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INVESTIGATION AND MODELING OF SPACE SHUTTLE MAIN ENGINE SHUTDOWN TRANSIENT CHUGGING

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BY

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ABSTRACT

The space shuttle main engines experience a low frequency pressure pulsation in both the fuel and oxidizer preburners during the shutdown transient. This pressure pulsation, called chugging, has been linked to undesirable bearing loads and possible damage to the spark ignitor supply piping for the fuel preburner. This report briefly describes the problem then proposes a model which includes: 1) a transient stirred tank reactor model for the combustion chamber, 2) a resistance capacitance model for the supply piping and 3) purge gas/liquid oxygen interface tracking.

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INTRODUCTION

The Space shuttle main engines have successfully completed 20 flights and several hundred test stand firings. They are stable for steady-state and programmed load change firing from minimum power level (~360,000 lbf thrust) to full power level (512,000 lbf). Upon shutdown, the engine oxidizer system is purged with helium prior to cutoff of the fuel. During this purge, the engines experience a low amplitude pressure pulsation in the preburners which is reflected as a slight variation in main combustion chamber pressure. Since the thrust is intentionally reduced to zero, this pulsation has no effect on space shuttle performance; however, the pulsations have been linked to undesirable bearing loads and damage to the augmented spark ignitor oxidizer supply piping.

This report begins with a brief description of main engine operation with emphasis on the shutdown transient. The chugging problem is then discussed along with a summary of the results from a previous investigation of the problem. Finally, a model for the transient behavior which can follow low frequency pressure pulsations in the time domain is proposed along with a discussion of the difficulties which were encountered in attempting to numerically solve the governing equations.

SSME DESCRIPTION

Figure 1 is a propellant flow schematic of the space shuttle main engines showing the major equipment and the propellant flow rates for full power level. Liquid hydrogen enters the engine from the external tank (flight configuration) via a low pressure pump which supplies a high pressure pump with sufficient head to prevent cavitation. The hydrogen leaves the pump at approximately 8000 psia and cools the nozzle, combustion chamber and throat prior to entering the preburners. The preburners partially oxidize the hydrogen to provide power to the turbines which drive the high pressure pumps. Almost all of the hydrogen enters the engine via the preburners. The oxidizer follows a similar path through a low then a high pressure pump; however, oxygen is not used for component cooling and most of the oxygen enters the main combustion chamber directly.

Engine power is controlled by throttling the oxidizer via the preburner oxidizer valves (FPOV and OPOV). The preburners operate at an equivalence ratio of about 8.0; the power available to the turbopumps and hence the reactant flow rate is controlled by the availability of oxygen to the preburners. Under steady conditions the preburners are operating very fuel rich. Oxidizer flow is halted prior to the fuel flow; therefore, combustion in the preburner and in the main chamber is extinguished by shifting the equivalence ratio beyond the rich combustion limit.

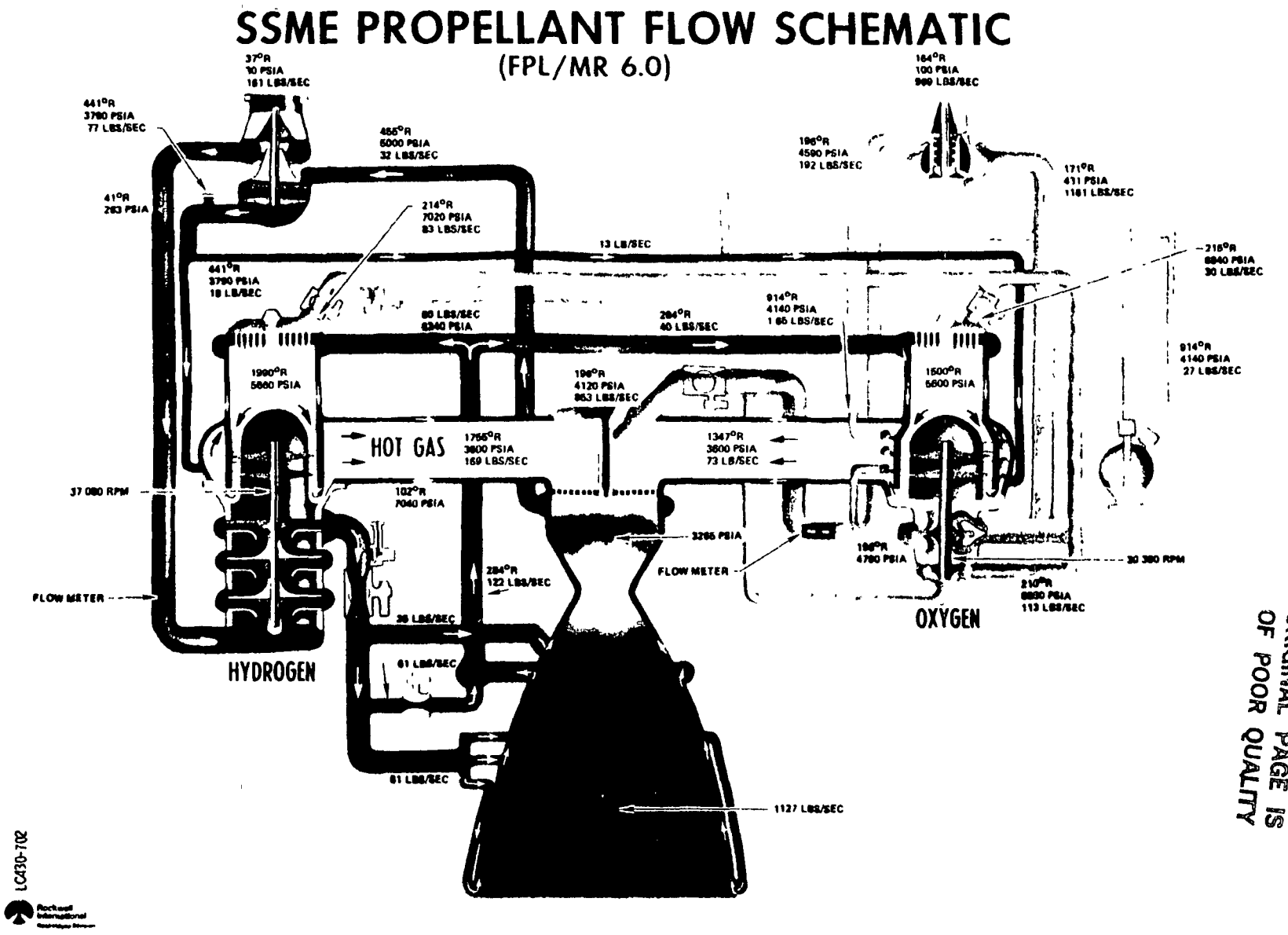


Figure 1: Propellant Flow Schematic

For flight conditions, the engines are typically throttled back prior to shutdown. Throttling is dictated by shuttle maximum acceleration limitations, not engine operation, and ground tests are frequently shutdown from 100% of rated power level or more. Figure 2 shows the valve sequence for a typical shutdown from near 100% of rated power. The oxidizer preburner oxidizer valve (OPOV) is ramped closed first followed shortly by the fuel preburner oxidizer valve (FPOV). Once the two preburner oxidizer valves are closed, the preburners are isolated from the oxygen system; the only oxidizer available to the preburners is the residual trapped between the oxidizer valve and the combustion chamber. This oxygen is expelled into the preburner combustion chamber by a helium purge.

Figure 3 is a detail of the purge and ignitor piping for the fuel preburner. A similar arrangement exists for the oxidizer preburner. As Figure 3 shows, there are check valves in the two helium purge supply lines which remain closed until pressure downstream of the valves has dropped to about 750 psia. These are poppet type valves and remain open even when the pressure drop across the valves is less than the cracking pressure. This inherent hysteresis avoids valve chatter while preventing any reverse flow. Oxygen is cleared from the ASI line and the preburner oxidizer valve into the preburner chamber where it combusts with the fuel. Although the flow rate varies, substantial fuel flow is maintained until after purge is complete.

Pressure pulsations in the fuel preburner, called chugging based on their relatively low frequency ($\frac{1}{4}$200 Hz), begin about 2.3-2.5 seconds after the cutoff command on ground tests. Flight data for chugging were not available; however, conditions are expected to be similar though perhaps more severe. Figure 3 shows the region where chugging is experienced. Although the start of chugging appears to correspond to the closing of the MOV, recall that the preburners are completely isolated from the oxidizer system at the time the valve closes; hence, the closing of the MOV is ruled out as a triggering mechanism.

A previous investigation (George, 1984) concentrated on identifying any possible triggering mechanisms and on determining operating procedures and hardware changes which had affected the chugging characteristics. That study concluded that there was probably not a simple "event" trigger for the chugging; rather, that the system passed through a region where chugging was possible and that natural fluctuations in the system were amplified into the observed chug. The rate of helium flow was found to affect the chug. Changing the helium purge orifice from 0.068" to 0.291" (Figure 3) reduced the amplitude but lengthened the duration of the chug. Although helium flow was increased by this change, the chug ending time was not affected by the increased flow, suggesting that some mechanism other than oxygen depletion is responsible for terminating the chug. Cut-off power was also shown to be significant with lower cutoff levels tending to exacerbate the chugging. For this reason, flight shutdowns are expected to experience more severe chugging.

Typical fuel preburner combustor pressure traces are shown for two tests in Figure 4. Figure 4a is for the small purge orifice. There are three significant factors which should be noted here. First, there is a low

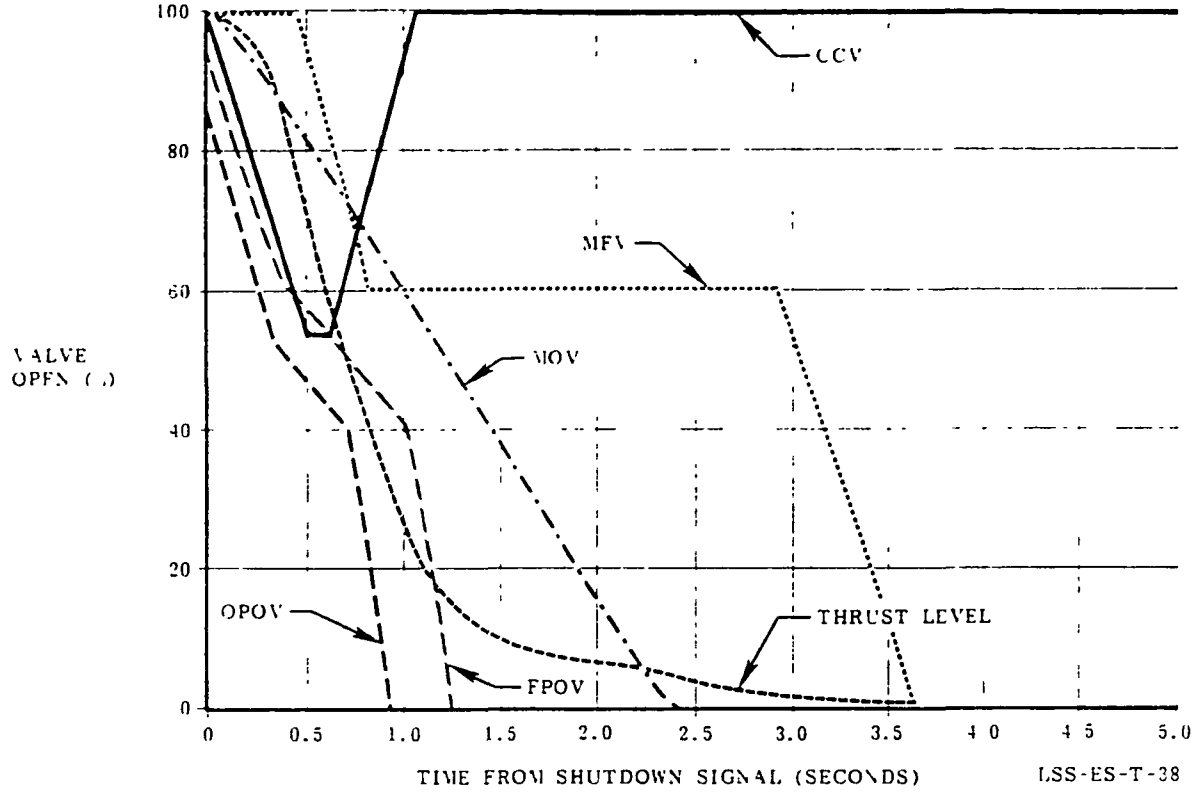


Figure 2. Typical SSME Shutdown Valve Sequence

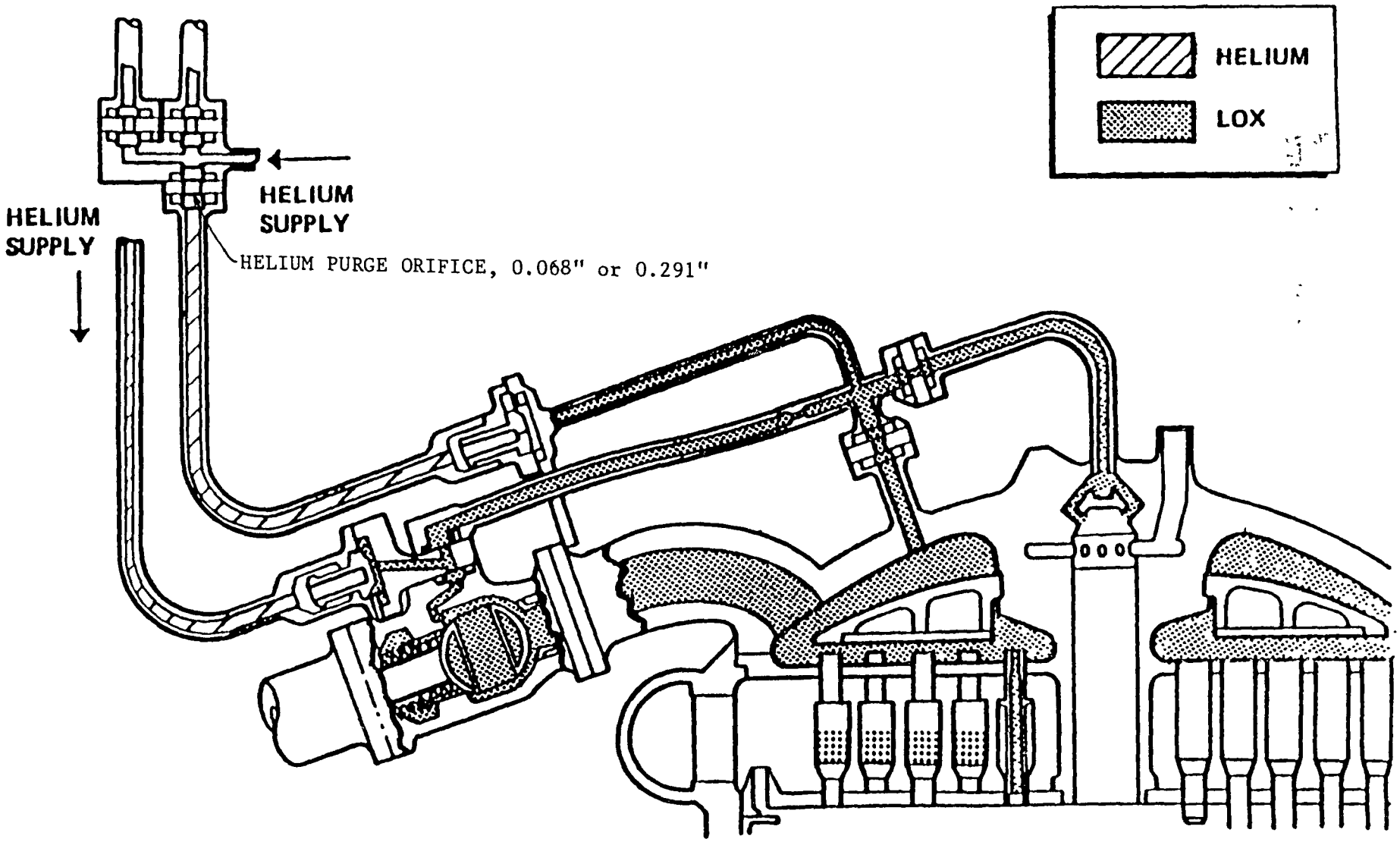
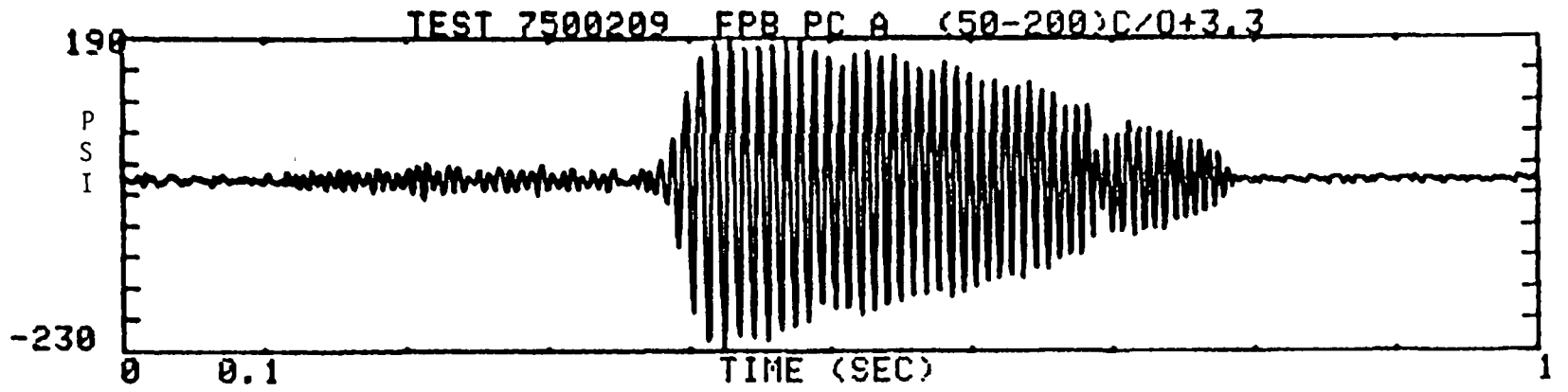
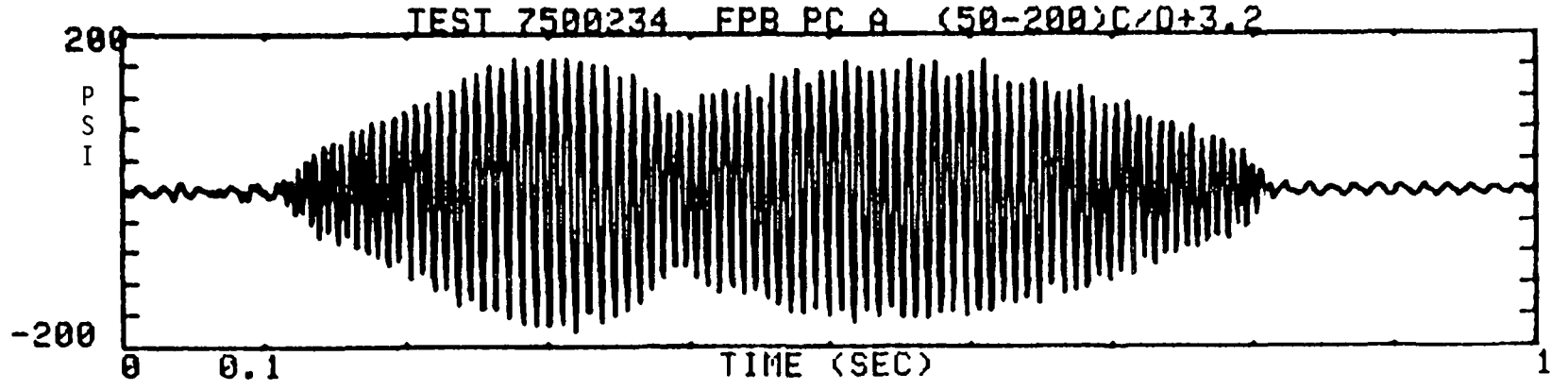


Figure 3. Fuel Preburner Manifold and Purge System Schematic



a. Test 209 using a small purge orifice



b. Test 234 using a large purge orifice

Figure 4: Typical Fuel Preburner Pressure Traces

amplitude chugging which occurs prior to the main chug in Figure 4a. In Figure 4b that chug has apparently been exacerabated by the higher purge flow rates available with the large orifice. Second, the maximum amplitude of the chug was reduced by the large orifice and the shape became somewhat smoother with an amplitude waist occuring at about the same time as the start of chugging with the small orifice. Finally, the chug frequency appears to decrease with amplitude. This is somewhat subjective when viewing traces in Figure 4 but has been confirmed by Fourier transform analysis of small sections of the trace. Clearly there is a non-linear coupling between frequency and amplitude and further, there is apparently an amplitude limiting mechanism since no chug has been observed to grow catastrophically.

MODELING OBJECTIVES

Combustion instability, particularly as applied to rocket engines, has been the subject of several previous investigations. Two of the more comprehensive are Crocco and Cheng (1956) and Harrje and Reardon (1972). The objectives of the previous studies were to identify conditions which should be avoided in rocket engine construction. The models developed were linearized and depended on a classical Eigenvalue analysis to identify any characteristic roots with non-negative real parts. These models have shown that chugging is critically sensitive to combustion time delay and to low injector pressure drop. Compressibility in the feed system is also considered to be a contributor to chugging; however, the actual requirement is that reactant feed rate be proportional in some way to the combustion chamber pressure. Linearized models are extremely useful but limited to defining conditions where chugging can occur while providing no information on amplitude limitations or non-linear instability. There is frequently significant uncertainty in the values to be used for such critical factors as combustion time delay.

The objectives of this study are 1) to provide a tool for the study of purge condition changes, most notably changes in the purge system orifices. 2) to identify any conditions traversed by the SSME during the shutdown purge which are conducive to chugging and to relate these to the onset or end of chugging. 3) to study amplitude/frequency coupling and amplitude limitations with the hope of utilizing these phenomena to limit the scope or intensity of the chug. The first two of these objectives can be met with existing models with the limitation that these models are subject to uncertainty in the fitting parameters used, most notably combustion time delays. The final objective can only be met with a non-linear model solved in the time (as opposed to the frequency) domain. There are secondary considerations which make development of a new time domain model desirable. First, in the process of defining the governing equations and seeking solutions, physical understanding of the problem can be gained. Second, a more fundamental model which does not depend as explicitly on the fitting parameters can be developed. These considerations are offset by the time required for model, particularly computer program, development.

Both modeling approaches are being followed. A chug analysis program has been requested from COSMIC (Szuch, 1971) and will be implemented when received. The program had not been received as of the end of the

summer program. A new model capable of satisfying all objectives was formulated and will be presented below.

MODEL DESCRIPTION

The combustion chamber and the feed system are coupled in a critical way when chugging occurs, however, it is desirable to separate the two when devising a model since different governing equations are required for each. The prime phenomena of interest in the combustion chamber is the release of energy with an attendant pressure rise. The primary interest in the feed system is the mass flow of reactants into the combustion chamber. The combustion chamber pressure serves as the coupling interface between the two systems.

Combustion Chamber

The fuel and oxidizer are admitted to the combustion chamber through an array of closely spaced concentric orifices. In the SSME fuel preburner, 264 injectors are used with fuel occupying an annular region surrounding the oxygen. Because the reactant jets are closely spaced, there is a dominant flow direction from the injector face to the nozzle; however, there is also a significant amount of turbulent mixing, both parallel and perpendicular to the flow direction. In addition, there are recirculation zones between the jets in the upper portion of the chamber.

Previous models have considerd the combustor to be a series of parallel stream tubes each behaving like an independent plug flow reactor. That approach ignores the importance of cross stream mixing and recirculation. At the other extreme of the simple chemical reactor models lies the continuous stirred tank reactor (CSTR) which assumes complete and random mixing of reactants with the entire contents of the vessel; any dominant flow direction is ignored. CSTR's are not usually applied to rocket combustion due to the perceived importance of the dominant flow direction; however, they offer the advantage that the behavior of the combustion chamber can be represented by a single volume without the necessity of spacial integration. There is also a mathematical advantage in that the governing equations are, at least at steady state, algebraic rather than differential equations. In view of the objective of determining the chemically controlled time delay between reactant introduction and pressure increase, a transient CSTR (TSTR) was chosen for this model. While the details of the combustor flow are obviously ignored, this model is still substantially superior to a constant time delay parameter in that the appropriate kinetic parameters may be determined from laboratory experiments and are in fact relatively well known for the H2 - 02 system. A substantial uncertainty enters through the kinetics of droplet dispersion. Since both oxidizer and fuel enter at supercritical conditions, no fundamental droplet dispersion model is available.

There are NS plus two governing equations for a CSTR undergoing transients where NS represents the number of species in the reactor. Conservation of species provides NS equations for the species

concentrations or mole numbers (kgmoles i/kg total) while the energy equation constrains the temperature and conservation of total mass constrains the pressure (or equivalently the density). The species conservation equations are of the form:

$$\dot{m}_f \sigma_{if} + \dot{m}_o \sigma_{io} + \dot{m}_p \sigma_{ip} - \dot{m} \sigma_i + \mathcal{R}_i V = \frac{d}{dt}(\sigma_i \rho V) \qquad i = 1, NS \tag{1}$$

where σ_i represents the mole number of species i, R the net reaction rate, V the reactor volume, m the mass flow rate and ρ the density. Subscripts f, o and p refer to the fuel, oxidizer and purge respectively. Unsubscripted variables refer to conditions in the reactor which are the same as the exit conditions. The energy equation is:

$$\sum_{i=1}^{NS} [\dot{m}_f \sigma_{if} h_{if} + \dot{m}_o \sigma_{io} h_{io} + \dot{m}_p \sigma_{ip} h_{ip} - \dot{m} \sigma_i h_i] - Q =$$

$$\frac{d}{dt}\left[\sum_{i=1}^{NS} (\sigma_i u_i \rho V)\right] \tag{2}$$

where we have introduced the additional variables h and u representing enthalpy and internal energy respectively. Q is the net heat loss from the reactor and is currently assumed to be a function of temperature (T) only. Conservation of mass is given by:

$$\dot{m}_f + \dot{m}_o + \dot{m}_p - \dot{m} = \frac{d}{dt}(\rho V) \tag{3}$$

The combustor pressure is determined via the equation of state (ideal gas assumed) and the computed temperature and density.

By expanding the multiple derivatives and combining equations the primary variables may be isolated as simple derivatives with respect to time. This yields a usable form of the equations:

$$\frac{d\sigma_i}{dt} = \frac{1}{\rho}\left(m_{vf}\sigma_{if} + m_{vo}\sigma_{io} + m_{vp}\sigma_{ip} - (m_{vf} + m_{vo} + m_{vp})\sigma_i + \mathcal{R}_i\right) \qquad i = 1, NS \tag{4}$$

$$\frac{dT}{dt} = \left\{\sum_{i=1}^{NS}(m_{vf}\sigma_{if}h_{if} + m_{vo}\sigma_{io}h_{io} + m_{vp}\sigma_{ip}h_{ip} - m_v\sigma_i h_i) - \frac{Q}{V} - (m_{vf} + m_{vo} + m_{vp} - m_v)\left(\sum_{i=1}^{NS}\sigma_i u_i\right) + \sum_{i=1}^{NS} u_i (m_{vf}\sigma_{if} + m_{vo}\sigma_{io} + m_{vp}\sigma_{ip} - (m_{vf} + m_{vo} + m_{vp})\sigma_i + \mathcal{R}_i)\right\} \Big/ \left\{\rho \sum_{i=1}^{NS}\sigma_i (C_p - Ru)\right\} \tag{5}$$

$$\frac{d\rho}{dt} = m_{vf} + m_{vo} + m_{vp} - m_v \tag{6}$$

where Mv is the throughput (mass flow rate/unit volume), Ru the universal gas constant and Cp the constant pressure specific heat.

Equations 4 through 6, along with appropriate expressions for the chemical kinetics and properties can be coupled directly to the feed system equations which supply the required mass flow rates. The

combustor also requires an expression for the exit flow as a function of combustor temperature and pressure. Neglecting turbine pumping contributions, this is given by:

$$\dot{m} = m_v V = C\,(T_{cc}\,P_{cc})\left[\left(\frac{P_{HG}}{P_{cc}}\right)^{1.4286} - \left(\frac{P_{HG}}{P_{cc}}\right)^{1.7143}\right]^{1/2} \qquad (7)$$

where C is an empirically determined constant; P and T are pressure and temperature. Subscripts CC and HG represent the combustion chamber and hot gas manifold respectively (Nguyen, 1981).

Equations 4 through 6 were not used as shown but were converted to integrate the natural logarithm of the variables. Since none of the variables may be negative, but species mole numbers may be very small, use of the log variables ensures that no negatives will be encountered while normalizing the magnitudes of the derivatives. This procedure has been found to be very beneficial in the solution of equilibrium and steady state kinetic problems (Gordon and McBride, 1976; Pratt and Wormeck, 1976). Case and Pratt (1977) recommend it for spacial and time integrations. Conversion to logarithimic variables is easily accomplished by noting that:

$$\frac{d\ln x}{dt} = \frac{1}{x}\frac{dx}{dt} \qquad (8)$$

e.g.

$$\frac{d\ln\rho}{dt} = \frac{1}{\rho}\left(m_{vf} + m_{vo} + m_{vp} - m_v\right) \qquad (9)$$

Supply System Equations

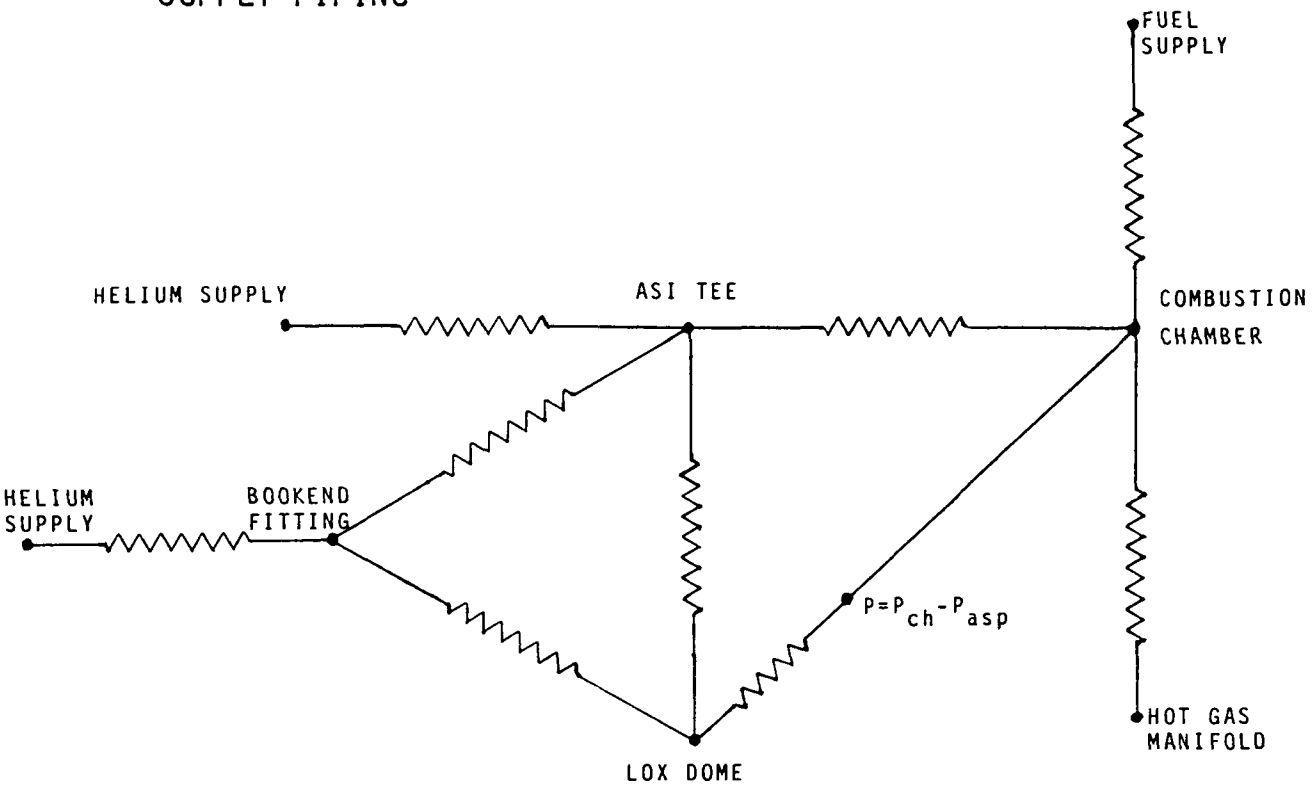
The supply system to be modeled consists of the Lox lines, including the ASI lines shown in Figure 3. Figure 5 shows the reduced resistance network used to represent the system for this model. The boundaries of the system are assumed to be constant pressure helium at the check valves and the combustion chamber pressure calculated above. Conservation of momentum is required in each pipe and conservation of mass is required for each node, i.e., no storage at the node. The gas/fluid interface is followed through the system since line pressure drop depends strongly on the fluid properties and it is necessary to know when the oxidizer has been exhausted. The gas/fluid interface is assumed to be perpendicular to the pipe centerline at all times.

Conservation of momentum for a general one dimensional case can be written:

$$\Sigma F = \frac{d}{dt}\iiint_{CV} \vec{U}\,\rho\,dV + \iint_{CS} \vec{U}\,\rho\,(\vec{U}\cdot\vec{n})\,dA \qquad (10)$$

where U is the velocity, A the cross sectional area and F the external forces acting on the fluid. For this case, the external forces are considered to consist of only the pressure drop and the pipe frictional loss. For a single inlet, single outlet system with uniform velocity profiles this reduces to:

SUPPLY PIPING



BOOKEND VOLUME ATTRIBUTED TO LOX VALVE LINE

LOX DOME VOLUME ATTRIBUTED TO INJECTOR

A.S.I. TEE - VOLUME NEGLECTED

Figure 5: Supply Piping Resistance Diagram

$$\left[P_1 - P_2 - f\left(\frac{\dot{m}^2}{\rho}\right)\right]\frac{1}{A} = \frac{d}{dt}\left(\rho_1 V U + \rho_2 V U\right) + \rho_2 U^2 A - \rho_1 U^2 A \tag{11}$$

where f is the friction factor and subscripts 1 and 2 refer to the two ends of the pipe. If a single phase, incompressible flow is considered, this further simplifies to:

$$P_1 - P_2 - f\frac{\dot{m}^2}{\rho} = \frac{1}{A}\frac{d}{dt}(\rho V U) \tag{12}$$

which is equivalent to the form proposed by Harrje and Reardon (1972). Such a reduction is not appropriate here since the density of the purge gas will be significantly different from that of the Lox; hence the two ends of the pipe must be retained. Note that the second term in Equation 11 is equivalent to using a weighted average density and a single characteristic velocity.

In order to track the interface location, one additional equation is needed for each pipe with an interface. Conservation of mass for each pipe provides this equation. Conservation of mass at each node provides closure and ensures proper coupling of the feed pipes. If we assume a single characteristic velocity for the pipe equal to the interface velocity (equivalent to assuming that each fluid is incompressible), then conservation of mass requires:

$$\frac{dV_g}{dt} = -\frac{dV_e}{dt} = \frac{\dot{m}_g}{\rho_g} = -\frac{\dot{m}_e}{\rho_e} = A\frac{d\ell_g}{dt} = -A\frac{d\ell_e}{dt} \tag{13}$$

At each node we also have:

$$\frac{d}{dt}\left(\sum_{j=11}^{NP}\dot{m}_{kj}\right) = 0 \qquad k = 1, NN \tag{14}$$

where V again represents volume, A is a characteristic area for each pipe, l the length along the pipe axis, NP the total number of pipes and NN the number of nodes. Subscripts g and l refer to the gas and liquid volumes respectively. As before, these equations may be combined to yield working equations; however, it is not possible to completely isolate the derivatives as was done for the combustion chamber. Non-dimensionalizing lg with the total pipe length and combining equations where possible yield:

$$\frac{d\ell_{gj}}{dt} = U_j \qquad j = 1, NP \tag{15}$$

$$U_j\left(\ell_{gj}\frac{d\rho_{1j}}{dt} + \ell_{\ell j}\frac{d\rho_{2j}}{dt}\right) + \left(\rho_{1j}\ell_{gj} + \rho_2\ell_{\ell j}\right)\frac{dU_j}{dt} = P_{1j} - P_{2j} - f\bar{\rho}_j U_j^2$$

$$j = 1, NP \tag{16}$$

where $\bar{\rho} = \frac{1}{V_j}\left(V_{gj}\rho_1 + V_{\ell j}\rho_2\right)$

$$\frac{d\rho_k}{dt}\sum_{j=1}^{NP}A_j U_{kj} + \sum_{j=1}^{NP}\rho_k A_j\frac{dU_j}{dt} = 0 \tag{17}$$

These are the final forms of the working equations. No conversion to logarithmic variables was undertaken since U may be positive or negative. Equations 16 and 17 are coupled and must be solved simultaneously for values of the first derivatives. In the computer program this is accomplished using Gauss iteration.

NUMERICAL METHODS

The governing equations derived above must be solved numerically in the time domain to determine the various species mole numbers, temperatures, pressures and flow rates as functions of time. Flow reversals and pressure oscillations are allowed. Auxilliary relations are used as needed to convert from primary variables to secondary variables, e.g. from temperature and density to pressure.

The solution of these equations is not straightfoward. The chemical kinetic equations are stiff; that is, they have widely varying characteristic times. When coupled with the inlet feed system, the problem is exacerbated. First order numerical techniques will not work because extremely small time steps are required to avoid instability and roundoff error becomes too large when small time steps are used. Higher order single step methods such as Runge-Kutta offer some hope for success but are generally prohibitively expensive due to the time required for multiple evaluations of the derivatives. Based on experience with this program, it appears that Runge-Kutta integration schemes are not appropriate for this equation set due to instability associated with single step explicit methods.

Because of the stiffness, these equations should be solved with a multi-step implicit integrator (Gerald, 1969). The most popular method is that proposed by Gear (1971) and modified by Hindmarsh (1974). A commercial version of the Hindmarsh subroutine is available through the Internation Mathematical and Scientific Library (IMSL). Unfortunately, that library was not implemented on the Sperry, Perkin-Elmer or VAX computers available for solving the problem at NASA, Marshall. A fourth order Runge-Kutta integrator was written to assist in debugging the program at NASA with hopes that the program could be transported to a machine with IMSL available. Success with the Runge-Kutta routine was not achieved due to apparent numerical difficulties, i.e. excessive rates of change of the primary variables, usually the chemical species mole numbers. Plans were made to transport the program to the University of Alabama, Huntsville computer where IMSL is available; however, transfer was not accomplished during the 10-week summer program.

PROGRAM DESCRIPTION

Table 1 provides a summary of the computer program (TRNCHG) and its associated subroutines. The equations presented above are programmed in subroutines CHGSLP and RATES. Subroutine DGEARX is the Runge-Kutta

TABLE 1

PROGRAM ROUTINE DESCRIPTION

ROUTINE	DESCRIPTION
TRNCHG	Main Program. Controls program flow and all I/O except debugging output which is local to the various subroutines.
BLKDTA	Block Data subroutine to set default values.
CHGSLP	Computes the first derivatives of all primary variables for use by the integrating subroutine. Contains the programming for the governing equations. Calls RATES to set the net rate of species production by chemical reaction.
DGEARX	Runge-Kutta integration subroutine which answers a call mimicking a call to IMSL subroutine DGEAR.
HCPS	Computes Enthalpy, Internal Energy and specific heat using the NASA "ODE" polynomial form: $H = R*T*(Z1 + \frac{Z2*T}{2} + \frac{Z3*T**2}{3} + \frac{Z4*T**3}{4} + \frac{Z5*T**4}{5})$.
NPRNT	Prints Reactant Streams.
NPT	Main input subroutine. Reads all thermochemical, kinetic and reactants data.
OUTPT	Prints final or intermediate output.
RATES	Computes net rate of species production due to chemical reaction and derivatives with respect to species mole numbers and temperature.

integrator subroutine. The remaining subroutines are associated with data input and solution output or thermodynamic properties. The program listing (>2000 lines) is not reproduced here for obvious reasons, not the least of which is that the program does not work.

As noted above, successful operation of the model was not achieved in the time available. A substantial effort was expended in setting up the proper input files and in I/O overhead. All of the I/O-setup problems seem to have been solved so that the work remaining is to solve the numerical difficulties. This may only require use of a Gear integration subroutine or it may be necessary to recouch the equations in a different form less susceptable to instability. Work on this problem will be continued at the University of Tennessee, Knoxville with support from NASA. Once operational, the program will be implemented on the NASA computers. The IMSL package will hopefully be available by that time.

CONCLUSIONS

Although a successful model was not achieved, the problem has been defined and much of the set-up work has been completed. A study of the shutdown chugging has shown that non-linear effects are important to the chugging amplitude and that equipment modifications can have an effect on chugging. A literature survey concerning methods which could be used for numerically solving the governing equations has suggested that implicit methods, most notably Gear's method, are available and that the equations can be solved without linearizing.

This summer has been most educational and enjoyable in spite of the frustration of not completing the model. I was afforded the opportunity to work with several outstanding engineers on other problems not mentioned here and to exchange ideas with NASA personnel and other summer faculty. The summer faculty fellowship program has been an outstanding opportunity to broaden my engineering background.