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PROGRAM USER'S MANUAL FOR OPTIMIZING THE DESIGN OF A LIQUID OR GASEOUS PROPELLANT ROCKET ENGINE WITH THE AUTOMATED COMBUSTOR DESIGN CODE AUTOCOM

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16. Abstract
This computer program manual describes in two parts the automated combustor design optimization code AUTOCOM. The program code is written in the FORTRAN IV language. In Part I the input data setup and the program outputs are described in detail, and a sample engine case is discussed. In Part II, which represents the program backup, the program structure and programming techniques are described, and the AUTOCOM program analysis is outlined.

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PROGRAM USER'S MANUAL FOR OPTIMIZING THE DESIGN OF A LIQUID OR GASEOUS PROPELLANT ROCKET ENGINE WITH THE AUTOMATED COMBUSTOR DESIGN CODE AUTOCOM

R. H. Reichel, D. S. Hague, R. T. Jones, and C. R. Glatt

PART I - DATA INPUT AND OUTPUT WITH A SAMPLE ENGINE TEST CASE

1. INTRODUCTION

In designing a liquid or gaseous propellant rocket combustion chamber the engineer must compromise between characteristics such as performance, stability, weight, injector complexity, cost, etc. These *engine characteristics* are not items which are directly controlled by the designer. Instead, they are complicated functions of the independent *design variables* available to the designer, for example, injector hole size, chamber length, etc. To further complicate the problem, frequently there are *several techniques* that can be used to predict how an engine characteristic (such as performance) varies with the independent design variables. An engine characteristic value computed by any one of these techniques will be referred to as a *specific engine characteristic.*

If the engine designer had infinite funds and time available to him, he could design many combustors with different combinations and permutations of the various independent design variables. Specific engine characteristics could then be calculated for each design with all the available techniques if the designer had the ability to digest his particular application. The selection would be made, of necessity, on the basis of *weighting factors*. These weighting factors would first be used to define an average combustor characteristic for each significant engine characteristic such as performance, stability, etc. These average combustor characteristics would then be weighted into a single combustor *value function* or *rating* which could be used, for example, as a measure of the payload loss associated with an ideal engine.

With limited funds and time, the designer can only examine a few designs, and, because he is familiar with only a few techniques for calculating the various characteristics, he uses only this limited set of techniques to test the acceptability of each design. Using this approach some characteristics are never determined until after the combustor has been built, tested, and often found unacceptable. For example, stability characteristics which are particularly difficult to assess frequently result in an unacceptable engine design. Usually the designs selected in a project are those that are very similar to designs that have been successful in the past. As a result, a design of another group that would be better for a particular application is frequently neglected or ignored. Similarly, when trouble is encountered with a particular engine characteristic during the development phase, changes are made to overcome the particular problem using past experience. An improved engine design probably could have been obtained by determining which design variable or set of variables should be used to overcome the problem with the least sacrifice to other characteristics.

The work performed under the present contract was directed to the development of a generalized computer program to calculate *all the characteristics* of a given combustor design. The program then uses a *perturbation technique* to determine the changes in the design variables that produce the greatest improvement in the rating of the combustor design. The program then follows sequentially the design path that produces the greatest improvement in the rating to arrive at a combustor design that has the best combination of all variables. This design is called the *optimum combustor design*. The automated combustor design code which generates the optimum combustor design has been given the acronym AUTOCOM. An interim report describing the design code AUTOCOM was issued earlier, Reference 1-1.

In any optimization situation, the engineer-designer is faced with the problem of selecting the *rating* or value function which is to be minimized. In this report the rating of a design is based on a weighted average of all the characteristics of a given combustor. Weighting factors are used to obtain both average characteristics and a unique combustor rating. The constants first allow the designer to introduce his views regarding the importance or validity of one technique for obtaining a given characteristic versus another technique for obtaining the same characteristic. For example, if the designer believes that only one technique is valid for predicting the performance of a given design, he will assign a unity value to the weighting factor constants for that specific characteristic, and the constants for all the other performance characteristics will be zero. Second, the weighting factor constants in the equation to obtain a single rating for a given combustor design allow the designer to introduce the relative importance of different types of characteristics, for example, stability versus performance. The weighting factor constants, therefore, *give the designer the same control and flexibility in the computer program as he has in the present "cut-and-try" system.* To establish a base point for the rating system, a hypothetical ideal combustor is given a rating of zero. The hypothetical ideal combustor would have one hundred per cent of theoretical C* performance, infinite damping rate for all modes of instability, zero pressure drop, zero chamber length, chamber diameter equal to the throat diameter, etc.

Techniques for obtaining the various specific engine and average combustor characteristics contained in the AUTOCOM code are outlined in this report. The code is written in a modular fashion which permits rapid extension of the combustor characteristic equations. This approach leads to an open ended engine model capable of future development and extension consistent with the growth of capability in combustor design analysis.

Designs are optimized by nonlinear multivariable search techniques embodied in an optimization program module. A variety of multivariable search techniques may be employed to define an optimal design including

a. One-parameter-at-a-time techniques

b. Organized techniques based on the computation of first- or second-order rating derivatives with respect to the design variables

c. Randomized techniques

Program operation is shown conceptually in Figure 1-1. Fixed engine and propellant data is input on punched cards together with the free design variable values. The specific engine characteristics are then computed and combined through user-specified weighting constants to form the average combustor characteristics for performance, stability, etc. The average combustor characteristics are then combined through a second set of user-specified weighting factors into the combustor rating which measures payload loss based on an ideal engine. The rated engine free design parameters are then perturbed in the optimization loop until an optimal design is evolved.

For the user's convenience this document is organized in two parts. Part I deals with the input data setup, the program outputs, and concludes with an engine test case. Part II represents the program backup and discusses the combustor program structure, the programming techniques, and the AUTOCOM program analysis. A more detailed master chart of the computer program can be found in Appendix A. A detailed description of the optimization subprogram AESOP is presented in Appendix B.

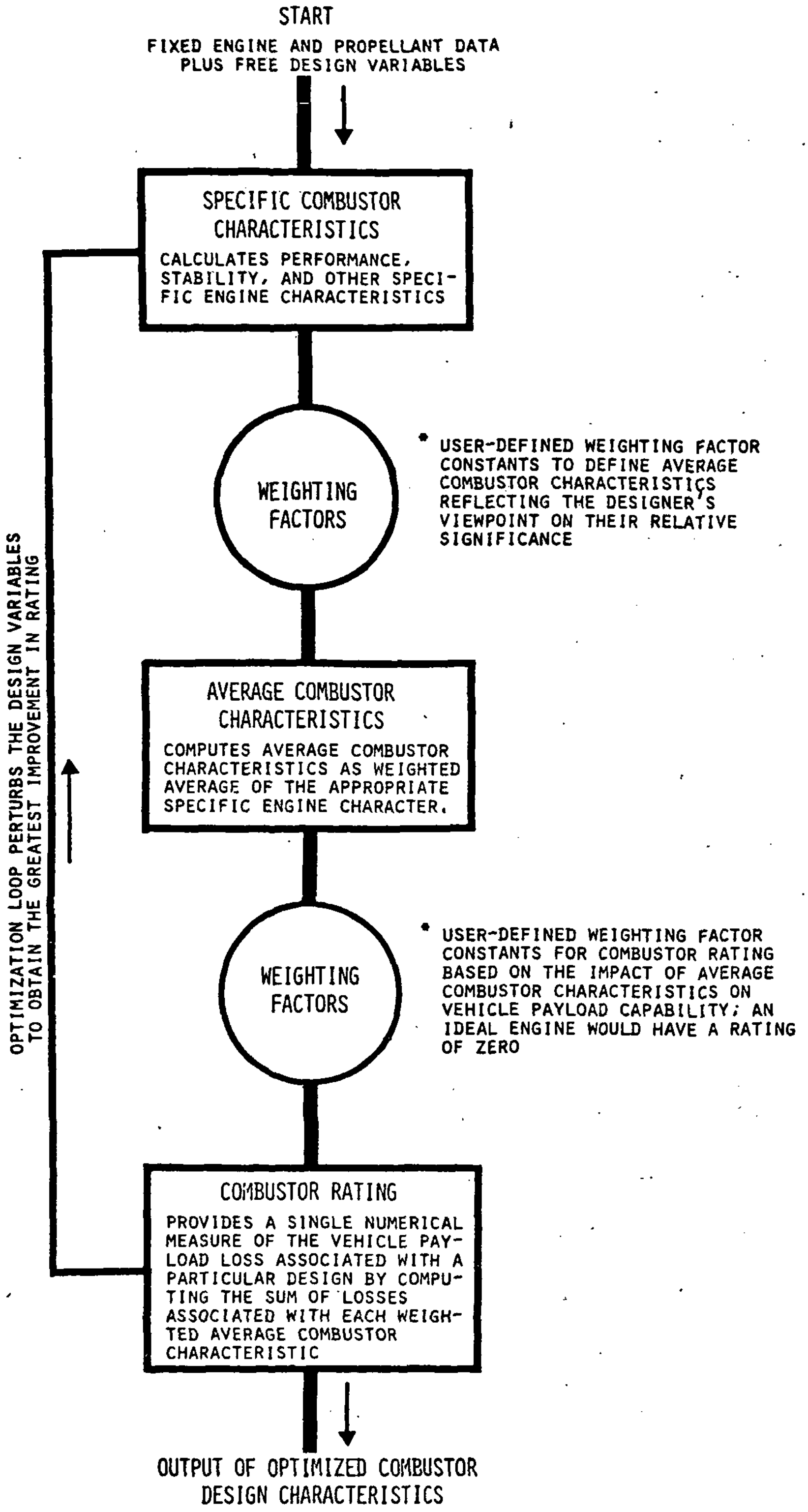


Figure 1-1. Conceptual Layout of the Optimization Computer Program

2. INPUT DATA SETUP

Figure 2-1 depicts the overall schematic of the AUTOCOM program with the respective input locations (heavy lines). The input data setup is entered in nine blocks within the program (two data blocks are optional). The data input sequence is presented in Figure 2-2.

The input data setup describes a nominal engine design (for input data listing see Table 4-1, Section 4.1). There are the following nine input data types for the program:

1. Informative data (title)
2. Weighting factors
3. Independent design variables
4. Fixed (miscellaneous) combustor data
5. Data for root guesses
6. "Read" and "write" control
7. Curve-fit data for propellant properties (optional)
8. Optimization data
9. Input for specific engine characteristics (optional)

Provisions are made in the coding to consider

Pump-fed or pressure-fed engines

Engines with or without preburners

Various injector element types, e.g., coaxial or non-coaxial injection, showerhead

Gaseous or liquid propellant state of propellants

Hypergolic or non-hypergolic propellants

Radial and/or circumferential baffles

The weighting factors are normally set equal to "1", and it is at the discretion of the designer to select his own inputs. (For the derivation of weighting factor constants see Section 5.5).

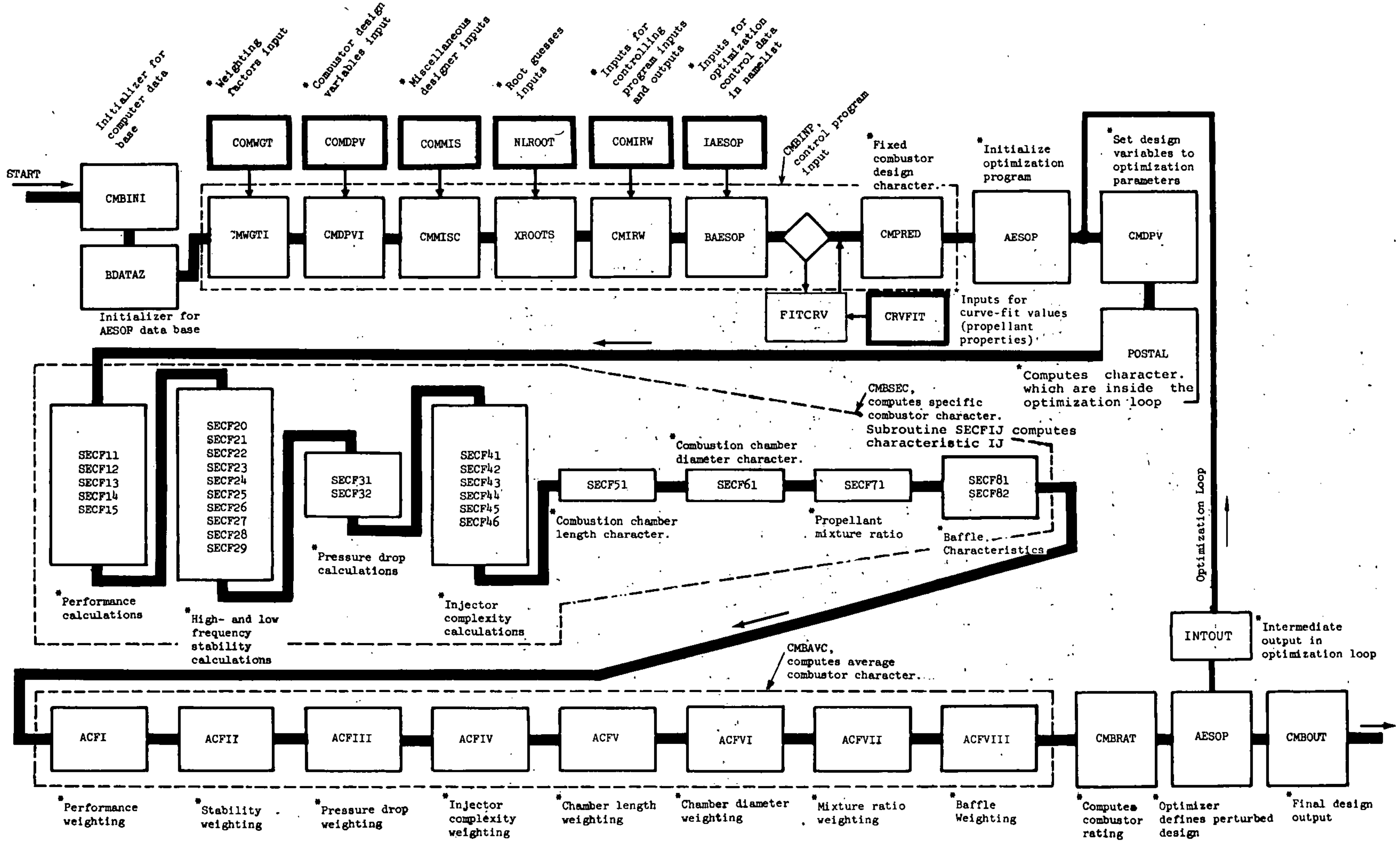


Figure 2-1
Overall Schematic of the AUTOCOM Program

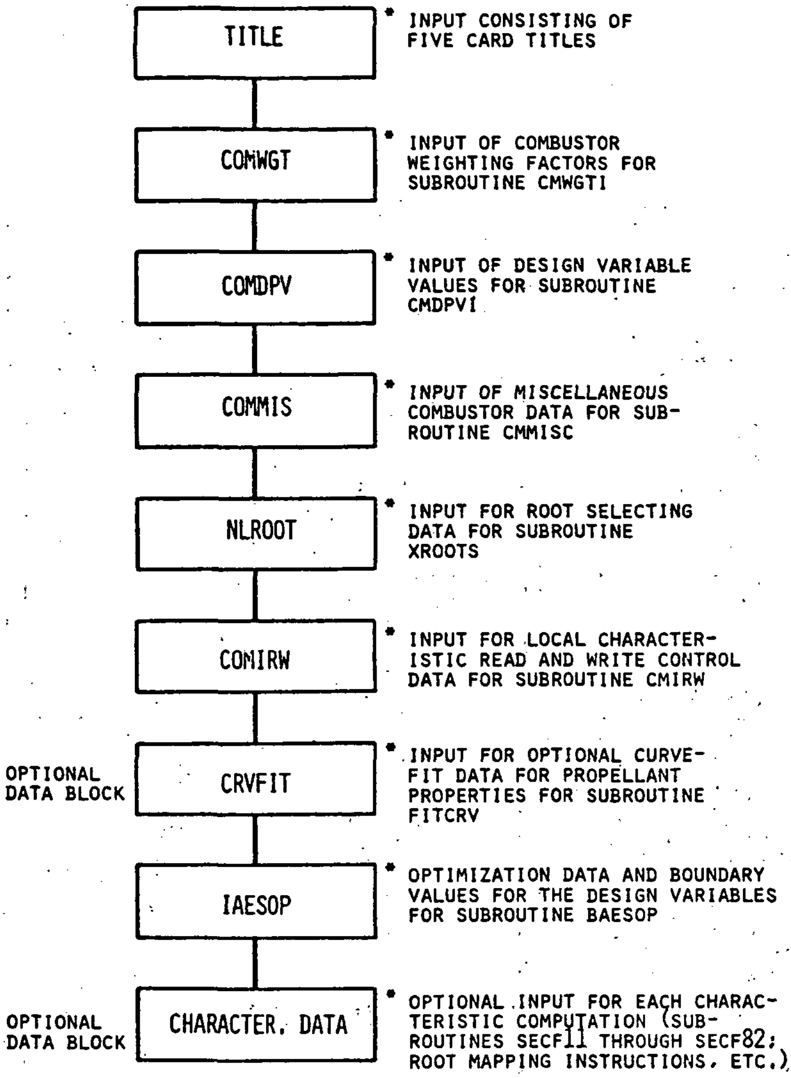


Figure 2-2. Namelist Data Input Sequence

The program coding is arranged in such a way that the subroutines for computing specific engine characteristics (SECF11 through SECF82) as well as for computing the combustor rating are only activated if the respective weighting factors (e.g., AF11, AF12, . . ., AFI, AFII, . . .,) are not "zero." This permits a user controlled bypass of undesired specific engine characteristic computations by choosing the respective weighting factors to be "zero." The average combustor characteristics modules for performance, stability, etc. will be bypassed if no computation within their respective specific engine characteristics modules takes place. Figure 2-3 depicts the schematic of this feature and indicates the relevant weighting factor inputs.

There are basically two options for applying AUTOCOM to an engine. These options, controlled by input data, are

1. point design or analysis
2. design optimization

The difference between these options is in the number of iterations determined by data input. For details see Section 2.8.

As mentioned before, it is possible to analyze selected engine characteristics by setting, for example, AF26 = 1, and bypassing all other engine characteristics (AFXX = 0).

There are provisions made in the AUTOCOM code for the input of characteristic data; for details see Section 2.9.

The input data deck setup is presented in Figure 2-4. Details regarding the individual input steps are treated in the following sections.

2.1 Title

Corresponding to Figure 2-2, the "title" is the first place where data inputs have to be executed. A "title" consisting of five cards provides user selected information about

1. The computer run number and the engine type to be analyzed
2. The type of run
3. The thrust level
4. The propellant combination
5. Whether or not it is a point design or an optimization run

There is no restriction on the type of information or on the number of card columns used. *There must be five cards in the title; blanks are acceptable.* A sample is presented in Figure 2-5.

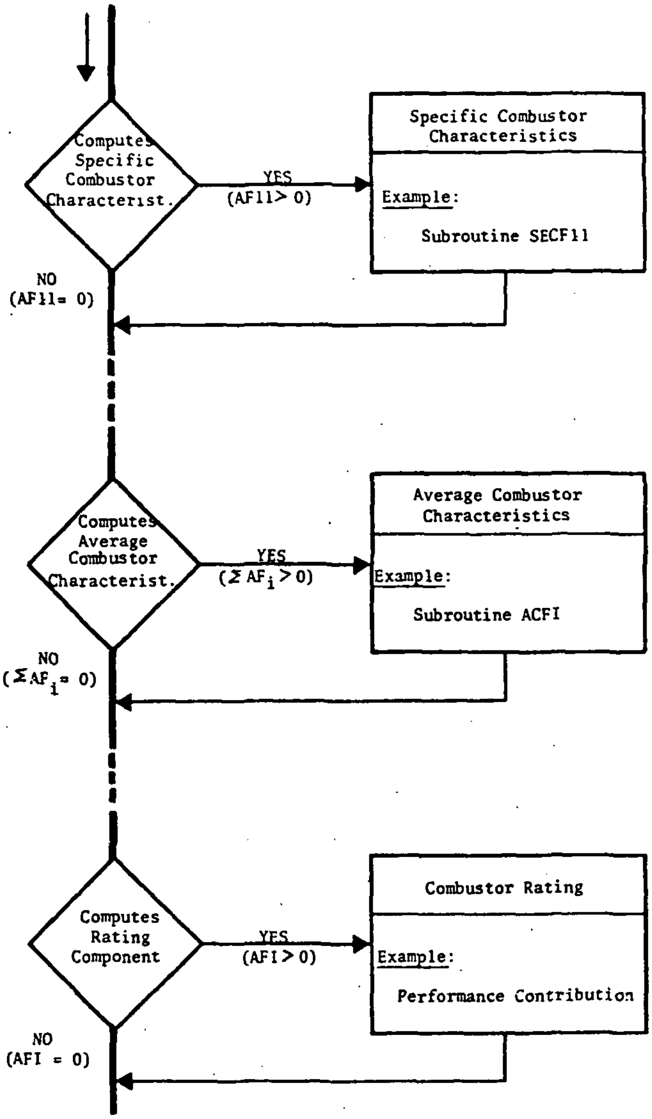


Figure 2-3. Logic of Bypass Arrangement for Combustor Characteristics and Rating

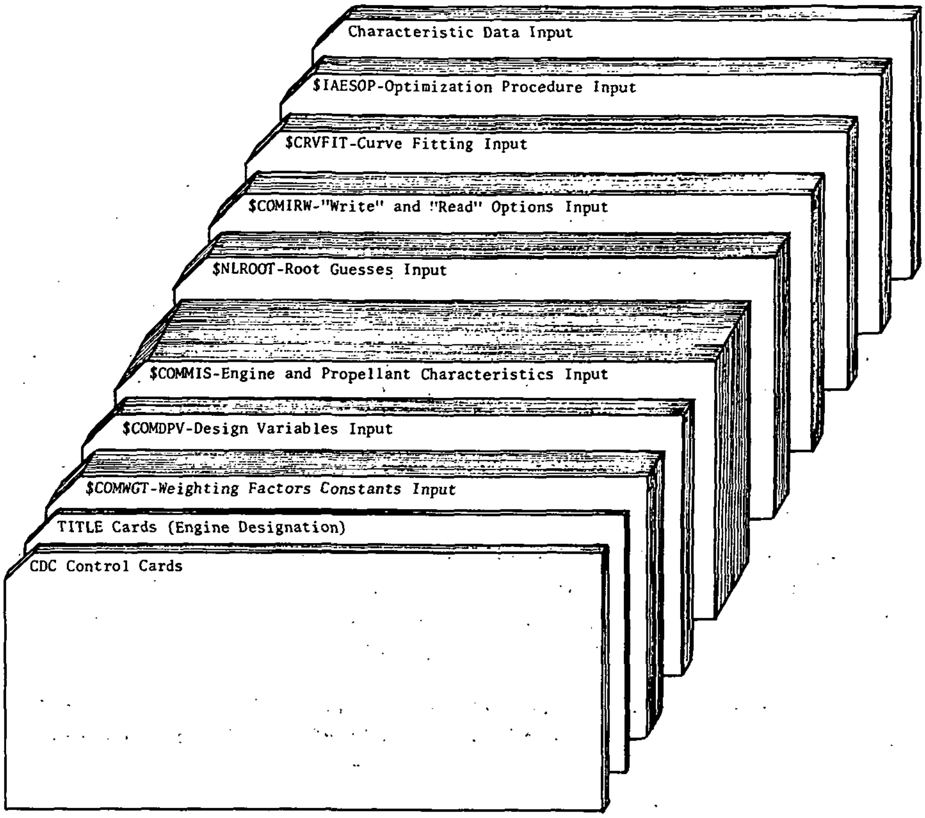


Figure 2-4. Deck Set Up with Namelist Names

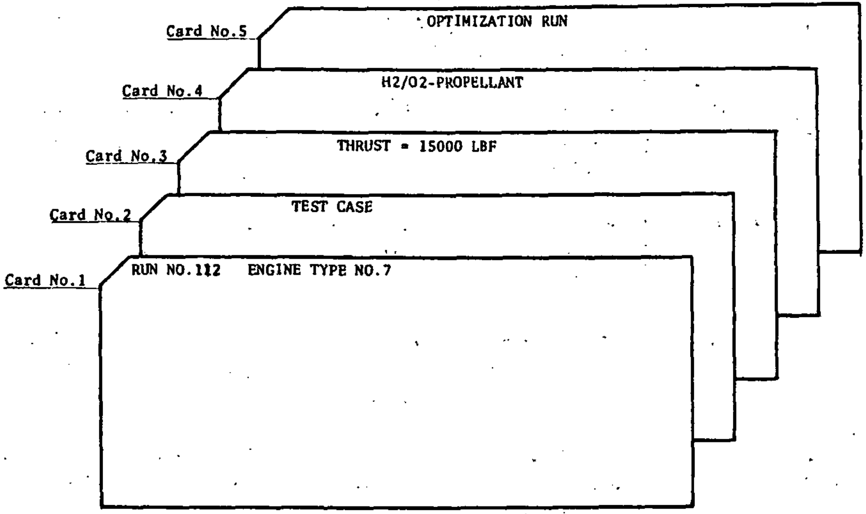


Figure 2-5. Sample Arrangement of Title Cards

2.2 Data Input Namelist COMWGT

The equation to obtain average engine characteristics as well as the rating equation contain weighting factor constants whose values are selected by the designer. These weighting factors reflect his view regarding the importance of each characteristic. In the general program coding the values are chosen to be "1" or "0" depending on whether the subroutine is activated ("1") or bypassed ("0"). In the following the specific engine characteristic weighting factor constants and their definitions are listed. (For derivation of the weighting factor constants for *rating an engine*, see Section 5.5).

PROGRAM SYMBOL	VALUE	DESCRIPTION
AF11	Positive number or 0.0	Weighting factor constant for fuel vaporization in the average performance characteristic equation. *If a gas, then AF11=0.*
AF12	Positive number or 0.0	Weighting factor constant for oxidizer vaporization in the average performance characteristic equation. *If a gas, then AF12=0.*
AF13	Positive number or 0.0	Weighting factor constant for C*-efficiency in the average performance characteristic equation.
AF20	Positive number or 0.0	Weighting factor constant for the fuel side chugging in the average combustor stability characteristic equation.
AF21	Positive number or 0.0	Weighting factor constant for the oxidizer side chugging in the average combustor stability characteristic equation.
AF22	Positive number or 0.0	Weighting factor constant for pulsed operation in the average combustor stability characteristic equation.
AF23	Positive number or 0.0	Weighting factor constant for non-pulsed operation in the average combustor stability charactersitic equation.
AF24	Positive number or 0.0	Weighting factor constant for the fuel stability decay rate in the average combustor stability characteristic equation.
AF25	Positive number or 0.0	Weighting factor constant for the oxidizer stability decay rate in the average combustor stability characteristic equation.

PROGRAM SYMBOL	VALUE	DESCRIPTION
AF26	Positive number or 0.0	Weighting factor constant for longitudinal modes in the average combustor stability characteristic equation
AF27	Positive number or 0.0	Weighting factor constant for transverse modes in the average combustor stability characteristic equation
AF28	Positive number or 0.0	Weighting factor constant for combustion response and flow response stability in the average combustor stability characteristic equation
AF29	Positive number or 0.0	Weighting factor constant for nonlinear stability analysis in the average combustor stability characteristic equation.
AF31	Positive number or 0.0	Weighting factor constant for fuel in the average pressure drop characteristic equation
AF32	Positive number or 0.0	Weighting factor constant for oxidizer in the average pressure drop characteristic equation
AF41	Positive number or 0.0	Weighting factor constant for fuel and oxidizer holes in the average injector complexity characteristic equation.
AF42	Positive number or 0.0	Weighting factor constant for the volume of the oxidizer dome in the average injector complexity characteristic equation.
AF43	Positive number or 0.0	Weighting factor constant for the volume of the fuel dome in the average injector complexity characteristic equation.
AF44	Positive number or 0.0	Weighting factor constant for the length of the oxidizer holes in the average injector complexity characteristic equation.
AF45	Positive number or 0.0	Weighting factor constant for the length of the fuel holes in the average injector complexity characteristic equation.
AF46	0.0	Weighting factor constant for the injector type in the average injector complexity characteristic equation. (At this time, the module SECF46 is not activated.)

PROGRAM SYMBOL	VALUE	DESCRIPTION
AF51	Positive number or 0.0	Weighting factor constant in the average combustor length characteristic equation
AF52	Positive number or 0.0	Weighting factor constant exponential in the average combustor length characteristic equation
AF61	Positive number or 0.0	Weighting factor constant in the average combustor diameter characteristic equation
AF71	Positive number or 0.0	Weighting factor constant in the average mixture ratio characteristic equation
AF72	Positive number or 0.0	Weighting factor constant exponential in the average mixture ratio characteristic equation
AF81	Positive number or 0.0	Weighting factor constant in the average baffle characteristic equation
AF82	Positive number or 0.0	Weighting factor constant in the average baffle characteristic equation
BF71	Greater than or Equal to O/F	Weighting factor constant in the average characteristic equation
AFI	Positive number or 0.0	Weighting factor constant of the performance characteristic in the rating equation
AFII	Positive number or 0.0	Weighting factor constant of the stability characteristic in the rating equation
AFIII	Positive number or 0.0	Weighting factor constant of the pressure drop characteristic in the rating equation
AFIV	Positive number or 0.0	Weighting factor constant of the injector complexity characteristic in the rating equation
AFV	Positive number or 0.0	Weighting factor constant of the chamber length characteristic in the rating equation
AFVI	Positive number or 0.0	Weighting factor constant of the chamber diameter characteristic in the rating equation
AFVII	Positive number or 0.0	Weighting factor constant of the mixture ratio characteristic in the rating equation
AFVIII	Positive number or 0.0	Weighting factor constant of the baffle characteristic in the rating equation

PROGRAM SYMBOL	VALUE	DESCRIPTION
BFI	Positive number or 0.0	Weighting factor constant exponential to the performance characteristic in the rating equation
BFII	Positive number or 0.0	Weighting factor constant exponential to the stability characteristic in the rating equation
BFIII	Positive number or 0.0	Weighting factor constant exponential to the pressure drop characteristic in the rating equation
BFIV	Positive number or 0.0	Weighting factor constant exponential to the injector complexity characteristic in the rating equation
BFV	Positive number or 0.0	Weighting factor constant exponential to the chamber length characteristic in the rating equation
BFVI	Positive number or 0.0	Weighting factor constant exponential to the chamber diameter characteristic in the rating equation
BFVII	Positive number or 0.0	Weighting factor constant exponential to the mixture ratio characteristic in the rating equation
BFVIII	Positive number or 0.0	Weighting factor constant exponential to the baffle characteristic in the rating equation
CFII	Positive number or 0.0	Weighting factor constant exponential to the stability characteristic in the rating equation

2.3 Data Input Namelist COMDPV

Each specific engine characteristic is a function of the design variables entering into the combustor design. Basically, there are fourteen design variables. One of these is not activated at this time but is available for program extension.

The combustor design variables are listed in the data input namelist COMDPV, consistent with the sequence coded in the program. Following this listing is the "Definition of circumferential and radial baffle arrangement," Figure 2-6.

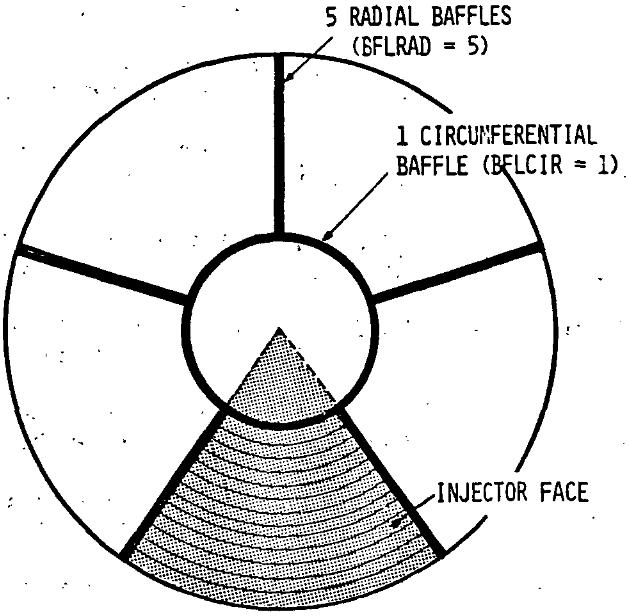


Figure 2-6. Definition of a Typical Circumferential and Radial Baffle Arrangement

PROGRAM SYMBOL	UNITS	VALUE	DESCRIPTION
DF	in.	Positive number	Minimum diameter of fuel orifices (determines pressure drop of the fuel side of the injector); see Figure 2-7
DX	in.	Positive number	Minimum diameter of oxidizer orifices (determines pressure drop of the oxidizer side of the injector); see Figure 2-7
NF	-	Positive integer	Number of fuel orifices
NOX	-	Positive integer	Number of oxidizer orifices
VOLF	in^3	Positive number	Volume of fuel manifold
VOLX	in^3	Positive number	Volume of oxidizer manifold
LF	in.	Positive number	Length of fuel orifices; see Figure 2-7
LOX	in.	Positive number	Length of oxidizer orifices; see Figure 2-7
-	-	---	Available for program extension
LC	in.	Positive number	Length of combustion chamber (from injector face to throat area); see Figures 2-8 and 2-12
DC	in.	Positive number	Chamber diameter at injector face; see Figures 2-8 and 2-12
OF	-	Positive number	Propellant mixture ratio (oxidizer/fuel)
BFLRAD	-	Positive integer or 0.0	Number of radial baffles; see Figure 2-6
BFLCIR	-	Positive integer or 0.0	Number of circumferential baffles; see Figure 2-6

2.4 Data Input Namelist COMMIS

The data input namelist COMMIS contains all miscellaneous inputs which define the combustor design as well as the propellant characteristics. The figures found subsequent to the COMMIS listing are as follows:

Figure 2-7	Coaxial injector definition
Figure 2-8	Combustor chamber geometry definition
Figure 2-9	Matrix for the input selection of ETYP, ICOAX, and INJCMP
Figure 2-10	Input definitions for pump-fed engine with single preburner
Figure 2-11	Input definitions for pump-fed engine with double preburners
Figure 2-12	Preburner input parameter definitions

PROGRAM SYMBOL	UNITS	VALUE	DESCRIPTION
ANGIMP	degree	0 to 180	Impingement angle of injection
CDF	-	Positive number	Discharge coefficient for fuel orifices (product of the velocity coefficient and the contraction coefficient). For more about CDF see Section 4.1
CDX	-	Positive number	Discharge coefficient for oxidizer orifices (product of velocity coefficient and the contraction coefficient). For more about CDX see Section 4.1
CPF	Btu/ lb-°F	Positive number	Specific heat of fuel (condition at injector exit)
CPX	Btu/ lb-°F	Positive number	Specific heat of oxidizer (condition at injector exit)
CHIF	-	Positive number	Compressibility of the fuel, defined as the per cent change in volume produced by a per cent change in pressure, $\mathrm{CHIF} = \frac{dv/V}{dp/P}$

PROGRAM SYMBOL	UNITS	VALUE	DESCRIPTION
CHIX	-	Positive number	Compressibility of the oxidizer, defined as the per cent change in volume produced by a per cent change in pressure $\text{CHIX} = \frac{dv/V}{dp/P}$
DFVEL	in.	Positive number	Exit diameter of the fuel orifices (determines fuel injection velocity); see Figure 2-7
DF1VEL	in.	Positive number	Inner diameter of the fuel ring (serves to compute DFVEL); see Figure 2-7
DF2VEL	in.	Positive number	Outer diameter of the fuel ring (serves to compute DFVEL); see Figure 2-7
DTHRTI	in.	Positive number	Combustion chamber throat diameter; see Figure 2-8
DXVEL	in.	Positive number	Exit diameter of the oxidizer orifices (determines oxidizer injection velocity); see Figure 2-7
DX1VEL	in.	Positive number	Inner diameter of the oxidizer ring (serves to compute DXVEL); see Figure 2-7
DX2VEL	in.	Positive number	Outer diameter of the oxidizer ring (serves to compute DXVEL); see Figure 2-7
D2	in.	Positive number	Combustion chamber diameter at the onset of the converging section; see Figures 2-8 and 2-12
ETYP	-	1,2,3, or 4	Principal element type. (Also see Figure 2-9) 1 = coaxial 2 = unlike impinging 3 = like impinging 4 = showerhead
FLINE	in.	LF	Length of the fuel supply line. In the present computer program the value for FLINE is the same as for LF
FLAREA	in^2	$\frac{DF^2 * PI}{4}$ NF	Cross sectional area of fuel supply line. In the present computer program the value for FLAREA = (DF**2 *PI/4)NF
F28TBS	radians	1.9	Phase angle due to delay in burning

PROGRAM SYMBOL	UNITS	VALUE	DESCRIPTION
ICOAX	-	0,1, or 2	Coaxial injection indicator (also see Figure 2-9): 0 = non-coaxial 1 = outer ring is fuel 2 = outer ring is oxidizer
IEQF	-	1 or 2	Fuel feed system indicator: 1 = pump-fed system (constant flow) 2 = pressure-fed system (constant pressure)
IEQX	-	1 or 2	Oxidizer feed system indicator: 1 = pump-fed system (constant flow) 2 = pressure-fed system (constant pressure)
INJCMP	-	0,1,2,3,4 or 5	Injector complexity index (see also Figure 2-9): 0 = showerhead injection with rigimesh 1 = showerhead injection (fuel and oxidizer) 2 = concentric tube injection (includes coaxial impingement) 3 = like impingement fuel (or oxidizer) with showerhead oxidizer (or fuel) 4 = unlike triplet injection 5 = pentad injection
ISTATF	-	1 or 2	Fuel state at injector exit: 1 = gas 2 = liquid
ISTATX	-	1 or 2	Oxidizer state at injector exit: 1 = gas 2 = liquid
ISTORF	-	0 or 1	Fuel hypergolic indicator: 0 = non-hypergolic 1 = hypergolic
ISTORX	--	0 or 1	Oxidizer hypergolic indicator: 0 = non-hypergolic 1 = hypergolic
LAMBDF	Btu/lb	Positive number or 0	Latent heat of vaporization of fuel (for fuel condition at injector exit). If a gas or above critical temperature, enter "0"
LAMBDX	Btu/lb	Positive number or 0	Latent heat of vaporization of oxidizer (for oxidizer condition at injector exit). If a gas or above critical temperature, enter "0"

PROGRAM SYMBOL	UNITS	VALUE	DESCRIPTION
LG50F	in.	2.75	Generalized chamber length to vaporize 50 per cent of fuel (see NASA TR R-67, Figure 28f)
LG50X	in.	2.75	Generalized chamber length to vaporize 50 per cent of oxidizer (see NASA TR R-67, Figure 28f)
LR	-	0 or 1	Liner indicator in A. D. Little correlations (NASA CR-72370): 1 = liner or absorber is present 0 = liner or absorber is not present
L1	in.	Positive number or 0	Length of cylindrical section of the combustion chamber; see Figures 2-8 and 2-12
MOLEF	lb/mole	Positive number	Molecular weight of fuel (for definition of input values see Section 7.9.19)
MOLEX	lb/mole	Positive number	Molecular weight of oxidizer (for definition of input values, see Section 7.9.19)
MUF	lb/in-sec	Positive number or 0	Viscosity of liquid or gaseous fuel (condition at injector exit). If a gas or above critical temperature, enter "0"
MUX	lb/in-sec	Positive number or 0	Viscosity of liquid or gaseous oxidizer (condition at injector exit). If a gas or above critical temperature, enter "0"
NTAUN1	-	Present value is .70	Propellant interaction index. Used for modifying PINTER in subroutine TAUN1
NTAUN3	-	Present value is .70	Propellant interaction index. Used for modifying PINTER in subroutine TAUN3
PCRITF	lb/in^2	Positive number or 1.0	Critical pressure of fuel. If a gas, PCRITF = 1.0
PCRITX	lb/in^2	Positive number or 1.0	Critical pressure of oxidizer. If a gas, PCRITX = 1.0

PROGRAM SYMBOL	UNITS	VALUE	DESCRIPTION
PTYP	-	1,2,3,4, or 5	Propellant type indicator: 1 = H2/O2 2 = RP1/LOX or JP5A/LOX 3 = N2/H4 - UDMH/N2O4 4 = Ethanol/LOX 5 = Others
RHOF	lb/in^3	Positive number	Density of fuel (condition at injector exit) NOTE: For an engine arrangement with preburners, the density of the gaseous fuel/OX mixture at main chamber entrance becomes $RHOF_{gas} = RHOF + [\frac{WXPREB}{WXPREB+WFPREB}(RHOX - RHOF)]$
RHOX	lb/in^3	Positive number	Density of oxidizer (condition at injector exit)
SIGLF	lb/in	Positive number or 0	Surface tension of fuel (condition at injector exit). If a gas or above critical temperature, enter "0"
SIGLX	lb/in	Positive number or 0	Surface tension of oxidizer (condition at injector exit). If a gas or above critical temperature, enter "0"
TCRF	°R	Positive number or 0	Critical temperature of fuel. If a gas or above critical temperature, enter "0"
TCRX	°R	Positive number or 0	Critical temperature of oxidizer. If a gas or above critical temperature, enter "0"
THRUST	lbf	Positive number or 0	Effective thrust for respective engine operating conditions. If a preburner is analyzed, enter "0"
TLOF	°R	Positive number	Droplet or gas initial temperature of fuel (condition at injector exit)
TLOX	°R	Positive number	Droplet or gas initial temperature of of oxidizer (condition at injector exit)
WFCOOL	lbm/sec	Positive number or 0	Fuel mass flow rate for cooling (separately injected into the combustion chamber upstream of the throat area). If no cooling flow exists, enter "0". See Figures 2-10 and 2-11 for definition

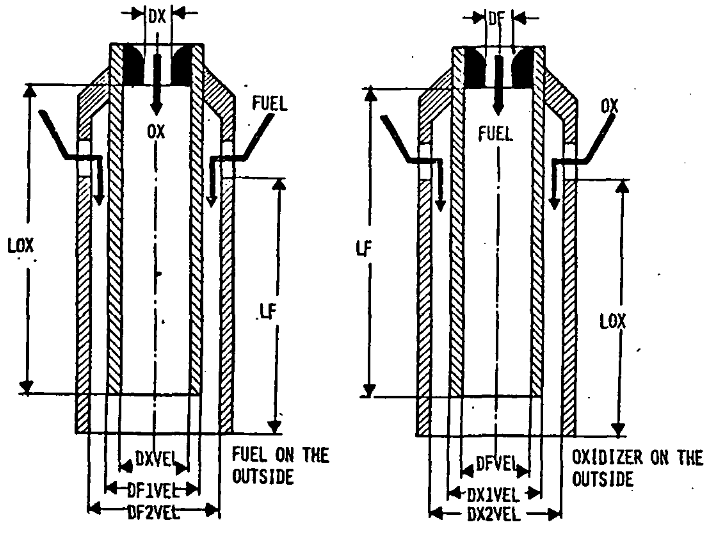


Figure 2-7. Coaxial Injector Definitions

NOTE: If a *gaseous propellant* (fuel or oxidizer) is injected through the ring shaped area, the program input consists of computing the equivalent diameter DF of a circular area. In case that the fuel is on the outside, DF becomes DFVEL. Therefore, the equivalent diameter is

$$DFVEL_{gas} = \sqrt{(DF2VEL)^2 - (DF1VEL)^2}$$

For oxidizer on the outside it becomes

$$DXVEL_{gas} = \sqrt{(DX2VEL)^2 - (DX1VEL)^2}$$

If a *liquid propellant* (fuel or oxidizer) is injected through the same ring shaped area, the program input has to provide for a good approximation of the appropriate physical conditions. It is assumed that the liquid sheet formed by the annulus can be broken up in individual quadratic flow elements of an area equal to

$$\left[\frac{(DF2VEL - DF1VEL)}{2}\right]^2 \text{ and } \left[\frac{(DX2VEL - DX1VEL)}{2}\right]^2$$

For fuel on the outside, this corresponds to an equivalent diameter of a circular area of

$$DFVEL_{liqu} = \frac{(DF2VEL - DF1VEL)}{\sqrt{\pi}}$$

and for oxidizer on the outside

$$DXVEL_{liqu} = \frac{(DX2VEL - DX1VEL)}{\sqrt{\pi}}$$

In addition, the equivalent number of injection holes has to become

$$NOF_{liqu} = \frac{TAF}{\frac{\pi * DFVEL^2}{4}} \text{ and } NOX_{liqu} = \frac{TAX}{\frac{\pi * DXVEL^2}{4}}$$

Here, the total injection areas, TAF and TAX, have to be hand-calculated. It is

$$TAF = \frac{\pi((DF2VEL)^2-(DF1VEL)^2)}{4} * \text{number of injector fuel elements}$$

and

$$TAX = \frac{\pi((DX2VEL)^2-(DX1VEL)^2)}{4} * \text{number of injector oxidizer elements}$$

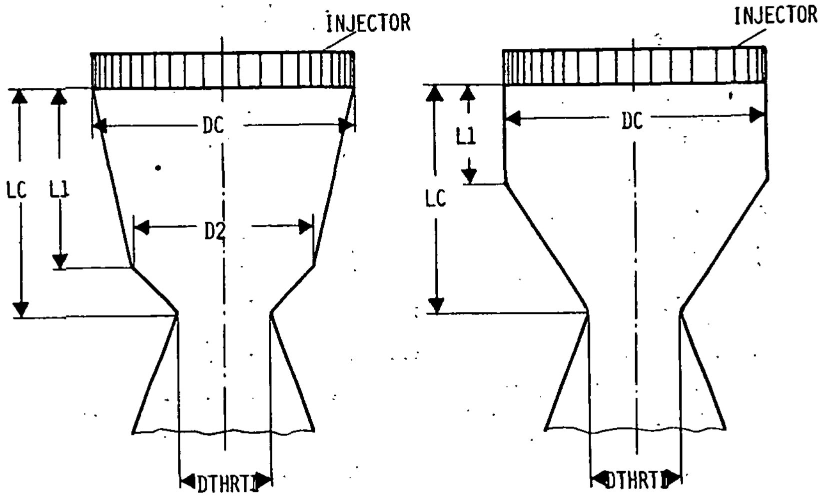


Figure 2-8. Combustion Chamber Geometry Definitions

INJCMP INJECTOR COMPLEXITY INDEX	ETYP PRINCIPAL ELEMENT TYPE			
	1 = coaxial	2 = unlike impinging	3 = like impinging	4 = shower-head
0 = showerhead injection with rigimesh	☒	☒	☒	●
1 = showerhead injection (fuel and oxidizer)	☒	☒	☒	●
2 = concentric tube injection (includes coaxial impingement)	●	☒	☒	☒
3 = like impingement fuel (or oxidizer) with showerhead oxidizer (or fuel)	☒	☒	●	☒
4 = unlike triplet injection	☒	●	☒	☒
5 = pentad injection	☒	●	☒	☒
ICOAX COAXIAL INJECTION INDICATOR	1 = outer ring is fuel 2 = outer ring is ox	0 = non-coaxial	0 = non-coaxial	0 = non-coaxial

Figure 2-9. Matrix for the Input Selection of ETYP, ICOAX, and INJCMP (crossed-out fields mean that no selection is possible)

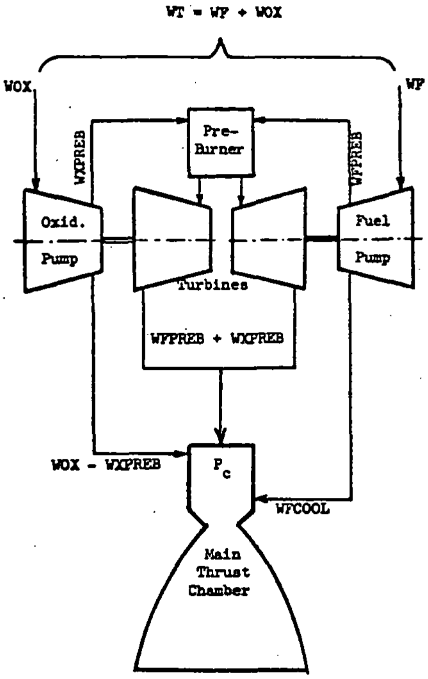


Figure 2-10. Input Definitions for Pump-Fed Engine with Single Preburner (Main thrust chamber and preburner are analyzed separately)

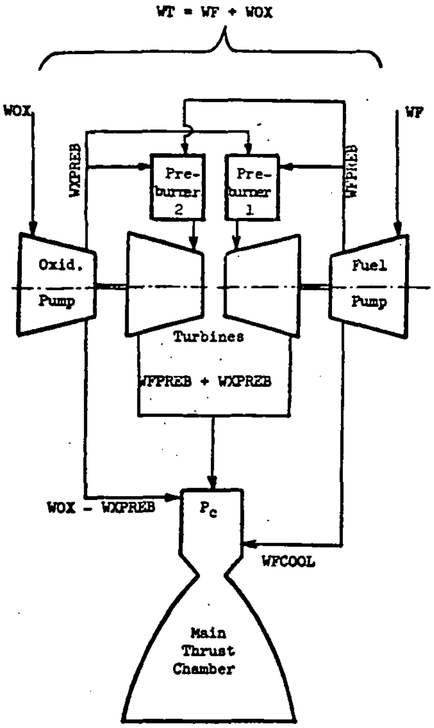


Figure 2-11. Input Definitions for Pump-Fed Engine with Double Preburners (Main thrust chamber and preburners are analyzed separately)

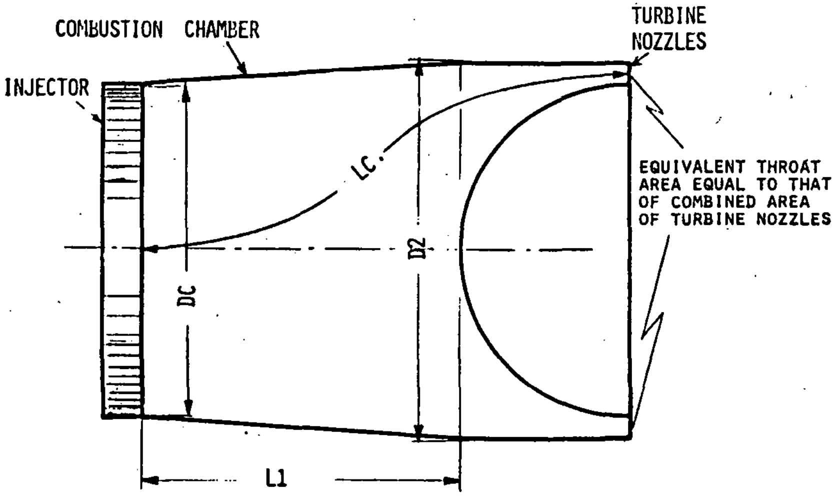


Figure 2-12. Preburner Input Parameter Definitions

PROGRAM SYMBOL	INPUT	VALUE	DESCRIPTION
WFPREB	lbm/sec	Positive number or 0	Fuel mass flow rate for preburner. If no preburner arrangement exists, enter "0". See Figures 2-10 and 2-11 for definition
WT	lbm/sec	Positive number	Total propellant mass flow rate entering the combustion chamber. See Figures 2-10 and 2-11 for definition
WXPREB	lbm/sec	Positive number or 0	Oxidizer mass flow rate for preburner. If no preburner arrangement exists, enter "0". See Figures 2-10 and 2-11 for definition
XLINE	in.	LOX	Length of oxidizer supply line. In the present computer program the value for XLINE is the same as for LOX
XLAREA	in^2	$\frac{DX^2*PI}{4}$ NOX	Cross sectional area of oxidizer supply line. In the present computer program the value for XLAREA = (DX**2*PI/4)NOX

2.5 Data Input Namelist NLROOT

Subroutines SECF20, 21, 26, 27, and 28 compute low and high frequency combustion stability modes which require the solution of complex characteristic equation roots. The root finding procedure is assisted by either nominal root guesses stored in the program code or by root guesses specified by the designer as inputs in input namelist NLROOT. Root guesses for namelist NLROOT are convenient for repetitive runs. Previously found roots are used to facilitate the searching process; i.e., to save computer time. In addition, various kinds of control statements are inputs in NLROOT.

There are three types of control statements; namely

1. general control statements
2. control statements for individual subroutines
3. control statements for root guesses

These control statements are discussed in the sections to follow.

2.5.1 General Control Statements. The general statements

ROOTS = .FALSE.

ROOTS = .TRUE.

indicate if there are any root guesses stored on tape. The general statements

IPROOT = .FALSE.

IPROOT = .TRUE.

are set true if a printout of the root table summary is desired.

2.5.2 Control Statements for Individual Subroutines. To determine if root guesses for the individual subroutines are stored in the program code (.FALSE.) or if root guesses are used in input data (.TRUE.), the respective control statements become

IGRF20 = .FALSE. (or .TRUE.)

IGRF21 = .FALSE. (or .TRUE.)

IGRF26 = .FALSE. (or .TRUE.)

IGRF27 = .FALSE. (or .TRUE.)

IGRF28 = .FALSE. (or .TRUE.)

The maximum number of roots possible to be solved is indicated as follows:

NRF20 = 20

NRF21 = 20

NRF26 = 20

NRF27 = 10

NRF28 = 10

It is at the user's discretion to select any smaller number of roots.

The maximum number of trials possible for each root is indicated as follows:

NTF20 = NRFXX * NTFXX $\leq$ 20

NTF21 = NRFXX * NTFXX $\leq$ 20

$$NTF26 = NRFXX * NTFXX \leq 20$$

$$NTF27 = NRFXX * NTFXX \leq 20$$

$$NTF28 = NRFXX * NTFXX \leq 20$$

Here, too, it is up to the judgment of the user, possibly to reduce the number of trials for a given root.

The search range for decay rate in the root finding is indicated by the statements

ALRN27 = 30

ALRN28 = 30

Other range definitions (for SECF20, 21, 26) are built in the program code and, therefore, cannot be varied.

In subroutine SECF27 the maximum number of modes of the oscillation constant, $\mathbf{s}_{\nu_h}$, is coded in the program; therefore,

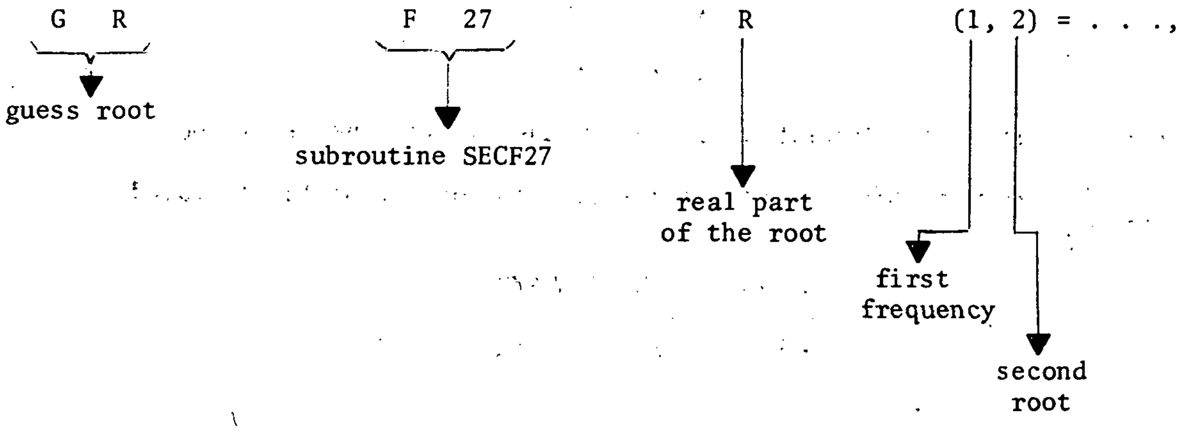
NF27 = 10

In subroutine SECF28 the maximum number of Bessel arguments, m, is coded in the program; therefore,

NB28 = 10

Note that if baffles are present the program will automatically determine NF27 and NB28.

2.5.3 Control Statements for Root Guesses. A typical root guess in data input NLROOT has the form



Corresponding

$$\underset{\substack{\big\downarrow\\ \text{imaginary part}\\ \text{of the root}}}{\text{GRF27I}}(1,\ 2) = \ldots\ldots,$$

The following Tables 2-1 to 2-4 list the root guesses for subroutines SECF20, 21, 26, 27, and 28, respectively, stored in the program code as well as the sequence for the data input namelist NLROOT.

2.6 Data Input Namelist COMIRW

During the construction of the computer program it became necessary to have the option "writing out" (IRWXX = 1) the results of a selected subroutine (DBFXX or BPAL namelist), to "read in" (IRWXX = 2) specific data; or by setting IRWXX = 0 to ignore "writing out" and "read in". Subroutines SECF11 through SECF82 can be controlled in this way as well as several other subroutines. Table 2-5 depicts the options for IRWXX contained in the program code. For more details about "writing out" and "read in" see Section 2.9.

2.7 Data Input Namelist CRVFIT

The curve fitting capability in the computer code is necessary because the four parameters

I_{sp} = specific impulse

K = specific heat ratio

M = molecular weight of exhaust gas

T_1 = temperature in combustion chamber

are, for optimization purposes, quantities as a function of the mixture ratio O/F. For point design, however, the listed parameters are fixed input values. Therefore, two possibilities for data input are considered:

1. Use of data stored in program. The input is

```
$CRVFIT
$
```

2. Use of fixed input values for point design if the relationship of the four propellant parameters as a function of O/F is not available. The input cards are then

	REAL		IMAGINARY	
	NAME IN PROGRAM	ROOT GUESS STORED IN PROGRAM	NAME IN PROGRAM	ROOT GUESS STORED IN PROGRAM*
Subroutine SECF20 (Fuel)	GRF20R(1)	-1.0	GRF20I(1)	0.0
	GRF20R(2)	-1.0	GRF20I(2)	$-\pi/\overline{\tau}$
	GRF20R(3)	-1.0	GRF20I(3)	$\pi/\overline{\tau}$
	GRF20R(4)	-1.0	GRF20I(4)	ω
	GRF20R(5)	-1.0	GRF20I(5)	-ω
Subroutine SECF21 (Oxidizer)	GRF21R(11)	-1.0	GRF21I(11)	0.0
	GRF21R(12)	-1.0	GRF21I(12)	$-\pi/\overline{\tau}$
	GRF21R(13)	-1.0	GRF21I(13)	$\pi/\overline{\tau}$
	GRF21R(14)	-1.0	GRF21I(14)	ω
	GRF21R(15)	-1.0	GRF21I(15)	-ω
Subroutine SECF26 (Fuel)	GRF26R(1)	-0.0101	GRF26I(1)	PIFAC
	GRF26R(2)	-0.0101	GRF26I(2)	-PIFAC
	GRF26R(3)	-0.0101	GRF26I(3)	PIFAC
	GRF26R(4)	-0.0101	GRF26I(4)	-PIFAC
Subroutine SECF26 (Oxidizer)	GRF26R(11)	0.0101	GRF26I(11)	PIFAC
	GRF26R(12)	0.0101	GRF26I(12)	-PIFAC
	GRF26R(13)	0.0101	GRF26I(13)	PIFAC
	GRF26R(14)	0.0101	GRF26I(14)	-PIFAC

*$\overline{\tau}$= TAU/Θg; ω=0.001;
PIFAC=π*FAC, FAC=0.25;

TABLE 2-1. Root Guesses for Subroutines SECF20, SECF21, and SECF26

			REAL		IMAGINARY	
	FREQUENCY MODE	Mode of Oscillation Constant (S_{vh})	Name in Program	Root Guess Stored in Program	Name in Program	Root Guess Stored in Program *
FUEL	FIRST TANGENTIAL	$S_{vh}(1)=$ 1.84129	GRF27R(1,1) to GRF27R(1,4)	-0.0101	GRF27I(1,1) to GRF27I(1,4)	±π/τ $\pm S_{vh(1)}$
	SECOND TANGENTIAL	$S_{vh}(2)=$ 3.0543	GRF27R(2,1) to GRF27R(2,4)	-0.0101	GRF27I(2,1) to GRF27I(2,4)	±π/τ $\pm S_{vh(2)}$
	FIRST RADIAL	$S_{vh}(3)=$ 3.8317	GRF27R(3,1) to GRF27R(3,4)	0.0101	GRF27I(3,1) to GRF27I(3,4)	±π/τ $\pm S_{vh(3)}$
	SECOND RADIAL	$S_{vh}(4)=$ 7.0156	GRF27R(4,1) to GRF27R(4,4)	0.0101	GRF27I(4,1) to GRF27I(4,4)	±π/τ $\pm S_{vh(4)}$
	COMBINED MODES	$S_{vh}(5)=$ 5.3313	GRF27R(5,1) to GRF27R(5,4)	0.0101	GRF27I(5,1) to GRF27I(5,4)	±π/τ $\pm S_{vh(5)}$
		$S_{vh(6)}=$ 8.5263	GRF27R(6,1) to GRF27R(6,4)	0.0101	GRF27I(6,1) to GRF27I(6,4)	±π/τ $\pm S_{vh(6)}$
		$S_{vh}(7)=$ 6.7060	GRF27R(7,1) to GRF27R(7,4)	0.0101	GRF27I(7,1) to GRF27I(7,4)	±π/τ $\pm S_{vh(7)}$
OXIDIZER	FIRST TANGENTIAL	$S_{vh}(1)=$ 1.84129	GRF27R(1,11) to GRF27R(1,14)	0.0101	GRF27I(1,11) to GRF27I(1,14)	±π/τ $\pm S_{vh(1)}$
	SECOND TANGENTIAL	$S_{vh}(2)=$ 3.0543	GRF27R(1,11) to GRF27R(2,14)	0.0101	GRF27I(2,11) to GRF27I(2,14)	±π/τ $\pm S_{vh(2)}$
	FIRST RADIAL	$S_{vh}(3)=$ 3.8317	GRF27R(3,11) to GRF27R(3,14)	0.0101	GRF27I(3,11) to GRF27I(3,14)	±π/τ $\pm S_{vh(3)}$
	SECOND RADIAL	$S_{vh}(4)=$ 7.0156	GRF27R(4,11) GRF27R(4,14)	0.0101	GRF27I(4,11) to GRF27I(4,14)	±π/τ $\pm S_{vh(4)}$
	COMBINED MODES	$S_{vh}(5)=$ 5.331	GRF27R(5,11) to GRF27R(5,14)	0.0101	GRF27I(5,11) to GRF27I(5,14)	±π/τ $\pm S_{vh(5)}$
		$S_{vh(6)}=$ 8.5263	GRF27R(6,11) to GRF27R(6,14)	0.0101	GRF27I(6,11) to GRF27I(6,14)	±π/τ $\pm S_{vh(6)}$
		$S_{vh(7)}=$ 6.7070	GRF27R(7,11) to GRF27R(7,14)	0.0101	GRF27I(7,11) to GRF27I(7,14)	±π/τ $\pm S_{vh(7)}$

* τ = TAUN1, TAUN2, or TAUN3

TABLE 2-2. Root Guesses for Subroutine SECF27

			REAL		IMAGINARY	
	FREQ. MODE	Bessel Argument (ω)	Name in Program	Root Guess Stored in Program*	Name in Program	Root Guess Stored in Program**
FUEL	FIRST TRANSVERSE	ω_1 = 1.8412	GRF28R(1,1) to GRF28R(1,4)	$R_{1,1}$ ⋮ $R_{1,10}$	GRF28I(1,1) to GRF28I(1,4)	$\pm(\omega_1)$ $\pm(\omega_1+\Delta\omega_1)$ $\pm(\omega_1+2\Delta\omega_1)$ $\pm(\omega_1+3\Delta\omega_1)$ $\pm(\omega_1+4\Delta\omega_1)$
	SECOND TRANSVERSE	ω_2 = 3.0543	GRF28R(2,1) to GRF28R(2,4)	$R_{2,1}$ ⋮ $R_{2,10}$	GRF28I(2,1) to GRF28I(2,4)	$\pm(\omega_2)$ $\pm(\omega_2+\Delta\omega_2)$ $\pm(\omega_2+2\Delta\omega_2)$ $\pm(\omega_2+3\Delta\omega_2)$ $\pm(\omega_2+4\Delta\omega_2)$
	THIRD TRANSVERSE	ω_3 = 4.2012	GRF28R(3,1) to GRF28R(3,4)	$R_{3,1}$ ⋮ $R_{3,10}$	GRF28I(3,1) to GRF28I(3,4)	$\pm(\omega_3)$ $\pm(\omega_3+\Delta\omega_3)$ $\pm(\omega_3+2\Delta\omega_3)$ $\pm(\omega_3+3\Delta\omega_3)$ $\pm(\omega_3+4\Delta\omega_3)$
	FIRST RADIAL	ω_4 = 3.8317	GRF28R(4,1) to GRF28R(4,4)	$R_{4,1}$ ⋮ $R_{4,10}$	GRF28I(4,1) to GRF28I(4,4)	$\pm(\omega_4)$ $\pm(\omega_4+\Delta\omega_4)$ $\pm(\omega_4+2\Delta\omega_4)$ $\pm(\omega_4+3\Delta\omega_4)$ $\pm(\omega_4+4\Delta\omega_4)$
	LONGITUDINAL	ω_5 = 0.0	GRF28R(5,1) to GRF28R(5,4)	$R_{5,1}$ ⋮ $R_{5,10}$	GRF28I(5,1) to GRF28I(5,4)	$\pm(\omega_5)$ $\pm(\omega_5+\Delta\omega_5)$ $\pm(\omega_5+2\Delta\omega_5)$ $\pm(\omega_5+3\Delta\omega_5)$ $\pm(\omega_5+4\Delta\omega_5)$
OXIDIZER	FIRST TRANSVERSE	ω_1 = 1.8412	GRF28R(1,11) to GRF28R(1,14)	$R_{1,1}$ ⋮ $R_{1,10}$	GRF28I(1,11) to GRF28I(1,14)	$\pm(\omega_1)$ $\pm(\omega_1+\Delta\omega_1)$ $\pm(\omega_1+2\Delta\omega_1)$ $\pm(\omega_1+3\Delta\omega_1)$ $\pm(\omega_1+4\Delta\omega_1)$
	SECOND TRANSVERSE	ω_2 = 3.0543	GRF28R(2,11) to GRF28R(2,14)	$R_{2,1}$ ⋮ $R_{2,10}$	GRF28I(2,11) to GRF28I(2,14)	$\pm(\omega_2)$ $\pm(\omega_2+\Delta\omega_2)$ $\pm(\omega_2+2\Delta\omega_2)$ $\pm(\omega_2+3\Delta\omega_2)$ $\pm(\omega_2+4\Delta\omega_2)$
	THIRD TRANSVERSE	ω_3 = 4.2012	GRF28R(3,11) to GRF28R(3,14)	$R_{3,1}$ ⋮ $R_{3,10}$	GRF28I(3,11) to GRF28I(3,14)	$\pm(\omega_3)$ $\pm(\omega_3+\Delta\omega_3)$ $\pm(\omega_3+2\Delta\omega_3)$ $\pm(\omega_3+3\Delta\omega_3)$ $\pm(\omega_3+4\Delta\omega_3)$
	FIRST RADIAL	ω_4 = 3.8317	GRF28R(4,11) to GRF28R(4,14)	$R_{4,1}$ ⋮ $R_{4,10}$	GRF28I(4,11) to GRF28I(4,14)	$\pm(\omega_4)$ $\pm(\omega_4+\Delta\omega_4)$ $\pm(\omega_4+2\Delta\omega_4)$ $\pm(\omega_4+3\Delta\omega_4)$ $\pm(\omega_4+4\Delta\omega_4)$
	LONGITUDINAL	ω_5 = 0.0	GRF28R(5,11) to GRF28R(5,14)	$R_{5,1}$ ⋮ $R_{5,10}$	GRF28I(5,11) to GRF28I(5,14)	$\pm(\omega_5)$ $\pm(\omega_5+\Delta\omega_5)$ $\pm(\omega_5+2\Delta\omega_5)$ $\pm(\omega_5+3\Delta\omega_5)$ $\pm(\omega_5+4\Delta\omega_5)$

* R_{ij} = random number between 0 and -0.001
** $\Delta\omega = \omega_i/2\pi$

TABLE 2-3. Root Guesses for Subroutine SECF28

```
$NLROOT
     ROOTS=.TRUE.,
     ROOTS=.FALSE.,
     IPROOT=.TRUE.,
     NRF20=3,NTF20=3,NRF21=3,NTF21=3,
     NRF26=5,NTF26=5,
     NRF26=3,NTF26=3,
     NRF28=2,NTF28=2,
     NF27=7, NR28=5,
     NRF27=3,NTF27=3,
     IGRF20=.FALSE.,
     IGRF20=.TRUE.,
     IGRF21=.FALSE.,
     IGRF21=.TRUE.,
     IGRF26=.FALSE.,
     IGRF26=.TRUE.,
     IGRF27=.TRUE.,
     IGRF27=.FALSE.,
     IGRF28=.FALSE.,
     IGRF28=.TRUE.,
     ALRN28=10.0, ALRN27=15.0,
     ALRN28=10.0, ALRN27=100.0,
GRF20R(1) = .16369, .16399,
GRF20I(1) = -.43481, .43481,
GRF21R(1) = 2.026219E-02, 2.026219E-02, -.850782,
GRF21I(1) = .833296, -.833296, 2.48576,
GRF26R(1) = -.37924,
GRF26I(1) = -7.83507E-08,
GRF26R(2) = -.33717,
GRF26I(2) = 3.2757,
GRF26R(3) = -.37969,
GRF26I(3) = 1.27032E-07,
GRF26R(4) = -.33456,
GRF26I(4) = 3.2786,
GRF26R(11) = -.37924,
GRF26I(11) = -7.83507E-08,
GRF26R(12) = -.33717,
GRF26I(12) = 3.2757,
GRF26R(13) = -.37969,
GRF26I(13) = 1.27032E-07,
GRF26R(14) = -.33456,
GRF26I(14) = 3.2786,
GRF28R(1,1) = 1.61195,
GRF28I(1,1) = -.145074,
GRF28R(1,2) = -1.61195,
GRF28I(1,2) = -.145074,
GRF28R(2,1) = 2.66034,
GRF28I(2,1) = -.229889,
GRF28R(2,2) = -2.66034,
GRF28I(2,2) = -.229889,
GRF28R(3,1) = 3.66597,
GRF28I(3,1) = -.43242,
GRF28R(3,2) = -3.66597,
GRF28I(3,2) = -.43242,
GRF28R(4,1) = 3.33687,
GRF28I(4,1) = -.34992,
GRF28R(4,2) = -3.33687,
GRF28I(4,2) = -.34992,
GRF28R(5,1) = 6.783433E-02,
GRF28I(5,1) = -6.872498E-02,
GRF28R(5,2) = -6.783433E-02,
GRF28I(5,2) = -6.872498E-02,
$
```

TABLE 2-4. Sample for Control Cards for Data Input Namelist NLROOT

IRWXX OPTIONS	SUBROUTINE NAME	NAMELIST NAME
IRWACW = 0, 1	ACWAVE	DBACW
IRWFLO = 0, 1	FLORES	DBFLO
IRWFRP = 0, 1, 2	FRPROP	DBFRP
IRWL50 = 0, 1	LFIFTY	DBL50
IRWNLS = 0, 1, 2	NLSTAB	DBNLS
IRWPAL = 0, 1	POSTAL	BPAL
IRWTAU = 0, 1	TAUN	DBTAU
IRWVAP = 0, 1, 2	VAPRIZ	DBVAP
IRW11 = 0, 1, 2	SECF11	DBF11
↓	↓	↓
IRW82 = 0, 1, 2	SECF82	DBF82

TABLE 2-5. Options for IRWXX Control Switch Contained in the Program Code

```
$CRVFIT
NPISP=0
NPK=0,
NPMOLW=0,
NPT1=0
PCISP(1)=. . .,
PCK(1) = . . .,
PCMOLW(1)=. . .,
PCT1(1)=. . .,
$
```

The program symbols are described in the list at the end of Section 2.7.

2.7.1 How to Store New Propellant Data. If optimization runs have to be performed, the relationship of the four quantities of I_{sp}, k, M, and T_1 as function of the mixture ratio O/F has to be stored in the program. For this purpose, subprogram FITCRV uses four pertinent propellant polynomial expressions. The independent variable of these polynomial functions is the mixture ratio O/F. (For more details see Section 6.6.3). The polynomial coefficients must be supplied by the designer either directly or indirectly by specification of the curves in tabular form. For a new propellant combination, the sample data deck is as follows:

```
$CRVFIT
 XFIT=OF1, OF2 . . . OFNPTS
 YFIT=ISP1, ISP2 . . . ISPNPTS
 NPTS=10,
 KPOLY=2,
 KIND=1,
 ICRVFT=1,
 LOOP=.TRUE.
$
$CRVFIT
 XFIT=OF1, OF2 . . . OFNPTS
 YFIT=K1, K2 . . . KNPTS
 NPTS=10,
 KPOLY=2,
 KIND=1,
 ICRVFT=2,
 LOOP=.TRUE.
$
$CRVFIT
 XFIT=OF1, OF2 . . . OFNPTS
 YFIT=M1, M2 . . . MNPTS
 NPTS=10,
 KPOLY=2,
 KIND=1,
 ICRVFT=3,
 LOOP = .TRUE.
$
```

Continued

```
$CRVFIT
 XFIT=OF1,OF2..... OFNPTS
 YFIT=T11,T12..... T1NPTS
 NPTS=10,
 KPOLY=2,
 KIND=1,
 ICRVFT=4,
 LOOP=.FALSE.
$
```

PROGRAM SYMBOL	DESCRIPTION
ICRVFT	=1, fit I_{sp} to O/F; =2, fit k to O/F; =3, fit M to O/F; =4, fit T1 to O/F
IOUT	Output polynomial values at input points
IPNAML	Causes to print out the namelist
JPOLY	Number of leading polynomial zero coefficients
KIND	Kind of fit: = 1 for LINX, LINY = 2 for LOXG, LINY = 3 for LINX, LOGY = 4 for LOGX, LOGY
KPOLY	Degree of approximating polynomial
LOOP	Logical variable indicating to loop back for the next case
LWGHT	Weight switch: = 0 for WEIGHT(I) = 1.0 = 1 for WEIGHT(I) = DATA
NPISP	Polynomial degree of the specific impulse, I_{sp}, as a function of the mixture ratio O/F
NPK	Polynomial degree of the specific heat ratio, k, as a function of the mixture ratio O/F
NPMOLW	Polynomial degree of the molecular weight of the combustion gas, M, as a function of the mixture ratio O/F
NPTS	Number of points on original curve
NPT1	Polynomial degree of the combustion temperature, T1, as a function of the mixture ratio O/F

(continued)

PROGRAM SYMBOL	DESCRIPTION
PCISP	Input polynomial coefficient for specific impulse, I_{sp}
PCK	Input polynomial coefficient for specific heat ratio, k
PCMOLW	Input polynomial coefficient for the molecular weight of the combustion gas, M
PCT1	Input polynomial coefficient for combustion temperature, T1
WEIGHT	Weighting matrix to be applied to the raw data
XFIT	X values
YFIT	Y values

2.8 Data Input Namelist IAESOP

In the present program code there are 14 design variables which are input data in namelist COMDPV. They are set in subroutine CMBDPV in the following sequence:

DF = ALPHA(1)
DX = " (2)
NF = " (3)
NOX = " (4)
VOLF = " (5)
VOLX = " (6)
LF = " (7)
LOX = " (8)
(available) = " (9)
LC = " (10)
DC = " (11)
OF = " (12)
BFLRAD = " (13)
BFLCIR = " (14)

For a deck setup, the boundaries (low and high) for these variables have to be determined and are inputs in IAESOP in the following manner:

ALPHA(1) = ..., ..., ..., ..., → (14)
ALPLO(1) = ..., ..., ..., ..., → (14)
ALPHI(1) = ..., ..., ..., ..., → (14)

In addition, the number of iterations for the optimization loop has to be an input such as

MAXJJJ = 10

for ten iterations or in case of a point design

MAXJJJ = 0

Table 2-6 depicts an input sample for IAESOP. A description of the program symbols is given in the following list. More details about the optimization program AESOP and its application are presented in Appendix B.

```
$IAESOP
     NALPHA=14,
     NFUNC = 15,
     IREPET=20,
     LUFIN=2, ITFIN=0,
     NUMOPT=2, METHOP(1)=10,2,
     MAXRRS=5,
     MAXRRS=4,
     IPGAIN=1,
     IPSRCH=1, IPACYC=1, IPFCYC=1,
MAXJJJ = 1,
MAXJJJ = 2,
MAXJJJ = 0,
ALPLO(1)= .020, .020, 100., 100., 100000., 100000., .050, .050,
ALPLO(9)= 0 ., 10., 70., 2.398, 7., 1.,
ALPHA(1)= .195, .242, 2000., 2000., 100000., 100000., 2.0, 5.0,
ALPHA(9)= 0 ., 50., 94., 2.398, 7., 1.,
ALPHI(1)= .50, 1.0, 10.0E+06, 10.0E+06, 100000., 100000., 12., 18.,
ALPHI(9)= 0 ., 150., 140., 2.398, 7., 1.,
$
```

TABLE 2-6. Input Sample for IAESOP

PROGRAM SYMBOL	DESCRIPTION
$ALPHA_i$	The nominal parameter values
$ALPHI_i$	Upper bounds on each parameter search range
$ALPLO_i$	Lower bounds on each parameter search range
IPACYC	Will cause print out of the control parameter values at the end of each optimization cycle
IPFCYC	Will cause print out of the function values at the end of each optimization cycle

(continued)

PROGRAM SYMBOL	DESCRIPTION
IPGAIN	Will cause print out of the function and control parameter values after each evaluation in which there was a gain in performance
IPSRCH	Will cause print out of the function and control parameter values at the end of each search
IREPET	The maximum number of times the search sequence (optimization cycle) defined in METHOP_i will be utilized
ITFIN	Controls content of final summary report
LUFIN	Tape or disk unit used to store the convergence histories of the function and control parameter values for tabular listing at the end of the optimization process
MAXJJJ	The maximum number of iterations
MAXRRS	The maximum number of random rays, one or two sided, investigated each time the optimization cycle requests a random ray search
METHOP_i	The search sequence by numeric identification
NALPHA	The number of parameters available for optimization
NFUNC	The total number of functions being defined and computed in the system model
NUMOPT	The number of optimization techniques to be employed

2.9 Data Input Namelist for Characteristic Data

The use of the data input namelist for characteristic data allows the designer to treat several program modules essentially in an independent fashion. By this it is possible to investigate the influence of selected parameters on the results of the respective module. Section 2.6 described the method for using the control switch for "reading in" characteristic data by setting IRWXX = 2. By doing this the data can be read in as follows:

```
$
DBXX
 .
 .
 .
$
```

A list of each DBXX namelist available in the program with a description of the namelist variables follows:

NAMELIST NAME	CONTROL SWITCH FOR READ AND PRINT :IRWXXX	SUBROUTINE NAME	NAMELIST VARIABLES	DESCRIPTION
DBFRP	IRWFRP	FRPROP	C	= RHO/SPHTH2*VIDOME/W
			CN	= (PCI/DELTP-1/SPHTH2)*(DELTP/PD)*C*S
			CP	Specific heat of liquid propellant; see Section 7.2.6
			CS	Speed of sound in combustion chamber; see Section 7.9
			CTBS	Complex TAUBS
			DC	Diameter of combustion chamber; see Section 2.3
			DELTP	Pressure drop in injector; see Section 7.9
			EP1TVS	Scale factor on TAUVS
			EP2TVS	Add on constant for TAUVS
			FACTR	CP/LAMBDA*TL/VPCPAR*TAUVS/TEMCOE
			FR	Flow response of the propellant FR=FR1+FR2; see Section 7.2.6
			FR1	CN/(1+2*DELTP/PD*C*S+CN*IFAC*S)
			FR2	CEXP(-CTBS)
			GREF	Gravitational constant
			IFAC	W*(LINJ/TA)/(GREF*12*PD)
			ISTAT	Fuel or oxidizer state at injector exit; see Section 2.4
			LAMBDA	Latent heat of vaporization for fuel or oxidizer; see Section 2.4

(continued)

NAMELIST NAME	CONTROL SWITCH FOR READ AND PRINT: IRWXXX	SUBROUTINE NAME	NAMELIST VARIABLES	DESCRIPTION
DBFRP	IRWFRP	FRPROP	LINJ	Length of the injection holes
			LOOP	Logical variable; see Section 2.7.1
			L50	Length of combustion chamber to vaporize 50 per cent of fuel or oxidizer; see Section 7.2.1
			OMEGA	Angular frequency of oscillations; see Section 7.2.6
			OMEGI	Imaginary part of complex OMEGA
			OMEGR	Real part of complex OMEGA
			PCI	Combustion chamber pressure; see Section 7.9
			PD	= PCI + DELTP
			RHO	Density of fuel or oxidizer; see Section 2.4
			S	Laplace operator
			SPHEAT	Specific heat ratio of combustion gas; see Section 2.4
			SPHTH2	Specific heat ratio of hydrogen; see Section 2.4
			TA	Total area of the injection holes; see Section 7.9
			TAUBS	Phase angle due to delay in burning; see Section 7.2.6
			TAUV	Mean drop life time; see Section 7.2.6
			TAUVS	Complex TAUV
			TEMCOE	Vapor pressure/liquid temperature coefficient; see Section 7.2.6

(continued)

NAMELIST NAME	CONTROL SWITCH FOR READ AND PRINT:IRWXXX	SUBROUTINE NAME	NAMELIST VARIABLES	DESCRIPTION
DBFRP	IRWFRP	FRPROP	TL	Temperature of liquid propellant
↓	↓	↓	VIDOME	Injector dome volume; see Section 7.2.6, Equation(11-53)
↓	↓	↓	VINJ	Fuel or oxidizer injection velocity; see Section 7.9
↓	↓	↓	VPCPAR	Vapor pressure-combustion chamber pressure parameter; see Section 7.2.6
↓	↓	↓	W	Flow rate through injector; see Section 7.2.6, Equation(11-53)
DBF11	IRW11	SECF11	AF11	Weighting factor constant for fuel vapoization; see Section 2.2
↓	↓	↓	F11	Per cent fuel mass vaporized; see Section 7.1.1
DBF12	IRW12	SECF12	F12	Weighting factor constant for oxidizer vaporizaiton; see Section 2.2
↓	↓	↓	AF12	Per cent oxidizer mass vaporized; see Section 7.1.1
DBF13	IRW13	SECF13	AF13	Weighting factor constant for C*-efficiency; See Section 2.2
↓	↓	↓	F13	C*-efficiency in per cent; see Section 7.1.2
DBF20	IRW20	SECF20	AF20	Weighting factor constant for the fuel side chugging; see Section 2.2
↓	↓	↓	DELPF	Injector pressure drop for fuel; see Section 7.9
↓	↓	↓	EFUEL	Elasticity parameter for fuel; see Section 7.2.1

(continued)

NAMELIST NAME	CONTROL SWITCH FOR READ AND PRINT:IRWXXX	SUBROUTINE NAME	NAMELIST VARIABLES	DESCRIPTION
DBF20	IRW20	SECF20	F20	Chugging decay rate for fuel; see Section 7.2.1
			IEQF	Fuel feed system indicator; see Section 2.4
			JFUEL	Inertia parameter for fuel; see Section 7.2.1
			LOOP	Logical variable; see Section 2.7.1
			L5FUEL	Length of combustion chamber to vaporize 50 per cent of fuel; see Section 7.2.1
			NFUEL	Pressure index of interaction; see Section 7.2.1
			PFACTR	Factor (=1.0) for pressure drop parameter; see Section 7.2.1, Equation(7-10)
			PFUEL	Pressure drop parameter for fuel; see Section 7.2.1
			TAU	Time lag; for definition see Equation(7-12)
			TAUBAR	Sensitive time lag: TAU/THETAG; see Section 7.2.1
			THETAG	Gas residence time; see Section 7.9
			VFUEL	Fuel injection velocity; see Section 7.2.1
DBF21	IRW21	SECF21	AF21	Weighting factor constant for the oxidizer side chugging; see Section 2.2
			DELPX	Injector pressure drop for oxidizer; see Section 7.9

(continued)

NAMELIST NAME	CONTROL SWITCH FOR READ AND PRINT:IRWXXX	SUBROUTINE NAME	NAMELIST VARIABLES	DESCRIPTION
DBF21	IRW21	SECF21	EOXID	Elasticity parameter for oxidizer; see Section 7.2.1
			F21	Chugging decay rate for oxidizer; see Section 7.2.1
			IEQX	Oxidizer feed system indicator; see Section 2.4
			JFUEL	Inertia parameter for oxidizer; see Section 7.2.1
			LOOP	Logical variable; see Section 2.7.1
			L50XID	Length of combustion chamber to vaporize 50 per cent of oxidizer; see Section 7.2.1
			NOXID	Pressure index of interaction; see Section 7.2.1
			NREPET	NOT USED
			PFACTR	Factor (=1.0) for pressure drop parameter; see Section 7.2.1, Equation(7-10)
			POXID	Pressure drop parameter for oxidizer; see Section 7.2.1
			TAU	Time lag. For definition see Equation(7-13)
			TAUBAR	Sensitive time lag: TAU/THETAG; see Section 7.2.1
			THETAG	Gas residence time; see Section 7.9
			VOXID	Oxidizer injection velocity; see Section 7.2.1

(continued)

NAMELIST NAME	CONTROL SWITCH FOR READ AND PRINT: IRWXXX	SUBROUTINE NAME	NAMELIST VARIABLES	DESCRIPTION
DBF22	IRW22	SECF22	AF22	Weighting factor constant for pulsed operation; see Section 2.2
			BF	Baffle parameter; see Section 7.2.2
			FO2	Propellant combination parameter; see Section 7.2.2
			F22	Stability characteristic for pulsed operation; see Section 7.2.2
			LD	Chamber length to diameter ratio; see Section 7.2.2
			LDF	Fuel orifice length to diameter ratio; see Section 7.2.2
			LDOF	Log of fuel orifice exit diameter; see Section 7.2.2
			LR	Liner parameter; see Section 7.2.2
			PE1	Principal element type 1; see Section 7.2.2
			PE2	Principal element type 2; see Section 7.2.2
			SP10	Magnitude of induced, undamped, high or intermediate frequency oscillations; see Section 7.2.2
			TPVM	Thrust per unit chamber volume; see Section 7.2.2
			VO	Oxidizer injection velocity; see Section 7.2.2

(continued)

NAMELIST NAME	CONTROL SWITCH FOR READ AND PRINT:IRWXXX	SUBROUTINE NAME	NAMELIST VARIABLES	DESCRIPTION
DBF23	IRW23	SECF23	AF23	Weighting factor constant for non-pulsed operation; see Section 2.2
			BF	Baffle parameter; see Section 7.2.2
			EPA	Number of injector elements per unit area of injector face; see Section 7.2.2
			FO2	Propellant combination parameter 2; see Section 7.2.2
			FO3	Propellant combination parameter 3; see Section 7.2.2
			F23	Stability characteristic for non-pulsed operation; see Section 7.2.2
			IDEF	Fuel injection distribution eccentricity; see Section 7.2.2
			LC	Combustion chamber length; see Section 2.2
			LD	Chamber length to diameter ratio; see Section 7.2.2
			LDF	Fuel orifice length to diameter ratio; see Section 7.2.2
			LDOF	Log of fuel orifice exit diameter; see Section 7.2.2
			LIDF	Log of fuel injection distribution; see Section 7.2.2
			LR	Liner parameter; see Section 7.2.2
			LRC	Log of chamber contraction ratio; see Section 7.2.2

(continued)

NAMELIST NAME	CONTROL SWITCH FOR READ AND PRINT:IRWXXX	SUBROUTINE NAME	NAMELIST VARIABLES	DESCRIPTION
DBF23	IRW23	SECF23	MPE	Propellant mass flow rate per injector element; see Section 7.2.2
			PCI	Combustion chamber pressure; see Section 7.9
			PE1	Principal element type 1; see Section 7.2.2
			PE2	Principal element type 2; see Section 7.2.2
			SP1A	Magnitude of spontaneous high and intermediate frequency oscillations; see Section 7.2.2
			TPVM	Thrust per unit chamber volume; see Section 7.2.2
			VO	Oxidizer injection velocity; see Section 7.2.2
DBF24	IRW24	SECF24	AF24	Weighting factor constant for the fuel stability decay rate; see Section 2.2
			F24	Decay rate for fuel side; see Section 7.2.3
DBF25	IRW25	SECF25	AF25	Weighting factor constant for the oxidizer stability decay rate; see Section 2.2
			F25	Decay rate for oxidizer side; see Section 7.2.3

(continued)

NAMELIST NAME	CONTROL SWITCH FOR READ AND PRINT:IRWXXX	SUBROUTINE NAME	NAMELIST VARIABLES	DESCRIPTION
DBF26	IRW26	SECF26	AF26	Weighting factor constant for longitudinal modes; see Section 7.2.4
			CS	Speed of sound in combustion gas; see Section 7.2.4
			DC	Diameter of combustion chamber; see Section 2.2
			EPSG1	Scaling factor for specific heat ratio SPHEAT
			EPSG2	Add-on constant for specific heat ratio SPHEAT
			EPSM1	Scaling factor for the Mach number MC
			EPSM2	Add-on constant for the Mach number MC
			EPSN1	Scaling factor for the propellant interaction index NFUEL or NOXID
			EPSN2	Add-on constant for the propellant interaction index NFUEL or NOXID
			EPST1	Scaling factor for the time delay TAU
			EPST2	Add-on constant for the time delay TAU
			F26	Decay rate for longitudinal modes; see Section 7.2.4
			IDB26	If .TRUE., causes print-out of additional detailed informations from SECF26
			LC	Length of combustion chamber; see Section 2.2
			LDUM	Acoustical length of combustion chamber; see Section 7.2.3.1

(continued)

NAMELIST NAME	CONTROL SWITCH FOR READ AND PRINT:IRWXXX	SUBROUTINE NAME	NAMELIST VARIABLES	DESCRIPTION
DBF26	IRW26	SECF26	LOOP	Logical variable; see Section 2.7.1
			MC	Mach number in combustion chamber; see Section 7.9
			NFUEL	Interaction index for fuel; see Section 7.2.4
			NOXID	Interaction index for oxidizer; see Section 7.2.4
			NR	Number of roots to be solved; see Section 2.5
			NTRY	Number of trials for root solving procedure; see Section 2.5
			PINTER	Interaction index of propellants; see Section 7.2.4
			RF26I	Imaginary part of the root
			RF26R	Real part of the root
			SPHEAT	Specific heat ratio of combustion gas
			TAU	Time lag; see Section 7.2.4
			TAUBAR	Sensitive time lag; for definition see Section 7.2.4, Equation(7-30)
DBF27	IRW27	SECF27	AF27	Weighting factor constant for transverse modes; see Section 2.2
			ALTMAP	AESOP variable; see Appendix B
			DC	Diameter of combustion chamber; see Section 2.2

(continued)

NAMELIST NAME	CONTROL SWITCH FOR READ AND PRINT:IRWXXX	SUBROUTINE NAME	NAMELIST VARIABLES	DESCRIPTION
DBF27	IRW27	SECF27	EPSG1	Scaling factor for specific heat ratio SPHEAT
↓	↓	↓	EPSG2	Add-on constant for specific heat ratio SPHEAT
			EPSM1	Scaling factor for the Mach number MC
			EPSM2	Add-on constant for the Mach number MC
			EPSN1	Scaling factor for the propellant interaction index NFUEL or NOXID
			EPSN2	Add-on constant for the propellant interaction index NFUEL or NOXID
			EPST1	Scaling factor for time delay TAU
			EPST2	Add-on constant for the time delay TAU
			F27	Stability decay rate for transverse modes of high frequency oscillations; see Section 7.2.5
			IDB27	Print control parameter. If IDB27=.TRUE., initializes debugging printout
			IPDMAP	AESOP variable; see Appendix B
			ISNSAV	Number of SNUH saved
			LC	Combustion chamber length; see Section 2.2
			LOOP	Logical variable; see Section 2.7.1
			LUFIN	AESOP variable; see Appendix B
			LUMAP	AESOP variable; see Appendix B
			MC	Mach number in combustion chamber; see section 7.9

(continued)

NAMELIST NAME	CONTROL SWITCH FOR READ AND PRINT:IRWXXX	SUBROUTINE NAME	NAMELIST VARIABLES	DESCRIPTION
DBF27	IRW27	SECF27	NFUEL	Interaction index for fuel; see Section 7.2.5
			NF27	Number of frequencies for F27
			NOXID	Interaction index for oxidizer; see Section 7.2.5
			NPI	N*π, used for computing τ_{lim}
			NR	Number of roots to be solved; see Section 2.5
			NTRY	Number of trials for root solving procedure; see Section 2.5
			PINTER	Interaction index of propellants; see Section 7.2.5
			RF27I	Imaginary part of the complex root
			RF27R	Real part of the complex root
			SNHSAV	Mode of oscillation constants saved; see Section 7.2.5
			SNUH	Mode of oscillation constant; see Section 7.2.5
			SPHEAT	Specific heat ratio; see Section 2.4
			TAU	Time lag; see Section 7.2.5
			TAUBAR	Sensitive time lag; for definition see Section 7.2.5
DBF28	IRW28	SECF28	ACRACY	$=1*10^{-8}$, used for convergence testing
			AF28	Weighting factor constant for combustion response and flow response stability; see Section 2.2

(continued)

NAMELIST NAME	CONTROL SWITCH FOR READ AND PRINT:IRWXXX	SUBROUTINE NAME	NAMELIST VARIABLES	DESCRIPTION
DBF28	IRW28	SECF28	ALRN28	Decay rate range
			AL1HI	Search boundary for AESOP (decay rate)
			AL1LO	Search boundary for AESOP (decay rate)
			AL2HI	Search boundary for AESOP (frequency)
			AL2LO	Search boundary for AESOP (frequency)
			BESARG	Argument of the Bessel function; see Section 7.2.6
			CS	Speed of sound in combustion gas; see Section 7.9
			DC	Diameter of combustion chamber; see Section 2.2
			DELPF	Injector pressure drop for fuel; see Section 7.9
			DELPX	Injector pressure drop for oxidizer; see Section 7.9
			EPSF31	Scaling factor for flow response
			EPSF32	Add-on constant for flow response
			EPSF41	Scaling factor for combustion response
			EPSF42	Add-on constant for combustion response
			F28	Stability decay rate for various high frequency oscillations; see Section 7.2.6
			GOMEGA	Logical switch for saving guesses for ω
			ISTATF	Fuel state at injector exit
			ISWEEP	Indicator for root sweeping

(continued)

NAMELIST NAME	CONTROL SWITCH FOR READ AND PRINT:IRWXXX	SUBROUTINE NAME	NAMELIST VARIABLES	DESCRIPTION
DBF28	IRW28	SECF28	LF	Length of fuel orifices; see Section 2.2
			LOOP	Logical variable; see Section 2.7.1
			LUFIN	AESOP variable; see Appendix B
			MAXJJJ	Number of iterations for optimization loop; see Section 2.8
			MC	Mach number in combustion chamber; see Section 7.9
			NALPHA	Number of parameters available for optimization; see Section 2.8
			NB28	Number of Bessel arguments coded into the program; see Section 2.5
			NFUNC	Total number of functions being defined and computed in the system model; see Section 2.8
			NPTSRY	AESOP variable; see Appendix B
			NR	Number of roots to be solved; see Section 2.5
			NTRY	Number of trials for root solving procedure; see Section 2.5
			OMEGA	Angular frequency of oscillations
			PCI	Combustion chamber pressure; see Section 7.9
			RALOHI	AESOP variable; see Appendix B
			RAYDIV	AESOP variable; see Appendix B
			RHOF	Density of fuel; see Section 2.4
			SPHEAT	Specific heat ratio of combustion gas; see Section 2.4

(continued)

NAMELIST NAME	CONTROL SWITCH FOR READ AND PRINT:IRWXXX	SUBROUTINE NAME	NAMELIST VARIABLES	DESCRIPTION
DBF28	IRW28	SECF28	TAF	Total fuel injection area; see Section 7.9
			USEPAT	Logical variable indicating use of the Pattern search
			USERAY	AESOP variable for ray search; see Appendix B
			VOLF	Volume of the injector dome for fuel; see Section 2.3
			VOLX	Volume of the injector dome for oxidizer; see Section 2.3
			WF	Total fuel mass flow rate; see Section 7.9
DBF29	IRW29	SECF29	AF29	Weighting factor constant for nonlinear stability analysis; see Section 2.2
			F29	Stability decay rate based on the nonlinear stability analysis; see Section 7.2.7
DBF31	IRW31	SECF31	AF31	Weighting factor constant for fuel pressure drop; see Section 2.2
			F31	Pressure drop characteristic for fuel; see Section 7.3.1
DBF32	IRW32	SECF32	AF32	Weighting factor constant for oxidizer pressure drop; see Section 2.2
			F32	Pressure drop characteristic for oxidizer; see Section 7.3.2
DBF41	IRW41	SECF41	AF41	Weighting factor constant for fuel and oxidizer holes; see Section 2.2
			F41	Number of fuel holes plus oxidizer holes minus 1; see Section 7.4.1

(continued)

NAMELIST NAME	CONTROL SWITCH FOR READ AND PRINT:IRWXXX	SUBROUTINE NAME	NAMELIST VARIABLES	DESCRIPTION
DBF42	IRW42	SECF42	AF42	Weighting factor constant for oxidizer dome volume; see Section 2.2
↓	↓	↓	F42	States the oxidizer dome volume; see Section 7.4.2
DBF43	IRW43	SECF43	AF43	Weighting factor constant for fuel dome volume; see Section 2.2
↓	↓	↓	F43	States the fuel dome volume; see Section 7.4.3
DBF44	IRW44	SECF44	AF44	Weighting factor constant for the length of the oxidizer holes; see Section 2.2
↓	↓	↓	F44	States the length of the oxidizer holes; see Section 7.4.4
DBF45	IRW45	SECF45	AF45	Weighting factor constant for the length of the fuel holes; see Section 2.2
↓	↓	↓	F45	States the length of the fuel holes; see Section 7.4.5
DBF46	IRW46	SECF46	AF46	Weighting factor constant for the injector type; see Section 2.2
↓	↓	↓	F46	NOT ACTIVE IN THE PRESENT PROGRAM
DBF51	IRW51	SECF51	AF51	Weighting factor constant in the average combustor length characteristic equation; see Section 2.2
↓	↓	↓	F51	Computes the chamber length to throat diameter ratio; see Section 7.5.1

(continued)

NAMELIST NAME	CONTROL SWITCH FOR READ AND PRINT:IRWXXX	SUBROUTINE NAME	NAMELIST VARIABLES	DESCRIPTION
DBF61	IRW61	SECF61	AF61	Weighting factor constant in the average combustor diameter characteristic equation; see Section 2.2
↓	↓	↓	F61	Computes the chamber diameter to throat diameter ratio; see Section 7.6.1
DBF71	IRW71	SECF71	AF71	Weighting factor constant in the average mixture ratio characteristic equation; see Section 2.2
↓	↓	↓	F71	States the propellant mixture ratio; see Section 7.7.1
DBF81	IRW81	SECF81	AF81	Weighting factor constant in the average baffle characteristic equation; see Section 2.2
↓	↓	↓	BFLRAD	Number of radial baffles; see Section 2.3
↓	↓	↓	F81	Radial baffle characteristic; see Section 7.8.1
DBF82	IRW82	SECF82	AF82	Weighting factor constant in the average baffle characteristic equation; see Section 2.2
↓	↓	↓	BFLCIR	Number of circumferential baffles; see Section 2.3
↓	↓	↓	F82	Circumferential baffle characteristic; see Section 7.8.2

(continued)

NAMELIST NAME	CONTROL SWITCH FOR READ AND PRINT:IRWXXX	SUBROUTINE NAME	NAMELIST VARIABLES	DESCRIPTION
DBNLS	IRWNLS	NLSTAB	AP	Pressure amplitude; see Section 7.2.7, Figure 7-18
			CS	Speed of sound in combustion gas; see Section 7.9
			DC	Diameter of combustion chamber; see Section 2.3
			DELTAV	1/CS*(600+.5*(F1+F2))
			DKRATE	Stability decay rate for high frequency oscillations; see Section 7.2.7
			DTHRTI	Diameter of combustion chamber throat; see Section 2.4
			F1	VLM50/(VL+VG)*VL**2/(VL+600); see Section 7.2.7
			F2	GMLM50**2/(VG**2-VL**2)*VG; see Section 7.2.7
			GMLM50	VG minus liquid velocity of propellant with largest L50,minus 600; see Section 7.2.7
			L	Burning parameter; see Section 7.2.7
			L50	Length of combustion chamber required to vaporize 50 per cent of the propellant; see Section 7.2.1
			VELC	Gas velocity in combustion chamber; see Section 7.9
			VG	Final gas velocity in combustion chamber; see Section 7.2.7

(continued)

NAMELIST NAME	CONTROL SWITCH FOR READ AND PRINT:IRWXXX	SUBROUTINE NAME	NAMELIST VARIABLES	DESCRIPTION
DBNLS	IRWNLS	NLSTAB	VL	Velocity of liquid propellant with largest L50; see Section 7.2.7, Equation (7-57)
			VGMVL	VG - VL
DBVAP	IRWVAP	VAPRIZ	ADIS	Constant for number distribution; see Section 7.1.1
			DJ	Equivalent jet diameter for injected liquid fuel or oxidizer; see Section 7.1.1
			GENL	Generalized length; see Section 7-3
			INJCMP	Injector complexity index; see Section 2.4
			LAMBDA	Latent heat of vaporization for fuel or oxidizer; see Section 2.4
			LC	Combustion chamber length; see Section 2.3
			MOLE	Molecular weight of fuel or oxidizer; see Section 2.4
			MU	Viscosity of fuel or oxidizer; see Section 2.4
			MUC	Viscosity of reference liquid heptane
			PCI	Combustion chamber pressure; see Section 7.9
			PMV	Per cent mass of propellant vaporized for generalized length; see Section 7.1.1
			RC	Combustion chamber contraction ratio; see Section 7.9
			RHO	Density of fuel or oxidizer; see Section 2.4
				(continued)

NAMELIST NAME	CONTROL SWITCH FOR READ AND PRINT:IRWXXX	SUBROUTINE NAME	NAMELIST VARIABLES	DESCRIPTION
DBVAP	IRWVAP	VAPRIZ	RHOC	Density of reference liquid heptane
			RM	Propellant drop size of liquid fuel or oxidizer; see Section 7.1.1
			SIGL	Surface tension of fuel or oxidizer; see Section 2.4
			SIGLC	Surface tension of reference liquid heptane
			TLOR	Propellant temperature ratio; see Section 7.1.1
			VO	Propellant injection velocity for oxidizer; see Section 7.1.1

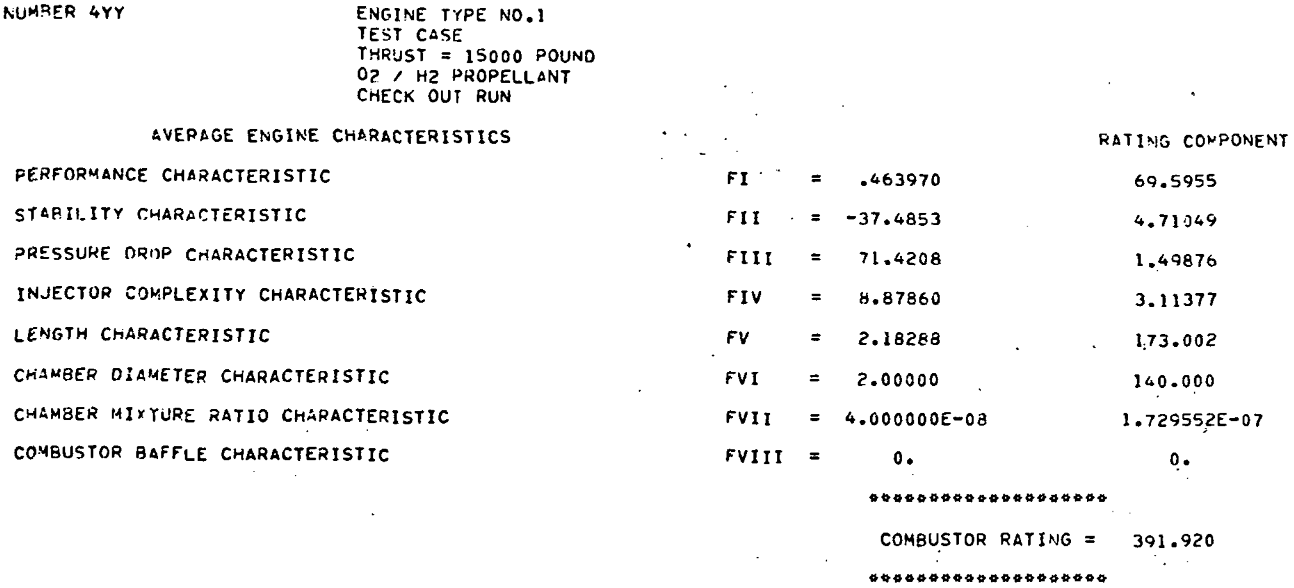
3. PROGRAM OUTPUT

The present program coding provides the print out of seven summary tables with parameter descriptions controlled by the following subroutines:

1. Subroutine OUTAEC, "Average Engine Characteristics," Table 3-1
2. Subroutine OUTFDV, "Final Values of the Design Variables," Table 3-2
3. Subroutine OUTGEP, "General Engine Parameters," Table 3-3
4. Subroutine OUTSCC, "Specific Combustor Characteristics," Table 3-4
5. Subroutine OUTSRS, "Stability Root Summary," Table 3-5
6. Subroutine OUTWAC, "Weighting Factors in Average Characteristics," Table 3-6
7. Subroutine OUTWTR, "Weighting Factors in Rating Equation," Table 3-7

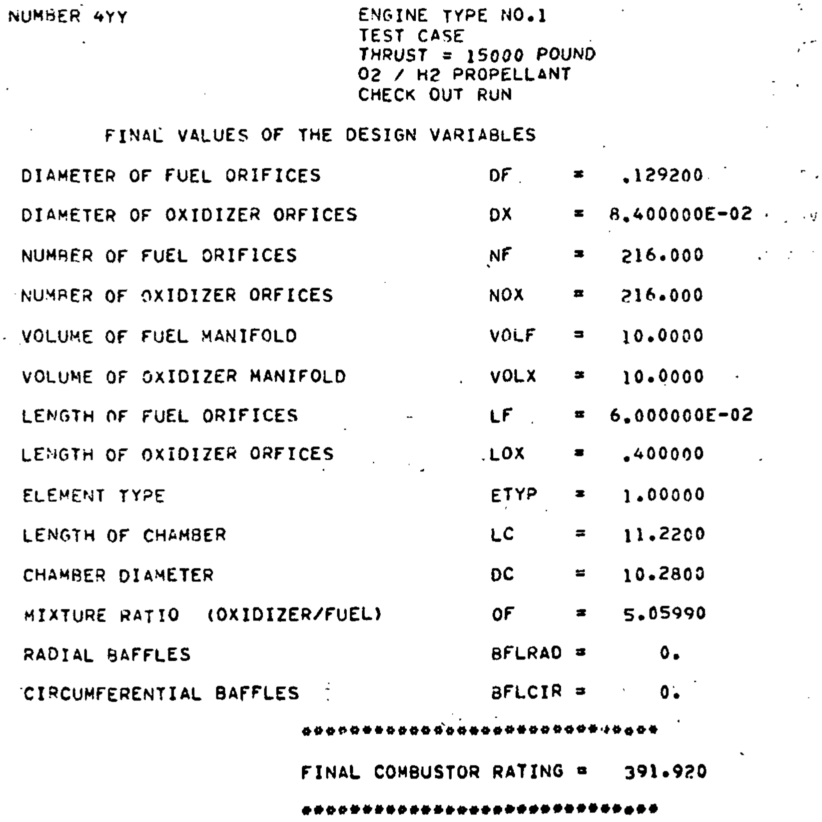
3.1 Data to Regulate Program Output

The print out of the seven summary tables is automatically regulated with each run. Other informative print outs are activated when using the control switch for "read in" and "print out" IRWXX = 1 or 2 (see Sections 2.6 and 2.9).



```
NUMBER 4YY                        ENGINE TYPE NO.1
                                  TEST CASE
                                  THRUST = 15000 POUND
                                  O2 / H2 PROPELLANT
                                  CHECK OUT RUN

         AVERAGE ENGINE CHARACTERISTICS                                                   RATING COMPONENT

 PERFORMANCE CHARACTERISTIC                             FI     =   .463970                    69.5955

 STABILITY CHARACTERISTIC                               FII    =  -37.4853                    4.71049

 PRESSURE DROP CHARACTERISTIC                           FIII   =   71.4208                    1.49876

 INJECTOR COMPLEXITY CHARACTERISTIC                     FIV    =   8.87860                    3.11377

 LENGTH CHARACTERISTIC                                  FV     =   2.18288                    173.002

 CHAMBER DIAMETER CHARACTERISTIC                        FVI    =   2.00000                    140.000

 CHAMBER MIXTURE RATIO CHARACTERISTIC                   FVII   =  4.000000E-08               1.729552E-07

 COMBUSTOR BAFFLE CHARACTERISTIC                        FVIII  =     0.                          0.

                                                                  ********************

                                                                  COMBUSTOR RATING =   391.920

                                                                  ********************
```

TABLE 3-1. Typical Printout for Average Engine Characteristics (Subroutine OUTAEC)



```
NUMBER 4YY                      ENGINE TYPE NO.1
                                TEST CASE
                                THRUST = 15000 POUND
                                O2 / H2 PROPELLANT
                                CHECK OUT RUN

           FINAL VALUES OF THE DESIGN VARIABLES

 DIAMETER OF FUEL ORIFICES                  DF       =   .129200

 DIAMETER OF OXIDIZER ORFICES               DX       =  8.400000E-02

 NUMBER OF FUEL ORIFICES                    NF       =   216.000

 NUMBER OF OXIDIZER ORFICES                 NOX      =   216.000

 VOLUME OF FUEL MANIFOLD                    VOLF     =   10.0000

 VOLUME OF OXIDIZER MANIFOLD                VOLX     =   10.0000

 LENGTH OF FUEL ORIFICES                    LF       =  6.000000E-02

 LENGTH OF OXIDIZER ORFICES                 LOX      =   .400000

 ELEMENT TYPE                               ETYP     =   1.00000

 LENGTH OF CHAMBER                          LC       =   11.2200

 CHAMBER DIAMETER                           DC       =   10.2800

 MIXTURE RATIO  (OXIDIZER/FUEL)             OF       =   5.05990

 RADIAL BAFFLES                             BFLRAD =        0.

 CIRCUMFERENTIAL BAFFLES                    BFLCIR =        0.
                             ******************************

                             FINAL COMBUSTOR RATING =   391.920

                             ******************************
```

TABLE 3-2. Typical Printout for Final Values of the Design Variables (Subroutine OUTFDV)

```
NUMBER 4YY                      ENGINE TYPE NO.1
                                TEST CASE
                                THRUST = 15000 POUND
                                O2 / H2 PROPELLANT
                                CHECK OUT RUN

             GENERAL ENGINE PARAMETERS

 COMBUSTOR THRUST FORCE                                THRUST =   15000.0

 PROPELLANT SPECIFIC IMPULSE                           ISP    =   444.840

 CHAMBER PRESSURE AT INJECTOR HEAD                     PCI    =   372.817

 TOTAL PROPELLANT FLOW RATE                            WT     =   33.7200

 FUEL WEIGHT FLOW RATE                                 WF     =   5.56445

 OXIDIZER WEIGHT FLOW RATE                             WOX    =   28.1556

 COMBUSTION TEMPERATURE IN CHAMBER                     TCOMB  =   5764.91

 RATIO OF SPECIFIC HEAT OF COMBUSTION GAS              SPHEAT =   1.24900

 GAS CONSTANT OF COMBUSTION GAS                        RGAS   =   127.131

 IDEAL THRUST COEFFICIENT                              CFIDEL =   1.93901

 ACOUSTICAL LENGTH OF CHAMBER                          LDUM   =   8.81574

 MOLECULAR WEIGHT OF COMBUSTION GAS                    MOLWT  =   12.1450

 MEAN RESIDENCE TIME OF GAS IN CHAMBER                 THETAG = 8.568235E-04

 SPEED OF SOUND IN CHAMBER                             CS     =   65123.3

 COMBUSTION CHAMBER MACH NUMBER                        MC     =   .201078

 INJECTOR PRESSURE DROP FOR FUEL                       DELPF  =   82.9049

 INJECTOR PRESSURE DROP FOR OXIDIZER                   DELPX  =   48.4525

 COMBUSTION CHAMBER VOLUME                             VC     =   681.565

 AVERAGE VELOCITY OF GASES IN CHAMBER                  VELC   =   13094.9

 FUEL INJECTION VELOCITY                               VFUEL  =   13013.0

 OXIDIZER INJECTION VELOCITY                           VOXID  =   339.511

 TOTAL AREA OF FUEL INJECTOR ORIFICES                  TAF    =   2.83184

 TOTAL AREA OF OXIDIZER INJECTOR ORIFICES              TAX    =   1.19702

 CHAMBER LENGTH TO VAPORIZE 50 PER-CENT OF FUEL        L5FUEL =      0.

 CHAMBER LENGTH TO VAPORIZE 50 PER-CENT OF OXIDIZER    L5OXID =   .649491

 BAFFLE LENGTH BASED ON LARGEST L50                    BAFLEN =   1.29898
```

TABLE 3-3. Typical Printout for General Engine Parameters
(Subroutine OUTGEP)

```
NUMBER 4YY                        ENGINE TYPE NO.1
                                  TEST CASE
                                  THRUST = 15000 POUND
                                  O2 / H2 PROPELLANT
                                  CHECK OUT RUN

          SPECIFIC COMBUSTOR CHARACTERISTICS

PER CENT MASS FUEL VAPORIZED                              F11   =        0.
PER CENT MASS OF OXIDIZER VAPORIZED                       F12   =   99.8845
C* EFFICIENCY MIXING MODEL                                F13   =   100.000
C* EFFICIENCY PULSED COMBUSTORS                           F14   =   91.3821
C* EFFICIENCY NON-PULSED COMBUSTORS                       F15   =   73.7667
FUEL SYSTEM CHUGGING DECAY RATE                           F20   =  -13004.4
OZIDIZER SYSTEM CHUGGING DECAY RATE                       F21   =  -259.892
PULSED INSTABILITY CHARACTERISTIC                         F22   =  -37.4853
NON-PULSED INSTABILITY CHARACTERISTIC                     F23   =        0.
DYKEMA FUEL STABILITY DECAY RATE                          F24   =        0.
DYKEMA OXIDIZER STABILITY DECAY RATE                      F25   =  -99.9432
STABILITY LONGITUDINAL TIME LAG                           F26   =  -6182.25
STABILITY TRANSVERSE TIME LAG                             F27   =  -413.671
STABILITY LRC RESPONSE FUNCTION                           F28   =  -356.492
STABILITY PRIEM LINEAR ANALYSIS                           F29   =  -160.494
FUEL PRESSURE DROP CHARACTERISTIC                         F31   =   82.9049
OXIDIZER PRESSURE DROP CHARACTERISTIC                     F32   =   48.4525
FUEL PLUS OXIDIZER HOLES CHARACTERISTIC                   F41   =   431.000
OXIDIZER DOME VOLUME CHARACTERISTIC                       F42   =   10.0000
FUEL DOME VOLUME CHARACTERISTIC                           F43   =   10.0000
OXIDIZER HOLE LENGTH CHARACTERISTIC                       F44   =   .400000
FUEL HOLE LENGTH CHARACTERISTIC                           F45   =  6.000000E-02
INJECTOR TYPE COMPLEXITY CHARACTERISTIC                   F46   =        0.
INJECTOR LENGTH CHARACTERISTIC                            F51   =   2.18283
CHAMBER DIAMETER CHARACTERISTIC                           F61   =   2.00000
MIXTURE RATIO CHARACTERISTIC                              F71   =   5.05990
RADIAL BAFFLES                                            F81   =        0.
CIRCUMFERENTIAL BAFFLES                                   F82   =        0.
```

TABLE 3-4. Typical Printout for Specific Combustor Characteristics (Subroutine OUTSCC)

```
NUMBER 4YY                ENGINE TYPE NO.1
                          TEST CASE
                          THRUST = 15000 POUND
                          O2 / H2 PROPELLANT
                          CHECK OUT RUN

           STABILITY ROOT SUMMARY

ROOTS FROM SECF20  (FUEL SYSTEM CHUGGING DECAY RATE)                            DECAY RATE        FREQUENCY
                                                                                 -.887950          3.445212E-07
                                                                                 -11.1425         -13.2157
                                                                                 -11.1425          13.2157

ROOTS FROM SECF21  (OXIDIZER SYSTEM CHUGGING DECAY RATE)                        DECAY RATE        FREQUENCY
                                                                                 -.222681         -1.56859
                                                                                 -.222681          1.56859
                                                                                 -.396833          5.402655E-07

ROOTS FROM SECF26  (STABILITY LONGITUDINAL TIME LAG)                            DECAY RATE        FREQUENCY
      COAXIAL INJECTION  (FUEL)                                                  -.325616         -1.396001E-07
                                                                                 -.963172         -1.610735E-08
                                                                                 -.227336          3.01091
      COAXIAL INJECTION  (OXIDIZER)                                              -.458582         -2.037704E-06
                                                                                 -.544600          4.654953E-08
                                                                                 -.836891          2.59526

ROOTS FROM SECF27  (STABILITY TRANSVERSE TIME LAG)                              DECAY RATE        FREQUENCY
      COAXIAL INJECTION  (OXIDIZER)     IFREQ = 1     SNUH =    1.84129          -.397937          2.09192
      COAXIAL INJECTION  (FUEL)         IFREQ = 2     SNUH =    3.05430        -3.264988E-02       3.05219
      COAXIAL INJECTION  (OXIDIZER)     IFREQ = 3     SNUH =    3.83170        -9.614408E-02       3.87701
      COAXIAL INJECTION  (FUEL)         IFREQ = 4     SNUH =    7.01560        -4.627049E-02       7.02832
      COAXIAL INJECTION  (OXIDIZER)     IFREQ = 4     SNUH =    7.01560          -.136781          7.07882
      COAXIAL INJECTION  (FUEL)         IFREQ = 5     SNUH =    5.33130        -8.547226E-02       5.28733
      COAXIAL INJECTION  (OXIDIZER)     IFREQ = 5     SNUH =    5.33130          -.189236          5.42041
      COAXIAL INJECTION  (FUEL)         IFREQ = 7     SNUH =    6.70600          -.250168          6.80062

ROOTS FROM SECF28 (STABILITY LRC RESPONSE FUNCTION)                             DECAY RATE        FREQUENCY
      (1) FIRST TRANSVERSE MODE            BESARG =    1.84120                   -.261052          2.22972
                                                                                 -.261034         -2.22972
      (2) SECOND TRANSVERSE MODE           BESARG =    3.05430                   -.274472          3.29973
                                                                                 -.274441         -3.29972
      (3) THIRD TRANSVERSE MODE            BESARG =    4.20120                   -.281460          4.94245
                                                                                 -.281413         -4.94244
      (4) FIRST RADIAL MODE                BESARG =    3.83170                   -.275233          4.93337
                                                                                 -.275197         -4.93335
      (5) LONGITUDINAL MODE                BESARG =       0.                   -2.813691E-02     -2.719821E-02
                                                                               -2.813695E-02      2.719814E-02
```

TABLE 3-5. Typical Printout for Stability Root Summary
(Subroutine OUTSRS)

```
NUMBER 4YY                    ENGINE TYPE NO.1
                              TEST CASE
                              THRUST = 15000 POUND
                              O2 / H2 PROPELLANT
                              CHECK OUT RUN

      WEIGHTING FACTORS IN AVERAGE CHARACTERISTICS

 CONSTANTS IN PERFORMANCE CHARACTERISTIC                     AF11   =      0.
                                                             AF12   =   1.00000
                                                             AF13   =   1.00000
                                                             AF14   =  1.000000E-02
                                                             AF15   =  1.000000E-02

 CONSTANTS IN ENGINE STABILITY CHARACTERISTICS               AF20   =   1.00000
                                                             AF21   =   1.00000
                                                             AF22   =   1.00000
                                                             AF23   =      0.
                                                             AF24   =      0.
                                                             AF25   =   1.00000
                                                             AF26   =   1.00000
                                                             AF27   =   1.00000
                                                             AF28   =   1.00000
                                                             AF29   =   1.00000

 CONSTANTS IN PRESSURE DROP CHARACTERISTICS                  AF31   =   2.00000
                                                             AF32   =   1.00000

 CONSTANTS IN THE INJECTOR COMPLEXITY CHARACTERISTICS        AF41   =  9.000000E-03
                                                             AF42   =   .125000
                                                             AF43   =   .125000
                                                             AF44   =   5.62500

 CONSTANTS IN THE ENGINE LENGTH CHARACTERISTICS              AF51   =   1.00000
                                                             AF52   =   1.00000

 CONSTANTS IN THE COMBUSTOR DIAMETER CHARACTERISTICS         AF61   =   1.00000
                                                             AF62   =   1.00000
                                                             AF63   =      0.

 CONSTANTS IN THE MIXTURE RATIO CHARACTERISTICS              AF71   =   4.00000
                                                             AF72   =   2.00000

 CONSTANTS IN THE BAFFEL CHARACTERISTICS                     AF81   =      0.
                                                             AF82   =      0.
```

TABLE 3-6. Typical Printout for Weighting Factors in Average Characteristics (Subroutine OUTWAC)

```
NUMBER 4YY                    ENGINE TYPE NO.1
                              TEST CASE
                              THRUST = 15000 POUND
                              O2 / H2 PROPELLANT
                              CHECK OUT RUN

        WEIGHTING FACTORS IN RATING EQUATION

 EXPONENTIAL ON PERFORMANCE CHARACTERISTICS                  AFI    =   150.000

 CONSTANTS OF STABILITY CHARACTERISTICS                      AFII   =   200.000
                                                             BFII   =      0.
                                                             CFII   =   .100000

 CONSTANTS OF THE PRESSURE DROP CHARACTERISTIC               AFIII  =  6.900000E-04
                                                             BFIII  =   1.80000

 CONSTANTS OF THE INJECTOR COMPLEXITY CHARACTERISTIC         AFIV   =  3.950000E-02
                                                             BFIV   =   2.00000

 CONSTANTS OF THE CHAMBER LENGTH CHARACTERISTIC              AFV    =   40.5000
                                                             BFV    =   1.86000

 CONSTANTS OF THE CHAMBER DIAMETER CHARACTERISTIC            AFVI   =   35.0000
                                                             BFVI   =   2.00000

 CONSTANTS OF THE MIXTURE RATIO CHARACTERISTIC               AFVII  =   66.0000
                                                             BFVII  =   1.16000

 CONSTANTS IN THE BAFFEL CHARACTERISTICS                     AFVIII =      0.
                                                             BFVIII =      0.
```

TABLE 3-7. Typical Printout for Weighting Factors in Rating Equation (Subroutine OUTWTR)

4. ENGINE TEST CASE

NOTE:

The following engine test run has been performed in the later part of 1971. Program modifications have been implemented since. Therefore, the printouts do not show these modifications; however, the numerical results would still be unchanged with the exception of Subroutines SECF14 and SECF15 (computes c^*-efficiency based on A.D.Little, Reference 7-4) which have been eliminated in the new AUTOCOM version at the request of NASA's technical monitor.

4.1 Data Input for Test Case

A 15,000-lbf-thrust LH_2/LO_2 pump-fed rocket engine has been selected for demonstration of the AUTOCOM program. Combustor design variables for this engine (with no baffles present) are:

1.	Fuel Orifice Diameter	.195 inches O.D., .145 inches I.D. (.129 inches diameter equivalent hole)
2.	OX Orifice ΔP Diameter	.084 inches
3.	Number of Fuel Elements	216
4.	Number of OX Elements	216
5.	Vol. of Fuel Manifold	10 in^3
6.	Vol. of OX Manifold	10 in^3
7.	Length of Fuel Orifices	.06 inches
8.	Length of OX Orifices	.40 inches
9.	Length of Combustion Chamber	11.22 inches
10.	Diameter of Combustion Chamber	10.28 inches
11.	Propellant Mixture Ratio	5.06 lbm OX/lbm Fuel

Other pertinent but fixed design parameters include:

Propellants	Hydrogen and LOX
Element Type	Concentric Tube (Hydrogen on outside)
OX Orifice Velocity Diameter	.11 inches
Element Impingement Angle	0 degrees
Total Propellant Flow	33.72 lbm/sec
Thrust	15000 lbf
LOX Temperature	Boiling

H_2 Temperature	349° R
Throat Diameter	5.14 inches

This engine runs at the following measured conditions:

Fuel Injection ΔP	83.1 psi
LOX Injection ΔP	48.3 psi
C*-Efficiency	98.6 per cent
I_{sp}	444 lbf-sec/lbm
Combustion Chamber Pressure (injector face, static)	396.4 psi

These running conditions were used to check the nominal engine description in the combustor synthesis and to determine the discharge coefficients CDF and CDX *).

The listing of the deck setup for input data is shown in Table 4-1.

---

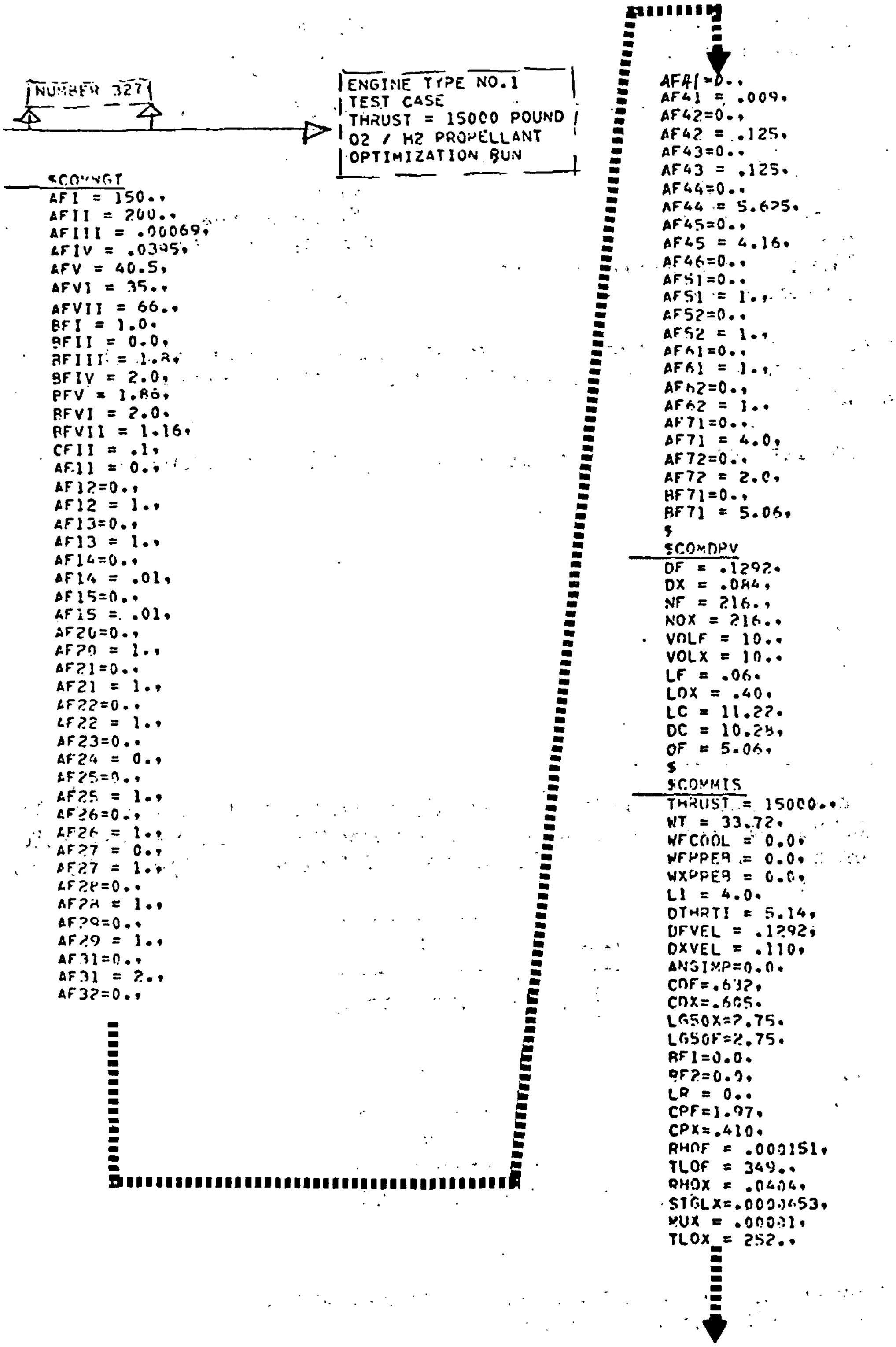
*) For an engine for which analytical or test results are available, ΔPFUEL and ΔPOX can be used to calculate the discharge coefficient for the orifices. Using Equations (7-67) and (7-70) from Section 7.3, Part 2:

$$CDF = \frac{WINJF}{\frac{\pi DF^2}{4} NF} \sqrt{\frac{1}{2gRHOF\ \Delta PFUEL}}$$

and

$$CDX = \frac{WINJX}{\frac{\pi DX^2}{4} NOX} \sqrt{\frac{1}{2gRHOX\ \Delta POX}}$$

For definition of symbols see Sections 2.3 and 2.4 (g = gravitational acceleration).



```
NUMBER 327

ENGINE TYPE NO.1
TEST CASE
THRUST = 15000 POUND
O2 / H2 PROPELLANT
OPTIMIZATION RUN
```

```
 $COMWGT
 AFI = 150.,
 AFII = 200.,
 AFIII = .00069,
 AFIV = .0395,
 AFV = 40.5,
 AFVI = 35.,
 AFVII = 66.,
 BFI = 1.0,
 BFII = 0.0,
 BFIII = 1.8,
 BFIV = 2.0,
 BFV = 1.86,
 BFVI = 2.0,
 BFVII = 1.16,
 CFII = .1,
 AF11 = 0.,
 AF12=0.,
 AF12 = 1.,
 AF13=0.,
 AF13 = 1.,
 AF14=0.,
 AF14 = .01,
 AF15=0.,
 AF15 = .01,
 AF20=0.,
 AF20 = 1.,
 AF21=0.,
 AF21 = 1.,
 AF22=0.,
 AF22 = 1.,
 AF23=0.,
 AF24 = 0.,
 AF25=0.,
 AF25 = 1.,
 AF26=0.,
 AF26 = 1.,
 AF27 = 0.,
 AF27 = 1.,
 AF28=0.,
 AF28 = 1.,
 AF29=0.,
 AF29 = 1.,
 AF31=0.,
 AF31 = 2.,
 AF32=0.,
```

```
 AF41=0.,
 AF41 = .009,
 AF42=0.,
 AF42 = .125,
 AF43=0.,
 AF43 = .125,
 AF44=0.,
 AF44 = 5.625,
 AF45=0.,
 AF45 = 4.16,
 AF46=0.,
 AF51=0.,
 AF51 = 1.,
 AF52=0.,
 AF52 = 1.,
 AF61=0.,
 AF61 = 1.,
 AF62=0.,
 AF62 = 1.,
 AF71=0.,
 AF71 = 4.0,
 AF72=0.,
 AF72 = 2.0,
 BF71=0.,
 BF71 = 5.06,
 $
 $COMDPV
 DF = .1292,
 DX = .084,
 NF = 216.,
 NOX = 216.,
 VOLF = 10.,
 VOLX = 10.,
 LF = .06,
 LOX = .40,
 LC = 11.22,
 DC = 10.25,
 OF = 5.06,
 $
 $COMMIS
 THRUST = 15000.,
 WT = 33.72,
 WFCOOL = 0.0,
 WFPPER = 0.0,
 WXPPER = 0.0,
 L1 = 4.0,
 DTHRTI = 5.14,
 DFVEL = .1292,
 DXVEL = .110,
 ANGIMP=0.0,
 CDF=.632,
 CDX=.605,
 LG50X=2.75,
 LG50F=2.75,
 BF1=0.0,
 BF2=0.0,
 LR = 0.,
 CPF=1.97,
 CPX=.410,
 RHOF = .000151,
 TLOF = 349.,
 RHOX = .0404,
 SIGLX=.0000453,
 MUX = .00031,
 TLOX = 252.,
```

TABLE 4-1. Complete Listing of the Deck Set Up for Input Data of Sample Engine (continued)

```
MOLFX=32.0,
LAMBDX = 88.0,
TCRX=278.6,
CHIF = .40,
FLINE = .06,
FLAREA = 2.74,
CHIX = .04,
XLINE = .40,
XLAREA = 1.19,
ETYP = 1.,
PTYP =1.,
ICOAX = 1,
INJCMP = 2,
IEQF=1,
IEQX=1,
ISTATF=1,
ISTATX=2,
ISTORF=0,
ISTORX=0,
     PCRC(1)=4*0.0,
     PCRF(1)=4*0.0,
     PCRX(1)=4*0.0,
     MUF=0.359E-6,
     LAMBDF=192.0,
     SIGLF=0.01,
     TCPF=59.5,
LAMF12=192.
F2BTBS=1.9,
     NTAUN1=.45,
     NTAUN3=.7,
$
$NLROOT
     IPROOT=.TRUE.,
     NRF20=3,NTF20=3,NRF21=3,NTF21=3,
     NRF26=5,NTF26=5,
     NRF26=3,NTF26=3,
     NRF28=2,NTF28=2,
     NF27=7, NR28=5,
     NRF27=3,NTF27=3,
     ROOTS=.TRUE.,
     ROOTS=.FALSE.,
     IGPF20=.FALSE.,
     IGPF21=.FALSE.,
     IGPF26=.FALSE.,
     IGPF27=.FALSE.,
     IGPF28=.FALSE.,
     IGRF20=.TRUE.,
     IGRF21=.TRUE.,
     IGRF26=.TRUE.,
     IGRF27=.TRUE.,
     IGRF28=.TRUE.,
     RCUT28=10.0,
     RCUT27=10.0,
     ALRN28=10.0, ALRN27=100.0,
     ALRN28=10.0, ALRN27=15.0,
GRF20R(1)=-.888512,-11.3752,-11.3752,
GRF20I(1)=0.,-13.3842,13.3842,
GRF21R(1)=-.225314,-.225314 -.400095,
GRF21I(1)=1.59577,-1.59577,-3.980412E-09,
GRF26R(1)=-.345095,-.218134,-.218141,-.885227,
GRF26I(1)=9.699875E-08,2.99431,-2.99432,-3.835812E-07,
```

```
GRF27I(1,1)=1.84129,
GRF27R(1,2)=0.,
GRF27I(1,2)=-1.84129,
GRF27R(2,1)=.03498,
GRF27I(2,1)=3.0535,
GRF27R(2,2)=.034977,
GRF27I(2,2)=-3.0535,
GRF27R(3,1)=0.,
GRF27I(3,1)=3.832,
GRF27R(3,2)=0.,
GRF27I(3,2)=-3.832,
GRF27R(4,1)=.016,
GRF27I(4,1)=7.016,
GRF27R(4,2)=.016,
GRF27I(4,2)=-7.016,
GRF27R(5,1)=-.013549,
GRF27I(5,1)=5.2934,
GRF27R(5,2)=-.013666,
GRF27I(5,2)=-5.2934,
GRF27R(6,1)=0.,
GRF27I(6,1)=8.526,
GRF27R(6,2)=0.,
GRF27I(6,2)=-8.526,
GRF27R(7,1)=-.2095,
GRF27I(7,1)=6.80184,
GRF27R(7,2)=-.2095,
GRF27I(7,2)=-6.80184,
GRF28I(1,1)=.136834,
GRF28R(1,1)=1.76662,
GRF28I(1,2)=.136824,
GRF28R(1,2)=-1.78661,
GRF28I(2,1)=.274302,
GRF28R(2,1)=3.29839,
GRF28I(2,2)=.274264,
GRF28R(2,2)=-3.29835,
GRF28I(3,1)=.273506,
GRF28R(3,1)=4.38735,
GRF28I(3,2)=.273462,
GRF28R(3,2)=-4.38732,
GRF28I(4,1)=.275405,
GRF28R(4,1)=4.03222,
GRF28I(4,2)=.275363,
GRF28R(4,2)=-4.03220,
GRF28I(5,1)=.0284499,
GRF28R(5,1)=.027628,
GRF28I(5,2)=.0284498,
GRF28R(5,2)=-.027628,
$
$COMIRW
     IRW11=1,
     IRW11=0,
     IRW12=1,
     IRW12=0,
     IRW13=1,
     IRW13=0,
     IRW14=1,
     IRW14=0,
       IRW15=1,
       IRW15=0,
     IRW20=1,
     IRW20=0,
     IRW21=1,
     IRW21=0,
     IRW22=1,
     IRW22=0,
```

TABLE 4-1. (continued)

```
   IRW23=0,
   IRW24=1,
 IRW24=0.
   IRW25=1,
 IRW25=0.
IRW26=2.
   IRW26=1,
   IRW26=0,
IRW27=2.
   IRW27=1,
   IRW27=0,
   IRW28=1,
   IRW28=0,
   IRW29=1,
   IRW29=0,
   IRW31=1,
 IRW31=0,
   IRW32=1,
 IRW32=0.
   IRW41=1,
   IRW41=0,
   IRW42=1,
   IRW42=0,
   IRW43=1,
   IRW43=0,
   IRW44=1,
   IRW44=0,
   IRW45=1,
   IRW45=0,
   IRW46=1,
   IRW46=0,
   IRW51=1,
   IRW51=0,
   IRW61=1,
   IRW61=0,
   IRW71=1,
   IRW71=0,
     IRWVAP=1,
 IRWVAP=0,
 IRWPAL=1,
 IRWPAL=0,
 IRWL59=1,
 IRWL59=0.
     IPROOT=.TRUE.,
     IPMISC=.TRUE.,
$
$CPVFIT
IPNAML=.FALSE.,
$
$IAFSOP
     NALPHA=12,
     IREPET=20,
     LUFIN=2, ITFIN=0,
     NUMOPT=2, METHOP(1)=9,2,
     MAXRHS=5,
     MAXRHS=4,
     IPGAIN=1,
     IPSRCH=1, IPACYC=1, IPFCYC=1,
MAXJJJ = 2,
     MAXJJJ=20,
     MAXJJJ=30,
     MAXJJJ=55,
     MAXJJJ=100,
ALPLO(1)=.097,.063,162.,162.,7.5,7.5,.045,.3,1.,8.42,7.61,3.79,
ALPHI(1)=.1615,.105,270.,270.,12.5,12.5,.075,.5,1.,14.04,12.86,5.0599,

 ALPHA(1)=.12111,.0712154,269.257,269.257,10.5488,10.3573,
 ALPHA(7)=.0665364,.37851,1.00,9.87075,7.04071,4.96744,
 MAXJJJ = 0.
 $
00000000000000000000000
00000000000000000000000
```

TABLE 4-1. (End)

4.2 Data Output for Test Case

Computed running conditions for this engine from the AUTOCOM code were

Fuel Injection ΔP	82.9 psi
LOX Injection ΔP	48.5 psi
C* Efficiency	see Table 4-3
I_{sp}	444.8 lbf sec/lbm
Chamber pressure (injector face, static)	372.8 psi

It is assumed that the low chamber pressure computed results from the ratio of specific heats employed for the propellant combination ($\Upsilon = 1.2505$) and the combustion temperature ($T_c = 5722°R$). A more complete set of computed engine running conditions is presented in Table 4-2.

4.2.1 Specific Combustor Characteristics. Specific combustor characteristics for the nominal engine are presented in Table 4-3. The average engine characteristics resulting from the selected specific combustor characteristics are shown in Table 4-4. The rating value resulting from the selected average engine characteristic weighting factors is also presented in Table 4.4.

It should be noted that the specific combustor stability characteristic consumes almost all the computational time required for the evaluation of a combustor. This is due to the time consuming complex characteristic equation solutions required for chugging (F20 and F21), longitudinal time lag stability analysis (F26), transverse time lag stability analysis (F27) and the Lewis response function stability analysis (F28). Table 4-5 presents a summary of the characteristic stability equation roots for the nominal engine. The least stable root is obtained from the transverse time lag analysis (F27) using a value of $S_{\nu h} = 3.0543$.

4.2.2 Stability Roots. Some difficulty was initially experienced in computing the nominal engine stability characteristics for the time lag analyses. The AUTOCOM program assumes a value of the Reardon interaction index, n, of 0.5 for the longitudinal time lag analyses and 1.0 for the transverse time lag analysis. With these interaction index values, the nominal engine was found to be slightly unstable in two of the transverse modes, Table 4-6. A sensitivity study on the effect of interaction index value was undertaken. As a result, an interaction index value of 0.90 was subsequently utilized in all transverse time lag analyses and an interaction index value of 0.45 was used for the longitudinal analysis. These values were used to obtain the time lag analysis roots shown in Table 4-5.

```
NUMBER 316                    ENGINE TYPE NO.1
                              TEST CASE
                              THRUST = 15000 POUND
                              O2 / H2 PROPELLANT
                              OPTIMIZATION RUN

               GENERAL ENGINE PARAMETERS

COMBUSTOR THRUST FORCE                                      THRUST =  15000.0

PROPELLANT SPECIFIC IMPULSE                                 ISP    =  444.840

CHAMBER PRESSURE AT INJECTOR HEAD                           PCI    =  372.765

TOTAL PROPELLANT FLOW RATE                                  WT     =  33.7200

FUEL WEIGHT FLOW RATE                                       WF     =  5.56445

OXIDIZER WEIGHT FLOW RATE                                   WOX    =  28.1556

COMBUSTION TEMPERATURE IN CHAMBER                           TCOMB  =  5764.91

RATIO OF SPECIFIC HEAT OF COMBUSTION GAS                    SPHEAT =  1.24944

GAS CONSTANT OF COMBUSTION GAS (ft.lb./lb.°R)               RGAS   =  127.127

IDEAL THRUST COEFFICIENT                                    CFIDEL =  1.93928

ACOUSTICAL LENGTH OF CHAMBER                                LDUM   =  8.81574

MOLECULAR WEIGHT OF COMBUSTION GAS                          MOLWT  =  12.1453

MEAN RESIDENCE TIME OF GAS IN CHAMBER                       THETAG = 8.567267E-04

SPEED OF SOUND IN CHAMBER                                   CS     =  65133.9

COMBUSTION CHAMBER MACH NUMBER                              MC     =  .201068

INJECTOR PRESSURE DROP FOR FUEL                             DELPF  =  82.9049

INJECTOR PRESSURE DROP FOR OXIDIZER                         DELPX  =  48.4525

COMBUSTION CHAMBER VOLUME                                   VC     =  681.565

AVERAGE VELOCITY OF GASES IN CHAMBER                        VELC   =  13096.4

FUEL INJECTION VELOCITY                                     VFUEL  =  13013.0

OXIDIZER INJECTION VELOCITY                                 VOXID  =  339.511

TOTAL AREA OF FUEL INJECTOR ORIFICES                        TAF    =  2.83184

TOTAL AREA OF OXIDIZER INJECTOR ORIFICES                    TAX    =  1.19702

CHAMBER LENGTH TO VAPORIZE 50 PER-CENT OF FUEL              LSFUEL*= 0.

CHAMBER LENGTH TO VAPORIZE 50 PER-CENT OF OXIDIZER          LSOXID =  .636932
```

---

* Fuel in a gaseous state

TABLE 4-2. Nominal Engine Running Conditions (Dimensions are in in., lb., sec, °R)

```
NUMBER 315                 ENGINE TYPE NO.1
                           TEST CASE
                           THRUST = 15000 POUND
                           O2 / H2 PROPELLANT
                           OPTIMIZATION RUN

          SPECIFIC COMBUSTOR CHARACTERISTICS

PER CENT MASS FUEL VAPORIZED                         F11  =  100. (Gaseous)

PER CENT MASS OF OXIDIZER VAPORIZED                  F12  = 99.8122

C* EFFICIENCY MIXING MODEL                           F13  = 100.000

C* EFFICIENCY PULSED COMBUSTORS                      F14  = 91.3821

C* EFFICIENCY NON-PULSED COMBUSTORS                  F15  = 73.7665

FUEL SYSTEM CHUGGING DECAY RATE                      F20  = -1036.

OZIDIZER SYSTEM CHUGGING DECAY RATE                  F21  = -261.5

PULSED INSTABILITY CHARACTERISTIC                    F22  = -37.4819

NON-PULSED INSTABILITY CHARACTERISTIC                F23  = Not Computed

DYKEMA FUEL STABILITY DECAY RATE                     F24  = Not Computed

DYKEMA OXIDIZER STABILITY DECAY RATE                 F25  = -2964.82

STABILITY LONGITUDINAL TIME LAG                      F26  = -1691.31

STABILITY TRANSVERSE TIME LAG                        F27  = -412.843

STABILITY LRC RESPONSE FUNCTION                      F28  = -360.322

STABILITY PRIEM LINEAR ANALYSIS                      F29  = -46427.6

FUEL PRESSURE DROP CHARACTERISTIC                    F31  = 82.9049

OXIDIZER PRESSURE DROP CHARACTERISTIC                F32  = 48.4525

FUEL PLUS OXIDIZER HOLES CHARATERISTIC               F41  = 431.000

OXIDIZER DOME VOLUME CHARACTERISTIC                  F42  = 10.0000

FUEL DOME VOLUME CHARACTERISTIC                      F43  = 10.0000

OXIDIZER HOLE LENGTH CHARACTERISTIC                  F44  = .400000

FUEL HOLE LENGTH CHARACTERISTIC                      F45  = 6.000000E-02

INJECTOR TYPE COMPLEXITY CHARACTERISTIC              F46  = Not Computed

INJECTOR LENGTH CHARACTERISTIC                       F51  = 2.18288

CHAMBER DIAMETER CHARACTERISTIC                      F61  = 2.00000

MIXTURE RATIO CHARACTERISTIC                         F71  = 5.05990
```

TABLE 4-3. Nominal Engine Specific Combustor Characteristics

```
NUMBER 316                  ENGINE TYPE NO.1
                            TEST CASE
                            THRUST = 15000 POUND
                            O2 / H2 PROPELLANT
                            OPTIMIZATION RUN

           AVERAGE ENGINE CHARACTERISTICS                                                  RATING COMPONENT

PERFORMANCE CHARACTERISTIC                                FI     =    .536361              80.4541

STABILITY CHARACTERISTIC                                  FII    =  -37.4919               4.71208

PRESSURE DROP CHARACTERISTIC                              FIII   =   71.4208               1.49876

INJECTOR COMPLEXITY CHARACTERISTIC                        FIV    =   8.37860               3.11377

LENGTH CHARACTERISTIC                                     FV     =   2.18288               173.002

CHAMBER DIAMETER CHARACTERISTIC                           FVI    =   1.00000               35.0000

CHAMBER MIXTURE RATIO CHARACTERISTIC                      FVII   =  4.000000E-08          1.729552E-07
                                                                    ********************

                                                                     COMBUSTOR RATING =    297.780

                                                                    ********************
```

TABLE 4-4. Nominal Engine Average Characteristics and Rating

```
NUMBER 316                  ENGINE TYPE NO.1
                            TEST CASE
                            THRUST = 15000 POUND
                            02 / H2 PROPELLANT
                            OPTIMIZATION RUN                                 INTERMEDIATE COMBUSTOR OUTPUT JJJ =      1

          STABILITY ROOT SUMMARY

ROOTS FROM SECF20  (FUEL SYSTEM CHUGGING DECAY RATE)                         DECAY RATE          FREQUENCY
                                                                              -.888230            0.
                                                                              -11.3546            -13.3781
                                                                              -11.3546             13.3781

ROOTS FROM SECF21  (OXIDIZER SYSTEM CHUGGING DECAY RATE)                     DECAY RATE          FREQUENCY
                                                                              -.224028             1.59349
                                                                              -.224028            -1.59349
                                                                              -.399442            -3.980412E-09

ROOTS FROM SECF26  (STABILITY LONGITUDINAL TIME LAG)                         DECAY RATE          FREQUENCY
          COAXIAL INJECTION                                                   -.325761            -1.981261E-07
                                                                              -.227561             3.01091
                                                                              -.227574            -3.01091
                                                                              -.962628            -2.335455E-06

ROOTS FROM SECF27  (STABILITY TRANSVERSE TIME LAG)                           DECAY RATE          FREQUENCY
          COAXIAL INJECTION              IFREQ = 1     SNUH =    1.84129      -.659403             1.48411
                                                                              -.659403            -1.48411
          COAXIAL INJECTION              IFREQ = 2     SNUH =    3.05430     -3.257925E-02         3.05211
                                                                             -3.257986E-02        -3.05211
          COAXIAL INJECTION              IFREQ = 4     SNUH =    7.01560     -4.582301E-02         7.02810
                                                                             -4.580937E-02        -7.02810
          COAXIAL INJECTION              IFREQ = 5     SNUH =    5.33130     -8.586577E-02         5.28712
                                                                             -8.587021E-02        -5.28712
          COAXIAL INJECTION              IFREQ = 6     SNUH =    8.52630      -.466415            -6.74870
          COAXIAL INJECTION              IFREQ = 7     SNUH =    6.70600      -.248839             6.80011
                                                                              -.248847            -6.80012

ROOTS FROM SECF28 (STABILITY LRC RESPONSE FUNCTION)                          DECAY RATE          FREQUENCY
          (1) FIRST TRANSVERSE MODE            BESARG =  1.84120              -.137018             1.78673
                                                                              -.137009            -1.78673
          (2) SECOND TRANSVERSE MODE           BESARG =  3.05430              -.274642             3.29860
                                                                              -.274604            -3.29859
          (3) THIRD TRANSVERSE MODE            BESARG =  4.20120              -.273774             4.38764
                                                                              -.273731            -4.38761
          (4) FIRST RADIAL MODE                BESARG =  3.83170              -.275702             4.03249
                                                                              -.275659            -4.03247
          (5) LONGITUDINAL MODE                BESARG =  0.                  -2.843458E-02         2.759602E-02
```

TABLE 4-5. Stability Roots in Time Lag Analysis
(F26: n = 0.45)
(F27: n = 0.90)

```
NUMBER 315                  ENGINE TYPE NO.1
                            TEST CASE
                            THRUST = 15000 POUND
                            O2 / H2 PROPELLANT
                            OPTIMIZATION RUN

               STABILITY ROOT SUMMARY

ROOTS FROM SECF20  (FUEL SYSTEM CHUGGING DECAY RATE)                                DECAY RATE        FREQUENCY
                                                                                     -.888230          0.
                                                                                     -11.3546          -13.3781
                                                                                     -11.3546           13.3781

ROOTS FROM SECF21  (OXIDIZER SYSTEM CHUGGING DECAY RATE)                            DECAY RATE        FREQUENCY
                                                                                     -.224028           1.59349
                                                                                     -.224028          -1.59349
                                                                                     -.399442         -3.980412E-09

ROOTS FROM SECF26  (STABILITY LONGITUDINAL TIME LAG)                                DECAY RATE        FREQUENCY
         COAXIAL INJECTION                                                           -.346317          9.699875E-08
                                                                                     -.221255           2.99487
                                                                                     -.221247          -2.99486
                                                                                     -.880123         -2.718380E-06

ROOTS FROM SECF27  (STABILITY TRANSVERSE TIME LAG)                                  DECAY RATE        FREQUENCY
         COAXIAL INJECTION                 IFREQ = 1     SNUH =   1.84129            -.620883           1.48820
                                                                                     -.620843          -1.48820
         COAXIAL INJECTION                 IFREQ = 2     SNUH =   3.05430            3.532250E-02       3.05238
                                                                                     3.532753E-02      -3.05238
         COAXIAL INJECTION                 IFREQ = 4     SNUH =   7.01560            2.195193E-02       7.02722
                                                                                     2.195308E-02      -7.02722
         COAXIAL INJECTION                 IFREQ = 5     SNUH =   5.33130           -2.028810E-02       5.29084
                                                                                    -2.028614E-02      -5.29084
         COAXIAL INJECTION                 IFREQ = 6     SNUH =   8.52630            -.421159           8.74290
         COAXIAL INJECTION                 IFREQ = 7     SNUH =   6.70600            -.190463           6.79456
                                                                                     -.190456          -6.79456

ROOTS FROM SECF28  (STABILITY LRC RESPONSE FUNCTION)                                DECAY RATE        FREQUENCY
         (1) FIRST TRANSVERSE MODE             BESARG =   1.84120                    -.137018           1.78673
                                                                                     -.137009          -1.78673
         (2) SECOND TRANSVERSE MODE            BESARG =   3.05430                    -.274642           3.29860
                                                                                     -.274604          -3.29859
         (3) THIRD TRANSVERSE MODE             BESARG =   4.20120                    -.273774           4.38764
                                                                                     -.273731          -4.38761
         (4) FIRST RADIAL MODE                 BESARG =   3.83170                    -.275702           4.03249
                                                                                     -.275659          -4.03247
         (5) LONGITUDINAL MODE                 BESARG =   0.                        -2.843458E-02      2.759602E-02
```

TABLE 4-6. Stability Roots in Time Lag Analysis
(F26: n = 0.5)
(F27: n = 1.0)

A second point should be noted regarding the stability roots. No root is found corresponding to the third value of $S_{\nu h} = 3.8317$ in the transverse time lag analysis. The missing root can be found by varying the initial guess value in the complex plane for this particular root. Following this procedure the missing root was found to be at the point (-.59424 ± j3.5144) where the Reardon interaction index was 0.9. The root is thus highly damped.

When commencing an optimization study, side analyses of the above type may be required to locate particularly difficult roots. This procedure should also be followed whenever the root imaginary part is not approximately equal to the corresponding value of $S_{\nu h}$ in the transverse time lag analysis and the Bessel argument, m, in the Lewis response function analysis. This point is discussed further in Section 4.3.1

4.3 Optimization Computations for Test Case

Optimization computations on the sample engine were initially undertaken using all specific combustor characteristics and all stability roots. However, it was noted that the design variable perturbations introduced little change in the computer time consuming stability equation roots. Accordingly the combustor analysis was divided into two classes of computation. These were an *approximate analysis* which considered fewer (possibly none) of the stability roots and a *complete analysis* in which all stability roots were computed. It is emphasized that the approximate analysis is only approximate in that the calculation of the less significant stability roots is omitted. Clearly, by a judicious mix of complete and approximate analyses the total elapsed computer time required for the definition of an optimum engine design can be drastically reduced.

4.3.1 The First Twenty Iterations. Following initial experimentation using all stability roots, the engine was subjected to twenty design iterations using all specific combustor characteristics. An approximate analysis mode was employed which considered only the relatively rapid calculation for the longitudinal time lag analysis (F26) and the transverse time lag analysis (F27) for the single $S_{\nu h}$ value of 3.0543 (the least stable transverse time lag root). This approximate analysis permits both longitudinal and transverse stability characteristics to be monitored.

Initial and final stability roots from this cptimization calculation are presented in Table 4-7. It can be seen that little change has occurred in the stability roots. The trend is to increased stability in the less stable transverse mode and to less stability in the more stable longitudinal mode. It may be noted that the transverse time lag analysis of Table 4-7

A. SELECTED STABILITY ROOTS, NOMINAL ENGINE

```
NUMBER 318                  ENGINE TYPE NO.1
                            TEST CASE
                            THRUST = 15000 POUND
                            O2 / H2 PROPELLANT
                            OPTIMIZATION RUN
                                                                             INTERMEDIATE COMBUSTOR OUTPUT JJJ =      1

               STABILITY ROOT SUMMARY

ROOTS FROM SECF26  (STABILITY LONGITUDINAL TIME LAG)                         DECAY RATE          FREQUENCY
       COAXIAL INJECTION                                                      -.325761            5.500834E-08
                                                                              -.227565             3.01091
                                                                              -.227564            -3.01092

ROOTS FROM SECF27  (STABILITY TRANSVERSE TIME LAG)                           DECAY RATE          FREQUENCY
       COAXIAL INJECTION                  IFREQ = 1     SNUH =   3.05430     -3.257876E-02         3.05211
                                                                              -1.22075            -1.52265
```

B. SELECTED STABILITY ROOTS AFTER TWENTY DESIGN PERTURBATIONS

```
NUMBER 318                  ENGINE TYPE NO.1
                            TEST CASE
                            THRUST = 15000 POUND
                            O2 / H2 PROPELLANT
                            OPTIMIZATION RUN
                                                                             FINAL COMBUSTOR OUTPUT  JJJ=21

               STABILITY ROOT SUMMARY

ROOTS FROM SECF26  (STABILITY LONGITUDINAL TIME LAG)                         DECAY RATE          FREQUENCY
       COAXIAL INJECTION                                                      -.315587            4.288281E-07
                                                                              -.223750             3.01519
                                                                              -.223748            -3.01520

ROOTS FROM SECF27  (STABILITY TRANSVERSE TIME LAG)                           DECAY RATE          FREQUENCY
       COAXIAL INJECTION                  IFREQ = 1     SNUH =   3.05430     -4.673174E-02         3.06709
                                                                              -1.24530            -1.57179
```

TABLE 4-7. Selected Stability Roots for Nominal Engine, and Engine after Twenty Design Perturbations
(F26: n = 0.45)
(F27: n = 0.90)

```
NUMBER 318                  ENGINE TYPE NO.1
                            TEST CASE
                            THRUST = 15000 POUND
                            O2 / H2 PROPELLANT
                            OPTIMIZATION RUN

          AVERAGE ENGINE CHARACTERISTICS                                                RATING COMPONENT

PERFORMANCE CHARACTERISTIC                        FI     =   .344513                   51.6770

STABILITY CHARACTERISTIC                          FII    =  -568.349                 4.149190E-23

PRESSURE DROP CHARACTERISTIC                      FIII   =   75.3314                   1.64971

INJECTOR COMPLEXITY CHARACTERISTIC                FIV    =   8.90264                   3.13079

LENGTH CHARACTERISTIC                             FV     =   2.20692                   176.563

CHAMBER DIAMETER CHARACTERISTIC                   FVI    =   1.08429                   41.1487

CHAMBER MIXTURE RATIO CHARACTERISTIC              FVII   =  7.097338E-05             1.015815E-03
                                                            *******************

                                                             COMBUSTOR RATING =     274.170

                                                            *******************
```

TABLE 4-8. Rating after Twenty Design Perturbations considers two solutions to the stability equation with $S_{\nu h} = 3.0543$. These are the true solution with the frequency approximating $S_{\nu h}$, and a spurious solution with the frequency approximating $\pi/2$. These spurious solutions with a frequency approximating $\pi/2$ are often encountered in the time lag analysis. If the true solution is not obtained on the nominal engine evaluation and the spurious solution is obtained, the AUTOCOM program will "track" the spurious root. Hence, the analyst must take care to insure that the correct roots are found on the nominal design before embarking on an optimization run. This point is also discussed in Section 4.2.2.

The engine rating after twenty design perturbations and the corresponding average engine characteristics are presented in Table 4-8. It can be seen that based on the selected average engine characteristic weights which provide the rating in the form of payload lost, a gain of 23-1/2 pounds of payload has resulted when compared to the nominal design of Table 4-4. It can also be seen that the average stability characteristic contribution to the rating is now negligible and that payload is being gained primarily by reduction of the performance characteristic penalty. Pursuing this payload improvement, it can be seen, Table 4-9, that the performance improvement stems from F12, per cent mass of fuel vaporized, and from slight improvement in C* efficiencies for both pulsed and non-pulsed combustors.

4.3.2 The First Hundred Iterations. Following the first twenty design iterations discussed in Section 4.3.1, the optimization problem was restarted without any stability analysis; and 100 successive design perturbations were introduced. A combination of the uniform random ray and pattern searches were employed, Reference 4-1. The approximate analysis employed completely neglects the stability characteristic. The rationale for this approach was the negligible stability characteristic contribution to the engine rating, Table 4-8. This table indicates that the stability characteristic affects the rating in the twenty-fourth significant figure. This is well below the accuracy of the CDC 6600 computer which, with sixty bits, is able to provide approximately ten significant decimal figures.

The nominal engine rating without the penalty of all stability characteristics (4.7 pounds, Table 4-4) is 293.1 pounds. After 100 successive design perturbations introduced through the References 4-1 and 4-2 multivariable search program, AESOP, the rating is reduced to 210.7 pounds. Rating convergence is illustrated in Figure 4-1. Convergence behavior of the combustor design variables is illustrated in Figures 4-2 through 4-4. The combustor design variables were allowed to fluctuate by plus or minus twenty-five per cent of the nominal values in this study. Two of the design variables, the chamber diameter and the number of fuel orifices (which equals the number of oxidizer orifices) are practically on the lower and upper bounds permitted.

```
NUMBER 318                        ENGINE TYPE NO.1
                                  TEST CASE
                                  THRUST = 15000 POUND
                                  O2 / H2 PROPELLANT
                                  OPTIMIZATION RUN

                SPECIFIC COMBUSTOR CHARACTERISTICS

   PER CENT MASS FUEL VAPORIZED                          F11    =  100.

   PER CENT MASS OF OXIDIZER VAPORIZED                   F12    =   100.000

   C*-EFFICIENCY MIXING MODEL                            F13    =   100.000

   C* EFFICIENCY PULSED COMBUSTORS                       F14    =   91.7089

   C* EFFICIENCY NON-PULSED COMBUSTORS                   F15    =   73.8398

   FUEL SYSTEM CHUGGING DECAY RATE                       F20    =  0.

   OZIDIZER SYSTEM CHUGGING DECAY RATE                   F21    =  0.

   PULSED INSTABILITY CHARACTERISTIC                     F22    =  0.

   NON-PULSED INSTABILITY CHARACTERISTIC                 F23    =  0.

   DYKEMA FUEL STABILITY DECAY RATE                      F24    =  0.

   DYKEMA OXIDIZER STABILITY DECAY RATE                  F25    =  0.

   STABILITY LONGITUDINAL TIME LAG                       F26    =  -1638.16

   STABILITY TRANSVERSE TIME LAG                         F27    =  -568.349

   STABILITY LPC RESPONSE FUNCTION                       F28    =  0.

   STABILITY PRIEM LINEAR ANALYSIS                       F29    =  0.

   FUEL PRESSURE DROP CHARACTERISTIC                     F31    =   87.9479

   OXIDIZER PRESSURE DROP CHARACTERISTIC                 F32    =   50.0986

   FUEL PLUS OXIDIZER HOLES CHARACTERISTIC               F41    =   433.943

   OXIDIZER DOME VOLUME CHARACTERISTIC                   F42    =   10.0228

   FUEL DOME VOLUME CHARACTERISTIC                       F43    =   9.97392

   OXIDIZER HOLE LENGTH CHARACTERISTIC                   F44    =   .399630

   FUEL HOLE LENGTH CHARACTERISTIC                       F45    =  6.005603E-02

   INJECTOR TYPE COMPLEXITY CHARACTERISTIC               F46    =  Not Completed

   INJECTOR LENGTH CHARACTERISTIC                        F51    =   2.20692

   CHAMBER DIAMETER CHARACTERISTIC                       F61    =   2.08429

   MIXTURE RATIO CHARACTERISTIC                          F71    =   5.05579
```

Only f_{26} and f_{27} stability roots were computed

TABLE 4-9. Specific Combustor Characteristics after Twenty Design Perturbations

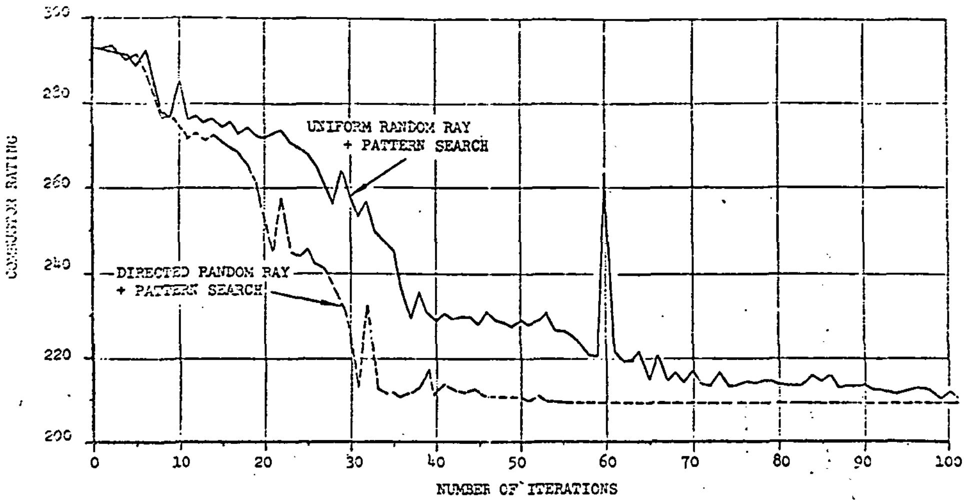


Figure 4-1. Combustor Rating Convergence

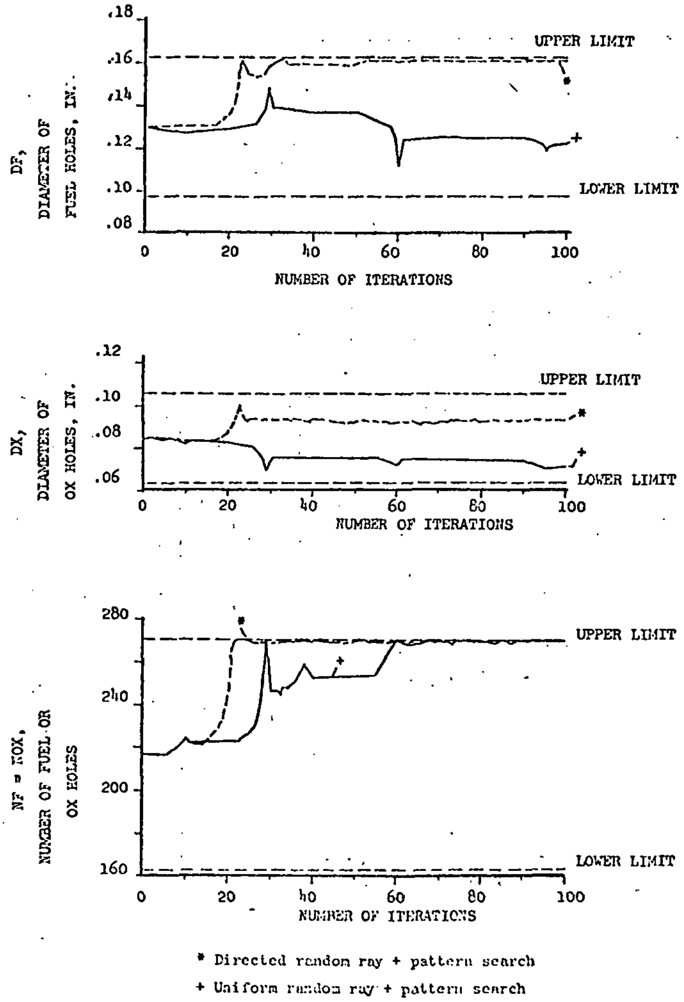


Figure 4-2. Combustor Design Variables Convergence

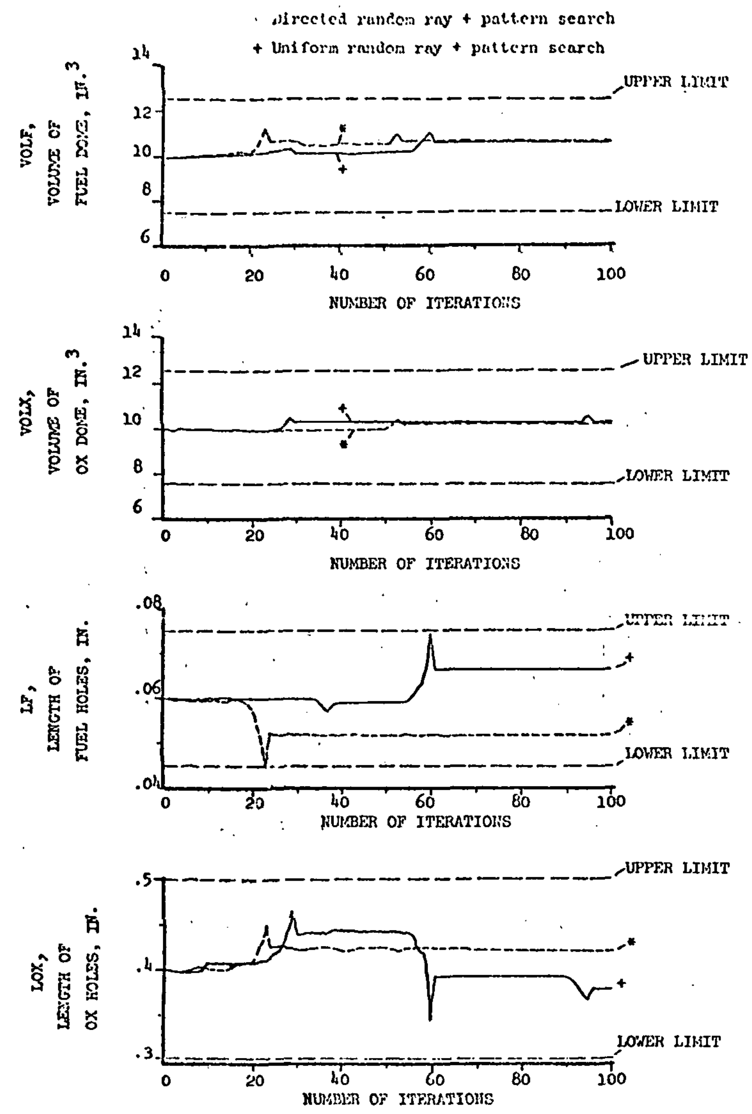
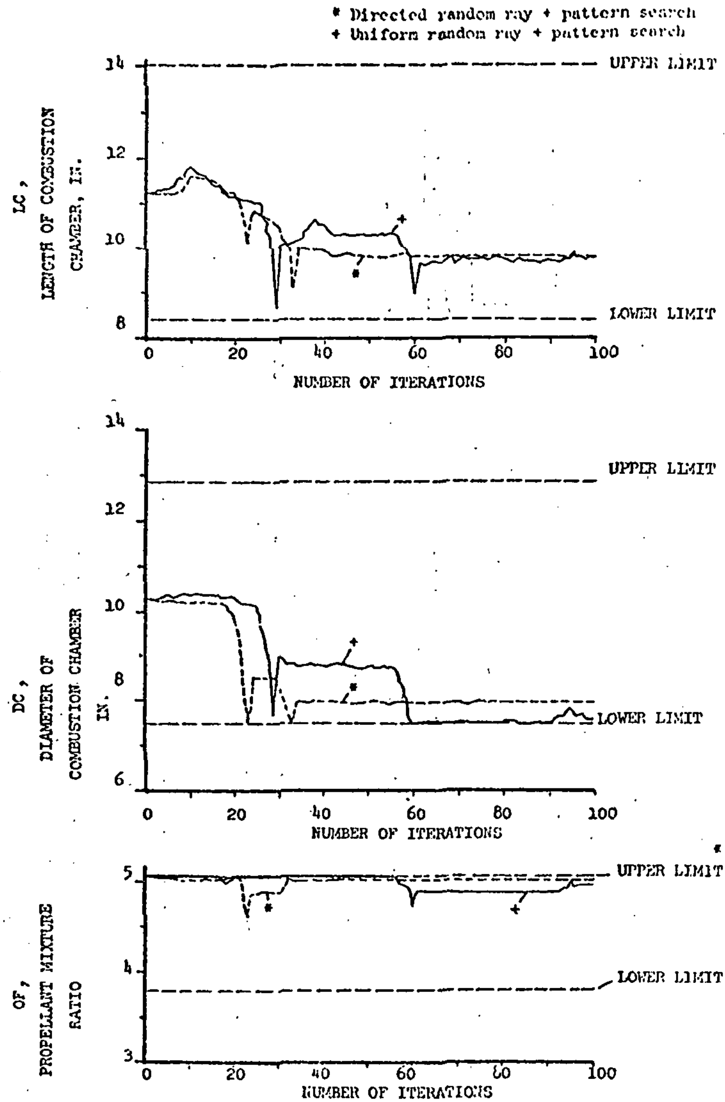


Figure 4-3.
Combustor Design Variables Convergence



*) NOTE: Weighting Factor BF71=5.06=OF

Figure 4-4.
Combustor Design Variables Convergence

The final rating and the characteristic components to the rating are presented in Table 4-10. Final design variable values together with the search limits employed are tabulated in Table 4-11. From Tables 4-4 and 4-10 the rating changes associated with each characteristic are seen to be

Performance Characteristic	20.9 lbs., gain
Stability Characteristic	Not considered
Pressure Drop Characteristic	0.14 lbs., gain
Injector Complexity Characteristic	0.72 lbs., loss
Length Characteristic	36.7 lbs., gain
Chamber Diameter Characteristic	26.7 lbs., gain
Chamber Mixture Ratio Characteristic	1.32 lbs., loss
Total gain	82.4 lbs.

The total rating gain of 82.4 lbs. produced by the optimization process of the AUTOCOM code ignores any stability characteristic effect. To assess this effect, a complete analysis was performed using the Table 4-11 vector of combustor design variables. The rating resulting from this complete analysis is presented in Table 4-12. The associated specific combustor characteristics are presented in Table 4-13. The stability characteristic produces a rating component of .16 pounds, a 4.55 pound improvement over the nominal engine stability characteristic. Comparing the final rating of 210.84 pounds, Table 4-12, with the complete nominal engine rating of 297.78 pounds, Table 4-4, the total rating gain obtained in 100 design perturbations is 86.94 pounds. It is interesting to note that despite the use of an approximate analysis which resulted in the stability characteristic being ignored, this characteristic nonetheless improved during the 100 design iterations. Elapsed computer time for the 100 iterations, the final complete analysis, and the initial complete analysis was 250 seconds on the CDC 6600 computer.

4.3.3 <u>A Note on Stability Roots After 100 Iterations</u>. The complete stability root set obtained after 100 iterations is presented in Table 4-14. It can be seen that the second frequency corresponding to $S_{\nu h} = 3.0543$ is missing. This root was the least stable on the nominal engine, Table 4-5, but became more stable in the first 20 iterations of Section 4.3.1, Table 4-7. Accordingly, a search for this root was initiated to confirm the stability improvement over 100 iterations. The root was located as a non-conjugate pair at the points

$$z_1 = (-.443094 + j2.73775)$$

and

$$z_2 = (-.552853 + j3.61289)$$

```
NUMBER 319                ENGINE TYPE NO.1
                          TEST CASE
                          THRUST = 15000 POUND
                          O2 / H2 PROPELLANT
                          OPTIMIZATION RUN                                                    NOMINAL RATING
        AVERAGE ENGINE CHARACTERISTICS                                   RATING COMPONENT     COMPONENT, TABLE III
PERFORMANCE CHARACTERISTIC                   FI     =  .397158               59.5737             80.4541
STABILITY CHARACTERISTIC                     FII    =  0.                    00.000               4.71208
PRESSURE DROP CHARACTERISTIC                 FIII   =  67.5013               1.35398              1.49876
INJECTOR COMPLEXITY CHARACTERISTIC           FIV    =  9.85680               3.83768              3.11377
LENGTH CHARACTERISTIC                        FV     =  1.92038               136.319            173.002
CHAMBER DIAMETER CHARACTERISTIC              FVI    =  .466520               8.28457             35.0000
CHAMBER MIXTURE RATIO CHARACTERISTIC         FVII   =  3.426861E-02          1.31833              1.729552 x 10^-7
                                                    ********************
                                                     COMBUSTOR RATING =   210.687
                                                    ********************
                                                    NOMINAL COMBUSTOR RATING = 297.780
```

TABLE 4-10. Rating after 100 Perturbations, Approximate Analysis

```
NUMBER 319                     ENGINE TYPE NO.1
                               TEST CASE
                               THRUST = 15000 POUND
                               O2 / H2 PROPELLANT
                               OPTIMIZATION RUN                   | α High  | α Low  | Nominal |
      FINAL VALUES OF THE DESIGN VARIABLES                        |---------|--------|---------|
DIAMETER OF FUEL ORIFICES          DF    =  .121110               | .1615   | .097   |  .129   |
DIAMETER OF OXIDIZER ORFICES       DX    =  7.121544E-02          | .105    | .063   |  .084   |
NUMBER OF FUEL ORIFICES            NF    =  269.257               | 270.    | 162.   |  216.   |
NUMBER OF OXIDIZER ORFICES         NOX   =  269.257               | 270.    | 162.   |  216.   |
VOLUME OF FUEL MANIFOLD            VOLF  =  10.5488               | 12.5    | 7.5    |  10.    |
VOLUME OF OXIDIZER MANIFOLD        VOLX  =  10.3573               | 12.5    | 7.5    |  10.    |
LENGTH OF FUEL ORIFICES            LF    =  6.653641E-02          | .075    | .045   |  .06    |
LENGTH OF OXIDIZER ORFICES         LOX   =  .378510               | .5      | .3     |  .4     |
ELEMENT TYPE                       ETYP  =  1.00000               | 1.      | 1.     |  1.     |
LENGTH OF CHAMBER                  LC    =  9.87075               | 14.04   | 8.42   |  11.22  |
CHAMBER DIAMETER                   DC    =  7.64071               | 12.86   | 7.51   |  10.28  |
MIXTURE RATIO  (OXIDIZER/FUEL)     OF    =  4.96744               | 5.0599  | 3.79   |  5.06   |
                 ******************************
                 FINAL COMBUSTOR RATING =   210.687
                 ******************************
                 NOMINAL COMBUSTOR RATING = 297.780
```

TABLE 4-11. Design Variable Values after 100 Perturbations

```
NUMBER 320                  ENGINE TYPE NO.1
                            TEST CASE
                            THRUST = 15000 POUND
                            O2 / H2 PROPELLANT
                            OPTIMIZATION RUN
                                                                                      NOMINAL RATING
          AVERAGE ENGINE CHARACTERISTICS                           RATING COMPONENT   COMPONENT, TABLE III

PERFORMANCE CHARACTERISTIC                    FI     =   .397158          59.5737       80.4541
STABILITY CHARACTERISTIC                      FII    =  -71.4163          .154260        4.71208
PRESSURE DROP CHARACTERISTIC                  FIII   =   67.5011          1.35397        1.49876
INJECTOR COMPLEXITY CHARACTERISTIC            FIV    =   9.85680          3.83768        3.11377
LENGTH CHARACTERISTIC                         FV     =   1.92038          136.319       173.002
CHAMBER DIAMETER CHARACTERISTIC               FVI    =   .486519          8.29454        35.0000
CHAMBER MIXTURE RATIO CHARACTERISTIC          FVII   =  3.426941E-02      1.31837        1.729552 x 10^-7
                                                      ********************
                                                       COMBUSTOR RATING =  210.845
                                                      ********************

                                                    NOMINAL COMBUSTOR RATING = 297.780
```

TABLE 4-12. Rating after 100 Perturbations, Complete Analysis

```
NUMBER 320                  ENGINE TYPE NO.1
                            TEST CASE
                            THRUST = 15000 POUND
                            O2 / H2 PROPELLANT
                            OPTIMIZATION RUN

        SPECIFIC COMBUSTOR CHARACTERISTICS

PER CENT MASS FUEL VAPORIZED                       F11    = 100.
PER CENT MASS OF OXIDIZER VAPORIZED                F12    =   100.000
C* EFFICIENCY MIXING MODEL                         F13    =   100.000
C* EFFICIENCY PULSED COMBUSTORS                    F14    =   87.7264
C* EFFICIENCY NON-PULSED COMBUSTORS                F15    =   72.5578
FUEL SYSTEM CHUGGING DECAY RATE                    F20    =  -1264.
OXIDIZER SYSTEM CHUGGING DECAY RATE                F21    =  -184.
PULSED INSTABILITY CHARACTERISTIC                  F22    =  -71.4163
NON-PULSED INSTABILITY CHARACTERISTIC              F23    =  Not Computed
DYKEMA FUEL STABILITY DECAY RATE                   F24    =  Not Computed
DYKEMA OXIDIZER STABILITY DECAY RATE               F25    =  -2920.49
STABILITY LONGITUDINAL TIME LAG                    F26    =  -2861.51
STABILITY TRANSVERSE TIME LAG                      F27    =  -840.869
STABILITY LRC RESPONSE FUNCTION                    F28    =  -423.008
STABILITY PRIEM LINEAR ANALYSIS                    F29    =  -27334.7
FUEL PRESSURE DROP CHARACTERISTIC                  F31    =   71.2588
OXIDIZER PRESSURE DROP CHARACTERISTIC              F32    =   59.9856
FUEL PLUS OXIDIZER HOLES CHARACTERISTIC            F41    =   537.514
OXIDIZER DOME VOLUME CHARACTERISTIC                F42    =   10.3573
FUEL DOME VOLUME CHARACTERISTIC                    F43    =   10.5468
OXIDIZER HOLE LENGTH CHARACTERISTIC                F44    =   .378510
FUEL HOLE LENGTH CHARACTERISTIC                    F45    =  6.653640E-02
INJECTOR TYPE COMPLEXITY CHARACTERISTIC            F46    = Not Computed
INJECTOR LENGTH CHARACTERISTIC                     F51    =   1.92038
CHAMBER DIAMETER CHARACTERISTIC                    F61    =   1.48652
MIXTURE RATIO CHARACTERISTIC                       F71    =   4.96744
```

TABLE 4-13. Specific Combustor Characteristics after 100 Design Perturbations

```
NUMBER 320                 ENGINE TYPE NO.1
                           TEST CASE
                           THRUST = 15000 POUND
                           O2 / H2 PROPELLANT
                           OPTIMIZATION RUN

             STABILITY ROOT SUMMARY

ROOTS FROM SECF20  (FUEL SYSTEM CHUGGING DECAY RATE)                                          DECAY RATE       FREQUENCY
                                                                                               -.851901         0.
                                                                                               -8.73039          12.0086
                                                                                               -8.73039         -12.0086

ROOTS FROM SECF21  (OXIDIZER SYSTEM CHUGGING DECAY RATE)                                      DECAY RATE       FREQUENCY
                                                                                               -.339437         2.168328E-07
                                                                                               -.124060          1.36177
                                                                                               -.124060         -1.36177

ROOTS FROM SECF25  (STABILITY LONGITUDINAL TIME LAG)                                          DECAY RATE       FREQUENCY
        COAXIAL INJECTION                                                                      -.443645        -3.841828E-07
                                                                                               -.346220          3.01183
                                                                                               -.346226         -3.01184

ROOTS FROM SECF27  (STABILITY TRANSVERSE TIME LAG)                                            DECAY RATE       FREQUENCY
        COAXIAL INJECTION               IFREQ = 1       SNUM =    1.84129                      -.340561         -2.66368
        COAXIAL INJECTION               IFREQ = 3       SNUM =    3.83170                     -5.376885E-02      3.55445
                                                                                              -5.376337E-02     -3.55449
        COAXIAL INJECTION               IFREQ = 4       SNUM =    7.01560                     -4.910274E-02      7.03408
                                                                                              -4.909611E-02     -7.03407
        COAXIAL INJECTION               IFREQ = 5       SNUM =    5.33130                     -9.847667E-02      5.38269
                                                                                              -9.847565E-02     -5.38269
        COAXIAL INJECTION               IFREQ = 7       SNUM =    6.70600                      -.266044          6.35468
                                                                                               -.266041         -6.35468

ROOTS FROM SECF28 (STABILITY LPC RESPONSE FUNCTION)                                           DECAY RATE       FREQUENCY
        (1) FIRST TRANSVERSE MODE            BESARG =   1.84120                                -.133496          1.79443
                                                                                               -.133488         -1.79442
        (2) SECOND TRANSVERSE MODE           BESARG =   3.05430                                -.266868          3.23054
                                                                                               -.266829         -3.23056
        (3) THIRD TRANSVERSE MODE            BESARG =   4.20120                                -.244308          4.34421
                                                                                               -.244291         -4.34415
        (4) FIRST RADIAL MODE                BESARG =   3.83170                                -.254212          3.98426
                                                                                               -.254184         -3.98422
        (5) LONGITUDINAL MODE                BESARG =  0.                                     -2.470107E-02      2.314476E-02
```

TABLE 4-14. Stability Root Set after 100 Perturbations

Both roots are well damped; however, since the imaginary parts of these roots differ markedly from the value of $S_{\nu h}$(3.0543) a "ray search" was carried out through the design space. This search proceeded along the ray joining the nominal engine design to the final design obtained after 100 iterations. The ability to carry out this type of ray search through an n-dimensional space (in this case, a twelve-dimensional space) is a standard feature of the AESOP program. Fifty-two points were equi-distributed along the ray search joining the nominal and final design. The root corresponding to $S_{\nu h} = 3.0543$ was *tracked along the ray* starting from the nominal design. Root variation along the ray is presented in Figure 4-5. The root at

$$z = (-.03257 + j3.0521)$$

presented in Table 4-7 tracks continually into the root at

$$z_1 = (-.443094 + j2.73775)$$

confirming this root as a valid solution to the stability root characteristic equation. Both final roots, z_1 and z_2, obtained for $S_{\nu h} = 3.0543$ are, therefore, considered to be valid roots. Their heavily damped nature results in their providing no contribution to the final engine rating. It can be seen from Figure 4-5 that the root at z_1 is becoming more stable as the design progresses and that the root at z_2 is becoming less stable.

4.3.4 Verification of Optimal Solution. The optimal solution reported in Section 4.3.2 was verified in two ways. *First,* the solution was continued for 100 additional iterations with the uniform random ray and pattern search algorithms. A slight performance improvement resulted. A final rating of 209.43 pounds was attained, a gain of 1.3 pounds over the solution of Section 4.3.2. *Second,* the solution was restarted from the nominal solution using a different search algorithm. The algorithm used in this second solution was a recently developed directed random ray search, Appendix B, in combination with the pattern acceleration algorithm. The final rating obtained by this method was 209.46 pounds after 100 iterations. Convergence of this solution has been added to Figure 4-1. It is clear that a final solution has been obtained. It is also clear that the newly developed search provides more rapid convergence to the solution than the older uniform directed ray search. This behavior is in keeping with other tests of the new search.

4.4 Conclusions for Sample Engine

The AUTOCOM code has successfully developed an improved engine design starting from the existing nominal engine. The payload potential of the engine was improved by 87 pounds as measured by the rating equation. The computer time required by the AUTOCOM code was minimal. The average time

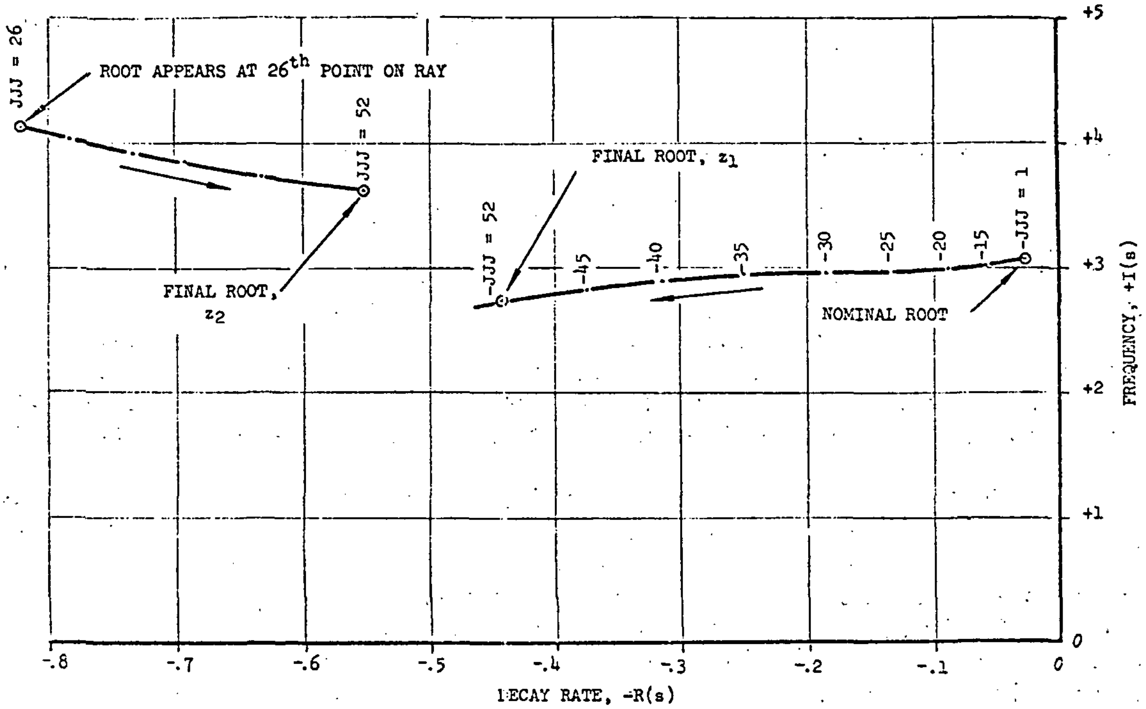


Figure 4-5. Root Locus Plot for Ray Search

requirement for an assessment of each combustor design was approximately two seconds on the CDC 6600 computer. Computer time absorbed by the optimization subprogram AESOP in determining suitable design variable perturbations was negligible--approximately 103 seconds. The engine was optimized in one hundred design perturbations; hence, total computer time required to optimize the design was approximately four (4) minutes. More computer time would be required if combustor stability problems had been encountered. In this eventuality, it is estimated that twenty (20) minutes computer time would be required to obtain a solution. A definitive assessment of computer time in such a case awaits further experience using the AUTOCOM code.

An examination of the optimal engine components reveals that the payload gain was largely obtained from improvements in the performance, chamber length, and chamber diameter characteristics. Small payload gains also resulted from improved stability and pressure drop characteristics. The injector complexity characteristic and the chamber mixture ratio characteristic both contributed performance losses when the final engine is compared to the nominal engine.

A complicated set of design variable perturbations were introduced to obtain the payload capability improvement. An assessment of the design variable changes by the optimization algorithms indicates that the number of fuel and oxidizer holes, volume of the oxidizer dome, volume of the fuel dome, length of the combustion chamber, chamber diameter, and the mixture ratio are all sensitive design variables in the engine considered. In particular, in both optimal solutions obtained the number of fuel and oxidizer holes rapidly rises to the upper limit permitted, indicating that further payload improvement might result from a further increase in the number of holes allowed. Diameter of the fuel holes, diameter of the oxidizer holes, length of the fuel holes, and length of the oxidizer holes were relatively insensitive design variables for the engine design considered, presumably because of the basic stability of this engine.

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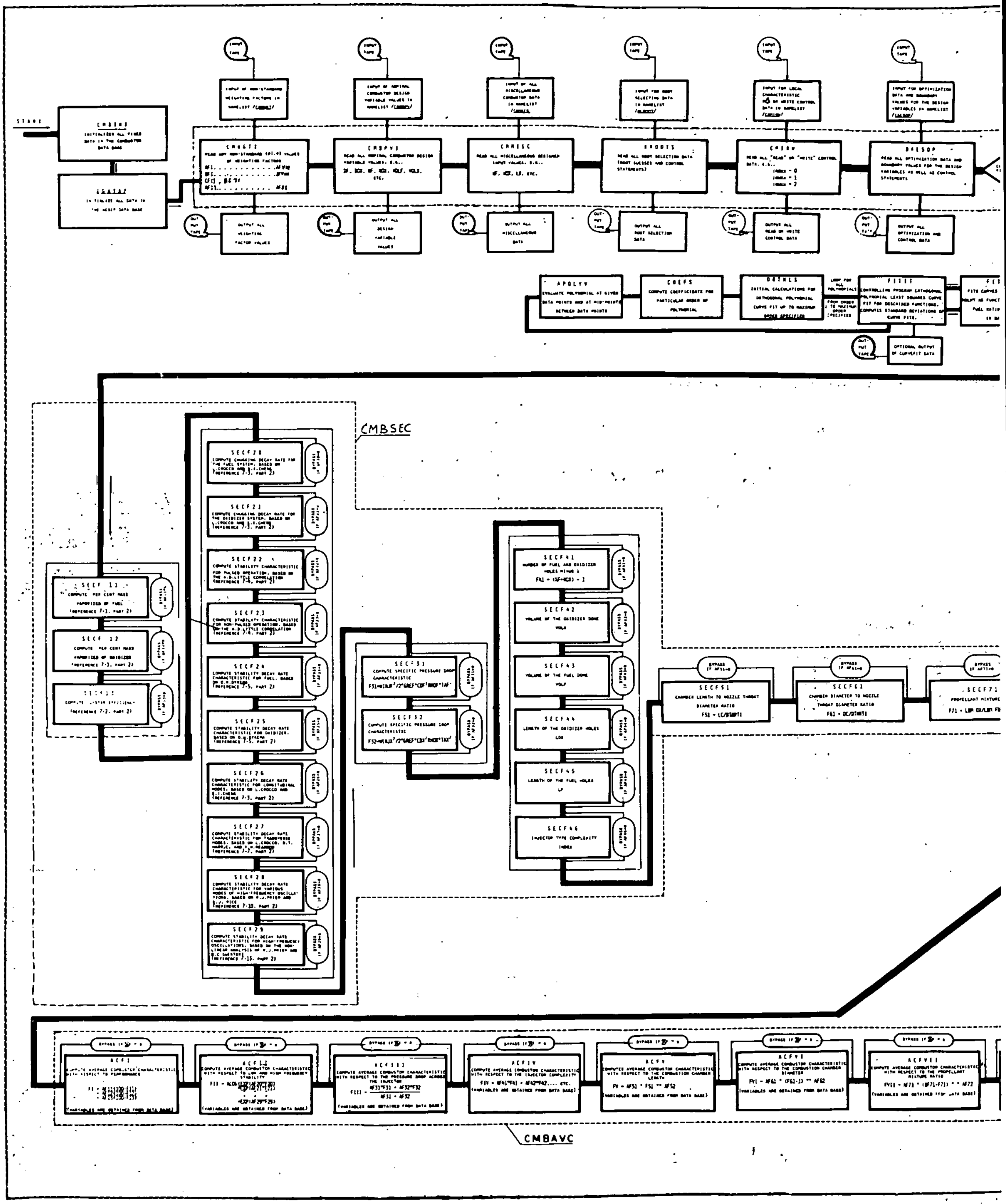
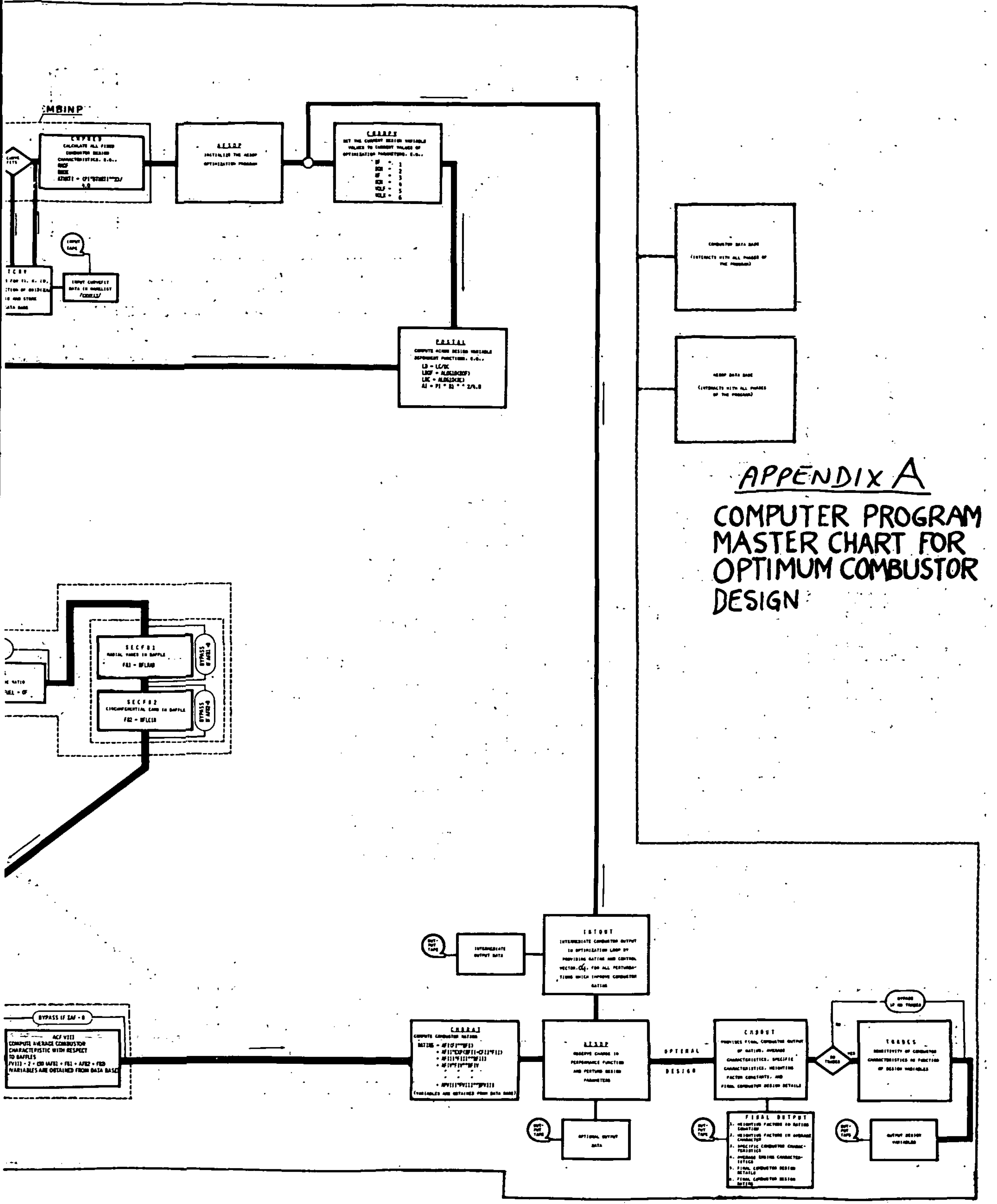
4-2 Hague, D. S. and Glatt, C. R., "A Guide to the Automated Engineering and Scientific Optimization Program (AESOP)," NASA CR-73201, April, 1968.

7-3 Bastress,E.K.,Harris,G.H., and Miller,I.,"Statistical Derivation of Design Criteria for Liquid Rocket Combustion Instability," NASA CR-72370, December, 1967.


START
CMBINI
INITIALIZES ALL FIXED DATA IN THE COMBUSTOR DATA BASE
INPUT TAPE
INPUT OF NON-STANDARD WEIGHTING FACTORS IN NAMELIST
CMWGTI
READ ANY NON-STANDARD VALUES OF WEIGHTING FACTORS
OUTPUT TAPE
OUTPUT ALL WEIGHTING FACTOR VALUES
INPUT OF NOMINAL COMBUSTOR DESIGN VARIABLE VALUES IN NAMELIST
CMDPVI
READ ALL NOMINAL COMBUSTOR DESIGN VARIABLE VALUES, E.G.,
DF, DCX, NF, NOX, VOLF, VOLX, ETC.
OUTPUT ALL DESIGN VARIABLE VALUES
INPUT OF ALL MISCELLANEOUS COMBUSTOR DATA IN NAMELIST
CMMISC
READ ALL MISCELLANEOUS DESIGNED INPUT VALUES, E.G.,
NF, NOX, LF, ETC.
OUTPUT ALL MISCELLANEOUS DATA
INPUT FOR ROOT SELECTING DATA IN NAMELIST
SROOTS
READ ALL ROOT SELECTION DATA (ROOT GUESSES AND CONTROL STATEMENTS)
OUTPUT ALL ROOT SELECTION DATA
INPUT FOR LOCAL CHARACTERISTIC READ OR WRITE CONTROL DATA IN NAMELIST
CMIRW
READ ALL "READ" OR "WRITE" CONTROL DATA, E.G.,
INDEX = 0
INDEX = 1
INDEX = 2
OUTPUT ALL READ OR WRITE CONTROL DATA
INPUT FOR OPTIMIZATION DATA AND BOUNDARY VALUES FOR THE DESIGN VARIABLES IN NAMELIST
DELSOP
READ ALL OPTIMIZATION DATA AND BOUNDARY VALUES FOR THE DESIGN VARIABLES AS WELL AS CONTROL STATEMENTS
OUTPUT ALL OPTIMIZATION AND CONTROL DATA
APOLYV
EVALUATE POLYNOMIAL AT GIVEN DATA POINTS AND AT MID-POINTS BETWEEN DATA POINTS
COEFS
COMPUTE COEFFICIENTS FOR PARTICULAR ORDER OF POLYNOMIAL
ORTHLS
INITIAL CALCULATIONS FOR ORTHOGONAL POLYNOMIAL CURVE FIT UP TO MAXIMUM ORDER SPECIFIED
LOOP FOR ALL POLYNOMIALS FROM ORDER 1 TO MAXIMUM ORDER SPECIFIED
FITIT
CONTROLLING PROGRAM ORTHOGONAL POLYNOMIAL LEAST SQUARES CURVE FIT FOR DESCRIBED FUNCTIONS. COMPUTES STANDARD DEVIATIONS OF CURVE FITS.
FITS CURVES
OPTIONAL OUTPUT OF CURVEFIT DATA
CMBSEC
SECF 11
COMPUTE PER CENT MASS VAPORIZED OF FUEL (REFERENCE 7-1, PART 2)
SECF 12
COMPUTE PER CENT MASS VAPORIZED OF OXIDIZER (REFERENCE 7-1, PART 2)
SECF13
COMPUTE C-STAR EFFICIENCY (REFERENCE 7-2, PART 2)
SECF20
COMPUTE CHUGGING DECAY RATE FOR THE FUEL SYSTEM, BASED ON L.CROCCO AND S.I.CHENG (REFERENCE 7-3, PART 2)
SECF21
COMPUTE CHUGGING DECAY RATE FOR THE OXIDIZER SYSTEM, BASED ON L.CROCCO AND S.I.CHENG (REFERENCE 7-3, PART 2)
SECF22
COMPUTE STABILITY CHARACTERISTIC FOR PULSED OPERATION, BASED ON THE A.D.LITTLE CORRELATION (REFERENCE 7-4, PART 2)
SECF23
COMPUTE STABILITY CHARACTERISTIC FOR NON-PULSED OPERATION, BASED ON THE A.D.LITTLE CORRELATION (REFERENCE 7-4, PART 2)
SECF24
COMPUTE STABILITY DECAY RATE CHARACTERISTIC FOR FUEL, BASED ON D.H.DYKEMA (REFERENCE 7-5, PART 2)
SECF25
COMPUTE STABILITY DECAY RATE CHARACTERISTIC FOR OXIDIZER, BASED ON D.H.DYKEMA (REFERENCE 7-5, PART 2)
SECF26
COMPUTE STABILITY DECAY RATE CHARACTERISTIC FOR LONGITUDINAL MODES, BASED ON L.CROCCO AND S.I.CHENG (REFERENCE 7-3, PART 2)
SECF27
COMPUTE STABILITY DECAY RATE CHARACTERISTIC FOR TRANSVERSE MODES, BASED ON L.CROCCO, D.T. HARRJE, AND F.H.REARDON (REFERENCE 7-7, PART 2)
SECF28
COMPUTE STABILITY DECAY RATE CHARACTERISTIC FOR VARIOUS MODES OF HIGH-FREQUENCY OSCILLATIONS, BASED ON R.J.PRIEM AND D.J. RICE (REFERENCE 7-10, PART 2)
SECF29
COMPUTE STABILITY DECAY RATE CHARACTERISTIC FOR HIGH-FREQUENCY OSCILLATIONS, BASED ON THE NON-LINEAR ANALYSIS OF R.J.PRIEM AND D.C GUENTERT (REFERENCE 7-15, PART 2)
BYPASS IF AF
SECF31
COMPUTE SPECIFIC PRESSURE DROP CHARACTERISTIC
F31=WFRJF²/2*GREF*CDF²RHOF*TAF²
SECF32
COMPUTE SPECIFIC PRESSURE DROP CHARACTERISTIC
F32=WXRJX²/2*GREF*CDX²RHOX*TAX²
SECF41
NUMBER OF FUEL AND OXIDIZER HOLES MINUS 1
F41 = (NF+NOX) - 1
SECF42
VOLUME OF THE OXIDIZER DOME
VOLX
SECF43
VOLUME OF THE FUEL DOME
VOLF
SECF44
LENGTH OF THE OXIDIZER HOLES
LOX
SECF45
LENGTH OF THE FUEL HOLES
LF
SECF46
INJECTOR TYPE COMPLEXITY INDEX
BYPASS IF AF51=0
SECF51
CHAMBER LENGTH TO NOZZLE THROAT DIAMETER RATIO
F51 = LC/DTHRT1
BYPASS IF AF61=0
SECF61
CHAMBER DIAMETER TO NOZZLE THROAT DIAMETER RATIO
F61 = DC/DTHRT1
BYPASS IF AF71=0
SECF71
PROPELLANT MIXTURE
F71 = LBM OX/LBM FU
BYPASS IF = 0
ACFI
COMPUTE AVERAGE COMBUSTOR CHARACTERISTIC WITH RESPECT TO PERFORMANCE
(VARIABLES ARE OBTAINED FROM DATA BASE)
ACFII
COMPUTE AVERAGE COMBUSTOR CHARACTERISTIC WITH RESPECT TO LOW AND HIGH FREQUENCY STABILITY
(VARIABLES ARE OBTAINED FROM DATA BASE)
ACFIII
COMPUTE AVERAGE COMBUSTOR CHARACTERISTIC WITH RESPECT TO THE PRESSURE DROP ACROSS THE INJECTOR
FIII = (AF31*F31 + AF32*F32)/(AF31 + AF32)
(VARIABLES ARE OBTAINED FROM DATA BASE)
ACFIV
COMPUTE AVERAGE COMBUSTOR CHARACTERISTIC WITH RESPECT TO THE INJECTOR COMPLEXITY
FIV = AF41*F41 + AF42*F42.... ETC.
(VARIABLES ARE OBTAINED FROM DATA BASE)
ACFV
COMPUTES AVERAGE COMBUSTOR CHARACTERISTIC WITH RESPECT TO THE COMBUSTION CHAMBER LENGTH
FV = AF51 * F51 ** AF52
(VARIABLES ARE OBTAINED FROM DATA BASE)
ACFVI
COMPUTE AVERAGE COMBUSTOR CHARACTERISTIC WITH RESPECT TO THE COMBUSTION CHAMBER DIAMETER
FVI = AF61 * (F61-1) ** AF62
(VARIABLES ARE OBTAINED FROM DATA BASE)
ACFVII
COMPUTE AVERAGE COMBUSTOR CHARACTERISTIC WITH RESPECT TO THE PROPELLANT MIXTURE RATIO
FVII = AF71 * (BF71-F71) ** AF72
(VARIABLES ARE OBTAINED FROM DATA BASE)
CMBAVC

APPENDIX A

COMPUTER PROGRAM MASTER CHART FOR OPTIMUM COMBUSTOR DESIGN



B.1. INTRODUCTION TO THE OPTIMIZATION PROGRAM AESOP

Program AESOP (Automated Engineering and Scientific Optimization Program) is a digital computer subprogram designed for solution of a wide range of multivariable parameter optimization problems on the CDC 6600, UNIVAC 1108, IBM 7094, or IBM 360 computers. The basic program described within this document has the ability to solve constrained nonlinear optimization problems involving up to one hundred free parameters and twenty nonlinear functional equality or inequality constraints. Of particular significance are the program's ability to

1. Use a combination of search procedures
2. Locate saddle points as well as maxima or minima
3. Locate more than one extremal

Thirteen search techniques available for problem solution are listed in Table I. The searches may be employed separately or in any sequential combination, at the user's option.

The AESOP program may be rapidly coupled to a wide class of parameter optimization problems including systems which have been synthesized as digital computer programs prior to their coupling to AESOP. For many problems this is achieved by adding a single named COMMON to the existing synthesis program and equating its controlling parameters to members of an array (ALPHA_i) and the output functions of interest to a second array (FUNCTN_j). Large scale synthesis programs will require additional effort if the combined AESOP/synthesis programs exceed core size and hence require the use of the overlay feature. Treatment of this size of problem is enhanced in AESOP by the provision of a single call to the synthesis program from the optimizer main program. This call is then utilized by all searches permitting overlay of the entire optimizer against the synthesis program.

The optimization program is written in the algebraic FORTRAN IV language. The program has been successfully operated on the CDC 6600, the UNIVAC 1108, the IBM 7094, and the IBM 360.

The subprogram AESOP may readily be retrieved from the AUTOCOM program and treated as a subprogram entity.

TABLE I. DESCRIPTION OF THIRTEEN SEARCH METHODS

SECTIONING SEARCH: The local performance minima in a sequence of searches parallel to the coordinate axes are located, and, hence, by repetition the extremal of the multivariable function is located.

PATTERN SEARCH: Explores the gross direction revealed by a preceeding search or search sequence.

MAGNIFICATION SEARCH: Searches the direction defined by a proportional change in all parameters.

STEEPEST-DESCENT SEARCH: Searches along a sequence of rays determined by the local direction in which performance decreases most rapidly for a given perturbation measure. Three perturbation measure options together with the relevant weighting matrices are available within the program.

ADAPTIVE CREEPING SEARCH: Similar to sectioning but instead of finding the local minima parallel to the axes, this search merely introduces small perturbations in the minimizing direction. The size of these perturbations is determined adaptively by the search algorithm.

QUADRITIC SEARCH: Similar to the steepest-descent except for search directions. These are aligned through the extremals of a sequence of locally osculating second-order surfaces (as opposed to the first-order) tangent planes employed in the steepest-descent search.

DAVIDON SEARCH: A particular form in the steepest-descent search. It progressively approaches the second-order quadratic search from information obtained by a sequence of first-order steepest-descent searches.

RANDOM POINT SEARCH: The performance is evaluated at the set of uniformly distributed random points in the parameter space in a Monte-Carlo-like manner.

UNIFORM RANDOM RAY SEARCH: Small perturbations are introduced sequentially along a series of randomly directed rays in the control space.

DIRECTED RANDOM RAY SEARCH: This search proceeds along a succession of random rays distributed about a best estimate of the gradient vector.

ARBITRARY RAY SEARCH: A search along an arbitrary multi-dimensional ray joining two points in the design variable space.

JACOBSON SEARCH: The jacobson algorithm is based upon homogeneous functions rather than quadratic models. A consequence of this is that (N+2) step convergence is obtained for homogeneous functions and that no one-dimensional search is required.

MAPPING SEARCH: Generates a contour map of the performance surface perturbing two parameters at a time holding all others constant.

B.2. A GUIDE TO PROGRAM AESOP USAGE

B.2.1 Outline of Program AESOP

AESOP is constructed in a modular fashion. It includes more than one hundred subroutines which, for descriptive purposes, can be arranged into the thirteen sets illustrated schematically in Figure 1. Each set of subroutines collectively function to perform one of the searches described in Table I. In addition to the thirteen major subroutine sets various ancillary subroutines are used in support of the search procedures. These include, for example, the multiple extremal search procedure and the saddle point search procedure.

. A flexible input format is provided through the FORTRAN NAMELIST input procedure. All AESOP data is entered through a single NAMELIST block labelled IAESOP. All optimization data is nominally set by block data within AESOP; this data may be modified at the user's option; only that data which varies from the standard value need be read into the program. This feature reduces data input and hence the tedium of preparing a case or the chance of input error.

The program structure employed in the synthesis program is entirely dependent on the particular problem being studied. For example, in Reference 1,an application to the design of hypersonic cruise vehicles, the MAIN program controlled an extensive overlayed program containing all major technologies entering into the design of a high speed aircraft. The structure for the polynomial valley function $\phi = (ax - b)^N + (cy - d)^N = exy$, on the other hand, would consist of a single coded expression. The optimizer structure is independent of the synthesis model employed. The optimizer selectively calls the thirteen search controlling subroutines. Each one of the thirteen search controlling subroutines may split into several lower level subroutines controlling major search functions. The two auxiliary subprograms WARPS (for multiple extremal search) and SADDLE (for solution of mini-max problems) may be used in conjunction with any search procedure or search procedure combination.

More detailed information is presented in Reference 2. Detailed results illustrating the application of program AESOP are contained in References 3, 4 , 5 , 6 , and 7. The analytical development of the program is contained in References 2 and 3.

B.2.2 Coupling of Mathematical Model to the Optimizer

Program AESOP assumes that it is operating on a programmed model of a nonlinear parametrically defined system and that a system evaluation with a given set of parameter values results in a unique evaluation of the system output functions.

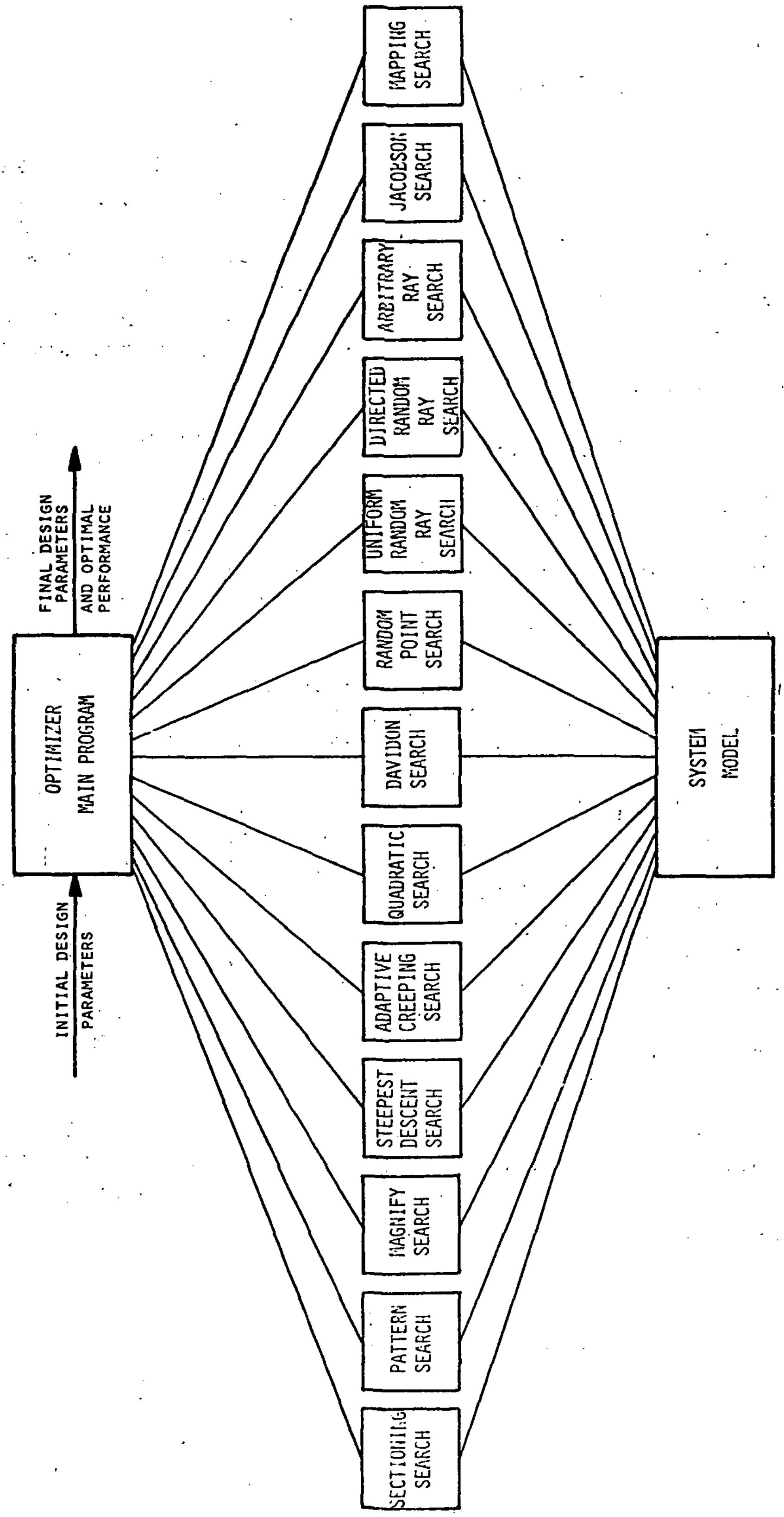


Figure 1. Schematic of Optimization Program - AESOP

Several modifications are required in the system main program, specifically:

1. COMMON/AESOPD/------, of the optimization program should be introduced.

2. The parameters to be optimized should be equated or equivalenced (being careful to avoid difficulties with COMMON) to the ALPHA array contained in COMMON/AESOPD/.

3. The functions of interest which include the performance and constraint functions should be equated or equivalenced to the array FUNCTN contained in COMMON/AESOPD/.

   NOTE: The performance function must be phrased as a function to be *minimized.*

4. Any system input data in addition to the optimization program input should only be read when JJJ = 1. This integer variable contains the number of performance evaluations performed by the optimizer and is also contained in COMMON/AESOPD/.

5. An initial call to AESOP must precede the optimization loop. The optimization loop must be created using the integer NSR contained in COMMON/AESOPD/.

This can be illustrated with a simple example. Suppose the function $\phi = 100(y-x^2)^2 + (1 - x)^2$ is to be minimized. A satisfactory CDC 6600 MAIN program would be

```
      PROGRAM MAIN (INPUT, OUTPUT, TAPE5=INPUT, TAPE6=OUTPUT,
     $                TAPE1, TAPE2)
      COMMON /AESOPD/ ADATA(5000)
C     DEFINE AESOP COMMON
      REAL ALPHA(100)
C     DEFINE THE PARAMETER ARRAY SIZE
      REAL FUNCTN(100)
C     DEFINE THE SYSTEM FUNCTION ARRAY SIZE
      EQUIVALENCE(ADATA( 742), ALPHA )
C     DEFINE POSITION OF FIRST PARAMETER
      EQUIVALENCE(ADATA(2552), FUNCTN)
```

```
C     DEFINE POSITION OF FIRST FUNCTION
      EQUIVALENCE{ADATA{3L25}, NSR   }
C     DEFINE POSITION OF AESOP LOOP INDICATOR
      EQUIVALENCE{ALPHA{1}, X},{ALPHA{2}, Y}
C     EQUATE SYSTEM PARAMETERS TO AESOP OPTIMIZATION PARAMETERS
      CALL AESOP
C     READ IN ANY NON STANDARD OPTIMIZATION DATA
 7777 CONTINUE
C     PARAMETER OPTIMIZATION LOOP
      F = 100.0*{Y -X**2}**2 +{1.0 -X}**2
C     EVALUATE SYSTEM
      FUNCTN{1}=F
C     TRANSFER SYSTEM OUTPUT INTO AESOP FUNCTION
      CALL AESOP
C     AESOP OPTIMIZATION POINT
      IF {NSR .EQ. 1}  GO TO 7777
C     RETURN FOR NEW EVALUATION UNTIL SYSTEM OPTIMIZED
      END
```

B.2.3 AESOP Overlay Structure

For programs that exceed core size the overlay structure shown in Figure 2 may be used. For the overlay version of AESOP it will be necessary to make several changes to the MAIN PROGRAM for links 0,0 and 1,0; the setup for overlay is shown in Figures 3 and 4. Figure 5 presents the overlay version of SELECT, and Figure 6 shows the additional programs required by the overlay structure. The text cards for COPYLIB are given in Figure 7 The total core required to load the AESOP overlay configuration shown in Figure 2 is approximately 50000_8.

(0,0)
MAIN PROGRAM *With Calls to the Synthesis and* AESOP *Subprograms*

(1,0)
Synthesis Subroutines

(2,0)

AESOP
SELECT
INITOP
WARPS
BESTAF
MAINOP
SADDLE
PENLTY
PGAIN

BESTRN
ALFLIM
INEVAL
FESET
SAVALF
PATERN
PSRCH
WEIGHT
ENDCYC

FNEVAL
OUTALF
OUTFUN
SUMARY
OUTWGT
OUTSUM
PCYCLE
PFINAL
HPLOT

MOVER
DRVR
MESSEG
PLOTS
TRACEX
XTENAL
PLOTE
PLOT
SYMBOL

LINE
AXIS
SCALE
WHERE
NUMBER

(2,1)	(2,2)	(2,3)	(2,4)	(2,5)	(2,6)	(2,7)	(2,10)	(2,11)	(2,12)	(2,13)	(2,14)	(2,15)
SRCH01	INPUTA	SRCH03	SRCH04	SRCH05	SRCH06	SRCH07	SRCH08	SRCH09	SRCH10	SRCH11	SRCH12	SRCH13
SECCOM	BAESOP	MAGNFY	STDESC	CREEPR	QUADRA	DAVIDN	RPOINT	RANRAY	RANRAY	RAYSEC	JACOBS	MAPPER
RANDUM	BDATA8		DERIV	RANDUM	MINALP	DERIV	RGEN	RANCOS	RANCOS		GRADV	OUTMAP
BOUND	NLOUTA		WMAT	ASVCHK	ALPERT	DMATRX	FESAV	FESAV	FESAV			CONMAP
SECTON	NLOUTS		INISTD	FESAV	ALFNUL	INISTD		RGEN	RGEN			
RGEN	NLOUTD		SECTON	RGEN	QDTRAN	SECTON						
SHELL	NLOUTC		STDALF	SHELL	QUADOP	SAVDER						
FUNTYP	NLOUTB		FUNTYP		MAXRDP	STDALF						
STDALF	NLOUTL				INISTD	FUNTYP						
	NLOUTI				SECTON							
	NLOUTX				MATMLT							
					QMXINV							
					STDALF							
					FUNTYP							

Figure 2. AESOP Overlay Structure for CDC 6600

```
      PROGRAM MAIN{INPUT, OUTPUT}, TAPE5=INPUT, TAPE6=OUTPUT,
     $             TAPE1, TAPE2}
      COMMON/AESOPD/ ADATA{8000}
      EQUIVALENCE{ADATA{3125}, NSR
  100 CONTINUE
      CALL OVERLAY{7LAESOPOL, 2, 0, 6HRECALL}
 7777 CONTINUE
      CALL OVERLAY{7LAESOPOL, 1, 0, 6HRECALL}
      CALL OVERLAY{7LAESOPOL, 2, 0, 6HRECALL}
      IF {NSR .EQ. 1}  GO TO 7777
      GO TO 100
      END
```

Figure 3. Sample MAIN Program for Link 0, 0

```
      PROGRAM EQNS
      COMMON/AESOPD/ ADATA{8000}
      REAL ALPHA{100}
      REAL FUNCTN{100}
      EQUIVALENCE{ADATA{ 742}, ALPHA }
      EQUIVALENCE{ADATA{2552}, FUNCTN}
      EQUIVALENCE{ALPHA{1}, X},{ALPHA{2}, Y}
C     ROZENBROCK VALLY
      FUNCTN{1} = 100.0*{Y -X2}**2 +{1.0 -X}**2
      END
```

Figure 4. Sample MAIN Program for Synthesis Link 1,0

```
      SUBROUTINE SELECT
      COMMON /AESOPD/ADATA(8000)
      EQUIVALENCE(ADATA(2952), METHOD)
      GO TO (1, 2, 3, 4, 5, 6, 7, 8, 9, 10,11, 12, 13), METHOD
    1 CONTINUE
      CALL OVERLAY(7LAESOPOL, 2, 1, 6HRECALL)
      RETURN
    2 CONTINUE
      RETURN
    3 CONTINUE
      CALL OVERLAY(7LAESOPOL, 2, 3, 6HRECALL)
      RETURN
    4 CONTINUE
      CALL OVERLAY(7LAESOPOL, 2, 4, 6HRECALL)
      RETURN
    5 CONTINUE
      CALL OVERLAY(7LAESOPOL, 2, 5, 6HRECALL)
      RETURN
    6 CONTINUE
      CALL OVERLAY(7LAESOPOL, 2, 6, 6HRECALL)
      RETURN
    7 CONTINUE
      CALL OVERLAY(7LAESOPOL, 2, 7, 6HRECALL)
      RETURN
    8 CONTINUE
      CALL OVERLAY(7LAESOPOL, 2, 10B, 6HRECALL)
      RETURN
    9 CONTINUE
      CALL OVERLAY(7LAESOPOL, 2, 11B, 6HRECALL)
      RETURN
   10 CONTINUE
      CALL OVERLAY(7LAESOPOL, 2, 12B, 6HRECALL)
      RETURN
   11 CONTINUE
      CALL OVERLAY(7LAESOPOL, 2, 13B, 6HRECALL)
      RETURN
   12 CONTINUE
      CALL OVERLAY(7LAESOPOL, 2, 14B, 6HRECALL)
      RETURN
   13 CONTINUE
      CALL OVERLAY(7LAESOPOL, 2, 15B, 6HRECALL)
      RETURN
      ENTRY AESOPI
      CALL OVERLAY(7LAESOPOL, 2, 2, 6HRECALL)
      RETURN
      END
```

Figure 5. Overlay Version of Subroutine SELECT

```
PROGRAM SRCH20
CALL AESOP
END
PROGRAM SRCH01
CALL SECCON
END
PROGRAM INPUTA
CALL B AESOP
END
PROGRAM SRCH03
CALL MAGNFY
END
PROGRAM SRCH04
CALL STDESC
END
PROGRAM SRCH05
CALL CREEPR
END
PROGRAM SRCH06
CALL QUADRA
END
PROGRAM SRCH07
CALL DAVIDN
END
PROGRAM SRCH08
CALL RPOINT
END
PROGRAM SRCH09
CALL RANRAY
END
PROGRAM SRCH10
CALL RANRAY
END
PROGRAM SRCH11
CALL RAYSEC
END
PROGRAM SRCH12
CALL JACOBS
END
PROGRAM SRCH13
CALL MAPPER
END
```

Figure 6. Additional Programs Required by the Overlay Version of SELECT

```
OVERLAY(AESOPOL,0,0)
MAIN
OVERLAY(AESOPOL,1,0)
EQNS
OVERLAY(AESOPOL,2,0)
SRCH20
OVERLAY(AESOPOL,2,1)
SRCH01
OVERLAY(AESOPOL,2,2)
INPUTA
OVERLAY(AESOPOL,2,3)
SRCH03
OVERLAY(AESOPOL,2,4)
SRCH04
OVERLAY(AESOPOL,2,5)
SRCH05
OVERLAY(AESOPOL,2,6)
SRCH06
OVERLAY(AESOPOL,2,7)
SRCH07
OVERLAY(AESOPOL,2,10)
SRCH08
OVERLAY(AESOPOL,2,11)
SRCH09
OVERLAY(AESOPOL,2,12)
SRCH10
OVERLAY(AESOPOL,2,13)
SRCH11
OVERLAY(AESOPOL,2,14)
SRCH12
OVERLAY(AESOPOL,2,15)
SRCH13
```

Figure 7. COPYLIB Text Cards

B.3. AESOP DATA INPUT

Program AESOP data can be conveniently grouped according to search and function. The user employing a particular search can independently specify the characteristics of that search and may not be concerned with input relevant to the other searches. Hence, a data grouping by search and by function is presented below for user convenience. It should be noted that certain inputs are common to more than one search; where this occurs, the input is repetitively defined in each search. All AESOP data is introduced through a single FORTRAN NAMELIST labelled IAESOP. All data is nominally established by the Block Data Subroutine BDATA7.

B.3.1 Search Selection and Control

There are thirteen search procedures embodied in the AESOP subprogram. The user may select any sequential combination of these searches through data input.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
NUMOPT	The number of optimization techniques to be employed. Each individual search request in a sequence of requests adds to this input (e.g., the search sequence 4,2,4,2 requires NUMOPT=4). Maximum number of searches employed must satisfy NUMOPT < 20.	2
METHOP$_i$	The search sequence by numeric identification. For example, the input METHOP(1) = 1,2,3,4,5, 6,7,8,9,10,11,12,13 signifies the following search sequence: 1 - Sectioning 2 - Pattern 3 - Magnification 4 - Steepest-Descent 5 - Adaptive Creeping 6 - Quadratic 7 - Davidon (Fletcher-Powell) 8 - Random Point (Monte-Carlo) 9 - Random Ray (random evolution) 10 - Directed Random Ray 11 - Arbitrary Ray 12 - Jacobson 13 - Mapper The complete search sequence will be referred to as an *optimization cycle*.	10, 2
MAXJJJ	The maximum number of system evaluations. A direct iteration number limit.	200
IREPET	The maximum number of times the search sequence (optimization cycle) defined in METHOP$_i$ will be utilized.	1

B.3.2 Parameter Selection

The user may equate any parameter in the system under study to an optimization parameter. This is usually most readily accomplished in the user's MAIN program. If the initial AESOP call follows the system program, input parameter values entered through AESOP override the system values.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
NALPHA	The number of parameters available for optimization. No more than one hundred parameters may be employed.	0
$ALPLO_i$	Lower bounds on each parameter search range.	100*0.0
$ALPHI_i$	Upper bounds on each parameter search range.	100*0.0
$ALPHA_i$	The nominal parameter values. Note that $ALPLO_i \leqslant ALPHA_i \leqslant ALPHI_i$ must be satisfied. If a particular parameter, say $ALPHA_j$, is to be fixed in value in a particular computation, then set $ALPLO_j = ALPHA_j = ALPHI_j$. This effectively reduces the parameter space dimension by one for each such parameter.	100*0.0
HILO	If HILO is greater than zero the lower and upper bounds on each parameter will be dynamically determined such that $\alpha_{L_i} = \alpha_i - \frac{HILO*\lvert\alpha_i\rvert}{2}$ $\alpha_{h_i} = \alpha_i + \frac{HILO*\lvert\alpha_i\rvert}{2}$ provided HILO * $\lvert\alpha_i\rvert > (\alpha'_{h_i} - \alpha'_{L_i})$ where α'_{h_i} and α'_{L_i} are the current values of the parameter bounds. This option permits the user to define dynamically a percentage search region centered about the current value for each parameter.	0

B.3.3 Multiple Extremal Option

AESOP contains a multiple extremal search procedure based on a warping of the response surface. In this transformation hypervolumes in the region of a known extremal point are reduced in magnitude and hypervolumes far removed are increased in magnitude.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
IWARP	Controls multiple extremal option: = 1, automatically warps the response surface = 0, leaves the response surface unmodified	0
$WARPAL_i$	The point at which the warping transformation is centered, i.e., the location of a known extremal point	100*0.0
WARPN	The degree of the warping transformation. The greater WARPN, the greater the response surface distortion.	2.0

B.3.4 Optimization Function Selection

AESOP operates on an internally defined array of functions. The function to be minimized and those to be constrained are defined by data input. This permits ready specification of alternate optimization problems. It should be noted that constraints are imposed on the basis of an external penalty function approach using quadratic penalty function terms. Penalty function weights are adaptively determined within the code.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
$FUNCTN_i$	An internal array containing all computed optimization functions	100*0.0
NFUNC	The total number of functions ($FUNCTN_i$) being defined and computed in the system model. NOTE: NFUNC $\leqslant$ 100.	1

MNEMONIC	DESCRIPTION	NOMINAL VALUES
NPHIAC	The function to be minimized. AESOP always searches for a minimum; to maximize $FUNCTN_m$ define $$FUNCTN_n = -FUNCTN_m$$ and minimize $$FUNCTN_n$$	1
NUMPSI	The total number of functions being constrained. Note that NUMPSI < 20.	0
$NPSI_i$	The functions to be constrained, e.g., NPSI(1) equal to 3, 5, 1, 7 indicates that $FUNCTN_3$, $FUNCTN_5$, $FUNCTN_1$, and $FUNCTN_7$ are to be constrained.	20*0
$SIBAR_i$	The desired values of the constraint functions defined by $NPSI_i$.	20*0.0
$FTOL_i$	The acceptable final tolerances on the constraint function values, $SIBAR_i$.	20*1.0
$TTOL_i$	Initial acceptable tolerances on the constraint function values (should be approximately 100 times greater than the corresponding $FTOL_i$). These tolerance bands are subsequently reduced in size at a problem dependent rate until they equal the appropriate $FTOL_i$.	20*100.0
$PSIWT_i$	Initial constraint error weighting factors in the augmented performance function, ϕ^*, where $$\phi^* = \phi + \sum_i W_i(\psi_i - \bar{\psi}_i)^2$$ Here $W_i \equiv PSIWT_i$	20*1.0
$WTUP_i$	Incremental multiplicative constants used to increase the W_i on constraints which prove difficult to satisfy. The nominal values of $WTUP_i$=2.0 should be acceptable.	20*2.0

MNEMONIC	DESCRIPTION	NOMINAL VALUES
$WTDOWN_i$	Decremental multiplicative constants used to decrease the W_i when a constraint is easily satisfied. The nominal values of $WTDOWN_i=0.5$ should be acceptable; hence, this input can normally be omitted.	20*0.5
$TOLFAC_i$	Constraint tolerance reduction factor.	20*0.5
INDPSI	Constraint indicator; if INDPSI >0, ψ_i will be constrained $>\bar{\psi}_i$ <0, ψ_i will be constrained $<\psi_i$ =0, ψ_i will be constrained to be within ±FTOL of $\bar{\psi}_i$	0
IPDWGT	Print indicator for constraint weights. Equals 1 to obtain print out of constraint weights each time they are modified.	0

B.3.5 Saddle Point Search

Saddle points are located by replacing a function minimization criteria. At the user's option a sign of curvature correction may be introduced as discussed in Reference 5.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
$MINMAX_i$	Used to indicate minimizing or maximizing control for each parameter -1 indicates minimizing control +1 indicates maximizing control	100*-1
SPOWER	Exponential power used in computing the penalty term when the curvature is the wrong way on a given control parameter.	10.0
SFACTR	Control step size for computing the gradient (i.e., .05 will produce a perturbation of 5% of the range $\alpha_i^{Lo} \rightarrow \alpha_i^{Hi}$	0.05

MNEMONIC	DESCRIPTION	NOMINAL VALUES
ISADEL	=0, saddle point search not used =1, saddle solution only =2, minimum only =3, maximum only =4, saddle, minimum or maximum (minimum gradient magnitude)	0
IPASAD	Print indicator for alpha array; equal to 1 to obtain alpha print from saddle	0
IPFSAD	Print indicator for function array; equal to 1 to obtain function print from saddle	0
IPDSAD	Detail print indicator; equal to 1 to obtain detail print from saddle	0

B.3.6 Detailed Search Data

Data for each of the ten searches is defined below.

B.3.6.1 <u>Sectioning Search Data (METHOP$_i$ = 1)</u>. Uses the Golden Section method to carry out a sequence of one parameter at a time optimization searches.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
LIMIT	The number of times each parameter will be sectioned during a single request for sectioning search.	2
NMAXLO	Maximum number of point evaluations employed in a single parameter's sectioning at search commencement (first optimization cycle). In successive cycles, the maximum number of points employed is increased by one.	15
ISECOF	Indicator used to "turn off" the sectioning search. When the number of optimization cycles exceeds ISECOF, the sectioning search will be "turned off."	1000

MNEMONIC	DESCRIPTION	NOMINAL VALUES
PHIEPS	Performance values within PHIEPS of the minimum value yet attained are treated as being equal in the Golden Section	0.0
NMAXUP	An upper bound on the maximum number of point evaluations employed in sectioning a particular parameter	25
ISIDE	Indicator specifying an arbitrary selection of left or right boundary for a parameter that does not appear to affect the system performance ISIDE=0, select lower limits ISIDE=1, select upper limits	0
$XTENHI_i$	Optional extension of higher search limits ($ALPHI_i$) for a parameter that has gone to the $ALPHI_i$ boundary	100*0.0
$XTENLO_i$	Optional extension of lower search limits ($ALPLO_i$) for a parameter that has gone to the $ALPLO_i$ boundary	100*0.0
IRANDM	Controls the order in which the parameters are sectioned: = 0, random order selected =1, natural order selected =2, reverse natural order selected =3, order of selection is input via KORDER	0
KORDER	An array that contains the subscripts of the parameters in the order that they are to be selected. Required input if IRANDM=3; otherwise generated automatically by AESOP	100*0.0
FACTHI	Section termination criteria. If three successive performance function values are within FACTHI of each other during sectioning of a given parameter on the first optimization cycle, the section search of that parameter will cease. The termination criteria is internally reduced with each optimization cycle.	1.0E-3

MNEMONIC	DESCRIPTION	NOMINAL VALUES
FACTLO	The lower limit on the termination criteria in any optimization cycle	1.0E-5
ITRADE	Optimization/trade study indicator: =0, carry out a normal optimization search =1, determine performance function sensitivity to each parameter by sectioning each parameter in turn about a given fixed point in parameter space.	0
IPASEC IPDSEC IPFSEC	Print indicators for parameter, detail, and function values during sectioning search.	0 0 0

B.3.6.2 Pattern Search Data (METHOP$_i$ = 2). Pattern search is a simple generalized acceleration procedure which may be employed to attempt an acceleration of the trend revealed by a previous search.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
IPAPAT IPDPAT IPFPAT	Pattern search print indicators for parameter detail and function values during pattern search.	0 0 0
NMAXUP	Maximum number of pattern steps; otherwise search will end when $\phi_{new} \geq \phi_{old}$; i.e., failure to "gain" performance	25

B.3.6.3 Magnification Search Data (METHOP$_i$ = 3). This search is useful when the unconstrained extremal solution is the null vector. It searches the ray joining the origin to the current point in parameter space.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
MAXMAG	Maximum number of point evaluations performed during a single magnification search	99

MNENOMIC	DESCRIPTION	NOMINAL VALUES
DELMAG	The magnification perturbation size, nominally set to one per cent of distance to origin. Not normally modified from nominal value.	0.01
IPAMAG IPDMAG IPFMAG	Point indicators for parameter, detail, and function values during each magnification search	0 0 0

B.3.6.4 Steepest-Descent Search Data ($METHOP_i = 4$). The AESOP steepest-descent search features several metric tensor options to deflect the search in a more promising direction than the gradient.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
NUMSTD	Number of gradient evaluations and one-dimensional searches performed each time that a steepest-descent search is requested during the optimization cycle	2
INDWMA	Steepest-descent weighting matrix indicator =0., unit matrix =1., empirical matrix =2., alternate on each cycle between unit and empirical matrices	1
$WITER_i$	Learning factors for steepest-descent weighting matrix	100*1.0
NMAXLO	Maximum number of point evaluations employed in the steepest-descent one-dimensional ray search at search commencement (first optimization cycle). In successive cycles the maximum number of point evaluations permitted is increased by 1.	15
NMAXUP	Upper bound on the number of point evaluations along a steepest-descent one-dimensional ray in *any* optimization cycle.	25

MNEMONIC	DESCRIPTION	NOMINAL VALUES
FACTHI	One-dimensional steepest-descent ray search termination criteria during first cycle. The termination criteria is reduced in each successive optimization cycle	1.0E-3
FACTLO	Lower limit on one-dimensional steepest-descent ray search termination criteria, in *any* optimization cycle.	1.0E-5
$XTENHI_i$	Optional extension of higher search limits ($ALPHI_i$) for a parameter that has gone to the upper bound	100*0.0
$XTENLO_i$	Optional extension of lower search limits ($ALPLO_i$) for a parameter that has gone to the lower bound	100*0.0
PHIEPS	Performance values within PHIEPS of the minimum value yet attained are treated as being equal in the Golden Section	0.0
DALFMN	Minimum parameter perturbation	5.0E-4
IPWMAT	Weighting matrix print control indicator: =1, to print weighting matrix	0
IPDRIV	Controls print out of derivatives: =1, to print derivatives	0
IPASTD IPDSTD IPFSTD	Steepest-descent search print control indicators for parameter, detail, and function values.	0 0 0

B.3.6.5 Adaptive Creeping Search Data ($METHOP_i = 5$). An elementary univariate search procedure which arrives at an optimum by a sequence of small parameter value perturbations. Perturbation size and direction are adaptively determined within the code.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
MAXCRP	Number of creeping search perturbations introduced into each parameter by a single adaptive creeping search in the optimization cycle.	5
IRANDM	Controls the order in which parameters are perturbed: =0, random order =1, natural order =2, reverse natural order =3, order of selection is input via KORDER	0
$KORDER_i$	An array that contains the subscripts of the parameters in the order that they are to be selected. Required input if IRANDM=3.	100*0
$DCREEP_i$	The initial perturbations to each parameter	100*1.0E-3
$CREPMN_i$	Minimum perturbations for each parameter	100*1.0E-7
$CREPMX_i$	Maximum perturbations for each parameter	100*1.0E+6
$ALFSIN_i$	Direction of perturbation for each parameter ($ALFSIN_j$=±1.0). May be used when picking up a search sequence to indicate the improving direction	100*1.0
IPACRP IPDCRP IPFCRP	Adaptive creeping search parameter, detail and function values print indicator	0 0 0

B.3.6.6 Quadratic Search Data ($METHOP_i$ = 6). The quadratic search is a second-order search procedure formally identical to the Newton-Raphson search.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
$QPERT_i$	Parameter perturbation magnitudes employed in computation of numerical partial derivative matrices $$\frac{\partial^2 \phi}{\partial \alpha_i \partial \alpha_j} \quad \text{and} \quad \frac{\partial \phi}{\partial \alpha_i}$$	20*5.0E-3
QFACTR	Scaling factor on the $QPERT_i$	1.0
NMAXLO	Maximum number of point evaluations employed in the quadratic one-dimensional ray search commencement (first optimization cycle). In successive optimization cycles, the number of point evaluations permitted increases by one.	15
NMAXUP	Upper bound on the number of point evaluations along a quadratic one-dimensional ray search, in *any* cycle.	25
FACTHI	One-dimensional quadratic ray search termination criteria during first cycle. The termination criteria is decreased in each successive optimization cycle.	1.0E-3
FACTLO	Lower limit on one-dimensional quadratic ray search termination criteria, in *any* cycle	1.0E-5
IPAQUA IPDQUA IPFQUA	Quadratic search parameter, detail, and function values print indicators	0 0 0

B.3.6.7 Davidon Search Data ($METHOP_i = 7$). Davidon's method is a pseudo-second order steepest-descent method. Second order information regarding the response surface characteristics is obtained indirectly and incorporated in the metric tensor.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
MAXDVD	Number of Davidon (Fletcher-Powell) gradient evaluations and one-dimensional searches performed each time that a Davidon search is requested in the optimization cycle	10
$QPERT_i$	Parameter perturbation magnitudes employed in computation in numerical partial derivatives $\frac{\partial\phi}{\partial\alpha_j}$	100*5.0E-3
NMAXLO	Maximum number of point evaluations employed in the Davidon one-dimensional ray search at commencement (first optimization cycle). In successive optimization cycles, the number of point evaluations permitted is increased by one	15
NMAXUP	Upper bound on the number of point evaluations along a Davidon search one-dimensional array in any cycle	25
FACTHI	One-dimensional Davidon ray search termination criteria during first optimization cycle. The termination criteria is decreased on each successive optimization cycle	1.0E-3
FACTLO	Lower limit on one-dimensional Davidon ray search termination criteria, in *any* optimization cycle	1.0E-5
DALFMN	Minimum parameter perturbation	5.0E-4
IPDRIV	Controls print out of derivatives: =1 to print derivatives	
IPADVD IPDDVD IPFDVD	Davidon search parameter, detail and function values print control indicators	0 0 0

B.3.6.8 Random Point Search (METHOP$_i$ = 8). A straightforward Monte-Carlo procedure involving a uniform distribution of random points in the feasible region. The search automatically turns itself "off" after the first optimization cycle.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
MAXRPT	The maximum number of random points to be employed in the first request for a random point search within the optimization cycle. In successive requests, MAXRPT is set to zero and no evaluations result.	10
IPARPT IPDRPT IPFRPT	Random point parameter, detail, and function values print indicators.	0 0 0

B.3.6.9 Random Ray Search (METHOP$_i$ = 9). An optimal point is found by means of an evolutionary sequence of small small random steps in the control space. If a random step is unsuccessful, the antiparallel step is always introduced.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
MAXRRS	The maximum number of random rays, one or two sided, investigated each time the optimization cycle requests a random ray search	3
RUFHI	The initial maximum non-dimension perturbation measure for each parameter. This is reduced each time random ray search consistently fails to improve performance	1.0E-2
RUFLO	Minimum-maximum dimensional perturbation measure for each parameter	1.0E-13

MNEMONIC	DESCRIPTION	NOMINAL VALUES
SPRANX	Starting trigger for the random number generator	33333333333
RUDOWN	Used to adaptively alter (increase or decrease) the step size for the random ray search	.25
INGRAN	Number of sequential two sided unsuccessful random steps required before the step size will be reduced ($\Delta S = \Delta S * \mathrm{RUDOWN}$)	6
IUPRAN	Number of sequential two sided successful random steps required before the step size will be increased ($\Delta S = (\Delta S/\mathrm{RUDOWN} + \Delta S)/2.0$)	6
RANGEN	Indicator for random number generator >0, generates uniformly distributed random numbers ≤0, generates normally distributed random numbers	1.0
FNORMAL	Value by which the normally distributed random numbers will be divided in order to reduce the 3σ value of the range over which random numbers will be generated. If FNORMAL = 1, the 3σ value will be approximately $\pm\pi$	5.0
IPARRS IPDRRS IPFRRS	Random ray search parameter, detail, and function values print indicators.	0 0 0

B.3.6.10 Directed Random Ray Search ($\mathrm{METHOP}_i = 10$). This search proceeds along a succession of random rays distributed about a best estimate of the gradient vector.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
MAXRRS	The maximum number of random rays, one or two sided, investigated each time the optimization cycle requests a random ray search	3
RNFHI	The initial maximum non-dimension perturbation measure for each parameter. This is reduced each time random ray search consistently fails to improve performance.	1.0E-2
RNFLO	Minimum-maximum dimensional perturbation measure for each parameter	1.0E-13
SPRANX	Starting trigger for the random number generator	33333333333
RNDOWN	Used to adaptively alter (increase or decrease) the step size for the random ray search	.25
INGRAN	Number of sequential two sided unsuccessful random steps required before the step size will be reduced $(\Delta S = \Delta S * \text{RUDOWN})$	6
IUPRAN	Number of sequential two-sided successful random steps required before the step size will be increased $(\Delta S = (\Delta S/\text{RUDOWN} + 2)/2.0)$	6
RANGEN	Indicator for random number generator: >0, generates uniformly distributed random numbers ≤0, generates normally distributed random numbers	1.0
FNORMAL	Value by which the normally distributed random numbers will be divided in order to reduce the 3σ value of the range over which random numbers will be generated. If FNORMAL=1.0, the 3σ value will be approximately $\pm\pi$	5.0

MNEMONIC	DESCRIPTION	NOMINAL VALUES
RBAR	The $\bar{R}$'s are the best historical estimate of the parameter perturbations required to produce a gain. The $\bar{R}$'s are adaptively determined by the program and may be input for the purpose of "picking up" an optimization run.	100*0.0
OLDRWT	Weighting constant applied to the old $\bar{R}$'s when updating the $\bar{R}$'s following a gain	5.0
OLDGWT	Weighting constant applied to $\overline{d\phi/ds}$ when updating $\overline{d\phi/ds}$ following a gain. Where $\overline{d\phi/ds}$ represents the historical estimate of the gradient	5.0
RRSEXP	Exponential constant applied to the ratio of current estimate of the gradient to the historical estimate of the gradient. The effect of this variable is to act as a dynamic weighting constant on the current random perturbation that produced a gain. The larger the gain the greater the effect on the R's	1.0
RLWT	Weighting constant applied to the $\bar{R}$'s in computing the current parameter perturbations.	2.5
IPARRS IPDRRS IPFRRS	Directed random ray search parameter, detail, and function values print indicators	0 0 0

B.3.6.11 Arbitrary Ray Search ($METHOP_j = 11$). The arbitrary ray search searches the ray passing through two specified points in the multidimensional control space. For printout, it is suggested that the tabular summary feature of AESOP be used.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
RALOHI	Defines which direction to search; i.e., TRUE, search "LO" → "HI" FALSE, search "HI" → "LO"	.TRUE.
NPTSRY	Total number of evaluations to be used on ray search	10
RAYDIV	Defines step size for ray search; i.e. *control parameter step size* = ($XTENHI_i$ - $XTENLO_i$)/RAYDIV	10.0
$XTENHI_i$	Defines the control parameter values at the "HI"† end of the multidimensional ray to be searched	100*0.0
$XTENLO_i$	Defines the control parameter values at the "LO"† end of the multidimensional ray to be searched.	100*0.0

† $XTENHI_i$ need not be greater than $XTENLO_i$, and $XTENLO_j$ need not be less than $XTENHI_j$ *in this search.* These two arrays merely define the end points of a ray in the multidimensional control space.

B.3.6.12 Jacobson Search ($METHOP_i$ = 12). The Jacobson search algorithm is based upon homogeneous function rather than quadratic models. A consequence of this is that (N+2) step convergence is obtained for homogeneous functions of any degree and that no one-dimensional search is required.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
JACMAX	Number of Jacobson searches carried out when the Jacobson search is called. (Number of Jacobson descents)	50
ANGRAD	If ANGRAD is .TRUE. the gradient vector ($\partial\phi/\partial\alpha_i$) is computed analytically by the system model. If NAGRAD is .FALSE. the gradient vector is computed numerically by AESOP using two-sided parameter perturbations	.FALSE.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
PFACTR	Controls the size of the parameter perturbations used for computing numerical gradient vector $\Delta\alpha_i = \text{PFACTR} * (\alpha_{HI_i} - \alpha_{LO_i})$	1.0E-7
IBX	An array describing the parameter bounds =1, α_i is lower and upper bounded =2, α_i is lower bounded only =3, α_i is upper bounded only =4, α_i is unbounded	50*1
IPDJAC	Detail print indicator for Jacobson search =1, to generate detail print	0

B.3.6.13 Contour Mapping Search (METHOP$_i$ = 13). The contour mapping option provides a two-dimensional graphic display of the performance function. The plane is selected by choosing any two parameters α_i and α_j. Plots are obtained on CALCOMP or Houston plotting devices.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
IPDMAP	Detail print indicator for mapper (Search 13)	0
NXMESH	Number of x mesh points for map (maximum of 52	0 0
NYMESH	Number of y mesh points for map (maximum of 52	0
NZCUTS	Number of contours for map	0
MAPALX	Subscript of parameter for x mesh	0
MAPALY	Subscript of parameter for y mesh	0
ZLMAX	Maximum z level for contour map If ZLMAX= ZLMIN, then the program will use the max and min z mesh values	0
ZLMIN	Minimum z level for contour map. If ZLMAX= ZLMIN, then the program will use the max and min z mesh values	0

MNEMONIC	DESCRIPTION	NOMINAL VALUES
LUMAP	Logical unit to be used as the map plot output device. LUMAP ≤ 0, no plot will be produced; if LUMAP > 0 the program will read the following six cards for the map titles: $\left.\begin{array}{ll}\text{NCXT} & \text{XTITLE}\\ \text{NCYT} & \text{YTITLE}\\ \text{NCT1} & \text{TITLE1}\\ \text{NCT2} & \text{TITLE2}\\ \text{NCT3} & \text{TITLE3}\\ \text{NCT4} & \text{TITLE4}\end{array}\right\}$ Format(3X,I2,1X,4A10) Where NCXT, NCYT, NCT1,... etc. are the number of BCD characters in each title and XTITLE, YTITLE,... etc. are the arrays that will receive the BCD characters of the titles. Each title may have a maximum of 40 BCD characters. Figure 8 presents a contour map produced by AESOP and shows the placement of the titles on the plot.	0
ALTMAP	Logical variable used to indicate which bounds apply to the parameters. If ALTMAP is .TRUE. the bounds on the parameters α_i will be taken as XTENLO_i and XTENHI_i. If ALTMAP is .FALSE. the bounds on the parameters α_i will be taken as ALPLO_i and ALPHI_i.	.FALSE.
XTENHI_i	Defines the upper bounds on the parameters α_i when ALTMAP is .TRUE.	100*0.0
XTENLO_i	Defines the lower bounds on the parameters α_i when ALTMAP is .TRUE.	100*0.0

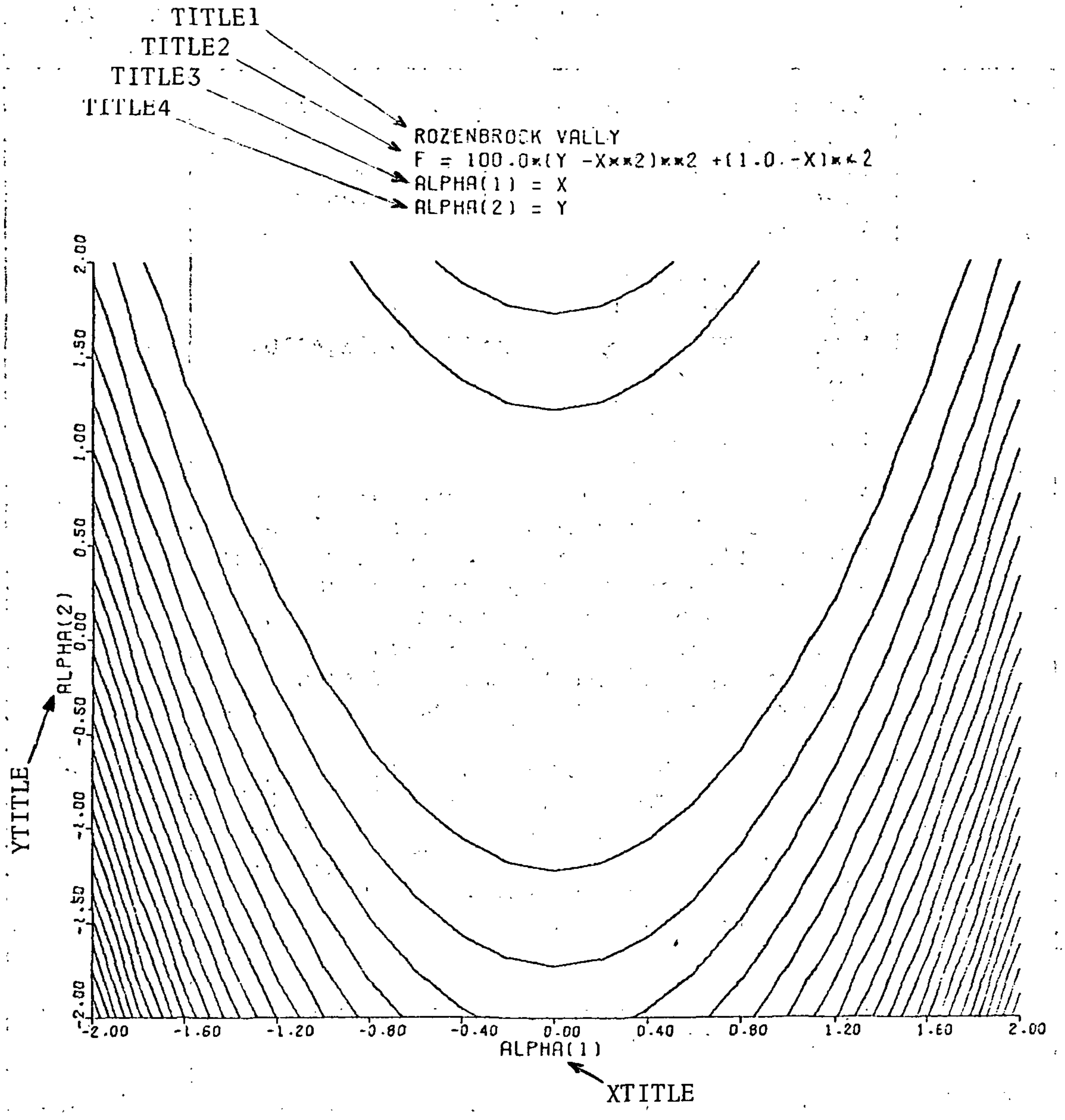


Figure 8. Contour Plot Example

B.3.7 AESOP Print Control

Program AESOP has a flexible print out capability. Varying levels of print out are available at the user's option. The print control for the individual searches was described in the previous section. This section will describe the general print controls that apply to all search algorithms.

In all cases a value of one for the print control variable will cause print out of the required data; a zero value will suppress the print out.

B. 3.7.1 Input Data Print Out. The data input to AESOP via FORTRAN namelist IAESOP is out by a simulated namelist AESOUT. The output is organized by search algorithms and only printed for the searches selected by the user.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
IPNAML	Controls print out of data input via FORTRAN namelist IAESOP	1

B.3.7.2 Print out of Function and Control Parameter Values During the Optimization Process.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
IPINEV	Will cause print out of the nominal values of the functions and control parameters for the initial report	1
IPDPEN	Will cause print out of the function and control parameter values after each evaluation	1
IPGAIN	Will cause print out of the function and control parameter values after each evaluation in which there was a gain in performance	0
IPSRCH	Will cause print out of the function and control parameter values at the end of each search	0
IPACYC	Will cause print out of the control parameter values at the end of each optimization cycle	0

MNEMONIC	DESCRIPTION	NOMINAL VALUES
IPFCYC	Will cause print out of the function values at the end of each optimization cycle	0
IPFNEV	Will cause print out of the function and control parameter values at the end of the optimization process (Final Report).	1

B.3.7.3 Tabular Summary Print Control. Tabular listing of the function and control parameter values can be produced to give the user a concise picture of the convergence history.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
LUCYC	Tape or disk unit used to store the convergence histories of the function and control parameter values for tabular listing at the end of each optimization cycle (cycle summary report). If LUCYC $\leq$ 0, no tabular listing at the end of a cycle will be produced.	0
LUFIN	Tape or disk unit used to store the convergence histories of the function and control parameter values for tabular listing at the end of the optimization process (Final Report)	0
ITCYC	Controls content of cycle summary report: =0, the function and parameter values for all evaluations will appear in the cycle summary report =1, the function and parameter values will appear only for evaluations in which there was a gain in performance =2, the function and parameter values at the end of each search comprise the cycle summary report	1
ITFIN	Controls concent of final summary report: =0, the function and parameter values for all evaluations will appear in the final summary report	2

MNEMONIC	DESCRIPTION	NOMINAL VALUES
	=1, the function and parameter values will appear only for evaluations in which there was a gain in performance =2, the function and parameter values at the end of each search comprise the final summary report =3, the function and parameter values at the end of each optimization cycle will comprise the final summary report	
LUCHDP	Logical unit (tape or disk) on which the final summary report data is to be reformatted into arrays for plotting of convergence histories. If LUCHDP $\leq$ 0, the data is not saved	0

B.3.8 Other AESOP Data

This section describes the AESOP input data not defined in the previous sections.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
IRLIST	Controls the reading of the AESOP namelist data IAESOP. If IRLIST=0, no namelist data is input. This is used to suppress the input when all data is specified internally by user's program	1
OPTIMA	Not used by AESOP	2
DIALOG	Logical variable used by AESOP. If .TRUE. the entire common for AESOP is to be saved and restored each evaluation by the main program	.FALSE.
EOF	Logical variable. If .TRUE. AESOP will call EXIT and terminate the computer run.	.FALSE.

MNEMONIC	DESCRIPTION	NOMINAL VALUES
JJJ	Evaluation counter	-1
MENTRY	Controls the optimization process. MENTRY is set to nine (9) by AESOP when number of cycles exceeds IREPET or JJJ ≥ MAXJJJ	0

B.4. REFERENCES (APPENDIX B)

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6. Hague, D.S., and Jones, R.T., Application of Multivariable Search Techniques to the Design of Low Sonic Boom Overpressure Body Shapes, NASA SP-255, 1970, pp.307-323.

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PART II - PROGRAM STRUCTURE, TECHNIQUES, AND ANALYSIS

5. COMBUSTOR PROGRAM STRUCTURE

The general structure of the AUTOCOM program is designed around the physical and operational characteristics of the combustor, the weighting of these characteristics, and the rating of the system which is also based on weighting factor constants. Accordingly, the description for the following elements

Combustor design inputs

Specific combustor characteristics

Average combustor characteristics

Rating equation

is given in Section 5.1 through 5.4.

Figure 5-1 depicts the task structure of the combustor program. As can be seen, the first set of designer inputs consisting of variable and fixed inputs describing the operational engine, is used to compute the specific combustor characteristics F11 through F82. Thereafter, the results of these computations are weighted by a second set of designer inputs, namely the weighting factor constants AF11 through AF82, and BF72. These weighting factor constants reflect the designer's view regarding the importance of each individual specific combustor characteristic. Finally, the payoff criterion which is represented by the rating equation, combines the average combustor characteristics (FI through FVIII), by using designer inputs for the weighting factor constants AFI through AFVIII, BFI through BFVIII, and CFII. This class of weighting factor constants reflects the designer's view regarding the importance of each group of average combustor characteristics such as those for performance, stability, pressure drop, injector complexity, etc. The derivation of the weighting factor constants is discussed in Section 5.5.

Sections 5.1 through 5.4 present a discussion of the various elements of the program structure as shown in Figure 5-1.

5.1 Design Inputs

5.1.1 Combustor Design Variables (Input data for namelist COMDPV). The independent design variables of the combustor are as follows with limits as indicated (for details see Section 2.3):

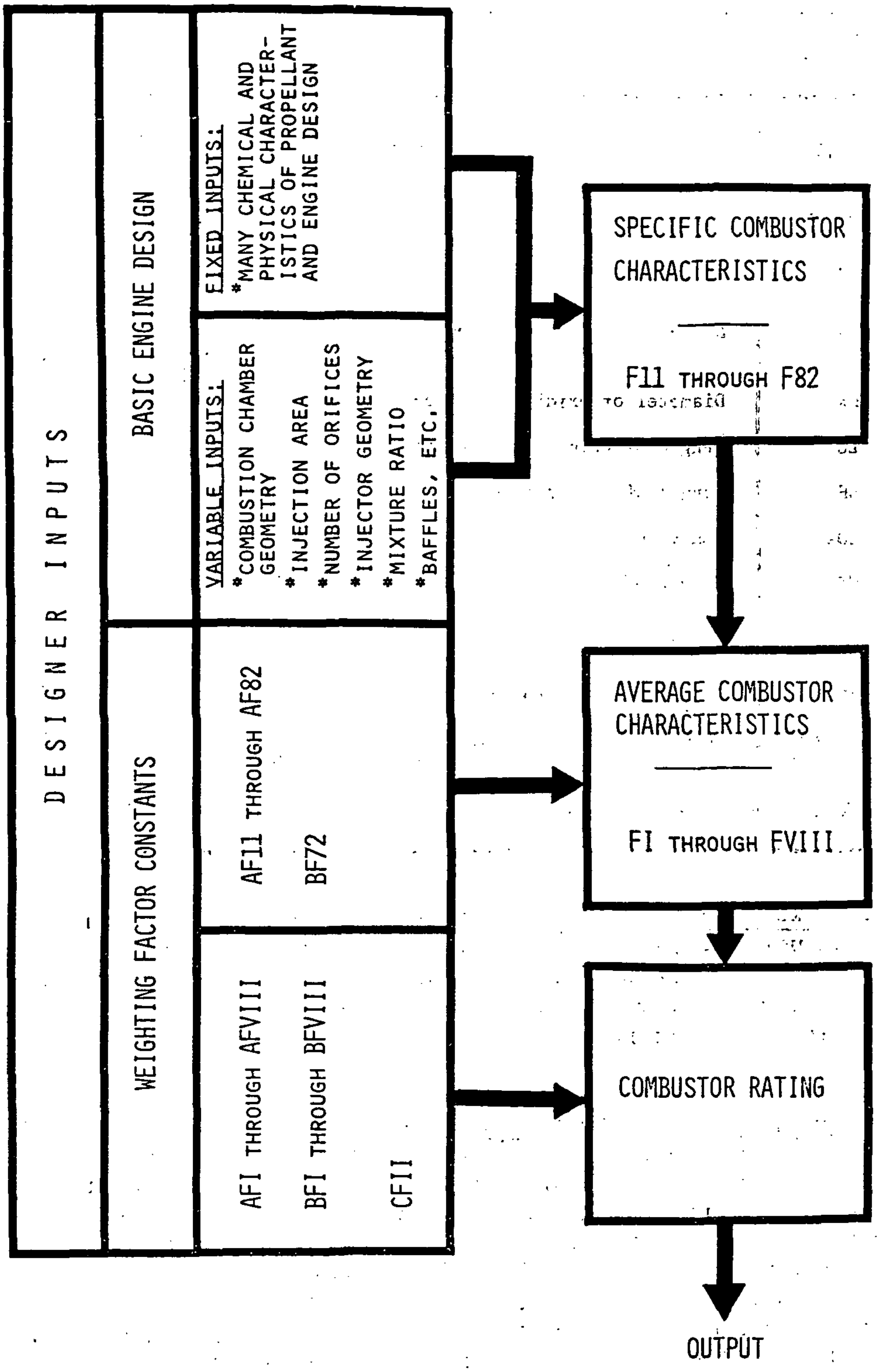

Figure 5-1
Task Structure of the Combustor
Program

PROGRAM SYMBOL	DESCRIPTION	MAXIMUM VALUE	MINIMUM VALUE
BFLCIR	Number of circumferential baffles	Positive Integer	0
BFLRAD	Number of radial baffles	"	0
DC	Chamber diameter, in.	Positive Number	Throat Diameter
DF	Diameter of fuel orifices, in.	"	.01
DX	Diameter of oxidizer orifices, in	"	.01
LC	Length of combustion chamber, in.	"	.01
LF	Length of fuel orifices, in.	"	.01
LOX	Length of oxidizer orifices, in	"	.01
NF	Number of fuel orifices	Positive Integer	1
NOX	Number of oxidizer orifices	"	1
OF	Propellant mixture ratio, ox/fuel	BF71	---
VOLF	Volume of fuel manifold, in^3	Positive Number	0
VOLX	Volume of oxidizer manifold, in^3	"	0

5.1.2 Fixed Combustor Design Parameters (Input data for namelist COMMIS). The fixed combustor design requirements are items which are not changed by the designer for a given engine. This includes all items that are required in those equations that could be different for combustors with different propellants or requirements (for details see Section 2.4).

5.1.3 Weighting Factor Constants (Input data for namelist COMWGT). The "rating" of a combustor design is based on using a weighted average of all the characteristics of a given combustor. The weighting factors are constants used in equations to obtain average characteristics or a rating. The constants are introduced to allow the designer to incorporate his views regarding the importance or validity of one technique for obtaining a given characteristic vs. another technique for obtaining the same characteristic. For example, if the designer believed that only one technique was valid for predicting the performance of a given design he would assign a unity value to the weighting factor constants for that specific characteristic and the constants for all the other performance characteristics would be zero. Similarly, the weighting factor constants in the equation to obtain a single rating for a given combustor design are introduced to allow the designer to introduce the relative importance of different types of characteristics (for example, stability vs. performance). The weighting factor constants, therefore, gives the designer the same control and flexibility in the computer program as he has with current "cut-and-try" design techniques. To establish a base point for the rating system a hypothetical ideal combustor is given a rating of zero. The hypothetical ideal combustor would have 100 percent of theoretical C* performance, infinite damping rate for all modes of instability, zero chamber length, chamber diameter equal to the throat diameter, etc. The weighting factors are terms beginning with the letters A, B, or C followed by the symbol for the characteristic with which it is to be used. A list of the weighting factor constants is given in Section 2.2, and their derivation for rating an engine is discussed in Section 5.5.

5.2 Specific Combustor Characteristics

The specific combustor characteristics are calculated from well-defined equations or curves that have been published and accepted by the professional community. The specific combustor characteristics are denoted by a capital F to designate a characteristic, followed by a two digit number. The first digit corresponds to the Roman Numeral which designates the average engine characteristic in which the specific characteristic will be used. The second digit then designates which characteristic is being considered. The specific combustor characteristic is calculated from an equation containing combustor design variables and fixed combustor design requirements. The following specific characteristics are available in the program code:

F11 is the percent mass vaporized of fuel

F12 is the percent mass vaporized of oxidizer

F13 is a C*-efficiency based on the mixing model

F14, F15 } Available for program extension. The former performance computations based on A. D. Little Correlations have been eliminated. They are, however, still included in Sections 4 and 5.5

F20 is the chugging decay rate based on the fuel system

F21 is the chugging decay rate based on the oxidizer system

F22 is the stability characteristic for pulsed operation based on a correlation

F23 is the stability characteristic for non-pulsed operation based on a correlation

F24 is a stability decay rate characteristic for fuel

F25 is a stability decay rate characteristic for oxidizer

F26 is the stability decay rate characteristic based on the sensitive time lag model for a longitudinal mode

F27 is the stability rate characteristic based on the sensitive time lag model for transverse modes

F28 is the stability decay rate characteristic based on the response function approach

F29 is the stability characteristic based on the non-linear stability analysis and includes various modes of oscillation

F31 is the fuel pressure drop characteristic

F32 is the oxidizer pressure drop characteristic

F41 is the number of fuel plus oxidizer holes characteristic

F42 is the volume of the oxidizer dome characteristic

F43 is the volume of the fuel dome characteristic

F44 is the length of the oxidizer holes characteristic

F45 is the length of the fuel holes characteristic

F46 is an injector type complexity characteristic

F51 is the length to nozzel throat diameter ratio characteristic

F61 is the chamber diameter to nozzel throat diameter ratio characteristic

F71 is the mixture ratio characteristic

F81 is the radial baffles characteristic

F82 is the circumferential baffles characteristic

The specific combustor characteristics F11 through F82 are computed in Subroutines SECF11 through SECF82 respectively. These subroutines are discussed in detail in Section 7.

5.3 Average Combustor Characteristics

Average combustor characteristics (FI through FVIII) are used in the rating equation (Section 5.4) to give the optimum combustor design; they are computed in Subroutines ACFI through ACFVIII. Average characteristics are specified by a capital F to denote a characteristic, followed by a Roman Numeral to designate which characteristic. The average characteristic is a weighted average of several specific combustor characteristics calculated by different techniques.

5.3.1 Average Performance Characteristic. FI is the average performance characteristic based on the vaporization efficiency and the c^*-efficiency, and varies from 0 to 100 percent. The average characteristic equation is

$$\begin{aligned} FI = {} & AF11\ (100-F11) \\ & + AF12\ (100-F12) \\ & + AF13\ (100-F13) \\ & + AF14\ (100-F14) \\ & + AF15\ (100-F15) \end{aligned} \qquad (5\text{-}1)$$

5.3.2 Average Stability Characteristic. FII is the average stability characteristic based on an equivalent damping rate and raries from − ∞ (damps at an infinite rate with time) to + ∞ (grows at an infinite rate with time). The average stability characteristics equation is

$$e^{FII} = \sum_{n=20}^{n=29} e^{AF(n)*F(n)} \qquad (5\text{-}2)$$

or

$$\begin{aligned} FII = {} & ALOG[EXP(AF20*F20) \\ & + EXP(AF21*F21) \\ & + EXP(AF22*F22) \\ & + EXP(AF23*F23) \\ & + EXP(AF24*F24) \\ & + EXP(AF25*F25) \\ & + EXP(AF26*F26) \\ & + EXP(AF27*F27) \\ & + EXP(AF28*F28) \\ & + EXP(AF29*F29)] \end{aligned} \qquad (5\text{-}3)$$

5.3.3 Average Pressure Drop Characteristic. FIII is the average pressure drop characteristic based on the pressure drop across the injector face and ranges from 0 to a positive number. The average stability characteristics equation is

$$FIII = \frac{AF31*F31 + AF32*F32}{AF31 + AF32} \qquad (5\text{-}4)$$

5.3.4 Average Injector Complexity Characteristic. FIV is the average injector complexity characteristic based on the number of injector elements, type of elements, injector dome volume and injector face thickness, and varies from 0 to a positive number. The average injector complexity characteristic equation is

$$FIV = AF41*F41 + AF42*F42 + AF43*F43 + AF44*F44 + AF45*F45 + AF46*F46 \quad (5\text{-}5)$$

5.3.5 Average Chamber Length Characteristic. FV is the average chamber length characteristic based on the chamber length to nozzel throat diameter ratio, and varies from 0 to a positive number. The average chamber length characteristics equation is

$$FV = AF51*(F51**AF52) \quad (5\text{-}6)$$

5.3.6 Average Chamber Diameter Characteristic. FVI is the average chamber diameter characteristic based on the chamber diameter at the injector face to nozzle throat diameter ratio, and varies from 0 to a positive number. The average chamber diameter characteristics equation is

$$FVI = AF61*[(F61-1)**AF62)] \quad (5\text{-}7)$$

5.3.7 Average Mixture Ratio Characteristic. FVII is the average mixture ratio characteristic which varies from 0 to a positive number. The average mixture ratio characteristics equation is

$$FVII = AF71*[(BF71-F71)**AF72] \quad (5\text{-}8)$$

5.3.8 Average Baffle Characteristic. FVIII is the average baffle characteristic which varies from 0 to a positive number, and is

$$FVIII = 2*L50(AF81*F81 + AF82*F82) \quad (5\text{-}9)$$

where L50 = length of combustion chamber required to vaporize 50 per cent of the propellant.

If AF81 and AF82 = 0, the computation for FVIII (Subroutine ACFVIII) will be bypassed.

5.4 Rating Equation

The specific equation to obtain a single numerical value, ϕ, for a combustor rating is given by

$$\begin{aligned}\phi = {} & AFI(FI)^{BFI} \\ & + AFII*e^{(BFII+CFII*FII)} \\ & + AFIII*FIII^{(BFIII)} \\ & + AFIV*FIV^{(BFIV)} \\ & + AFV*FV^{(BFV)} \\ & + AFVI*FVI^{(BFVI)} \\ & + AFVII*FVII^{(BFVII)} \\ & + AFVIII*FVIII^{(BFVIII)} \qquad (5\text{-}10)\end{aligned}$$

5.5 The Derivation of the Weighting Factor Constants for Rating an Engine

The combustor rating is based on the payload penalty of an envisioned rocket using this engine. Payload penalties mean an increase in rating. The derivation of the weighting factor constants takes the "Engine Test Case" of Section 4 into consideration. However, this approach can also be applied correspondingly for other engines. Based on the 15000 lbs. thrust engine using H_2/O_2 propellants, the following assumptions can be made:

1. Rating is in terms of payload.
2. Cost of 1 lb. of payload is $4,000. (This is obtained by dividing total vehicle cost by number of pounds of payload.)
3. Reducing cost of engine by $4,000 is equivalent to adding 1 lb. of payload to the rating.
4. Adding 1 lb. of weight to engine is equivalent to taking a pound of payload out of the rating.
5. Increasing the engine performance (specific impulse) by 1 second or 0.22 units of efficiency is equivalent to adding 33 lbs. of payload. (This is obtained by performing a mission analysis with various impulse values.)

For the <u>first term</u> in the rating equation, based on the 15000 lbs. thrust engine:

AF11 is 0 because fuel is gas and already vaporized.

AF12 and AF13 are considered to be of equal importance (% LOX vaporized + % mixed); therefore are assigned a value of 1.

AF14 and AF15 are much less than AF11 and AF12 beacuse the A. D. Little correlations are not considered to have a very high level of confidence in the prediction of performance. A 99% vaporized propellant can be considered equivalent to about a 1% value for F14 and F15. Therefore, AF14 and AF15 are given values of .01.

BFI is unity because a trade study of payload with impulse shows a linear dependency between payload and impulse.

AFI is 150 under the assumption of item 5 that for increasing performance, .22 units result in 33 pounds of payload.

For the second term in the rating equation:

F24 is not applicable to this engine as fuel is vaporized and, hence, Dykema's vaporization model is not valid. Therefore, AF24 = 0.

All other AF20 to AF29 stability indices are considered of equal importance and significance; therefore, AF20, AF21, AF22, AF23, AF25, AF26, AF27, AF28 and AF29 are assigned unity values.

The AFII, BFII, and CFII weighting factor constants are obtained by the following three data points:

FII = negative decay rate, then rating is 0.

FII = 0 (Neutral stability) is equivalent in importance to losing six seconds of impulse of 200 lbs. payload under the assumption of item 5, so rating is +200.

FII = 10 (very unstable engine) is equivalent to 16 seconds of impulse or 527 lbs. payload, so rating is +527.

For the third term in the rating equation:

Analysis of turbopump has indicated that an increase in pressure or pressure drop of 200 psi will increase the weight of pump 8 lbs. and cost $8,000 for an equivalent rating of 10. An increase of pressure of 400 psi increases the weight 30 lbs. and cost $20,000 for an equivalent rating of 35. Therefore, with FIII in units of psi:

FIII = 0 Rating = 0

FIII = 200 Rating = 10

FIII = 400 Rating = 35

From these conditions

$$AFIII = .00069$$

$$BFIII = 1.8$$

Pressure increase on fuel side results in a weight and cost penalty twice as large as LOX pressure due to low density of hydrogen. Hence,

$$AF31 = 2.0$$

$$AF32 = 1.0$$

The fuel pump etc. for H_2-O_2 system is approximated twice as big as the LOX pump, etc. Therefore, it costs about twice as much also.

For the <u>fourth term</u> in the rating equation:

For F41 it is estimated that increasing the number of holes from 432 to 864 would increase the cost $12,250 or an equivalent of 3.06 lb. payload. Also it would increase the weight 1 lb. Therefore,

$$AF41 = \frac{3.06 + 1}{432} = .009$$

For F42 it is estimated that increasing of the LOX volume by 10 inches^3 would increase the cost $1,000 and the weight by 1 lb.

$$AF42 = \frac{.25 + 1}{10} = .125$$

For F43 apply the same results as for F42.

For F44, a length increase of .4 inches is estimated to cost $1,000 and increases the weight by 2 lbs. Therefore,

$$AF44 = \frac{.25 + 2}{.4} = 5.625$$

For F45 a length increase of .06 inches is extimated to cost $200 and increase the weight by .2 lbs. Therefore,

$$AF45 = \frac{.05 + .2}{.06} = 4.16$$

For F46 the element type is not varied, so AF46 = 0.

With respect to the rating equation it is reasoned that the rating goes as the square of FIV rather than the linear assumption used for F41,etc. in a region of doubling the size. Therefore BFIV = 2.

Thus it follows, with $FIV = \sum AF_{(n)} * F_{(n)}$:

$FIV = 0$ Rating $= 0$

$FIV = 8.625$ Rating $= X$

$FIV = 17.25$ Rating $= X + 8.625$

For an engine with FIV = 17.25 by doubling engine size, rating increase is 8.625. Then

$$X = 2.942$$

$$AFIV = .0395$$

$$BFIV = 2$$

Since rating $X = AFIV\ (8.625)^2$, it becomes

$$X + 8.625 = AFIV(17.25)^2$$

For the fifth term in the rating equation:

Under the assumption that FV is linear with F51, AF51 and AF52 (AF51 and AF52 = 1), all rating is taken up in AFV and BFV.

To calculate FV coefficients the following data were used:

F51	Wt(lbs)	Cost	I_{sp} Loss	Total
0	0	0	0	0
1	5	10,000	.1	40.5
2	10	20,000	4	147

Therefore

$$BFV = 1.86$$

$$AFV = 40.5$$

For the <u>sixth term</u> in the rating equation:

To calculate FVI coefficients, it is again assumed that AF61 and AF62 are unity and all rating is taken up in AFVI and BFVI. The following data were used:

F61	(D_c-1)	Wt	Cost	Total
1	0	0	0	0
2	1	10	100,000	35
3	2	40	400,000	140

Therefore, BFVI = 2

AFVI = 35

For the <u>seventh term</u> in the rating equation:

To calculate I_{sp} from mixture ratio, the following data is used:

M.R.	I_{sp} Loss	Rating
4.06	10	330
4.56	2	66
5.06	0	0
5.56	2	666
6.06*)	10	330

*) According to the expression for FVII (Equation (5-8)), the magnitude of F71 as a variable can never reach the value of 5.06.

Therefore BF71 = 5.06, then AF72 = 2 (to make a parabola).

Arbitrarily set AF71 = 4, then

M.R.	FVII	Rating
5.06	0	0
4.56 & 5.56	1	66
4.06 & 5.06	4	330

Then

$$BFVII = 1.16$$

$$AFVII = 66$$

Based on the preceding assumptions, the weighting factor constants used for the sample case of the 15000-lbs.- thrust engine in Section 4, are listed as follows:

AFI = 150.0	Constant of the performance characteristic in the rating equation.
AFII = 200.0	Constant of the stability characteristic in the rating equation.
AFIII = .00069	Constant of the pressure drop characteristic in the rating equation.
AFIV = .0395	Constant of the injector complexity characteristic in the rating equation.
AFV = 40.5	Constant of the chamber length characteristic
AFVI = 35.0	Constant of the chamber diameter characteristic
AFVII = 66.0	Constant of the mixture ration characteristic in the rating equation.

BFI = 1.0	Exponential on the performance characteristic in the rating equation.
BFII = 0.0	Exponential on the stability characteristic in the rating equation.
BFIII = 1.8	Exponential on the pressure drop characteristic in the rating equation.
BFIV = 2.0	Exponential on the injector complexity characteristic in the rating equation.
BFV = 1.86	Exponential on the chamber length characteristic.

BFVI = 2.0	Exponential on the chamber diameter characteristic.
BFVII = 1.16	Exponential on the mixture ratio characteristic in the rating equation.
CFII = .1	Exponential on the stability characteristic in the rating equation.

AF11 = 0.0	Constant in the performance characteristic equation.
AF12 = 1.0	Constant in the performance characteristic equation.
AF13 = 1.0	Constant in the performance characteristic equation.
AF14 = .01	Constant in the performance characteristic equation.
AF15 = .01	Constant in the performance characteristic equation.

AF20 = 1.0	Constant in the combustor stability characteristic equation.
AF21 = 1.0	Constant in the combustor stability characteristic equation.
AF22 = 1.0	Constant in the combustor stability characteristic equation.
AF23 = 0.0	Constant in the combustor stability characteristic equation.
AF24 = 0.0	Constant in the combustor stability characteristic equation.
AF25 = 1.0	Constant in the combustor stability characteristic equation.
AF26 = 1.0	Constant in the combustor stability characteristic equation.
AF27 = 1.0	Constant in the combustor stability characteristic equation.
AF28 = 1.0	Constant in the combustor stability characteristic equation.
AF29 = 1.0	Constant in the combustor stability characteristic equation.

AF31 = 2.0	Constant in the fuel pressure drop characteristic equation.
AF32 = 1.0	Constant in the oxidizer pressure drop characteristic equation.

AF41 = .009	Constant for the injector orifice number.
AF42 = .125	Constant for the oxidizer dome volume.
AF43 = .125	Constant for the fuel dome volume.
AF44 = 5.625	Constant for the length of the oxidizer orifices.
AF45 = 4.16	Constant for the length of the fuel orifices.
AF46 = 0.0	Constant for the injector type complexity.

AF51 = 1.0	Constant for the chamber length characteristic.
AF52 = 1.0	Exponential on the chamber length characteristic.

AF61 = 1.0	Constant for the chamber diameter characteristic.
AF62 = 1.0	Exponential on the chamber diameter characteristic.

AF71 = 4.0	Constant for the mixture ratio characteristic.
BF71 = 5.06	Constant for the mixture ratio characteristic.
AF72 = 2.0	Exponential on the mixture ratio characteristic equation.

AF81 = 0	Constant for the radial baffle characteristic.
AF82 = 0	Constant for the circumferential baffle characteristic.

6. DESCRIPTION OF AUTOCOM PROGRAMMING TECHNIQUES

Implementation of the application of multivariable search techniques to optimum combustor design follows three steps which form the basis for the computer program design:

1. Combustor Point Design. A modular approach permitting user understanding and subsequent refinement, and rapid extension of the point design computer code, is employed in conjunction with algebraic FORTRAN IV coding throughout the program.

2. Combustor Optimization. Optimization is performed using the existing multivariable search program AESOP (Automated Engineering and Scientific Optimization Program), Appendix B*) This program can rapidly be coupled to any point design program where the performance criterion is a computable function of a finite number of design controlled parameters, here a complicated weighted function of a set of specified combustor characteristics.

3. Payoff Criterion. Combustor design performance comparisons are based on a single numerical value combining a set of average engine characteristics in a weighted fashion; in this case, the rating equation. The weighting factors are set to nominal values within the program. The designer is able to modify the weighting factors through the data input.

To implement the three steps, the program is, in principle, synthesized by using the following building blocks:

- Input/Output Control Program
- Combustor Characteristics Computation Program (including average combustor characteristics)
- Combustor Rating
- Optimization Program AESOP
- General Subprograms

All program coding utilizes the algebraic FORTRAN IV language. FORTRAN subset common to the following major digital computer systems is employed:

IBM 7040/7094

IBM 360 Series

UNIVAC 1107/1108

CDC 6400/6600

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*) Appendix B is included in Part I

6.1. Modular Programming

Modular programming is applied. Essentially, it consists of the use of a well ordered tree of subroutines which utilize a system of user-(combustor designer) oriented names to perform user-oriented functions. Subroutines communicate with each other through a single "COMMON" block containing all data necessary for evaluation of the combustor rating once a set of combustor design variables have been specified.

6.1.1 Use of COMMON. The combustor design program module utilizes a single named COMMON which contains all combustor data, specific engine characteristics, weighting constants, average engine characteristics, fixed design variables, free design variables, and combustor rating. These quantities are preserved in a single array;access to any item of information in the array is by the "EQUIVALENCE" technique. A typical example illustrating this procedure follows:

```
SUBROUTINE SECF11
COMMON/COMBST/CMDATA(2000)
EQUIVALENCE (LC, CMDATA(123))
------------------------------
------------------------------


RETURN
END
```

Here,the subroutine "SECF11" requires as input the combustor length, LC. This information is contained in the combustor design program array "CMDATA" at the (123)rd position. This method of communication between subroutines is rigidly followed. A directory subroutine contains a complete listing of all data in the common block. Two hundred vacant positions are maintained at the rear of the common block for subsequent program expansion.

6.1.2 Combustor Program Outline. The combustor main program controls the combustor analysis and optimization procedure through a sequence of major subroutines designated as subprograms. Each of these subprograms performs a gross function such as input, output, optimization, specific engine characteristic evaluation, etc. A schematic diagram of the combustor main program illustrating major subprograms and their function is presented in Figure 6-1. Each subprogram defined in this figure consists of a number of subroutines.

6.2 Input/Output Formats

6.2.1 Input Format. An input procedure employing user-oriented mnemonics is applied. This approach avoids the tedious, rigidly formatted data input procedure employed by many existing FORTRAN IV and symbolic coded programs. The input procedure employed is the FORTRAN IV "NAMELIST" option. There are nine places for the input data setup of which two are optional. For more details see Section 2.

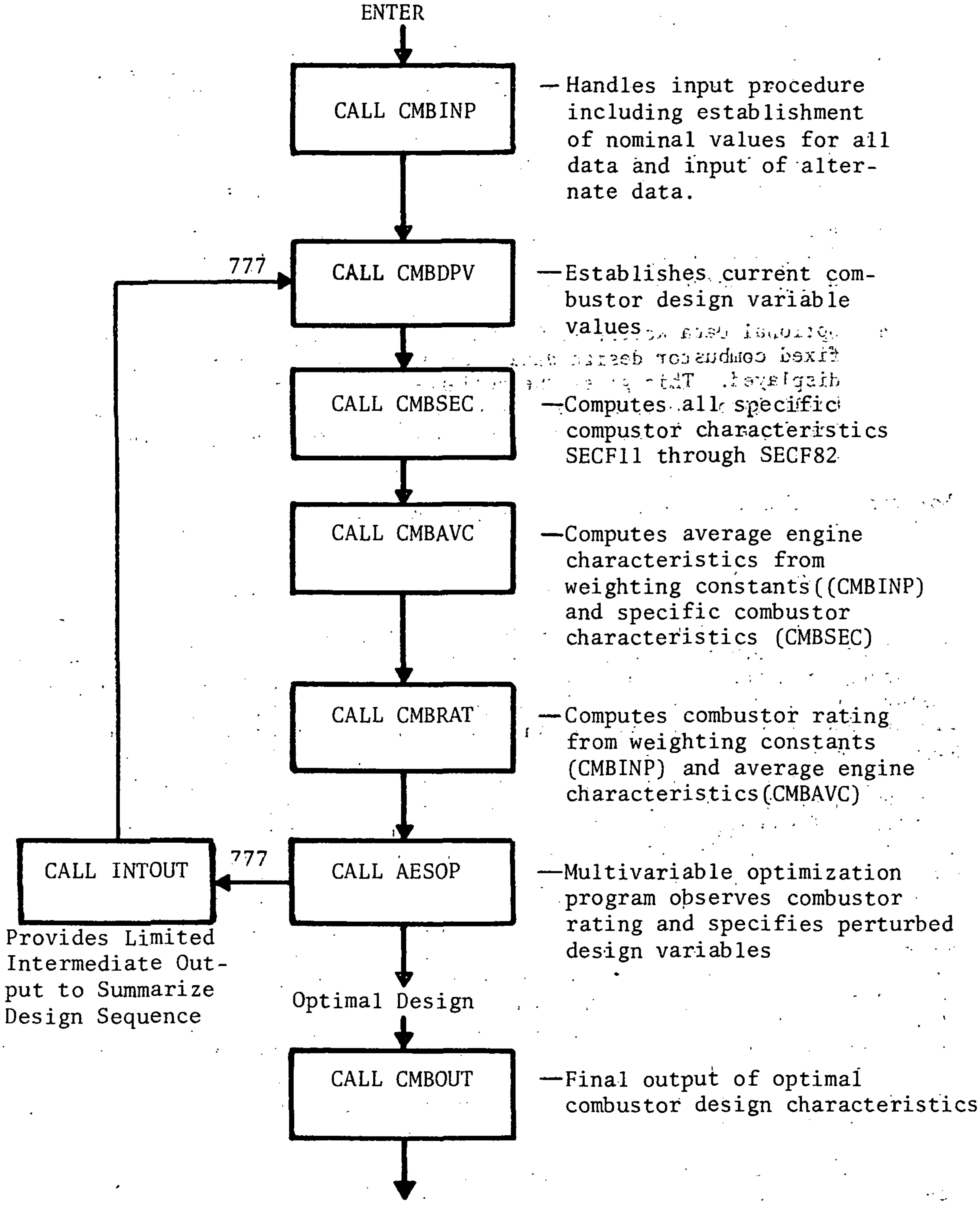


Figure 6-1. Schematic of Combustor Optimization Procedure

6.2.2 Output Formats. Several output data formats are supplied.

1. Data Output. Relevant data output are printed at the beginning of a case to provide a record of assumed combustor data.
2. Design Iteration Output. A running summary of major combustor characteristics is provided in the design optimization loop to aid the designer in interpretation of combustor design progress.
3. Final Design Output. A detailed description of final combustor design variables and characteristics following completion of the design iteration loop is available.
4. Optional Data Retrieval Output. At the designer's option all fixed combustor design data including tabular properties are displayed. This gives the designer the ability to verify all data built into the combustor design program and, in combination with the input package, the ability to modify the fixed data in a particular study.

For more details about program outputs see Section 3.

6.3 Combustor Characteristics Computation Program

The specific combustor characteristics subprogram (CMBSEC) will be described to illustrate the programming philosophy. This subprogram computes the specific combustor characteristics F11 to F82. Each of these specific characteristics is computed in a separate subroutine. The subroutines are named by a six-letter word commencing with the letters SEC (Specific Engine Characteristic) and terminating with three characters indicating which specific engine characteristic is computed. Thus, for example, subroutine SECF11 will compute the per cent mass vaporized of fuel. The structure of subprogram CMBSEC is shown schematically in Figure 6-2. It consists of a sequence of calls to working level subroutines each of which computes a particular specific engine characteristic. These working level subroutines vary in complexity from simple equations to complex tabular data computations. Each working level subroutine contains logic to bypass the particular specific engine calculation when the designer has indicated this requirement through the input weighting constants (see Figure 2-3). Thus, for example, if the weighting constant AFI is zero, subroutines SECF11 to SECF13 will return without computing F11 to F13, thus saving unnecessary computation. Again, if the weighting constant AF13 is zero, subroutine SECF13 will independently return without computation of F13 since the designer has indicated this particular specific engine characteristic is to be omitted from the rating equation (see Appendix A).

A similar structure to that described for specific engine characteristic computation is employed for average engine characteristic computation. Subprogram "CMBAVC" thus calls eight subroutines, ACFI, ACFII, . . . , ACFVIII, raspectively, to compute the eight average engine characteristics. Again, computation by-passes on appropriate weighting constant values are provided (see Appendix A).

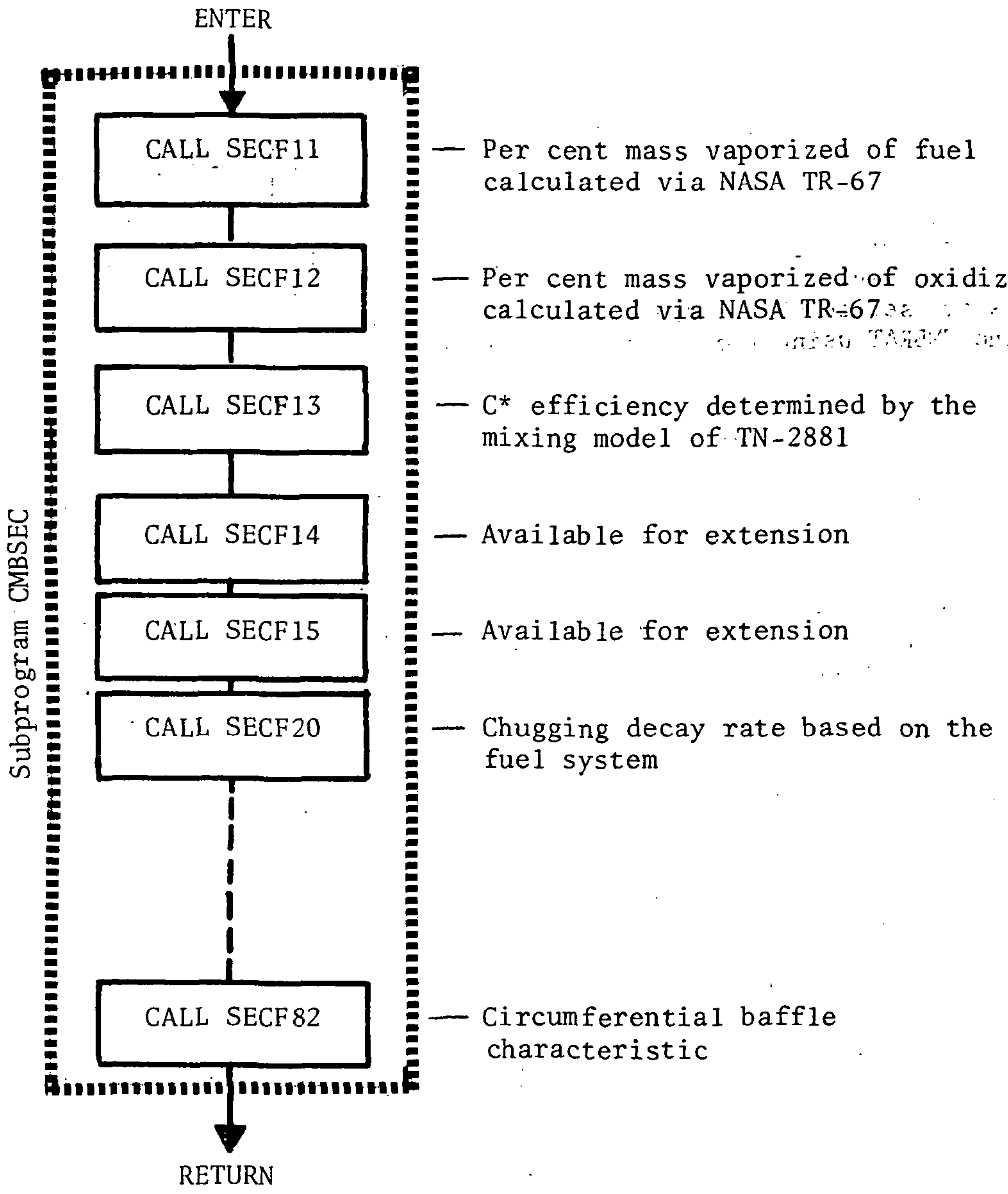


Figure 6-2. Schematic of Specific Engine Characteristic Subprogram "CMBSEC"

6.4 Combustor Rating

The combustor rating as the payoff criterion provides a single numerical measure of the combustor's capability and is constructed on the basis of a weighted sum of the average engine characteristics. The weighting factors employed in computing the combustor rating are user-defined in the AUTOCOM code (see Section 5.5). These weighting factors are based on the impact of each average engine characteristic on vehicle payload capability; they define the payload penalty associated with each characteristic. The combustor design optimization process is based on minimization of the combustor rating and, hence, the payload penalty. The rating is clearly a function of the combustor design variables, and the weighting factors entering into both the rating equation and the average engine characteristics. In the present general AUTOCOM coding, the values for the weighting factor constants are set to "1" or "0". The combustor rating is computed in subroutine CMBRAT using the rating equation given in Section 5.4.

6.5 Combustor Optimization Program

6.5.1 The General Optimal Design Problem for AUTOCOM. The optimal combustor design problem is essentially a large scale, non-linear multivariable optimization problem. The independent variables are the geometric and physical parameters defining the combustor in detail--the combustor design variables. The dependent variables are the specific combustor characteristics--the combustion efficiencies, statbility characteristics, etc. The specific combustor characteristics in turn define a higher order set of dependent variables, the average engine characteristics, which define a payoff function through the rating equation.

In the general design problem, Reference 6-1, a set of design variables, $\bar{\alpha}$, are defined. A unique set of design characteristics, $\bar{F}$, are obtained from the vector of design variables

$$\bar{F} = \bar{F}(\bar{\alpha}) \qquad (6\text{-}1)$$

In the design process one of these characteristics is selected for minimization or maximization. This is the payoff function

$$\phi = \phi(\bar{\alpha}) \qquad (6\text{-}2)$$

In some designs the payoff criteria to employ will not be self-evident to the designer. In this case he may seek to define value function, V, which involves some combination of the performance characteristics

$$V = V(\bar{F}) \qquad (6\text{-}3)$$

The value function is then employed as the payoff function. In the optimal combustor design problem, V is specified by the rating equation as a weighted combination of average engine characteristics. An alternate approach to the use of the rating equation is that of seeking constrained extremal. Constraint functions, ψ, are selected from the average engine performance characteristics. These constraints can always be defined such that

$$\overline{\psi} = \overline{\psi}(\overline{\alpha}) = \overline{0} \tag{6-4}$$

With this approach, for example, the designer seeks the optimum combustor design on the basis of one set of average engine characteristics while constraining other average engine characteristics to acceptable values. Both methods, the value function approach and that of the constrained extremal, are included in the combustor design procedure. A general technique for incorporating constraints into the optimization formulation is the well-known "penalty function" approach. An augmented payoff function, $\overline{\phi}$, is constructed by

$$\overline{\phi} = \phi + \sum_{i=1}^{M} W_i \psi_i^2 \tag{6-5}$$

Here, the W_i are a set of positive constraint weighting factors. Provided the W_i are sufficiently large in magnitude, minimization of Equation (6-5) corresponds to minimization of Equation (6-2) in the presence of the constraints of Equation(6-4). In practice, the W_i are automatically determined within the optimization algorithms employed in adaptive fashion on the basis of constraint behavior.

The designer may wish to impose inequality constraints on the design. For example, he may seek the best combustor design based on a weighted combination of efficiency and stability characteristics with constraints on pressure drop, injector complexity, chamber length characteristics, chamber diameter characteristics, and propellant mixture ratio characteristics. Inequality constraints can be imposed on the formulation by a transformation into equality constraint form, Equation (6-4). Suppose an inequality is to be placed on the ith performance function; then define a constraint, ψ_j, such that

$$\begin{aligned} \psi_j &= F_i^2 \;;\; F_i > 0 \\ &= 0;\; F_i \leqslant 0 \end{aligned} \tag{6-6}$$

Constraining ψ_j to zero is now equivalent to the constraint $F_i \leqslant 0$.

Frequently the designer imposes inequality constraints directly on the design parameters. (Thus, for example, the fuel orifice diameter must be greater than .010 inches). These limits are dictated by a priori knowledge of the combustor and its operating environment. Generally, then, the design parameters are subject to lower and upper limiting values, $\overline{\alpha}^L$ and $\overline{\alpha}^H$, such that

$$\overline{\alpha}^L \leqslant \overline{\alpha} \leqslant \overline{\alpha}^H \tag{6-7}$$

These constraints limit the region of feasible designs to a hyper-rectangle lying in the multidimensional design parameter space. Equations (6-1) through (6-7) define in symbolic fashion the optimal combustor design problem.

Conceptually, they define most industrial design problems; for, in practice, a designer must always seek to express his problem in terms of a finite number of parameters.

6.5.2 Optimal Design Techniques. Methods for solution of non-linear multivariable optimization problems have received considerable attention during the sixties. In general, solutions are obtained by the iterative search procedures which are collectively becoming known as "optimal seeking methods." The increasing interest in these techniques stems both from their ready application through the digital computer and the ease with which their theoretical basis can be grasped. Generally, the non-linear optimal seeking method has its basis in logic rather than the higher branches of analytic mathematics. In essence, the technique corresponds quite closely to the traditional design cycle. Parameters are perturbed; the system is evaluated, and, on the basis of resulting performance characteristics, a new design is evolved. Figure 6-3 presents a schematic diagram of the optimal seeking approach. A nominal design variable vector $\bar{\alpha}_0$, is supplied to the optimization algorithm. The optimizer, in turn, supplies the design parameter values to a digital model of the system being designed--in the present study a digital combustor point design evaluation module. This system functions in "black box" fashion and returns the corresponding performance characteristics, $\bar{F}$, to the optimizer. Based on inspection of these characteristics, which define payoff (value function) and constraint values, a new design, $\bar{\alpha}$, is supplied to the system, and the process repeats in iterative fashion until the optimal performance $\phi = \phi^*$ for the constraint levels $\bar{\psi} = \bar{0}$ is attained.

It can be seen that the optimization process is largely divorced from the system model. This fact permits construction of generalized optimization programs which can readily be coupled to digital system models. These models may be expressly constructed with this object in mind, or, equally, they may be existing digital system models constructed for conventional designer control and perturbation. An example of this type of generalized optimization is program AESOP, (Automated Engineering and Scientific Optimization Program), References 4-1 and 4-2 recently constructed under contract to the National Aeronautics and Space Administration's Office of Advanced Research and Technology. A detailed discussion of Program AESOP can be found in Appendix B, Part I.

6.6 General Subprograms

Evaluation of specific combustor characteristics requires the use of a variety of standard numerical subprograms for tabular data storage, table look-up, non-linear complex equation solution, etc. The Aerophysics Research Corporation program library, which consists of approximately 500,000 cards containing all basic numerical subprograms required in construction of the combustor design procedure, has been employed for these basic operations. The four major subprograms whose positions in the master chart, Appendix A, Part I, are indicated and are listed in the following:

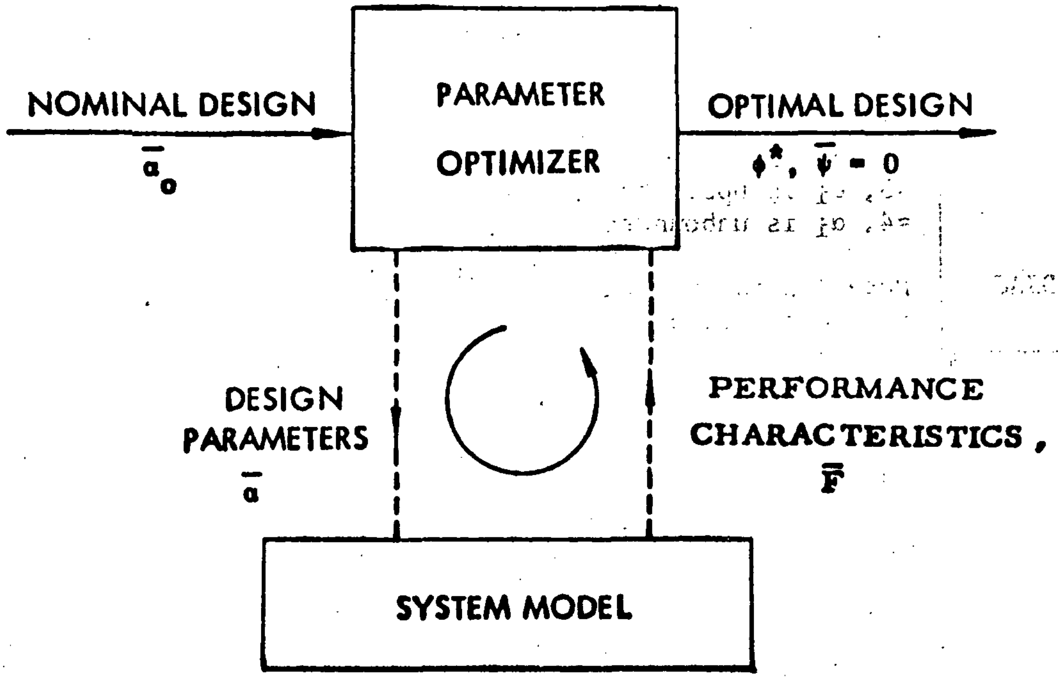


Figure 6-3. Optimizer Schematic

Subprogram Name	Description
CMBINI	Initializes all fixed data in the combustor data base
CMPRED	Calculates and/or stores all fixed combustor design characteristics.
FITCRV	Fits curves for specific impulse, combustion temperature, specific heat ratio and molecular weight of the combustion gas as a function of the propellant mixture ratio and stores this information in the data base.
POSTAL	Computes minor design variables dependent functions.

6.6.1 Subprogram CMBINI. This subprogram initializes all fixed data in the combustor data base. Several kinds of data are stored in subprogram CMBINI:

1. Constants such as:

   -Phase angle due to delay in burning in Subroutine SECF28, F28TBS = 1.9

   -Acceleration of gravity, in/sec^2, GREF = 32.174*12

   -Fuel injection distribution eccentricity in Subroutine SECF23, IDEF = 1.0

   -Log of fuel injection distribution in Subroutine SECF23, LIDF = 0.0

   -Constant PI = 3.14159

   -Universal gas constant, in-lb/mole^{o}R, RGUNIV = 1544*12

   -Vapor pressure liquid temperature coefficient in Subroutine SECF28, TEMCOE = 8.0

   -Turbulence intensity in Subroutine SECF13, %, TURBIN = 3.0

   -Specific heat ratio for hydrogen in Subroutine SECF28, SPHTH2 = 1.2

2. Physical constants for heptane as required for the scaling relation presented in Equation (7-2). The following table depicts the heptane values stored:

Program Symbol	Value	Description
MUC	$1.74*10^{-5}$	Viscosity of heptane, lb/in.-sec
RHOC	$2.47*10^{-2}$	Density of heptane, lb/in^3
SIGLC	$1*10^{-4}$	Surface tension of liquid heptane, lb/in.
TLOC	528.0	Temperature of heptane, ^{o}R

3. The propellant interaction index, n, for non-hypergolic propellants with coaxial injection in Subroutine SECF26

   NTAUN1 = 0.45

   and the propellant interaction index, n, for hypergolic propellants in Subroutine SECF26.

   NTAUN3 = 0.70

4. Modes of oscillations in Subroutine SECF27 if no baffles are present:

   SNUH(1) = 1.8412
   SNUH(2) = 3.0543
   SNUH(3) = 3.8317
   SNUH(4) = 7.0156
   SNUH(5) = 5.3313
   SNUH(6) = 8.5263
   SNUH(7) = 6.7060

5. Argument of Bessel function in Subroutine SECF28 if no baffles are present:

   BESARG(1) = 1.8412
   BESARG(2) = 3.0543
   BESARG(3) = 4.2012
   BESARG(4) = 3.8317
   BESARG(5) = 0.0 (longitudinal)

6.6.2 Subprogram CMPRED. This subprogram calculates and/or stores fixed combustor design characteristics such as:

1. Constant for number distribution in Subroutines SECF11 and SECF12, ADIS = 1.0

2. Combustion chamber throat area: ATHRTI = (PI*DTHRTI**2)/4.0

3. A matrix of the relationship for the injector element type, ETYP; the propellant type indicator, PTYP; the propellant combination parameters FO2 and FO3; and the principal element type PE1 and PE2 required for Subroutines SECF22 and SECF23

4. The reduced initial propellant temperature for fuel, TLORF, and for oxidizer, TLORX, as used in Subroutines SECF11 and SECF12:

$$TLORF = TLOF/TCRF$$

and

$$TLORX = TLOX/TCRX$$

(for definition of the program symbols see listing of Section 2.4)

6.6.3 Subprogram FITCRV. Subprogram FITCRV is used for optimization runs to determine the four parameters:

I_{sp} = Specific impulse

k = Specific heat ratio

M = Molecular weight of combustion gas

T_1 = Temperature in combustion chamber

as a function of the propellant mixture ratio O/F. The procedure for storing new propellant data is described in Section 2.7.1.

Subprogram FITCRV is a simple and rapid degital computer code used to find the polynomial $P_k(x)$ of degree $\leq$ k which best approximates, in the least squares sense, a weighted set of data points, x_i, y_i, with i = 1, 2, ---- N, using orthogonal polynomials. Moreover, this subprogram calculates the coefficients of the fitted polynomial and the fitted values for a given set of arguments.

For the propellant combination H_2/O_2 as an example, the four propellant polynomial functions, I_{sp}, k, M, and T_1, are nominally established within the program as the following functions of the oxidizer/fuel ratio, O/F:

$$\begin{aligned} I_{sp} &= 235.436554 + 121.376531*OF \\ &- 24.6650523*(OF)^2 \\ &+ 2.09800922*(OF)^3 \\ &- .0733124871*(OF)^4 \end{aligned}$$

$$k = 1.46481804 - .106859541*OF$$
$$+ .0213594157*(OF)^2$$
$$- .0021301452*(OF)^3$$
$$+ (83.0205334*10^{-6})*(OF)^4$$

$$T_1 = 3022.96538 - 554.118155*OF$$
$$+ 478.420285*(OF)^2$$
$$- 71.4672888*(OF)^3$$
$$+ 3.19696006*(OF)^4$$

$$M = 1.39758043 + 3.03152880*OF$$
$$- .530108602*(OF)^2$$
$$+ .107300022*(OF)^3$$
$$- .00750532403*(OF)^4$$

When tabular data is entered, the subprogram will fit the polynomial curves through the tabulated points by a least squares procedure. Maximum polynomial order which can be specified is ten. In the case of H_2/O_2 propellant properties, this could be adequately represented by fourth order polynomials. The "goodness of fit" is illustrated by Figure 6-4. Here, the input curves are compared to the polynomial approximation at two sets of points. The circled points represent input tabular points; the crossed points represent evaluations midway between the input points.

A broader treatment of the computer code for curve-fitting can be found in Reference 6-2.

6.6.4 Subprogram POSTAL. Subprogram POSTAL computes characteristics and minor design variable dependent functions which are inside the optimization loop. A detailed discussion of the computations performed in Subprogram POSTAL is presented in Section 7.9, "Minor Design Variable Dependent Functions."

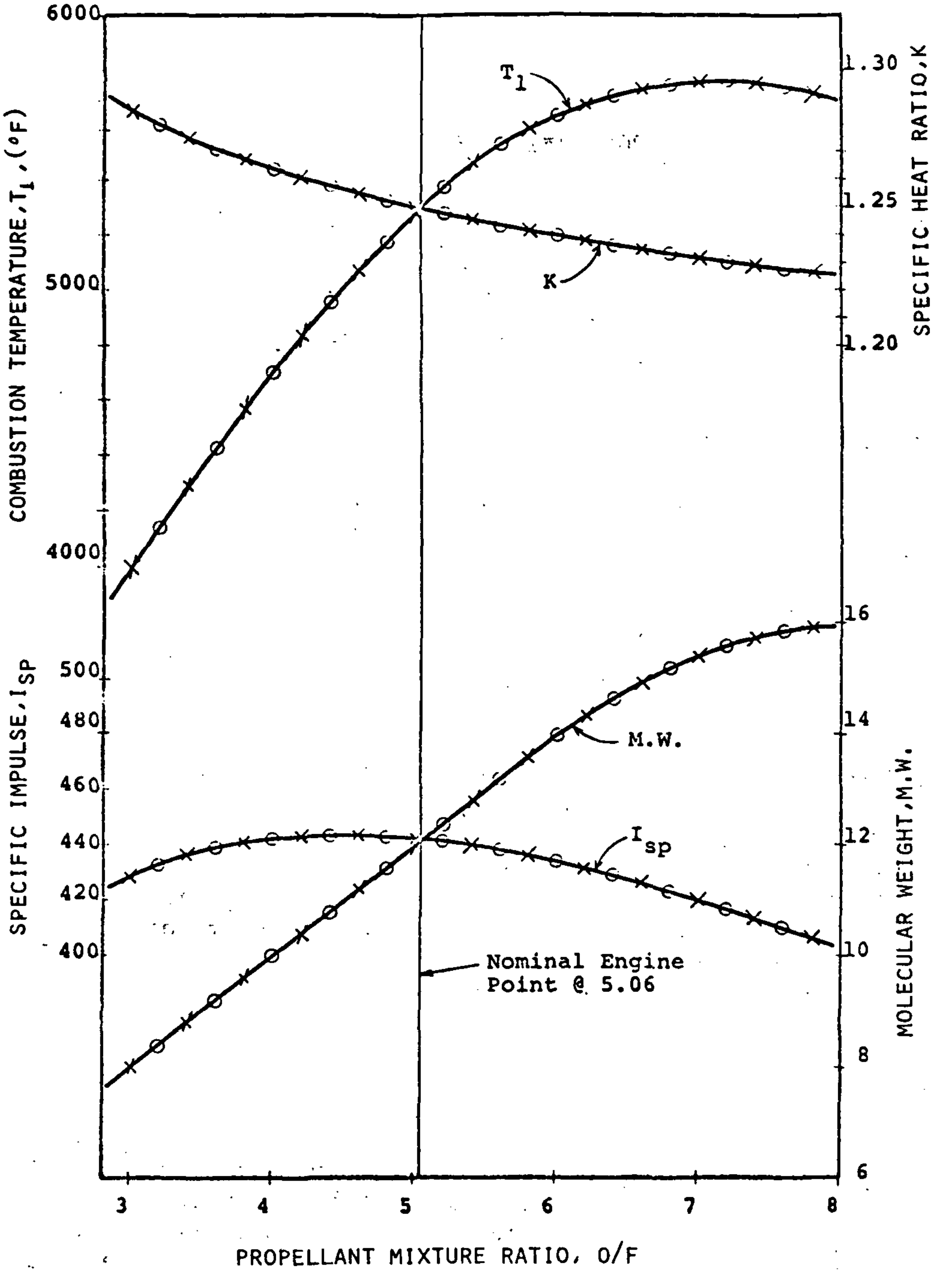


Figure 6-4. Polynomial Propellant Properties

7. OUTLINE OF THE AUTOCOM PROGRAM ANALYSIS

The AUTOCOM program automatically determines the combustor characteristics given the chamber design variables and fixed input values. The analysis considers performance, stability, combustion chamber geometry , injector complexity and baffle characteristics. In an optional mode of operation, the program possesses the ability to automatically perturb the design parameters defining the engine characteristics (optimization). Performance and stability analysis modules (subroutines) as well as several other combustor characteristics modules (subroutines) available within the program are listed below and described in the following:

* Performance characteristic modules

* Stability characteristic modules

* Pressure drop characteristic modules

* Combustor complexity characteristic modules

* Combustor chamber length characteristic modules

* Combustor chamber diameter characteristic modules

* Propellant mixture ratio characteristic modules

* Baffle characteristic modules

7.1 Performance Characteristic Modules (Subroutines)

There are three subroutines, SECF11 through SECF13, which compute performance related characteristics. In addition the two modules, SECF14 and SECF15, are available for program extension.

7.1.1 Subroutines SECF11 and SECF12. Subroutine SECF11 computes the per cent mass vaporized of fuel, F11, and Subroutine SECF12 computes the per cent mass vaporized of oxidizer, F12. If the propellant is in a gas phase when injected, the mass vaporized is assigned a value of 100 per cent (executed by input of ISTATF = 1, or ISTATX = 1 in Input Namelist COMMIS). Both subroutines are based on the same method using the same propellant vaporization subroutine VAPRIZ (Figure 7-4) and the polynomial curve fit routine YPOLYV.

The values for F11 and F12 are determined from the technique described in Reference 7-1. The drop size is first determined for heptane using Figure 7-1 (Figure 32 of Reference 7-1). Options for parallel jets, impinging jets, and triplet jets are provided. The data of Figure 7-1 indicates the drop size r_m of heptane; for the three types can be determined from an equation involving the jet diameter, d_j, of the form

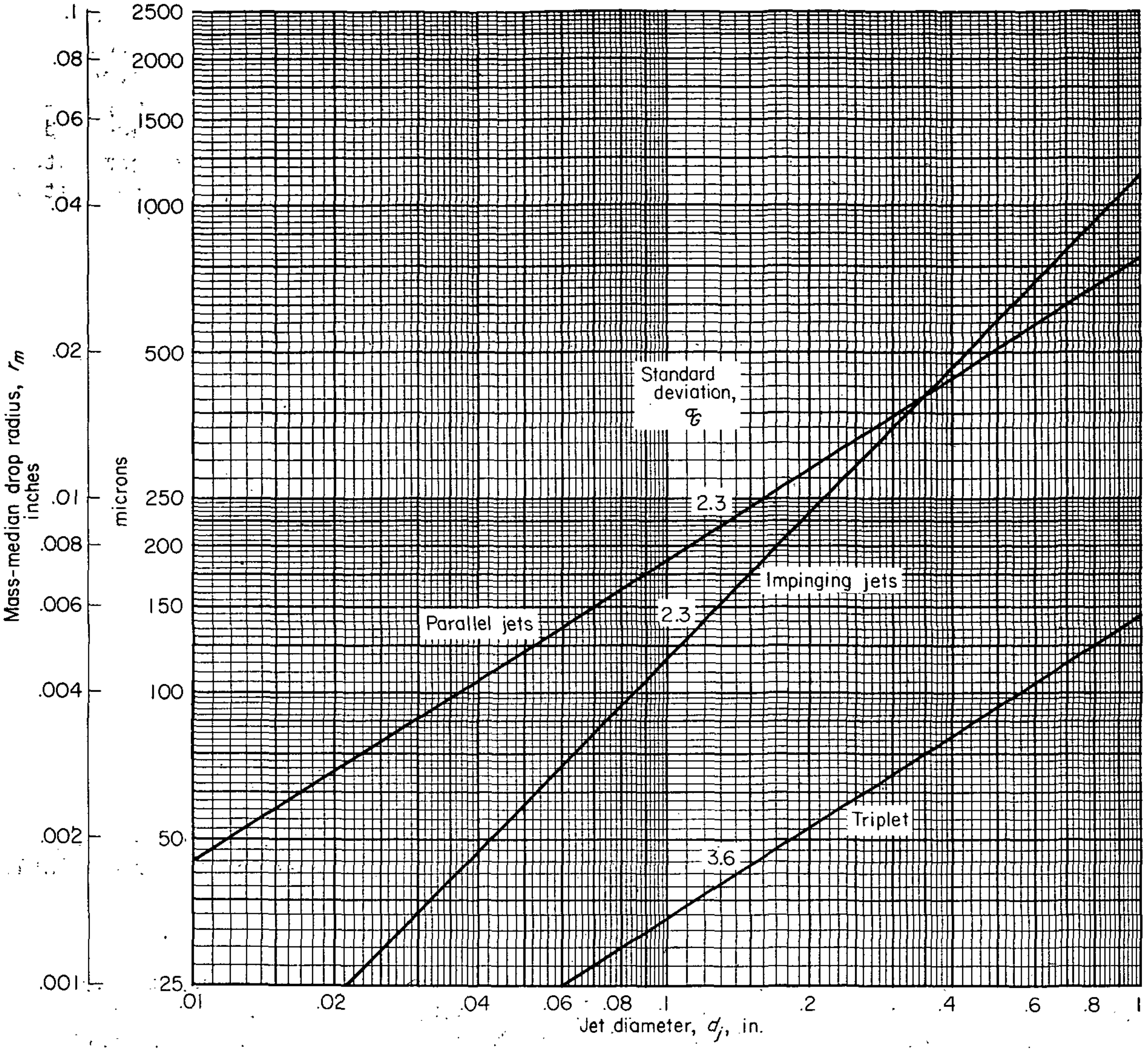


Figure 7-1. Drop Sizes Determined from Experimental Engine Performance

$$r_m = A d_j^{\,B} \tag{7-1}$$

which generates a straight line on log-log scales. The constants A and B for the three types of jets shown are given in the table below.

	A	B
Parallel jets	.0312	.6194
Impinging jets	.046	.9935
Triplet jets	.00575	.6217

Once the drop size for heptane is determined, the drop size for any other propellant, fuel or oxidizer, can be determined from the scaling relation :

$$r_{m_x} = r_m \left| \frac{\rho}{\rho_x} \cdot \frac{\sigma_{\ell x}}{\sigma_\ell} \cdot \frac{\mu_x}{\mu} \right|^{1/4} \tag{7-2}$$

where

ρ = liquid density of the propellant at injector exit conditions, lbm/in^3

σ_ℓ = surface tension of the liquid propellant, lbf/in.

μ = viscosity of the liquid propellant, lbf/in.-sec

The non-subscripted values represent heptane values while the subscript x denotes the input propellant values. From the drop size determined in this way and adding other propellant and chamber characteristics, a generalized length can be calculated as shown below (Equation (103) of Reference 7-1).

$$\ell_{gen} = \left[\frac{\ell_c}{A^{.44}} \right] \cdot \frac{\left(\frac{P_c}{300}\right)^{.66}}{(1-T_{\ell,o,R})^{.4} \left(\frac{r_m}{.003}\right)^{1.45} \left(\frac{V_o}{1200}\right)^{.75} \left(\frac{\lambda}{140}\right)^{.8} \left(\frac{M \cdot a}{100}\right)^{.35}} \tag{7-3}$$

where

ℓ_c = chamber length , inches

A = chamber contraction ratio

P_c = chamber pressure , lb/in^2

V_o = injection velocity, inches/sec

$T_{\ell,o,R}$ = initial propellant temperature ratio

r_m = propellant drop size, inches

λ = heat of vaporization of liquid propellant, BTU/lbm

M = molecular weight of liquid propellant, lbm/lb.Mole

a = constant for number distribution

The generalized length approach was selected over the effective length approach as discussed in Reference 7-1 because of the applicability of the former approach to all propellants. With the generalized length calculation, the per cent mass vaporized may be determined from Figure 7-2 (Figure 28f, Reference 7-1). This curve was fitted with a sixth order log-linear polynomial of the form

$$PMV = A_0 + A_1 \log(\ell_{gen}) + A_2[\log(\ell_{gen})]^2 + \ldots + A_6[\log(\ell_{gen})]^6$$

where

$A_0 \simeq 25.67$

$A_1 \simeq 19.47$

$A_2 \simeq 5.013$

$A_3 \simeq .381$

$A_4 \simeq -.394$

$A_5 \simeq -.007$

$A_6 \simeq .012$

The correlated results of this curve fit are also shown in Figure 7-2. The symbols denote values from the polynomial approximation.

Figure 7-3 depicts the flow chart for controlling subroutines SECF11 and SECF12. The computation of subroutine VAPRIZ is presented in a more detailed flow chart, Figure 7-4.

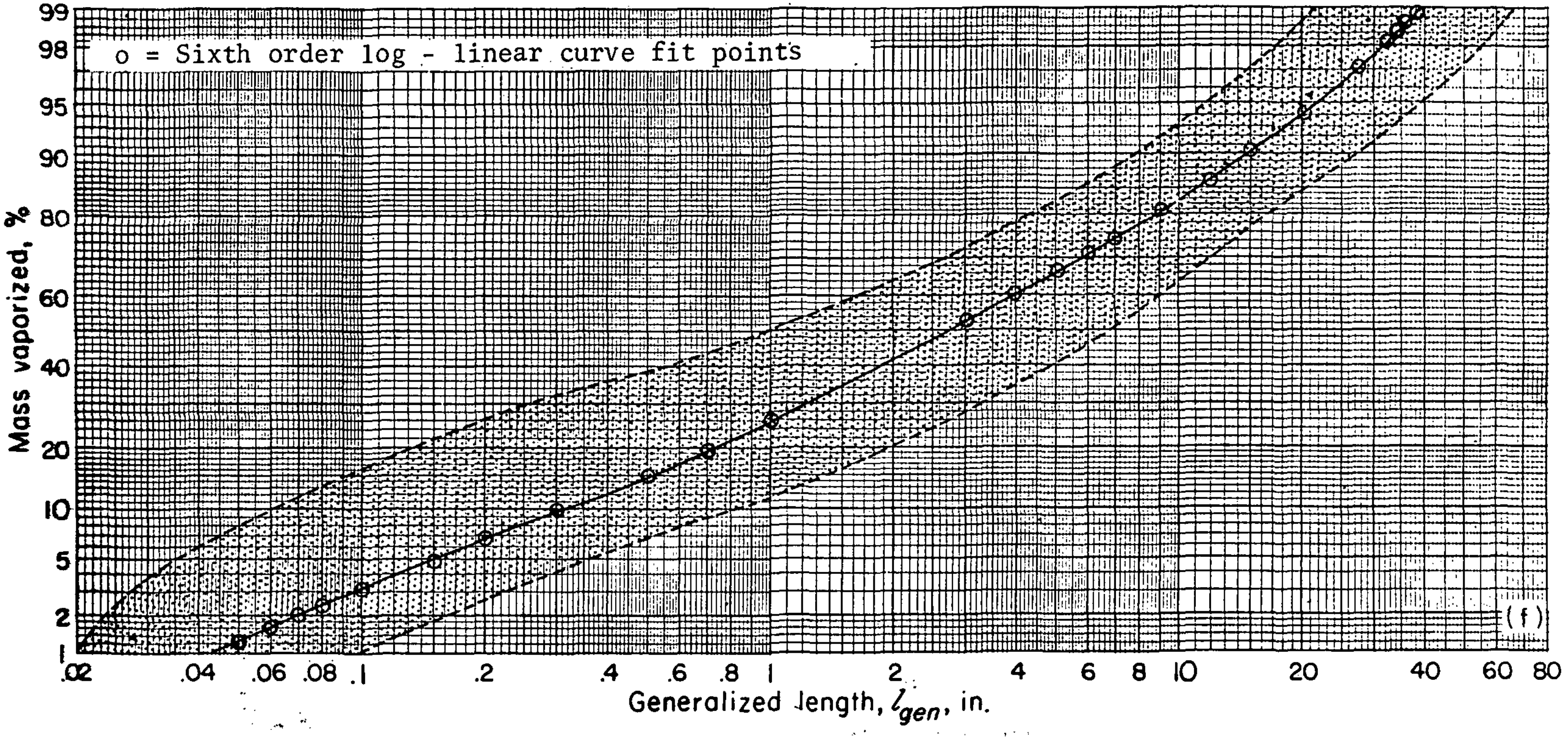


Figure 7-2. Correlated Results for Mass Vaporized as a Function of the Generalized Length (All Propellants, Operating Conditions, and Design Conditions, with a Geometric Standard Deviation of 2.3)

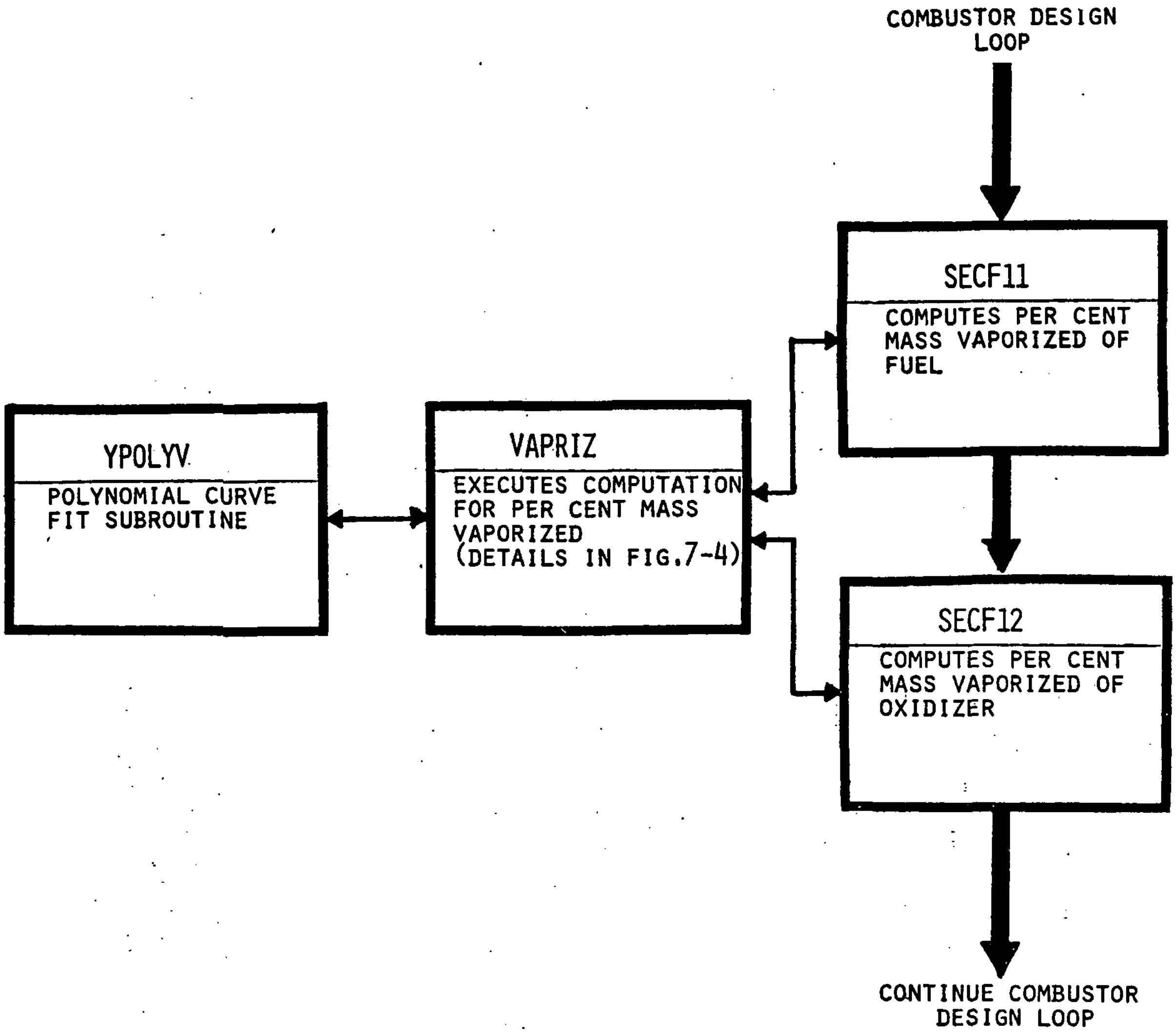


Figure 7-3. Flow Chart for Subroutines SECF11 and SECF12 for Computing Per Cent Mass Vaporized of Fuel (F11) and of Oxidizer (F12).

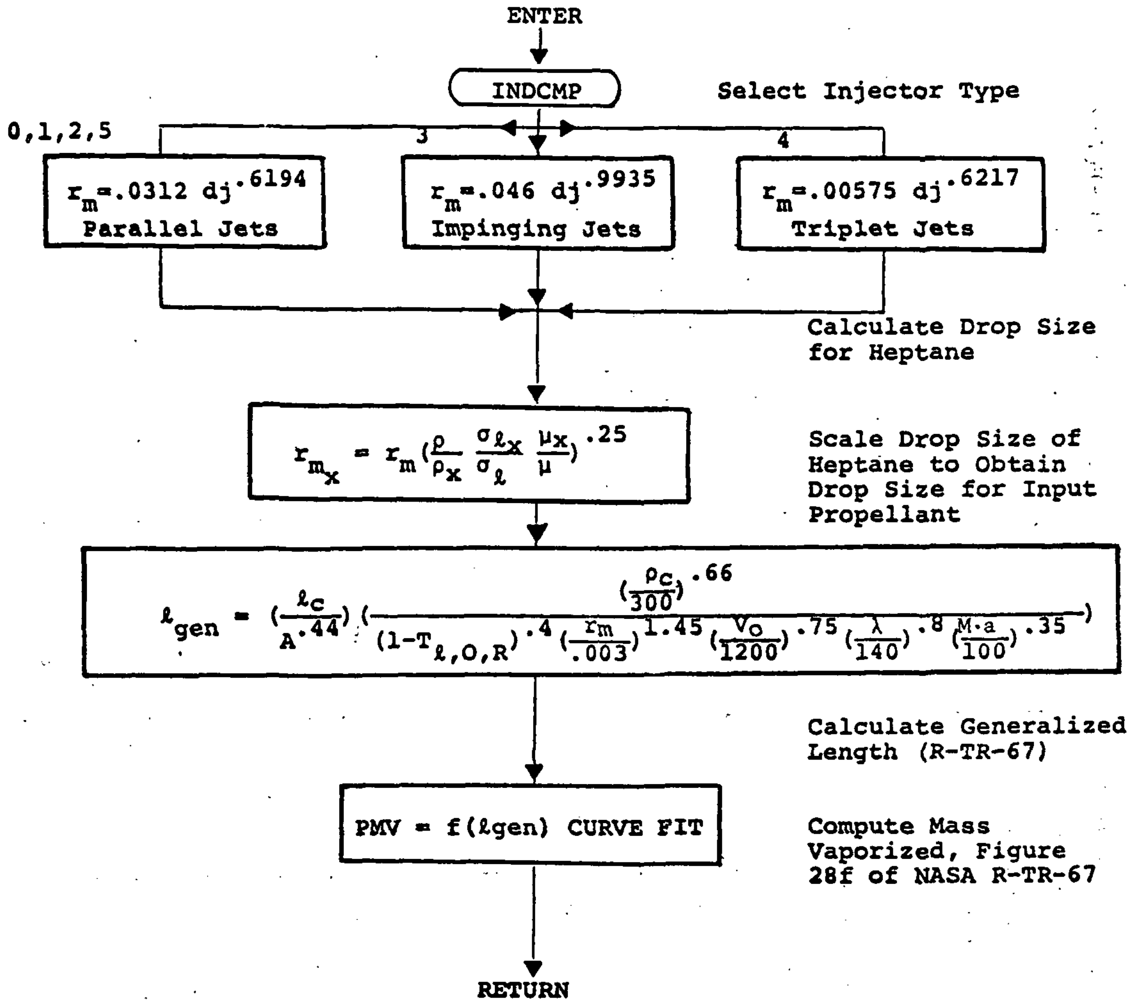


Figure 7-4. Detailed Flow Chart for Subroutine VAPRIZ (for Definition of Symbols see Equation (7-3))

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF11 AND SECF12

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
ADIS	a	–	1.0 (in CMPRED)	–	Constant for number distribution: = $100/(\sqrt{2\cdot\pi}\cdot\log_e\sigma_G)$; ($\sigma_G$ = geometric standard deviation)
AF11	–	–	0 or 1	I	Weighting factor constant for fuel vaporization in the average performance characteristic equation
AF12	–	–	0 or 1	I	Weighting factor constant for oxidizer vaporization in the average performance characteristic equation
DFVEL or DXVEL	dj	inches	Positive Number	I	Propellant jet diameter for fuel or oxidizer
F11 or F12	–	per cent	0 to 100	O	Per cent mass vaporized of fuel or oxidizer
GENL	ℓ_{gen}	inches	Positive Number	O	Generalized length; see Equation (7-3)
INJCMP	-	–	0, 1, 2, 3, 4, or 5	I	Injector complexity index (for definition see Section 2.4)
IRWVAP	–	–	0, 1, 2	I	Read or write option for subroutine VAPRIZ; see Section 2.6
IRW11 or IRW12	–	–	0, 1, 2	I	Read or write option for subroutines SECF11 and SECF12; see Section 2.6

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF11 and SECF12

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
ISTATF or ISTATX	—	—	1 or 2	I	Fuel or oxidizer state at injector exit: 1 = gas 2 = liquid
LAMBDF or LAMBDX	λ	BTU/lbm	0 or Positive Number	I	Latent heat of vaporization for input fuel or oxidizer (condition at injector exit)
LC	ℓ_c	inches	Positive Number	I	Combustion chamber length (distance from injector face to throat area)
MOLEF or MOLEX	M	lbm/Mole	Positive Number	I	Molecular weight of fuel or oxidizer
MUC	μ	lbf/in-sec	.0000174	—	Viscosity of liquid heptane (condition at injector exit)
MUF or MUX	μ_x	lbf/in-sec	Positive Number	I	Viscosity of fuel or oxidizer (condition at injector exit)
PCI	P_c	lbf/in^2	Positive Number	0	Combustion chamber pressure at injector face
RC	A		Positive Number	0	Combustion chamber contraction ratio
RHOC	ρ	lbm/in^3	.0247	—	Density of reference liquid heptane (condition at injector exit)

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF11 AND SECF12

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
RHOF or RHOX	ρ_x	$\mathrm{lbm}/\mathrm{in}^3$	Positive Number	I	Density of input fuel or oxidizer (condition at injector exit)
RMC	r_m	inches	Positive Number	0	Propellant drop size for heptane (calculated in Equation (7-1) for parallel jets, impinging jets, or triplet jets)
RM	r_{m_x}	inches	Positive Number	0	Propellant drop size for input propellant; i.e., fuel or oxidizer
SIGLC	σ_ℓ	lbf/in	.0001	—	Surface tension of liquid heptane (condition at injector exit)
SIGLF, SIGLX	σ_{ℓ_x}	lbf/in	Positive Number	I	Surface tension of input liquid fuel or oxidizer (condition at injector exit)
TLORF or TLORX	$T_{\ell,o,R}$	—	Positive Number	0	Propellant temperature ratio (Propellant temperature at injector exit/critical temperature)
VO or VFUEL	V_o	in/sec	Positive Number	0	Propellant injection velocity; i.e., fuel or oxidizer

7.1.2 Subroutine SECF13. Subroutine SECF13 computes the C*-efficiency in in per cent, F13, based on the mixing model as presented in Reference 7-2. Figure 7-5 (Figure 4 of Reference 7-2) depicts the relationship of the C*-efficiency vs. the mixing parameter, α . If a propellant combination is not in Figure 7-5, the curve for JP-4/O_2 can be taken. It is

$$\alpha = T*L_c/S \qquad (7\text{-}4)$$

where

T = turbulence intensity

L_c = combustion chamber length

S = average spacing between elements .

C* is found by a polynomial curve fit procedure YPOLYV so that F13 = YPOLYV (ALPHA, PCCSTR, NPCSTR). The polynomial coefficients PCCSTR and NPCSTR are stored in subroutine CMBINI.

The flow chart for the controlling subroutine SECF13 is presented in Figure 7-6.

7.2 Stability Characteristic Modules (Subroutines)

Combustor stability characteristics are evaluated on the basis of the methods given in References 7-3 through 7-13. Several of these methods require the solution of characteristic equations in the complex plane (Subroutines SECF20, 21, 26, 27, and 28). In certain cases, the neutral stability boundaries can be found in closed form. In the AUTOCOM method the actual decay rate rather than the neutral stability boundary is required; for the method must recognize how stable or unstable an engine is in order to define an improved design.

A general technique for solving complex characteristic equations is embedded within the AUTOCOM code. This method is again based on multi-variable search,-this time in an inner optimization loop within the system evaluation module.

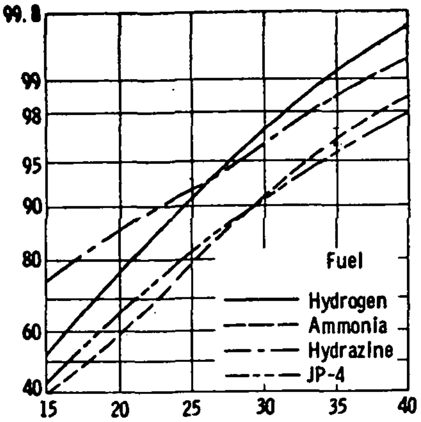
Let a particular complex characteristic equation be represented by

$$F_i(\overline{z}) = 0$$

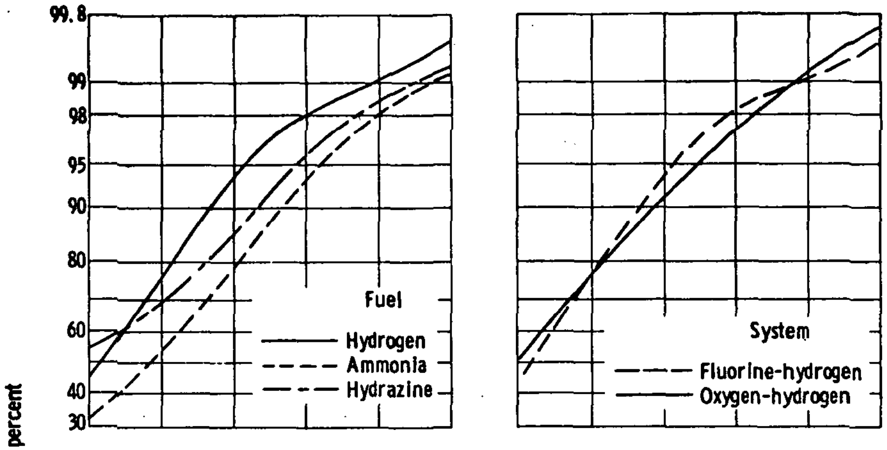
where $\overline{z}$ is position in the complex plane, and let

$$\overline{z} = \overline{(\alpha_1, \alpha_2)}$$

Then the roots of the characteristic equation can readily be found by solving the nonlinear optimization problem

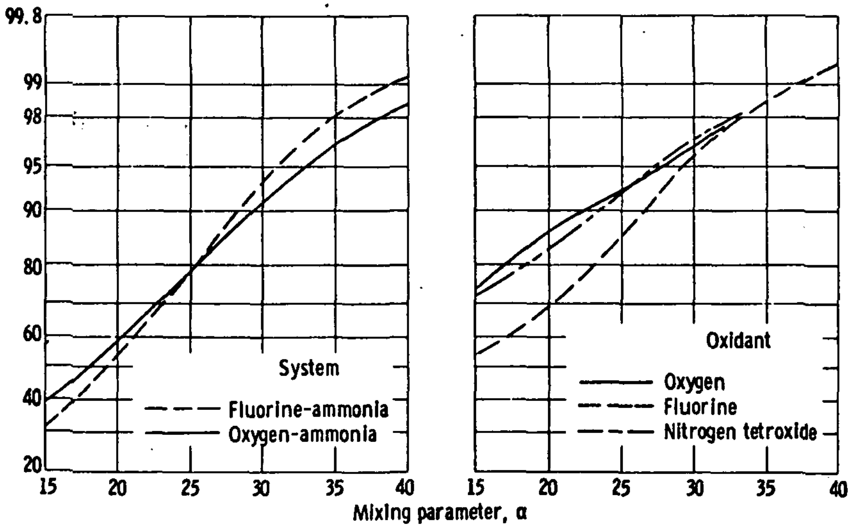


(a) Oxygen with various fuels.



(b) Fluorine with various fuels.

(c) Oxygen and fluorine with hydrogen.



(d) Oxygen and fluorine with ammonia.

(e) Hydrazine with various oxidants.

Figure 7-5. Characteristic Exhaust Velocity Efficiency as a Function of Mixing Parameter at Oxidant-Fuel Weight Ratio for Maximum Theoretical Characteristic Exhaust Velocity

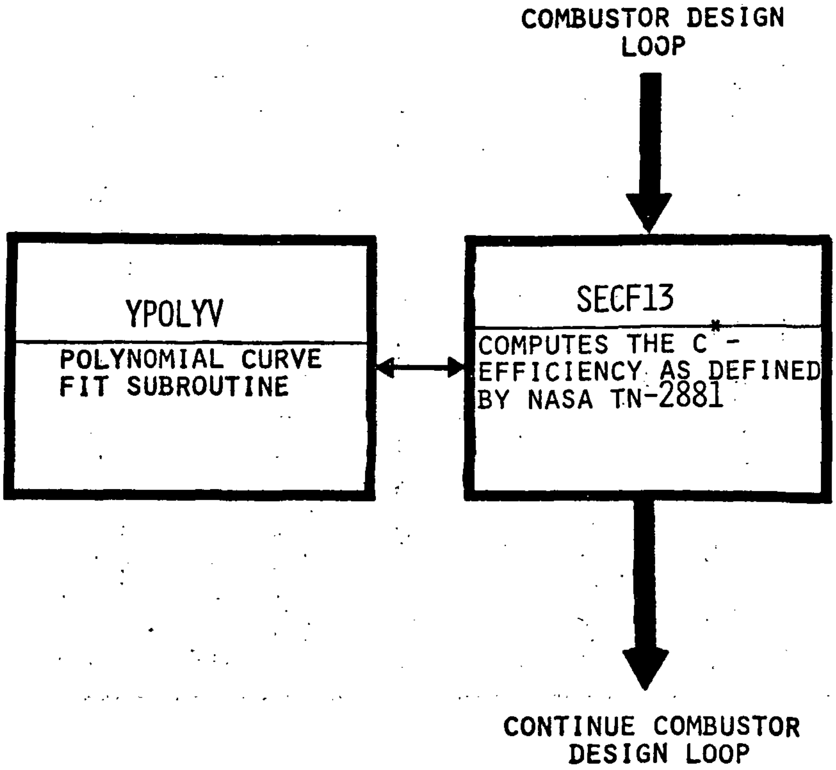


Figure 7-6. Flow Chart for Subroutine SECF13 for Computing C*-Efficiency

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF13

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
AF13	—	—	0 to 1	I	Weighting factor constant in the average performance characteristic equation
FJSPAC	S	inches	Positive Number	0	Average spacing between injector elements determined by: (injector face area/number of injector elements)$^{1/2}$. Computed in subroutine POSTAL; see Section 7.9
F13	—	per cent	0 to 100	0	C*-efficiency in per cent
IRW13	—	—	0, 1, 2	I	Read or write option for subroutine SECF13; see Section 2.6
LC	ℓ_c	inches	Positive Number	I	Combustion chamber length (injector face to throat area)
NPCSTR	—	—	10	—	Number of coefficients for C* calculation, stored in subroutine CMBINI
PCCSTR	—	—	—	—	Coefficients for C* calculation, stored in subroutine CMBINI
TURBIN	T	%	.03	—	Turbulence intensity in per cent (it is assumed equal to 3 per cent for this model.); value is stored in Subroutine CMBINI

$$\Phi^* = \underset{\alpha}{\underline{\mathrm{Min}}}[|F_i(\bar{z})|]$$

Where multiple roots exist, each root obtained may be swept out of the characteristic equation by multiplication by $(\bar{z} - \bar{z}_{root})$; in this manner all acceptable roots within a region of the complex plane (the decay rate/frequency-plane) may be found.

The above method is particularly appropriate in a combustor design optimization in which a sequence of perturbed engine designs are evolved. For in every design evaluation following the nominal, the approximate location of stability roots are known from the previous engine design. This results in greatly improved convergence rates for location of perturbed stability roots on successive designs.

Typical contours of the function $|F_i(\bar{z})|$ for the stability analysis are presented for illustrative purposes in Figure 7-7. The effect of boundary selection in dicated. Thus, with the original search boundaries, shown dashed, no root is located; however, by increasing the search boundaries the desired root is found. In evaluation of a nominal design, some manipulation of search boundaries is often required (for contour mapping see Appendix B, Part I).

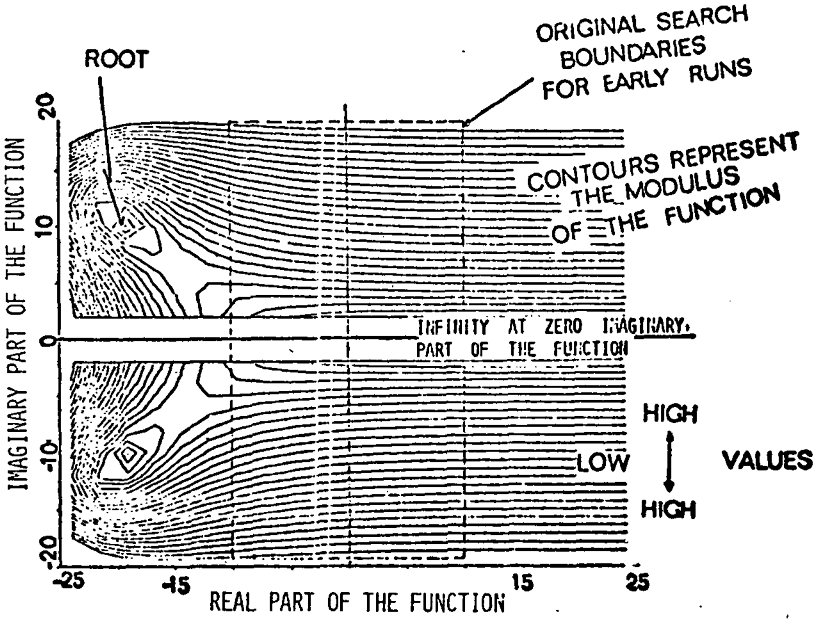


Figure 7-7. Typical Roots from Stability Transverse Mode, Non-Coaxial Injection, Oxidizer

7.2.1 Subroutines SECF20 and SECF21. Subroutine SECF20 computes the chugging decay rate, F20, based on the fuel feed system; and subroutine SECF21 computes the chugging decay rate, F21, based on the oxidizer feed system. Both, F20 and F21, are determined from L. Crocco and S. I. Cheng's theory as given in Refenence 7-3.

For pump-fed systems, Equation (2.04.03) of Reference 7-3 is used in the form

$$(1 + Es + JEs^2)[1 + s - n + ne^{-\tau s}] + PEse^{-\tau s} = F(s) \equiv 0 \qquad (7\text{-}5)$$

This equation is coded in subroutine C20403.

For pressure-fed systems, Equation (2.05.02) of Reference 7-3 is used in the form

$$[1+Js + JEys^2 + J^2Ey(1-y)s^3](1+s-n + ne^{-\tau s}) + Pe^{-\tau s}(1+JEys^2) = F(s) \equiv 0 \qquad (7\text{-}6)$$

This equation is coded in subroutine C20502.

The definition of the constants in Equations (7-5) and (7-6) is

$$E = \frac{2\Delta P\rho\chi}{\dot{m}\ \Theta_g} \qquad \text{[elasticity parameter]} \qquad (7\text{-}7)$$

$$P = \frac{P_c}{2\Delta P} \qquad \text{[pressure drop parameter]} \qquad (7\text{-}8)$$

$$J = \frac{\ell\ \dot{m}}{2\Delta PA\Theta_g} \qquad \text{[inertia parameter]} \qquad (7\text{-}9)$$

The optimization program AESOP is used in an inner loop as a root finder by minimization of the function $|F(s)|$ in Equation (7-5) or Equation (7-6). The Laplace transformation variable "s" has been solved for in terms of a real and an imaginary value. These are the elements of the complex root, defining decay rate and frequency of oscillation.

The root searching procedure begins with activating subroutine STARTR which computes a neutral stability point for solving Equation (2.04.06) or Equation (2.05.04) of Reference 7-3 based on the coded-in guessed roots presented in Table 2-1. This is executed in subroutines C20406 and C20504, respectively. The neutral stability point thus found is used as the starting point in a search for the roots of Equation (7-5) or Equation (7-6).

When a root is found, it is swept out by a root sweeping routine, SWEEPR, and another root solution is attempted. This process is continued for a predetermined number of roots. The resulting complex roots are examined, and the root with the largest positive real part and a non-negative imaginary part is selected. The characteristic function is the real part of the root devided by the gas residence time, Θ_g. Thus,

$$F20 = Re(s)_{fuel}/\Theta_g \tag{7-10}$$

and

$$F21 = Re(s)_{ox}/\Theta_g \tag{7-11}$$

where the imaginary part of the solution represents the angular frequency.

The symbols used in Equation (7-5) through Equation (7-11) are:

n = pressure index of interaction between combustion processes and oscillations in the combustion chamber

P_c = combustion chamber pressure

ΔP = injector pressure drop

$\dot{m}$ = steady state mass flow rate

ℓ = length of feed line (the orifice length of the injector for fuel or oxidizer is replacing "ℓ" in this computer model)

A = cross-sectional area of feed line (the total cross-sectional area for fuel or oxidizer holes is replacing "A" in this computer model)

$\bar{\tau} = \tau/\Theta_g$ = sensitive time lag

$\tau = L_{50}/V_{inj}$ = time lag

For the case of supercritical or gaseous state of the fuel, the definition for τ has been modified to the expression:

$$\tau_{fuel} = \frac{L_{50(ox)}}{1/3\ V_{inj(fuel)}} \qquad (7\text{-}12)$$

and

$$\tau_{ox} = \frac{L_{50(fuel)}}{1/3\ V_{inj(ox)}} \qquad (7\text{-}13)$$

Θ_g = gas residence time

ω = angular frequency

L_{50} = length of combustion chamber required to vaporize 50 per cent of the propellant

V_{inj} = propellant injection velocity

y = position of the equivalent concentrated line capacitance as fraction of feed line length. In the present program coding, y is 1.0

χ = compressibility factor of propellants

ρ = propellant density

s = Laplace transformation variable

Note: If both, fuel and oxidizer, are in a gaseous state, the expressions for τ_{fuel} and τ_{ox} (Equations (7-12) and (7-13), respectively) are not longer valid.

The designer's choice for a pump-fed or pressure-fed system can be executed by input of the cards, listed below, in Data Input Namelist COMMIS (see Section 2.4):

	PUMP-FED	PRESSURE-FED
Fuel	IEQF = 1,	IEQF = 2,
Oxidizer	IEQX = 1,	IEQX = 2,

Figure 7-8 shows the flow chart for the controlling subroutines SECF20 and SECF21. Figure 7-9 depicts the logic of subroutine STARTR, whereas Figure 7-10 shows a detailed flow chart for function LFIFTY.

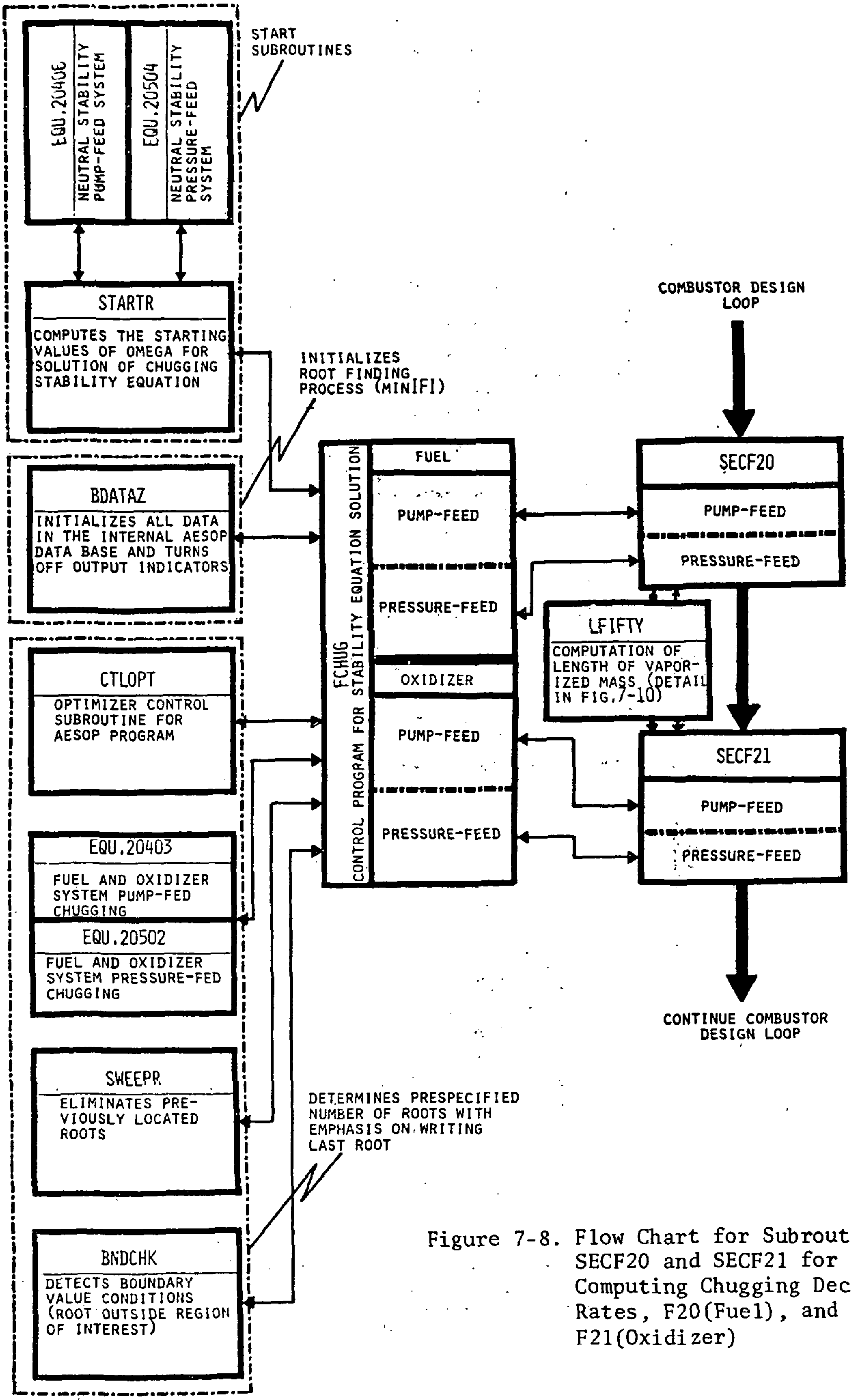


Figure 7-8. Flow Chart for Subroutines SECF20 and SECF21 for Computing Chugging Decay Rates, F20(Fuel), and F21(Oxidizer)

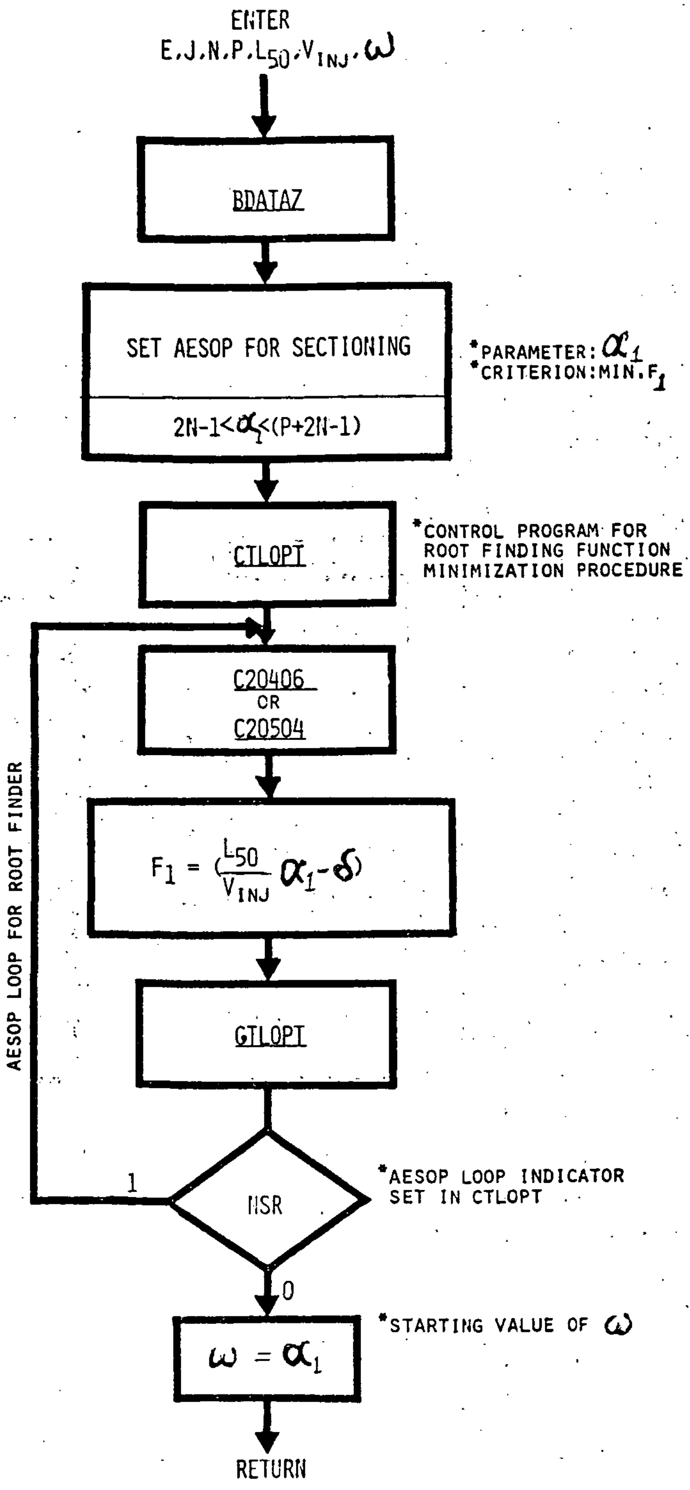


Figure 7-9. Flow Chart for Subroutine STARTR to Compute a Neutral Stability Starting Point for Solving Equations (2.04.03) and (2.05.02) in Subroutines SECF20 and SECF21

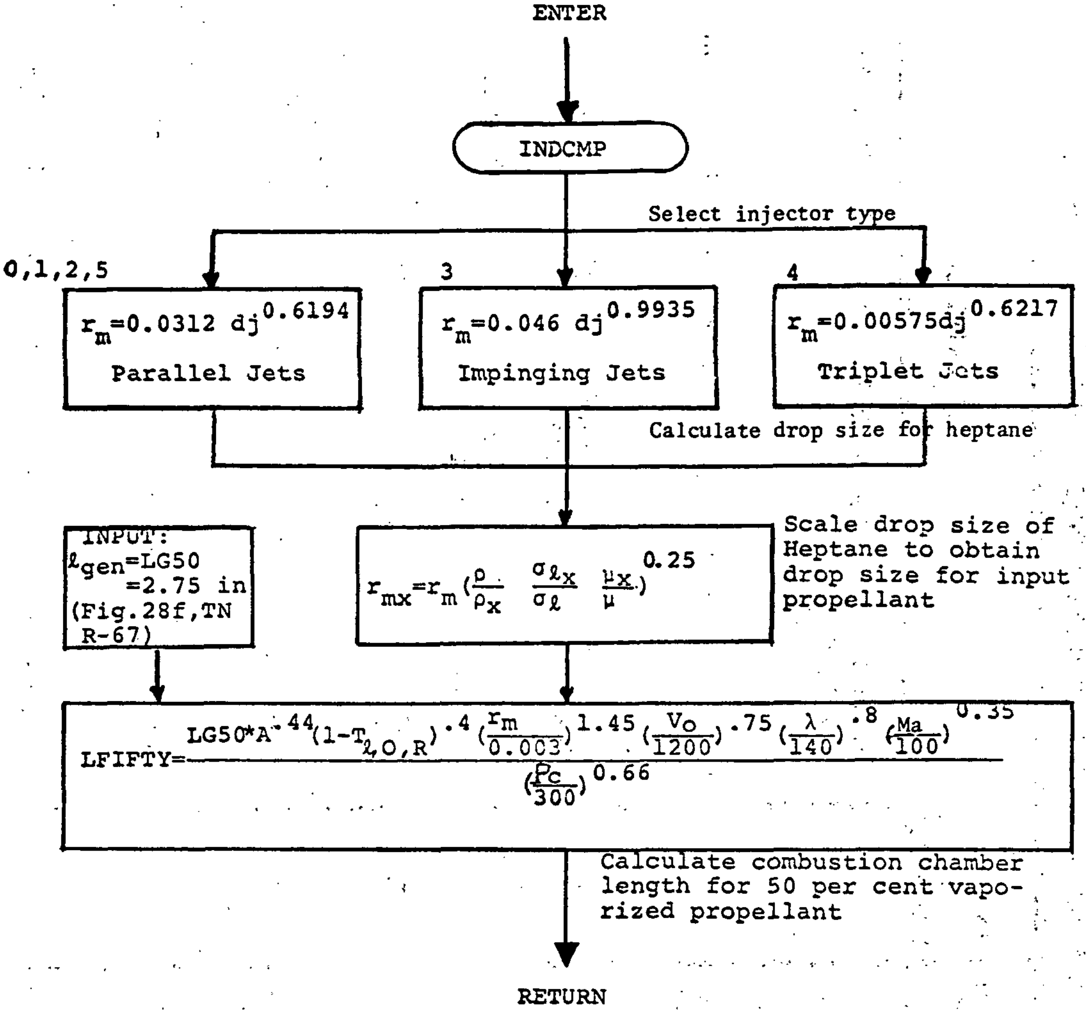


Figure 7-10. Detailed Flow Chart for Function LFIFTY which Computes the Length of the Combustion Chamber to Vaporize 50 per cent of Fuel or Oxidizer. (For Definition of Symbols see Section 7.1.1)

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF20 AND SECF21

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
ADIS	a	—	1.0 (in subroutine CMPRED)	—	Constant for number distribution; for definition see Section 7.1.1
AF or AOX	—	in^2	Positive Number	—	Gross-sectional area of a single fuel or oxidizer hole
AF20	—	—	0 or 1	I	Weighting constant, exponential on the combustor stability characteristic equation
AF21	—	—	0 or 1	I	Weighting constant, exponential on the combustor stability characteristic equation
CHIF or CHIX	χ	—	Positive Number	I	Compressibility of the fuel or the oxidizer. For definition see Section 2.4
DELTPF or DELTPX	ΔP	lbf/in^2	Positive Number	O	Pressure drop in injector for fuel or oxidizer
DFVEL or DXVEL	d_j	inches	Positive Number	I	Propellant injector holes diameter for fuel or oxidizer
EFUEL or EOXID	E	—	Positive Number	O	Elasticity parameter. For definition see Equation (7-7) in Section 7.2.1

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF20 AND SECF21

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
FLAREA	A	in^2	Positive Number	O	Effective cross-section area of fuel feed line (the total area of the fuel holes is replacing FLAREA in the program coding)
FLINE, LF or XLINE, LOX	ℓ	inches	Positive Number	I	Length of fuel or oxidizer supply lines. In the present program, the length of fuel or oxidizer orifices (LF or LOX) is the input
F20	–	–	Positive or Negative Number	O	Chugging decay rate based on the fuel feed system
F21	–	–	Positive or Negative Number	O	Chugging decay rate based on the oxidizer feed system
GREF	g	in/sec^2	32.2*12	I	Gravitational constant
GRF20R, I	–	–	Positive or Negative Number	I	Root guesses for the real or imaginary part in Subroutine SECF20; see Section 2.5, Table 2-1
GRF21R, I	–	–	Positive or Negative Numbers	I	Root guesses for the real or imaginary part in Subroutine SECF21; see Section 2.5, Table 2-1

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF20 and SECF21

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
IEQF or IEQX	—	—	1 or 2	I	Fuel or oxidizer feed system indicator: 1 = pump-fed system 2 = pressure-fed system
IGRF20 or IGRF21	—	—	1 or 2	I	Control statement for Subroutine SECF20 or SECF21 if root guesses for the individual subroutines are stored in the program code, or if root guesses are used in input data; see Section 2.5.2
INJCMP	—	—	0, 1, 2, 3, 4, or 5	I	Injector complexity index; see listing in Section 2.4
IRW20 or IRW21	—	—	0, 1, or 2	I	"Read" or "Write" option in Subroutine SECF20 or SECF21; see Section 2.6
ISTATF or ISTATX	—	—	1 or 2	I	Fuel or oxidizer state at injector exit: 1 = gas 2 = liquid
JFUEL or JOXID	J	—	Positive Number	0	Inertia parameter. For definition see Equation (7-9) in Section 7.2.1
LAMBDF or LAMBDX	λ	BTU/lbm	Positive Number or 0	I	Latent heat of vaporization of fuel or oxidizer (condition at injector exit)

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF20 AND SECF21					
PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
L5FUEL or L5OXID	L_{50}	inches	Positive Number	O	Length of combustion chamber to vaporize 50 per cent of fuel or oxidizer
LG50F or LG50X	ℓ_g	inches	2.75	I	Generalized chamber length to vaporize 50 per cent of fuel or oxidizer
MOLEF or MOLEX	M	lbm/mole	Positive Number	I	Molecular weight of fuel or oxidizer
MUF or MUX	μ_x	$\text{lbf}/\text{in-sec}$	Positive Number or 0	I	Viscosity of liquid or gaseous fuel or oxidizer (condition at injector exit)
NFUEL or NOXID	n	—	0.0	—	Pressure index of interaction between combustion process and oscillations in the combustion chamber (defined in Reference 7-3, Equation (1.11.01))
NF or NOX	—	—	Positive Integer	I	Number of fuel or oxidizer orifices
NRF20 or NRF21	—	—	≤ 20	I	The maximum of roots possible to be solved in Subroutines SECF20 and SECF21; see Section 2.5.2
NTF20 or NTF21	—	—	≤ 20	I	The maximum umber of trials for each root in Subroutines SECF20 and SECF21; see Section 2.5.2

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF20 AND SECF21

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
PFUEL or POXID	P	—	Positive Number	O	Pressure drop parameter for fuel or oxidizer. For definition see Equation (7- 8) in Section 7.2.1
PCI	P_c	lbf/in^2	Positive Number	O	Combustion chamber pressure for steady state operation
RC	A	—	Positive Number	O	Combustion chamber contraction ratio
RHOC	ρ	lbm/in^3	.0247	I	Density of liquid heptane (condition at injector exit)
RHOF or RHOX	ρ_x	lbm/in^3	Positive Number	I	Density of fuel or oxidizer (condition at injector exit)
SIGLC	σ	lbf/in	$1*10^{-4}$	I	Surface tension of heptane (condition at injector exit)
SIGLF or SIGLX	σ_x	lbf/in	Positive Number or 0	I	Surface tension of fuel or oxidizer if in a liquid state (condition at injector exit)
THETAG	Θ_g	sec	Positive Number	O	Mean gas residence time
VFUEL or VOXID	V_o	in/sec	Positive Number	O	The initial fuel or oxidizer injection velocity

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF20 AND SECF21

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT(I) or OUTPUT(O)	DESCRIPTION
VOLF or VOLX	V	in^3	Positive Number	I	Volume of fuel or oxidizer manifold
TAF or TAX	A	in^2	Positive Number	O	Total area of fuel or oxidizer orifices
TLORF or TLORX	$T_{\ell,o,R}$	—	Positive Fraction	O	Reduced initial fuel or oxidizer temperature (propellant temperature at injector exit/critical temperature)
WF,WINJF or WOX,WINJX	$\dot{m}$	lbm/sec	Positive Number	I	The fuel or oxidizer flow rate passing the injector; for definition see Section 2.4
XLAREA	A	in^2	Positive Number	O	Effective cross-section area of oxidizer feed line (the total area of the oxidizer holes is replacing XLAREA)

7.2.2 Subroutines SECF22 and SECF23. Subroutine SECF22 computes the stability characteristics for pulsed operation based on the A. D. Little correlation (Table II of Reference 7-4), F22, and subroutine SECF23 determines the stability characteristics for non-pulsed operations, F23, also based on the A. D. Little correlation (Table I of Reference 7-4). The correlation equations are shown in Tables 7-1 and 7-2. Here, SP10 indicates the occurrence of an induced, undamped, high or intermediate frequency oscillation, and SP1A indicates the occurrence of a spontaneous, high and intermediate frequency oscillation.

The stability characteristics are obtained from:

$$F22 = 200(SP10 - .5) \tag{7-14}$$

and

$$F23 = 200(SP1A - .5) \tag{7-15}$$

$$\begin{aligned}
SP\ 10 = [&- 5.56684 - 0.16675(LD - 1.45926) - 0.26577(LD_f - 8.20992) \\
&+ 0.3456\ (TPVM - 4.40439) + 0.00009267(V_o - 1065.97697) \\
&- 13.67851(\log D_{of} - 1.69583) + 0.15923(FO2 - 0.12461) \\
&- 74.95672(LR - 0.08022) - 0.36162(BF - 0.11682) \\
&+ 12.57151(LR - 0.08022)\ (PE1 - 0.14330) \\
&+ 0.27624(BF - 0.11682)(PE2 - 0.42991) \\
&- 0.003242(TPVM - 4.40439)^2 - 0.42891(\log D_{of} - 1.69583)^2 \\
&- 0.044068(LD - 1.45926)(TPVM - 4.40439) \\
&+ 0.0003075(V_o - 1065.97697)(\log D_{of} - 1.69583) \\
&- 3.09641(LR - 0.08022)(LD_f - 8.20992) \\
&+ 0.0003577(LR - 0.08022)(V_o - 1065.97697) \\
&- 163.91664(LR - 0.08022)(\log D_{of} - 1.69583) \\
&- 0.12184(PE1 - 0.14330)(LD_f - 8.20992) \\
&- 0.15581(PE\ 2 - 0.42991)(LD - 1.45926) \\
&- 0.00002194(PE2 - 0.42991)(V_o - 1065.97697) \\
&+ 0.03835(PE2 - 0.42991)(TPVM - 4.40439) \\
&- 0.40008(PE2 - 0.42991)(\log D_{of} - 1.69583)\ ]
\end{aligned}$$

TABLE 7-1. A.D.Little Correlation Equation to Determine the Stability Characteristics for Pulsed Operation

$$
\begin{aligned}
\mathrm{SP1A} = [\, & 0.49583 - 0.0014639(\mathrm{LR} - 0.25068)(P_{ci} - 329.95023) \\
& + 0.024960(L_1 - 16.24385) - 0.45096(\log R_c - 0.33429) \\
& - 7.15205(\mathrm{BF} - 0.36833)(\log \mathrm{ID}_f + 0.01452) \\
& + 0.11250\,(\mathrm{LR} - 0.25068)\,(\mathrm{LD} - 2.13785) \\
& - 0.05177(\mathrm{F03} - 0.28507)(\mathrm{IDE}_f - 1.92209) \\
& - 0.27789(\mathrm{F03} - 0.28507) \\
& - 0.0006173(\mathrm{IDE}_f - 1.92209)(\mathrm{EPA} - 3.76607) \\
& + 1.43317(\mathrm{LR} - 0.25068)(\mathrm{MPE} - 1.93154) \\
& + 2.09309(\mathrm{LR} - 0.25068) - 0.30534(\mathrm{BF} - 0.36833) \\
& - 0.80153(\mathrm{PEL} - 0.16561) + 0.001229(L_1 - 16.24385)^2 \\
& + 0.002199(\mathrm{MPE} - 1.93154)^2 - 0.26849(\log R_c - 0.33429)^2 \\
& + 0.00035321(P_{ci} - 329.95023)(\mathrm{LD} - 2.13785) \\
& - 0.087008(L_1 - 16.24385)(\log R_c - 0.33429) \\
& - 0.17222(L_1 - 16.24385)(\log \mathrm{ID}_f + 0.01452) \\
& - 0.000131(L_1 - 16.24385)(\mathrm{MPE} - 1.93154) \\
& - 0.81565(\log \mathrm{ID}_f + 0.01452)(\mathrm{IDE}_f - 1.92209) \\
& - 0.030990(\mathrm{LD} - 2.13785)(\mathrm{MPE} - 1.93154) \\
& - 0.033444(\mathrm{IDE}_f - 1.92209)(\mathrm{MPE} - 1.93154) \\
& + 0.25448(\mathrm{PE1} - 0.06561)(\mathrm{LD} - 2.13785) \\
& - 0.90924(\mathrm{PE1} - 0.16561)(\mathrm{MPE} - 1.93154) \\
& + 0.17428(\mathrm{PE1} - 0.16561)(\mathrm{IDE}_f - 1.92209) \\
& + 0.0957(\mathrm{PE1} - 0.16561)(\log R_c - 0.33429) \\
& - 0.0003465(\mathrm{F03} - 0.28507)(P_{ci} - 329.95023) \\
& + 0.03243(\mathrm{F03} - 0.28507)(L_1 - 16.24385) \\
& + 0.00098624(\mathrm{BF} - 0.36833)(P_{ci} - 329.95023) \\
& - 1.20213(\mathrm{LR} - 0.25068)(\log R_c - 0.33429)\,]
\end{aligned}
$$

TABLE 7-2. A.D.Little Correlation Equation to Determine the Stability Characteristics for Non-Pulsed Operation

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF22 AND SECF23

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
AF22	—	—	0 or 1	I	Weighting constant, exponential on the combustor stability characteristic equation
AF23	—	—	0 or 1	I	Weighting constant, exponential on the combustor stability characteristic equation
BF	BF1	—	1.0 or 0.	—	Baffle parameter, BF = 1, automatically determined if F81 or F82 > 0; and BF = 0 if F81 and F82 = 0
EPA	EPA	$^1/_{in^2}$	Positive Number	0	Number of injector elements per unit area of injector face; for definition see Section 7.9.9
F02	F02	—	—	—	Propellant combination parameter 2; automatically determined by PTYP input (set in subroutine CMPRED)
F03	F03	—	—	—	Propellant combination parameter 3; automatically determined by PTYP input (set in subroutine CMPRED)
F22	—	—	Positive or negative Number	0	Stability characteristic for pulsed operation; see Equation (7-14)
F23	—	—	Positive or negative Number	0	Stability characteristic for non-pulsed operation; see Equation (7-15)
IDEF	IDE_f	—	1.0	I	Fuel injection distribution eccentricity. (Fixed input for the present computer program)

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF22 AND SECF23

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
IRW22	—	—	0, 1, or 2	I	"Read" or "Write" option in subroutine SECF22; see Section 2.6
IRW23	—	—	0, 1, or 2	I	"Read" or "Write" option in Subroutine SECF23; see Section 2.6
LC	L_1	inches	Positive Number	I	Combustion chamber length (injector face to throat area)
LD	LD	—	Positive Number	O	Chamber length to diameter ratio
LDF	LD_f	—	Positive Number	O	Fuel orifice length to diameter ratio
LDOF	$\log(D_{of})$	—	—	—	Log of fuel orifice exit diameter D_{of} in 1000^{ths} of inches
LIDF	$\log(ID_f)$	—	0.0	—	Log of fuel injection distribution. (Fixed input for the present computer program)
LR	LR	—	1.0 or 0	I	Liner parameter. (LR = 1.0 if liner is present; 0.0 if no liner)
LRC	$\log(R_c)$	—	—	—	Log of chamber contraction ratio: log(chamber diameter/throat diamter)^2
MPE	MPE	lbm/sec	Positive Number	—	Propellant mass flow rate per injector element

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF22 AND SECF23

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT(I) or OUTPUT(O)	DESCRIPTION
PCI	P_{ci}	lbf/in^2	Positive Number	O	Combustion chamber pressure
PE1	PE1	—	1.0	—	Principal element type 1, automatically determined by ETYP input (set in Subroutine CMPRED)
PE2	PE2	—	1.0	—	Principal element type 2, automatically determined by ETYP input (set in Subroutine CMPRED)
TPVM	TPVM	lbf/in^3	Positive Number	—	Thrust per unit chamber volume; for definition see Section 7.9.32
VO	V_o	in/sec	Positive Number	O	Oxidizer injection velocity

7.2.3 Subroutines SECF24 and SECF25. Subroutine SECF24 computes the decay rate for fuel, and Subroutine SECF25 computes the decay rate for oxidizer based on the high-frequency stability analysis of O. W. Dykema (Reference 7-5). He arrives at a dimensionless correlating parameter, N_s, called the stability number, which essentially represents the dimensionless ratio of a characteristic molecular diffusion time to a characteristic acoustic time. The stability number is

$$N_s = A[nd^3]\left[\frac{f\,P_c}{\dot{w}}\right] \qquad (7\text{-}16)$$

where

A = stability constant

d = injector orifice diameter (fuel or oxidizer), in.

f = frequency that gives maximum value for per cent combustion gain, cps

n = number of injector orifices (fuel or oxidizer)

P_c = combustion chamber pressure at injector end, psia

$\dot{w}$ = propellant flow rate (fuel or oxidizer), lbm/sec

Because the constant A is very difficult to evaluate for an operating thrust chamber, it must be determined by correlation of instability data. An average value of $6.0*10^{-3}$ has been assumed for this study. Thus, the equation for N_s can be rewritten

$$N_s = 6.0*10^{-3}*\rho(n*d^3)\left(\frac{f\,P_c}{\dot{w}}\right) \qquad (7\text{-}17)$$

where ρ is the specific gravity of the propellant.

The first bracket in the above equation includes the only terms which define the injector geometry. The second term includes the operating conditions of chamber mode frequencies, chamber pressure, and propellant flow rate.

Frequency modes which have been considered are:

- * Frequencies of the 1st, 2nd, and 3rd longitudinal mode
- * Frequencies of the 1st, 2nd, and 3rd tangential mode
- * Frequencies of the 1st and 2nd radial mode
- * Frequencies of the 1st longitudinal with the 1st tangential mode
- * Frequencies of the 1st longitudinal with the 2nd tangential mode

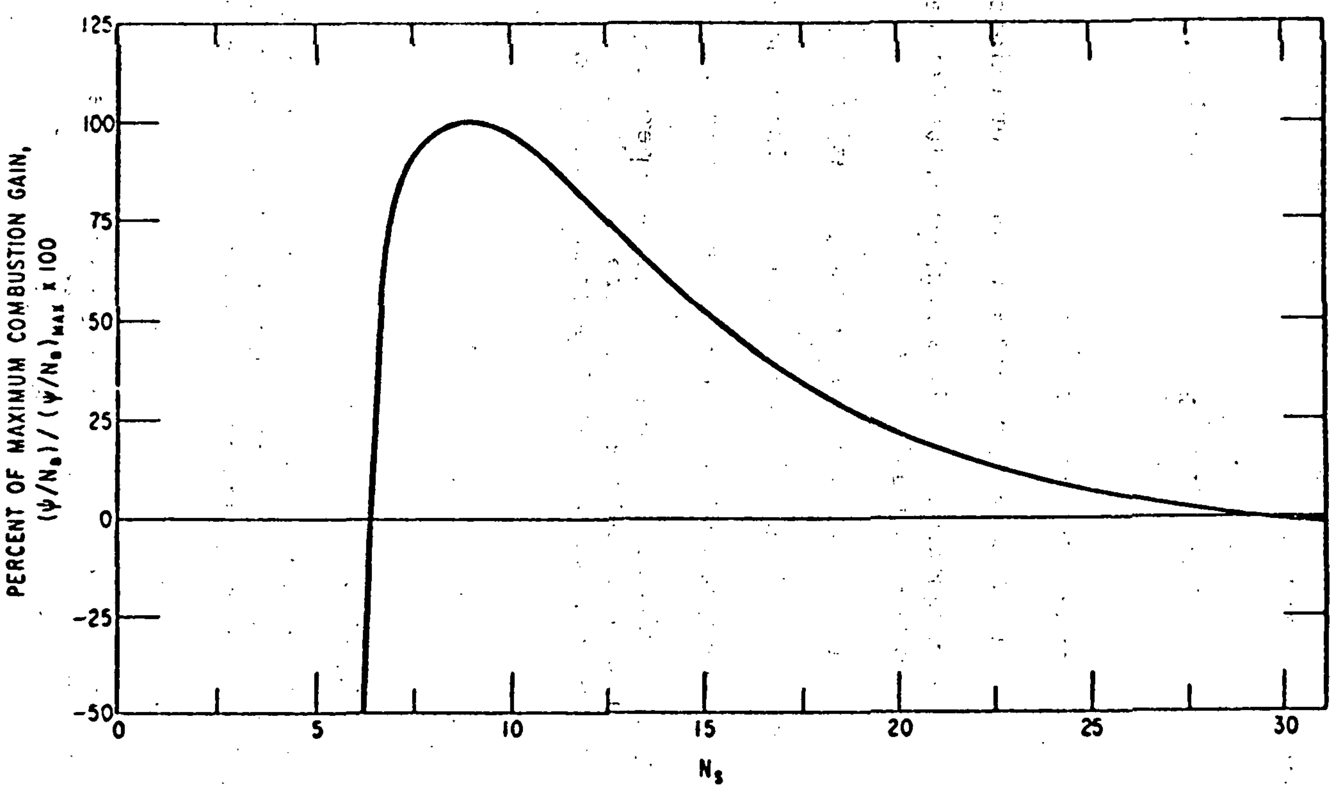


Figure 7-11. Theoretical Variation of Combustion Gain with the Stability Parameter N_S

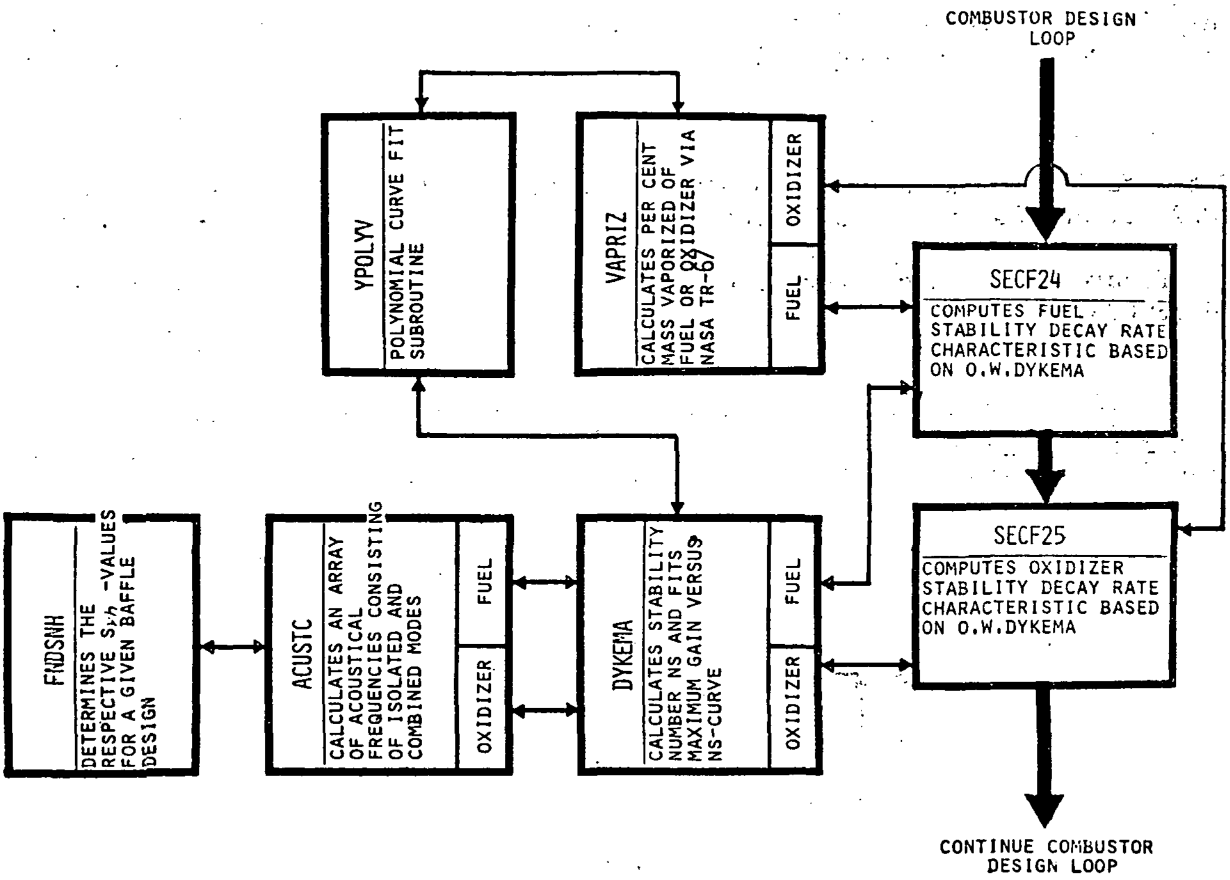


Figure 7-12. Flow Chart for Subroutines SECF24 and SECF25 Computing the Decay Rates F24(Fuel) and F25(Oxidizer)

A definition of the respective frequency modes is given in the following Section 7.2.3.1

After calculating the stability numbers, N_s, for all ten frequency modes, the per cent of maximum combustion gain is found from the relationship presented in Figure 7-11 which is coded into the program (Subroutine DYKEMA).

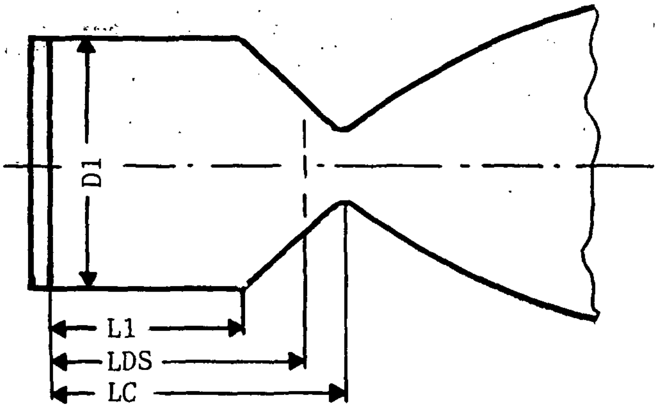
Based on the assumption that a decay rate of 100 is assigned to be equivalent to a value of 0 for the per cent of maximum combustion gain, and a growth rate of 100 is equivalent to 100 per cent of maximum gain, then

$$F24, F25 = 2(\text{max. gain} - 50) \qquad (7\text{-}18)$$

If the fuel or oxidizer is in a gaseous state (ISTATF or ISTATX = 1), Subroutine SECF24 or SECF25 will be bypassed.

Figure 7-12 depicts the flow chart for the controlling subroutines SECF24 and SECF25.

7.2.3.1 Definition of Frequency Modes for Subroutines SECF24 and SECF25 Without Baffles Present. (Computed in Subroutines ACUSTC). Figure 7-13 defines the symbols used in the following equations.



L1 = chamber length without converging section
LC = chamber length including " "
LDS= acoustical length of chamber
D1 = chamber diameter (near injector face)

Figure 7-13. Combustion Chamber Geometry Definition

LONGITUDINAL MODES. Longitudinal vibrations can be caused by either

1. A resonance effect analogous to a stretched string or an organ pipe where a supposedly homogeneous gas column exercises acoustical vibrations of various modes, or by,

2. Changing gas properties in the combustion chamber (e.g., shifting mixtures ratio) generating entropy waves.

To keep the program input requirements to a minimum only the conventional acoustical vibrations (Case 1) are being considered.

It can be supposed that the near throat area of the nozzle acts as a closed boundary to the pressure fluctuations, Reference 7-6. Then a pressure pulsation generated at the injector face might propagate downstream at the speed of sound, be reflected near the throat area, and then return to the injector at the speed of sound. The frequency is determined by the time required for the pressure pulse to perform the complete cycle. Thus for the 1st mode

$$\text{[freq. 1]:} \quad f_{L(1)} = \frac{C}{2*LDS}, \text{ cps} \qquad (7\text{-}19)$$

where C is the speed of sound of the gas in the combustion chamber and is defined by

$$C = \sqrt{gkRT} \qquad (7\text{-}20)$$

where

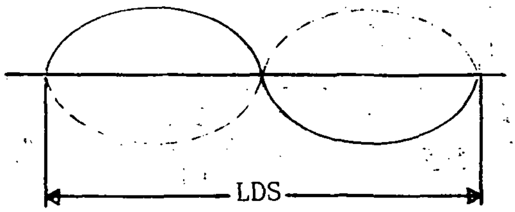
g = gravitational constant

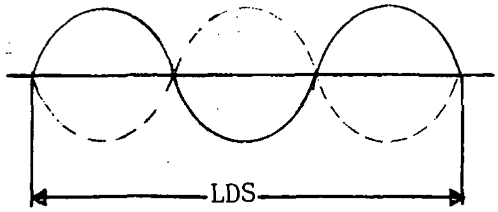
k = ratio of specific heat

R = gas constant

T = combustion temperature

When using the analogy with the vibrating string, i.e., that a nodal point at the reflection areas exists, the second and third modes can be represented by the following sketch.





Accordingly, the second mode of the longitudinal vibration can be expressed by:

$$[\text{freq. } 2] = f_{L(2)} = \frac{C}{LDS}\ \text{, cps} \qquad (7\text{-}21)$$

and the third mode

$$[\text{freq. } 3]: f_{L(3)} = \frac{C}{2{*}LDS}\text{, cps} \qquad (7\text{-}22)$$

Using the material presented in References 7-7 and 7-8 and considering the above mentioned requirements, tangential, radial, and combined modes can be presented as follows:

TANGENTIAL MODES

First mode:

$$[\text{freq. } 4]: f_{T(1)} = 0.586\frac{C}{D1}\text{, cps} \qquad (7\text{-}23)$$

Second mode:

$$[\text{freq. } 5]: f_{T(2)} = 0.972\frac{C}{D1}\text{, cps} \qquad (7\text{-}24)$$

Third mode:

$$[\text{freq. } 6]: f_{T(3)} = 1.337\frac{C}{D1}\text{, cps} \qquad (7\text{-}25)$$

RADIAL MODES

First mode:

$$[\text{freq.}7]: f_{R(1)} = 1.22\frac{C}{D1}\text{, cps} \qquad (7\text{-}26)$$

Second mode:

$$[\text{freq. } 8]: f_{R(2)} = 2.233\frac{C}{D1}\text{, cps} \qquad (7\text{-}27)$$

LONGITUDINAL MODE 1 WITH TANGENTIAL MODE 1

$$[\text{freq.}9]: f_{L(1),\,T(1)} = \sqrt{f^2_{L(1)} + f^2_{T(1)}}$$

$$= \sqrt{\left(\frac{C}{2LDS}\right)^2 + \left(0.586\,\frac{C}{D1}\right)^2}\ \text{,cps} \qquad (7\text{-}28)$$

LONGITUDINAL MODE 1 WITH TANGENTIAL MODE 2

$$[\text{freq.}10]:\quad f_{L(1),T(2)} = \sqrt{f^2_{L(1)} + f^2_{T(2)}}$$

$$= \sqrt{\left(\frac{C}{2\ LDS}\right)^2 + \left(0.972\ \frac{C}{D1}\right)^2} \qquad (7\text{-}29)$$

7.2.3.2 Definition of Frequency Modes for Subroutines SECF24 and SECF25 with Baffles Present. If there are radial and/or circumferential baffles present, the equation for the frequency, f, that gives maximum value for the combustion gain with respect to transverse and radial modes, becomes

$$f = \frac{a^* s_{\nu h}}{r^* 2\pi} \qquad (7\text{-}30)$$

where

a = speed of sound in combustion gas, in/sec

r = combustion chamber radius near the injector plane, ft

$s_{\nu h}$ = Eigenvalues given in Table 7-7 (Section 7.8.3) for various ν and h numbers

ν = number of transverse modes

h = number of radial modes

The program coding selects the original three longitudinal modes as defined in Section 7.2.3.1 (Subroutine ACUSTIC) and, via Subroutine FNDSNH (see Section 7.8.3), the lowest six $s_{\nu h}$-values, satisfying the exclusion rules as given in Section 7.8.3 (for more details for program provisions to accept baffles see Section 7.8.3).

7.2.4 Subroutine SECF26. Subroutine SECF26 computes the decay rate for the longitudinal modes of high frequency oscillations based on the sensitive time lag model of L. Crocco and S. I. Cheng, Reference 7-3, with the correlation equations for the interaction index, n, and time lag, τ , developed by D. T. Harrje and F. H. Reardon, Reference 7-9. According to the Equation (3.01.20) of Reference 7-3, the decay rate, F26, can be calculated by *)

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*)This a shorter version of Equation (3.01.20) of Reference 7-3 in accordance with the "Special Instructions for Task II" of Contract NAS 3-13331.

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF24 AND SECF25

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
ADIS	a	—	1.0	—	Constant for number distribution; see Section 7.1.1
AF24	—	—	0 or 1	I	Weighting constant, exponential on the combustor stability characteristic equation
AF25	—	—	0 or 1	I	Weighting constant, exponential on the combustor stability characteristic equation
BFLCIR	—	—	0 or Positive Integer	I	Number of circumferential baffles; for definition see Section 2.3
BFLRAD	—	—	0 or Positive Integer	I	Number of radial baffles; for definition see Section 2.3
CS	C	in/sec	Positive Number	O	Speed of sound of gas in combustion chamber
DC	D1	inches	Positive Number	I	Combustion chamber diameter at injector face
DFVEL or DXVEL	d_j	inches	Positive Number	I	Diameter of fuel or oxidizer injector holes
F24	—	—	Positive or Negative Number	O	Decay rate for fuel based on the high frequency stability analysis of O. W. Dykema

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF24 AND SECF25

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
F25	—	—	Positive or Negative Number	O	Decay rate for oxidizer based on the high frequency stability analysis of O. W. Dykema
GENL	ℓ_{gen}	inches	Positive Number	O	Generalized length; see Equation (7-3)
INJCMP	—	—	0, 1, 2, 3, 4, or 5	I	Injector complexity index (for definition see Section 2.4)
IRWVAP	—	—	0, 1, 2	I	Read or write option for Subroutine VAPRIZ; see Section 2.6
IRW24 or IRW25	—	—	0, 1, 2	I	Read or write option for Subroutine SECF24 or SECF25; see Section 2.6
ISNSAV	—	—	Positive integer or 0	O	Number of selected $s_{\nu h}$ - values from Subroutines FNDSNH (See Section 7.8.3)
ISTATF or ISTATX	—	—	1 or 2	I	Fuel or oxidizer state at injector exit: 1 = gas 2 = liquid
LAMBDF or LAMBDX	λ	Btu/lbm	Positive Number or 0	I	Latent heat of vaporization of fuel or oxidizer (condition at injector exit)

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF24 AND SECF 25

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
LC	LC	inches	Positive Number	I	Combustion chamber length (distance from injector face to throat area)
LDUM	LDS	inches	Positive Number	0	Acoustical length of combustion chamber. For definition see Section 7.2.3.1
MFRQF or MFRQX	—	—	10	—	Array of frequency modes to be checked for fuel or oxidizer
MOLEF or MOLEX	M	lbm/mole	Positive Number	I	Molecular weight of fuel or oxidizer
MUC	μ	lbf/in-sec	.0000174	I	Viscosity of liquid heptane (condition at injector exit)
MUF or MUX	μ_x	lbf/in-sec	Positive Number	I	Viscosity of fuel or oxidizer (condition at injector exit)
NF or NOX	n	—	Positive Integer	I	Number of fuel or oxidizer holes in the injector
NFRQF or NFRQX	—	—	Positive Integer	I	Number of frequency modes to be checked for fuel or oxidizer
PCI	P_c	lbf/in^2	Positive Number	O	Combustion chamber pressure near the injector face for steady state conditions

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF24 AND SECF25

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
RC	A	–	Positive Number	O	Combustion chamber contraction ratio
RHOC	ρ	lbm/in^3	.0247	I	Density of reference liquid heptane (condition at injector exit)
RHOF or RHOX	ρ_x	lbm/in^3	Positive Number	I	Density of fuel or oxidizer (condition at injector exit)
RMC	r_m	inches	Positive Number	O	Propellant drop size for heptane (condition at injector exit)
RMF or RMX	d	inches	Positive Number	O	Propellant drop size for fuel or oxidizer from correlation in Subroutines SECF11 and SECF12
SIGLC	σ_ℓ	lbf/in	.0001	I	Surface tension of reference heptane (condition at injector exit)
SIGLF or SIGLX	σ_{ℓ_x}	lbf/in	Positive Number	I	Surface tension of fuel or oxidizer (condition at injector exit)
SNHSAV	–	–	–	–	$s_{\nu h}$ - value saved from Subroutine FNDSNH
TLORF or TLORX	$T_{\ell,o,R}$	–	Positive Number	Computed in CMPRED	Propellant temperature ratio: (propellant temperature at injector exit/critical temperature)

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF24 AND SECF25

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT(I) or OUTPUT(O)	DESCRIPTION
VFUEL or VO	V_o	in/sec	Positive Number	O	Fuel or oxidizer injection velocity
WF, WINJF or WOX,WINJX	$\dot{w}$	lbm/sec	Positive Number	I	Fuel or oxidizer flow rate through the injector (for definition see Section 2.4)

$$\frac{1 - B \exp[2s]}{1 + B \exp[2s]} - M[(1-\gamma n) + \gamma n \exp(-s\bar{\tau})] = F(s) \equiv 0 \qquad (7\text{-}30)$$

where

$$B = \frac{1 + 1/2(\gamma-1)M}{1 - 1/2(\gamma-1)M} \qquad (7\text{-}31)$$

M = Mach number of gases in chamber

s = Laplace transformation variable

$\bar{\tau} = \tau * \frac{C_s}{1000 * LDUM}$

τ = Time lag

C_s = Speed of sound in chamber

LDUM = Acoustical length of chamber

γ = Ratio of specific heat

n = Interaction index

<u>For non-hypergolic propellants with coaxial injection:</u>

$$\tau_1 = 0.076 * P_{VR}/M^{1/2}\ F_p \text{ ,millisec} \qquad (7\text{-}32)$$

where

$$F_p = \begin{cases} P_c/P_{crit} < 1 = (P_c/P_{crit}) \\ P_c/P_{crit} \geqslant 1 = 1 \end{cases}$$

$P_{VR} = 1.446 - 0.4 * VR * \sin\phi + 0.0685 * (VR * \sin\phi)^2$

$VR = \frac{\text{Velocity of outer ring propellant}}{\text{Velocity of inner hole propellant}}$

ϕ = Impingement angle

n = 0.45 (can be modified by input in COMMIS where it is designated NTAUN1)

NOTE: τ_1 is computed in Subroutine TAUN1.
VR is computed if input for ICOAX=1, then VR=VFUEL/VOXID;
or for ICOAX=2, then VR=VOXID/VFUEL

For non-hypergolic propellants with non-coaxial injection:

$$\tau_2 = .165 * D_i^{1/2} / M^{1/3} * F_p, \text{ millisec} \qquad (7\text{-}33)$$

where

D_i = injector orifice diameter

The interaction index, n, satisfies a fourth order polynomial curve-fit, and is

$$n = \exp[A_0 + A_1 \ell n D_i + A_2(\ell n D_i)^2 + A_3(\ell n D_i)^3 + A_4(\ell n D_i)^4]$$

with

A_0 = -55.5352E-02

A_1 = -96.4330E-03

A_2 = -28.1489E-03

A_3 = -59.2126E-05

A_4 = 66.5459E-04

These data are coded in Subroutine TAUN2, and τ_2 is computed in the same subroutine.

For hypergolic propellants:

$$\tau_3 = 10 * D_i / M^{1/3} * P_c^{1/3}, \text{ millisec} \qquad (7\text{-}34)$$

where

P_c = chamber pressure

n = .7 (can be modified in Subroutine COMMIS and is designated NTAUN3)

τ_3 is computed in Subroutine TAUN3, where D_i equals DFVEL or DXVEL.

Figure 7-14 depicts the structure of the controlling Subroutine SECF26. The optimization program AESOP (Subroutine CTLOPT) is used in an inner loop as a root finder by minimization of $|F(s)|$ in Equation (7-30). The parameters are the elements of the complex root defining decay rate and frequency of oscillation.

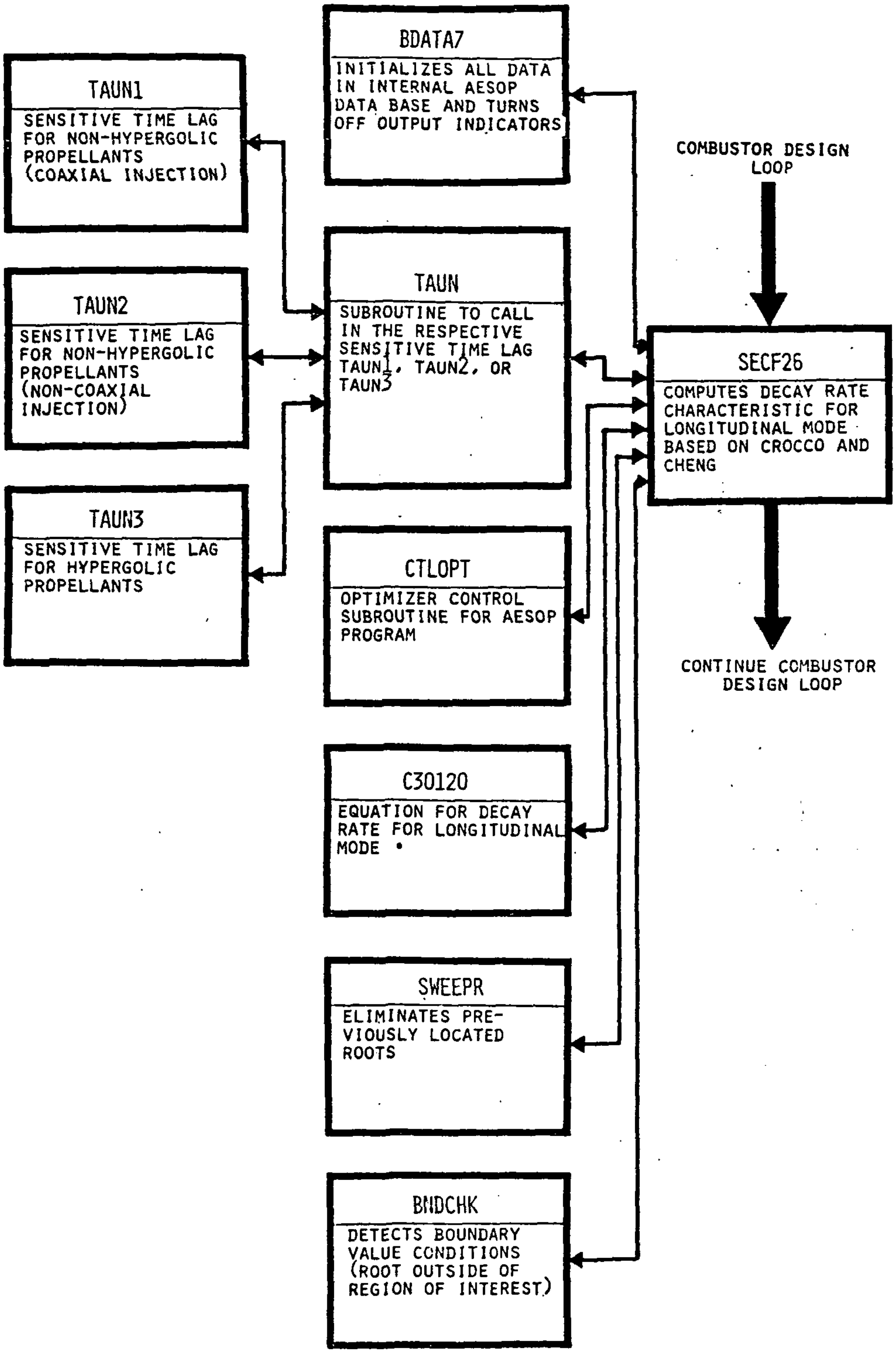

Figure 7-14. Flow Chart for Subroutine SECF26 Computing the Decay Rate Characteristic for Longitudinal Mode, F26

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF26

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
AF26	—	—	0 or 1	I	Weighting factor constant for longitudinal modes exponential on the average combustor stability characteristic equation
ANGIMP	ϕ	degree	0 to 180	I	Impingement angle of injection
CS	C_S	in/sec	Positive Number	O	Speed of sound in combustion gas (computed in Subroutine POSTAL)
DC	D_c	inches	Positive Number	I	Diameter of combustion chamber at injector face
DFVEL or DXVEL	D_i	inches	Positive Number	I	Injector orifice diameter for fuel or oxidizer. For definition see Section 2.4
F26	—	—	Positive or Negative Number	O	Decay rate for longitudinal modes
GREF	g	in/sec^2	32.2*12	I	Gravitational constant
GRF26R or GRF26I	—	—	Positive or Negative Value	I	Real or imaginary part of the root guesses
ICOAX	—	—	0, 1, or 2	I	Coaxial injection indicator. For definition see Section 2.4

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF26

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
ICONTP	—	—	1 = fuel 2 = ox	—	Selection for fuel-critical or for ox-critical. Used in TAUN1, TAUN2 and TAUN3
IGRF26	—	—	.FALSE. or .TRUE.	I	Control statement for Subroutine SECF26 if root guesses are stored in the program
IRWTAU	—	—	0, 1	I	Write out option for Subroutine TAUN
IRW26	—	—	0, 1 or 2	I	Read or write option for Subroutine SECF26
ISTORF or ISTORX	—	—	0 or 1	I	Fuel or oxidizer storability indicator. For definition see Section 2.4
LC	L_c	inches	Positive Number	I	Length of combustion chamber (from injector face to throat area)
LDUM	LDS	inches	Positive Number	O	Acoustical length of combustion chamber. For definition see Section 7.2.3.1 (computed in Subroutine POSTAL)
MC	M	—	0 to 1.0	O	Mach number in combustion chamber (computed in Subroutine POSTAL)
NR	—	—	Positive Integer 0 to 20	I	Number of roots to be solved

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF26

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
NRF26	—	—	20	I	Maximum number of roots possible to be solved
NTAUN1	n	—	Positive Value	I	Optional input value for the interaction index modification in Subroutine TAUN1
NTAUN3	n	—	Positive Value	I	Optional input value for the interaction index modification in Subroutine TAUN3
NTRY	—	—	Positive Integer	I	Number of trials for root solving procedure
PCI	P_c	lb/in^2	Positive Number	O	Combustion chamber pressure at injector face (computed in Subroutine POSTAL)
PCOPCR	—	—	Positive Number	O	Ratio of critical pressure; for definition see Equation (7-32)
PCRITF	P_{crit}	lb/in^2	Positive Number	I	Critical pressure for fuel. If a gas, PCRITF = 1.0 (used in Subroutine POSTAL)
PCRITX	P_{crit}	lb/in^2	Positive Number or 1.0	I	Critical pressure for oxidizer. If a gas, PCRITX = 1.0 (used in Subroutine POSTAL)
PINTER	n	—	Positive Number	I	Interaction index of propellants, used for computing Subroutines TAUN1, TAUN2, and TAUN3
SPHEAT	$\underline{\gamma}$	—	Positive Number	I or curve-fit	Specific heat ratio of the combustion gases

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF26

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
TAU	τ_1	sec	Positive Number	O	Time lag for non-hypergolic propellants with coaxial injection. (Computed in Subroutine TAUN1)
TAU	τ_2	sec	Positive Number	O	Time lag for non-hypergolic propellants with non-coaxial injection (computed in Subroutine TAUN2)
TAU	τ_3	sec	Positive Number	O	Time lag for hypergolic propellants (computed in Subroutine TAUN3)
VFUEL or VOXID	—	in/sec	Positive Number	O	Fuel or oxidizer injection velocity (computed in Subroutine POSTAL using the orifice exit areas)

When a root is found, it is swept out by a root sweeping routine, SWEEPR, and another root solution is attempted. This process is continued for a predetermined number of roots. The resulting complex roots are examined, and, from a series of solutions possible, the roots with the largest positive real part having the three smallest values of the non-negative imaginary part are selected.

The characteristic function F26 is the real part of the root multiplied by a factor which considers the combustion chamber geometry. It becomes

$$F26 = Re * \frac{CS}{LDS} \tag{7-35}$$

where

CS = speed of sound in combustion chamber

LDS = acoustical length of combustion chamber

7.2.5 Subroutine SECF27. Subroutine SECF27 computes the stability decay rate for the transverse modes of high frequency oscillations, F27, based on the sensitive time lag model of L. Crocco, D. T. Harrje, and F. H. Reardon, Reference 7-7, with the correlation equations for the interaction index, n, and time lag, τ, developed by D. T. Harrje and F. H. Reardon, Reference 7-9. The interaction index, n, is twice that of Subroutine SECF26, and the time lag τ is the same as in Subroutine SECF26. SECF27 considers the boundary condition at the convergent nozzle entrance (nozzle admittance) in an approximate manner by the complex admittance coefficient E (frequency, mode and nozzle entrance velocity), as well as by the geometric relationship of the combustion chamber, RA.

The subroutine for solution of F27 is similar in structure to that employed for the computation of F26. The same routines TAUN1, TAUN2, and TAUN3 are utilized in the computation.

Figure 7-15 shows the structure of the controlling Subroutine SECF27. The primary difference between this routine and the controlling subroutine SECF26 is in the stability characteristic equation employed. This equation is coded in Subroutine TCOMBI. SECF27 calls subroutine TCOMBI on an inner AESOP loop. TCOMBI generates the complex function for neutral stability

$$h_1 P + h_2 = F(s) \equiv 0 \tag{7-36}$$

as defined in Equation (28) of Reference (7-7). In this equation is:

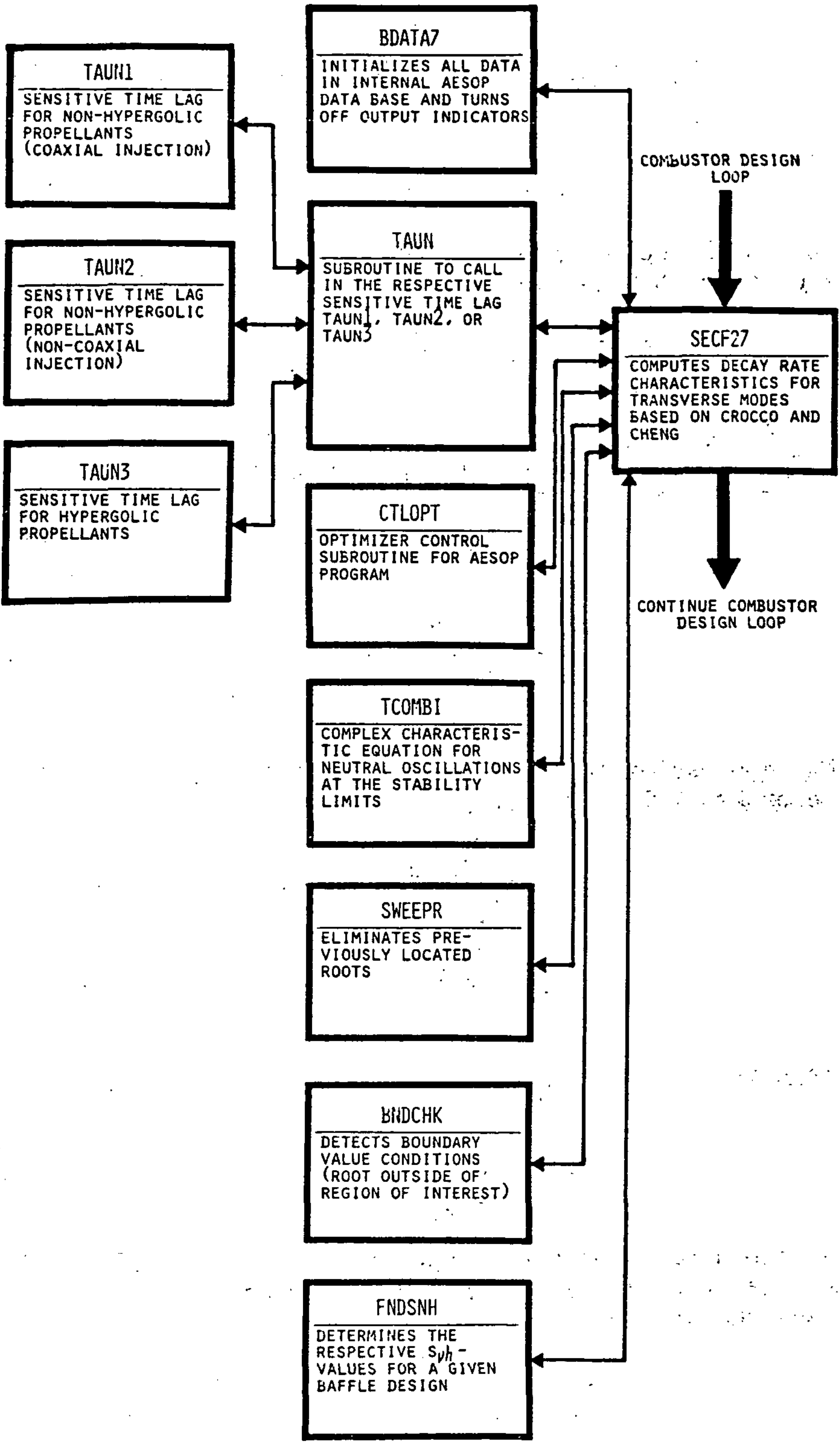

Figure 7-15. Flow Chart for Subroutine SECF27 Computing the Sensitive Time Lag Characteristic for Transverse Modes, F27

$$h_1 = \gamma\bar{u}_e[1 - is_{\nu h}E\int_0^{z_e}(\bar{u}/\bar{u}_e)\cdot dz] \qquad (7\text{-}37)$$

and

$$P = n(1-e^{-s\tau}) \qquad (7\text{-}38)$$

and, omitting parts of the function in accordance with the Special Instructions for Task II of Contract NAS 3-13331,

$$h_2 = -(\gamma+1)\bar{u}_e - i(f - \frac{1}{f})s_{\nu h}z_e +$$

$$E[\frac{1}{f} - \frac{s_{\nu h}^2 z_e^2}{2}(f - \frac{1}{f}) + i(\gamma+1)\,s_{\nu h}\bar{u}_e\int_0^{z_e}(\frac{\bar{u}}{\bar{u}_e})dz] \qquad (7\text{-}39)$$

and

$$E = \frac{1-\gamma}{2}\,\frac{\omega}{s_{\nu h}}\,\frac{\bar{u}}{c_o} \qquad (7\text{-}40)$$

Note: The expression for E is derived from Equation (26a) in Reference 7-7 as follows:

$$E = \frac{-fP_o}{P_e}\,\frac{\gamma U_e}{P_o}$$

$$= -\gamma f\frac{U_e}{P_e} \qquad (7\text{-}41)$$

Introducing $f = \omega/s_{\nu h}$

$$E = \frac{-\gamma\omega}{s_{\nu h}}\,\frac{U_e}{P_e} \qquad (7\text{-}42)$$

Furthermore, assume that the nozzle is distributed nozzle so that the exit volocity of the chamber is at a constant Mach number then

$$U^* = \frac{\bar{u}}{c_o}\sqrt{\gamma RT^*}$$

$$c_o = \sqrt{\gamma R T_o}$$

$$\frac{U^*}{c_o} = U_e = (T^*/T_o)^{1/2}\ \bar{u}/c_o$$

Furthermore, assuming adiabatic law

$$\frac{T^*}{T_o} = \left(\frac{P^*}{P_o}\right)^{\frac{\gamma-1}{\gamma}}$$

or

$$= P_e^{\frac{\gamma-1}{\gamma}}$$

Therefore

$$U_e = P_e^{\frac{\gamma-1}{2\gamma}}\ \frac{\bar{u}}{c_o} \qquad (7\text{-}43)$$

Using a linear analysis for Equation (7-43)

$$U_e = \left[\frac{\gamma-1}{2\gamma}\right]\ \frac{\bar{u}}{c_o}\ P_e \qquad (7\text{-}44)$$

Substituting Equation (7-44) in Equation (7-42)

$$E = \frac{-\gamma\omega}{s_{\nu h}}\ \frac{\gamma-1}{2\gamma}\ \frac{\bar{u}}{c_o}$$

$$= \frac{1-\gamma}{2}\ \frac{\omega}{s_{\nu h}}\ \frac{\bar{u}}{c_o} \qquad (7\text{-}45)$$

Symbols in Equations (7-36) through (7-45) mean:

c_o = Speed of sound in combustion chamber

E = Nozzle admittance coefficient

f = Reduced frequency = $\omega/s_{\nu h}$

n = Interaction index of propellants

P = Proportionality factor relating burning rate perturbation to pressure perturbation

P_e = Combustion chamber pressure at nozzle entrance

P_o = Combustion chamber pressure near injector

P^* = Dimensional quantity of the chamber pressure

R = Gas constant of the combustion gas

s = Laplace transformation variable

$s_{\nu h}$ = Mode of oscillation constant

T_o = Combustion temperature near injector

T^* = Dimensional quantity of combustion temperature

U_e = Velocity perturbation distribution function at nozzle entrance conditions

U^* = Dimensional quantity of the velocity perturbation distribution function

$\bar{u}$ = Steady state axial gas velocity

$\bar{u}_e$ = Steady state chamber exit velocity

z_e = Chamber length to exit

γ = Specific heat ratio

ω = Angular frequency

τ = Time lag

In accordance with NASA's technical monitor, the expressions for h_1 in Equation (7-37) and h_2 in Equation (7-39) are modified for coding purposes as follows

(1) The integral expression $\int_0^{z_e} (\overline{u}/\overline{u}_e)\,dz$ is being replaced by the geometric relationship of the combustion chamber

$$\begin{aligned} RA &= LC/R \\ &= 4LC/(D1 + D2) \qquad (7\text{-}46) \end{aligned}$$

(2) z_e becomes RA

(3) $\overline{u}_e$ becomes Mach number M

where

LC = Combustion chamber length

R = Mean radius of combustion chamber

D1 = Combustion chamber diameter at injector face

D2 = Combustion chamber diameter at the onset of the converging section

Thus

$$h_1 = \gamma M(1 - i\cdot s_{\nu h}\ E * RA) \qquad (7\text{-}47)$$

$$\begin{aligned} h_2 = {} & -(\gamma+1)M - i(f - \tfrac{1}{f})s_{\nu h}\ RA + \\ & E[\frac{1}{f} - \frac{s_{\nu h}^2\ RA^2}{2}(f - \frac{1}{f}) + i(\gamma+1)s_{\nu h}M\cdot RA] \qquad (7\text{-}48) \end{aligned}$$

where M is the mean Mach number in the combustion chamber.

The optimization program AESOP is used as a root finder by minimization of $|F(s)|$ in Equation (7-36) for the various modes of oscillations. The optimization parameters are the elements of the position in the complex plane. The resulting roots define decay rate and frequency of oscillation. When a root is found it is swept out by the root sweeping routine, SWEEPR, and another root solution is attempted. This process is continued for a predetermined number of roots. The characteristic function F27 is the real part of this root multiplied by a factor which considers the geometry of the combustion chamber:

$$F27 = Re(s) * \frac{CS}{DC/2} \qquad (7\text{-}49)$$

where

CS = speed of sound in combustion chamber

DC = Combustion chamber diameter

A characteristic function for both, fuel and oxidizer, is determined in this manner. Currently, the larger of the two values is retained.

At the present time the critical value of F27 is obtained for the seven modes listed in Reference 7-7, and presented in Table 7-3. Within the program, the frequency modes are stored in Subroutine CMBINI as SNUH(1) through SNUH(7).

	Purely Tangential Modes		Purely Radial Modes		Combined Modes		
	First	Second	First	Second	-	-	-
$s_{\nu h}$ =	1.84129	3.0543	3.8317	7.0156	5.3313	8.5263	6.7060

TABLE 7-3. Modes of Oscillation for Transverse Combustion Instability in a Circular Chamber

7.2.5.1 Definition of Frequency Modes for Subroutine SECF27 with Baffles Present. If there are radial and/or circumferential baffles present, the program selects $s_{\nu h}$-values determined by Subroutine FNDSNH under the condition that $s_{\nu h}$-values have to be omitted according to:

$\nu \geqq F81/2$, if F81 is an even number

$\nu \gtrless F81$, if F81 is an odd number

and

$h > F82$, if F82 is an odd or an even number.

Furthermore, two additional conditions have to be met:

(1) The integer number, n_o, of $s_{\nu h}$ values has to satisfy

$$n_o \leqslant \frac{18}{s_{\nu h(min)}} \tag{7-50}$$

where $s_{\nu h(min)}$ is the lowest allowable $s_{\nu h}$-value selected from Table 7-4, Section 7.8.3

(2) $s_{\nu h}$ values have to satisfy

$$s_{\nu h} \leqslant \frac{r*6280}{a*\tau} \tag{7-51}$$

where

r = combustion chamber radius at the injector plane, ft

a = speed of sound in combustion gas, ft/sec

τ = sensitive time lag as used before in Subroutine SECF26, millisec

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF27

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT(I) or OUTPUT(O)	DESCRIPTION
AF27	—	—	0 or 1	I	Weighting factor constant for transverse modes exponential on the average combustor stability characteristic equation
ALRN27	—	—	30	I	Statement for search range of decay rate; see Section 2.5.2
ANGIMP	ϕ	degree	0 - 180	I	Impingement angle of injection
BFLCIR	—	—	0 or a Positive Integer	I	Number of circumferential baffles (see Figure 2-6)
BFLRAD	—	—	0 or a Positive Integer	I	Number of radial baffles (see Figure 2-6)
CS	C_s	in/sec	Positive Value	O	Speed of sound in combustion gas (computed in Subroutine POSTAL)
DC	D_c	inches	Positive Value	I	Diameter of combustion chamber at injector face
DFVEL or DXVEL	D_i	inches	Positive Value	I	Injector orifice diameter for fuel or oxidizer For definition see Section 2.4.
D2	D2	inches	Positive Number	I	Diameter of combustion chamber at the onset of the converging section of the nozzle

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF27

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
F27	—	—	Positive or Negative Number	O	Decay rate for transverse modes of combustion stability
GRF27R or GRF27I	—	—	Positive or Negative Number	I	Real or imaginary part of the root guesses
ICOAX	—	—	0,1,or 2	I	Coaxial injection indicator. For definition see Section 2.4
ICONTP	—	—	1 = fuel 2 = ox	—	Selection for fuel-critical or for ox-critical. Used in TAUN1, TAUN2, and TAUN3
IGRF27	—	—	.FALSE. or .TRUE.	I	Control statement for Subroutine SECF27 if root guesses are stored in the program
IRWTAU	—	—	0, 1	I	Write out option for Subroutine TAUN
IRW27	—	—	0,1, or 2	I	Read or write option for Subroutine SECF27
ISNSAV	—	—	10	I	Number of selected $s_{\nu h}$ values from Subroutine FNDSNH; see Section 7.8.3.
ISTORF or ISTORX	—	—	0 or 1	I	Fuel or oxidizer storability indicator. For definition see Section 2.4

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF27

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
LC	L_c	inches	Positive Value	I	Length of combustion chamber (from injector face to throat area)
LDUM	LDS	inches	Positive Value	O	Acoustical length of combustion chamber. For definition see Section 7.2.3.1 (computed in Subroutine POSTAL)
MC	M	—	$0<MC\leqslant 1$	O	Mach number in combustion chamber (computed in Subroutine POSTAL)
NF27	–	–	7	I	Number of $s_{\nu h}$ values for which roots are to be obtained
NR	—	—	Positive Integer 0 to 10	I	Number of roots to be solved
NRF27	—	—	$\leqq 10$	I	Maximum number of roots possible to be solved
NTAUN1	n	—	Positive Value	I	Value for the interaction index modification in Subroutine TAUN1
NTAUN3	n	–	Positive Value	I	Value for the interaction index modification in Subroutine TAUN3
NTF27	—	—	Positive Integer	I	The maximum number of trials possible for each root
NTRY	—	—	Positive Integer	I	Number of trials for root solving procedure

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF27

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
PCI	P_c	$^{lb}/_{in^2}$	Positive Value	O	Combustion chamber pressure at injector face (computed in Subroutine POSTAL)
PCOPCR	P_c/P_{crit}	–	Positive Value	O	Ratio of critical pressures; for definition see Equation (7-32)
PCRITF	P_{crit}	$^{lb}/_{in^2}$	Positive Value or 1	I	Critical pressure for fuel. If a gas, PCRITF = 1 (used in Subroutine POSTAL)
PCRITX	P_{crit}	$^{lb}/_{in^2}$	Positive Value or 1	I	Critical pressure for oxidizer. If a gas, PCRITX = 1 (used in Subroutine POSTAL)
PINTER	n	–	Positive Value	I	Interaction index of propellants, used for computing Subroutines TAUN1, TAUN2, and TAUN3
RA	RA	–	Positive Value	O	Geometric relationship of the combustion chamber; see Equation (7-46)
SNHSAV	$s_{\nu h}$	–	See Table 7-4	–	$s_{\nu h}$ value saved from Subroutine FNDSNH; see Section 7.8.3
SHUH	$s_{\nu h}$	–	See Table 7-3	–	$s_{\nu h}$ value used if no baffles are present
SPHEAT	γ	–	Positive Value	I or curve-fit	Specific heat ratio of the combustion gases
TAU	τ_1	sec	Positive Value	O	Time lag for non-hypergolic propellants with coaxial injection (computed in Subroutine TAUN1)

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF27

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
TAU	τ_2	sec	Positive Value	O	Time lag for non-hypergolic propellants with non-coaxial injection (computed in Subroutine TAUN2)
TAU	τ_3	sec	Positive Value	O	Time lag for hypergolic propellants (computed in Subroutine TAUN3)
VFUEL or VOXID	—	in/sec	Positive Value	O	Fuel or oxidizer injection velocity (computed in Subroutine POSTAL using the orifice exit areas)

7.2.6 Subroutine SECF28. Subroutine SECF28 computes the stability decay rate for various modes of high-frequency oscillations (longitudinal, transverse, radial), F28; it is based on the acoustic wave solutions for combustion response by R.J.Priem and E.J.Rice, Reference 7-10. The method uses the flow response functions as determined by Equation(11) in Reference 7-11 for liquid propellants, and by Equation(18) in Reference 7-12 for gaseous propellants. Because system stability is obtained when the combustion response line intersects the flow response line at the same frequency in the complex plane:

(Frequency of combustion response, N_C) = (Frequency of flow response, N_{FL})

or

$$N_C - N_{FL} = F(s) \equiv 0 \tag{7-52}$$

Specific equations which have been coded for computing the combustion response, N_C, are Equations(6), (13), and (14) of Reference 7-10:

$$\begin{aligned} N_C &= \mathrm{Re}(N_C) + i\,\mathrm{Im}(N_C) \\ &= \frac{1}{\gamma}\left\{1 - \frac{\left(B_1 e^{-i\frac{L}{R}B_1} + B_2 C e^{-i\frac{L}{R}B_2}\right)}{M\left[\omega\left(e^{-i\frac{L}{R}B_1} + C e^{-i\frac{L}{R}B_2}\right) + M\left(B_1 e^{-i\frac{L}{R}B_1} + B_2 C e^{-i\frac{L}{R}B_2}\right)\right]}\right\} \end{aligned} \tag{7-53}$$

where

$$B_1 = \frac{\omega M + \sqrt{\omega^2 M^2 + (M^2-1)(m^2-\omega^2)}}{1 - M^2} \tag{7-54}$$

$$B_2 = \frac{\omega M - \sqrt{\omega^2 M^2 + (M^2-1)(m^2-\omega^2)}}{1 - M^2} \tag{7-55}$$

$$C = -\left[\frac{B_1(1-M^2+\gamma G M^2) + \omega(\gamma G-1)M}{B_2(1-M^2+\gamma G M^2) + \omega(\gamma G-1)M}\right] \tag{7-56}$$

where

N_C = Combustion response

L = Length of combustion chamber

R = Radius of combustion chamber at injector face

M = Mach number in combustion chamber

γ = Ratio of specific heat of combustion gas

G = Nozzle response factor

m = Argument of Bessel function satifying wall boundary conditions:

The following values are used:

(1) First transverse mode = 1.8412

(2) Second transverse mode = 3.0543

(3) Third transverse mode = 4.2012

(4) First radial mode = 3.8317

(5) Longitudinal mode = 0.
(The m-values are stored as BESARG(1) to (5) in Subroutine CMBINI).

ω = Angular frequency of oscillations

To compute the flow response, N_{FL}, it is

$$N_{FL} = \frac{OF}{OF+1} N_{OX} + \frac{1}{OF+1} N_F \qquad (7\text{-}57)$$

where

OF = Oxidizer to fuel mixture ratio

N_{OX} = Flow response for oxidizer

N_F = Flow response for fuel

If the propellant is in a liquid state, the transfer function, Equation (11) of Reference 7-11, is used:

$$N_{\text{liquid}} = \frac{W'}{P_c'} = \frac{1}{2}\left[\frac{2\tau_v s}{1+2\tau_v s}\right]\left[\frac{1+(1-2\beta)\,\dfrac{c_p\,T_L}{\lambda\,\beta\,b}\,\tau_v s}{1+\dfrac{c_p\,T_L}{\lambda\,\beta\,b}\,\tau_v s}\right] \qquad (7\text{-}58)$$

If the propellant is in a gaseous state, the transfer function, Equation (18) of Reference 7-12, is used (modified shorter version according to the Special Instructions of Contract NAS 3-13331). Based on the definitions depicted in Figure 7-16, it is:

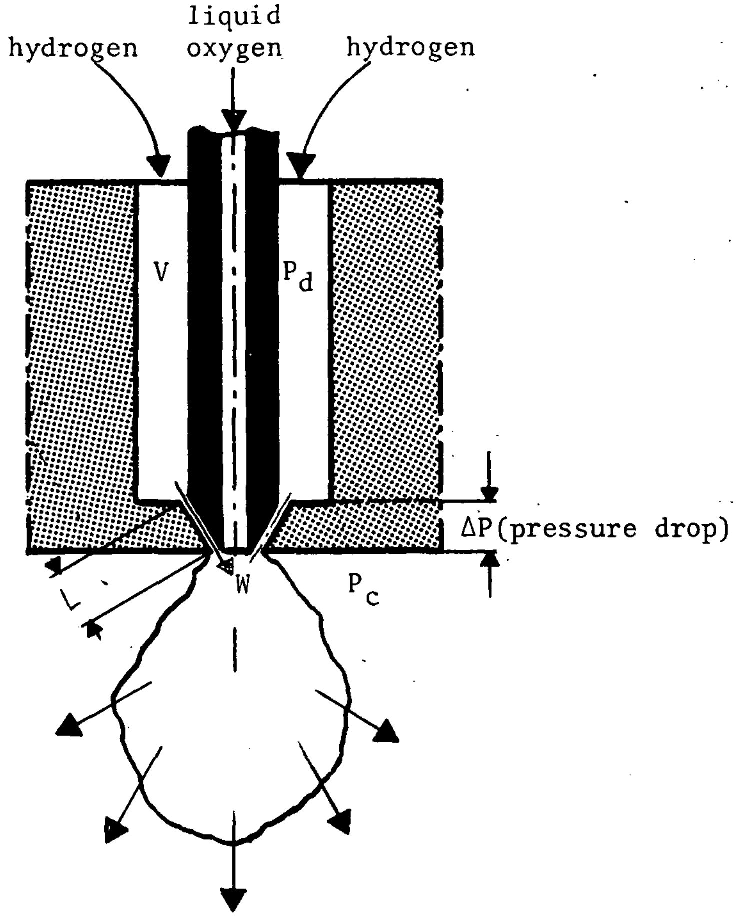

Figure 7-16. Injector Element Definitions

$$N_{gas} = \frac{W'}{P'_c} = - \frac{\left(\frac{P_c}{\Delta P} - \frac{1}{\gamma_H}\right)\left(\frac{\Delta P}{P_d}\right) Cse^{-\tau_b s}}{1 + 2\frac{\Delta P}{P_d} Cs + \frac{\Delta P}{P_d}\left(\frac{P_c}{\Delta P} - \frac{1}{\gamma_H}\right) CIs^2} \qquad (7\text{-}59)$$

where

$$C = \frac{\rho \; V}{\gamma_H \; W} \qquad (7\text{-}60)$$

$$I = \frac{W\left(\frac{L}{A1}\right)}{g \; P_d} \qquad (7\text{-}61)$$

A_1 = Cross-sectional area of injector (injection area)

b = Vapor pressure/liquid temperature coefficient

c_p = Specific heat of liquid

g = Gravitational constant

L = Hydrogen annulus length

P_c = Combustion chamber pressure

P_d = Dome pressure = $P_c + \Delta P$.

ΔP = Injection pressure drop

T_L = Temperature of propellant

V = Injector dome volume

$\dot{W}$ = Flow rate through injector

β = Vapor pressure-comubstion chamber pressure parameter

γ = Specific heat ratio for combustion gas

γ_H = Specific heat ratio for hydrogen

λ = Latent heat of vaporization

ρ = Hydrogen density

τ_b = Time delay constant for burning

$\tau_b s$ = Phase angle due to delay in burning = 1.9 rad

s = Laplace operator

τ_v = Mean drop life time = $\overline{M}/\overline{W}$ (coded as TAUV = L50/VINJ*2*CS/DC in Subroutine FRPROP)

Figure 7-17 depicts the structure of the controlling Subroutine SECF28. The equation for combustion response is computed in Subroutine ACWAVE, and the equation for flow response is computed in Subroutine FLORES. This subroutine also calls upon subroutine FRPROP to calculate the flow response for individual propellants (using Equation (11) of Reference 7-11, and Equation (18) of Reference 7-12, respectively).

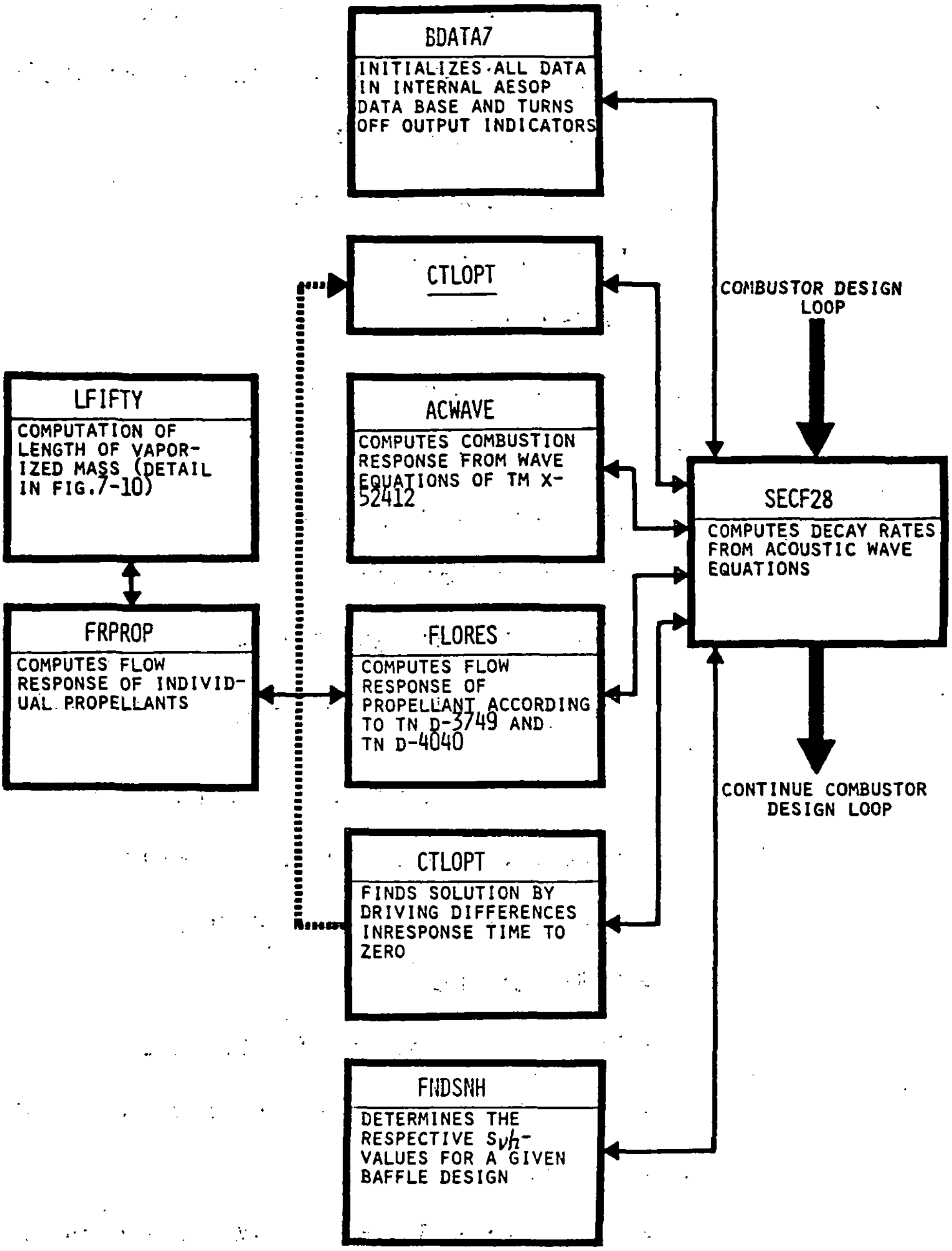

Figure 7-17. Flow Chart for Subroutine SECF28 Computing the Decay Rate for Various Modes of High-Frequency Oscillations, F28

The optimization program AESOP is here also used as a root finder by minimizing of $|F(s)|$ in Equation (7-50). The optimization parameters are the elements of position in the complex plane. The resulting complex roots define decay rate and frequency of oscillation. The frequencies of both response functions are compared in Subroutine CTLOPT which finds the solution by driving differences to zero for the various Bessel arguments, m.

The resulting characteristic function F28 is then the real part of that root which is least stable, multiplied by a factor which depends on the geometry of the combustion chamber:

$$F28 = \mathrm{Re}(s) * \frac{CS}{DC/2} \tag{7-62}$$

where

CS = Speed of sound in combustion gas

DC = Combustion chamber diameter

7.2.6.1 Definition of Frequency Modes for Subroutine SECF28 with Baffles Present. If there are radial and/or circumferential baffles present, the values of the Bessel arguments which appear in the equations for computing the combustion response (Equations (7-54) and (7-55)), have been replaced by $s_{\nu h}$ values, except for the case of m=0. The program selects the lowest four $s_{\nu h}$ values via Subroutine FNDSNH which are not forbidden by

$\nu \geqq F81/2$, if F81 is an even number

$\nu \geqq F81$, if F81 is an odd number

and

$h > F82$, if F82 is an odd or an even number.

Furthermore, the following condition has to be met: the integer number N_x of $s_{\nu h}$ values has to satisfy

$$4 \geqq N_x \geqq \frac{5}{s_{\nu h(\min)}} \tag{7-63}$$

where $s_{\nu h(\min)}$ is the lowest allowable $s_{\nu h}$ value selected from Table 7-4 via Subroutine FNDSNH.

In addition, the longitudinal mode (m=0) of the original code is retained.

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF28

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT(I) or OUTPUT(O)	DESCRIPTION
ADIS	a	—	1.0	in CMPRED	Constant for number distribution; see Section 7.1.1
AF28	–	–	0 or 1	I	Weighting factor constant for combined modes exponential on the average combustor stability characteristic equation
ALRN28	–	–	30	I	Statement for search range of decay rate; see Section 2.5.2
BESARG	m	–	1.8412, 3.0543, 4.2012, 3.8317, 0.0	I	Argument of the Bessel function satisfying wall boundary conditions. BESARG(1) through BESARG(5) is stored in Subroutine CMBINI
BFLCIR	–	–	Positive Integer or 0	I	Number of circumferential baffles (see Figure 2-6)
BFLRAD	–	–	Positive Integer or 0	I	Number of radial baffles (see Figure 2-6)
CPF or CPX	c_p	Btu/lbm-°R	Positive Value	I	Specific heat of liquid propellant (fuel or oxidizer)
CS	c_o	in/sec	Positive Value	O	Speed of sound in combustion gas (computed in Subroutine POSTAL)
DC	DC	inches	Positive Value	I	Diameter of combustion chamber at injector face

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF28

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
DFVEL or DXVEL	d_j	inches	Positive Value	I	Injector orifice diamter for fuel or oxidizer. For definition see Section 2.4
DELPF or DELPX	ΔP	$\mathrm{lbf}/\mathrm{in}^2$	Positive Value	O	Pressure drop for fuel or oxidizer in the injector due to the orifice (computed in Subroutine POSTAL)
F28			Positive or Negative Value	O	Decay rate for combined modes of combustion stability
F28TBS	$\tau_b s$	rad.	1.9	I	Phase angle due to delay in burning
GNRESP	G		.9166 in CMBINI	I	Nozzle response factor assumed equal to 0.9166 for the present program code
GREF	g	$\mathrm{in}/\mathrm{sec}^2$	32.2*12	I	Gravitational constant
GREF28R or GRF28I			Positive or Negative Value	I	Real or imaginary part of the root guesses
IGRF28			.FALSE. or .TRUE.	I	Control statement for Subroutine SECF28 if root guesses are stored in the program

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF28

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
INJCMP	—	—	0, 1, 2, 3, 4, or 5	I	Injector complexity index; for definition see Section 2.4
IRWFLO	—	—	0, 1	I	"Writing out" option for Subroutine FLORES
IRWFRP	—	—	0, 1, or 2	I	Read or write option for Subroutine FRPROP
IRW28	—	—	0, 1, or 2	I	Read or write option for Subroutine SECF28
ISNSAV	—	—	10	I	Number of selected $s_{\nu h}$ values from Subroutine FNDSNH; see Section 7.8.3
ISTATF or ISTATX	—	—	1 or 2	I	Fuel or oxidizer state at injector exit: 1 = gas 2 = liquid
NB28	m	—	10	I	Maximum number of Bessel arguments coded in the program
LAMBDF or LAMBDX	λ	Btu/lbm	Positive Value or 0	I	Latent heat of vaporization for fuel or oxidizer
LC	L	inches	Positive Value	I	Combustion chamber length (distance from injector face to throat area)
LF	L	inches	Positive Value	I	Length of fuel orifice

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF28

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
L5FUEL or L5OXID	L_{50}	inches	Positive Value	O	Length of combustion chamber to vaporize 50 per cent of fuel or oxidizer
LG50F or LG50X	ℓ_g	inches	2.75	I	Generalized chamber length to vaporize 50 per cent of fuel or oxidizer
MC	M	–	$0<MC\leq1$	O	Mach number in combustion chamber (computed in Subroutine POSTAL)
MOLEF or MOLEX	M	lbm/mole	Positive Value	I	Molecular weight of fuel or oxidizer
MUC	μ	lbf/in-sec	.0000174	I	Viscosity of liquid heptane (condition at injector exit
MUF or MUX	μ_x	lbf/in-sec	Positive Value or 0	I	Viscosity of input liquid fuel or oxidizer (condition at injector exit)
NR	–	–	Positive Integer 0 to 10	I	Number of roots to be solved
NRF28	–	–	≤10	I	Maximum number of roots possible to be solved
NTF28	–	–	≤20	I	Maximum number of trials possible for each root

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF28					
PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
NTRY	—	—	Positive Integer	I	Number of trials for root solving procedure
OF	OF	—	Positive Value	I	Propellant mixture ratio: oxidizer/fuel
PCI	P_c	lbf/in^2	Positive Value	O	Combustion chamber pressure at injector face
RC	—	—	Positive Number	O	Combustion chamber contraction ratio
RHOC	ρ	lbm/in^3	.0247	I	Density of reference liquid heptane (condition at injector exit)
RHOF or RHOX	ρ_x	lbm/in^3	Positive Value	I	Density of input fuel or oxidizer (condition at the injector exit)
SIGLC	σ_1	lbf/in	.0001	I	Surface tension of liquid heptane (condition at injector exit)
SIGLF or SIGLX	σ_{1_x}	lbf/in	Positive Value	I	Surface tension of input liquid fuel or oxidizer (condition at injector exit)
SNHSAV	$s_{\nu h}$	—	See Table 7-4	—	$s_{\nu h}$ value saved from Subroutine FNDSNH; see Section 7.8.3
SPHEAT	γ	—	Positive Value	I or Curve-fit	Specific heat ratio of combusiton gas

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF28

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
SPHTH2	γ_H	—	1.2	I	Specific heat ratio of hydrogen gas
TAF or TAX	A_1	in^2	Positive Value	O	Total area of fuel or oxidizer orifices
TEMCOE	b	$lbf/in^2-°R$	8.0 in CMBINI	I	Vapor pressure/liquid temperature coefficient, P_L/T_L; (NASA TN D-3749, Table 1)
TLOF or TLOX	T_L	°R	Positive Value	I	Temperature of fuel or oxidizer at injector exit plane
VFUEL or VOXID	V_o	in/sec	Positive Value	O	Fuel or oxidizer injection velocity
VOLF or VOLX	V	in^3	Positive Number	I	Volume of the injector dome for fuel or oxidizer side
VPCPAR	β	—	2.0 in CMBINI	I	Vapor pressure-combustion chamber pressure parameter
WF or WOX	—	lbm/sec	Positive Value	O	Fuel or oxidizer mass flow rate; see Section 7.9
WINJF or WINJX	W	lbm/sec	Positive Value	O	Fuel or oxidizer mass flow rate through injector; see Section 7.9

7.2.7 Subroutine SECF29. Subroutine SECF29 computes the decay rate, F29, based on the non-linear stability analysis of R. J. Priem and D. C. Guentert, Reference 7-13. This analysis calculates the regions of high-frequency combustion instability from two models which determine the local burning rate. The stability decay rate becomes

$$F29 = -100\log_{10}(A_p/.04) \qquad (7\text{-}64)$$

where A_p is the pressure amplitude and is obtained from Figure 7-18 as a function of the burning-rate parameter, L, and the reduced velocity difference ΔV.

In Figure 7-18

$$L = \text{Burning-rate parameter} = \frac{D_T^2}{D_C} * \frac{M}{M_{XX}}$$

where

D_T = Diameter of combustion chamber throat

D_C = Diameter of combustion chamber near the injector plane

$M = .25/L_{50}$

L_{50} = Length of combustion chamber required to vaporize 50 per cent of the propellant as determined in subroutines SECF20 and SECF21

M_{XX} = Considers the presence of radial baffles as follows*:

(1) M_{XX} becomes a positive integer and is equal to F81, if F81 is an odd integer, and

(2) M_{XX} becomes a positive integer and is equal to F81/2, if F81 is an even integer

If no baffles are present, M_{XX} becomes 1, and thus the original expression for the burning-rate parameter, L, is retained. The expression for L is coded is subroutine NLSTAB, for which subroutine SECF29 is the controlling subroutine

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*According to Reference 7-13, Appendix B, the radial velocity and all derivatives in the radial direction are assumed to be zero and, therefore, the effect of circumferential baffles, is omitted.

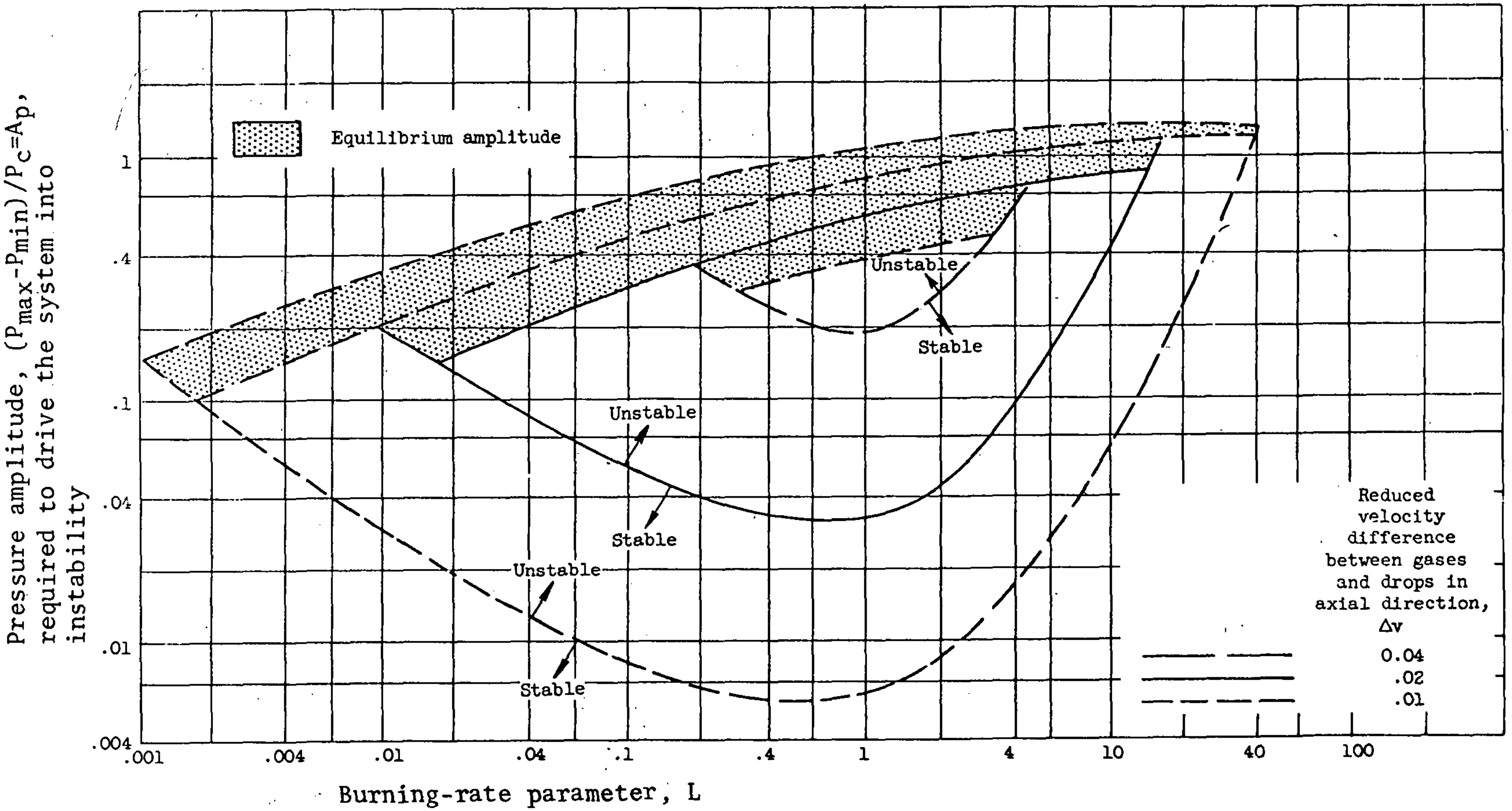


Figure 7-18. Stability Limits of Vaporization-Rate and Chemical-Reaction-Rate Models. (Figure 8a of Reference 7-13).

ΔV = Reduced velocity difference between gases and liquid. It is obtained by assuming the gas velocity to vary linearly with chamber length, liquid velocity is constant, and an average velocity is then calculated using a minimum of 50 fps difference in averaging. It becomes:

$$\Delta V = \frac{1}{a}\left[50 + \frac{(V_L - 50)V_L^2}{2(V_L + 50)(V_L + V_g)} + \frac{(V_g - V_L - 50)^2 V_g}{2(V_g^2 - V_L^2)} \right] \tag{7-65}$$

if $V_L<50$, then $V_L - 50=0$;

if $V_g-V_L<50$ then $V_g - V_L - 50=0$

where

a = Speed of sound in combustion gas
V_g = Final gas velocity in combustion chamber
V_L = Liquid velocity of propellant with largest L_{50}

The data of Figure 7-18 is stored in Subroutine NLSTAB and is treated as a three-dimensional surface. The pressure amplitude $A_p(z)$ is determined for a given burning rate parameter (x) and reduced velocity (y) by the use of a general purpose two-dimensional table look-up routine. This subroutine incorporates arbitrary scale transformations. In the present application log-log scale transformations in both the x-y and y-z planes are employed.

The burning rate parameter, L, and the reduced velocity difference, ΔV, are also calculated in Subroutine NLSTAB. The coding is done in such a way that only the largest L_{50} is considered. If the propellant state is a gas plus a liquid, then only the liquid is considered. If both propellant components are gaseous, then the subroutine is not used at all.

Figure 7-19 depicts the structure of the controlling Subroutine SECF29.

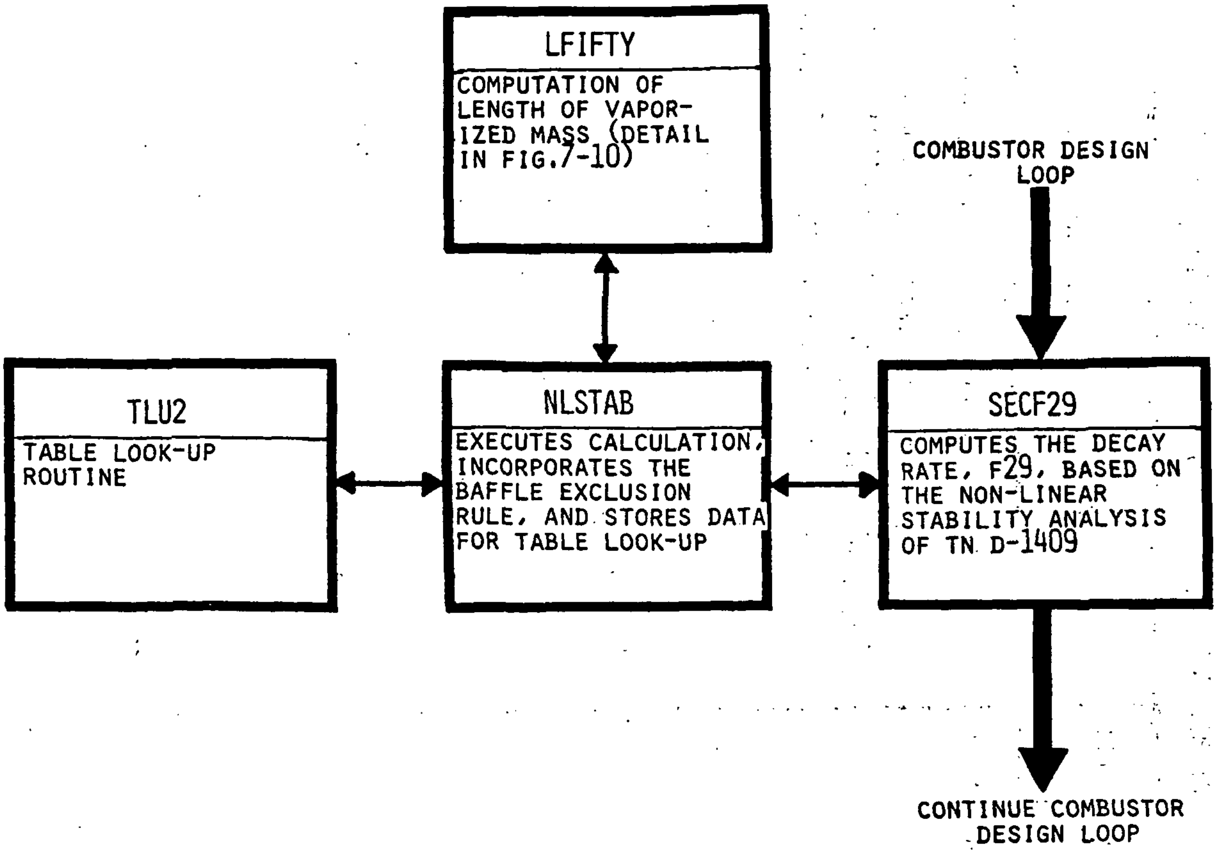


Figure 7-19. Flow Chart for Subroutine SECF29 for Calculating the Decay Rate Based on Non-Linear Stability Analysis

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF29

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
ADIS	a	–	1.0	in CMPRED	Constant for number distribution; see Section 7.1.1
AF29	–	–	0 or 1	I	Weighting factor constant for combined modes exponential on the average combustor stability characteristic equation
CS	a	in/sec	Positive Value	O	Speed of sound in combustion gas (computed in Subroutine POSTAL)
DC	D_C	inches	Positive Value	I	Diameter of combustion chamber at injector face
DTHRTI	D_T	inches	Positive Value	I	Diameter of combustion chamber throat
F29	–	–	Positive or Negative Value	O	Decay rate based on the non-linear stability analysis
INJCMP	–	–	0, 1, 2, 3, 4, or 5	I	Injector complexity index; for definition see Section 2.4
IRWNLS	–	–	0, 1, or 2	I	Read or write option for Subroutine NLSTAB
IRW29	–	–	0, 1, or 2	I	Read or write option for Subroutine SECF29

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF29

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
L5FUEL or L5OXID	L_{50}	inches	Positive Value	O	Length of combustion chamber required to vaporize 50 per cent of fuel or oxidizer
MUC	μ	lbf/in-sec	.0000174	I	Viscosity of liquid heptane (condition at injector exit)
PCI	P_C	lbf/in^2	Positive Value	O	Combustion chamber pressure at injector face
RC	–	--	Positive Value	O	Combustion chamber contraction ratio
RHOC	ρ	lbm/in^3	.0247	I	Density of reference liquid heptane (condition at injector exit)
SIGLC	σ_1	lbf/in	.0001	I	Surface tension of liquid heptane (condition at injector exit)
VELC	V_g	in/sec	Positive Value	O	Gas velocity in combustion chamber
VFUEL or VOXID	V_L	in/sec	Positive Number	O	Velocity of liquid at injector exit

7.3 Pressure Drop Characteristic Modules (Subroutines)

The Subroutines SECF31 and SECF32 for the injector pressure drop characteristics are only output subroutines. The actual computation is executed in Subroutine POSTAL independently of the weighting factors AF31 and AF32 which may be equal to zero. However, the injector pressure drop, ΔP, is required for:

1. Computation of the chugging stability characteristics F20 and F21, and there for the following parameters:

   P (pressure drop parameter)

   E (elasticity parameter)

   J (inertia parameter)

2. Computing the acoustic stability characteristic, F28, and there for the transfer function (Equation (7-59)).

3. Computing the specific pressure drop characteristics F31 and F32.

7.3.1 <u>Subroutine SECF31</u>. Subroutine SECF31 is activated as long as the weighting factor AF31 is not zero. The pressure drop for the fuel side of the injector becomes

$$\Delta P_f = \frac{\dot{W}_f^{\,2}}{2*g*C_{D_f}^{\,2}*\rho_f\left(\frac{\pi}{4}\,DF^2*\,NF\right)^2} \qquad (7\text{-}66)$$

where

C_{Df} = Discharge coefficient for fuel orifices

DF = Equivalent diameter of fuel hole (smallest diameter)

g = Gravitational constant

NF = Number of fuel holes

$\dot{W}_f$ = WT/(1+OF); fuel flow rate through injector

WT = Total propellant flow rate through injector

ρ_f = Fuel density at injector entry

OF = Propellant mixture ratio

Because the computer program is able to take into account a pump-fed engine with preburners, the equation for the pressure drop takes the following form:

$$\Delta P_f = \frac{WINJF^2}{2*g*C_{D_f}^{\ 2} * \rho_f \left(\frac{\pi}{4} DF^2*NF\right)^2} \qquad (7\text{-}67)$$

where

WINJF = WF + WXPREB - WFCOOL

(For definitions see Figures 2-10 and 2-11 in Section 2.4). Finally,

$$F31 = \Delta P_f \qquad (7\text{-}68)$$

7.3.2 Subroutine SECF32. Subroutine SECF32 is activated as long as the weighting factor AF32 is not zero. The pressure drop for the oxidizer side of the injector becomes

$$\Delta P_{ox} = \frac{\dot{W}_{ox}^{\ 2}}{2*g*C_{D_x}^{\ 2}*\rho_{ox}\left(\frac{\pi}{4} DX^2*NOX\right)^2} \qquad (7\text{-}69)$$

where

C_{D_X} = Discharge coefficient for fuel orifices

DX = Equivalent diameter of oxidizer hole (smallest diameter)

g = Gravitational constant

NOX = Number of oxidizer holes

$\dot{W}_{ox}$ = WT/(1+1/OF); oxidizer flow rate through injector

WT = Total propellant flow rate through injector

ρ_{ox} = Oxidizer density at injector entry

OF = Propellant mixture ratio

Since the computer program may be applied to a pump-fed engine with preburners, the equation for the pressure drop takes the following form:

$$\Delta P_{ox} = \frac{WINJX^2}{2*g*C_{D_X}{}^2 *\rho_{ox}(\frac{\pi}{4} DX^2*NOX)^2} \qquad (7\text{-}70)$$

where

$$WINJX = WOX - WXPREB$$

(For definitions see Figures 2-10 and 2-11 in Section 2.4). Finally,

$$F32 = \Delta P_{ox} \qquad (7\text{-}71)$$

A flow chart for subroutines SECF31 and SECF32 and their interaction with Subroutine POSTAL is depicted in Figure 7-20.

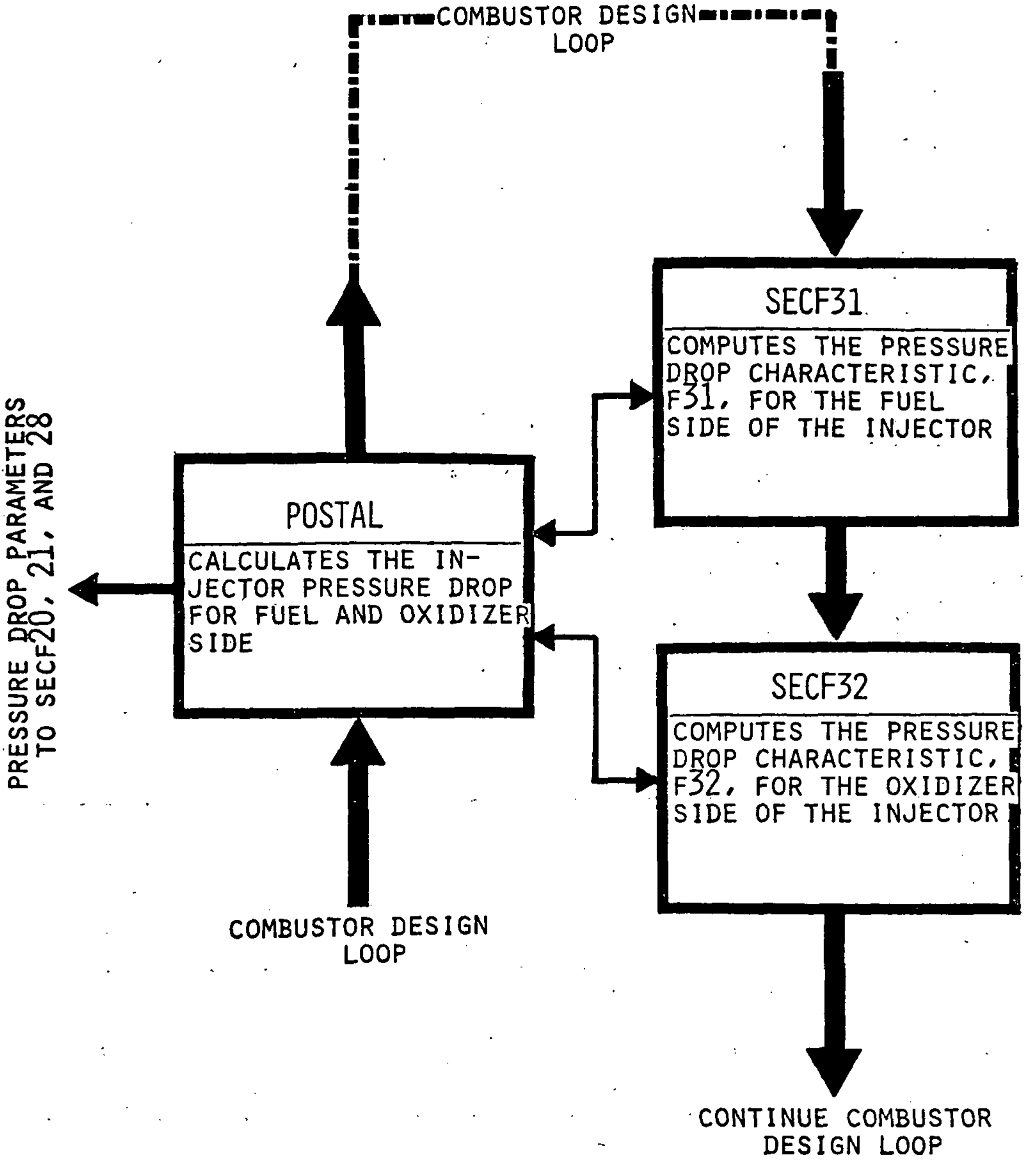


Figure 7-20. Flow Chart for Subroutines SECF31 and SECF32 for Calculating the Pressure Drop Characteristics F31 and F32

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF31 AND SECF32

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
AF31 or AF32	—	—	Positive Value or 0	I	Weighting factor constant in the fuel or oxidizer pressure drop characteristic equation
CDF or CDX	C_{D_f} or C_{D_x}	—	Positive Value	I	Discharge coefficient for fuel or oxidizer orifices (product of the velocity coefficient and the contraction coefficient)
DELTPF or DELTPX	ΔP_f or ΔP_{ox}	$\mathrm{lbf}/\mathrm{in}^2$	Positive Value	O	Injector pressure drop for fuel or oxidizer side
DF or DX	DF or DX	inches	Positive Value	I	Minimum diameter of fuel orifices (determines pressure drop of the fuel or oxidizer side of the injector); see Figure 2-7 in Section 2.4
F31 or F32	F31 or F32	—	Positive Value	O	Pressure drop characteristic for fuel or oxidizer
GREF	g	$\mathrm{in}/\mathrm{sec}^2$	32.2*12	I	Gravitational constant
IRW31 or IRW32	—	—	0, 1, or 2	I	Read or write option for Subroutine SECF31 or SECF32
NF or NOX	NF or NOX	—	Positive Integer	I	Number of oxidizer orifices; for definition see Section 2.4

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF31 AND SECF32

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
OF	OF	—	Positive Value	I	Propellant mixture ratio (oxidizer/fuel)
RHOF or RHOX	ρ_f or ρ_{ox}	lbm/in^3	Positive Value	I	Density of fuel or oxidizer at injector entry
WF or WOX	WF or WOX	lbm/sec	Positive Value	O	Total fuel or oxidizer flow rate
WFCOOL	WFCOOL	lbm/sec	Positive Value	I	Fuel flow rate for combustor cooling
WINJF or WINJX	WINJF or WINJX	lbm/sec	Positive Value	O	Fuel or oxidizer flow rate through the injector: WINJF = WF + WXPREB - WFCOOL WINJX = WOX - WXPREB
WT	WT	lbm/sec	Positive Value	I	Total propellant flow rate (fuel + oxidizer)
WXPREB	WXPREB	lbm/sec	Positive Value	I	Oxidizer flow rate through preburner

7.4 Combustor Complexity Characteristic Modules (Subroutines)

7.4.1 Subroutine SECF41. Subroutine SECF41 is the number of fuel plus oxidizer holes characteristic, and is given by

$$F41 = (NF + NOX) - 1 \qquad (7\text{-}72)$$

7.4.2 Subroutine SECF42. Subroutine SECF42 is the volume of the oxidizer dome characteristic and is given by

$$F42 = VOLX \qquad (7\text{-}73)$$

7.4.3 Subroutine SECF43. Subroutine SECF43 is the volume of the fuel dome characteristic and is given by

$$F43 = VOLF \qquad (7\text{-}74)$$

7.4.4 Subroutine SECF44. Subroutine SECF44 is the length of the oxidizer holes characteristic and is given by

$$F44 = LOX \qquad (7\text{-}75)$$

7.4.5 Subroutine SECF45. Subroutine SECF45 is the length of the fuel holes characteristic and is given by

$$F45 = LF \qquad (7\text{-}76)$$

7.4.6 Subroutine SECF46. Subroutine SECF46 is the injector type complexity characteristic and is given by the index INJCMP (for definition of INJCMP, see Section 2.4). At this time, Subroutine SECF46 is not active. Therefore,

$$F46 = 0 \qquad (7\text{-}77)$$

However, INJCMP is an input parameter in Data Input Namelist COMMIS and is selected according to Figure 2-9, Section 2.4.

Figure 7-21 depicts the flow chart for Subroutines SECF41 through SECF46.

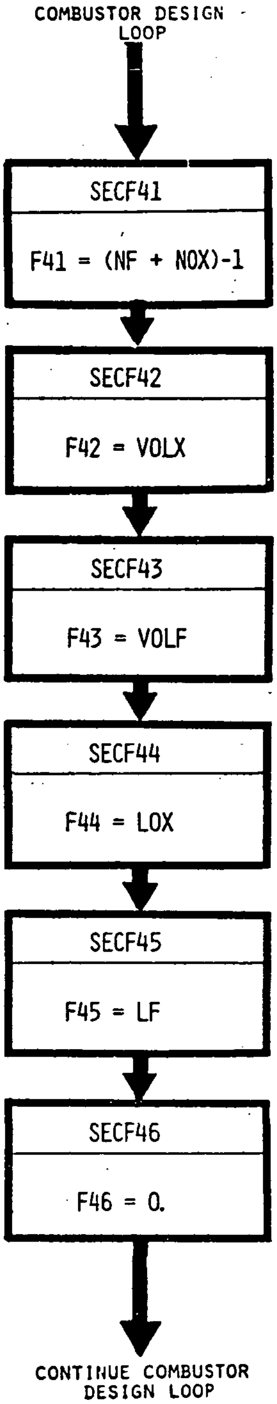


Figure 7-21. Flow Chart for Subroutines SECF41 through SECF46

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF41 THROUGH SECF46

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
AF41	—	—	Positive Value or 0	I	Weighting factor constant for the injector orifice number characteristic
AF42 or AF43	—	—	Positive Value or 0	I	Weighting factor constant for the oxidizer or fuel dome volume characteristic
AF44 or AF45	—	—	Positive Value or 0	I	Weighting factor constant for the length of the oxidizer or fuel orifices characteristic
AF46	—	—	0.0	I	Weighting factor constant for the injector type complexity characteristic
F41	—	—	Positive Value	O	Number of fuel plus oxidizer holes characteristic
F42 or F43	—	—	Positive Value	O	Volume of the oxidizer or fuel dome characteristic
F44 or F45	—	—	Positive Value	O	Length of the oxidizer or fuel holes characteristic
F46	—	—	0.0	O	Injector type complexity characteristic
INJCMP	—	—	0, 1, 2, 3, 4, or 5	I	Injector complexity index

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF41 THROUGH SECF46

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
IRW41	—	—	0, 1, or 2	I	Read or write option for Subroutine SECF41
IRW42 or IRW43	—	—	0, 1, or 2	I	Read or write option for Subroutine SECF42 or SECF43
IRW44 or IRW45	—	—	0, 1, or 2	I	Read or write option for Subroutine SECF44 or SECF45
IRW46	—	—	0.0	I	Read or write option for Subroutine SECF46
LF or LOX	LF or LOX	inches	Positive Value	I	Length of fuel or oxidizer orifices
NF or NOX	NF or NOX	—	Positive Integer	I	Number of fuel or oxidizer holes in the injector
VOLF or VOLX	VOLF or VOLX	in^3	Positive Value	I	Volume of the fuel or oxidizer dome

7.5 Combustor Chamber Length Characteristic Module (Subroutine)

7.5.1 Subroutine SECF51. Subroutine SECF51 computes the chamber length characteristic by

$$F51 = LC/DTHRTI \qquad (7\text{-}78)$$

where

LC = Combustion chamber length

DTHRTI = Diameter of throat

Figure 7-22 depicts the flow chart for subroutine SECF51.

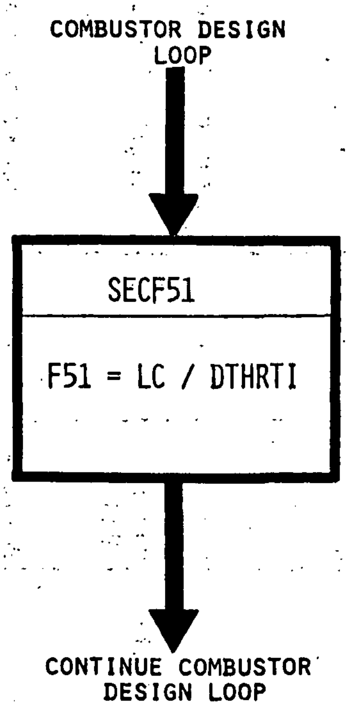


Figure 7-22. Flow Chart for Subroutine SECF51

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF51

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT(I) or OUTPUT(O)	DESCRIPTION
AF51	—	—	Positive Value or 0	I	Weighting factor constant for the chamber length characteristic
DTHRTI	DTHRTI	inches	Positive Value	I	Diameter of throat of combustion chamber
F51	—	—	Positive Value	O	Chamber length characteristic
IRW51	—	—	0, 1, or 2	I	Read or write option for Subroutine SECF51
LC	LC	inches	Positive Value	I	Combustion chamber length (distance from injector face to throat area)

7.6 Combustion Chamber Diameter Characteristic Module (Subroutine)

7.6.1 Subroutine SECF61. Subroutine SECF61 computes the chamber diameter by

$$F61 = DC/DTHRTI \qquad (7\text{-}79)$$

where

DC = Combustion chamber diameter

DTHRTI = Diameter of throat

Figure 7-23 depicts the flow chart for Subroutine SECF61.

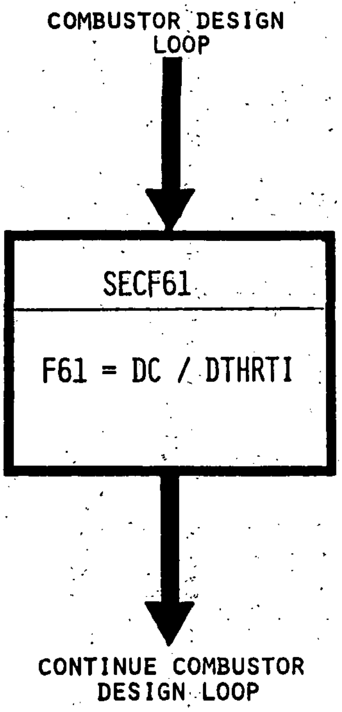


Figure 7-23. Flow Chart for Subroutine SECF61

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF61

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT(I) or OUTPUT(O)	DESCRIPTION
AF61	—	—	Positive Value or 0	I	Weighting factor constant for the chamber diameter characteristic
DC	DC	inches	Positive Value	I	Diameter of the combustion chamber at the injector face
DTHRTI	DTHRTI	inches	Positive Value	I	Diameter of throat of combustion chamber
F61	—	—	Positive Value	O	Chamber diameter characteristic
IRW61	—	—	0, 1, or 2	I	Read or write option for Subroutine SECF61

7.7 Propellant Mixture Ratio Characteristic Module (Subroutine)

7.7.1 Subroutine SECF71. Subroutine SECF71 is the mixture ratio characteristic and is given by

$$F71 = OF \tag{7-80}$$

OF as a free variable is perturbed by AESOP and the respective value used in other subroutines.

Figure 7-24 depicts the flow chart for Subroutine SECF71.

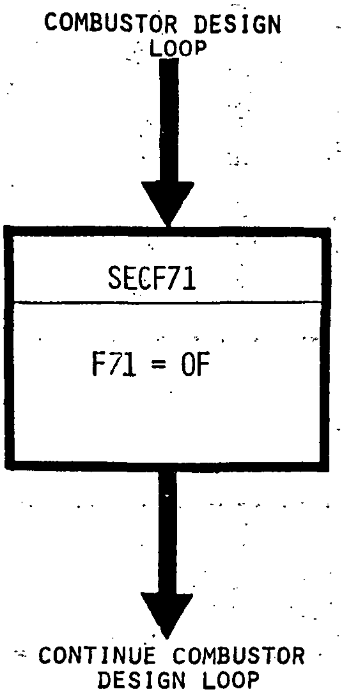


Figure 7-24. Flow Chart for Subroutine SECF71

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF71

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT(I) or OUTPUT(O)	DESCRIPTION
AF71	–	–	Positive Value or 0	I	Weighting factor constant for the mixture ratio characteristic
F71	–	–	Positive Value	O	Mixture ratio characteristic
IRW71	–	–	0, 1, or 2	I	Read or write option for Subroutine SECF71
OF	OF	–	Positive Value	I	Propellant mixture ratio (oxidizer/fuel)

7.8 Baffle Characteristic Modules (Subroutines)

7.8.1 Subroutine SECF81. Subroutine SECF81 is a baffle characteristic given by the number (integer) of radial vanes in baffle (BFLRAD):

$$F81 = BFLRAD \qquad (7\text{-}81)$$

BFLRAD as an independent variable may be perturbed by Subroutine AESOP, and the respective value influences the specific combustor characteristics F22, F23, F24, F25, F27, F28, and F29 as presented in Section 7.8.3.

7.8.2 Subroutine SECF82. Subroutine SECF82 is a baffle characteristic given by the number (integer) of circumferential cans in baffle (BFLCIR):

$$F82 = BFLCIR \qquad (7\text{-}82)$$

BFLCIR as an independent variable may be perturbed by Subroutine AESOP, and the respective value influences the specific combustor characteristics F22, F23, F24, F25, F27, F28, and F29 as presented in Section 7.8.3.

Figure 7-25 depicts the flow chart for Subroutines SECF81 and SECF82.

7.8.3 Program Provisions to Accept Baffles (Subroutine FNDSNH). The incorporation of baffles makes necessary the use of a new set of transverse and radial frequency modes for Subroutines SECF24, 25, 27, and 28. The selection of these frequency modes is implemented by introducing proper exclusion rules. Subroutine FNDSNH serves this purpose. First, it contains the oscillation constants, $s_{\nu h}$, as functions of the transverse and radial mode numbers. Table 7-4 lists these values as they are contained in the coded arrays.

Second, it contains the exclusion rules for the selection of the lowest six $s_{\nu h}$ values not forbidden by:

$\nu \geqq F81/2$, if F81 is an even number

$\nu \geqq F81$, if F81 is an odd number, and

$h \geq F82$, if F82 is an odd or even number

Note: For all $s_{\nu h}$ selections, the case where $\nu = 0$ with $h > 1$, is alos included.

Additional selection criteria for $s_{\nu h}$ values are discussed in the respective sections for Subroutines SECF24, 25, 27, and 28.

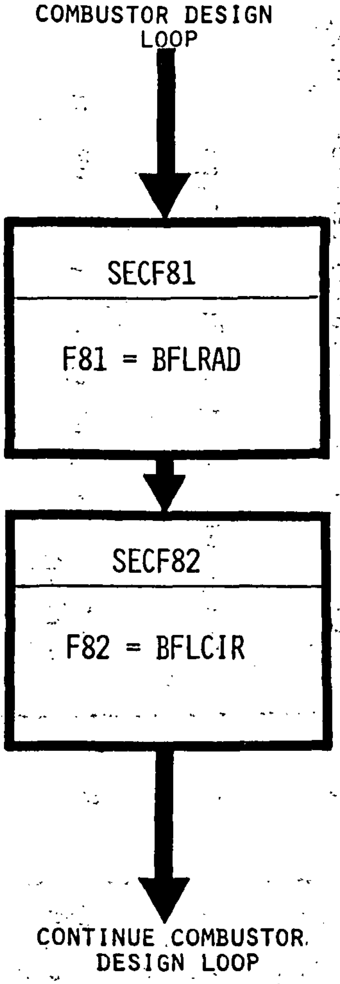


Figure 7-25. Flow Chart for Subroutines SECF81 and SECF82

PARAMETERS (COMMON) USED IN SUBROUTINE(S) SECF81 AND SECF82

PROGRAM SYMBOL	TECHNICAL SYMBOL	UNITS	NOMINAL VALUE	INPUT (I) or OUTPUT (O)	DESCRIPTION
AF81 or AF82	–	–	0 or 1	I	Weighting factor constant for radial or circumferential baffles in the average baffle characteristic equation
BFLCIR	–	–	Positive Integer or 0	I	Number of circumferential baffles (integer)
BFLRAD	–	–	Positive Integer or 0	I	Number of radial baffles (integer)
F81 or F82	–	–	Positive Integer or 0	O	Number of radial (F81) or Circumferential (F82) baffles
IRW81 or IRW82	–	–	0, 1, 2	I	Read or write option for Subroutine SECF81 or SECF82; see Section 2.6

TRANSVERSE MODE NUMBER, ν (RADIAL BAFFLES)	RADIAL MODE NUMBER, h (CIRCUMFERENTIAL B.)	$S_{\nu h}$-VALUE	TRANSVERSE MODE NUMBER, ν (RADIAL BAFFLES)	RADIAL MODE NUMBER, h (CIRCUMFERENTIAL B.)	$S_{\nu h}$-VALUE
0	1	0.00000	14	1	15.97544
1	1	1.84118	2	5	16.34752
2	1	3.05424	10	2	16.44785
0	2	3.83170	0	6	16.47063
3	1	4.20119	7	3	16.52937
4	1	5.31755	15	1	17.02032
1	2	5.33144	5	4	17.31284
5	1	6.41562	11	2	17.60027
2	2	6.70613	8	3	17.77401
0	3	7.01558	3	5	17.78875
6	1	7.50127	1	6	18.01553
3	2	8.01524	16	1	18.06326
1	3	8.53632	6	4	18.63744
7	1	8.57784	12	2	18.74509
4	2	9.28240	9	3	19.00459
8	1	9.64742	17	1	19.10446
2	3	9.96947	4	5	19.19603
0	4	10.17346	2	6	19.51291
5	2	10.51986	0	7	19.61585
9	1	10.71143	13	2	19.88322
3	3	11.34592	7	4	19.94185
1	4	11.70600	18	1	20.14408
6	2	11.73494	10	3	20.22303
10	1	11.77088	5	5	20.57551
4	3	12.68191	3	6	20.97248
11	1	12.82649	14	2	21.01540
7	2	12.93239	1	7	21.16437
2	4	13.17037	19	1	21.18227
0	5	13.32369	8	4	21.22906
12	1	13.87884	11	3	21.43085
5	3	13.98719	6	5	21.93172
8	2	14.11552	15	2	22.14225
3	4	14.58585	20	1	22.21915
1	5	14.86359	4	6	22.40103
13	1	14.92837	9	4	22.50140
6	3	15.26818	12	3	22.62930
9	2	15.28674	2	7	22.67158
4	4	15.96411	0	8	22.76008

TABLE 7-4. Arrays for the Frequency Modes, $s_{\nu h}$, and their Components Stored in Subroutine FNDSNH

7.9 Minor Design Variable Dependent Functions

There are several minor design variable dependent functions which are computed in Subroutine POSTAL (Section 6.6.4). Their analytical definitions follow in the alphabetical sequence.

7.9.1 AF, the Area of a Single Injector Fuel Orifice.

$$AF = \pi * DF ** 2/4 \qquad (7\text{-}83)$$

where DF is the minimum diameter of the fuel orifice, and determines the pressure drop of the fuel side of the injector. (For more details see Section 2.4, Figure 2-7).

7.9.2 AI, the Area of the Injector Face.

$$AI = \pi * D1 ** 2/4 \qquad (7\text{-}84)$$

where D1 = DC is the combustion chamber diameter at the injector face.

7.9.3 AOX, the Area of a Single Injector Oxidizer Orifice.

$$AOX = \pi * DX ** 2/4 \qquad (7\text{-}85)$$

where DX is the minimum diameter of the oxidizer orifice, and determines the pressure drop of the oxidizer side of the injector. (For more details see Section 2.4, Figure 2-7).

7.9.4 CFIDEL, the Ideal Thrust Coefficient.

$$CFIDEL = THRUST/(PC*ATHRTI) \qquad (7\text{-}86)$$

where PC = combustion chamber pressure; ATHRTI = throat area.

7.9.5 CS, the Speed of Sound in the Combustion Chamber.

$$CS = \sqrt{TCOMB*SPHEAT*RGAS*GREF} \qquad (7\text{-}87)$$

where

TCOMB = Combustion temperature

SPHEAT = Specific heat ratio

RGAS = Gas constant per unit weight

GREF = Gravitational acceleration

7.9.6 CSTR, the Characteristic Exhaust Velocity.

$$\mathrm{CSTR} = \frac{\mathrm{CS}}{\mathrm{SPHEAT}\sqrt{[2/(\mathrm{SPHEAT} + 1)]^{(\mathrm{SPHEAT} + 1)/(\mathrm{SPHEAT} - 1)}}} \qquad (7\text{-}88)$$

where

CS = Speed of sound in combustion chamber

SPHEAT = Specific heat ratio

7.9.7 DELPF, the Pressure Drop Between Fuel Manifold and Combustion Chamber.

$$\mathrm{DELPF} = \frac{\mathrm{WINJF{*}{*}2}}{\mathrm{2{*}RHOF{*}GREF(CDF{*}{*}2)((NF{*}AF){*}{*}2)}}$$

where

WINJF = Fuel flow rate for injector (see WINJF in this listing)

RHOF = Density of fuel

GREF = Gravitational acceleration

CDF = Discharge coefficient for fuel orifices

NF = Number of fuel holes

AF = Area of a single fuel hole

7.9.8 DELPX, the Pressure Drop Between Oxidizer Manifold and Combustion Chamber.

$$\text{DELPX} = \frac{\text{WINJX**2}}{\text{2*RHOX*GREF(CDX**2)((NOX*AOX)**2)}} \qquad (7\text{-}90)$$

where

WINJX = Oxidizer flow rate for injector
(ee WINJX in this listing)

RHOX = Density of oxidizer

GREF = Gravitational acceleration

CDX = Discharge coefficient for oxidizer orifices

NOX = Number of oxidizer holes

AOX = Area of a single oxidizer hole

7.9.9 EPA, Injector Elements per Unit of Injector Face.

$$\text{EPA} = \text{NE/AI} \qquad (7\text{-}91)$$

where

NE = Number of injector elements

AI = Area of injector face

7.9.10 FJSPAC, Spacing of Fuel Holes.

$$\text{FJSPAC} = \sqrt{\text{AI/NF}} \qquad (7\text{-}92)$$

where

AI = Area of injector face

NF = Number of fuel holes in injector

7.9.11 ISP, Specific Impulse.

For optimization runs:

$$ISP = YPOLYV(OF,PCISP,NPISP) \quad (7\text{-}93)$$

For point design:

$$PCISP(1) = --.,$$

in Data Input Namelist CRVFIT (see Section 2.7).

7.9.12 LD, Combustion Chamber Length/Diameter Ratio.

$$LD = LC/DC \quad (7\text{-}94)$$

where

LC = Length of combustion chamber

DC = Diameter of combustion chamber at injector face

7.9.13 LDF, Average Fuel Orifice Length/Diameter Ratio.

$$LDF = LF/DF \quad (7\text{-}95)$$

where

LF = Length of the fuel hole (for definition see Section 2.3)

DF = Diameter of the fuel hole (for definition see Section 2.3)

7.9.14 LDOF, Log of Average Fuel Orifice Diameter.

$$LDOF = ALOG10(DOF) \quad (7\text{-}96)$$

where

DOF = 1000*DF

DF = Diameter of the fuel hole (for definition see Section 2.3)

7.9.15 LDUM, Acoustical Length of Combustion Chamber.

$$LDUM = L1 + .667(L2 - L1) \quad (7\text{-}97)$$

where

L1 = Chamber length without converging section

L2 = Chamber including converging section (distance from injector face to throat area)

(For more details see Section 7.2.3.1).

7.9.16 LRC, Log of Combustion Chamber Contraction Ratio.

$$LRC = ALOG10(RC) \quad (7\text{-}98)$$

where

RC = Combustion chamber contraction ratio (for definition of RC see this listing)

7.9.17 LSTR, the Characteristic Chamber Length.

$$LSTR = VC/ATHRTI \quad (7\text{-}99)$$

where

VC = Volume of the combustion chamber (for definition of VC see this listing)

ATHRTI = Throat area of the combustion chamber

7.9.18 MC, Mach Number in Combustion Chamber

$$MC = VELC/CS \quad (7\text{-}100)$$

where

VELC = Average velocity of the gas in the combustion chamber (for definition of VELC see this listing)

CS = Speed of sound in combustion gas

7.9.19 MOLWT, the Molecular Weight of the Combustion Gas. For optimization runs:

$$\mathrm{MOLWT} = \mathrm{YPOLYV(OF,\ PCMOLW,\ NPMOLW)} \qquad (7\text{-}101)$$

For point design:

PCMOLW(1) = --.,

in Data Input Namelist CRVFIT (see Section 2.7).

7.19.20 MPE, The Mass Flow Rate per Element.

$$\mathrm{MPE} = (\mathrm{WT} - \mathrm{WFCOOL})/\mathrm{NE} \qquad (7\text{-}102)$$

where

WT = Total propellant mass flow rate

WFCOOL = Fuel flow rate for cooling

NE = Number of injector elements

7.9.21 NE, Number of Injector Elements.

$$\mathrm{NE} = (\mathrm{NF} + \mathrm{NOX})/\mathrm{DIVIDE} \qquad (7\text{-}103)$$

where

NF = Number of fuel orifices

NOX = Number of oxidizer orifices

DIVIDE = 2 if INJCMP LE.3

= 3 if INJCMP EQ. 4

= 4 if INJCMP EQ. 5

(values for INJCMP see Figure 2-9).

7.9.22 PC, the Combustion Chamber Pressure.

$$PC = \frac{WT}{ATHRTI*GREF*SPHEAT\sqrt{\dfrac{[2/(SPHEAT+1)]^{(SPHEAT+1)/(SPHEAT-1)}}{GREF*SPHEAT*RGAS*TCOMB}}} \qquad (7\text{-}104)$$

where

WT = Total propellant mass flows rate

ATHRTI = Throat area

GREF = Gravitational constant

SPHEAT = Propellant specific heat ratio

RGAS = Propellant gas constant

TCOMP = Combustion temperature

7.9.23 PCOCRF, the Critical Pressure Ratio for Fuel.

$$PCOCRF = PCI/PCRITF \qquad (7\text{-}105)$$

where

PCI = Chamber pressure

PCRITF = Critical pressure of fuel (input for Input Data Namelist COMMIS)

PCOCRF is used in Subroutines TAUN1 and TAUN2 for computing the decay rates F26 and F27.

7.9.24 PCOCRX, the Critical Pressure Ratio for Oxidizer.

PCOCRX = PCI/PCRITX (7-106)

where

PCI = Chamber pressure

PCRITX = Critical pressure of oxidizer (input for Input Data Namelist COMMIS)

PCOCRX is used in Subroutines TAUN1 and TAUN2 for computing the decay rates F26 and F27.

7.9.25 RC, the Combustion Chamber Contraction Ratio.

RC = (D2/D3)**2 (7-107)

where

D2 = Combustion chamber diameter at nozzle entrance (For a cylindrical chamber: D2 = D1 = DC)

D3 = DTHRTI = throat diameter

7.9.26 RGAS, the Gas Constant per Unit Weight.

RGAS = RGUNIV/MOLWT (7-108)

where

RGUNIV = Universal gas constant

MOLWT = Propellant molecular weight;(for definition of MOLWT see this listing)

7.9.27 SPHEAT, the Specific Heat Ratio. For optimization runs:

SPHEAT = YPOLYV(OF, PCK, NPK) (7-109)

For point design:

PCK(1) = --.,

in Data Input Namelist CRVFIT (see Section 2.7).

7.9.28 TAF, the Total Area of Fuel Orifices.

$$\mathrm{TAF} = \mathrm{NF}*\mathrm{AF} \qquad (7\text{-}110)$$

where

NF = Number of fuel orifices

AF = Area of a single fuel orifice

7.9.29 TAX, the Total Area of Oxidizer Orifices.

$$\mathrm{TAX} = \mathrm{NOX}*\mathrm{AOX} \qquad (7\text{-}111)$$

where

NOX = Number of oxidizer orifices

AOX = Area of a single oxidizer orifice

7.9.30 THETAG, the Mean Gas Residence Time.

$$\mathrm{THETAG} = \frac{\mathrm{LSTR/CSTR}}{\mathrm{SPHEAT}\left[\dfrac{2}{\mathrm{SPHEAT}+1}\right]^{(\mathrm{SPHEAT}+1)/(\mathrm{SPHEAT}-1)}} \qquad (7\text{-}112)$$

where

LSTR = Characteristic chamber length

CSTR = Characteristic exhaust velocity

SPHEAT = Specific heat ratio of the combustion gas

THETAG is used in Subroutines SECF20 and SECF21 (Section 7.2.1) for computing $\bar{\tau}$ E, J, and in Subroutine POSTAL (Section 7.9.34) for computing VELC. Its definition is given in Reference 7-3, page 29.

7.9.31. TCOMB, The Combustion Temperature.

For optimization runs:

$$\text{TCOMB} = \text{YPOLYV (OF, PCT1, NPT1)} \tag{7-113}$$

For point design:

PCT1(1) = --.,

in Data Input Namelist CRVFIT (see Section 2.7).

7.9.32 TPVM, the Modified Thrust per Unit Volume.

$$\text{TPVM} = \text{PCI*ATHRTI/VC} \tag{7-114}$$

where

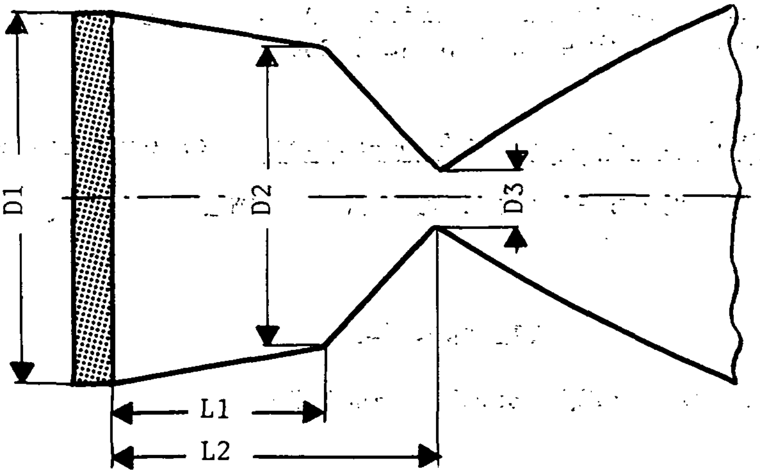
PCI = Combustion chamber pressure

ATHRTI = Throat area

VC = Combustion chamber volume (for definition see this listing)

7.9.33 VC, the Volume of the Combustion Chamber.

$$\text{VC} = \frac{\pi}{12}\left(\text{L1}(\text{D1}^2 + \text{D2}^2 + \text{D1*D2}) + (\text{L2} - \text{L1})(\text{D2}^2 + \text{D3}^2 + \text{D2*D3})\right) \tag{7-115}$$



where

L1 = Length of the combustion chamber from the injector face to the onset of the converging section

L2 = Length of the converging section plus L1

D1 = Combustion chamber diameter at injector face

D2 = Combustion chamber diameter at the onset of the converging section. For cylindrical chamber it is D1 = D2.

D3 = Throat diameter

7.9.34 VELC, the Average Velocity of the Combustion Gases in the Combustion Chamber.

$$VELC = LC/THETAG \qquad (7\text{-}116)$$

where

LC = Length of the combustion chamber from the injector face to the throat area

THETAG = The mean gas residence time (for definition see this listing)

7.9.35 VFUEL, the Average Fuel Injection Velocity.

$$VFUEL = WINJF/(NF*RHOF*\pi*DFVEL^2/4) \qquad (7\text{-}117)$$

where

WINJF = Fuel mass flow rate passing through the injector

NF = Number of fuel orifices

RHOF = Density of fuel (condition at injector face)

DFVEL = Exit diameter of the fuel orifices

7.9.36 VO, the Average Oxidizer Injection Velocity.

$$VO = VOXID = WINJX/(NOX*RHOX*\pi*DXVEL^2/4) \qquad (7\text{-}118)$$

where

WINJX = Oxidizer mass flow rate passing the injector

NOX = Number of oxidizer orifices

RHOX = Density of oxidizer (condition at injector exit)

DXVEL = Exit diameter of the oxidizer orifices

7.9.37 WF, the Total Fuel Mass Flow Rate.

$$WF = WT/1 + OF \qquad (7\text{-}119)$$

where

WT = Total propellant mass flow rate

OF = Propellant mixture ratio

7.9.38 WINJF, the Fuel Mass Flow Rate Passing through the Injector.

$$WINJF = WF + WXPREB - WFCOOL \qquad (7\text{-}120)$$

where

WF = Total fuel mass flow rate

WXPREB = Oxidizer mass flow rate for preburner. If no preburner, WXPREB becomes 0

WFCOOL = Fuel mass flow rate for cooling. If no cooling flow exists, WFCOOL becomes 0

7.9.39 WINJX, The Oxidizer Mass Flow Rate Passing through the Oxidizer Orifices.

$$WINJX = WOX - WXPREB \qquad (7\text{-}121)$$

where

WOX = Total oxidizer mass flow rate (for definition see this listing)

WXPREB = Oxidizer mass flow rate passing the preburner and therefore, injected with the fuel into the main chamber

7.9.40 WOX, the Total Oxidizer Mass Flow Rate.

$$WOX = WT/\ 1 + \frac{1}{OF} \qquad (7\text{-}122)$$

where

WT = Total propellant mass flow rate

OF = Propellant mixture ratio

7.9.41 WT, the Total Propellant Mass Flow Rate.

$$WT = THRUST/ISP \qquad (7\text{-}123)$$

where

THRUST = Rocket engine thrust

ISP = Specific impulse

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