established the feasibility of a one-piece baffle assembly. The furling concept does allow metal-to-metal contact between adjacent baffles when the baffle assembly is in the furled condition; however, metal-to-metal rubbing between adjacent baffles or between baffles and furling rods is minimized by supporting each rod on roller bearings.

As a result of the fabrication and testing of the spherical tank device, the baseline propellant management device for Viking 75 Orbiter was selected to have a one-piece, electron-beam welded baffle assembly. The selected baseline design, shown in Fig. 10, incorporates most of the recommendations of the concept selection phase of the Orbiter propellant management program.

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Verification of a Comprehensive Thrust Chamber Compatibility Model for Liquid Rocket Engines

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The objective of this effort was to assess the accuracy and validity of the Injector Chamber Compatibility model coupled with the Aerotherm Thermal/Chemical Ablation Analysis as a design tool for analyzing liquid rocket ablative or refractory thrust chamber durability. This evaluation consisted of analyzing and predicting chamber and/or throat erosion for five liquid rocket engine firings. The results demonstrated that the analysis can be used with a high degree of confidence to predict the amount of erosion and the location and depth of chamber and/or nozzle streaking.

Introduction

A CRITICAL aspect of liquid engine thrust chamber design is the relationship between the injector configuration and the durability of the chamber liner materials. Consequently, the Air Force Rocket Propulsion Lab. sponsored the development of a series of computerized models for predicting liner material performance. The main products of this effort were the Injector Chamber Compatability (ICC) Model[1,2] developed by Rocketdyne and the Aerotherm Thermal/Chemical Ablation Analysis.[3] When combined, these models constitute a design tool for analyzing: 1) the injector induced three-dimensional combustion and gas dynamic environment in the thrust chamber; 2) boundary-layer characteristics and subsequent heat transfer to the chamber wall; 3) the rate of material erosion and pyrolysis due to chemical and thermal attack. The purpose of the effort discussed herein was to assess the validity of this design tool through a systematic comparison of analysis and experiment.

This evaluation was accomplished by predicting chamber and nozzle liner erosion for five liquid rocket engine firings. In an attempt to ensure the objectivity of this evaluation, all but one of these predictions were accomplished before the experiments were conducted.

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Index categories: Liquid Rocket Engines; Combustion in Heterogeneous Media; Material Ablation.

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Description of the Analytical Model

The ICC model was specifically developed to account for the effect of the injector configuration on the mass distribution and mixture ratio variation within the chamber. Consequently, this model is capable of relating the injector design to the performance of the chamber and nozzle liner materials.

Analysis of the combustion gas dynamics within the chamber is accomplished through a series of theoretical models which describe the progression of the liquid spray and exhaust gas from the combustion zone to the throat plane (Fig. 1). These calculations are usually accomplished for a wedge shaped portion of the chamber which has been selected upon consideration of symmetry.

The behavior of the liquid spray in the region immediately adjacent to the injector is calculated by the Liquid Injector

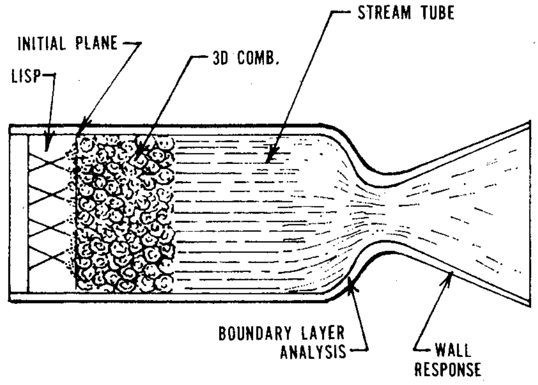

Fig. 1 Injector/Chamber Compatibility analysis.

Spray Pattern (LISP) segment of the model. This computerized technique calculates spray mass fluxes, droplet size and velocity vectors at a large number of mesh points in an "initial plane" located a short distance downstream from the injector face. An estimate of the extent of vaporization at this location is also accomplished by the LISP analysis. These calculations are based upon injector design data including the number and type of injection elements, element locations and orientation, and empirical parameters which correlate a single element's spray mass flux distribution and mean droplet size with its design and operating parameters. The spray mass flux distribution is obtained by cold flowing individual injector elements with water and trichlorethylene and collecting the spray in a sectioned container.

The second segment of the analysis is accomplished by the Three Dimensional Combustion (3D COMBST) program which accepts the results of LISP at the initial plane and proceeds to calculate axial and transverse combustion gas and liquid spray parameters such as velocity, temperature, pressure, and droplet vaporization. Combustion is assumed to occur immediately upon vaporization from the liquid droplets at the local O/F mixture ratio. Mixing of the liquid fuel and oxidizer results from droplet disperion; gaseous diffusion and mixing is produced by the transverse convective flowfield.

Once the transverse velocities become small in comparison to the axial velocity, a more economical one-dimensional model can be used to describe the combustion process to the throat plane. The Stream Tube (STRMTB) model accomplishes this calculation in the following manner. The combustion gas and liquid spray field produced by the 3D COMBST analysis is used to initialize the conditions in a series of stream tubes. As implied by the name "stream tubes," propellant which enters the tube at the initial plane is constrained to flow only in that particular tube. Although the variation in total mass and mixture ratio predicted by 3D COMBST is preserved; the STRMTB analysis does allow for axial variation in gas mixture ratio due to continuing droplet vaporization.

The end product of the LISP, 3D COMBST, and STRMTB computer programs is a description of the circumferential and axial variation in gas mixture ratio throughout the combustion chamber. This data can then be used to calculate adiabatic wall temperature, convective heat-transfer coefficients and the concentration of any corrosive species in the combustion gas adjacent to the chamber liner. These quantities are then used to determine the local wall response as a function of time during the firing.

The actual calculation of the transient wall response involves a description of the energy exchange between the surface and the gas as well as a definition of the surface chemical reactions as a function of temperature. Figure 2 schematically illustrates the basic problem.

The mass balance for the surface control volume in Fig. 2 is written as

$$\dot{M}_D \text{ out} = \dot{M}c + \dot{M}pg + \dot{M}_D \text{ in}$$

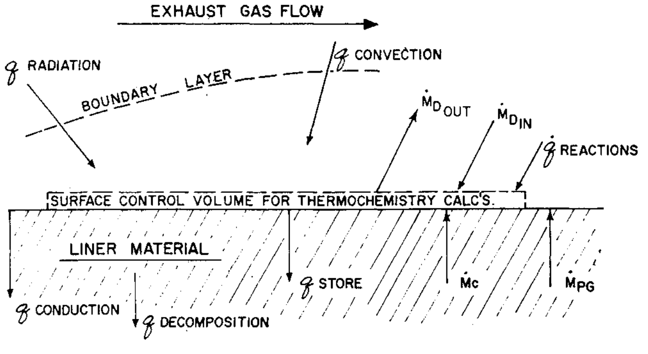

Fig. 2 Schematic of energy balance.

where $\dot{M}_{D_{in}}$ represents the diffusion flux of combustion gas into the control volume; $\dot{M}c$ represents the mass flux into the control volume due to chemical reactions between the surface and the combustion gas; $\dot{M}pg$ represents the mass flux into the control volume due to pyrolysis of the liner material; $\dot{M}_{D_{out}}$ represents the net mass flux out of the control volume.

The solution to the mass balance expression was determined in accordance by the methods suggested by Ref. 3. Individual chemical reactions were considered to be occurring in either one of two regimes: diffusion limited or rate limited. For a diffusion limited system, the reaction can be considered to occur infinitely fast (equilibrium); the limiting process then becomes the rate at which the reactants can reach the material surface by diffusing through the boundary layer. At the opposite extreme is the kinetic rate limited regime. For a purely kinetics limited system, it is assumed that there are more than sufficient reactants present; the limiting step then becomes the rate at which the reaction can occur. Experience indicates that the ablative materials (carbon and silica cloth phenolic) fall in the diffusion regime while the graphites (ATJ, P.G., etc.) are best analyzed by assuming a rate limited phenomena. Table 3 lists the techniques and sources of kinetic data used in this program. Note that the strict equilibrium assumption was modified in certain cases (i.e., the silicon carbide) by the inclusion of a "fail temperature" to account for material melting.

An energy balance would be written as

$$\dot{q} \text{ radiation} + \dot{q} \text{ convection} + \dot{q} \text{ reactions} = \dot{q} \text{ conduction} + \dot{q} \text{ store} + \dot{q} \text{ decomposition}$$

Convection heat-transfer coefficients were obtained by the method of Elliott, Bartz and Silver.[4] Radiative heat transfer was asssumed to be negligible since the combustion gases are largely transparent. The energy contribution due to the chemical reactions which are occurring is calculated coincidentally with the mass balance analysis for the surface control volume. A solution to the energy balance is obtained by a finite-difference approximation to the conduction heat-transfer equation for an externally heated cylinder with a receding wall.[5]

Analytical Predictions and Experimental Results

A total of five engine firings were analyzed during this study. Table 1 summarizes the five cases and illustrates the broad cross section of thrust chamber technology that was considered. Both oxidizing and reducing propellants were used in conjunction with various fuels. Thrust levels ranged from a few pounds to several thousand while operating pressures as high as 500 psia were obtained.

Case 1

The initial analysis predicted the performance of a 15,000 lb thrust engine which operated at 500 psia for 120 sec. A blend of 80% hydrazine—20% MMH in conjunction with ClF_3 constituted the propellant system. Injector elements were of the "like doublet" configuration; the outboard oxidizer elements were canted 12° inward to provide a cooler, fuel rich boundary layer along the chamber surface (Fig. 3). The liner material consisted of a precharred graphite phenolic (AG Carb) overwrapped with silica phenolic (Fig. 4).

Application of the ICC model to this particular engine design was not totally straightforward. Both the LISP and 3D COMBST models assume a cylindrically shaped chamber with an internal diameter equal to that of the injector. This particular engine utilized a tapered chamber; consequently the LISP and 3D COMBST analyses were accomplished over comparatively short segments. As a result of this approach, the analyses may not have predicted the degree of fuel and oxidizer mixing which occurred experimentally at the wall; thus the subsequent prediction of wall erosion may be expected to be less than measured by the experiment.

Table 1 Summary of test cases

Case	Propellants	Thrust level, lbf	Firing duration, sec	Chamber pressure, psia	Injector type	Chamber and/or throat material
1	ClF_3/20% MMH 80% N_2H_4	15,000	120	500	Like doublet	Precharred graphite phenolic
2	N_2O_4/N_2H_4	3,000	376	300	Hyperthin	Precharred graphite phenolic
3	IRFNA/HYDYNE[a]	Small		High	Oxidizer on fuel triplet	Throat: silicon carbide Chamber: silica phenolic
4	IRFNA/HYDYNE	Small		Low	Same as Case 3	Same as Case 3
5	ClF_3/75% N_2H_4 25% NH_3	20	45	90	Fuel on oxidizer triplet	Pyrolytic graphite coated (0.030") carbitex

[a] HYDYNE is composed of 60% UDMH and 40% Diethylene Triamine.

The ICC model predicted a circumferential mixture ratio variation of 0.747 to 0.848 along the material surface at the throat plane: the over-all mixture ratio was 3.0. Zero surface regression was predicted by the Aerotherm model for both the 0.747 and the 0.848 mixture ratio. Actual measured erosion at the throat was 0.25 in. producing a throat area increase of 4.6%.

Case 2

A 376 sec firing of the Aerojet AJ 10-179 engine was used for the second case. Test particulars are listed in Table 1. Again, application of the ICC model was not straightforward due to the hyperthin injector design and complicated baffle arrangement. Figure 5 shows the simplified injector design used for the analysis. The barrier injector pattern remained identical to the actual injector. LISP, however, is limited to an analysis of 50 injector elements; thus several of the elements near the injector center were combined to contain the total number within this limitation. The baffles were ignored; thus any localized streaking due to baffle induced flow effects could not be considered. Figure 6 illustrates the configuration used for the STRMTB analysis.

The average mixture ratio adjacent to the nozzle surface was 0.22 compared to the over-all value of 1.0. Subsequent analysis of the wall response predicted a total increase in radius at the throat of 0.024 in. (3.5% area increase). Neglecting some minor streaking induced by the baffles, the measured surface regression was 0.028 in.

The analysis of this case was extended to include a parametric study of the effect of local mixture ratio variation on predicted material erosion. The wall temperature was assumed to always equal the local gas recovery temperature.

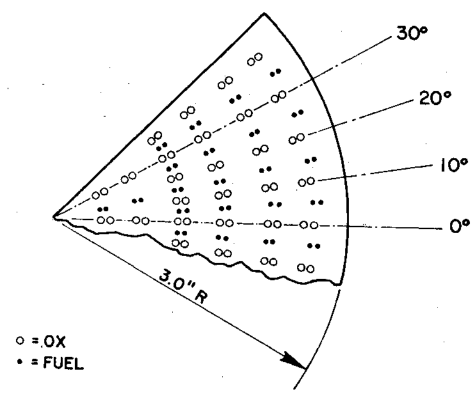

Fig. 3 Injector design for Case 1.

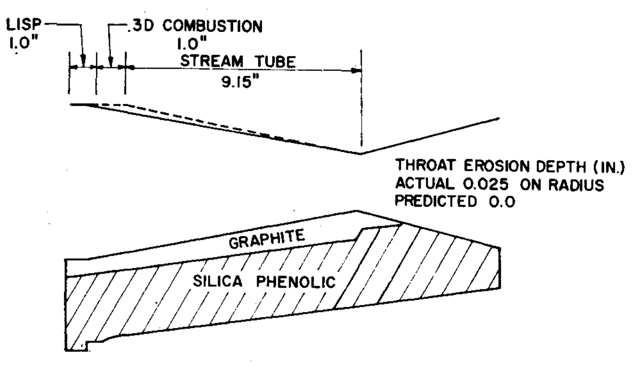

Fig. 4 Thrust chamber design for Case 1.

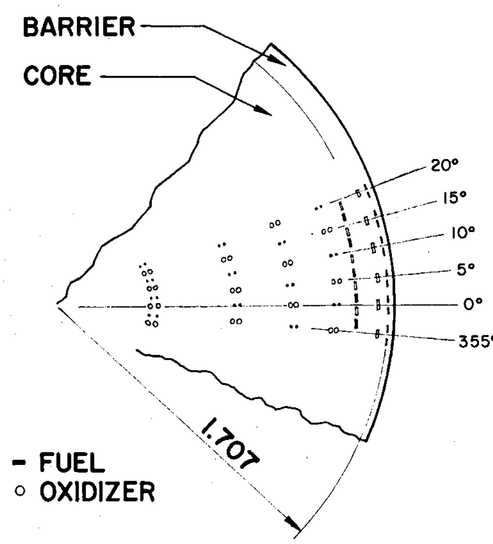

Fig. 5 Assumed injector design for Case 2.

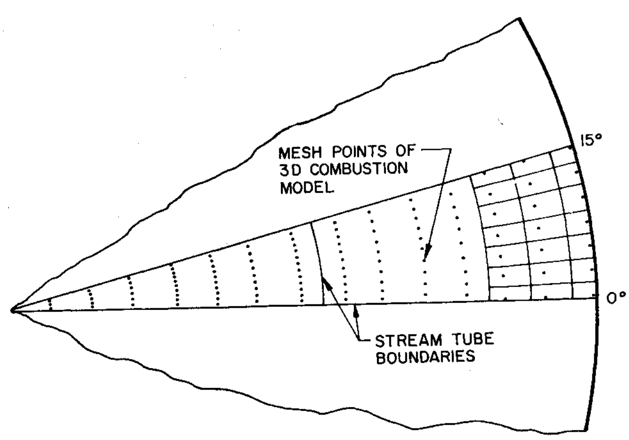

Fig. 6 Placement of stream tubes for Case 2.

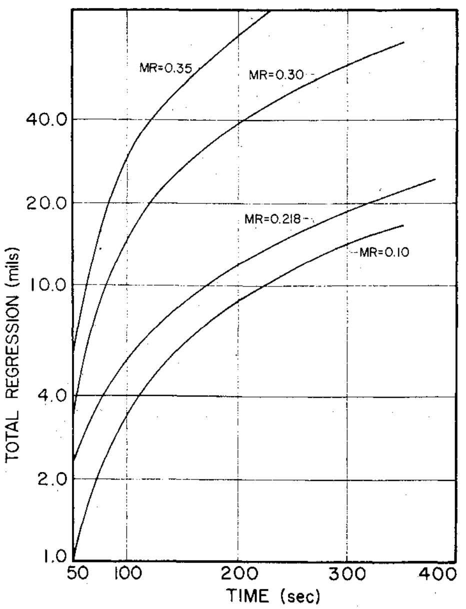

Fig. 7 Throat regression vs firing time as a function of film mixture ratio for Case 2.

The results of this analysis are shown in Figs. 7 and 8. It is clearly evident that small changes in gas conditions can produce significant changes in predicted regression. For example, a $\pm 10\%$ error in the adiabatic wall temperature at a mixture ratio of 0.218 results in a $\pm 2000\%$ error in the regression rate. Similarly a $\pm 10\%$ error in predicted mixture ratio at the adiabatic wall temperature of 2720°R results in a $\pm 40\%$ error in regression rate.

Cases 3 and 4

The subsequent two predictions were made on one engine which was tested at two different operating conditions and throat diameters. The injector design consisted of oxidizer on center fuel triplets (Fig. 9). For the chamber depicted in Fig. 10, a silicon carbide material was originally considered for both the high and low pressure throat packages; however, a high density, graphite impregnated silicon carbide material (KT-SiC) was later substituted for the high pressure test.

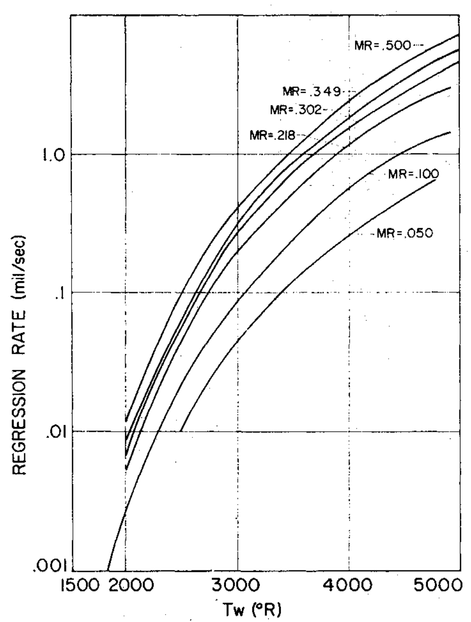

Fig. 8 Regression rate vs throat wall temperature for various mixture ratios, Case 2.

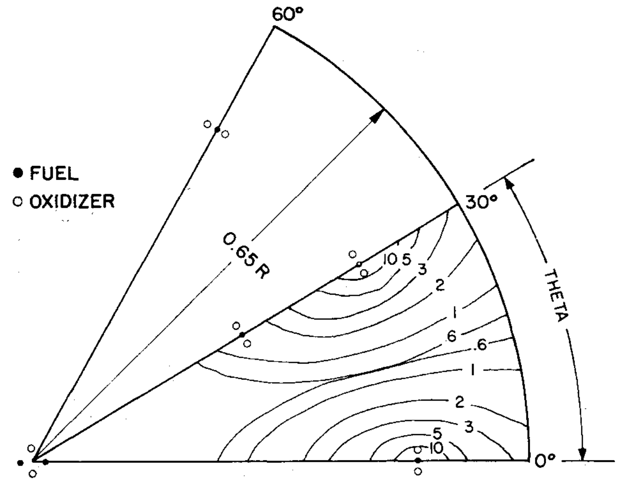

Fig. 9 Case 3 injector design with superposition of O/F mixture ratio distribution at $Z = 2.0$.

The 3D COMBST analysis predicted that the wall mixture ratio would vary from 2.2 adjacent to the triplets to 0.63 between the elements. The mixture ratio variation at a plane 2.0 in. from the injector is depicted in Fig. 9.

Analysis of the high pressure case indicated that throat erosion of the KT-SiC would not occur; however, erosion of the original silicon carbide would produce a throat area increase of 25%. As a result of this analysis, the original silicon carbide was eliminated from the high-pressure design. Measured erosion of the KT-SiC was 0.005 in.

A medium density silicon carbide was tested at the higher pressure. This material experienced erosion sufficient to produce an area increase of 7.5%, thus providing an indication of the accuracy of the prediction for the original material.

Analysis of the low-pressure case was more extensive. At the throat plane, no erosion was predicted. This was later verified by experimental testing. At a distance of 4.5 in. from the injector face, the 2.2 wall mixture ratio gas in line with the triplet elements was predicted to cause streaking to a depth of 0.120 in. while the lower mixture ratio zone between the triplet elements was projected to cause no erosion. In the subsequent testing, streaking occurred in the exact positions predicted to an average depth of 0.111 in.; however, erosion between the streaks did occur to an average depth of 0.028 in. The comparison of the predicted and measured results is shown in Fig. 11. It should be noted that the wall response analysis was one dimensional and therefore ignored any circumferential heat transfer, which could easily account for the small amount of erosion between the streaks.

Erosion was also predicted at a location 2.5 in. downstream of the injector face. A radius increase of 0.126 in. was predicted within the streak and 0.0 between the streaks. Experimental erosion averaged 0.066 in. within and 0.017 in. between the streaks.

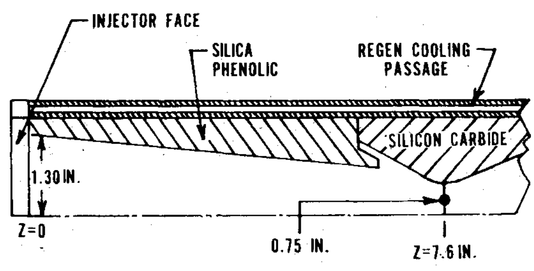

Fig. 10 Case 3 chamber design.

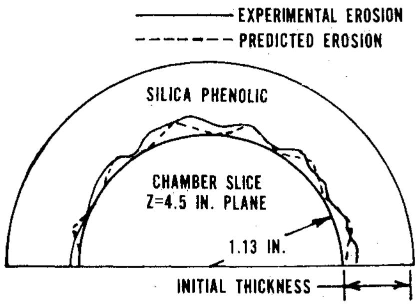

Fig. 11 Case 4 comparison of experimental and predicted results.

Table 2 Comparison of predicted and measured erosion for Case 5

Location in chamber	Predicted erosion[a]	Measured erosion[a]
0.75 in. from injector (average of three streaks)	0.0135	0.051
2.0 in. from injector (average of three streaks)	0.00495	0.0175
Throat		
No film cooling	0.00675	0.010
Film cooling	0.004	0.0075

[a] Inches measured on radius.

Although the ICC analysis predicted that a large amount of liquid propellant would impinge on the wall at this location, the cooling effect produced by this impingement was not considered by the wall analysis. The discrepancy between the predicted and measured erosion could have resulted from this droplet cooling.

Case 5

The final case consisted of a continuous 45 sec firing of a 20 lb thrust attitude control engine. The injector consisted of three triplet elements with showerhead elements located near the wall for film cooling as shown in Fig. 12. Note that the film cooling holes at the 30° location were intentionally plugged. This was accomplished specifically to provide additional verification of the analytical model. The chamber was constructed of Carbitex with a 0.030 layer of pyrolytic graphite deposited on the gas side wall. The analysis considered a 100 sec firing; however, the experimental test was terminated at 45 sec due to an instrumentation problem. Since the heat transfer to the chamber reached steady state within 2 sec, the prediction could be interpolated to the 45 sec duration.

The LISP and 3D COMBST analysis predicted that the fans from the triplet elements would impinge upon the chamber wall at the 30°, 150°, and 270° locations. This resulted in a peak mixture ratio of 2.5 at these locations compared to the overall mixture ratio of 1.25. Erosion was not predicted to occur at any location except as streaks at these three high-mixture ratio zones. This was verified in the testing. Table 2 presents the results of the predicted and experimental results; note the excellent agreement in the region where film cooling was disrupted.

User Considerations

During the accomplishment of this program, it was noted that errors in input data frequently would produce only subtle discrepancies in the computed output. These discrepancies were often not noticed until the analysis had progressed to the point where the errors had compounded and were producing obviously erroneous data. It is for this reason that practical application of this analysis should be accomplished by personel of sufficient experience to notice the existence of errors in the early stages of the study.

A complete analysis of a typical engine design would probably require two to five manweeks of effort and 15 to 30 min of CDC 6400 series computer time. This estimate assumes that erosion predictions are accomplished at several (about 5) locations throughout the chamber and allows for the extensive problem setup that is always required of sophisticated computerized models.

Extremely useful qualitative design information can be extracted from the LISP and Aerotherm models without conducting a rigorous analysis of the entire chamber. LISP would be used to obtain a qualitative estimate of the circumferential variation in gas wall mixture ratio. This data is then input to the Aerotherm model and a steady-state analysis of erosion is accomplished. Predictions obtained in this manner are usually conservative and can be used to judge the over-all acceptability of the design. This method can also be used to evaluate the effect of injector design modifications.

It should be noted that the application of these models to a typical engine configuration is seldom straightforward. Tapered chambers, complex baffles, nonstandard injectors and other unique design features tend to force one to approximate the engine configuration in order to satisfy particular constraints within the model. Several compromises in modeling the exact configuration were required in this study before the predictions could be accomplished; yet the favorable comparison between experiment and theory justifies this approach.

Care should be exercised when analyzing materials whose response to the particular environment is kinetic rate controlled. As discussed in Case 2, regions can be encountered wherein the erosion has a high dependence on surface temperature. It thus becomes important to emphasize the definition of the parameters which control surface temperature.

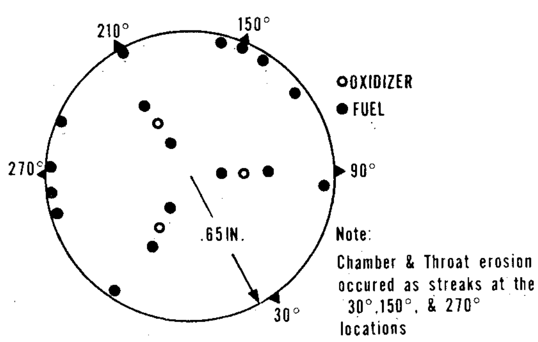

Fig. 12 Case 5 injector design.

Summary and Conclusions

Although this particular study was limited to an analysis of ablative and carbonaceous materials, application to refractory and regeneratively cooled chambers should be relatively straightforward.[2]

A summary of the measured and predicted erosion for each test case is presented in Table 3. Based on the data presented, it is easily seen that the initial program objective, i.e., verification of the design tool, was successfully accomplished. The combined methods of Aerotherm and Rocketdyne can be used to quantitatively predict liner material performance in typical liquid propellant rocket engines. These predictions can be accomplished prior to actual hardware fabrication and testing and the data used with confidence to enhance overall reliability and performance through design iteration.

Table 3 Comparison of predicted and experimental results

Case	Location	Predicted area increase, %	Measured area increase, %	Material	Control mechanism	Data source
1	Throat	0.0	4.3	AG carb	Kinetics	a
2	Throat	3.5	4.1	AG carb		
3	Throat	0.0	1.7	KT silicon carbide	Diffusion	
4	Throat	0.0	0.0	Silicon carbide	Melt at 4200°R	c
	Chamber, $Z = 4.5$ in.	4.3	5.8	Silica phenolic	Diffusion	
	Chamber, $Z = 2.5$ in.	3.9	1.8	Silica phenolic	Melt at 4200°R	c
5	Throat	1.4	2.8	Pyrolytic graphite		
	Chamber, $Z = 0.75$ in.	Insignificant	1.1	Pyrolytic graphite	Kinetics	b
	Chamber, $Z = 2.0$ in.	Insignificant	Insignificant	Pyrolytic graphite		

[a] AFRPL-TR-67-159, Designer's Guide and Computer Program for Ablative Materials in Liquid Rocket Thrust Chambers, Final report contract AF04(611) 11415, June 1967, Edwards Air Force Base, Calif.
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