTING THEM.
C
      IF(IP.EQ.0) RETURN
      GO TO 30
   20 IP = 1
C
C      RESTORE OMEGA AND SAVE VALUES FOR COMPUTATION OF DERIVATIVES.
C
```

```
      OMEGA = OMEGO
      HND = CABS(FN)
      GN = FN
      GO TO 10
C
C      COMPUTE D(CNOZA-NOZA)/D(IMAG(OMEGA)), CALLED GN, AND
C      D(CABS(CNOZA-NOZA)**2)/D(IMAG(OMEGA)), CALLED XIMAGF.
C
   30 GN = (GN-FN)/DM
      XIMAGF = (HND**2-HN**2)/DM
      RETURN
      END
```

F S C S M SUBROUTINES

```
      SUBROUTINE ZADAMS(N,H,X,Y,DY,IQZ)                                 00001340
C                                                                       00001350
C     ROUTINE FOR SUBPROGRAM NOZADM                                     00001360
C     PROGRAM DEVELOPED BY GEORGIA INSTITUTE OF TECHNOLOGY              00001370
C        REF. NASA CR=121129                                            00001380
C                                                                       00001390
      IMPLICIT REAL*8(A-H,O-Z)                                          00001400
      COMMON /X1/GAM,SVN,ANGLE,RCT,RCC /X2/T,RT,Q,R1,R2,WC,IP           00001410
     1       /X4/CM                                                     00001420
      DIMENSION COR(5), DP(5), DY(5,4), PRED(5), Y(5), G(5), GP(5)      00001430
   10 CONTINUE                                                          00001440
      DO 15 I=1,N                                                       00001450
      PRED(I)=Y(I)+H*(55.*DY(I,4)-59.*DY(I,3)+37.*DY(I,2)-9.*DY(I,1))   00001460
     1        /24.0                                                     00001470
   15 CONTINUE                                                          00001480
      X = X+H                                                           00001490
      U = PRED(1)                                                       00001500
      ZR = PRED(2)                                                      00001510
      ZI = PRED(3)                                                      00001520
      PHIR = PRED(4)                                                    00001530
      PHII = PRED(5)                                                    00001540
      C = 1-(GAM-1)*U*0.5                                               00001550
      R = Q*((C)**(-1./(2.*(GAM-1.))))*(U**(-0.25))*4.0                 00001560
   16 FORMAT(3X,'PRINTING FROM CARD 3430',/,3X,'R=',E15.8,              00001570
     1   3X,'R1=',E15.8,3X,'RT=',E15.8)                                 00001580
      IF(R-1) 17,17,100                                                 00001590
   17 IF(R-R1) 20,25,25                                                 00001600
   20 DR = -((2*RCT*(R-RT)-(R-RT)*(R-RT))**0.5)/(RT+RCT-R)              00001610
      GO TO 40                                                          00001620
   25 IF(R-R2) 30,35,35                                                 00001630
   30 DR = -DTAN(T)                                                     00001640
      GO TO 40                                                          00001650
   35 DR = ((2*RCC*(1-R)-(1-R)*(1-R))**0.5)/(1-R-RCC)                   00001660
```

```
40 DU = -(U**0.75)*(C**((2*GAM-1)/(2*(GAM-1))))/(Q*(1-(GAM+1)*U*0.5))
   DP(1) = DR*DU
   A = U*(C-U)
   BR = U*DP(1)/C
   BI = 2*WC*U
   CR = WC*WC-(SVN*SVN*C)/(R*R)
   CI = -(GAM-1)*WC*U*DP(1)*0.5/C
   DP(2) = ((BR*ZR-BI*ZI-CR)/A)-ZR*ZR+ZI*ZI
   DP(3) = ((BI*ZR+BR*ZI-CI)/A)-2*ZR*ZI
   DP(4) = ZR*PHIR-ZI*PHII
   DP(5) = ZR*PHII+ZI*PHIR
   DO 45 I=1,N
   COR(I) = Y(I)+H*(DY(I,2)-5.*DY(I,3)+19.*DY(I,4)+9.*DP(I))/24.0
45 Y(I) = (251.*COR(I)+19.*PRED(I))/270.0
   U = Y(1)
   ZR = Y(2)
   ZI = Y(3)
   PHIR = Y(4)
   PHII = Y(5)
   C = 1-(GAM-1)*U*0.5
52 DO 55 I=1,N
   DY(I,1) = DY(I,2)
   DY(I,2) = DY(I,3)
55 DY(I,3) = DY(I,4)
   ZMAG = (ZR*ZR+ZI*ZI)**0.5
   IF(ZMAG-10) 60,90,90
60 R = Q*((C)**(-1./(2.*(GAM-1.))))*(U**(-0.25))*4.0
61 FORMAT(3X,'PRINTING FROM CARD 3790',/,3X,'R=',E15.8,
  1   3X,'R1=',E15.8,3X,'RT=',E15.8)
   IF(R-1) 62,62,100
62 IF(R-R1) 65,70,70
65 DR = -((2*RCT*(R-RT)-(R-RT)*(R-RT))**0.5)/(RT+RCT-R)
   GO TO 85
```

```
 70 IF(R-R2) 75,80,80
 75 DR = -DTAN(T)
    GO TO 85
 80 DR = ((2*RCC*(1-R)-(1-R)*(1-R))**0.5)/(1-R-RCC)
 85 DU = -(U**0.75)*(C**((2*GAM-1)/(2*(GAM-1))))/(Q*(1-(GAM+1)*U/2))
    DY(1,4) = DR*DU
    A = U*(C-U)
    BR = U*DY(1,4)/C
    BI = 2*WC*U
    CR = WC*WC-(SVN*SVN*C)/(R*R)
    CI = -(GAM-1)*WC*U*DY(1,4)*0.5/C
    DY(2,4) = (BR*ZR-BI*ZI-CR)/A-ZR*ZR+ZI*ZI
    DY(3,4) = (BI*ZR+BR*ZI-CI)/A-2.*ZR*ZI
    DY(4,4) = ZR*PHIR-ZI*PHII
    DY(5,4) = ZR*PHII+ZI*PHIR
    IF(IP.EQ.0) GO TO 87
    PR = WC*PHII-U*DY(4,4)
    PI = -WC*PHIR-U*DY(5,4)
    PMAG = (PR*PR+PI*PI)**0.5
    PARG = DATAN(PI/PR)
    WRITE(6,1000) X, PMAG, PARG
 87 GO TO 10
 90 IQZ = 1
    Z2 = ZMAG*ZMAG
    Y(2) = ZR/Z2
    Y(3) = -ZI/Z2
    ZPR = DY(2,4)
    ZPI = DY(3,4)
    DY(2,4) = -(ZPR*(ZR*ZR-ZI*ZI)+2.*ZR*ZI*ZPI)/(Z2*Z2)
    DY(3,4) = (2.*ZPR*ZR*ZI-ZPI*(ZR*ZR-ZI*ZI))/(Z2*Z2)
    G(1) = U
    G(2) = Y(2)
    G(3) = Y(3)
```

```
      G(4) = PHIR
      G(5) = PHII
      DY(1,1) = DY(1,4)
      DY(2,1) = DY(2,4)
      DY(3,1) = DY(3,4)
      DY(4,1) = PHIR*ZR-PHII*ZI
      DY(5,1) = PHII*ZR+PHIR*ZI
      DO 95 I=2,4
      CALL RKTZ(5,H,X,G,GP,IQZ)
      X = X+H
      U = G(1)
      TR = G(2)
      TI = G(3)
      PHIR = G(4)
      PHII = G(5)
      DY(1,I) = GP(1)
      DY(2,I) = GP(2)
      DY(3,I) = GP(3)
      DY(4,I) = GP(4)
   95 DY(5,I) = GP(5)
      Y(1) = U
      Y(2) = TR
      Y(3) = TI
      Y(4) = PHIR
      Y(5) = PHII
      CALL TADAMS(N,H,X,Y,DY,IQZ,IQ)
      GO TO (10,100),IQ
 1000 FORMAT(46X,F6.4,1X,F10.5,3X,F10.5)
  100 RETURN
      END
```

```
      SUBROUTINE ZERO(FI,T1I,T2I,F1I,F2I,ANS,FANS,EPSF,EPSX,AF,ICNT,
     1               NCNT,IER,K)
C
C       ROUTINE TO FIND T  S.T.  F(T) = 0  WHERE  FI(T1)*F(T2)<= 0
C       PROGRAMMED BY K. W. FERTIG, ROCKETDYNE, MAY 1975
C
      F(X) = SN*FI(X)
      ICNT = 0
      SN = 1.
      T4 =  1.E+60
      IER = 0
      T1 = T1I
      T2 = T2I
      IF ( K.EQ. 0) GO TO 15
      F1 = F(T1)
      F2 = F(T2)
    5 IF (F1*F2.LE.0.) GO TO  50
C
C       ROOT IS NOT BRACKETTED.
C
   10 IER = -1
      RETURN
   15 F1 = F1I
      F2 = F2I
      GO TO 5
   50 SN = 1.
      IF ( F2.LT.0. .OR. F1.GT. 0.) SN=-1.
      F1 = F1*SN
      F2 = F2*SN
C
C       BEGIN ITERATION TO FIND ROOT. FIRST GUESS USES BISECTION.
C
  220 T3 = (T1+T2)/2.
```

```
      ICNT = ICNT + 1
      IF ( ICNT .GT. NCNT) GO TO 500
      F3 = F(T3)
      T4OLD = T4
C
C      CONVERGENCE TEST FOR BISECTION GUESS.
C
      IF(ABS((T1-T2)/T3).LE.EPSX.AND.ABS(F3)/AF.LE.EPSF) GO TO 300
      A = F1-2.*F3+F2
      B = F2-F1
      C = 2.*F3
C
C      TEST TO MAKE SURE MAXIMUM/MINIMUM OF PARABOLA FITTING T1,T2,T3
C      IS OUTSIDE THE INTERVAL (T1,T2). IF SO, UPDATE T USING PARABOLIC
C      INTERPULATION.
C
      IF (  ABS( 2.*A/B) .GT. 0.9) GO TO 245
      B4AC =  B**2-4.*A*C
      IF ( B4AC.LT. 0.) GO TO 600
      B4AC = SQRT(B4AC)
      IF ( ABS( A*C/B**2) .GT. EPS/100. ) GO TO 230
      T4 = T3 + (T3-T1)*(-C/B -A*C**2/B**3)
      GO TO 240
  230 T4 =((-B+B4AC)/(2.*A))*(T3-T1) + T3
C
C      MAKE SURE T4 IS COMPATABLE WITH PREVIOUS VALUES; TEST FOR
C      CONVERGENCE AND THEN REPLACE T1,T2,F1, AND F2 APPROPRIATELY.
C
  240 IF (  T4.LE.T3 .AND. T4.GE.T1 .AND. F3.GE. 0.) GO TO 250
      IF (  T4.LE.T2 .AND. T4.GE.T3 .AND. F3.LE. 0.) GO TO 260
  245 IF ( F3.LE. 0.) GO TO 270
      T2 = T3
      F2 = F3
```

```
      GO TO 220
  250 F4 = F(T4)
      IF(ABS((T4-T4OLD)/T4).LE.EPSX.AND.ABS(F4)/AF.LE.EPSF) GO TO 400
      IF ( F4.LT. 0.) GO TO 255
      T2 = T4
      F2 = F4
      GO TO 220
  255 T1 = T4
      F1 = F4
      T2 = T3
      F2 = F3
      GO TO 220
  260 F4 =  F(T4)
      IF(ABS((T4-T4OLD)/T4).LE.EPSX.AND.ABS(F4)/AF.LE.EPSF) GO TO 400
      IF ( F4. GT. 0.) GO TO 265
      T1 = T4
      F1 = F4
      GO TO 220
  265 T1 = T3
      F1 = F3
      T2 = T4
      F2 = F4
      GO TO 220
  270 T1 = T3
      F1 = F3
      GO TO 220
  300 T4 = T3
      F4 = F3
  400 ANS = T4
      FANS = F4
      RETURN
  500 IER = 1
      RETURN
```

```
  600 IER = 2                                                           00000980
      RETURN                                                            00000990
      END                                                               00001000
```

APPENDIX D

SAMPLE CASE INPUT

FSCIP SAMPLE INPUT [illegible]

```
 OME FEED SYSTEM COUPLED STABILITY INVESTIGATION - [illegible]
      6K OMS ENGINE TECHNOLOGY PROGRAM - [illegible]
    2      1      4      1      [illegible]
0.6        7.7         4.1         1.72       [illegible]
   -1      0      0     50    100   [illegible]
  190.0         -0.1        40[illegible]        [illegible]        [illegible]        [illegible]
  0.01          0.01        [illegible]        .00[illegible]
71.15          6.573        3.4[illegible]
          26 150.0          4[illegible]
4.11           0.993        1[illegible]        1.9[illegible]
&HYD V=30*38400,A=30*1.33,[illegible]
R(23)=0,L(23)=2,R(24)=.51,L(24)=[illegible]
L(25)=17.5,R(26)=.429,L(26)=[illegible]
R(30)=1.765,L(30)=15,V(22)=[illegible]
V(25)=63650,V(26)=[illegible]
VULO=20.21,ZU=.00171,[illegible]
L(3)=20,R(5)=.037,L(5)=[illegible]
L(9)=41.33,L(10)=2,R(10)=[illegible]
ITERM=0,ICRT=1, &END
2.0            0.00664      [illegible]
0.57           0.01         3.[illegible]
2.0            0.00462      [illegible]      -1[illegible]
0.57           0.01         3.[illegible]
21.628         5667.1     -1[illegible]
 OME FEED SYSTEM COUPLED STABILITY INVESTIGATION - [illegible]
      6K OMS ENGINE TECHNOLOGY PROGRAM - [illegible]
    3      1      4      1      [illegible]
0.8        7.7         4.1         1.[illegible]
   -1      0      0     50    [illegible]
  265.0         -0.1        [illegible]
  0.01          0.01        [illegible]
71.15          6.573        3.[illegible]
2.0            0.00664      [illegible]
0.57           0.01         3.[illegible]
2.0            0.00462      3[illegible]      -1[illegible]
0.57           0.01         3.0[illegible]
21.628         5667.1     -[illegible]
```

ORIGINAL PAGE IS
OF POOR QUALITY

APPENDIX E

SAMPLE CASE OUTPUT

ANALYTICAL DESCRIPTION
FEED SYSTEM COUPLED
STABILITY MODEL

COMPUTER MODEL

PROGRAM NAME: FSCSM, FIV VERSION, MAY 1975

DEVELOPED BY: M. D. SCHUMAN, J. K. HUNTING, AND K. W. FERTIG
ADVANCED PROGRAMS, ROCKETDYNE
DIVISION OF ROCKWELL INTERNATIONAL
CANOGA PARK, CALIF 91304

SPONSERED BY: NASA/LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS 77058
UNDER CONTRACT NAS9-14315

```
                    FEED  SYSTEM  COUPLED  STABILITY  MODEL
        OME FEED SYSTEM COUPLED STABILITY INVESTIGATION - MODEL VERIFICATION
           6K OMS ENGINE TECHNOLOGY PROGRAM - TEST NUMBER 12 - CASE #1

INPHYD = 2    INPCOM = 1     INPNOZ = 3     ITAPH =  1     ITAPC =  2     ITAPN =  3
IPRHYD = 1    IPRCOM = 1     IPRNOZ = 1     IPRCHM = 1     IPRSTE = 1     NXP =  70

XO = 8.0000E-01       XNOZ = 7.7000E+00     RINJ = 4.1000E+00    GAMO = 1.2300E+00
                      CO = 3.9851E+03       DELP = 1.0000E-01

NROOT = -1     IWRT = 0       IWSKP = 0      KNTMX =  50    KNTRMX = 100   KNTSMX =  20

OMEGA(R)= 1.9000E+02  OMEGA(I)=-1.0000E-01  FRQMAX = 4.0000E+02   DELFRQ = 5.0000E+00
                      DELMX = 5.0000E+01    CTEST = 7.5000E+01

EPSF = 1.0000E-02     EPSX = 1.0000E-02     EPSFS = 5.0000E-04   EPSXS = 5.0000E-04

PC = 7.1150E+01       MBOXI = 6.5730E+00    MBFUI = 3.4030E+00

NFREQT =  26          FREQMI = 1.5000E+02   FREQMX = 4.0000E+02

RCCX = 4.1100E+00     RCTX = 9.9300E-01     ANGLEX = 1.9550E+01  CRR = 1.9850E+00
```

THEORETICAL NOZZLE ADMITTANCES

MACH NUMBER = .31 SVN = 0.0 GAMMA = 1.230

NOZZLE ANGLE = 19.6 RADII OF CURVATURE: THROAT = 0.9930 ENTRANCE = 4.1100

FC	YR	YI	F	SYR	SYI	ALPHA	BETA
150.0	0.03305	0.09816	150.85	0.03849	0.11432	0.00100	0.49704
160.0	0.03334	0.10477	160.90	0.03883	0.12202	0.00107	0.49663
170.0	0.03365	0.11139	170.96	0.03919	0.12972	0.00115	0.49620
180.0	0.03398	0.11802	181.02	0.03957	0.13744	0.00123	0.49573
190.0	0.03432	0.12466	191.07	0.03997	0.14518	0.00131	0.49524
200.0	0.03469	0.13132	201.13	0.04040	0.15293	0.00139	0.49473
210.0	0.03508	0.13799	211.19	0.04085	0.16070	0.00148	0.49418
220.0	0.03549	0.14468	221.24	0.04133	0.16849	0.00157	0.49361
230.0	0.03592	0.15136	231.30	0.04183	0.17630	0.00166	0.49301
240.0	0.03637	0.15810	241.36	0.04235	0.18413	0.00175	0.49238
250.0	0.03684	0.16484	251.41	0.04290	0.19198	0.00185	0.49173
260.0	0.03733	0.17160	261.47	0.04348	0.19985	0.00195	0.49104
270.0	0.03785	0.17838	271.52	0.04408	0.20774	0.00205	0.49033
280.0	0.03839	0.18518	281.56	0.04471	0.21566	0.00216	0.48959
290.0	0.03895	0.19200	291.64	0.04537	0.22360	0.00227	0.48862
300.0	0.03954	0.19884	301.69	0.04605	0.23157	0.00238	0.48803
310.0	0.04015	0.20571	311.75	0.04676	0.23957	0.00250	0.48720
320.0	0.04078	0.21260	321.81	0.04750	0.24759	0.00262	0.48635
330.0	0.04144	0.21951	331.86	0.04827	0.25565	0.00274	0.48540
340.0	0.04213	0.22645	341.92	0.04906	0.26373	0.00287	0.48451
350.0	0.04284	0.23342	351.98	0.04989	0.27184	0.00300	0.48361
360.0	0.04357	0.24041	362.03	0.05075	0.27999	0.00314	0.48263
370.0	0.04434	0.24743	372.09	0.05163	0.28816	0.00328	0.48163
380.0	0.04513	0.25448	382.15	0.05255	0.29638	0.00343	0.48060
390.0	0.04594	0.26156	392.20	0.05351	0.30462	0.00358	0.47954
400.0	0.04679	0.26868	402.26	0.05449	0.31241	0.00374	0.47845

```
                FEED  SYSTEM  COUPLED  STABILITY  MODEL
   OME FEED SYSTEM COUPLED STABILITY INVESTIGATION - MODEL VERIFICATION
      6K OMS ENGINE TECHNOLOGY PROGRAM - TEST NUMBER 12 - CASE #1
&HYD
L=  29.0000000   ,  2.00000000     ,  20.0000000     ,  .999999931E-03,  2.00000000     ,
  27.0000000     ,  .999999931E-03,  5.00000000     ,  41.3300018     ,  2.00000000     ,  .999999931E-03,
  .999999931E-03,  .999999931E-03,  .999999931E-03,  .999999931E-03,  .999999931E-03,  .999999931E-03,
  .999999931E-03,  .999999931E-03,  .999999931E-03,  2.00000000     ,  26.0000000     ,  2.00000000     ,
  40.7500000     ,  17.5000000     ,  34.2500000     ,  .999999931E-03,  2.00000000     ,  9.19999981     ,
  15.0000000     ,R=  .526000023    ,  .0             ,  .362999976     ,  1000000.00     ,
  .370000005E-01,  .490000010     ,  1000000.00     ,  .910000205E-01,  .750999987     ,  .370000005E-01,
  1000000.00     ,  1000000.00     ,  1000000.00     ,  1000000.00     ,  1000000.00     ,  1000000.00     ,
  1000000.00     ,  1000000.00     ,  1000000.00     ,  1000000.00     ,  .0             ,  .240999997     ,
  .0             ,  .509999990     ,  .218999982     ,  .429000020     ,  1000000.00     ,  .125000000     ,
  .601999986     ,  1.76500034     ,A=  1.32999992    ,  1.32999992     ,  1.32999992     ,
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  1.32999992     ,  1.32999992     ,  1.32999992     ,  1.32999992     ,  1.32999992     ,  1.32999992     ,
  1.32999992     ,  1.32999992     ,  1.32999992     ,  1.32999992     ,  1.32999992     ,  1.32999992     ,
  1.32999992     ,  1.32999992     ,  1.32999992     ,  1.32999992     ,  1.32999992     ,  1.32999992     ,
  1.32999992     ,  3.52999973     ,  1.02999973     ,V=  38400.0000    ,  38400.0000     ,
  38400.0000     ,  38400.0000     ,  38400.0000     ,  38400.0000     ,  38400.0000     ,  38400.0000     ,
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  63700.0000     ,  63826.0000     ,  63800.0000     ,  63750.0000     ,  63650.0000     ,  63600.0000     ,
  38400.0000     ,  63550.0000     ,  61241.0000     ,  55168.0000     ,OMI=  150.847260    ,OMFL=
  402.259277     ,FREQ=  189.999924     ,NFREQT=          26,IWRITE=           1,ICRT=            1,ZF=
  .225999998E-02,RF=  6.46100044    ,VOLF=  60.8399963    ,VF=  51404.0000    ,ZO=  .170999998E-02,RO=
  4.50000000     ,VOLO=  20.2100067   ,VO=  38400.0000    ,FREQT=  150.847260    ,  160.903748     ,
  170.960236     ,  181.016724     ,  191.073196     ,  201.129684     ,  211.186172     ,  221.242661     ,
  231.299149     ,  241.355621     ,  251.412109     ,  261.468506     ,  271.524902     ,  281.581543     ,
  291.637939     ,  301.694336     ,  311.750977     ,  321.807373     ,  331.863770     ,  341.920410     ,
  351.976807     ,  362.033447     ,  372.089844     ,  382.146240     ,  392.202881     ,  402.259277     ,
  .250980377     ,  .250980377     ,  .250980377     ,  .250980377     ,  .250980377     ,  .250980377     ,
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 -1028.01562     , -.489377824E+25,  .360355377     ,  .250980377     ,  .250980377     ,  .250980377     ,
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  .250980377     ,  .250980377     ,  .250980377     ,  .250980377     ,  .250980377     , -.590786010E+58,
 -.949242105E+59,  .250980377     , -.590786010E+58, -.608017007E+58,  .0             ,  .0             ,
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  .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       ,IH=      -1,        -1,        -1,        -1,        -1,
        -1,        -1,        -1,        -1,        -1,        -1,        -1,        -1,
        -1,         0,        -1,        -1,         0,         1,        -1,        -1,
        -1,        -1,        -1,        -1,        -1,        -1,        -1,        -1,
        -1,        -1,        -1,        -1,        -1,        -1,        -1,        -1,
        -1,        -1,        -1,        -1,        -1,        -1,        -1,        -1,
        -1,        -1,        -1,        -1,        -1,        -1,        -1,        -1,
        -1,         0,        -1,        -1,         0,         1,        -1,        -1,
         0,        -1,        -1,        -1,        -1,        -1,        -1,        -1,
        -1,        -1,        -1,        -1,        -1,        -1,        -1,        -1,
        -1,        -1,        -1,        -1,        -1,        -1,        -1,        -1,
        -1,        -1,        -1,        -1,        -1,        -1,        -1,        -1,
        -1,        -1,        -1,        -1,        -1,        -1,        -1,        -1,
        -1,        -1,        -1,        -1,        -1,        -1,        -1,        -1,
        -1,        -1,        -1,        -1,        -1,        -1,        -1,        -1,
        -1,        -1,        -1,        -1,        -1,        -1,        -1,        -1,
        -1,ITERM=           0,IRFLAG=          0,KO=  .0       ,KF=  .0       ,CW=
 .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       ,
RHOL=  .399999991E-01,  .399999991E-01,  .399999991E-01,  .399999991E-01,  .399999991E-01,
  .399999991E-01,  .399999991E-01,  .399999991E-01,  .399999991E-01,  .399999991E-01,  .399999991E-01,
  .399999991E-01,  .399999991E-01,  .399999991E-01,  .399999991E-01,  .399999991E-01,  .399999991E-01,
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  .399999991E-01,ID= 1476449028,ITYPE=          1,IX=           0
&END
```

```
                  FEED  SYSTEM  RESPONSE  PARAMETERS

FREQUENCY      OXIDIZER INJECTION RATE       FUEL  INJECTION RATE
                 AMPLITUDE      PHASE        AMPLITUDE       PHASE
  150.847       1.8274E+00     165.42       3.7451E-01      262.56
  160.904       5.3892E-01     107.51       4.5190E-01      260.85
  170.960       2.4679E-01      98.76       5.5606E-01      258.46
  181.017       1.2781E-01      95.61       7.1297E-01      254.68
  191.073       5.8226E-02      94.64       9.9354E-01      247.46
  201.130       8.7560E-03     104.80       1.6312E+00      228.22
  211.186       3.2075E-02     266.27       2.1617E+00      164.52
  221.243       6.8631E-02     267.14       9.3812E-01      118.97
  231.299       1.0466E-01     266.67       4.1875E-01      106.63
  241.356       1.4327E-01     265.84       1.7884E-01      103.57
  251.412       1.8866E-01     264.69       3.8063E-02      119.61
  261.469       2.4836E-01     263.06       6.8477E-02      259.11
  271.525       3.4028E-01     260.41       1.4746E-01      264.44
  281.582       5.2332E-01     254.86       2.1603E-01      264.79
  291.638       1.1343E+00     234.15       2.7931E-01      264.28
  301.694       1.1594E+00     129.46       3.4106E-01      263.46
  311.751       3.6691E-01     103.02       4.0468E-01      262.44
  321.807       1.5683E-01      97.16       4.7377E-01      261.22
  331.864       5.6576E-02      95.90       5.5330E-01      259.71
  341.920       7.6234E-03     250.46       6.5131E-01      257.73
  351.977       5.5028E-02     267.03       7.8301E-01      254.93
  362.033       9.5480E-02     267.03       9.8190E-01      250.42
  372.090       1.3307E-01     266.46       1.3357E+00      241.63
  382.146       1.7096E-01     265.55       2.0667E+00      218.24
  392.203       2.1235E-01     264.52       2.1736E+00      157.47
  402.259       2.6173E-01     263.20       9.5958E-01      120.13
```

```
                    FEED  SYSTEM  COUPLED  STABILITY  MODEL
         OME FEED SYSTEM COUPLED STABILITY INVESTIGATION - MODEL VERIFICATION
             6K OMS ENGINE TECHNOLOGY PROGRAM - TEST NUMBER 12 - CASE #1

XKOX = 2.0040E+00     TAUBOX = 6.6900E-03   VBOX = 2.0849E+01    DELHOX = 9.5908E+03
                      TORAGO = 0.0          ADVOX =-7.5000E-01

ADDOX = 5.7000E-01    DELVOX = 1.0000E-02   NUBOX = 3.2300E+00   DTOXDM = 0.0
                      XIMPOX = 1.8800E-01

XKFU = 2.0000E+00     TAUBFU = 4.6300E-03   VBFU = 3.5139E+01    DELHFU =-1.0790E+03
                      TORAGF = 0.0          ADVFU =-7.5000E-01

ADDFU = 5.7000E-01    DELVFU = 1.0000E-02   NUBFU = 3.6720E+00   DTFUDM = 0.0
                      XIMPFU = 1.8000E-01

MWG = 2.1628E+01      CS = 5.6671E+03       DRGDMR =-1.5200E+01  DCSDMR = 0.0
                      DHDMR = 1.6517E+03
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STEADY STATE SOLUTION

DISTANCE (INCHES)	TEMPERATURE (RANKINE)	VELOCITY (FT/S)	MIXTURE RATIO	DENSITY (LBM/FT**3)	PERCENT VAPORIZED FUEL	PERCENT VAPORIZED OXIDIZER
0.8500	5435.33	24.89	1.6309	2.47964E-02	2.53	2.14
0.9500	5440.96	72.97	1.6374	2.48029E-02	7.40	6.27
1.0500	5446.45	118.85	1.6438	2.48097E-02	12.02	10.23
1.1500	5451.81	162.63	1.6501	2.48168E-02	16.41	14.02
1.2500	5457.01	204.41	1.6564	2.48242E-02	20.59	17.65
1.3500	5462.08	244.27	1.6625	2.48319E-02	24.55	21.13
1.4500	5467.02	282.30	1.6686	2.48399E-02	28.32	24.46
1.5500	5471.80	318.59	1.6746	2.48482E-02	31.90	27.65
1.6500	5476.47	353.21	1.6805	2.48566E-02	35.30	30.71
1.7500	5481.00	386.24	1.6864	2.48653E-02	38.53	33.64
1.8500	5485.42	417.75	1.6921	2.48742E-02	41.60	36.44
1.9500	5489.71	447.82	1.6978	2.48832E-02	44.51	39.13
2.0500	5493.88	476.49	1.7033	2.48925E-02	47.28	41.70
2.1500	5497.92	503.85	1.7088	2.49019E-02	49.92	44.16
2.2500	5501.86	529.94	1.7142	2.49114E-02	52.42	46.52
2.3500	5505.66	554.83	1.7195	2.49211E-02	54.79	48.78
2.4500	5509.37	578.57	1.7248	2.49308E-02	57.05	50.94
2.5500	5512.97	601.21	1.7299	2.49407E-02	59.20	53.02
2.6500	5516.45	622.81	1.7349	2.49506E-02	61.23	55.00
2.7500	5519.84	643.41	1.7399	2.49606E-02	63.17	56.90
2.8500	5523.12	663.05	1.7448	2.49707E-02	65.01	58.72
2.9500	5526.31	681.78	1.7496	2.49807E-02	66.75	60.47
3.0500	5529.40	699.65	1.7543	2.49909E-02	68.41	62.14
3.1500	5532.39	716.68	1.7589	2.50010E-02	69.99	63.74
3.2500	5535.29	732.93	1.7634	2.50111E-02	71.49	65.27
3.3500	5538.11	748.43	1.7678	2.50212E-02	72.91	66.73
3.4500	5540.83	763.20	1.7722	2.50313E-02	74.27	68.14
3.5500	5543.47	777.29	1.7765	2.50414E-02	75.55	69.49
3.6500	5546.02	790.72	1.7807	2.50514E-02	76.77	70.77
3.7500	5548.49	803.53	1.7848	2.50615E-02	77.93	72.01
3.8500	5550.89	815.74	1.7888	2.50714E-02	79.03	73.19
3.9500	5553.21	827.38	1.7927	2.50813E-02	80.08	74.32
4.0500	5555.45	838.49	1.7965	2.50911E-02	81.07	75.41
4.1500	5557.62	849.07	1.8003	2.51009E-02	82.02	76.45
4.2500	5559.73	859.16	1.8040	2.51105E-02	82.92	77.44
4.3500	5561.77	868.79	1.8076	2.51201E-02	83.77	78.40

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4.4500     5563.73    877.96    1.8111    2.51295E-02     84.58    79.31
4.5500     5565.64    886.71    1.8146    2.51389E-02     85.35    80.18
4.6500     5567.48    895.05    1.8179    2.51482E-02     86.06    81.02
4.7500     5569.26    903.00    1.8212    2.51573E-02     86.78    81.82
4.8500     5570.99    910.58    1.8244    2.51663E-02     87.44    82.59
4.9500     5572.65    917.80    1.8276    2.51752E-02     88.06    83.33
5.0500     5574.26    924.69    1.8306    2.51840E-02     88.66    84.03
5.1500     5575.82    931.26    1.8336    2.51927E-02     89.23    84.70
5.2500     5577.32    937.52    1.8365    2.52012E-02     89.76    85.35
5.3500     5578.77    943.49    1.8394    2.52096E-02     90.28    85.97
5.4500     5580.18    949.18    1.8422    2.52178E-02     90.76    86.56
5.5500     5581.54    954.61    1.8449    2.52259E-02     91.22    87.13
5.6500     5582.85    959.78    1.8475    2.52339E-02     91.66    87.67
5.7500     5584.12    964.71    1.8501    2.52417E-02     92.08    88.19
5.8500     5585.34    969.41    1.8526    2.52494E-02     92.47    88.69
5.9500     5586.52    973.89    1.8550    2.52569E-02     92.85    89.17
6.0500     5587.66    978.16    1.8574    2.52643E-02     93.21    89.63
6.1500     5588.77    982.23    1.8597    2.52716E-02     93.55    90.07
6.2500     5589.84    986.12    1.8619    2.52787E-02     93.87    90.49
6.3500     5590.86    989.82    1.8641    2.52856E-02     94.17    90.89
6.4500     5591.86    993.35    1.8663    2.52924E-02     94.46    91.27
6.5500     5592.81    996.71    1.8683    2.52991E-02     94.74    91.64
6.6500     5593.75    999.92    1.8704    2.53056E-02     95.00    91.99
6.7500     5594.64   1002.98    1.8723    2.53120E-02     95.25    92.33
6.8500     5595.50   1005.89    1.8742    2.53182E-02     95.49    92.66
6.9500     5596.34   1008.67    1.8761    2.53243E-02     95.72    92.97
7.0500     5597.14   1011.32    1.8779    2.53302E-02     95.93    93.26
7.1500     5597.91   1013.85    1.8796    2.53360E-02     96.13    93.55
7.2500     5598.67   1016.26    1.8813    2.53417E-02     96.33    93.82
7.3500     5599.38   1018.55    1.8830    2.53472E-02     96.51    94.08
7.4500     5600.09   1020.74    1.8846    2.53525E-02     96.68    94.33
7.5500     5600.77   1022.83    1.8861    2.53578E-02     96.85    94.57
7.6500     5601.42   1024.82    1.8876    2.53629E-02     97.01    94.80
7.7500     5602.04   1026.72    1.8891    2.53679E-02     97.16    95.02
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                 FEED  SYSTEM  COUPLED  STABILITY  MODEL
   OME FEED SYSTEM COUPLED STABILITY INVESTIGATION - MODEL VERIFICATION
        6K OMS ENGINE TECHNOLOGY PROGRAM - TEST NUMBER 12 - CASE #1


             COMBUSTION DYNAMIC COEFFICIENTS

COX( 1) = 2.0719E-01: 5.4497E-02     CFU( 1) =-5.2935E+00: 1.1404E+01
COX( 2) = 0.0       : 0.0            CFU( 2) = 0.0       : 0.0
COX( 3) = 0.0       : 0.0            CFU( 3) = 0.0       : 0.0
COX( 4) = 1.9040E-01: 0.0            CFU( 4) = 2.2767E-01: 0.0
COX( 5) = 0.0       : 0.0            CFU( 5) = 0.0       : 0.0
COX( 6) = 0.0       : 0.0            CFU( 6) = 0.0       : 0.0
COX( 7) = 0.0       : 0.0            CFU( 7) = 0.0       : 0.0
COX( 8) = 0.0       : 0.0            CFU( 8) = 0.0       : 0.0
COX( 9) = 1.1451E-02:-9.5491E-03     CFU( 9) = 5.2994E-01: 7.4232E-01
COX(10) = 0.0       : 0.0            CFU(10) = 0.0       : 0.0
COX(11) = 0.0       : 0.0            CFU(11) = 0.0       : 0.0
COX(12) =-1.9040E-01: 0.0            CFU(12) =-2.2767E-01: 0.0
COX(13) = 0.0       : 0.0            CFU(13) = 0.0       : 0.0
COX(14) = 0.0       : 0.0            CFU(14) = 0.0       : 0.0
COX(15) = 0.0       : 0.0            CFU(15) = 0.0       : 0.0
COX(16) = 0.0       : 0.0            CFU(16) = 0.0       : 0.0


   FREQUENCY =  210.42 HZ,
   DECREMENT =-0.06144

   NOZZLE ADMITTANCE =  0.04082:    0.16011

   FEED SYSTEM RESPONSE
         OXIDIZER = -0.00210:    0.02891
             FUEL = -2.00708:   -0.43958
```

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                    FEED  SYSTEM  COUPLED  STABILITY  MODEL
       OME FEED SYSTEM COUPLED STABILITY INVESTIGATION - MODEL VERIFICATION
          6K OMS ENGINE TECHNOLOGY PROGRAM - TEST NUMBER 1[illegible] - CASE #1
                  OSCILLATORY           OSCILLATORY           OSCILLATORY            OSCILLATORY
DISTANCE      PRESSURE  RATIO        VELOCITY  RATIO      TEMPERATURE RATIO       MIXTURE RATIO
(INCHES)     AMPLITUDE   PHASE     AMPLITUDE   PHASE     AMPLITUDE   PHASE      AMPLITUDE   PHASE

 0.8000       0.09998   -0.00       0.00180    93.52      0.33561    88.64       1.67995    91.83
 0.9000       0.10000    0.03       0.00409  -111.60      0.26984   102.58       1.69734   101.09
 1.0000       0.10003    0.14       0.00896   -97.10      0.26425   111.05       1.69569   110.16
 1.1000       0.10001    0.31       0.01314   -86.70      0.25801   119.75       1.68232   118.97
 1.2000       0.09989    0.51       0.01656   -77.12      0.25036   128.35       1.65705   127.55
 1.3000       0.09966    0.70       0.01920   -67.83      0.24129   136.75       1.62026   135.88
 1.4000       0.09934    0.86       0.02109   -58.69      0.23394   144.94       1.57259   143.96
 1.5000       0.09896    0.95       0.02224   -49.62      0.21946   152.89       1.51469   151.78
 1.6000       0.09857    0.96       0.02271   -40.60      0.20705   160.56       1.44816   159.30
 1.7000       0.09822    0.90       0.02256   -31.61      0.19390   167.93       1.37360   166.51
 1.8000       0.09794    0.76       0.02186   -22.65      0.18022   174.96       1.29252   173.35
 1.9000       0.09778    0.56       0.02068   -13.72      0.16622  -178.42       1.20640   179.79
 2.0000       0.09775    0.38       0.01912    -4.83      0.15213  -172.20       1.11683  -174.25
 2.1000       0.09786    0.18       0.01726     4.01      0.13816  -166.52       1.02552  -168.84
 2.2000       0.09808    0.01       0.01518    12.77      0.12455  -161.46       0.93433  -164.09
 2.3000       0.09840   -0.11       0.01296    21.39      0.11152  -157.13       0.84523  -160.12
 2.4000       0.09877   -0.17       0.01068    29.77      0.09931  -153.07       0.76038  -157.08
 2.5000       0.09915   -0.16       0.00840    37.69      0.08815  -151.23       0.68207  -155.13
 2.6000       0.09951   -0.09       0.00619    44.68      0.07830  -149.95       0.61271  -154.42
 2.7000       0.09980    0.04       0.00411    49.39      0.06998  -149.91       0.55468  -155.01
 2.8000       0.09995    0.20       0.00224    46.48      0.06338  -151.08       0.50997  -156.80
 2.9000       0.10009    0.38       0.00103     3.69      0.05859  -153.18       0.47968  -159.47
 3.0000       0.10008    0.55       0.00175   -52.06      0.05555  -155.74       0.46345  -162.47
 3.1000       0.09997    0.71       0.00302   -57.96      0.05404  -158.21       0.45933  -165.19
 3.2000       0.09978    0.82       0.00419   -53.62      0.05368  -160.10       0.46422  -167.19
 3.3000       0.09954    0.89       0.00519   -46.37      0.05407  -161.13       0.47469  -168.25
 3.4000       0.09927    0.90       0.00601   -37.94      0.05465  -161.24       0.48760  -168.38
 3.5000       0.09900    0.86       0.00666   -28.93      0.05569  -160.54       0.50047  -167.70
 3.6000       0.09876    0.77       0.00716   -19.63      0.05641  -159.16       0.51153  -166.38
 3.7000       0.09858    0.64       0.00752   -10.23      0.05685  -157.28       0.51965  -164.61
 3.8000       0.09846    0.49       0.00776    -0.85      0.05694  -155.05       0.52420  -162.55
 3.9000       0.09842    0.32       0.00788     8.39      0.05666  -152.63       0.52498  -160.34
 4.0000       0.09845    0.15       0.00791    17.37      0.05602  -150.13       0.52[illegible]10  -158.09
 4.1000       0.09854    0.00       0.00785    25.98      0.05535  -147.65       0.51592  -155.92
```

4.2000	0.09868	-0.13	0.00771	34.[illegible]0	0.05381	-145.29	0.50699	-15[illegible].91
4.3000	0.09884	-0.22	0.00750	41.60	0.05236	-143.12	0.49598	-152.13
4.4000	0.09902	-0.26	0.00723	48.34	0.05079	-141.20	0.48367	-150.64
4.5000	0.09919	-0.32	0.00691	54.16	0.04917	-139.57	0.47086	-149.47
4.6000	0.09934	-0.32	0.00657	58.89	0.04758	-138.25	0.45834	-148.64
4.7000	0.09945	-0.31	0.00622	62.34	0.04608	-137.24	0.44683	-148.14
4.8000	0.09952	-0.28	0.00590	64.36	0.04473	-136.51	0.43694	-147.92
4.9000	0.09954	-0.24	0.00563	64.86	0.04358	-136.02	0.42907	-147.91
5.0000	0.09951	-0.21	0.00545	63.97	0.04266	-135.70	0.42345	-148.04
5.1000	0.09945	-0.20	0.00540	62.03	0.04196	-135.46	0.42005	-148.20
5.2000	0.09936	-0.19	0.00550	59.64	0.04148	-135.23	0.41866	-148.31
5.3000	0.09925	-0.21	0.00574	57.43	0.04118	-134.93	0.41894	-148.30
5.4000	0.09913	-0.24	0.00611	55.87	0.04102	-134.51	0.42041	-148.13
5.5000	0.09901	-0.30	0.00657	55.18	0.04097	-133.94	0.42259	-147.77
5.6000	0.09891	-0.37	0.00708	55.33	0.04099	-133.20	0.42502	-147.22
5.7000	0.09882	-0.45	0.00761	56.20	0.04102	-132.30	0.42728	-146.51
5.8000	0.09875	-0.55	0.00814	57.62	0.04104	-131.27	0.42906	-145.66
5.9000	0.09871	-0.64	0.00864	59.40	0.04102	-130.12	0.43014	-144.71
6.0000	0.09869	-0.74	0.00911	61.40	0.04096	-128.91	0.43039	-143.71
6.1000	0.09870	-0.83	0.00951	63.49	0.04083	-127.65	0.42979	-142.68
6.2000	0.09871	-0.91	0.00987	65.54	0.04065	-126.39	0.42838	-141.66
6.3000	0.09874	-0.98	0.01016	67.49	0.04041	-125.15	0.42628	-140.69
6.4000	0.09876	-1.04	0.01041	69.26	0.04014	-123.96	0.42365	-139.79
6.5000	0.09879	-1.09	0.01061	70.79	0.03983	-122.83	0.42070	-138.97
6.6000	0.09880	-1.13	0.01077	72.05	0.03951	-121.79	0.41761	-138.24
6.7000	0.09880	-1.16	0.01091	73.03	0.03919	-120.83	0.41460	-137.61
6.8000	0.09879	-1.19	0.01104	73.72	0.03889	-119.94	0.41183	-137.05
6.9000	0.09877	-1.22	0.01118	74.15	0.03863	-119.13	0.40944	-136.55
7.0000	0.09873	-1.25	0.01133	74.36	0.03840	-118.38	0.40751	-136.11
7.1000	0.09868	-1.28	0.01150	74.39	0.03822	-117.68	0.40609	-135.69
7.2000	0.09862	-1.32	0.01171	74.31	0.03808	-116.99	0.40516	-135.27
7.3000	0.09855	-1.36	0.01195	74.19	0.03799	-116.32	0.40469	-134.84
7.4000	0.09848	-1.41	0.01223	74.07	0.03795	-115.64	0.40458	-134.38
7.5000	0.09840	-1.46	0.01253	74.00	0.03794	-114.95	0.40474	-133.89
7.6000	0.09834	-1.52	0.01286	74.01	0.03795	-114.22	0.40507	-133.34
7.7000	0.09827	-1.58	0.01320	74.12	0.03799	-113.47	0.40545	-132.76

ANALYTICAL DESCRIPTION
FEED SYSTEM COUPLED
STABILITY MODEL

COMPUTER MODEL

PROGRAM NAME: FSCSM, FIV VERSION, MAY 1975

DEVELOPED BY: M. D. SCHUMAN, J. K. HUNTING, AND K. W. FERTIG
ADVANCED PROGRAMS, ROCKETDYNE
DIVISION OF ROCKWELL INTERNATIONAL
CANOGA PARK, CALIF 91304

SPONSERED BY: NASA/LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS 77058
UNDER CONTRACT NAS9-14315

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                         FEED  SYSTEM  COUPLED  STABILITY  MODEL
        OME FEED SYSTEM COUPLED STABILITY INVESTIGATION - MODEL VERIFICATION
            6K OMS ENGINE TECHNOLOGY PROGRAM - TEST NUMBER 12 - CASE #2

   INPHYD = 3    INPCOM = 1     INPNOZ = 4     ITAPH =  1     ITAPC =  2     ITAPN =  3
   IPRHYD = 0    IPRCOM = 0     IPRNOZ = 0     IPRCHM = 0     IPRSTE = 0     NXP =  70

   XO = 8.0000E-01          XNOZ = 7.7000E+00       RINJ = 4.1000E+00      GAMO = 1.2300E+00
                            CO = 3.9851E+03         DELP = 1.0000E-01

   NROOT = -1    IWRT = 0       IWSKP = 0      KNTMX =  50   KNTRMX = 100   KNTSMX =  20

   OMEGA(R)= 2.6500E+02     OMEGA(I)=-1.0000E-01    FRQMAX = 4.0000E+02    DELFRQ = 5.0000E+00
                            DELMX = 5.0000E+01      CTEST = 7.5000E+01

   EPSF = 1.0000E-02        EPSX = 1.0000E-02       EPSFS = 5.0000E-04     EPSXS = 5.0000E-04

   PC = 7.1150E+01          MBOXI = 6.5730E+00      MBFUI = 3.4030E+00

   XKOX = 2.0000E+00        TAUBOX = 6.6900E-03     VBOX = 2.8859E+01      DELHOX = 9.5908E+03
                            TDRAGO = 0.0            ADVOX =-7.5000E-01

   ADDOX = 5.7000E-01       DELVOX = 1.0000E-02     NUBOX = 3.2300E+00     DTOXDM = 0.0
                            XIMPOX = 1.8800E-01

   XKFU = 2.0000E+00        TAUBFU = 4.6300E-03     VBFU = 3.5139E+01      DELHFU =-1.0790E+03
                            TDRAGF = 0.0            ADVFU =-7.5000E-01

   ADDFU = 5.7000E-01       DELVFU = 1.0000E-02     NUBFU = 3.6720E+00     DTFUDM = 0.0
                            XIMPFU = 1.8800E-01

   MWG = 2.1628E+01         CS = 5.6671E+03         DRGDMR =-1.5200E+01    DCSDMR = 0.0
                            DHDMR = 1.6517E+03
```

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                    FEED  SYSTEM  COUPLED  STABILITY  MODEL
 OME FEED SYSTEM COUPLED STABILITY INVESTIGATION - MODEL VERIFICATION
      6K OMS ENGINE TECHNOLOGY PROGRAM - TEST NUMBER 12 - CASE #2

FREQUENCY =  280.62 HZ,
DECREMENT = 0.09211

NOZZLE ADMITTANCE =  0.04465:    0.21491

FEED SYSTEM RESPONSE
         OXIDIZER = -0.12902:     0.48896
             FUEL = -0.01911:     0.20861
```

ANALYTICAL DESCRIPTION
FEED SYSTEM COUPLED
STABILITY MODEL

COMPUTER MODEL

PROGRAM NAME: FSCSM, FIV VERSION, MAY 1975

DEVELOPED BY: M. D. SCHUMAN, J. K. HUNTING, AND K. W. FERTIG
ADVANCED PROGRAMS, ROCKETDYNE
DIVISION OF ROCKWELL INTERNATIONAL
CANOGA PARK, CALIF 91304

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