

NASA Contractor Report

187109

User's Manual for Rocket Combustor Interactive Design (ROCCID) and Analysis Computer Program

Volume I—User's Manual

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May 1991

Prepared for
Lewis Research Center
Under Contract NAS3-25556



National Aeronautics and
Space Administration

(NASA-CR-187109) USER'S MANUAL FOR ROCKET
COMBUSTOR INTERACTIVE DESIGN (ROCCID) AND
ANALYSIS COMPUTER PROGRAM. VOLUME 1: USER'S
MANUAL. Final Report. (Aerojet-General Corp.)
92-10

N91-24230

unclas

CSCL 21H G5/20 0013554

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(ROCCID) AND ANALYSIS COMPUTER PROGRAM
VOLUME I - USER'S MANUAL

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SUMMARY

This report is the User's manual for the Rocket Combustor Interactive Design (ROCCID) computer program. The program, written in FORTRAN 77, provides a standardized methodology using state-of-the-art codes and procedures for the analysis of a liquid rocket engine combustor's steady state combustion performance and combustion stability. ROCCID is currently capable of analyzing mixed element injector patterns containing impinging like doublet or unlike triplet, showerhead, shear coaxial and swirl coaxial elements as long as only one element type exists in each injector core, baffle or barrier zone. Real propellant properties of oxygen, hydrogen, methane, propane and RP-1 are included in ROCCID. The properties of other propellants can be easily added. The analysis models in ROCCID can account for the influences of acoustic cavities, helmholtz resonators and radial thrust chamber baffles on combustion stability. ROCCID also contains the logic to interactively create a combustor design which will meet input performance and stability goals. A preliminary design results from the application of historical correlations to the input design requirements. The steady state performance and combustion stability of this design is evaluated using the analysis models, and ROCCID guides the user as to the design changes required to satisfy the user's performance and stability goals, including the design of stability aids. Output from ROCCID includes a formatted input file for the standardized JANNAF engine performance prediction procedure.

ACKNOWLEDGEMENT

This report has been prepared in partial fulfillment of contract NAS3-25556 from the National Aeronautics and Space Administration. Mr. Mark Klem of the NASA Lewis Research Center was the Technical Monitor. The program was managed at Aerojet by Dr. Marvin Young. Mr. Jerry Pieper served as Aerojet Project Engineer.

In addition to the authors, other personnel at both Aerojet and Software and Engineering (SEA) played a significant role in the development of ROCCID. Mr. Stu Dunn and Mr. Gary Nickerson were invaluable in the adaptation of the IFE generation software and the ODE module of TDK for use in ROCCID. Mr. John Stephens, and Ms. Yuriko Jones were instrumental in the timely development and debugging of the Point Design Module.

Mr. Dick Walker of Aerojet and Mr. Kevin Breisacher of NASA/Lewis have used the code during the testing period. Their providing constructive feedback and suggestions has resulted in substantial improvement in code operation.

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1.0 OVERVIEW

The Rocket Combustor Interactive Design (ROCCID) program provides the combustion analyst with a tool to analyze an existing combustor design (point analysis), or design a high performing, stable combustor given a set of input design requirements (point design). ROCCID was created by concatenating the best existing performance and combustion stability models into one comprehensive design tool. An interactive front end (IFE) has been incorporated to facilitate user input generation, track user input options and display selected output data.

The structure of ROCCID is illustrated in Figure 1.1. ROCCID contains three main components which are:

1. An interactive front end (IFE) that provides guidance to the user for input setup, input and output control and the generation and maintenance of library files for replay, restart and combustion gas properties.
2. A point analysis option that provides performance and combustion stability analysis of existing combustor designs.
3. A point design option that creates the essential combustor design features for a high performance and stable rocket engine from specified design requirements.

The point analysis and point design options access a variety of performance and combustion stability analysis models, identified in Table 1.1, that were selected from an industry-wide inventory of existing models. These analysis models are contained within ROCCID in a modular format. This permits the user to access specific models for a specialized sub-analysis or to use two or more models that perform similar functions to define and resolve uncertainties in the particular area of the analysis. Modular construction also permits ROCCID to be easily upgraded as new analysis models are developed or refined.

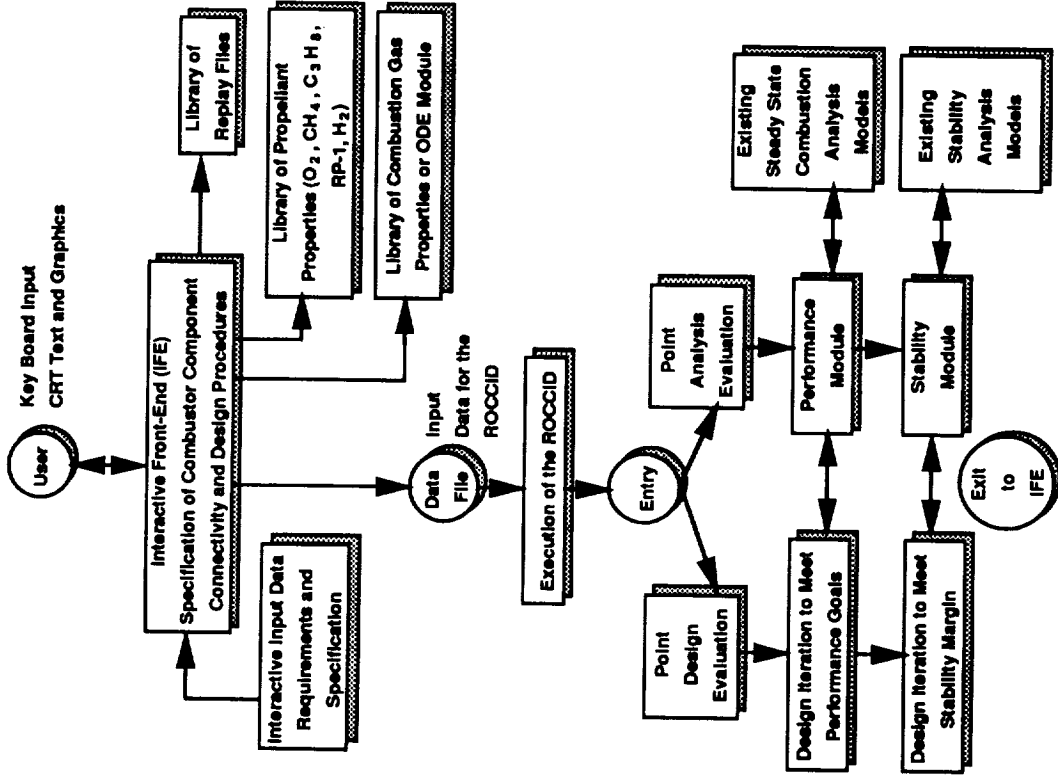
A steady state combustion analysis, which includes propellant atomization, vaporization and mixing, supplies key input for the performance and stability analyses. Four models for propellant droplet size are included for standard injector elements - showerhead, doublet, triplet, shear coaxial elements, and swirl coaxial elements. Droplet sizes from all applicable correlations are calculated and displayed for comparison. The user may select any of the calculated values, or provide their own estimates for these values. Propellant (fuel or oxidizer) vaporization is

Methodology Development

Funded By:
NASA Lewis Research Center

Developed By:
Aerojet Propulsion Division
and
Software and
Engineering Asdassociates, Inc.

ROCCID Flowchart



Analysis Models

Government Agencies

AFAL
 NASA LeRC
 NASA MSFC
 NBS
 CPIA

Propulsion Companies

Aerojet Propulsion Division
 Rocketdyne
 SEA Inc.
 UTRC
 WJSA

Universities

Colorado State
 Princeton
 California State University at
 Sacramento

3.28.0.9

Figure 1.1. ROCCID is an Industry Developed Tool

Table 1.1
Performance and Stability Models Contained in ROCCID

Steady State Combustion	Performance	Combustion Stability
Vaporization - Priem TR-67 Approach Atomization - Aerojet (Impingement & Coax Model) Dropmix (Impinging & Shear Coax) Priem TR-67 (Impinging) UTRC (Swirl Coax)	JANNAF Simplified Procedure $\eta_{ERE} = \eta_{VAP} * \eta_{MIX}$ η_{VAP} Included Vaporization Mass Defect η_{MIX} Includes Multi-Zone Mixture Ratio Maldistribution	Chamber Response HIFI DIST3D FDORC Burning Response N/ τ Correlations CRP Injector Response Aerojet Inject Lewis Non-Linear
Mixing - User Supplied Em		

1.0, Overview (cont.)

calculated using the Generalized Length Correlation developed by Priem and Heidmann (Ref. 1). Propellant mixing utilizes a two-zone/four-streamtube model, with a Rupe mixing efficiency (E_m) defining the mixing in each zone. Currently, this value is supplied by the user. Guidelines for determining value of E_m are provided in Section 2.2.

The performance of the combustor is defined by the C^* and ISP-based energy release (ERE) efficiencies. These account for combustion efficiency losses resulting from incomplete propellant vaporization and/or mixing. The energy release efficiency is calculated using the JANNAF simplified performance calculation procedure (Ref. 2) with the propellant vaporization and mixing efficiencies calculated by the steady state combustion analysis. An input file for the TDK/BLM computer program (Ref. 3) is also generated, so the user can perform a rigorous performance analysis of the complete rocket engine.

The combustion stability analyses can be performed with any combination of several models used to calculate the chamber, intrinsic burning and injection responses. These models provide the capability to estimate combustion stability margin for low frequency non-acoustic (chug) and high frequency acoustic modes. The effects of damping devices, including acoustic cavities (1/4 wave cavities and Helmholtz resonators) and radial thrust chamber baffles, are also considered by these models. A listing of the combustion stability models included in ROCCID is contained in Table 1.1.

The design requirements for combustor cooling must be determined by the user outside of ROCCID. These requirements may include estimates of fuel film cooling required for chamber walls and baffle blades, dump cooling off baffle tips, and bulk temperature increases resulting from regenerative cooling of the nozzle chamber and resonator/baffle components. This information is used to calculate ROCCID inputs, such as the propellant injection temperatures, injection orifice distribution requirements and the local flow injection mixture ratios. This method of accounting for the temperature limits of the injector/thrust chamber materials was selected to keep ROCCID focused on the combustion stability and performance issues, while providing a useful and practical combustor design tool.

ROCCID has been constructed with an interactive front end that provides the user with a convenient interactive tool for input generation, file creation and output display. The IFE has been developed by Software and Engineering Associates (SEA) Inc., of Carson City, Nevada.

1.0, Overview (cont.)

Each input character is checked in the IFE for validity, and warnings are displayed when input errors are sensed. Replay files, which contain a record of all case inputs, are created and maintained. These files can be edited and used as input for a subsequent session. Required combustion gas property tables are internally generated and maintained in files.

Upon completion of input generation, the user may execute either the point analysis or point design options. These options also contain many interactive decision points for the user. Upon completion of an analysis or user termination, the IFE prints pertinent information and prepare inputs for the next run.

CAPABILITIES AND LIMITATIONS

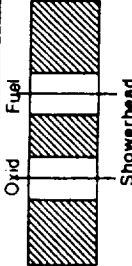
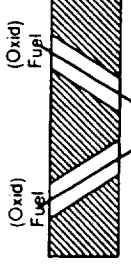
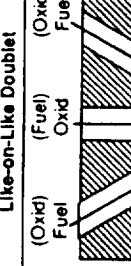
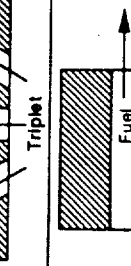
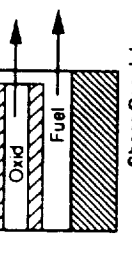
ROCCID has been specifically formulated to be applicable to combustor designs for LOX/HC and LOX/H₂ propellants. Propellant and combustion gas properties for LOX/RP-1, LOX/CH₄, LOX/C₃H₈ and LOX/H₂ are internally calculated. Both gas/liquid and liquid/liquid propellant injection are considered. Conventional impinging like doublet and triplet (OFO and FOF) elements, non-impinging showerhead and shear and swirl coaxial elements are modelled. The injector can consist of a mixed element pattern, including core, baffle, barrier and fuel film/cavity cooling elements. Different element types can exist in different zones (i.e., baffle, core, barrier). However, in any one zone only one element type may exist and doublet elements must be in matched pairs of oxidizer and fuel.

The point design option permits the user to constrain some design parameters, such as contraction ratio (CR) and chamber length (L'), thereby focusing on the best trade-off between performance and combustion stability. A simple trade-off between nozzle length and chamber length is also included to optimize engine delivered specific impulse for an envelope limited system. Acoustic damping devices are also recommended and their design features specified to provide the required combustion stability margin. Design trade-offs for a throttling engine are also performed.

The point design option features an optimization of the injector element design. The guidelines in Table 1.2 are provided to aid the user in injector element type selection for a particular application. The quantity of elements and the injector orifice size are calculated through a series of trade studies to satisfy performance and high frequency combustion stability requirements, chug stability and other user-specified constraints.

Table 1.2

Element Characteristics for Several Conventional Liquid Rocket Injector Elements Modeled Within ROCCID

Injection Element Type	Propellant State Application	Key Design Parameters	Atomization	Mixing	Performance	Combustion Stability		Compatibility
						Characteristic	Control Method	
 <p>Oxid Fuel Showerhead</p>	Liquid/Liquid Gas/Liquid Gas/Gas	<ul style="list-style-type: none"> Orifice Size Injection Velocity Chamber Gas Density 	Poor But Well Characterized	<ul style="list-style-type: none"> Very Poor Used Generally for Film or Barrier Cooling 	Very Poor	<ul style="list-style-type: none"> Generally Detuned From Chamber Acoustic Modes 	Not Generally Required	<ul style="list-style-type: none"> Very Good When Used as Fuel Film Coolant Injection Potential for LOX Impingement on Chamber Walls
 <p>(Oxid) Fuel Like-on-Like Doublet</p>	Liquid/Liquid Gas/Liquid Gas/Gas	<ul style="list-style-type: none"> Orifice Size Like Impingement Angle Unlike Impingement Angle Spray Overlap 	<ul style="list-style-type: none"> Good Independent of Momentum Ratio and Relative Orifice Size 	<ul style="list-style-type: none"> Very Sensitive to Unlike Impingement Angle Insensitive to Conditions or Relative Orifice Size Generally Requires Inter-Element Mixing for High Em 	<ul style="list-style-type: none"> Good for Wide Range of Applications when Proper Unlike Impingement Angle & Thrust/Element Are Used 	<ul style="list-style-type: none"> Burning Rate Coupled Non-Linear 	<ul style="list-style-type: none"> Multiple Chamber Acoustic Damping Derate Performance by Increasing Thrust/Element 	<ul style="list-style-type: none"> Very Good with Proper Spray Orientation May Require Film Cooling Between Elements
 <p>(Oxid) Fuel Oxid Fuel Triplet</p>	Liquid/Liquid Gas/Liquid Gas/Gas	<ul style="list-style-type: none"> Orifice Size Relative Orifice Size 	<ul style="list-style-type: none"> Superior Sensitive to Relative Orifice Size 	<ul style="list-style-type: none"> Excellent Intra-Element Mixing with Equal Orifice Diameter Sensitive to Design Operating Conditions with Unequal Orifice Size 	<ul style="list-style-type: none"> Excellent for Limited Design Conditions (Equal Orifice Size) Best for Maximum Thrust/Element 	<ul style="list-style-type: none"> Burning Rate Coupled Non-Linear 	<ul style="list-style-type: none"> Maximize Thrust/Element Chamber Acoustic Damping 	<ul style="list-style-type: none"> Good with Proper Spray Orientation Generally Requires Film or Barrier Cooling Particularly, with the OFO Configuration
 <p>Fuel Oxid Fuel Shear Coaxial</p>	Gas/Liquid Gas/Gas	<ul style="list-style-type: none"> LOX Tube Size Velocity Ratio Tube Recess Fuel Injection Velocity 	<ul style="list-style-type: none"> Moderate Controlled by Shear Not Well Characterized 	<ul style="list-style-type: none"> Intra-Element Controlled Element Size Limited 	<ul style="list-style-type: none"> Excellent with Limited Thrust/Element Fuel-to-Oxygen Velocity Ratio Sensitive 	<ul style="list-style-type: none"> Injection Coupled Linear Total Time Lag Sensitive 	<ul style="list-style-type: none"> Injection Velocity and Velocity Ratio Limit Operating Region Chamber/Manifold Acoustic Damping 	<ul style="list-style-type: none"> Generally Good - Potential for LOX Impingement on Chamber Walls
 <p>Fuel Oxid Fuel Swirl Swirl Coaxial</p>	Gas/Liquid Gas/Gas	<ul style="list-style-type: none"> LOX Tube Size Degree of Swirl Fuel Injection Velocity 	<ul style="list-style-type: none"> Good Controlled by LOX Swirl and Fuel Shear Not Well Characterized 	<ul style="list-style-type: none"> Intra-Element Controlled Improved Over Shear Coaxial Element 	<ul style="list-style-type: none"> Excellent Less Restricted Thrust/Element Constraint 	<ul style="list-style-type: none"> Injection Coupled Linear Total Time Lag Sensitive 	<ul style="list-style-type: none"> Injection Velocity, Velocity Ratio and LOX Swirl Angle Limit Operating Condition Chamber Acoustic Damping 	<ul style="list-style-type: none"> High Potential for LOX Impingement on Chamber Walls Increased Sensitivity to Operating Conditions

1.0, Overview (cont.)

ROCCID has been prepared with certain limitations in order to simplify its construction and guarantee its timely and affordable initial development. No supersonic nozzle effects are currently included. The nozzle design and engine specific impulse must be determined outside of ROCCID. Precombusted fuel (staged combustion cycle) is not presently considered. Mass addition from ablation, igniters, gas generator dump or transpiration cooling is not modelled. As previously noted, cooling requirements are defined outside ROCCID, but their effects on performance and stability are considered.

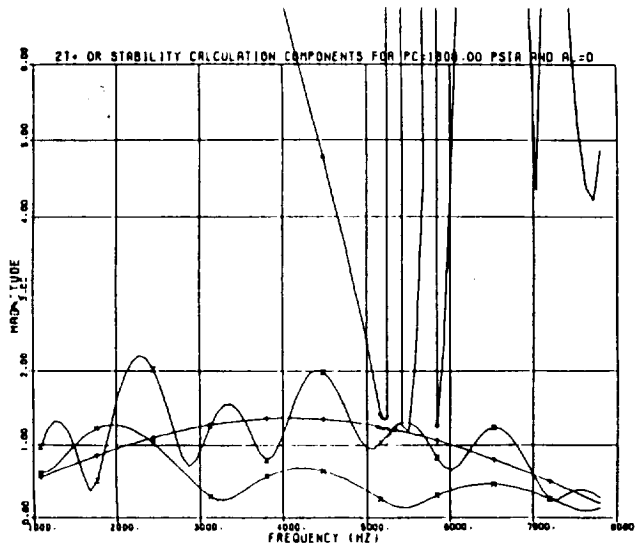
ROCCID has been developed and is operational on VAX 8600 series computers at both Aerojet and NASA Lewis Research Center. It has also been run on a SUN 4/SPARC architecture computer at SEA, Inc. Interactive graphics for Tektronix 40XX and 41XX terminals is also provided. The code has been constructed without machine dependent instructions, but operation on other computer systems remains to be verified.

2.0 POINT ANALYSIS

The point analysis portion of ROCCID (POINTA) is structured to evaluate the performance and stability of an existing combustor design. POINTA is composed of three modules that control the calculation of steady-state combustion and performance (SSCI), low frequency stability (LFCS) and high frequency stability (HFCS). Each of these modules in turn utilize a collection of models to perform the required calculations. A complete flowchart of POINTA is contained in Appendix F.

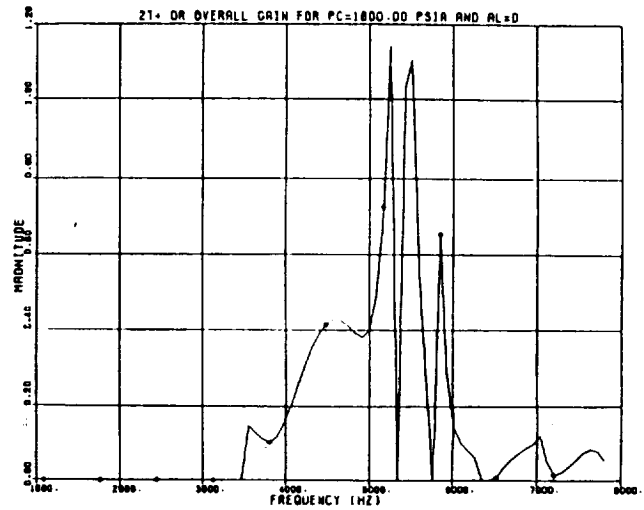
The steady state combustion iteration module evaluates the combustor operation and performance at the nominal chamber pressure, as well as two throttled chamber pressures, to generate the flowrate, pressure drop, timelag and mean combustion gas composition data required as input to the combustion stability modules (LFCS and HFCS).

ROCCID evaluates combustion stability using the transfer function approach, whereby the ability of the chamber to dissipate acoustic oscillations is compared to the oscillatory combustion driving mechanisms (Refs. 4, 16). The driving mechanisms are classified by the source of the oscillation, either unsteady propellant injection (injection-coupling) or unsteady propellant burning (intrinsic or burning-coupling). The oscillations in pressure and mass flowrate are characterized as admittances, the ratio of the mass flowrate-to-pressure perturbations normalized by the local mean pressure and flowrate. These complex variables permit the magnitude and phase relationship to be expressed as a single term. The low and high frequency combustion stability calculations, controlled by the LFCS and HFCS modules, respectively, evaluate the linearized transfer function of the relevant system components and the resultant overall system gain. Figure 2.1a is a typical graphical representation of the component transfer function magnitude, with the injection (Y_j) and the burning (Y_b) representing the drivers in the system and the chamber ($1/Z_c$) the coupling element. As indicated, neither Y_b nor Y_j have a large enough magnitude to result in a potentially unstable system, but their vector sum does, as indicated by the magnitude of (Y_b+Y_j) being greater than that of $1/Z_c$. Figure 2.1b contains the associated phase angle as a function of frequency for each of the system components. The system stability can be recast in terms of overall system gain by considering the product $Z_c*(Y_b+Y_j)$ (Fig. 2.1c). This representation also indicates that the system has the potential to be unstable, since the system gain is greater than 1.0. The occurrence of an instability can then be determined by considering the phase angle relationship of the overall system. Since linearized modelling techniques are being used, an instability will occur at the frequency where the system

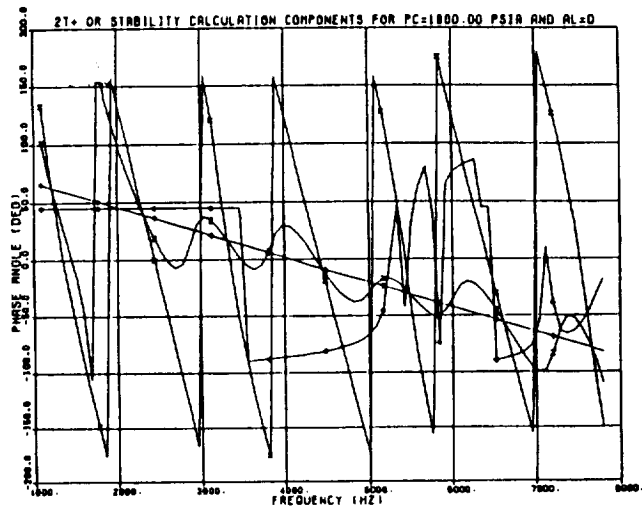


a) Component Transfer Function Magnitude

$\diamond = 1/ZC$
 $\uparrow = YB$
 $\times = YJ$
 $Z = YB+YJ$

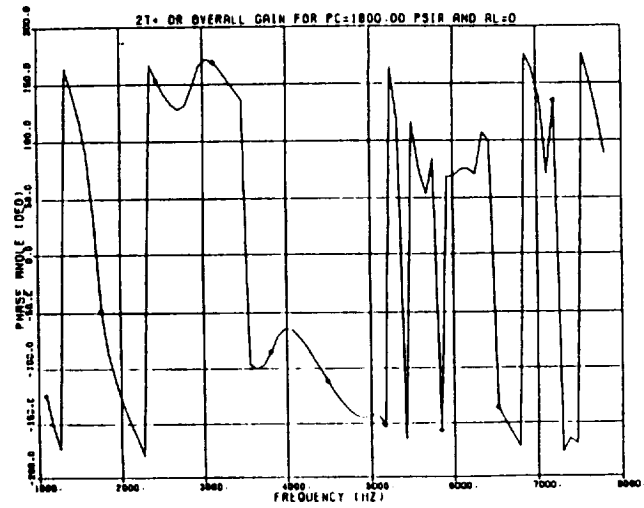


c) Overall Gain Magnitude



b) Component Transfer Function Phase Angle

$\diamond = 1/ZC$
 $\uparrow = YB$
 $\times = YJ$
 $Z = YB+YJ$



d) Overall Gain Phase Angle

Figure 2.1. Transfer Function Approach to Combustion Stability

2.0, Point Analysis (cont.)

gain is in-phase, i.e. when the phase angle goes from 180 to -180 degrees (Fig. 2.1d). Therefore, by considering only the frequencies where the correct phase relationship occurs, and then determining whether the system has a gain magnitude greater than 1.0 at those frequencies, the system stability can be evaluated.

The following subsections describes required POINTA inputs, the layout of the modules and connection of the individual submodels within the modules. A brief discussion of the individual submodels is included, while more substantive discussion can be found in the submodel reference documents contained in Appendix J.

2.1 POINTA INPUT

The input to POINTA consists of the propellant type and manifold temperatures, chamber geometry descriptor, injection element type, quantity and geometry, and combustor operating condition, specified as injected oxidizer-to-fuel flowrate mixture ratio (MR) and injector face stagnation pressure (P_c). Four categories of injector elements are permitted in POINTA - core, baffle, barrier and fuel film/cavity cooling (FFC) elements. All combustors must include a core element. The baffle element can be either a compatibility element or an integral part of the baffle, e.g. SSME, and its definition includes the axial injection point for both the fuel and oxidizer. Detailed description of the input, including range and units, are included in the description of the IFE (Section 4) and Appendix C. It should be noted that variables in namelists \$BURN, \$INJ (except for manifold geometry variables), and some variables in \$FDORC and \$CHAMBER are calculated by SSCI and should not be input unless SSCI is not being run (all are Path Level 2-4, see IFE description in Section 4.0 for further details).

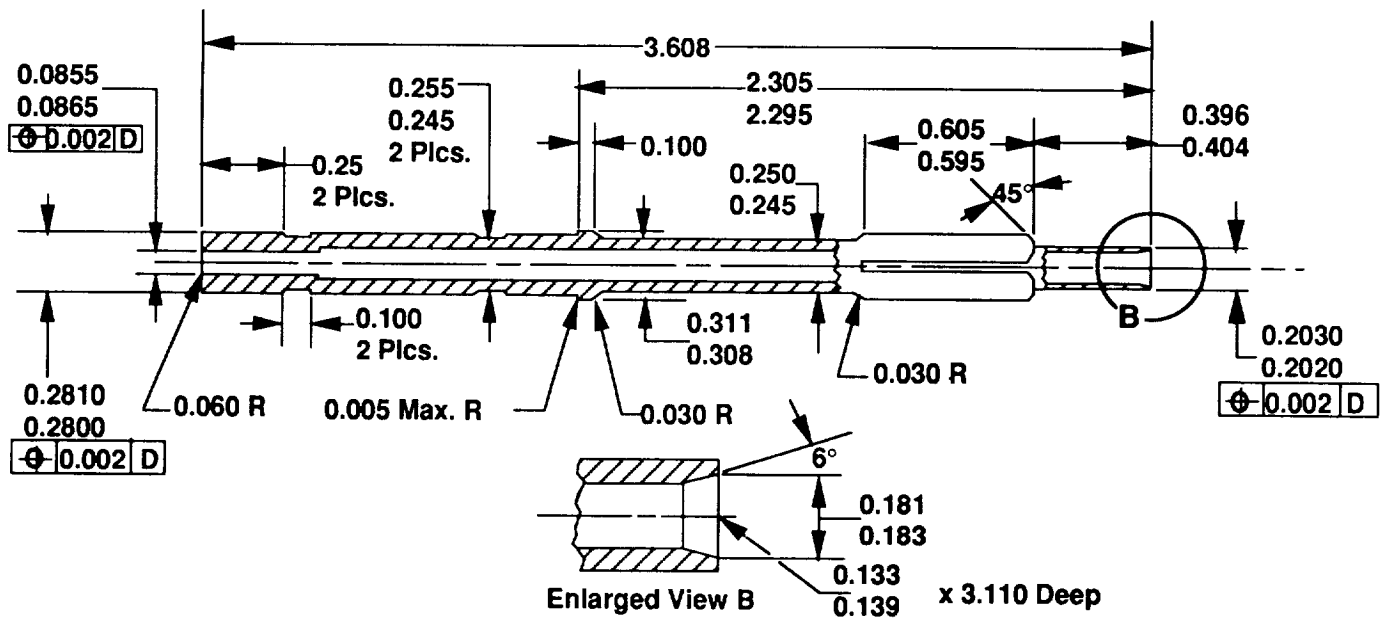
Using the specified propellant combination and the input chamber geometry, ROCCID uses the module ODE to calculate tables of theoretical characteristic velocity (C^*) and specific impulse (ISP) versus mixture ratio. The ISP values are calculated at the engine exit area ratio.

An overall Rupe mixing efficiency (E_m) is currently a required input for the core and barrier (if present) zones. More details about the usage and determination of E_m is covered in the SSCI subsection (Section 2.2).

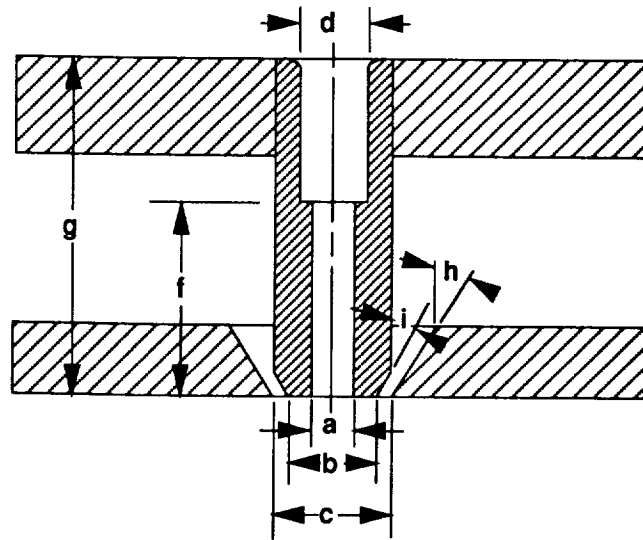
2.1, POINTA Input (cont.)

The shear coaxial flow and atomization model contained in ROCCID was originally developed for the Space Shuttle Main Engine (SSME) element (Ref. 7). As a result, the geometry description was geared towards 1970-1980's style shear coaxial element designs, i.e. a contoured inlet metering section feeding a pressure diffusion section, where the metering section diameter is smaller than the diffuser section diameter. This configuration typically has a diffuser section several times longer than the metering section, thereby permitting the flow to reattach to the element wall. The metering and diffuser section lengths must be finite (non-zero), as noted in Appendix C. This can be awkward to adapt to many of the designs evaluated during the 1960's (Ref. 20). Figure 2.2 contains sketches of a) the 1988 Rocketdyne LOX/CH₄ shear coax element (Ref. 21), b) the 1968 NASA/LeRC LOX/H₂ element (Ref. 20) and c) the ROCCID input geometry assistance graphic. Description of the Rocketdyne element is fairly straight forward, with DMS=0.086, DDIF=0.136, XDJ=0.182, XMS~0.45 and XDL~3.158. The model assumes that the flow in the divergent portion of the tip has the same Cd as the end of the diffuser section, i.e., the influence of divergence angle on flow separation is not accounted for. The best way to adapt the NASA/LeRC element to this configuration would require the user to calculate a vena contracta resulting from the sudden contraction, and the associated equivalent orifice diameter (See Ref. 6). The equivalent orifice diameter should be used for the metering orifice diameter (DMS), while the metering section length (XMS) should be calculated so the metering section volume is the same as the counterbore section (dimension d). This would result in a slight overprediction in the oxidizer injection pressure, but the element inertance calculations would be correct. The description of the remainder of the element geometry is straight forward, DDIF=dimension a and XDL=dimension f. It should be noted that the atomization models can not account for the effect of the non-zero fuel injection angle (relative to the element centerline).

If the user is using the NASA/LeRC injection response model (LEINJ) for the injector type that has a tube area upstream of the orifice, he should modify the element's oxidizer diameter and length descriptors in namelist \$INJ after running steady-state performance predictions and prior to running stability predictions (See Appendices C and J for more details on LEINJ input). To modify these values without losing all other values calculated by the steady-state performance the code requires that the user terminate the session after running steady-state performance and resume the session after re-entering ROCCID. The input can be modified by using the "set variables" option in the menu, setting variable path level to 3, and selecting the "set manifold descripton" option.

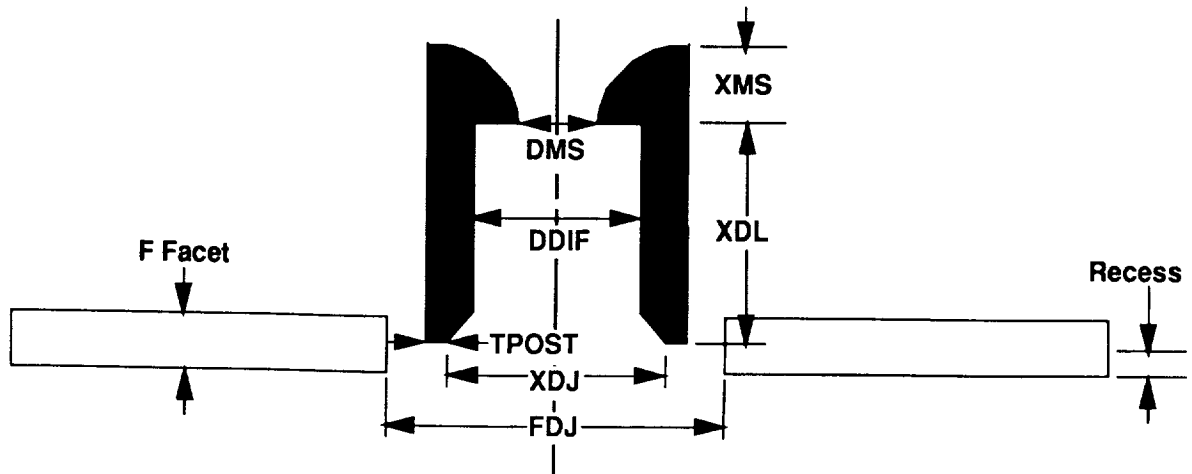


a) Rocketdyne LOX/CH₄ Element Design



General Element

b) Mid 1960's NASA/LeRC Element Design



c) ROCCID Input Assistance Schematic

3.50.0.8

Figure 2.2. Shear Coaxial Element Description

2.0, Point Analysis Description (cont.)

2.2 STEADY STATE COMBUSTION ITERATION (SSCI)

The SSCI module is actually an executive routine that calls the steady state combustion and performance model, COMBUST. Each steady state combustion iteration is comprised of three calls to COMBUST, one at the nominal P_c and two reduced chamber pressures, in order to create tables of engine operating parameters versus chamber pressure that are required inputs to the stability analysis models. COMBUST is the heart of ROCCID, in that it defines engine operating conditions, e.g. flowrates, injection pressure drops, etc., as well as calculating many of the parameters required as input to the individual stability models. COMBUST receives chamber pressure and mixture ratio as input from SSCI and iterates to a converged solution for flowrate, injection pressure drop, delivered characteristic velocity (C^*) and throat stagnation pressure. Propellant injection velocities, atomization characteristics, vaporization profiles and the resultant C^* and ISP-based energy release (ERE) efficiencies are also determined by COMBUST. Figure 2.3 depicts the iteration and closure procedure in COMBUST. The individual submodels and their interaction are discussed in the following paragraphs.

ROCCID is capable of modelling thrust chambers that use oxygen as the oxidizer and propane, hydrogen, methane or RP-1 as the fuel. Propellant properties, i.e. density, viscosity and surface tension, are determined from the input temperature and the calculated manifold pressures. These properties are calculated with routines taken from the NBS program MIPROPS (Ref. 5) for oxygen, hydrogen, propane and methane, and from curve fits of data for RP-1. Propellant properties not in MIPROPS should be incorporated in ROCCID using curve fit techniques similar to those used for RP-1. All propellants may be injected as either a liquid or a gas, except for RP-1 which is only allowed to exist as a liquid. The propellant state is determined from the propellant manifold temperature and the propellants critical temperature, and the relationship of the manifold pressure to the critical pressure is not considered. If the manifold temperature is below the critical temperature, the propellant is considered to be a liquid, while propellants with manifold temperatures above the critical temperature are treated as gases. It should be noted that ROCCID may not properly handle propellant which is injected at conditions corresponding to either a 2-phase condition (under the saturation dome) or a low pressure gas ($T_j < T_{critical}$). In the case of gaseous propellant injection, propellant injection conditions are calculated using real propellant properties from MIPROPS, i.e. density, enthalpy and entropy, and the conservation equations for mass and energy (see discussion of injection velocity calculation below).

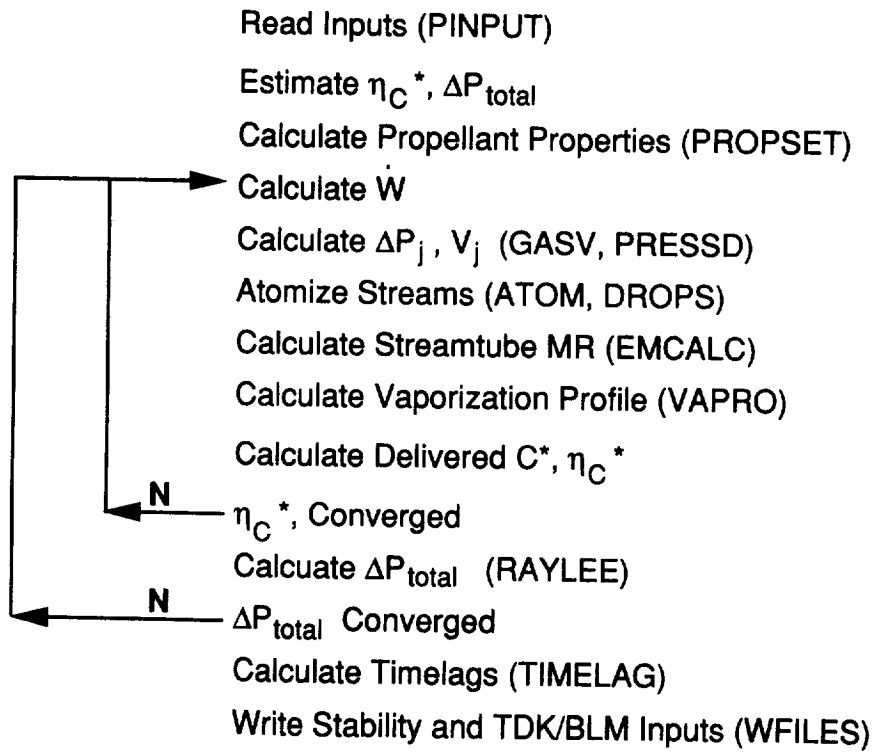


Figure 2.3. Point Analysis Performance Schematic

2.2, Steady State Combustion Iteration (SSCI) (cont.)

The propellant injection velocity and pressure drop are based on total flowrate requirements and input total element flow area. The propellant flowrates are determined by the C^* of the operating condition and the delivered efficiency, while the flow area is input in the form of number of elements, injection orifice diameter and orifice discharge coefficient (C_d). Since mixed element patterns are permitted and common manifolding is assumed, the manifold pressure must be solved iteratively to satisfy the specified propellant flowrate. Two routines have been written to control this iteration, PRESSD for liquid propellant injection and GASV for gaseous propellant injection.

The injection velocity (V_j) of liquid propellants with impinging type elements, i.e. like doublet, triplet or showerhead, is related to injection pressure drop using Bernoulli's equation, assuming inviscid flow:

$$V_j = 96.2606\sqrt{\Delta P_j/\rho} \quad (2.1)$$

where ρ is the propellant density, in lbm/ft^3 , ΔP_j is the injection pressure drop, in psid , and V_j is in ft/s . The injection velocity and pressure drop for the center oxidizer post of the shear coaxial element is calculated by considering the geometry of the oxidizer post, i.e. metering, diffuser and final tip divergence sections, and by evaluating the discharge coefficient (C_d), pressure drop and resultant 2-D velocities within these sections (Refs. 6,7). The injection velocity for the center oxidizer post of swirl coaxial elements related to the pressure drop and post geometry using the methodology of Doumas and Laster (Ref. 8).

In the case of gaseous propellants, the calculation of V_j requires iteration on the manifold pressure, since only the chamber pressure and manifold temperatures are known. Even though real gas properties are used, it is assumed that the injection process is isentropic and can be characterized with the following equations:

$$H_o = H_j + 0.5 V_j^2 \quad (2.2)$$

$$W_j = \rho_j V_j C_d A_{\text{tot}} \quad (2.3)$$

where the subscripts "o" and "j" refer to the manifold stagnation and injection condition, respectively, H is the enthalpy at the reference temperature and pressure, W_j is the total injected

2.2, Steady State Combustion Iteration (SSCI) (cont.)

flowrate, in lbm/s, and A_{tot} is the total flow area, in ft². It should be noted that the C_d is only used to reduce the flow area.

COMBUST accesses propellant atomization models for like doublets (LOL), unlike triplets (OFO and FOF), showerhead (SHD), shear coaxial (SHC) and hollow cone hydraulic swirl coaxial (SWC) elements. The coaxial elements are limited to gaseous fuel, no fuel swirl, and liquid oxidizer, with the oxidizer in the center tube. The user can choose from several models for propellant atomization, including the Aerojet analytical atomization models for LOL, OFO, FOF, SHD, SHC, and SWC elements, the Priem dropsize correlation for LOL, triplet and showerhead elements, the Dropmix LOL, triplet and shear coaxial correlations and the UTRC swirl coaxial element correlation (Refs. 1, 7, 9, 10, and 12). These models account for the influence of injection velocity, orifice diameter and propellant properties. It is strongly recommended that the user consults the appropriate references to determine the validity of the drop size results selected. The user can use the values generated by any of these correlations, or they can input a value they feel to be more appropriate. In all cases, the atomization length is calculated using the Aerojet analytical models.

Propellant vaporization is determined using the Generalized Length correlation developed by Priem and Heidmann (Ref. 1), with droplet vaporization beginning at the end of the atomization length. This correlation accounts for the effects of propellant properties, injection velocity and temperature, and chamber geometry. This correlation does not contain a relationship between the chamber pressure to the critical pressure, so droplets can exist above the propellant critical pressure without encountering numerical difficulties.

Propellant mixing efficiency is calculated using a two zone, four streamtube model. The mixing model scheme considers the core and baffle element flows to be mixed and constrained in the core zone, while the barrier and fuel film/cavity cooling (FFC) element flows are mixed to comprise the barrier zone. Currently, there is no interaction between the core and barrier zones. Each of the zones is divided into two streamtubes of mixture ratio above (MR_L) and below (MR_R) the zone's mean vapor mixture ratio (MR_M). The mixture ratio and mass fraction of the streamtubes are determined by the local vapor mixture ratio and the value of the overall Rupe mixing efficiency (E_m) of the zone using the methodology developed by Ito and Calhoon (Ref. 11):

2.2, Steady State Combustion Iteration (SSCI) (cont.)

$$MR_R = MR_M * \eta_m \quad X_R = \frac{1 + MR_R}{(1 + \eta_m) * (1 + MR_M)} \quad (2.4a)$$

$$MR_L = MR_M / \eta_m \quad X_L = 1.0 - X_R \quad (2.4b)$$

where X_L and X_R are the streamtube mass fractions for the above and below mean mixture ratio streamtubes, respectively, and η_m is related to the overall Rupe mixing efficiency E_m as follows:

$$\eta_m = 0.449 - 0.399 E_m + 0.944 E_m^2 \quad (2.5)$$

The overall zone E_m can be determined several ways - based on correlated hotfire test results of similar hardware, calculated with the Liquid Impinging Spray Program, LISP (Ref. 12), or using the simplified empirical technique developed by Nurick (Ref. 9). Nurick's correlation relates the unielement E_{mi} to the overall E_m by considering the pattern's element density, thereby permitting the zone's overall E_m to be determined from correlations of unielement coldflow data:

$$E_m = 61.5 + 0.385 * E_{mi} + (0.15 * E_{mi} - 14.99) * \ln(A_{pel}) \quad (2.6)$$

with A_{pel} being the injector face area per element, in square inches.

The vapor mixture ratio of the streamtubes at the chamber throat is used to determine the streamtube's C^* and ISP, which are used in turn to determine the delivered C^* (C^*_{Del}), C^* efficiency (η_{C^*}) and ISP-based energy release efficiency (ERE) by mass weighting the individual streamtube contributions and correcting for any mass defect resulting from incomplete vaporization:

The vaporization efficiency is calculated as:

$$\eta_{vap} = \frac{\dot{W}_{vapor}}{\dot{W}_{inj.}} \quad (2.7)$$

and the C^* and Isp based energy release efficiencies are calculated as follow:

$$C^*_{Del} = \eta_{vap} \{ \xi_C [X_{RC} C^* (MR_{RC}) + X_{LC} C^* (MR_{LC})] + \xi_B [X_{RB} C^* (MR_{RB}) + X_{LB} C^* (MR_{LB})] \} \quad (2.8)$$

2.2, Steady State Combustion Iteration (SSCI) (cont.)

$$\eta_{C^*} = \frac{C^*_{Del}}{C^*_{(MR_{injected})}} \quad (2.9)$$

$$ISP_{M.Z.} = \eta_{vap} \{ \xi_C [X_{RC} ISP(MR_{RC}) + X_{LC} ISP(MR_{LC})] + \xi_B [X_{RB} ISP(MR_{RB}) + X_{LB} ISP(MR_{LB})] \} \quad (2.10)$$

$$\eta_{ERE_{ISP}} = \frac{ISP_{M.Z.}}{ISP(MR_{injected})} \quad (2.11)$$

where ξ_C and ξ_B are the mass flow rate fraction in the core and barrier zones, respectively; the subscripts "C" and "B" refer to the core and barrier zones, respectively, $C^*(x)$ and $ISP(x)$ implies the C^* or ISP at mixture ratio "x", and "M.Z." denotes the mass-weighted multi-zone value.

COMBUST iterates to converge injected propellant flowrate, delivered C^* and C^* efficiency, while holding injected mixture ratio and injector face stagnation pressure constant. The iteration process is deemed converged when the calculated values of both the throat vaporized mixture ratio and the C^* efficiency stop changing.

During the first pass, several correlations are used to estimate total pressure loss, and therefore throat stagnation pressure. Once the C^* - C^* efficiency-flowrate iteration has converged, the resulting axial mass addition profile, total temperature profile (based on the local overall vapor mixture ratio), and chamber contour are passed to the 1-D Shapiro influence coefficient model, RAYLEE, to determine the total pressure loss resulting from simultaneous heat and mass addition and area change. This calculation integrates Shapiro's influence coefficients, as described in Reference 13, and outputs the axial static pressure profile, which is useful in code verification. The calculated total pressure loss is compared to the value used by COMBUST during the last delivered C^* - C^* efficiency-flowrate iteration. If the newly calculated and old values of total pressure loss, and therefore the throat total pressure, do not match, it is modified and the C^* - C^* efficiency-flowrate iteration is repeated until total pressure loss has converged.

After steady state performance calculation is completed, COMBUST calculates parameters that will be used as input to stability models, such as timelags, injector resistance and inertance, manifold capacitance and mean chamber gas properties. Mean chamber gas properties are based on the axial vaporization profile in the cylindrical portion of the combustor. SSCI also estimates the gas properties that would exist in an acoustic cavity, regardless of whether the

2.2, Steady State Combustion Iteration (SSCI) (cont.)

current design actually has cavities. Calculation of these properties requires the determination of the near-face recirculation zone, which is assumed to end when the 1-D gas velocity equals the mass-weighted propellant injection velocity. The cavity gas properties are calculated at the mean vapor mixture ratio of the fuel-rich streamtube of the outer zone, e.g barrier zone if it exists, or core if not, over the recirculation zone length. The user is permitted to override these values. Timelag components, i.e. injection, atomization and vaporization, are calculated for both propellant circuits for each element type, and an effective mass-weighted value is also generated for both propellant circuits. Timelags are defined in the conventional manner:

$$\tau_c = L_{\text{process}} / V_j \quad (2.12)$$

where τ_c is the timelag, in sec., L_{process} is the characteristic process length, in ft., and V_j is in ft/s. A TDK input file, containing model control, streamtube definition, combustor geometry and kinetic rate cards, is also generated for the nominal operating pressure.

2.3 LOW FREQUENCY COMBUSTION STABILITY (LFCS)

The low frequency combustion stability module determines the marginally stable chamber pressure (P_c), i.e. the pressure at which the combustor operation transitions from low frequency, or chug, stable to unstable. This analysis is performed by throttling the combustor at a constant operating mixture ratio until the maximum in-phase system gain is 1.0. This analysis assumes that the changes in the combustor's operating characteristics with changing chamber pressure can be adequately characterized by curve-fitting the throttled operating data generated by SSCI (See Section 2.2). LFCS calculates the chamber and injection responses (admittances), $1/Z_c$ and Y_j , over a range of frequencies at each chamber pressure, and then determines the frequency and magnitude that the overall system gain, $Z_c * Y_j$, is a maximum. It should be noted that LFCS ignores the contribution of oscillatory intrinsic burning, Y_b , and the effect of any damping devices that might be contained in the design. If the gain magnitude is greater than 1.0, the system is chug unstable, and the operating pressure is throttled up, while gain magnitudes less than 1.0 indicate chug stable operation, so P_c is throttled down. The iteration process contained in LFCS, discussed in the following paragraphs, is depicted in Figure 2.4.

LFCS uses HIFI (Ref. 23) to evaluate the chamber response, while the injection response can be analyzed using either a lumped parameter, INJ (see Appendix J), or a non-linear

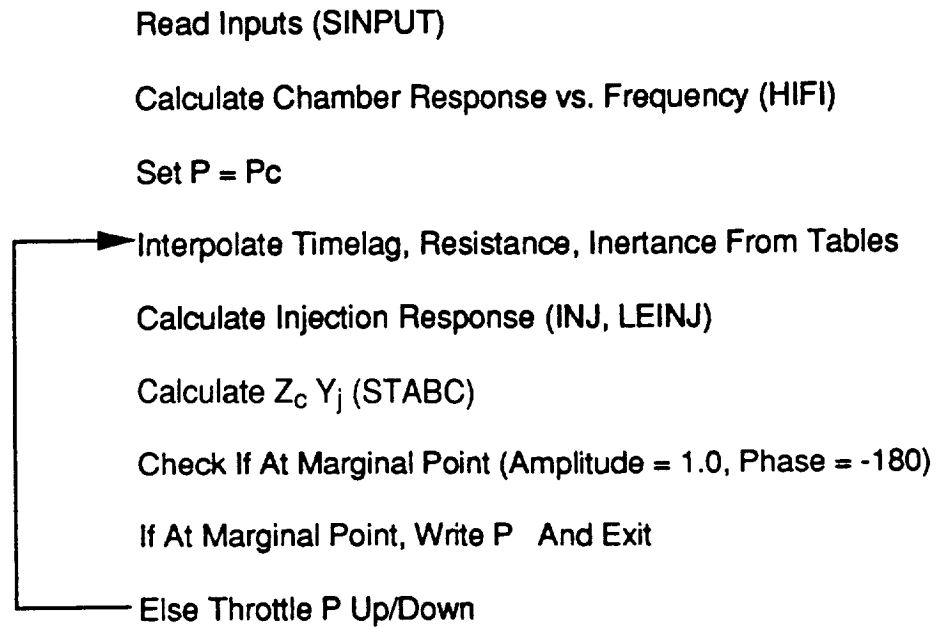


Figure 2.4. Low Frequency Stability Analysis Schematic

2.3, Low Frequency Combustion Stability (LFCS) (cont.)

injection element acoustics, LEINJ (Ref. 27), model (further details on the derivation and assumption of the component models are contained in Appendix J). However, it is recommended that the low frequency chug stability evaluations use the INJ model rather than LEINJ.

HIFI is used to evaluate the chamber response as a function of frequency between 1 hz and the frequency of the first longitudinal (1L) resonance mode. Between these frequencies, the chamber response magnitude reaches a maximum, and the corresponding frequency serves as the highest frequency analyzed for potential chug instability by LFCS (corresponding to 0L), as well as the lowest frequency used by HFCS for acoustic longitudinal mode analysis (See Section 2.4 for more details about HFCS). While an acoustic model, like HIFI, requires more computer time to calculate the chamber response than the typical lumped-parameter chamber model (Ref. 14), the formulation contained in the lumped-parameter chamber response is not compatible with either of the injector response models, INJ or LEINJ. HIFI is run only at the nominal chamber pressure, since the chamber response is not a function of P_c . The additional computer time required by the acoustic model is not significant. LFCS calculates the injector response at the nominal chamber pressure at the same frequencies HIFI used, with the user-selected injection response model. The routine STABC is used to form the gain function, $Z_c*(Y_b+Y_j)$, and to determine the maximum magnitude, and corresponding frequency, where the gain function satisfies the phase angle requirement, i.e. passing between 180 and -180 degrees. LFCS prints the chamber pressure, the maximum gain magnitude and the associated frequency, then it adjusts the chamber pressure. If the maximum magnitude is greater than 1.0, the chamber pressure is throttled up, and conversely the chamber pressure is throttled down if the gain magnitude is less than 1.0. The injection response is calculated at the new P_c , and then the gain function is again evaluated. This procedure is continued until a gain magnitude of 1.0 is achieved, that is the marginal chamber pressure and the associated frequency are found.

2.4 HIGH FREQUENCY COMBUSTION STABILITY (HFCS)

The high frequency combustion stability module determines the frequency, exponential growth coefficient (AL or lambda) and dominant coupling mechanism for each of the applicable high frequency acoustic modes of the combustor. It should be noted that a negative growth coefficient implies that oscillations will decay. The user can select from several models for each of the system component responses - chamber, burning and injection.

Three acoustic chamber response models are available, HIFI (Ref. 23), DIST3D (Ref. 24), and FDORC (Ref. 25). HIFI assumes concentrated combustion at an axial plane and can

2.4, High Frequency Combustion Stability (HFCS) (cont.)

account for the effects of acoustic resonators. DIST3D considers the effect of radial thrust chamber baffles and the influence of linearly distributed combustion. DIST3D can also evaluate the secondary influence of acoustic resonators. FDORC can account for the effects of the distributed combustion and acoustic resonators including quarterwave cavities, Helmholtz resonators, and unconventional geometry cavities on the chamber response.

The intrinsic burning response (Y_b) can be modelled using either the analytical vaporization response model CRP (Ref. 26) or by converting empirical N and τ data into a frequency domain burning response:

$$Y_b = N*(1 - e^{-s\tau}) \quad (2.13)$$

$$S = \lambda + 2\pi fi \quad (2.14)$$

where τ is the sensitive time lag, in seconds, λ is the exponential growth coefficient, in 1/sec, f is oscillation frequency, in hz, and i is the square root of -1 (Ref. 4). N can be determined using either the historical correlations of Reardon and Smith (Ref. 15) or with empirical values determined by the user. τ can be determined using either of these techniques, or by using the Aerojet empirical method of equating τ to the timelag for 20% vaporization of the sensitive (least volatile) propellant. N and τ are determined from the amplitude and frequency of the peak burning response if CRP is used to evaluate the burning response, since N and τ are used in several other places within ROCCID:

$$N = Y_{b_{max}}/2.0 \quad (2.15)$$

$$\tau = 1/(2.0 * f(Y_{b_{max}})) \quad (2.16)$$

where $Y_{b_{max}}$ is the maximum burning response, and $f(Y_{b_{max}})$ is the frequency at which the maximum response occurs, in hz.

The injection response can be analyzed using either a lumped parameter, INJ, or a non-linear injection element acoustics, LEINJ, models. Further details on the derivation and assumption of the component stability models are contained in Appendix K.

2.4, High Frequency Combustion Stability (HFCS) (cont.)

The high frequency stability analysis begins by determining the burning response as a function of frequency for the desired frequency range. Since the burning response is not a function of stability mode, except if CRP is run in the non-linear mode, Y_b need be calculated only once. The frequency range is bounded by either the peak frequency below the 1L (See Section 2.3) or 67% of the 1T frequency, whichever is lower, on the low end and the frequency corresponding to the initial estimate of sensitive timelag at the high end:

$$f_{\max} = 1/\tau \quad (2.17)$$

The analysis continues as HFCS steps through all the applicable high frequency modes to determine the combustor stability characteristics. The first mode evaluated is the pure longitudinal modes (L), followed by 1T, 2T, 1R, 3T, 4T, 1T+1R, etc., in increasing fundamental mode frequency. HFCS centers the frequency range used to evaluate a mode about the calculated fundamental frequency, f_{res} in Hz:

$$f_{\text{res}} = \frac{S_{vn} * a_0}{\pi D_c} \quad (2.18)$$

where S_{vn} is the eigenvalue of the v th tangential and n th radial mode (see HIFI documentation in Appendix K), a_0 is the mean chamber sonic velocity, in ft/s, and D_c is the chamber diameter in ft. HFCS evaluates the injection and chamber response over this frequency range, using a neutral exponential growth coefficient ($\lambda = 0$). HFCS checks that a minimum in the chamber response has been found. While more than one minimum may exist, corresponding to mixed longitudinal and transversed mode, e.g. 1T+1L is the mixed first longitudinal and first tangential mode, if no minimums are found, HFCS shifts the frequency range examined to a lower frequency in an effort to find a minimum. It should be noted that there is currently no mechanism by which to limit the number of longitudinal harmonics that HFCS considers for a given mode. If a minimum exists, HFCS calls STABC to evaluate the system response, $Z_c^*(Y_b+Y_j)$, and determine the frequency where the system gain is the greatest with the phase relationship satisfied, i.e. phase angle changes between 180 and -180. STABC also determines the relative magnitudes of Y_b and Y_j at the highest response frequency, thereby indicating whether stability is dominated by injection or burning-coupling mechanisms. The user should be aware that the frequency at which the maximum system response occurs is not necessarily the resonant frequency of the chamber, although it is usually very close to a chamber resonance. Additionally, the minimum

2.4, High Frequency Combustion Stability (HFCS) (cont.)

system response may occur at a longitudinal harmonic of the pure mode, especially if damping devices have been included in the design, since these usually shift the fundamental mode to a lower frequency with a higher minimum response magnitude.

Once HFCS has determined the maximum system gain for a given mode, it will iterate on the exponential growth coefficient in the chamber response model to determine the stability margin for the mode. The system is considered to be neutrally stable if the maximum system gain is 1.0. If the gain is less than 1.0, HFCS will decrease the growth coefficient in the chamber model (more negative) in an effort to reduce the chamber's dissipative characteristics, while a gain greater than 1.0 will cause HFCS to increase the growth coefficient. At this point, the user should be reminded that the chamber response models determine the level of combustion driving, i.e. $(Y_b + Y_j)$, required to sustain an oscillation of a specified mode, frequency and growth coefficient. Therefore, a negative growth coefficient indicates that a lower level of combustion driving is required to sustain the specified oscillation than would be required for a zero growth coefficient. The growth coefficient iteration determines the growth coefficient value at which the driving required by the chamber to sustain the waveform exactly equals the driving response present within the system. The resultant growth coefficient can be related to the damp time requirements for dynamic stability, as prescribed by CPIA 247 (Ref. 17):

$$t_{\text{CPIA}} = \frac{1.250}{\sqrt{f}} \quad (2.19)$$

$$\lambda = \frac{\ln(0.1)}{t_{\text{CPIA}}} \quad (2.20)$$

where f is the frequency of the oscillation, in hz, t is the required damp time, in sec., and the growth coefficient, λ , is in 1/sec.

HFCS will calculate the frequency, growth coefficient and ratio of driving component amplitudes for all modes with a nominally calculated resonant frequency (Eq. 2.18) below 85% of the f_{max} (Eq. 2.17). Currently there is no mechanism by which to extend or limit the number of resonant modes that HFCS examines. A schematic of the iteration process in HFCS is contained in Figure 2.5.

Read Inputs (SINPUT,
Calculate Combustion Response (CRP, NTAU)
Determine Frequency Of Maximum Response
Determine Maximum Mode Of Concern
DO I = 1, Max Mode

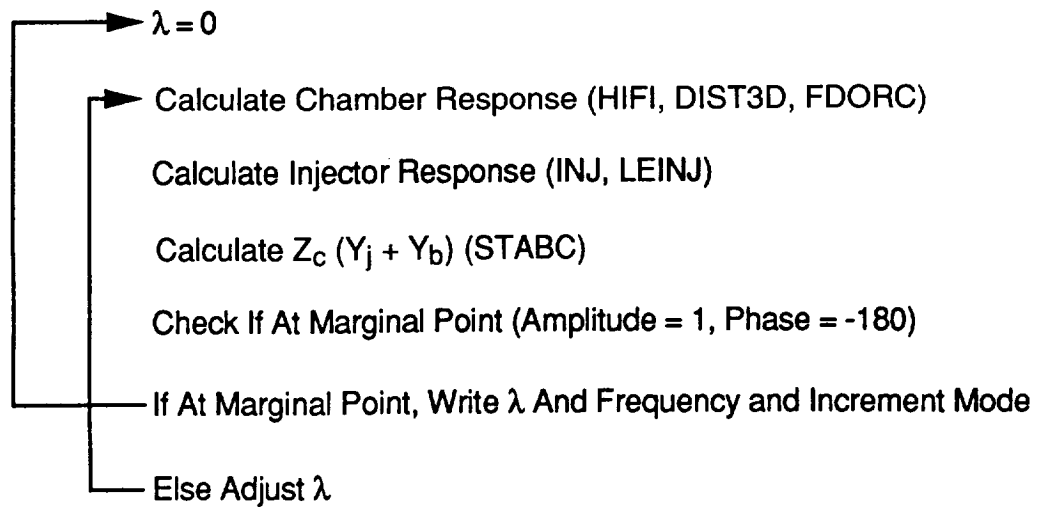


Figure 2.5. High Frequency Stability Analysis Schematic

2.0, Point Analysis Description (cont.)

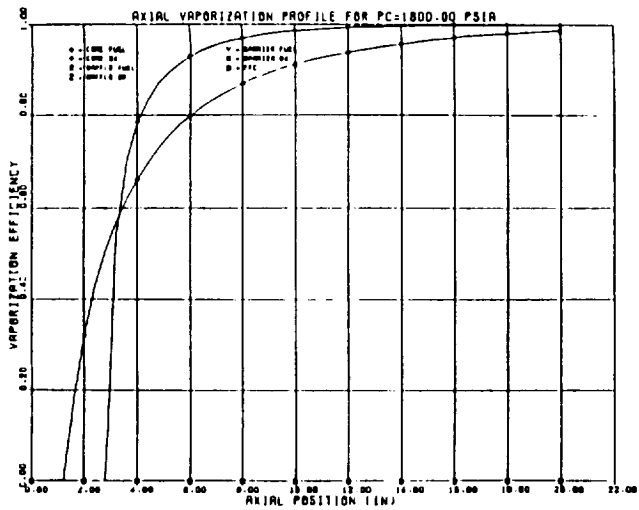
2.5 PLOT DESCRIPTION

The analysis modules contained in ROCCID generate formatted ASCII plot files that can be displayed interactively on Tektronix terminals (See Section 4.0 for more information), or read by third-party plotting software with minor modification. SSCI produces 2 plot series (Fig. 2.6) for each of the 3 chamber pressures analyzed, LFCS produces 1 plot series (Fig. 2.7), and HFCS produces 1 plot series (Fig. 2.8) for each high frequency mode evaluated. If an analysis module is executed more than once, such as during a design iteration, only the data from the most recent run will be contained in the plot file.

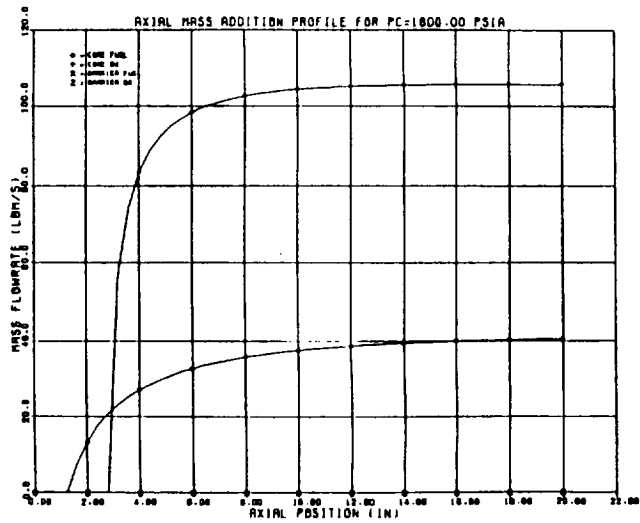
SSCI generates two plot series at each chamber pressure. The first series is a single plot of the axial vaporization profile for the fuel and oxidizer for each of the element types, i.e. core, baffle, barrier and ffc. The second series contains three plots. The first plot is the axial fuel and oxidizer mass addition profiles for the core and barrier zones. The two plots that follow are axial profiles of the overall vapor mixture ratio and the delivered C^* efficiency. The overall vapor mixture ratio is calculated by dividing the total oxidizer vapor mass flowrate (core plus barrier zone) by the total fuel vapor flowrate. The axial C^* efficiency is calculated using the methodology presented in Section 2.2, but the streamtube mean vapor mixture ratios are defined by the oxidizer and fuel vapor flowrates within the zone at the specific axial position.

The plot series generated by LFCS contains 4 individual plots. The first two plots display magnitude and phase angle versus frequency for the chamber ($1/Z_c$) and injection Y_j responses, and they are followed by plots of the overall gain function, $Z_c * Y_j$, magnitude and phase angle versus frequency. These plots apply to the nominal chamber pressure only.

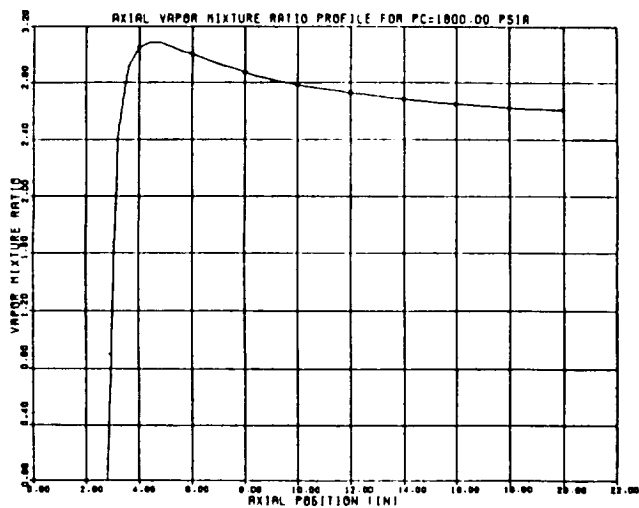
HFCS generates a series of plots for each high frequency mode evaluated. Each of these series contains 4 plots, the first two display the magnitude and phase angle versus frequency of the chamber ($1/Z_c$), burning (Y_b), injection (Y_j) and overall driving ($Y_b + Y_j$) responses, followed by plots of the overall gain function, $Z_c * (Y_b + Y_j)$, magnitude and phase angle versus frequency. These plots apply to the case where the exponential growth coefficient, λ , is zero.



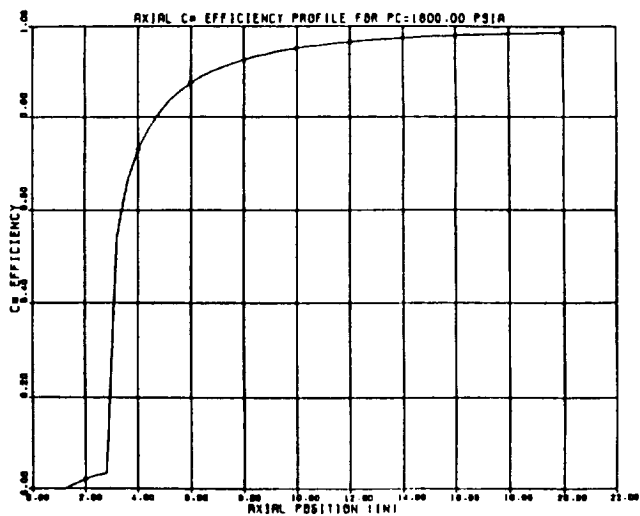
a) Axial Vaporization Profile



b) Mass Addition Profile

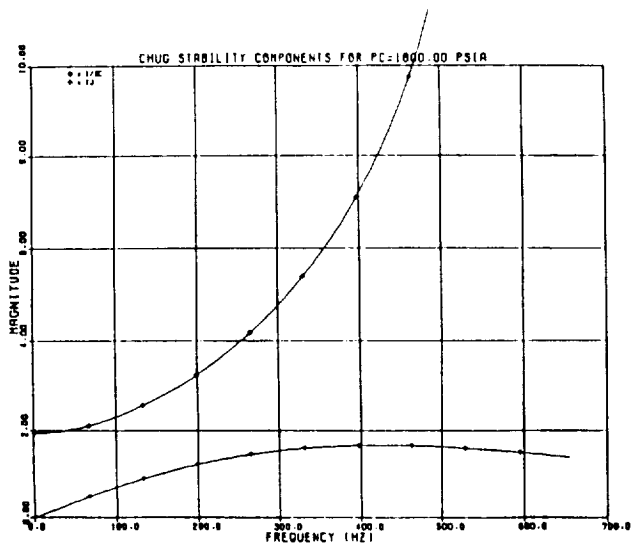


c) Vapor MR Profile

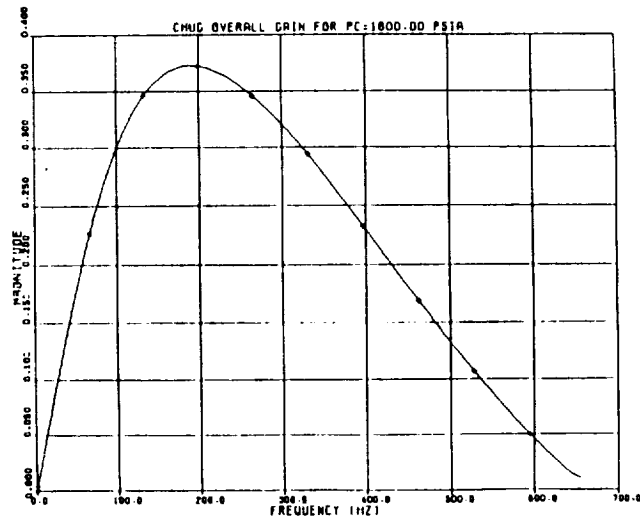


d) C* Efficiency Profile

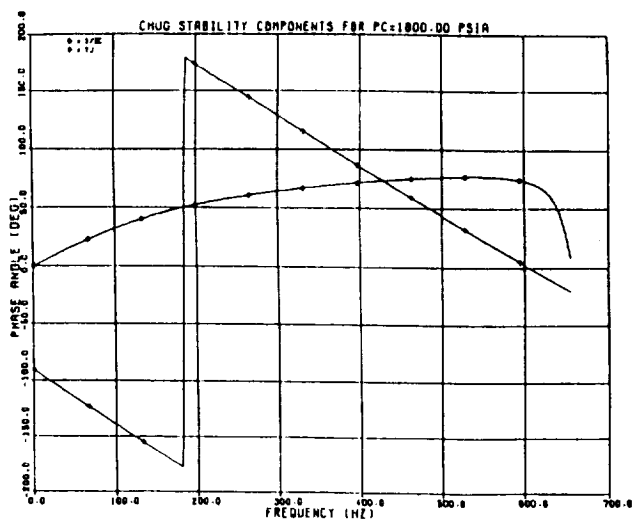
Figure 2.6. Typical SSCI Plots



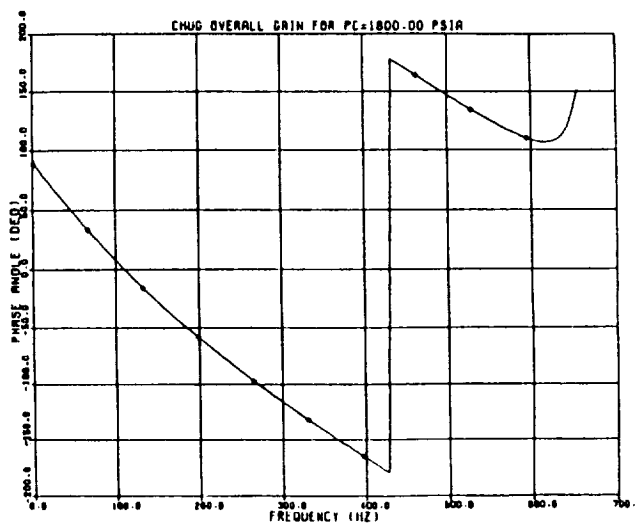
a) Component Transfer Function Magnitude



c) Overall Gain Magnitude



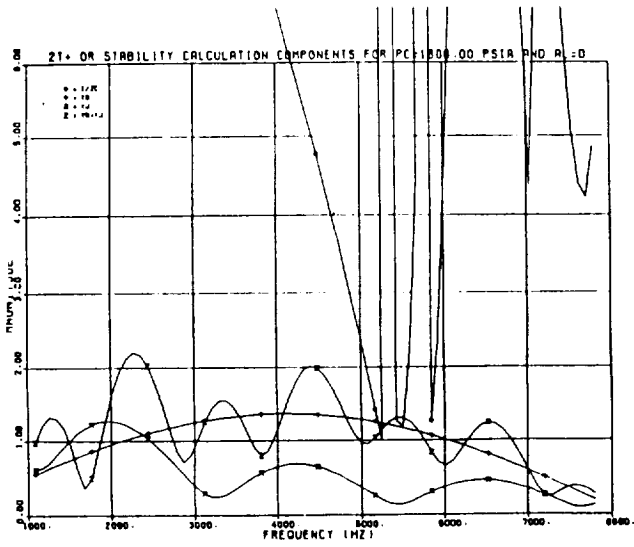
b) Component Transfer Function Phase Angle



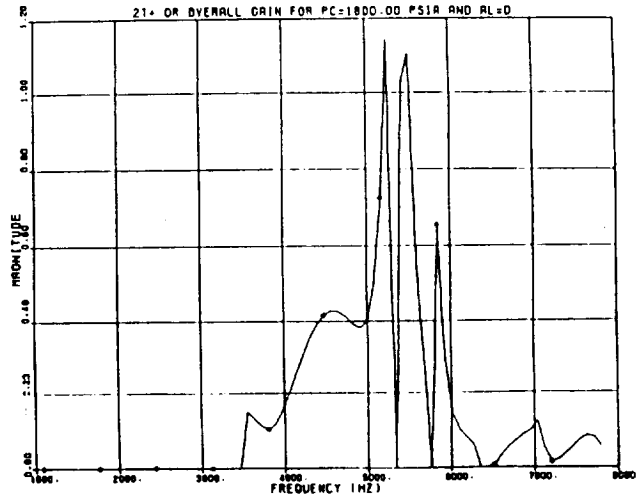
d) Overall Phase Angle

Figure 2.7. Typical LFCS Plots

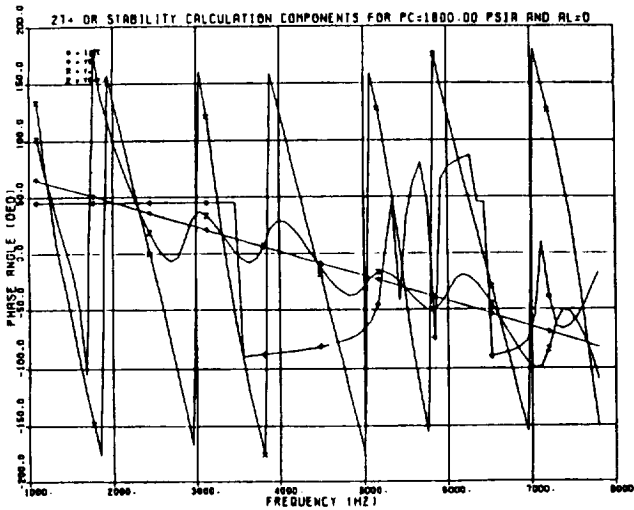
ORIGINAL PART IS
OF POOR QUALITY



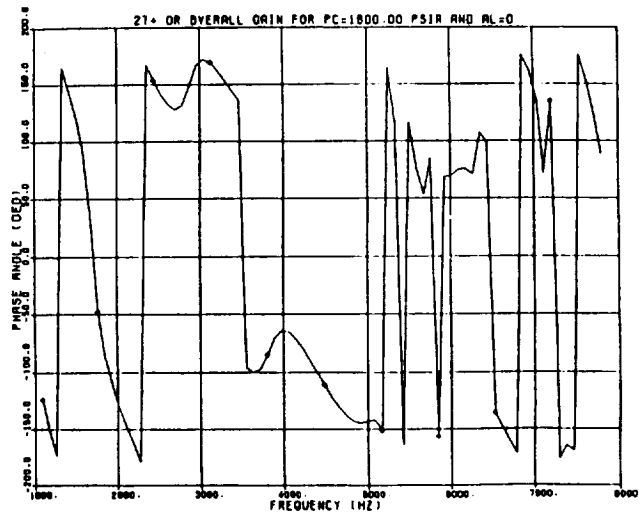
a) Component Transfer Function Magnitude



c) Overall Gain Magnitude



b) Component Transfer Function Phase Angle



d) Overall Gain Phase Angle

Figure 2.8. Typical HFCS Plots

3.0 POINT DESIGN

The point design portion of ROCCID (POINTD) aids the user in the creation of a combustor design that provides high frequency stable combustion and satisfies minimum performance and chug stability requirements. POINTD utilizes the analysis models contained in POINTA to evaluate the current performance and stability characteristics of a design, and then recommends design changes to the user that will remedy performance and stability shortfalls. POINTD contains two modules for the creation of designs (PRELIMD and REDESIGN) and three modules to control the steady-state combustion and performance (PERFIT), low frequency stability (CHUGIT) and high frequency stability (HIFIT) design iterations. A complete flowchart of POINTD is contained in Appendix F.

The preliminary design module develops a first estimate of the combustion chamber and injector configuration that will satisfy the user's performance and stability operating constraints. The output of PRELIMD includes the input files that are utilized by the analysis modules. The steady state combustion and performance design iteration module accesses SSCI to evaluate the combustor operation and performance characteristics of the design, and it helps the user refine the design in order to meet the input performance and flowrate goals.

The following subsections describes required POINTD inputs, the layout of the modules and connection of the individual submodels within the modules. Detailed description of the analysis modules accessed by the POINTD modules is contained in Section 2.0.

POINTD is currently capable of designing combustor chamber, damping devices such as baffles, conventional acoustic cavities and Helmholtz resonators, and injector core element pattern. If the user needs to incorporate baffle compatibility, barrier and/or film cooling elements, and unconventional cavities into the final design, the Point Analysis portion of ROCCID will have to be run iteratively, with the definition of these element types added to the POINTA input file by the user (See Section 2.0). POINTD is still useful for the development of core element designs, since the user need only input core element rather than combustor values for operating mixture ratio and total flowrate (See Sections 3.1 and 4.3 for more details).

3.1 POINTD INPUT

The input to POINTD consists of the propellant type and manifold temperatures, core injection element type, combustor operating variables, including nominal and throttled mass flowrate, injected oxidizer-to-fuel flowrate mixture ratio (MR) and either injector face stagnation

3.1, POINTD Input (cont.)

pressure (P_c) or maximum propellant manifold pressures, and performance and stability goals. The performance goal is specified as either a characteristic velocity efficiency or an ISP-based energy release efficiency. The user specification of the anticipated damping devices that will be required in a dynamically stable combustor are used to set the injector element's peak burning response frequency, that is the highest frequency that the burning should respond to:

<u>Anticipated Damping Devices</u>	<u>Highest Burning Response Frequency</u>
None	80% of 1T
Baffles only	80% of 1R
Cavities only	80% of 3T
Baffles and Cavities	3T

In all cases, POINTD will guide the user towards designs that are statistically high frequency stable, i.e. growth coefficients less than zero, and chug stable at the throttled P_c (which will be determined by the program from input flowrate).

POINTD design inputs also permit the user to input a maximum combustor diameter (injector-end) and a maximum engine length (combustor plus supersonic nozzle), thereby establishing a maximum envelope that is not to be violated (See Section 3.2 for more details). If the combustor length-supersonic nozzle length optimization is not performed, i.e. no data is input for nozzle efficiency versus nozzle length, then the maximum engine length is actually the maximum combustor length. POINTD is capable of evaluating the optimum split of engine length between the combustor and the supersonic nozzle. The user must input a table of nozzle efficiency versus nozzle length, where the nozzle efficiency includes all efficiencies associated with nozzle contour and/or expansion ratio. The optimum combustor length is defined as the length where the maximum overall efficiency (the product of combustion and nozzle efficiencies) is achieved (See Section 3.3 for more details).

The user may also constrain all or a portion of the chamber geometry, e.g. throat diameter, chamber length, etc., thereby facilitating injector design improvements for existing combustion chambers. POINTD also accesses design definition data, which is contained in the .DEF files (See Section 4.0 and Appendix E). Design definition data are values, typically nondimensional, which determine the physical characteristics of the injector and chamber,

3.1, POINTD Input (cont.)

e.g. nondimensional nozzle radii of curvature, orifice length to diameter ratios, etc. ROCCID contains built in default values that are based on historical experience, but the user may need to customize them for their application. Detailed description of the input, including range and units, are included in the description of the IFE (Section 4.0) and Appendix C.

ROCCID requires input tables of theoretical characteristic velocity (C^*) and specific Impulse (Isp) versus mixture ratio. The Isp values should be at the engine exit area ratio. The source of these values should be the One-Dimensional Kinetic (ODK) module of TDK (Ref. 3), or an equivalent basis. ROCCID neglects any change in these C^* and Isp values with chamber pressure as it throttles the combustor operating pressure, so the P_c basis should be selected judiciously (see Section 2.2). The tables are either input directly by the user or are calculated by ROCCID. In the latter case, the values are calculated using the ODE module.

3.2 PRELIMINARY DESIGN (PRELIMD)

The preliminary design module creates a combustor design that, to the first order, satisfies the user's performance and stability goals. The combustor design includes definition of the nominal and throttled operating pressure schedules, combustion chamber dimensions and core element size, number and layout. The preliminary sizing is accomplished using a combination of empirical correlation and analytical relationships. The following paragraphs describe the methodology and equations used in the preliminary design process.

Chamber Design:

PRELIMD begins by determining the combustor operating pressure schedule and combustion chamber geometry. If manifold pressures are prescribed, the chamber pressure is solved iteratively, otherwise the procedure is the same for either type of input (maximum manifold pressures or nominal chamber pressure). The injection pressure drop is assumed to be equal for both propellants, except if the element is a triplet, where input orifice diameter ratio (DODF in design definition inputs) defines the ratio of the fuel to oxidizer injection pressure drops. The contraction ratio (ϵ_c) is calculated using correlations developed by Hewitt (Ref 18):

$$\begin{array}{ll} \text{Liquid-Liquid:} & \epsilon_c = 4.8865 * F^{(-1/14)} \\ \text{Gas-Liquid:} & \epsilon_c = 3.0 \end{array} \quad (3.1)$$

3.2, Preliminary Design (PRELIMD) (cont.)

where F is the vacuum thrust, in Lbf, estimated from the input efficiency goal, nominal flowrate and an assumed overall nozzle efficiency of 95%. Once the contraction ratio has been determined, the total pressure loss, and therefore throat stagnation pressure, can be estimated. The throat stagnation pressure, P_{0t} in psia, efficiency goal, η and nominal flowrate, \dot{W} in lbf/s are used to determine the throat area:

$$A_t = \frac{\eta C^*(MR) \dot{W}}{P_{0t} g_c} \quad (3.2)$$

where A_t is in inches², $C^*(MR)$ is the characteristic velocity at the overall mixture ratio, in ft/s, and g_c is the gravitational constant. The injector-end chamber diameter and nozzle radii of curvature are calculated from the throat diameter, contraction ratio and input nondimensional radii of curvature. The combustion chamber length (L') is calculated from the correlations developed by Hewitt (Ref. 18):

$$\begin{aligned} \text{Liquid-Liquid:} \quad L' &= 7.0795 * (F/P_c)^{0.23} \\ \text{Gas-Liquid:} \quad L' &= 6.2675 * (F/P_c)^{0.23} \end{aligned} \quad (3.3)$$

where F is in Lbf, P_c is in psia, and L' is in inches. PRELIMD checks that neither the chamber diameter nor the combustor length exceed the user input maximums, and that the resulting chamber is self-consistent, e.g. the tangency points match, etc. If any of these problems exist, PRELIMD will present the user with options to remedy them.

The throttled chamber pressure and the nominal and throttled injection pressure drops are determined from the input flowrates and DPPCS. DPPCS is a POINTD design definition input, the ratio of injection pressure drop to chamber pressure at the throttled chamber pressure, and it is intended to define the minimum resistance needed for chug stable operation:

$$P_{cmin} = P_{cnom} * (\dot{W}_{min} / \dot{W}_{nom}) \quad (3.4)$$

$$\Delta P_{jmin} = P_{cmin} * DPPCS \quad (3.5)$$

$$\Delta P_{jnom} = \Delta P_{jmin} * (W_{nom}/W_{min})^2 \quad (3.6)$$

where \dot{W} is the total mass flowrate, ΔP_j is the injection pressure drop, the subscripts "min" and "nom" refer to the minimum (throttled) and nominal chamber pressures, respectively. If the manifold pressures were specified, PRELIMD checks that all the available pressure drop has

3.2, Preliminary Design (PRELIMD) (cont.)

been used without exceeding the limits. If the available pressure drop is greater than that used, the estimate for chamber pressure is increased, and the calculations are repeated. Conversely, if the required injection pressure drop exceeds the available pressure drop, the chamber pressure is decreased. This process is repeated until the design converges.

PRELIMD sizes the propellant manifold diameter, D_{manifold} and length, L_{manifold} using the following estimates:

$$D_{\text{manifold}} = D_c \quad (3.7)$$

$$L_{\text{manifold}} = \text{Maximum of (1.0 inch or } 0.5 D_{\text{manifold}}) \quad (3.8)$$

These dimensions influence the manifold acoustics, and therefore the injection-coupled stability characteristics of the combustor.

Element Sizing:

The core injector element can be sized once the chamber geometry and pressure schedule have been defined. Different element sizing procedures exist for impinging, shear and swirl coaxial elements. High frequency combustion stability is the driving parameter for impinging elements, while coaxial element design is mainly driven by performance concerns. The underlying assumption is that impinging element high frequency stability can be directly related to the sensitive timelag and the resonant frequencies of the chamber, while coaxial element stability is dominated by the gas-to-liquid injection velocity. While the minimum acceptable velocity ratio is input by the user, historical data indicates that ratios in excess of 10 yield dynamically stable injectors (10 is the model default). An additional assumption in coaxial element design is that the injector's performance is mixing limited. Since the input velocity "defines" the element's high frequency stability, the preliminary design can focus on achieving a high level of mixing, and therefore satisfying the performance goal.

Impinging elements are sized so that the element's peak burning response frequency does not exceed the damping capabilities of the anticipated damping devices the user specified (See Section 3.1). The injector element's peak burning response frequency is equated to the resonant frequency of appropriate chamber mode, f_{res} , calculated using Equation 2.18. The injector element's resonant burning response frequency is then converted to a sensitive vaporization length (L_{vap}), that is the length for 20% of the propellant vaporization to occur (an Aerojet estimate of sensitive timelag), for each propellant using the injection velocity (V_j):

$$L_{\text{vap}} = V_j / f_{\text{res}} / 2 \quad (3.10)$$

3.2, Preliminary Design (PRELIMD) (cont.)

where L_{vap} is in ft and V_j is in ft/s. The vaporization model is used to convert L_{vap} into mass median dropletsizes, which is then related to an orifice sizes using Priem's droplet correlations (Ref. 1). Finally, the number of injection elements required for each propellant can be determined from continuity:

$$N_{el} = \frac{\dot{W}}{\rho C_d A_{el} V_j} \quad (3.11)$$

where ρ is the propellant density, in lbm/ft^3 , A_{el} is the flow area per element for the propellant circuit, in ft^2 , C_d is the orifice discharge coefficient, and \dot{W} is the total core element flowrate of the propellant, in Lbm/s . If the combustor is a liquid-liquid system, PERFIT sets the number of elements equal to the larger of the calculated values for fuel or oxidizer, since the number of elements calculated for the fuel, in general, may not match that for the ox. If the system is gas-liquid, the number of elements is set to the number calculated for the liquid propellant circuit. The number of injection elements is always required to accommodate the symmetry needed for radial baffle blades, at least 3 blades, even though baffles may not be included with the current injector. Once the number of elements has been set, the final orifice diameters are calculated by inverting Equation 3.11.

Shear coaxial injection elements are sized to 1) meet user imposed design constraints, e.g. minimum velocity ratio and annular gap width, 2) satisfy jet stability and pressure schedule requirements, 3) satisfy user performance goals. Since the satisfaction of conditions 1 and 2 may preclude achieving the performance goal, the user is allowed to override their enforcement (interactively). The performance of shear coaxial elements is assumed to be mixing limited, and furthermore, it is assumed that no interelement mixing occurs. These assumptions imply that the unielement mixing efficiency must equal the overall mixing efficiency, and the overall performance efficiency goal. First, PRELIMD calculates fuel injection velocity using the available fuel injection pressure drop. Next, it calculates the oxidizer injection velocity using the correlation developed by Nurick (Ref. 9) which relates the oxidizer injection velocity to the fuel injection velocity and the mixing efficiency. PRELIMD then checks that the injection velocity is achievable with the available injection pressure. If insufficient injection pressure exists, the user is given the option of either lower the injection velocity or increase the injection pressure. If, however, the available injection pressure exceeds that required, the excess oxidizer pressure drop

3.2, Preliminary Design (PRELIMD) (cont.)

is dissipated through a metering orifice. Finally, the fuel-to-oxidizer velocity ratio is checked to ensure that the user input minimum is exceeded. Again, if problems exist, PRELIMD will recommend changes to oxidizer injection velocity or fuel injection pressure to correct the deficiency. PRELIMD informs the user of the impact of the recommended change on the unelement E_m during all these checks. After the injection velocities have been defined, the maximum number of elements that satisfy the minimum annular fuel gap requirement (user input) is determined iteratively. The final oxidizer post geometry, including metering and diffuser section dimensions, are computed using the calculated injection velocity, element mass flowrate and available injection pressure drop. Nurick's correlation may predict extremely low E_m 's, especially for dense fuels. The user is permitted to override this value. If meaningful results are to be obtained with ROCCID, the user must be consistent in the manner in which the E_m is overridden, as noted in Section 3.3.

The preliminary element design procedure for swirl coaxial elements is, in many ways, similar to the shear coaxial element. Like the shear coaxial element, the high frequency stability is assumed to be controlled by the injection velocity ratio and the performance of the swirl coax is assumed to be limited by mixing. Unlike the shear coax, the interelement mixing is assumed to play a strong part in the overall mixing efficiency, much like impinging elements. This fact permits the required element density to be calculated using Nurick's element density- E_m correlation (Ref 9):

$$A_{pel} = \text{EXP} \left[\frac{E_{m_{required}} - 61.5 - 0.385 * E_{m_{uni}}}{0.15 * E_{m_{uni}} - 14.99} \right] \quad (3.13)$$

where $\text{EXP}(x)=e^x$, $E_{m_{required}}$ is the Rupe mixing efficiency necessary to achieve the performance efficiency goal, $E_{m_{uni}}$ is the unelement mixing efficiency and A_{pel} is the required injector face area per element, in square inches. The oxidizer swirl chamber and post geometry, injection velocity, tip C_d and fuel annulus gap width are solved iteratively using the equations of Doummas and Laster (Ref. 8). In this process, the number of elements, and therefore the flowrate per element is varied until the minimum gap is exceeded. The fuel-to-injection velocity ratio of the acceptable gap design is compared to the required minimum, and if it is found to be unacceptable, PRELIMD will recommend a new fuel injection pressure drop.

The final preliminary design activity is to estimate the element pattern layout. While the element layout is not currently used by ROCCID, it is included to guide the user in the feasibility of the

3.2, Preliminary Design (PRELIMD) (cont.)

design, i.e. can it be easily packaged. The layout procedure estimates the radial and circumferential element spacing, assuming concentric rings of elements. Each ring is assumed to contain only 1 row of elements, except for like doublet elements where the pattern may be herringboned, if necessary. PRELIMD tries to distribute the elements to yield a uniform radial mass distribution profile. If this is not possible, it will bias the distribution so that the excess mass is at the injector periphery, thereby creating an inward radial wind.

The calculations begin by estimating the element radial and circumferential spacing requirements, i.e how much space does the element occupy. This algorithm utilizes the element geometry and estimates of the structurally required minimum distance between adjacent holes and between holes and channel lands. The algorithm does not permit intersection of holes on the inlet side of the faceplate. The active injector face is decreased to account for an axial acoustic cavity, if included in the design, and then it calculates the number of rows that can be accommodated. With the row width and the number of rows determined, PRELIMD calculates the fraction of the active face area contained in the row, and therefore the fraction of the total number of elements that the row should contain. Starting from the outer row, it compares the circumferential spacing required for each element with the mid-row circumference. If the required circumferential distance exceeds the available, PRELIMD will remove the excess elements. This process is repeated until the innermost row is reached. Any elements that remain after the center is reached are spread over the outermost rows. If this final distribution of elements causes the row to contain more elements than will fit circumferentially, a warning message will be printed, so the user can evaluate the potential packaging problem more rigorously.

3.3 STEADY STATE PERFORMANCE ITERATION (PERFIT)

The steady state performance design iteration module evaluates the combustion performance of the current combustor design, and recommends design changes that will move the performance towards the specified goal. As with the POINTA steady state combustion analysis (See Section 2.2), SSCI is the executive routine for this design iteration module. When SSCI is called by POINTD, initially COMBUST is run for the nominal chamber pressure to determine the combustor operating characteristics. PERFIT is then executed to compare the current performance to the desired goal (See flowcharts in Appendix F). PERFIT will determine whether the current performance is higher or lower than the goal, and recommend design changes to converge to the performance goal. The user selects the design variable they wish to change and enters the new parameter value, either the recommended value or a value they feel more appro-

3.3, Steady State Performance Iteration (PERFIT) (cont.)

priate, as long as the change is in the correct direction, e.g. reducing the chamber length to reduce delivered efficiency. The desired change is passed to REDESIGN, where the overall combustor design is updated (See Section 3.6), and COMBUST is executed again for the nominal chamber pressure. When the user determines the performance efficiency is adequate, PERFIT checks that the input total propellant flowrate is satisfied, and then runs COMBUST for two throttled chamber pressures, one of which corresponds to the input minimum flowrate, to determine the engine throttling characteristics that are required as input for the stability modules (See Section 2.2).

Each performance iteration begins with the user selecting the dropsize model to use in COMBUST. At the end of the COMBUST run, PERFIT prints a summary of the performance at the nominal operating point, including the combustion efficiency goal and basis (C^* or ISP-based ERE), overall fuel and oxidizer vaporization efficiency, C^* and ISP-based mixing efficiency and delivered C^* and ISP-based energy release efficiencies. If data for nozzle efficiency versus nozzle length is input, PERFIT will also output the current and optimal combustor length. The optimal combustor length is the length that produces the maximum overall efficiency, and is calculated as follows:

$$L_{\text{noz}} = L_{\text{max}} - L_{\text{c}} \quad (3.14)$$

$$\eta_{\text{overall}} = \eta_{C^*}(L_{\text{c}}) \eta_{\text{noz}}(L_{\text{noz}}) \quad (3.15)$$

where L_{max} , L_{c} , and L_{noz} are the maximum engine, combustor and nozzle lengths, respectively, η_{overall} is the overall efficiency, $\eta_{C^*}(L_{\text{c}})$ is the delivered C^* efficiency for a combustor of length L_{c} , interpolated or extrapolated from the axial C^* efficiency profile, and $\eta_{\text{noz}}(L_{\text{noz}})$ is the nozzle efficiency for a nozzle of length L_{noz} . Figure 3.1 is an example of the component and overall efficiency plots available to the user when ROCCID is run on a terminal with interactive plotting capabilities.

PERFIT then calculates the design changes that will drive the performance towards the performance goal. The performance is mixing limited if the delivered performance and mixing efficiencies are below the performance goal, i.e. additional vaporization will not satisfy the performance goal. PERFIT will recommend that the injection element density be increased, i.e. add more elements, thereby increasing the overall E_{m} and mixing efficiency. The estimate for the number of elements required is determined using Nurick's element density- E_{m} correlation (Ref 9):

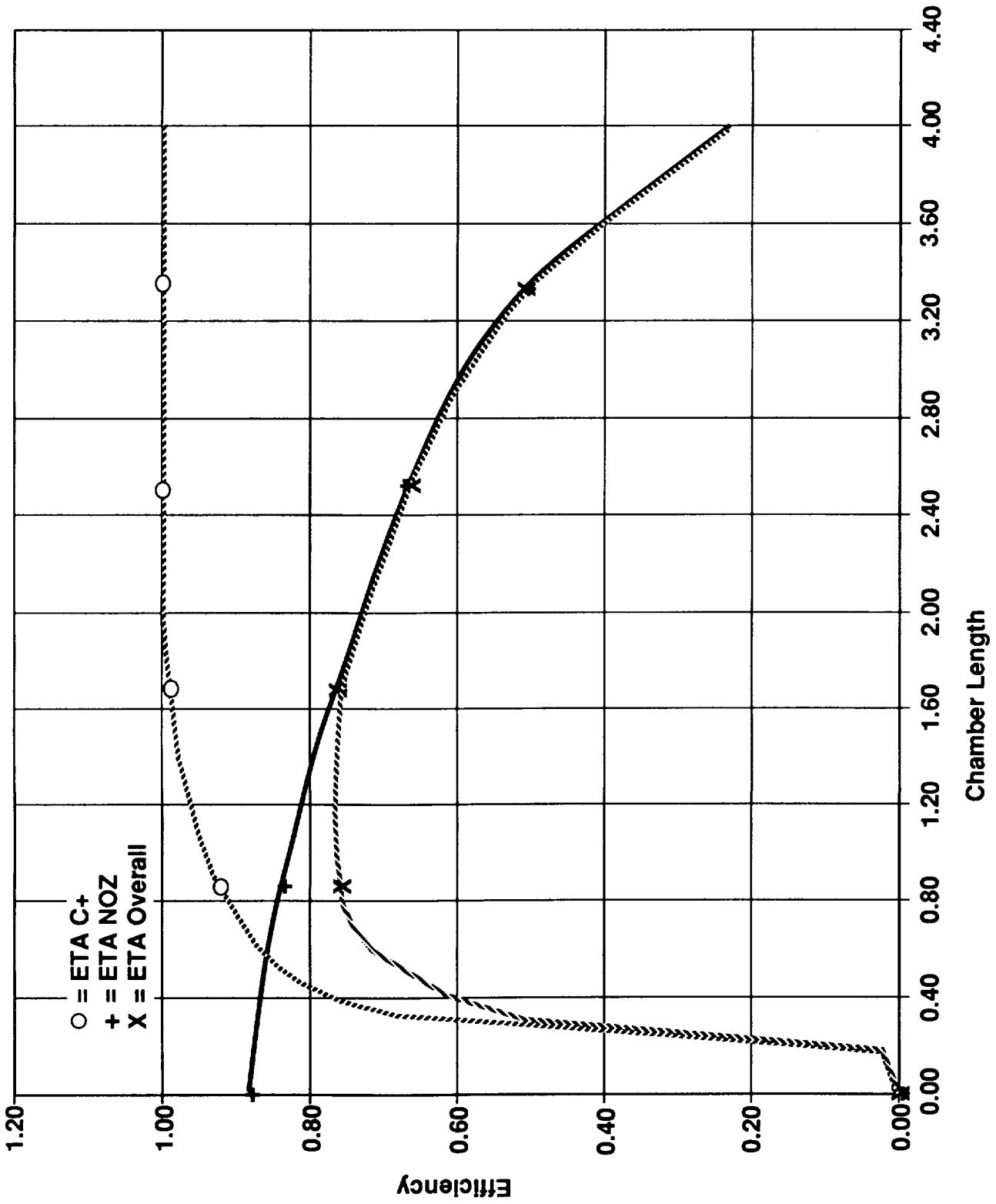


Figure 3.1. Overall Efficiency vs. Chamber Length

3.3, Steady State Performance Iteration (PERFIT) (cont.)

$$A_{pel} = EXP \left[\frac{E_{m_{required}} - 61.5 - 0.385 * E_{m_{uni}}}{0.15 * E_{m_{uni}} - 14.99} \right] \quad (3.16)$$

where $E_{m_{required}}$ is the Rupe mixing efficiency necessary to achieve a mixing efficiency equal to the performance efficiency goal, A_{pel} is the required new injector face area per element, in square inches. PERFIT corrects the required element density from Eq. 3.16 to account for any user override included in the current overall E_m by calculating the effective element density of the current design. The current effective element density is calculated with Eq. 3.16 by replacing $E_{m_{required}}$ with the current E_m . It is important to note that the user should be consistent in their methodology of overriding calculated values, especially E_m , e.g. if 1.0 in² of face area per element results in an E_m of 70, then 0.5 in² of face area per element should result in a higher E_m . The new element quantity can then be converted into recommended design changes, either reduced orifice diameter or decreased injection pressure drop, and therefore injection velocity.

Conversely, PERFIT considers the performance to be vaporization limited if the delivered mixing efficiency exceeds the efficiency goal. PERFIT will recommend appropriate changes in orifice diameter, injection pressure drop and chamber length to move the performance towards the goal. The required new droplet size (R_m), injection velocity (V_j) and chamber length (L) can be calculated using the vaporization model (Ref. 1):

$$R_{m_{new}} = R_{m_{old}} * (\eta_{vap_{new}} / \eta_{vap_{old}})^{(1/1.45)} \quad (3.17)$$

$$V_{j_{new}} = V_{j_{old}} * (\eta_{vap_{new}} / \eta_{vap_{old}})^{(1/1.75)} \quad (3.18)$$

$$L_{new} = L_{old} * (\eta_{vap_{new}} / \eta_{vap_{old}}) \quad (3.19)$$

where η_{vap} is the vaporization efficiency and the subscripts “old” and “new” refer to the current and recommended values, respectively. The new dropsize can be related to a new orifice diameter using Priem's dropsize correlations (Ref. 1), corrected by the ratio of the dropsize predicted with the user-selected model and the dropsize predicted by the correlations for the current design. The injection velocity is related to the injection pressure drop using the relationships outlined in Section 2.2. This process requires that the effect of the change on both the fuel and oxidizer vaporization efficiency be considered, since the desire is to reach some overall vaporization efficiency. For simplicity, these estimates of new design parameters neglect any influence of the change in overall vapor mixture ratio at the throat, and the resulting change in mixing efficiency (See Section 2.2). In an effort to minimize the overshoots in performance

3.3, Steady State Performance Iteration (PERFIT) (cont.)

change that result due to this simplification, some under relaxation has been included in the recommended change.

When acceptable performance has been predicted for the nominal operating condition, PERFIT checks that all other operating inputs have been satisfied. First, the calculated total flowrate is compared to the desired, and appropriate changes to either chamber pressure, throat diameter or required total flowrate are presented to the user. If the throat diameter or chamber pressure are modified, the user is returned to the performance iteration to confirm the effect on combustor operation and performance. If the maximum manifold pressures were specified, PERFIT also check that the calculated pressures do not exceed them. With these gates successfully passed, PERFIT returns control of the steady state combustion iteration to SSCI so the operating parameters at the two throttled chamber pressures can be determined.

3.4 CHUG STABILITY DESIGN ITERATION (CHUGIT)

The low frequency non-acoustic stability, or chug, design iteration module (CHUGIT) uses the POINTA low frequency combustion stability analysis module (LFCS) to evaluate the chug stability of the current combustor design, and if the chug stability margin requirements are not satisfied, CHUGIT recommends design changes that push the design towards the desired marginal chamber pressure. The minimum chamber pressure at which the combustor must be chug stable is initially set at the throttled P_c , as determined from user inputs by PRELIMD (See Section 3.2), but the user has the option to reduce the minimum desired stable chamber pressure further. CHUGIT receives the marginal chamber pressure for the current configuration from LFCS, and after comparing it to the desired marginal P_c , CHUGIT will recommend changes in the combustor length or injection pressure that will drive the marginal P_c towards the desired value. CHUGIT accepts the user defined change in design parameter, and it calls the combustor redesign module, REDESIGN, to properly modify the current design. After REDESIGN has been executed, CHUGIT calls LFCS to reassess the chug stability of the new design. This process is repeated until a combustor design with acceptable chug stability is achieved. Since REDESIGN only makes first order approximations of the effects of change in design variables on combustor operation, the user must rerun SSCI, either using POINTA or PERFIT, to rigorously update combustor operating parameters, and then run LFCS, either using POINTA or CHUGIT, to determine the true marginal chug P_c . The user should be aware that design changes that increase chug stability margin, i.e. increasing chamber

3.4, Chug Stability Design Iteration (CHUGIT) (cont.)

length and injection pressure drop, can adversely effect high frequency acoustic stability. Therefore, the user may want to evaluate both the high frequency and chug stability characteristics of the initial design before entering either of the stability design iterations loops.

Since it is difficult to analytically determine the magnitude of design variable changes that will yield the desired chug margin, the values recommended by CHUGIT are the current values bumped by 10% in the proper direction, i.e. longer chamber and higher injection pressures for increased margin. If the "excess" margin changes sign, i.e. the design goes from insufficient margin to excessive margin, CHUGIT will linearly interpolate design variable changes to converge to the desired chug stability margin.

A third design change option available in CHUGIT is to alter the atomization lengths, thereby directly modifying the calculated timelags. This design change option is provided to give the user an indication of the magnitude of atomization length, and therefore timelag, that is required to attain the desired chug margin. ROCCID is currently not capable of determining the injector design change required to accomplish this change in atomization length, so the user is required to modify element design variables, e.g. like impingement half-angle, in order to have this change in total timelag reflected in the combustor design. The validity of these design changes must be subsequently verified by rerunning SSCI.

3.5 HIGH FREQUENCY ACOUSTIC STABILITY DESIGN ITERATION (HIFIT)

The high frequency acoustic stability design iteration module (HIFIT) uses the POINTA high frequency combustion stability analysis module (HFCS) to evaluate the stability of the current combustor design, and if high frequency combustion stability is a problem, it recommends design changes that will remedy the problem. The high frequency design iteration begins by analyzing the high frequency stability of the current design using HFCS. The analysis is limited to the third tangential mode (3T) and below, and the growth coefficient is not determined. If the analysis indicates no potential instabilities, the current design is considered to be stable, and the user has the opportunity to evaluate the growth coefficient. If, however, the analysis indicates any potential instabilities, HIFIT will recommend design changes that should improve stability characteristics. The user selects one of the design changes and the new design is reanalyzed using HFCS. This iteration is continued until the stability characteristics are considered acceptable. HIFIT will recommend several different types of design changes,

3.5, High Frequency Stability Design Iteration (HIFIT) (cont.)

depending on the instability mechanism linked to the predicted instability, i.e. injection-coupled versus burning-coupled. In the case of burning-coupled instabilities, the user is given a choice of adjusting the injector design or adding damping devices. The logic contained in each of the redesign sections is discussed in the following subsections. A schematic of the high frequency stability design iteration procedure is contained in Figure 3.2.

The high frequency stability design iteration utilizes the outputs from HFCS, such as frequency, gain, and relative magnitude of driving mechanisms, to determine the stability of the current design and to determine the appropriate design change. HIFIT first checks that the resonant frequency of the 3T mode is greater than the peak response frequency of the burning response. If this is not the case, the design is assumed to be capable of change element with modes higher than 3T, an undesirable condition since it can not be easily solved with damping devices alone, so the model jumps to the change element redesign portion of the program (see below). When it has been determined that modes higher than 3T are not expected, HIFIT checks the modes analyzed, first longitudinal (1L) through 3T, for instabilities, i.e. is the maximum in-phase system gain greater than 1.0. If no instabilities are found, the user is given an option to evaluate the stability margin, as implied by the growth coefficient, or return to the main menu. If instabilities exist, they are classified as injection-coupled or burning-coupled, and the appropriate remedial action is initiated.

Currently there are no provisions in HIFIT to add or improve damping device designs to enhance stability margin in designs that are statistically stable, i.e. maximum in-phase gain is less than 1.0. This can be accomplished by exiting POINTD and then manually adding or adjusting the damping device configuration in POINTA. Similarly, HIFIT currently has no mechanism by which to derate the stability of a design, so this too must be addressed using POINTA.

Injection-Coupled Instabilities:

HIFIT next checks for the presence of injection-coupled instabilities. If any of the unstable modes are found to be injection-coupled, i.e. ratio of burning response to injection response amplitude is less than unity, HIFIT will recommend changes in chamber length or injection pressure drops that should reduce or eliminate the injection-coupled instabilities. Since the absolute value of change required to stabilize a combustor is not easily calculated, the program currently recommends reducing the chamber length by 10 percent (for longitudinal

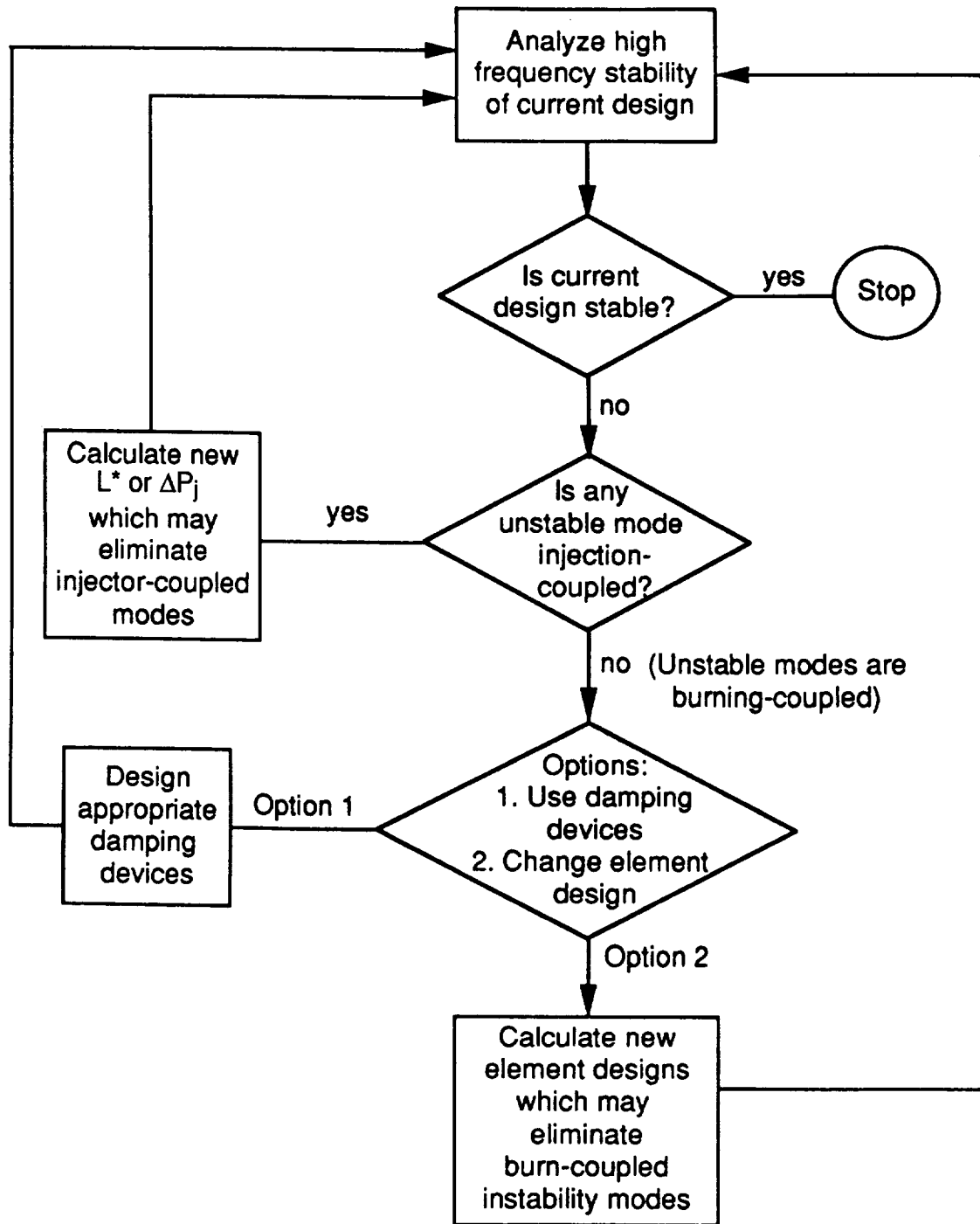


Figure 3.2. High Frequency Stability Design Iteration Schematic

3.5, High Frequency Stability Design Iteration (HIFIT) (cont.)

instabilities) or increasing the injection pressure drops by 5 percent, both of which move towards a more injection-coupled stable configuration. The user selects either option, and then they can either accept the recommended change, or input their own change, as long as the change is in the correct direction, i.e. shorter chamber length or higher injection pressure drop. The desired design change is fed to REDESIGN to reconfigure the combustor and analysis model input files (See Section 3.6), and the new design is analyzed using HFCS to obtain the high frequency stability characteristics of the new design. This process will be repeated until no injection-coupled instabilities are found or the user accepts the existing instability.

Burning-Coupled Instabilities:

The only high frequency acoustic instabilities that remain after the injection-coupled iteration has been completed are intrinsic burning-coupled. HIFIT will recommend design changes that should eliminate any remaining burning-coupled instabilities. The design changes fall into two general categories, the addition of damping devices and changes to the injection element design.

Injection element design changes for burning-coupled instabilities are currently limited to increasing the element sizes or decreasing the injection velocity of the sensitive propellant circuit. The new design should have a maximum burning response magnitude less than the minimum chamber response magnitude. The new design is calculated assuming the injection response magnitude is negligible compared to the intrinsic burning response. Element redesign begins by determining the frequency, f^* , of the lowest mode with a chamber response magnitude less than the maximum burning response, Y_b^* . The element's new peak burning response frequency, f_{new} , is then shifted such that the burning response magnitude at f^* is less than the minimum chamber response magnitude, $1/Z_c^*$:

$$f_{new} = \frac{\pi f^*}{2\pi - \cos^{-1} \left[1 - 2 \left(\frac{1}{Z_c Y_b} \right)^2 \right]} \quad (3.20)$$

The new peak burning response frequency is then related to a new droplet size or injection velocity by considering the change in vaporization timelag, as predicted with the vaporization model (See Section 2.2):

3.5, High Frequency Stability Design Iteration (HIFIT) (cont.)

$$R_{m_{\text{new}}} = R_{m_{\text{old}}} * (f_{\text{new}}/f_{\text{old}})^{(1/1.45)} \quad (3.21)$$

$$V_{j_{\text{new}}} = V_{j_{\text{old}}} * (f_{\text{new}}/f_{\text{old}})^{(1/.75)} \quad (3.22)$$

where R_m is the mass median droplet radius, V_j is the injection velocity and f_{old} is the peak burning response frequency of the current design. This procedure assumes that changes in drop-size or injection velocity required to provide the desired change in peak burning response frequency results in a negligible change in the magnitude of the peak response, while in reality, reducing an injector's peak burning response frequency will usually also reduce the peak magnitude. The routine that resizes the injector as the result of the design change, REDESIGN, makes first order corrections that should properly affect the burning response magnitude during the next pass through HFCS (See Section 3.6 for more details).

The recommended new orifice diameter, which will give the desired dropsizes, is calculated for impinging elements using Priem's dropsizes correlations (Ref. 1), corrected by the ratio of the dropsizes predicted with the user-selected model (during the performance iteration) and the dropsizes predicted by the correlations for the current design. Coaxial elements are redesigned, using the atomization correlation contained in CICM (Ref. 19), by relating the desired dropsizes to the velocity ratio, and thus a new fuel injection velocity.

Damping Device Design:

The user may also select to add damping devices to a design to solve burning-coupled instability problems. If damping devices are selected, HIFIT will determine the appropriate damping device design. The highest instability mode predicted for the current design dictates what damping device options are appropriate and their designs. Table 3.1 shows the damping device options available for predicted highest instability mode. As an example, if the highest instability mode predicted is the first longitudinal mode (1L), the only options are either a monotune quarter wave acoustic cavity or a monotune Helmholtz resonator. A baffle is not an option since it is not effective for stabilizing longitudinal modes. Neither bitune quarter wave cavities nor bitune Helmholtz resonators are options in this case either, since there is only one mode to be damped. Once the user selects a damping device type, HIFIT will define the critical design parameters, permitting the user to override any of them, if desired.

Table 3.1
HIFIT Damping Device Design Summary

Highest Instability Mode	Damping Device Options	Sizing Procedure
1L	Monotune Quarter-Wave or Helmholtz Resonator	<ul style="list-style-type: none"> • Tune for 1L frequency
1T	Monotune Quarter-Wave, Helmholtz Resonator or Radial Baffles	<ul style="list-style-type: none"> • Radial Baffles: 3 blades, Length=0.2Dc • QW* or HH Tune for 1T Frequency
2T	Bitune Quarter-Wave, Helmholtz Resonator or Radial Baffles	<ul style="list-style-type: none"> • Radial Baffles: 5 blades, Length=0.2Dc • QW or HH Tune for 1T and 2T Frequency
1R	Bitune Quarter-Wave, Helmholtz Resonator or Radial Baffles with Quarter-Wave or Helmholtz	<ul style="list-style-type: none"> • QW or HH Tune for mode(s) specified by users • Radial Baffles with QW or HH 5 blades, Length=0.2Dc QW or HH tuned for 1R frequency
3T	Bitune Quarter-Wave, Helmholtz Resonator, Radial Baffles or Radial Baffle with Quarter-Wave or Helmholtz	<ul style="list-style-type: none"> • QW or HH Tune for mode(s) specified by users • Radial Baffles: 7 blades, Length=0.2Dc • Radial Baffles with QW or HH 7 blades, Length=0.2Dc QW or HH tuned for 1R frequency
>3T	Redesign of Injector is Required	

* QW = Quarter-Wave Cavity
 HH = Helmholtz Resonator

3.5, High Frequency Stability Design Iteration (HIFIT) (cont.)

Baffle Design:

The number of radial baffle blades is set by the highest instability mode observed:

<u>Highest Mode</u>	<u>Number of Blades</u>
1T	3
2T or 1R	5
3T	7

Since the model can not account for radial baffle hubs, radial mode problems must be solved using acoustic resonators. Baffle blade length is initially specified as 20% of the combustor diameter. If the initial configuration does not yield a stable configuration (for tangential modes), the user should increase the blade length in 5 percent increments until stability is achieved or the baffle length exceeds some limit. It should be noted that increasing the baffle length can sometimes be a destabilizing effect. In this case, the user will actually have to shorten the baffle length from the original length.

1/4 Wave Acoustic Cavity Design:

The effective depth, D_c , of a 1/4 wave cavities is determined by the resonant frequency, f_{tune} , of the mode to be damped, using the standard 1/4 wave acoustic relationship:

$$D_c = 0.25 * A_{\text{cavity}} / f_{\text{tune}} \quad (3.23)$$

where A_{cavity} is the mean speed of sound of the gas in the cavities, in ft/s, and D_c and f_{tune} are expressed in ft and hz, respectively. The value of A_{cavity} is calculated from the average mixture ratio in the recirculation region near the injector face by SSCI (See Section 2.2).

Cavities may be bituned (two types of cavities with different depths) to provide damping for more than one mode. The total cavity open area is assumed to equal 15 percent of the injector face. The cavity width is then determined from the cavity open area, knowing the chamber diameter. The number of long and short cavity sections contained in a bitune cavity are initially set at 4 and 8, respectively. These design parameters, e.g. speed of sound, cavity open area, cavity depth, and numbers of cavities, are presented to the users, and they can be overridden, since the design presented to the user should be close to but not necessarily the optimal

3.5, High Frequency Stability Design Iteration (HIFIT) (cont.)

design. If the initial design does not completely damp the intended modes, the users should make slight changes in the design parameters until a stable design is achieved. It should be noted that cavity partitions or separators will not be included unless the design definition variable TPART is given a non-zero value. Additionally, the individual cavity sizes will have to be specified for monotune cavities if partitions are included.

Helmholtz Resonator Design:

The back volume, which forms the Helmholtz resonator, is considered to be a cube of linear dimension, L_h (see Section 4.0, Figure 4.5). L_h should be smaller than the wavelength inside the cavity, and is chosen to be 20% of the wavelength:

$$L_h = \frac{0.2 a_c}{f} \quad (3.24)$$

where a_c is the speed of sound in the cavities, and f is the resonant frequency of the instability mode to be damped. The value of a_c is determined by SSCI, during the performance iteration, from the average mixture ratio in the recirculation region near the injector face (See Section 2.2 for more details). The orifice length to orifice diameter ratio is assumed to be 0.20, thereby permitting the orifice diameter, d_c , to be calculated using the expression:

$$d_c = 3.2\pi \left(\frac{f}{a_c}\right)^2 L_h^3 \quad (3.25)$$

The total resonator open area is assumed to equal to 10 percent of the injector face. The number of cavities can then be calculated from the total resonator open area and the orifice cross-sectional area. If a bitune resonator is used, the total resonator open areas of each of the two resonator types is assumed to be equal (each at 5 percent of injector face area). As with the quarter wave cavity design, the design parameters, e.g. speed of sound, cavity open area, back volume linear dimension, and numbers of cavities, can be overridden by the user, if desired.

3.6 REDESIGN MODULE (REDESIGN)

The redesign module is responsible for converting user input design changes into a consistent combustor design. It also modifies model inputs to reflect these design changes. Four design change options exist within redesign, 1) chamber geometry, 2) orifice diameter, 3) injection pressure drop, and 4) propellant atomization length. Changes in chamber geometry only

3.6, Redesign Module (REDESIGN) (cont.)

require the appropriate quantity to be updated and the new configuration output. Changes in atomization length requires the appropriate timelags to be modified, but the injector design is not changed, as noted in Section 3.4. Changes in a propellant circuit orifice diameter or injection pressure drop, however, requires an injector design rebalance, so as to maintain total flowrate and mixture ratio. Additionally, REDESIGN makes first order changes to derived stability model inputs, so the stability influences of the design change can be evaluated without having to rerun SSCI immediately. The remainder of this section discusses the methodology REDESIGN uses to rebalance the injector and to update stability model inputs.

The decision to change a propellant circuit orifice diameter necessitates that the number of orifices or propellant injection velocity be modified to maintain the total propellant flowrate. Since changing pressure drop and diameter at the same time can mask the effect of the desired design change, REDESIGN changes the number of elements, thereby maintaining the current injection velocity and injection resistance. The change in element quantity requires the other propellant circuit orifice diameter or injection velocity to change, since equal number of elements must exist. Although REDESIGN contains the logic to change either the orifice diameter or injection velocity of the other propellant circuit regardless of which parameter was changed in the first propellant, in practice it always changes the same parameter as changed for the first propellant.

The redesign of coaxial elements can result in several conditions that require user interaction to resolve. Changing the oxidizer post exit diameter can result in an annular fuel gap that is smaller than the input minimum. REDESIGN will identify this condition and recommend design changes that should correct the problem. The user is permitted to accept the undersized annular gap, but if it is too small, sonic flow will occur at the exit of the fuel annulus, a condition that will cause ROCCID to stop. Solution of this problem by increasing the fuel annulus outer diameter may result in violation of the minimum velocity ratio constraint. If the resulting velocity ratio does not exceed the minimum, REDESIGN will recommend an increase in fuel injection pressure to resolve this problem. It should become quickly apparent that this iteration to satisfy the minimum annular gap and velocity ratio may not converge. If this is the case, the users will have to evaluate if their design constraints are too restrictive. It should be noted that the resizing of coaxial elements includes resizing the oxidizer post geometry and post length.

3.6, Redesign Module (REDESIGN) (cont.)

REDESIGN's other major function is to correct derived data for the first order influences of the design changes. Derived quantities refer to values calculated by SSCI as inputs for the stability modules, including timelags, inertances, dropsizes, etc. The update process neglects any change in performance efficiency, and its influence on flowrate and injection velocity.

Dropsizes are updated using the Priem dropsize correlations (Ref. 1), with REDESIGN attempting to modify the value to maintain consistency with the user selected drop-size model:

$$R_{mnew} = R_{mold} * (R_{m,priemnew} / R_{m,priemold}) \quad (3.26)$$

where the $R_{m,priem}$ is the dropsize predicted with Priem's correlations, and the subscripts "new" and "old" refer to the values associated with the new and old element designs, respectively.

The pressure interaction index, N, is updated using the Smith-Reardon correlation (Ref. 15) with the new element design. The sensitive timelag, τ , may be updated using two methods. The Smith-Reardon correlation is applied to the new geometry, or the old τ is modified to account for changes in dropsize and injection velocity:

$$\tau_{new} = \tau_{old} * \frac{V_{jold}}{V_{jnew}} * \left(\frac{R_{mnew}}{R_{mold}}\right)^{1.45} * \left(\frac{V_{jnew}}{V_{jold}}\right)^{0.75} \quad (3.27)$$

where the first term reflects the change in timelag due to change in injection velocity, while the last two terms account for the change in vaporization rate, and therefore sensitive time. The user has the option to select either value of τ . The user is permitted to override the new values for both τ and N.

4.0 INTERACTIVE FRONT END DESCRIPTION

This section describes terminology and intended usage of the Interactive Front End (IFE). It describes how the user accesses the analysis modules in ROCCID, as well as the IFE's computer aided input generation capabilities. Usage of the interactive output plotting capabilities of the IFE are also discussed in this section.

The IFE provides the ROCCID user with a convenient interactive tool to run performance and stability analyses on rocket engines. It links rocket engine analysis codes by creating input data files for each to run. It also displays analysis results graphically and provides visual aids for entering the data required. User friendliness is the main goal of the IFE.

The IFE is a menu driven pre-processor, constructed using an extensive library of interactive subroutines. Each input character is checked for validity, and error messages are displayed when input errors are encountered. In addition, a replay file is created, containing all user keystrokes. This file can be used as a starting point for a subsequent ROCCID session. The user may repeatedly alter the input until the desired result is achieved. Any analysis can be completely rerun with minimal effort.

The IFE has been designed to decouple the module inputs as much as possible. This allows greater flexibility, since most module changes will not effect other parts of the system. With the exception of the combustion gas table, all data is transferred through files consisting of namelists. Namelists are very convenient for data transfer because of their flexible and easily understood format.

ROCCID has an IFE instruction/help screen, which delineates most information required to run the program. Data entry, aborting, and replay file usage are covered along with other important IFE features. The help screen can be accessed at any time by entering @HELP.

Variable descriptions can be abbreviated to accelerate input for the advanced users. Additionally, input variables have been divided into 3 different groups, with a PATH level defining which need to be input, 1) those always input, 2) those input sometimes and 3) those hardly ever input. There are actually two higher PATH levels, PATH levels 4 and 5. PATH level 5 contains variables that are inactive (ROCCID does not use them) but were included in anticipation of future code enhancements. PATH level 4 contains variables which only need to be accessed in unusual circumstances, e.g. during ROCCID debugging.

4.0, Interactive Front End Description (cont.)

The following sections describes the IFE features and their usage within ROCCID. Appendix A is a reprint of the IFE instruction/help screens contained in ROCCID. Appendix C contains a list of all namelist variables, and Appendix D contains information on creating combustion gas tables for new propellant combinations. Appendix E lists the file definitions and naming conventions.

4.1 PRELIMINARY QUESTIONS

The ROCCID program starts by asking the user several questions that set the environment of the session. Once set, the environment cannot be changed so it is important the these questions are answered correctly. Section 4.1 reviews these preliminary questions.

Instructions:

The first question asked by the IFE is:

Do you want instructions (Y or N)?

See Appendix A for a hard copy of the instructions.

Replaying files:

The following two questions concern executing and creating replay files:

Do you want to REPLAY a file (Y or N)?

Do you want to enter a name and description for the REPLAY file. NOTE: if you reply N, the file will be named REPLAY.DAT without a description (Y or N)?

There are two ways to recall old runs; one is to use a replay file, and the other is to read existing model input file(s) (**resume** a session). Each time the code is run it saves all user keystrokes on the replay file. The second question shown above allows the user to name the replay file and give it a one line description. As soon as the filename has been chosen, that file and the one line description (if it exists) will be added to the user's replay file library. The replay file library, named FILES.DAT, is a list of all replay files created in the users current directory. If the user chooses to run a replay file, the program will list the user's replay file library, and then

4.1, Preliminary Questions (cont.)

give the user three options. The user can choose a listed file, enter the filename of an "unknown" replay file (one not in the library), or continue without replaying a file.

After choosing the appropriate file, the user will be asked if the replay file is to be altered. A NO answer to this question will cause the replay file to be executed. If the user chooses to alter the file, the program will show each command in the replay file then ask the user to enter a command, or press <RETURN> to default to the replay command.

Four special commands can be used when running ROCCID with a replay file, if the user has selected to alter it. These commands are entered at the command prompt instead of accepting or replacing the current value:

- @OFF** Stop input from the replay file. (This command can aid in keeping the replay file synchronized when entering a new menu option.)
- @ON** Resume input from the replay file (after the next input from the terminal).
- @GO** Finish processing using the replay file without further keyboard input.
- @SEARCH 'NAME'** Search through the replay file for a variable name. This may be used to get the REPLAY file synchronized if a different menu option has been chosen, causing the replay input to not match the IFE queries. This command must be preceded with the @ON command if @OFF was entered.

The replay system will read ROCCID inputs from the replay file until the end of the file is reached, at which time it will return input control to the user. All subsequent user inputs will be appended to the replay file.

Synchronization problems with replay files occur when the replay system reads a response from the replay file that is not a valid response to the question, or when questions are asked that were not asked during the original session, e.g. running a replay file created on a Tektronix on a VT100 terminal. In these cases, the replay system will read through the replay file until a valid answer is found. To minimize synchronization problems, the terminal type can not be changed during replay mode.

4.1, Preliminary Questions (cont.)

Terminal Type:

If a replay file is NOT being used, the IFE asks the user to enter the terminal type:

IN ORDER FOR THE GRAPHICS TO PERFORM CORRECTLY THE PROGRAM MUST KNOW WHAT TYPE OF TERMINAL IS BEING USED. VALID OPTIONS ARE:

1 - VT100/VT220

2 - TEKTRONIX 40XX SERIES

3 - TEKTRONIX 41XX/42XX SERIES

ENTER TERMINAL TYPE <1>:

The ROCCID program supports three levels of graphics; no graphics, Tektronix 40XX series graphics, and Tektronix 41XX series graphics. The 40XX graphics allows the user to display X-Y plots, but does not support the visual input aids possible with the 41XX series terminals. Since the Tektronix terminals are downward compatible, any Tektronix 42XX terminal can be used in the 41XX graphics mode.

When using the 41XX option the user should be aware of the following: 1) It is always best to reset the terminal before beginning a session (this will insure proper figure loading and proper color assignment), 2) The ROCCID program loads the figures into graphic segments and simply turns off and on each segment as required. This greatly accelerates the time required to "repaint" the screen with a new segment. However, in order to minimize the initial loading of the segments the program does not erase the old segments either when starting or exiting the program. If the segments were loaded from a previous session, there is no need to load them again. If the segments are not loaded, answer YES to the appropriate prompt right after choosing the 41XX series terminal. The figure loading will take approximately three minutes depending upon the terminal baud rate.

Remember, these terminals are downwards compatible. If you are not interested in graphics, but are using a 41XX series terminal, you may choose a terminal type of 1 (VT100) to run the program. The terminal type cannot be changed in the middle of a session, so make sure you choose the appropriate terminal at the start. The user should also be aware that the terminal type will affect the questions that ROCCID asks, so replay files created for Tektronix terminals are not compatible with VT100 terminals and vice versa.

4.1, Preliminary Questions (cont.)

Variable Descriptions:

The next question asked sets the prompt level:

What level of prompting do you want

- 0 Examples of prompting levels**
- 1 Detailed descriptions and definitions**
- 2 Abbreviated descriptions and definitions**
- 3 Expert level...NO descriptions and definitions**

Enter Prompt level:

An example of the three different description levels are displayed below:

=====

**** Sample output for prompt level of 1 ****

```
NAME : RCHAMB
DESCR : CHAMBER RADIUS (FT.)
DESTIN : $DATA
DIMENSION :      1
TYPE : REAL
RANGE : >      0
RCHAMB =      0.0000E+00
```

=====

**** Sample output for prompt level of 2 ****

```
NAME : RCHAMB
DESCR : CHAMBER RADIUS (FT.)
RCHAMB =      0.0000E+00
```

=====

**** Sample output for prompt level of 3 ****

```
RCHAMB =      0.0000E+00
```

=====

Entering a zero at this prompt will display the above prompt levels.

4.1, Preliminary Questions (cont.)

Aborting:

Since there are often times when a session must be terminated in a hurry, the program has two ways of aborting a ROCCID session. The first and most severe way is to enter CONTROL Y. CONTROL Y kills everything and closes all files currently open.

The program can be aborted more gracefully by entering "~ <RETURN>". This command will allow the user to create files named RESUME.ft, where "ft" refers to the ROCCID input file types (See Appendix E), which contains all non-zero namelist variables. These files can then be given the appropriate file name, and reread by the ROCCID program. Note, if the tilde command (~) is used during an analysis, the RESUME.ft files will contain the variable values from the beginning of the analysis session.

Analysis Request Menu:

The analysis request menu determines what type of analysis will be run. A copy of the analysis request menu is included below, with each option described in the following subsections. Additional details of the menu screens are contained in Appendix F.

ANALYSIS REQUEST MENU

- 1. Point Analysis**
- 2. Point Design**
- 3. Utility Routines**
- 4. Stop**

4.2 POINT ANALYSIS MENU

The point analysis option allows the user to analyze a completed engine design. The user will be required to enter all variables including operating conditions, chamber geometry, injector type and geometry, stability aid information and model control information (many default values will be appropriate).

Upon entering the point analysis module you will be asked:

Do you want to resume a session?

4.2, Point Analysis Menu (cont.)

If you answer **YES**, you will be prompted to enter the session name, i.e the input file name, with the extension **.INP** being assumed. The program will then open and read a series of files, after the IFE asks you two more questions. The first question is:

Do you plan on modifying the input before your next run?

The IFE will read the input (filetype · INP) and control (file type · CNT) regardless of your response to the question. If you answer **NO**, however you will be asked a second question:

Would you like to append the current output files?

A **YES** response will cause all succeeding output to be appended to the current output files, while a **NO** will cause new output files to be created (resulting in new version numbers on the VAX). Further description of the output files is contained in Appendix E.

The following describes the point analysis menu options:

Set Variables:

This section allows the user to enter all combustion design variables in preparation for an analysis run. Upon entering this option all analysis files are closed; when leaving this option the user will be asked if the analysis files are to be opened in preparation for a run (the files must be opened to run any analysis option).

Path Levels:

The IFE allows the user to set the path level:

Current PATH LEVEL is : 1

1 : Only prompt for variable that are ALWAYS input

2 : Prompt for variables that are SOMETIMES input in addition to the above

3 : Prompt for variables that are RARELY input in addition to the above two

Enter PATH LEVEL or <ret> :

The user can limit the number of variables to input by choosing the appropriate path. Path level 1 displays the least number of variables while path level 3 displays all the variables. The user should be aware that once a level is selected, it can not be changed during the session. There are actually two higher path levels, path levels 4 and 5. Path level 5 contains variables that

4.2, Point Analysis Menu (cont.)

are inactive (ROCCID does not use them) but were included in anticipation of future code enhancements. Path level 4 contains variables which only need to be accessed in unusual circumstances, e.g. during ROCCID debugging. These are typically variables that SSCI generates for the stability model inputs. If the user finds that they routinely need to access only a couple of the variables contained in a higher path level than they would otherwise need, the path level of the variable can be modified in the **VARIABLES.DAT** file (See Appendix H).

The user is next prompted for a three line title which will be used to identify the input and output files created. Each line can be up to 80 characters long, and blank lines will be accepted.

The following section briefly describes the variables that can be set through this menu branch (see Appendix C for the list of all namelist variables). Additional information on the determination of input data can be found in Section 2.1.

The namelists associated with each option is shown in parentheses next to the option heading. The appropriate Figures are also referenced.

Complete Setup

The user will be prompted to set all appropriate variables below. Model control variables are not included in this set.

Models (\$MODELS)

Selects analytical models to be used in the analysis.

Operating Conditions (\$OPCOND)

Sets operating temperatures, pressures, mixture ratios, etc. C* and ISP vs MR tables are either input by user or generated using the ODE module.

Geometry (\$GEOM)

Sets and checks chamber geometry (Figure 4.1). Checks entries to make sure the geometry is possible.

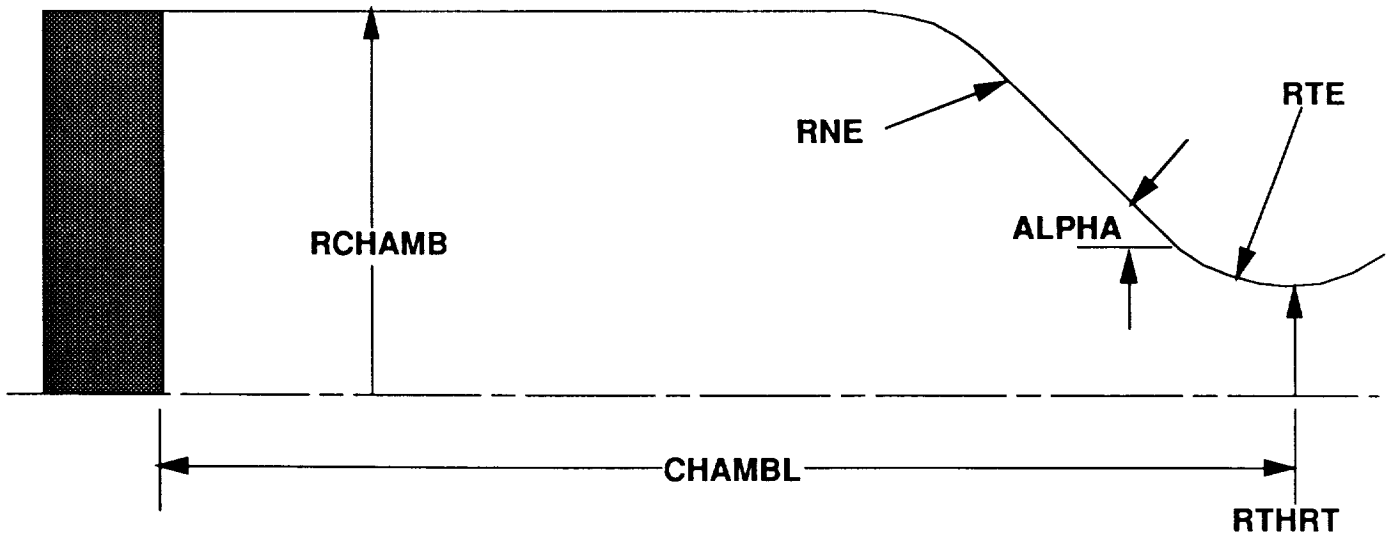


Figure 4.1. Chamber Geometry Schematic

3.50.0.7

4.2, Point Analysis Menu (cont.)

Injector Element Type (\$FINJ)

This option lets the user set the existence of baffle elements, barrier elements, and fuel film/cavity cooling elements. The menu options for these elements will only appear if the elements exist.

Core Element (\$CORE)

Sets the core element type, and the appropriate parameters for that type (Figures 4.2a, b, c, d, e, and f).

Baffle Element (\$BAFFLE)

Sets the baffle element type, and the appropriate parameters for that type (Figures 4.2a, b, c, d, e, and f). This option only appears if IBFE = 1.

Barrier Element (\$BARRIER)

Sets the barrier element type and the appropriate parameters for that type (Figures 4.2a, b, c, d, e, and f). This option only appears if IBRE = 1.

Fuel Film/Cavity Cooling Element (\$FFC)

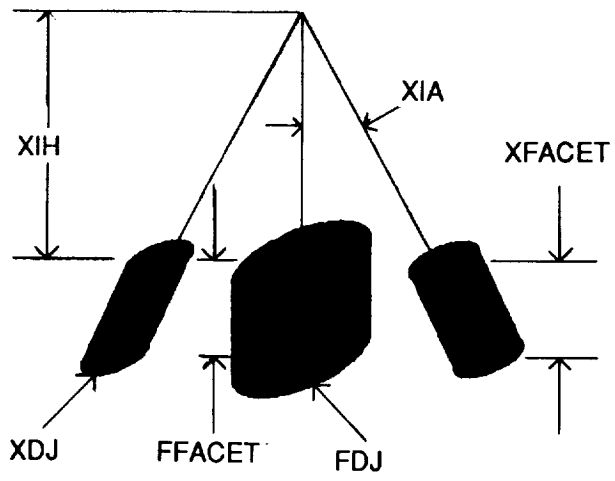
Sets the fuel film/cavity cooling element type and the appropriate parameters for that type (Figures 4.2c and d). This option only appears if IFFE = 1.

Stability Aid Type (\$STUFF, \$CHAMBER)

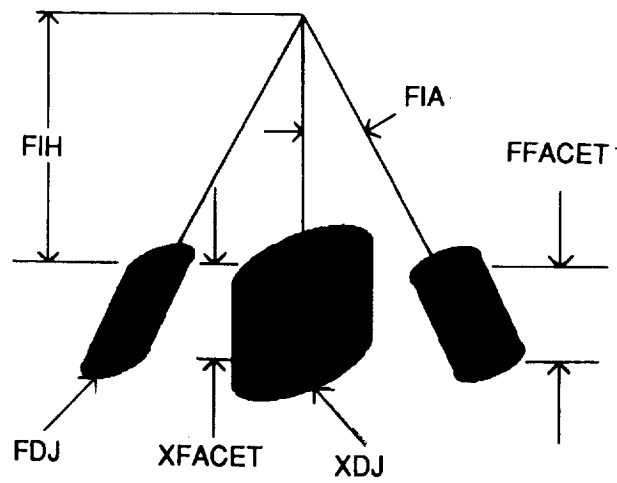
This option lets the user set the existence of radial baffles, 1/4 wave cavities, and helmholtz resonators. The respective menu options will not appear unless the stability aid exists. This option will also not appear if FDORC is being used (MCHAMB = 3).

Manifold Description (\$INJ, \$BURN)

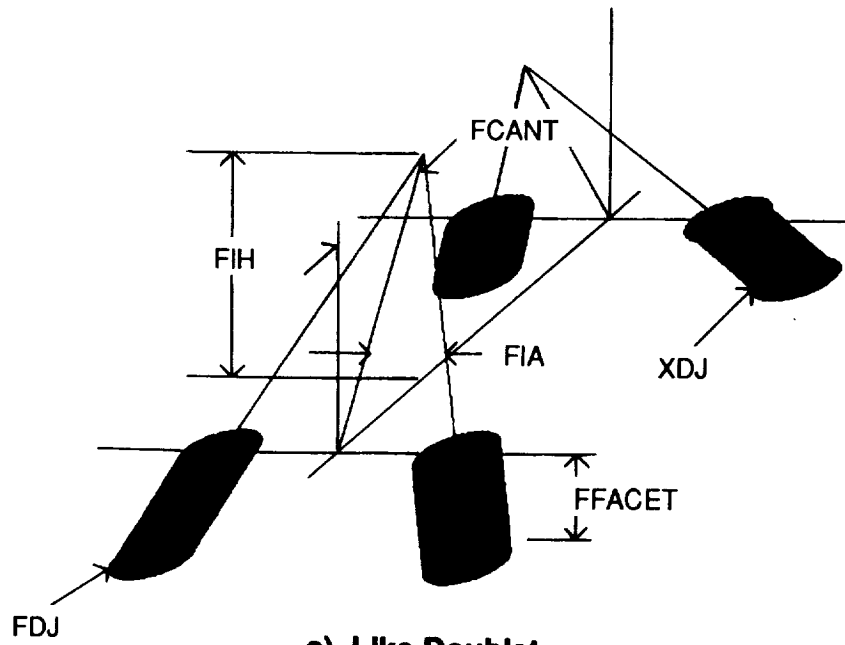
Sets manifold length and diameter only, if the path level is 1, while other variables in both namelists \$INJ and \$BURN can be accessed if the path level is set higher.



a) OFO Triplet

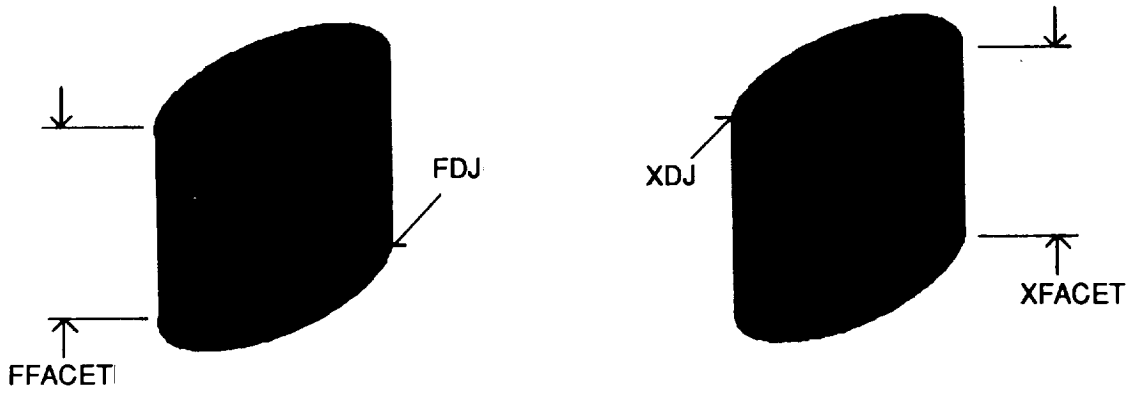


b) FOF Triplet

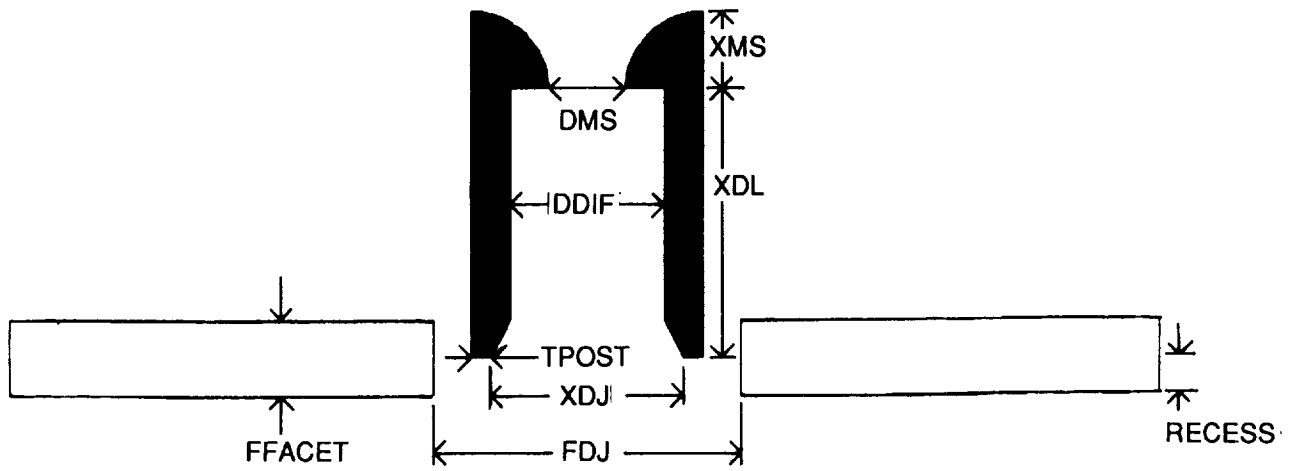


c) Like Doublet

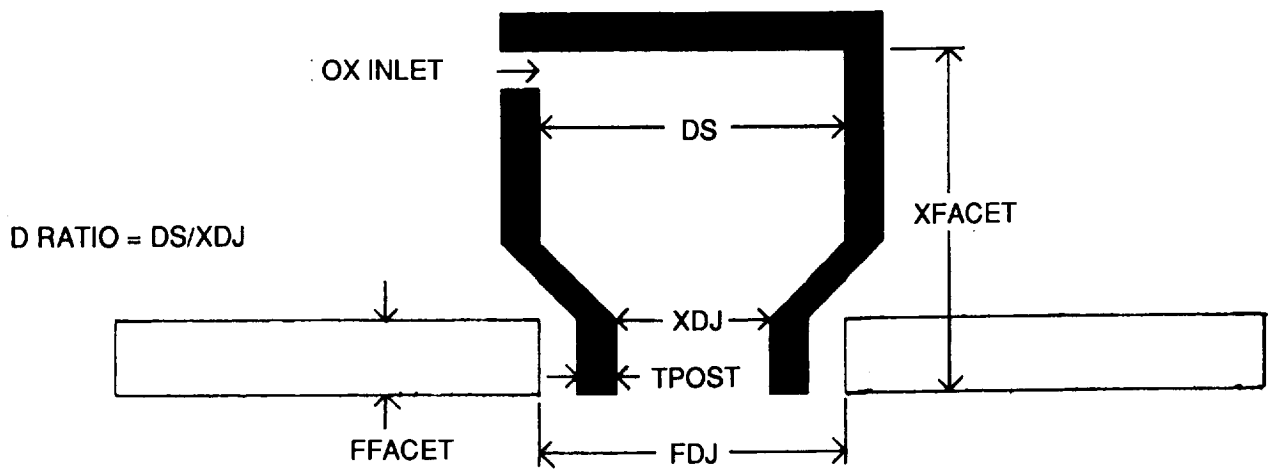
Figure 4.2. Element Definition Schematics



d) Showerhead



e) Shear Coaxial



$D \text{ RATIO} = DS/XDJ$

f) Swirl Coaxial

Figure 4.2. Element Definition Schematics (cont.)

4.2, Point Analysis Menu (cont.)

Baffle Configuration (\$CHAMBER)

Sets baffle dimensions (Figure 4.3). This option will only appear if IBAF = 1.

1/4 Wave Cavity (\$CHAMBER)

Sets and checks 1/4 wave cavity configuration and dimensions (Figure 4.4a and b). This option will only appear if ICAV = 1, and MCHAM = 1 or 2.

Helmholtz Resonators (\$CHAMBER)

Sets and checks Helmholtz resonators configuration and dimensions (Figures 4.5a and b). This option will only appear if ICAV = 2, and MCHAM = 1 or 2.

FDORC Input (\$FDORC)

Sets and checks the input used by the FDORC chamber response model. There are currently no interactive graphics or Figures for this option, so Reference 25 should be consulted for more information, although the naming convention is similar to Figures 4.4b and 4.5b. This option will only appear if MCHAM = 3.

Model Control Variables

This option allows the user to modify the default controls variables for the different analysis modules, e.g. number of integrations per cycle,. Immediately after entering this option the user can resume these variables from any previous session (file type .CNT), or use the defaults as a template by answering **NO** to the resume question.

Debug (\$DEBUGC)

Sets debug output flag. Debugging turns on the output to the debug file (file type .DBG), increasing printout to help trouble-shoot the analysis.

HIFI Control (\$HIFIC)

HIFI chamber response model control parameters.

DIST3D Control (\$DIST3DC)

3 dimensional baffle model (DIST3D) chamber response control parameters.

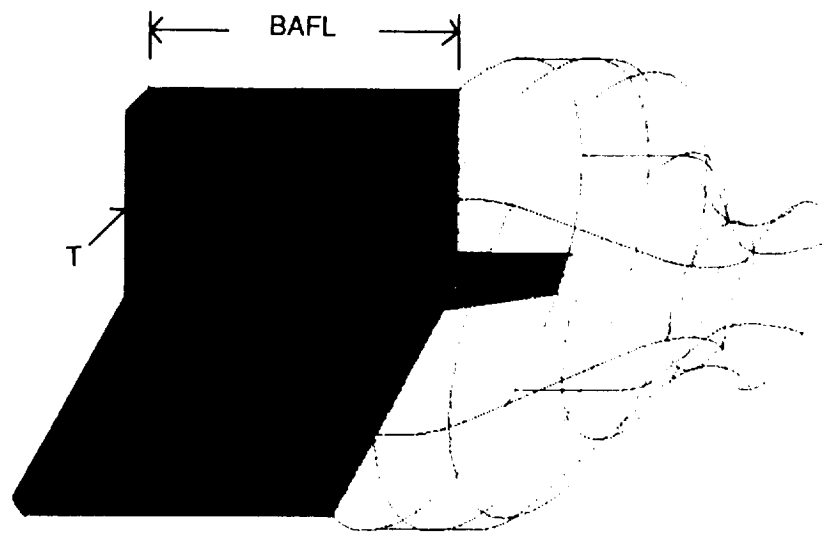
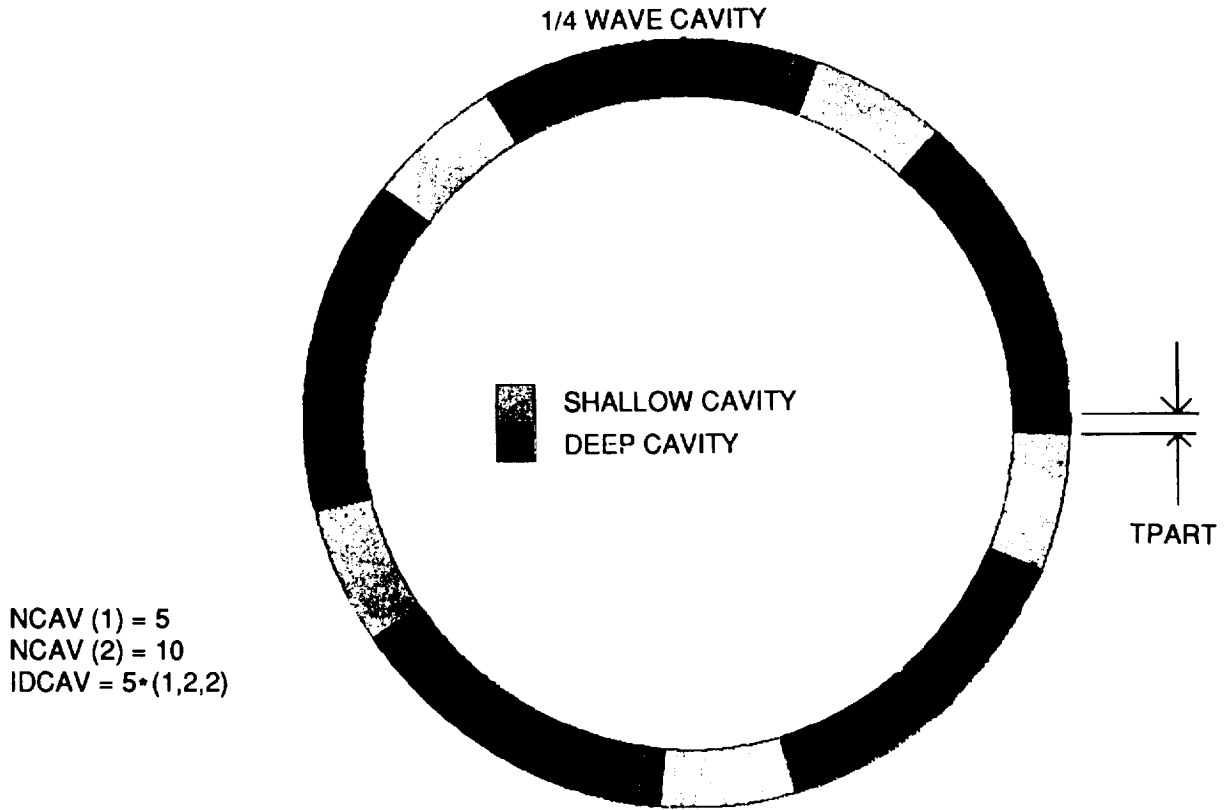
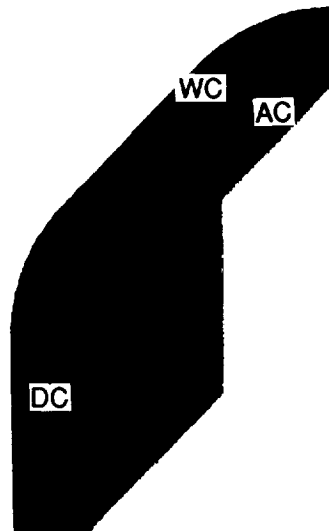


Figure 4.3. Radial Baffle Schematic

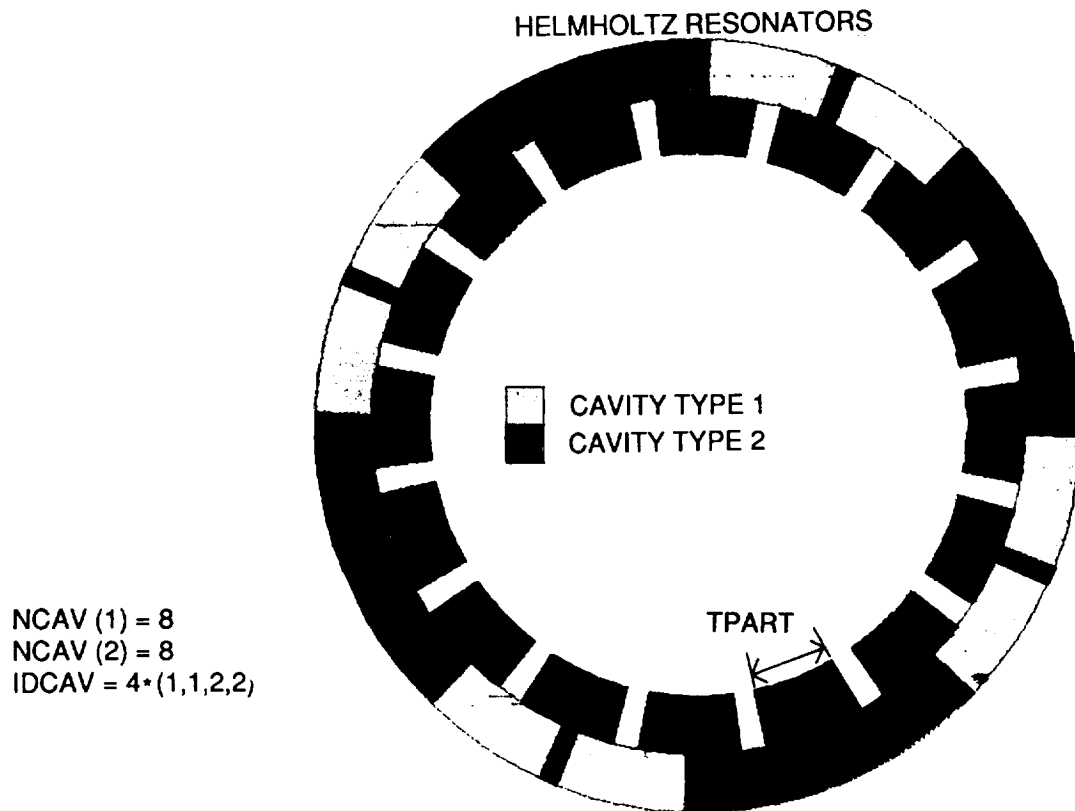


a) Cavity Relative Orientation Definition

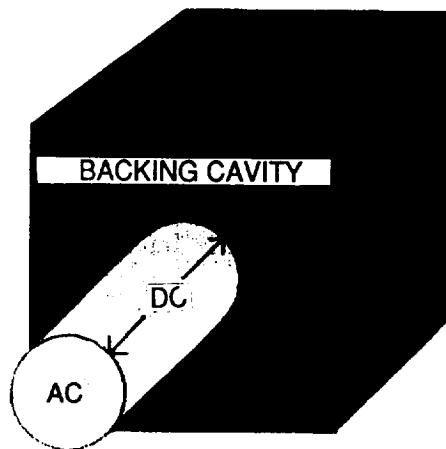


b) Individual Cavity Definition

Figure 4.4. 1/4 Wave Cavity Schematic



a) Resonator Relative Orientation Definition



b) Individual Resonator Definition

Figure 4.5. Helmholtz Resonator Schematic

4.2, Point Analysis Menu (cont.)

CRP Control (\$CRPC)

Combustion response prediction model control parameters.

LEINJ Control (\$LEINJC)

NASA/LeRC nonlinear injection response model (LEINJ) control parameters.

COMBUST Control (\$COMBUSTC)

Anchoring multipliers.

After the point analysis has been executed for a given design, if additional analyses with few changes in the input variables are desired, e.g., during parametric studies, the user has three options to do so: 1) rerun ROCCID and makes the changes interactively using REPLAY OPTION, 2) edit the files *. INP and * · CNT to make changes and rerun ROCCID with RESUME SESSION OPTION or, 3) Resume the session and make changes interactively.

Steady State Performance:

This option runs the steady state combustion analysis module (SSCI). The steady state analysis must be run before either combustion stability analysis modules can be run, since output from SSCI is used as input to the stability modules. See the Section 2.2 for more information on the steady state combustion analysis module.

Low Frequency Stability:

The low frequency combustion stability module (LFCS) can be run after the steady state performance analysis has been run. See Section 2.3 for more information on the LFCS module.

High Frequency Stability:

The high frequency combustion stability module (HFCS) can be run after the steady state performance analysis has been run. See Section 2.4 for more information on the HFCS module.

4.2, Point Analysis Menu (cont.)

Plot Output:

After running any of the analysis modules, results can be plotted using this option, if the user path is set for a Tektronix 40XX or 41XX terminal. Upon entering this option a menu of all existing plots will be displayed. The user may then draw the plot by choosing that menu option. After reviewing the plot a <RETURN> will redisplay the plotting menu. See Section 2.5 for more information on the available plots.

4.3 POINT DESIGN MENU

The point design section allows the user to design a rocket combustor. The user can enter a minimal amount of operating condition and geometry constraints, and this section of ROCCID will guide the user through design iterations, using the Point Analysis modules described in Section 2.0, until satisfactory performance and stability are achieved. It should be noted that this is not necessarily an optimized design. Again the same resume options, as described in Section 4.2 will appear when entering the point design module, however, design definition (file type .DES) and design default parameters (file type .DEF) input files will be opened in addition to the input and control files. The following subsections describe the point design menu options.

Set Variables:

This section allows the user to enter the combustor design constraints in preparation for the design iterations. Upon entering this option all point design files are closed; when leaving this option the user has the option of opening the files in preparation for a run or leaving them closed. Note, the files must be opened to perform any design iteration, or to save the variables for later use. As with the point analysis input, the user will be allowed to set the path level. The user will also be asked to supply a three line descriptive title (see Section 3.1).

The following namelist variables can be set through this option (see Appendix C for a complete list of all namelist variables). Additional information on the determination of input data can be found in Section 3.1. The namelist associated with each option is shown in parentheses next to the option heading.

4.3, Point Design Menu (cont.)

Complete Setup

The user will be prompted to set all variables below. Default and control variables are not included in this set.

Models (\$MODELS)

Selects stability model to be used.

Design Setup (\$DESIGN)

This option brings up a menu of assorted design variables that must be set before a design iteration can begin. The ten options under the design setup are:

Propellant Properties

Sets propellants, and suggested mixture ratios for the C* and ISP arrays.

Manifold Temperatures

Sets fuel and oxidizer manifold temperatures.

Pressure and Flow Rates

Allows user to set either chamber or manifold pressures and nominal and minimum flow rates.

Element Type

Sets element type. Valid types are like doublet pairs (LOL), ox-fuel-ox (OFO) and fuel-ox-fuel (FOF) unlike triplets, showerhead (SHD), shear coaxial (SHC), and hydraulic swirl coaxial (SWC).

Mixture Ratio

Sets overall mixture ratio.

4.3, Point Design Menu (cont.)

Performance Goal

Allows user to set either C* or ISP-based energy release efficiency goal (the other efficiency will be zeroed).

Chamber Size Constraints

Sets maximum chamber length and diameter.

C* and ISP Curves

Allows entry of C* and ISP vs mixture ratio curves. If a Tektronix 40XX or 41XX series terminal is being used these curves can be plotted for input validity checking.

Nozzle Length/Efficiency

Allows entry of overall nozzle efficiency versus nozzle length curve (See Section 3.1 for more details). If a Tektronix 40XX or 41XX series terminal is being used, this curve can be plotted.

Stability Aid Flags

Shows user preference/requirements for stability aids, including radial thrust chamber baffles, 1/4 wave cavities or helmholtz resonators into the design.

Fixed Geometry (\$FGEOM)

Allows part or all of the chamber geometry to be fixed (see Figure 4.1). Checks to make sure set geometry is physically possible.

Default Design Parameters

These variables affect the design guidelines that are used in combustor design. The variables are initially set to the default values, and these values can be altered in this menu. The user is provided with an opportunity to resume an old definition file (file type .DEF) immediately after entering this section. The options available under this menu choice are:

4.3, Point Design Menu (cont.)

Design Control (\$CONTROL)

Sets control parameters used in a design.

Element Parameter (\$LOLC, \$TRIPC, \$SHDC, \$SHEAR, \$SWIRL)

Sets element parameters (Figure 4.2a - f). Namelist and parameters set depend on element type.

Stability Aid Parameters (\$SAID)

Sets stability aid parameters.

Model Control Variables

This option is identical to the control menu options in the Point Analysis side (See Section 4.2).

Preliminary Sizing:

This module uses the design input to create a "first guess" design. Before any design iterations can be run, the preliminary sizing module must be exercised. However, because of the method in which the current values of certain input and design variables are saved (namelist \$SAVE at the end of the .DES file), **extreme care** should be used if the preliminary design is run more than once, since these values will override values in \$DESIGN and \$FIX. See Section 3.2 for more information on the preliminary design module.

Performance Iteration:

After the preliminary sizing is complete this module allows the user to iterate the injector configuration and the chamber geometry until an acceptable performance is achieved. As with the Point Analysis, this option must be run before the stability iterations can be started, since output from the steady state combustion model serves as input for the stability models. If combustion stability is a larger driver than performance, the performance iteration can be exited after the first pass (accept current results), and then iterated upon after stability iterations have been performed. See Section 3.3 for more information on this module.

4.3, Point Design Menu (cont.)

Chug Stability Iteration:

The chug stability iterations may be run after the performance iteration is complete. See Section 3.4 for more information on the chug stability iteration module.

High Frequency Stability Iteration:

The high frequency stability iteration may be run after the performance iteration is complete. See Section 3.5 for more information on the high frequency combustion stability iteration module.

Plot Output:

After running any of the iterations, results from the analysis modules can be plotted using this option, if the user path is set for a Tektronix 40XX or 41XX terminal. Upon entering this option a menu of all existing plots will be displayed. The user may then draw the plot by choosing that menu option. After reviewing the plot a <RETURN> will redisplay the plotting menu. See Section 2.5 for more information on the available plots.

4.4 UTILITIES MENU

This module contains a version of ODE to create combustion gas tables and an auxiliary plotting module.

Create ODE Combustions Tables:

This option allows the user to generate combustion gas tables for new propellant combinations, using ODE. See Appendix D for instructions on using this module.

Display Results:

This option allows the user to plot analysis model output files. Any ROCCID plot file can be displayed. It prompts the user for the file name of the plot data to display, and the file type must be included. The nomenclature used in naming plot data files is shown in Appendix E.

5.0 OUTPUT FILE DESCRIPTION

5.1 POINT ANALYSIS OUTPUT

The summarized output file (file type .OUT) provides the user with a convenient summary of the ROCCID POINTA module input and final results. In general, the output is self explanatory, however, a brief description is provided here for the user's reference. The output file description included in this section refers to the POINTA sample case 1, ACASE1, which is contained in Appendix I.

Direct Input Echo:

The direct echo portions of the output are line for line copies of the input file (file type .INP).

Steady State Combustion Analysis Output (SSCI):

SSCI output begins with a formatted (organized) listing of the module inputs. The formatted output includes only the variables that are used by SSCI, i.e. inputs specific to the stability modules are left out. It is organized to provide the user with an easy to comprehend description of the combustion chamber geometry and operating conditions. Next, the fuel and oxidizer type and respective manifold temperatures are printed. The sample case uses RP-1 at 70F and LOX at -272F. Chamber geometry is provided in a single section, and followed by description of the injector element type(s), including critical dimensions and discharge coefficient. Finally, the overall zone mixing efficiencies input by the user are output.

The formatted output is followed by pertinent results from calculations performed by COMBUST. The heading **Begin Steady State Combustion Analysis** identifies the beginning of calculations for each of the chamber pressures analyzed. The first set of calculations are performed for the nominal chamber pressure. The injector face chamber pressure is 1800 psia for the sample case. The propellant properties (density, viscosity, and surface tension) at the chamber pressure and manifold temperature are provided. The required injector pressure drop and respective injection velocity for the current chamber operating pressure and mixture ratio are printed.

The atomization output is provided next. The output records the selected droptime model for each element category, i.e core, baffle, barrier and FFC. For the case at hand the Aerojet model was used for element type 1 (core). The element type is printed along with the

5.0, Output File Description (cont.)

computed atomization length and drop sizes. The Aerojet model utilizes a distribution of drop-sizes, so all drop-sizes and their breakdown are listed. The vaporization model output follows. It prints the calculated percent vaporized of fuel and oxidizer versus axial position for each zone of the element categories. The sample case contains only core elements, so all other element categories contain zeros. The section titled **Mass Distribution Profile** contains the fuel and oxidizer vapor mass flowrates as a function of axial position for the core and barrier zones. The vaporized mass at each point is used to determine the local vapor mixture ratio and the effective characteristic velocity efficiency (ETA-C*). The mass distribution profile is followed by a section titled **Axial Pressure Profile**, which contains the converged output from the RAYLEE routine. This output includes axial profiles of total and static pressure and temperature, 1-D Mach number and total mass flowrate.

A summary of performance components is contained in the next section. The injected mixture ratio (MR) and corresponding characteristic velocity (C*) are listed in the first line. This line also includes the overall mixing factors (Em) for the core and barrier zones. The results of the vaporization and mixing calculations are printed for both the core and barrier zones. The quantity **CSTAR-MIX** is the mass averaged two-stream C* efficiency, and does not reflect any loss resulting from incomplete propellant vaporization. The engine C* is the mass weighted performance from all zones and includes the effects of incomplete mixing and vaporization, as defined in Section 2.2. Since the core contains all of the mass in this case, the difference between the engine and core C* reflects the mass defect from incomplete vaporization. The specific impulse (ISP) calculations are presented next. The One Dimensional Kinetic (ODK) specific impulse for the overall injected mixture ratio (MR) is printed. The next line contains the mass-weighted multi-zone (M.Z.) injected and throat vaporized specific impulses, with the multi-zone ISP defined by Equation 2.10. The injected multi-zone ISP is calculated by substituting the injected zone mixture ratios for the throat vapor MR's in Equations 2.4 and 2.5. A lower vaporization efficiency will result in a throat vaporized ISP lower than the injected ISP. The overall ISP-based mixing and vaporization efficiencies, and energy release efficiency are contained in the following lines. A note, defining the nomenclature for determining delivered ISP (ISP-Del), is included to ensure proper usage of the resulting efficiency:

$$\text{ISP-Del} = \text{ISP-ODK}_{\text{inj}} * \text{ERE} * \text{ETA-Div} - \text{dISP-BL} \quad (5.1)$$

5.0, Output File Description (cont.)

where the subscript "inj" refers to the overall injected MR, ETA-Div is the divergence efficiency, dISP-BL is the ISP decrement due to boundary layer losses and ISP-Del, ISP-ODK_{inj}, and ISP-BL are vacuum quantities.

The last section of the current Pc analysis includes information on the timelags and variables used in their calculation. Timelags are presented for both propellant circuits of each element category. The vaporization model is used to calculate the vaporization length (L_{vap}) required for 20% of the propellant to vaporize. The equation used to calculate the vaporization length is derived from the Generalized Length Correlation (Ref. 1):

$$L_{vap} = 23.778 * L_{gen} * C_{cham} * C_{chem} * C_{inj} \quad (5.2)$$

$$C_{cham} = \epsilon_c^{0.44} / P_c^{0.66} \quad (5.3)$$

$$C_{chem} = (1 - T_j / T_{crit})^{0.4} * H_v^{0.8} * MW^{0.35} \quad (5.4)$$

$$C_{inj} = R_m^{1.45} * (V_j * \cos(\theta))^{0.75} \quad (5.5)$$

where L_{vap} is in inches, ϵ_c is the contraction ratio, P_c is the chamber pressure, in psia, T_j and T_{crit} are the propellant injection and critical temperatures, respectively, in degrees R, H_v is the heat of vaporization, in BTU/Lbm, MW is the propellant molecular weight, R_m is propellant droplet radius, in inches, V_j is the injection velocity, in ft/s and θ is the resultant injection angle, in degrees. The terms C_{cham}, C_{chem} and C_{inj} represent the contributions of the chamber, propellant and injection velocity to the propellant vaporization, respectively. The total timelag is a sum of the impingement, atomization and vaporization timelags. If the propellant is gaseous, only an impingement timelag is calculated ($\tau_{imp} = \tau_{total}$), and it corresponds to the time for the gaseous propellant to reach the axial location corresponding to the liquid propellant total timelag:

$$\tau_{imp_{gas}} = \tau_{total_{liquid}} * V_{j_{liquid}} / V_{j_{gas}} \quad (5.6)$$

where τ_{imp} and τ_{total} are the impingement and total timelags, respectively. An effective timelag for both the fuel and oxidizer circuits is computed with mass-weighted average of the component timelags for each element type (category). The effective and individual timelags are identical in this case, since there is only one element type.

5.0, Output File Description (cont.)

The steady state performance calculations are now repeated for two mid-pressure values, in this case 1440 and 1080 psia. These calculations are necessary to create a table of time-lags for the combustion stability calculations. The format of the output is identical to that of the nominal pressure case.

Low Frequency Combustion Stability Module Output (LFCS):

This section reflects the results of the low frequency combustion stability calculations. The output starts with a direct echo of the input files, including any modifications SSCI has made to the input files and the model control inputs (contained in file type .CNT). The stability input is repeated in a formatted form. The models to be used in the analysis are identified, N-Tau for burning response, INJ for injector response and HIFI for chamber response in the sample case. The output confirms that chamber is axisymmetric and the user has not requested the optional DEBUG output. It should be noted that ROCCID capabilities are limited to only axisymmetric chambers. The chamber geometry and operating conditions are again given. The inputs for the individual response models is contained in the next blocks of output. Note that the selected burning response model and its inputs are included in the output, even though LFCS does not use them (See Section 2.3). In the sample case, the INJ injection response model inputs include the inertance, resistance, capacitance and total timelag arrays (for each element category) at each chamber pressure. The HIFI input indicates that the nozzle admittance is computed for the real nozzle geometry rather than using a short nozzle approximation. HIFI input also describes the acoustic cavity/resonator design configuration. In the sample case, no cavities are included. Note that the cavity designs are printed even though LFCS ignores their presence in the current analysis (See Section 2.3).

The next output section records the results of the chug iteration calculation. In the sample case, the chamber pressure is gradually lowered until the operating condition lies on the neutral stability curve, as indicated by a maximum in-phase gain amplitude of 1.0. The output includes the maximum gain amplitude and the associated frequency for each chamber pressure evaluated. The iteration stops when the neutral stability condition is found. The engine in the sample case was throttled to 322 psia before the marginal condition was reached, and the corresponding chug frequency is 520 Hz.

5.0, Output File Description (cont.)

High Frequency Combustion Stability Output (HFCS):

The initial output from HFCS is the same as that described for LFCS. The output begins with direct echo and formatted versions of the module input data. Since HFCS does consider the effects of stability aids, it is appropriate to briefly discuss their formatted output. The description of the acoustic cavities used in the sample case includes the input variables, e.g. cavity width, depth, cross sectional area and inlet type, etc., and the parameters derived during the steady state combustion iteration, e.g. cavity sonic velocity. The user should examine these variables to ensure that the values used are correct. The tabulated output also includes the variables contained in the model control file (file type .CNT), e.g. the oscillation amplitude to mean pressure ratio (P'/P_c). Output for combustors with radial baffles and/or Helmholtz resonators will contain similar tables. It is always recommended that the user check these values to ensure that the problem definition is as they expect.

Output begins with direct echo and formatted versions of the module input data. HFCS performs stability calculations for each applicable mode (See Section 2.4), starting with the pure longitudinal mode (0 Tangential + 0 Radial), and progressing to successively higher modes. Each mode consists of iterative calculations of maximum in-phase gain with varying growth coefficient (λ). When the maximum in-phase gain reaches a magnitude of 1.0, the iterations are deemed converged and the calculations proceed to the next mode. Results for each growth coefficient iteration are printed. The output records the growth coefficient, maximum in-phase amplitude of the gain function, $Z_c^*(Y_b+Y_j)$, and the corresponding frequency. The ratio of the burning admittance (Y_b) to injector admittance (Y_j) magnitudes is also output. This ratio provides an indication of whether the stability characteristics are dominated by burning or injection-coupling. If the ratio is greater than one, the stability is dominated by burning-coupling. Conversely, if the ratio is less than one, the stability is dominated by injection-coupling. Similar output is provided for the first and second tangential modes of the sample case. Note that the sample case HFCS output includes a warning that the stability iteration did not converge for the second tangential. The user can obtain more information on the error and warning message by referring to the Error Message Description (Appendix B), which includes a description of any action which may correct this situation.

5.0, Output File Description (cont.)

5.2 POINT DESIGN OUTPUT

The POINTD summarized output file (file type .OUT) records the design iteration process and the resulting changes in performance and combustion stability. The output is similar to the POINTA option (Section 5.1), since the same analysis module are used. In general, the output is self-explanatory, however, a brief description is provided here for the user's reference. The output file description provided in the following paragraphs refers to the POINTD sample case 1, DCASE1, which is contained in Appendix I.

POINTD output begins with a direct echo of the design and model control input files (file types .DES and .DEF and .CNT). The direct echo is followed by a formatted version of the input. The user selected or default stability analysis models are identified. The sample case uses the N-Tau burning response model, the INJ injector response model, and the HIFI chamber response model. The flag for debug output is also listed, followed by the user selected propellant type and manifold temperatures. The next output section contains the user defined operating condition requirements, including element type, overall mixture ratio, nominal and throttled propellant flowrates, efficiency goal and basis, and maximum envelope. This section also includes the user specifications for either the nominal chamber pressure or maximum manifold pressures. The sample case consists of a Like-On-Like (LOL) injector element, an injected MR of 2.88, a nominal Pc of 2118 psia, and nominal and throttled flowrates of 179.3 and 129.9 Lbm/s, respectively. The maximum engine dimensions are 0.75 ft for the chamber diameter and 4.0 ft for the engine length. The efficiency goal is 95.86%, and the efficiency basis is characteristic velocity (C^*).

The section titled **Stability Aid Preference** indicates the stability aids which the user anticipates will be required to achieve dynamically stable combustion (See Section 3.1). The sample case is expected to require neither baffles nor cavities. The **Fixed Chamber Geometry** section defines any user-specified geometry constraints. The sample case contains specifications for the nozzle and throat entrance radii of curvature and the nozzle convergence half-angle.

The **Design Control Parameters**, contained in file type .DEF, composes the last set of the formatted POINTD input. It includes the ratio of the injection pressure drop to the chamber pressure at the throttled (minimum) Pc and chamber and element design constraints. If the user had not constrained the chamber geometry, as described in **Fixed Chamber Geometry**, the design module would use the nondimensional values for nozzle and throat entrance radius of

5.2, Point Design Output (cont.)

curvature, and the default value for nozzle convergence half-angle. The element **design definition variables**, for an LOL pair in the sample case, includes element "operating" parameters, such as fuel and oxidizer discharge coefficients (C_d), unielement mixing factor (E_m) and geometry definition parameters, like impingement angles and orifice length to diameter ratios. Stability aid design constraints are also listed. See Sections 3.1 and 4.3 for more details on the model input requirements and definitions.

The **results** of the preliminary design sizing are reported in three sections. The first describes the combustor operating conditions and chamber geometry. This is followed by a definition of the core **element sizing** and the **element spacing**. PRELIMD output includes an estimate of the injection velocity. Similar output is printed by REDESIGN after each injector redesign iteration, so the evolution of the combustor design can be tracked.

The preliminary design must be followed by the steady state performance iteration, as discussed in Section 3.0. Each time COMBUST is called at the nominal chamber pressure, it will echo the module inputs, print the input in formatted form and perform the nominal chamber pressure run. Since this output is discussed in Section 5.1, no further discussion is included here. The nominal P_c performance summary would be followed by the output of the combustor length-nozzle length optimization run, if the user included the necessary data. The output tabulates the C^* , nozzle, and resultant overall efficiencies as a function of combustor (designated as **chamber** in the output) length. It lists the optimum combustor length and the corresponding overall efficiency.

The "Redesigned Chamber Results" and "Performance Calculation" sections are repeated successively until the performance goal is met. The sample case, the user selected a slightly higher nominal chamber pressure ($P_c=2141$ psia) for the final performance calculation, in order to meet the mass flow input nominal requirements. When the design iteration has yielded acceptable performance at the nominal operating P_c , COMBUST is run for two lower chamber pressure (throttled) conditions.

The low frequency stability iteration begins by running LFCS for the current design (See Section 3.4). The output of LFCS has been discussed in Section 5.1, so it will not be repeated here. CHUGIT prints a summary of the chug results at the conclusion of the low frequency calculation. It includes a determination of the current chug margin relative to the desired margin, and the chug frequency. The sample case is "stable" and the marginal chug pressure is

5.2, Point Design Output (cont.)

much lower than the desired chug margin, i.e. the configuration is more stable than necessary. The user is interactively queried whether the configuration is acceptable or if a design iteration is desired. If the user selects to iterate on the design, as in the case of the sample case, REDESIGN is called, and the new design configuration is output. The low frequency calculations are then repeated, and the iteration process continues until the user finds a design with acceptable chug margin.

The high frequency stability iteration (HIFIT) begins by running HFCS for the current design (See Section 3.5). The resultant output is the input echo, formatted input and modal analysis, as discussed in Section 5.1. As noted in the discussion on HIFIT, the growth coefficient iteration is not initially performed, so the output will differ slightly from that described in Section 5.1. HIFIT summarizes the results of the high frequency stability calculation, including the mode, gain magnitude, frequency and coupling mechanism of any observed instabilities. The first iteration of the sample case found a burning-coupled instability in the first tangential mode with a frequency of 4196 hz. The user is given the option of changing the combustor design or adding damping devices. The new combustor design features or damping device design are printed, and the calculations are repeated. The sample case uses a monotuned quarter-wave acoustic cavity to improve stability during the first iteration. This process is repeated until acceptable high frequency stability is achieved.

If the configuration is found to be stable, the stability calculation outputs, including gain, frequency and $|Y_b|/|Y_j|$, are tabulated for each mode. The user may evaluate the growth coefficients for statistically stable designs, i.e. the maximum gain magnitude is less than 1.0. This output is identical to the output described for HFCS in section 5.1.

As the user cycles through the performance, chug and high frequency stability iterations, the output, as described above, is repeated. The sample case consists of a pass through PRELIMD, PERFIT, CHUGIT and HFCS, followed by a return to PERFIT. The second pass through PERFIT is required to evaluate the performance impact of the design changes implemented to achieve acceptable stability, and rigorously update the derived stability model inputs. The repeat of the chug and high frequency stability iterations has been deferred to another sample case, DCASE1A, which is just a copy of the DCASE1 input, design, definition and control files (file types .INP, .DES, .DEF and .CNT, respectively).

6.0 LIMITATIONS

ROCCID contains several limitations in its current form. It is capable of analyzing liquid rocket axisymmetric combustors which use liquid oxygen as the oxidizer and either hydrogen, propane, methane or RP1 as the fuel. Injectors can consist of a mixed element patterns, but the element types are limited to like doublet pairs (LOL), unlike triplets (both OFO and FOF), showerheads, shear coaxial and hydraulically swirled coaxial. The coaxial elements are limited to gaseous fuel-liquid oxidizer operation, and the oxidizer must be in the center. Combustion chamber cooling methods are not explicitly addressed in ROCCID, although their influences can be accounted for. Due to limitations imposed by the chamber response models, combustion chambers must have a finite cylindrical section, and a substantial portion (>80%) of the combustion must be completed in the cylindrical section. Additionally, ROCCID injectors must be flat faced. ROCCID can currently evaluate the influence of axial and radial inlet 1/4 wave acoustic cavities or Helmholtz resonators, as long as they begin at the injector-combustion chamber interface, and radial thrust chamber baffles. In addition, ROCCID is capable of analyzing rocket combustor with unconventional acoustic cavities. It is not, however, capable of designing unconventional acoustic cavities. There are no capabilities for evaluating baffle hubs or axially distributed acoustic liners.

The Combustion Response Prediction (CRP) model has been included as a burning response model option. While it works correctly, in its current form it may require an excessive amount of computer time (in excess of 1 CPU hr on a VAX 8650). Simplified methods have been developed, but are not included in the current code.

The module FDORC was recently included in ROCCID. The use of FDORC as contained within ROCCID has the following limitations. 1) It can be used only in the point analysis mode. 2) Only first longitudinal, pure tangential, pure radial, and mixed tangential and radial modes are automatically evaluated. Higher longitudinal modes, and mixed longitudinal and transverse modes can be evaluated but the modes must be specified by the user. 3) Two test cases using FDORC within ROCCID were run with different degrees of success. The sample case shown in Appendix I (successfully run using HIFI in ROCCID), which is the LOX/RP1 3-D subscale hardware without damping devices (see Ref. 22), was successfully run using FDORC (i.e., set MCHAM = 3 in NAMELIST \$MODELS) within ROCCID. However, when FDORC was run using cavity type ICTYPI = 4 (absorber flag, ICTYPI = 4 is for input geometry and temperature) it was not successful. The run was terminated with a FORTRAN error message: arithmetic fault, floating overflow. Due to budget and schedule constraints, no attempts has been made to investigate the problem for this release of ROCCID.

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1. Report No. NASA CR -187109		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle User's Manual for Rocket Combustor Interactive Design (ROCCID) and Analysis Computer Program Volume I—User's Manual				5. Report Date May 1991	
				6. Performing Organization Code	
7. Author(s) J.A. Muss, T.V. Nguyen, and C.W. Johnson				8. Performing Organization Report No. None	
9. Performing Organization Name and Address Gencorp, Aerojet Propulsion Division Sacramento, California 95813 - 6000 and Software and Engineering Associates Carson City, Nevada 89701				10. Work Unit No. 582 - 01 - 21	
				11. Contract or Grant No. NAS3 - 25556	
				13. Type of Report and Period Covered Contractor Report Final	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135 - 3191				14. Sponsoring Agency Code	
15. Supplementary Notes Project Manager, Mark D. Klem, Space Propulsion Technology Division, NASA Lewis Research Center, (216) 433 - 2450. J.A. Muss and T.V. Nguyen, Gencorp Aerojet Propulsion Division; C.W. Johnson, Software and Engineering Associates.					
16. Abstract This report is the User's manual for the Rocket Combustor Interactive Design (ROCCID) computer program. The program, written in FORTRAN 77, provides a standardized methodology using state-of-the-art codes and procedures for the analysis of a liquid rocket engine combustor's steady state combustion performance and combustion stability. ROCCID is currently capable of analyzing mixed element injector patterns containing impinging like doublet or unlike triplet, showerhead, shear coaxial and swirl coaxial elements as long as only one element type exists in each injector core, baffle or barrier zone. Real propellant properties of oxygen, hydrogen, methane, propane and RP - 1 are included in ROCCID. The properties of other propellants can be easily added. The analysis models in ROCCID can account for the influences of acoustic cavities, helmholtz resonators and radial thrust chamber baffles on combustion stability. ROCCID also contains the logic to interactively create a combustor design which will meet input performance and stability goals. A preliminary design results from the application of historical correlations to the input design requirements. The steady state performance and combustion stability of this design is evaluated using the analysis models, and ROCCID guides the user as to the design changes required to satisfy the user's performance and stability goals, including the design of stability aids. Output from ROCCID includes a formatted input file for the standardized JANNAF engine performance prediction procedure.					
17. Key Words (Suggested by Author(s)) Combustion stability; Rocket engine design; Liquid propellant rocket engines; Launch vehicles; Booster rocket engines; Propellant combustion; Engine design; Dynamic stability; Acoustic velocity; Velocity coupling			18. Distribution Statement Unclassified - Unlimited Subject Categories 5 and 20		
19. Security Classif. (of the report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of pages 90	22. Price* A05