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PREDICTION OF ENGINE PERFORMANCE AND WALL EROSION DUE TO FILM COOLING FOR THE "FAST-TRACK" ABLATIVE THRUST CHAMBER

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Efforts have been made at the Propulsion Laboratory, MSFC to design and develop new rocket liquid engines for small-class launch vehicles. Emphasis of the efforts is to reduce the engine development time with the use of conventional designs while meeting engine reliability criteria. Consequently, the engine cost should be reduced. A demonstrative ablative thrust chamber, called "fast-track", has been built. At the time of writing this report, the chamber will be tested in two weeks.

To support the design of the "fast-track" thrust chamber, predictions of the wall temperature and ablation erosion rate of the "fast-track" thrust chamber have been performed using the computational fluid dynamics program REFLEQS[1] (Reactive Flow Equation Solver). The analysis is intended to assess the amount of fuel to be used for film cooling so that the erosion rate of the chamber ablation does not exceed its allowable limit. In addition, the thrust chamber performance loss due to an increase of the film cooling is examined.

It is well known that physical processes occurring in the combustion chamber consist of atomization, evaporation, two-phase mixing, chemical kinetic reaction, etc... they are highly complex and strongly coupled. Due to the current simulation limitations, a number of assumptions have to be imposed to solve the problem. They are listed below:

- Only an axisymmetric flow field of the thrust chamber is simulated. The chamber inlet is divided radially into two regions. The outer region, called the film cooling ring, represents the film cooling inlet, while the inner one, called the hot core, operates at uniform mixture ratio (MR).
- The propellants being injected into the hot core region are assumed to be gaseous, completely mixed, and react in a chemical equilibrium fashion at the injector face. The film coolant is considered to be gaseous at the inlet. Its properties are estimated based on the ideal-gas relationship and the chemical equilibrium postulate.
- The estimation of the erosion rate of the ablative silica phenolic material is based on limited test data reported in 1969 by Aerojet-General Corporation[2]. The test series were conducted for a large hydrogen/oxygen thrust chamber. The only reported data (see Fig.1), which are relatively suitable for the present analysis, are the erosion rates of silica phenolic at the chamber throat. The erosion rate, then, is assumed to be a function of the chamber pressure and the ideal recovery temperature (equivalent to the adiabatic wall temperature). Moreover, the erosion rate is considered to be applicable for every point along the chamber wall.

Due to the aforementioned assumptions, the results of the present analysis should not be interpreted as representative of the actual thrust chamber characteristics. They rather provide the trend of the thrust chamber behavior and tend to portray the upper bound on the wall temperature because of the gaseous propellant and chemical equilibrium assumptions. Consequently, the estimated erosion rate may be higher than the actual rate. On the other hand, the solutions seem to provide the lower bound on the performance loss, since the simulation excludes other combustion losses.

The calculations have been conducted for various operating conditions, film cooling flow rates, and two chamber lengths. Hence, the results provide some understandings of the sensitivity among the parameters involved. The computational domain of the thrust chamber, shown in Fig.2, is enclosed by a grid mesh size of 61x121. Typical flow field temperature and velocity within the chamber are presented in figures 3 and 4, respectively. A summary of the thrust chamber geometry and operating conditions used in the analysis is given below:

Chamber Pressure (psia)	300
Overall Mixture Ratio (MR)	2.34
Fuel (RP-1) Flow Rate (lbm/sec)	14.19
Oxidizer (LOX) Flow Rate (lbm/sec)	33.19
Fuel for Film cooling (% in mass)	0, 4, 6, 8, 12, 14
Combustion Chamber Length (in)	16.0, 21.0
Contraction Area Ratio	2.45

Because of the assumption of gaseous film coolant, the actual inlet area of the film cooling has been adjusted in order to converse its mass flow rate and inlet velocity. As a result, the inlet momentum may not be correctly simulated. To examine the solution dependence on the inlet momentum change, calculations for a fixed film cooling flow rate have been performed for several film cooling inlet momentum values by varying the inlet area, velocity, and density. As shown in figures 5 and 6, the wall temperature and erosion rate are not significantly sensitive to the change in the film cooling momentum. The wall temperatures and erosion rates for the chamber length of 16-inches at various film cooling percentages are presented in figures 7 and 8. The corresponding maximum wall temperature and erosion rate of each film cooling value are plotted in figures 9 and 10. The results indicate that the maximum values of temperature and erosion rate are located slightly upstream of the throat. Moreover, when the percentage of fuel to be used for film cooling is greater than 10%, the chamber wall conditions no longer strongly respond to an increase of film cooling. It should be noted that the additional fuel to be used for film cooling results in a higher hot core MR. The hot core flow, accordingly, has a higher temperature. Therefore, adding more film coolant no longer has a strong effect on the wall temperature reduction. On the other hand, the thrust chamber performance loss, shown in Fig. 11, linearly increases with the film coolant increase.

By extending the combustion chamber length from 16.0 to 21.0- inches, the wall temperature peak, shown in Fig. 12, increases by an amount of 10%. This result is expected, since the longer combustion chamber allows the extension of the hot gas entrainment to the boundary layer, and the chemical reaction process near the wall. The corresponding erosion rate at the peak, Fig. 13, climbs at a steep rate. As seen from Fig.1, when the recovery temperature exceeds 3500 Rankine, the erosion rate curves have steeper slopes than the rate at the low temperature. These erosion characteristics reflect the solutions for the chamber length of 21-inches, which is shown in Fig.12. Although the wall temperature, as mentioned previously, increases only 10% at the peak point, the corresponding erosion rate increases by as much as 120% due to the peak temperature exceeding 3500 Rankine for the 21-inch long chamber.

References:

1. Przekwas,A.J., Lai,Y.G., Krishnan,A., Avva,R.K., Giridharan, M.G.,"Combustion Chamber Analysis Code, Final Report", NASA contract number: NAS8-37824.
2. Moise, J.C., Kovach R.J.,"Performance of Various Ablative Materials in a Large Hydrogen/Oxygen Thrust Chamber", AIAA paper 69-442.

Fig.1: Erosion Rate of Ablative Silica-Phenolic Material

(Data From Aerojet-General Corporation)

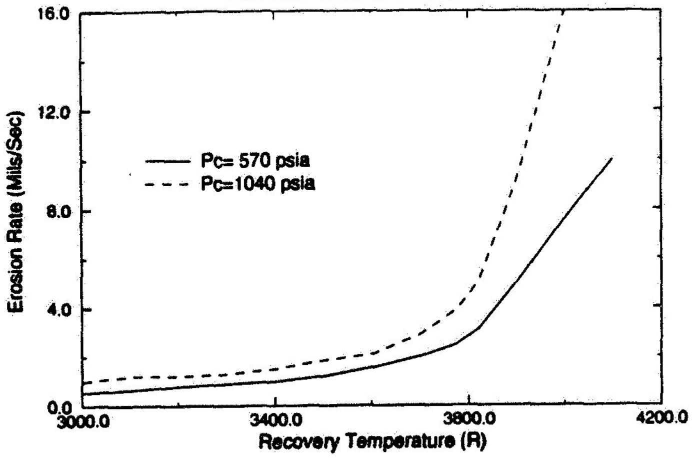


FIG.2: COMPUTATION GRID MESH (61x121)

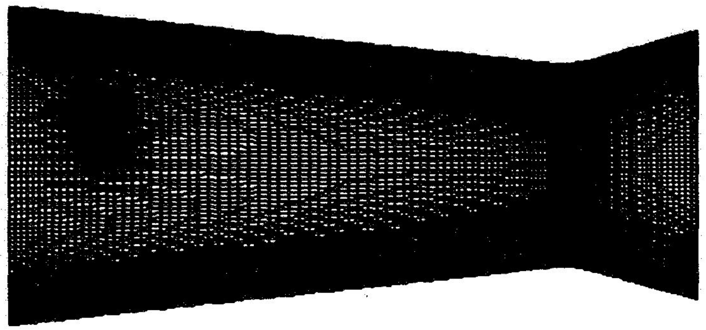


FIG.3: FAST-TRACK CHAMBER TEMPERATURE (KELVIN)
PC=300PSI, MR(overall)=2.34

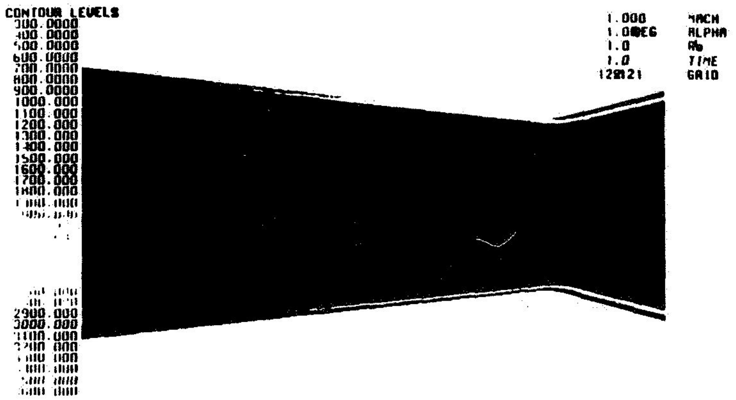


FIG.4: FAST-TRACK CHAMBER VELOCITY VECTOR
COLORED BY TEMPERATURE FIELD (KELVIN)

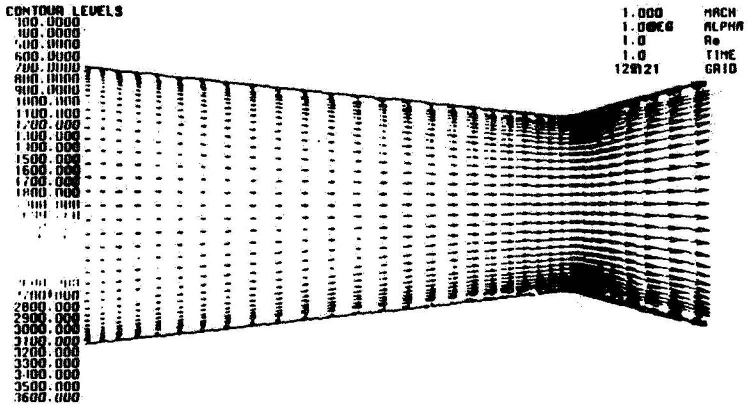


Fig.5: Change in Wall Temperature Due To Various Film Cooling Inlet Momentum

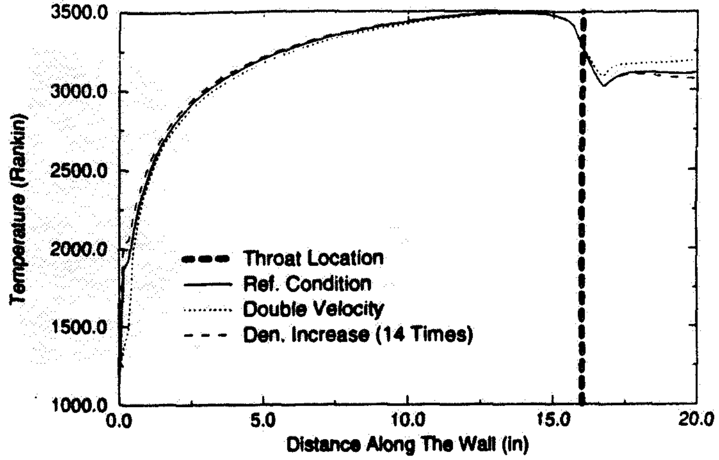


Fig.6: Change in Erosion Rate Due To Various Film Cooling Inlet Momentum

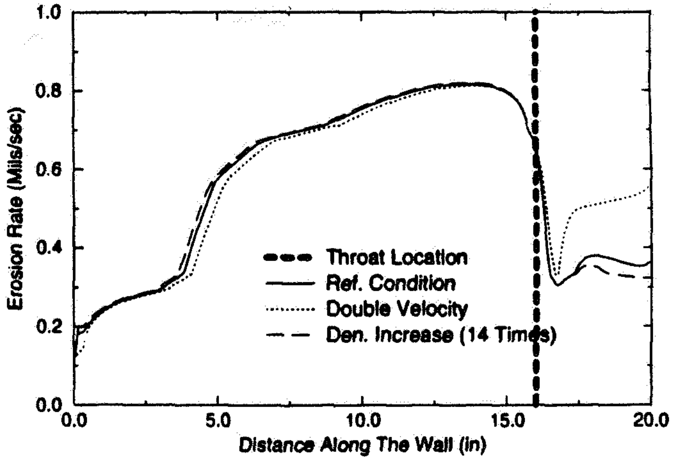


Fig.7: Wall Temperature Profiles at Various Film Cooling Rates

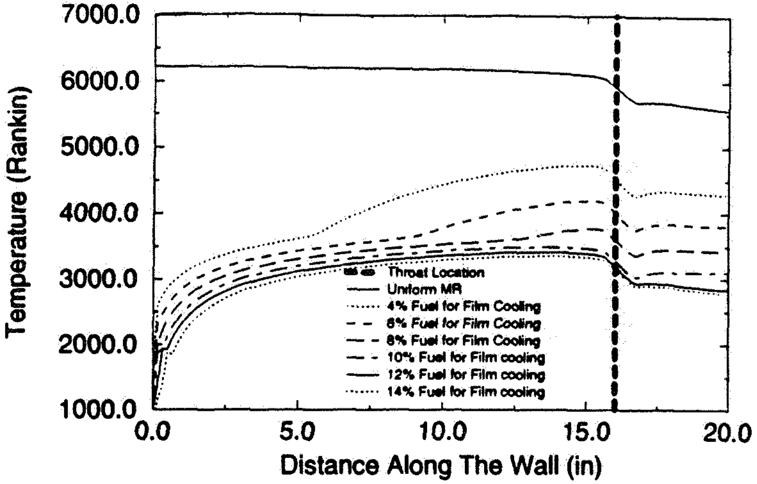


Fig.8: Wall Erosion Rate Profiles at Various Film Cooling Rates

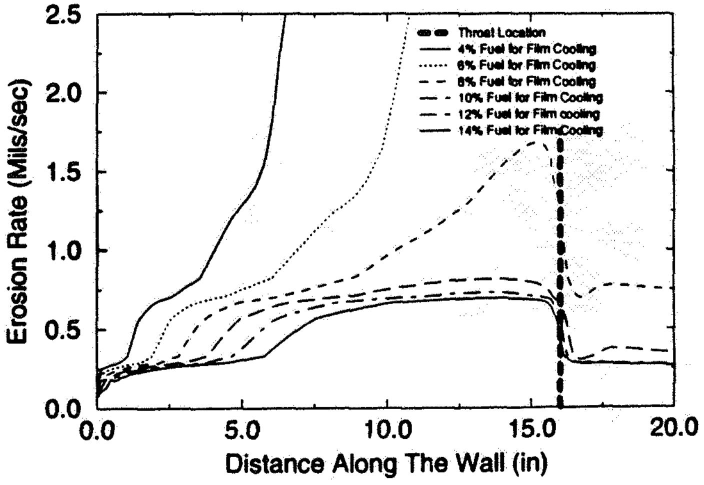
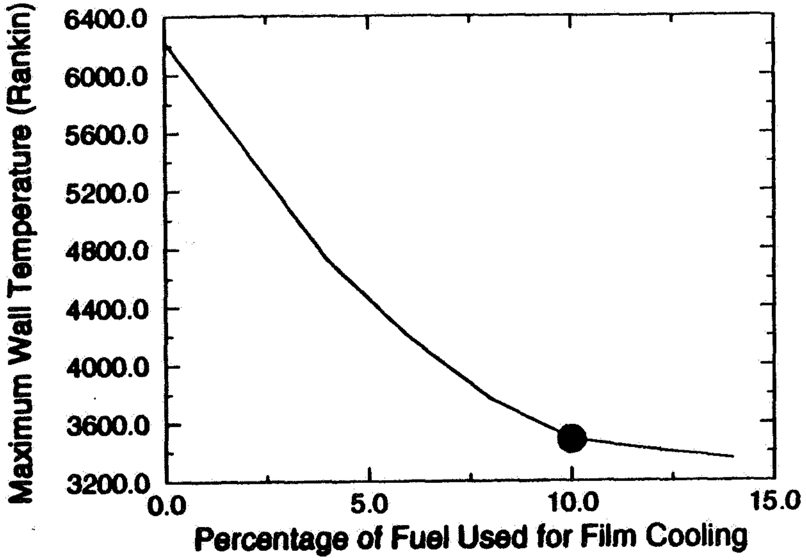


Fig.9: Change in Maximum Wall Temperature Due to Film Cooling Increase



● Projected test point

Fig.10: Change in Maximum Erosion Rate Due to Film Cooling Increase

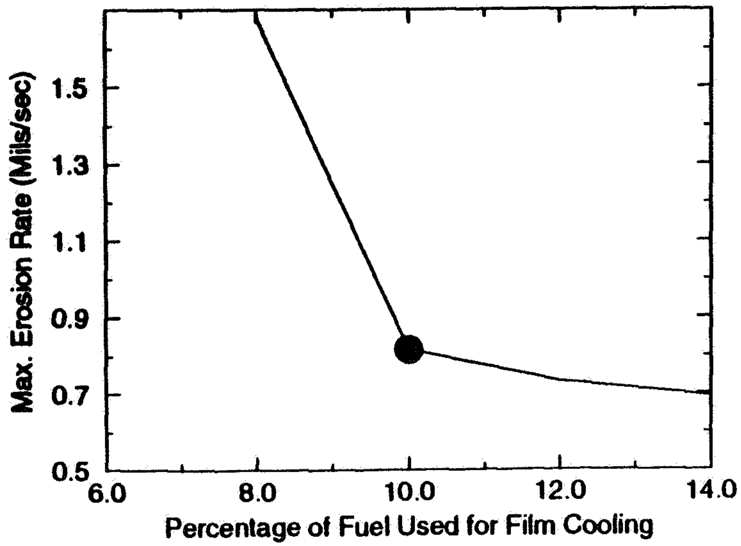


Fig.11: Performance Loss Due to Film Cooling Increase

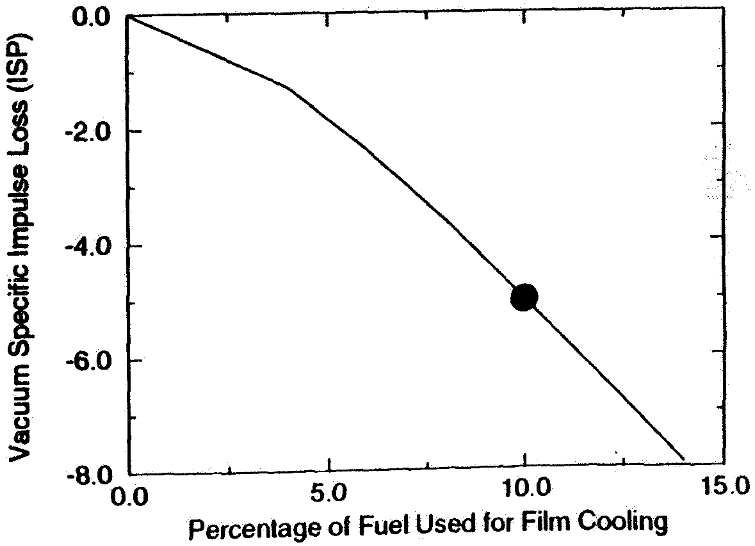


Fig.12: Wall Temperatures for Two Different Chamber Lengths (10% Fuel for Film Cooling)

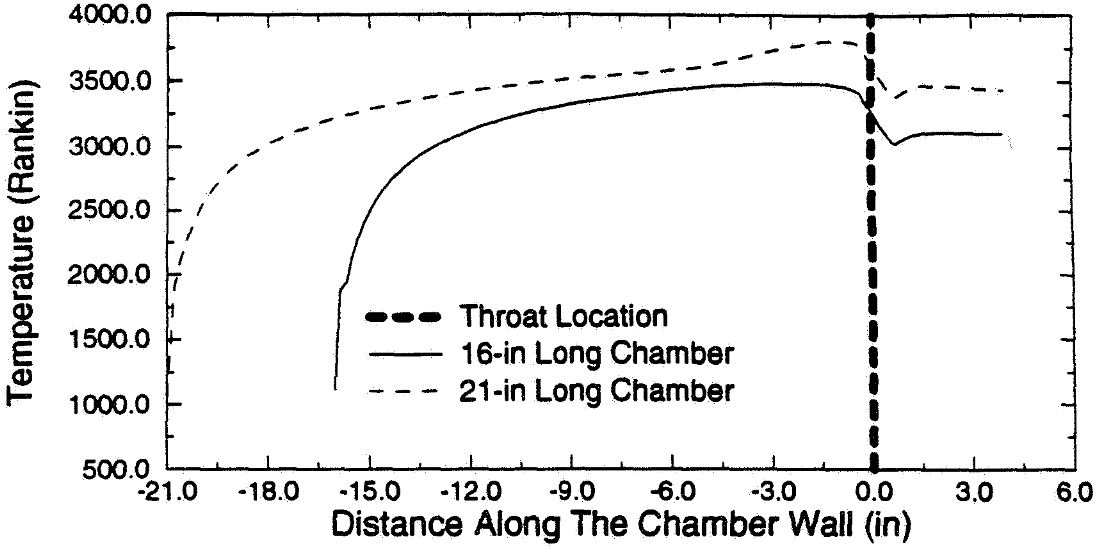


Fig.13: Wall Erosion Rate Profiles for Two Different Chamber Lengths (10% Fuel for Film Cooling)