20266-6025-RO-00

MONOPROPELLANT HYDRAZINE RESISTOJET

DATA CORRELATION TASK SUMMARY REPORT

TRW SYSTEMS GROUP
ONE SPACE PARK
REDONDO BEACH, CALIFORNIA 90278

MARCH 1973

Prepared for
GODDARD SPACE FLIGHT CENTER
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FOREWORD

This is the fifth Task Summary Report submitted under Contract NAS5-11477, "Design, Development, and Testing of an Engineering Model 20-Millipound Thrust Monopropellant Hydrazine Resistojet." The program originated in the Auxiliary Propulsion Branch of the NASA/Goddard Space Flight Center. Mr. Dennis Asato is the Technical Officer for NASA/GSFC. Mr. Charles K. Murch is the Project Manager for TRW Systems Group. Much of the content of this report is taken from "Electrothermal Hydrazine Thruster Analyses and Performance Evaluation," by R. A. Callens and Charles K. Murch, AIAA Paper No. 72-1152, November 1972.

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1.0 INTRODUCTION AND SUMMARY

The "Design, Development and Testing of an Engineering Model Nominal 20-Millipound Thrust Monopropellant Hydrazine Resistojet Program" is divided into six basic tasks. Included in these tasks are analyses, design, test, and data correlation of the Electrothermal Hydrazine Thruster (EHT). This report summarizes briefly the analyses conducted for the EHT and the design of the Engineering Model Thruster. Some of the results of the Engineering Model tests are then compared with the analytical performance models generated early in the program.

During the development phase of the EHT, the analyses proved to be a valuable tool for establishing thruster configuration changes. Later in the program, the analytical models aided in the interpretation of test data.

2.0 THRUSTER DESCRIPTION

The Engineering Model Electrothermal Hydrazine Thruster is shown in Figures 1 and 2. In Figure 1, the external shield and a portion of the insulation package is removed to show the thrust chamber assembly. The Haynes 25 thrust chamber is about 0.25-inch in diameter by about 0.5-inch long and contains a composite platinum/Haynes 25 screen pack. The chamber is supported by a thermal barrier tube attached to a right-angle bracket. The barrier tube was designed to support the thruster with a minimum heat loss. The heater element is a double-wire, tubular unit wrapped around and brazed to the chamber. The heater resistance was selected to produce a 5-watt output at 26 Vdc.

Figure 2 shows the unit with the external heat shield. For the Engineering Model, the insulation package and heat shield were split to allow the installation of the thermocouples and a chamber pressure tap. The valve is a Parker Model 5700060-103. The valve requires 3 watts of power at 27 Vdc. The entire assembly as shown in Figure 2 weighs less than 0.5 pound. A more complete description of the basic design of the EHT is given in Reference 1, which also includes a description of the thruster test facility and output data format.

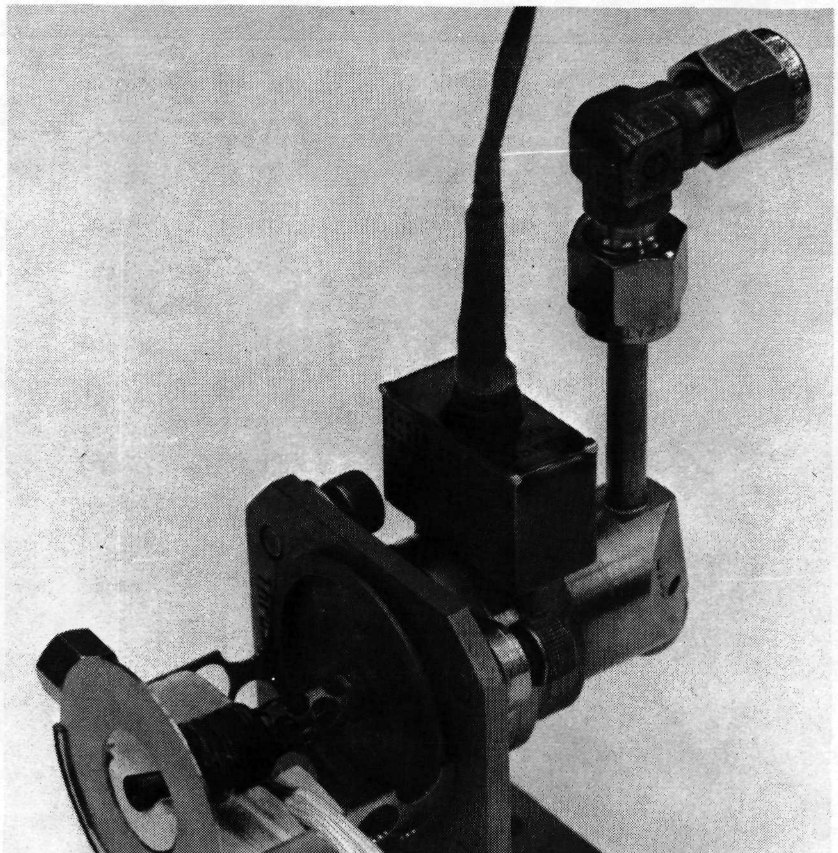

Figure 1. ENGINEERING MODEL ELECTROTHERMAL HYDRAZINE THRUSTER (HEAT SHIELD AND INSULATION PARTIALLY REMOVED)

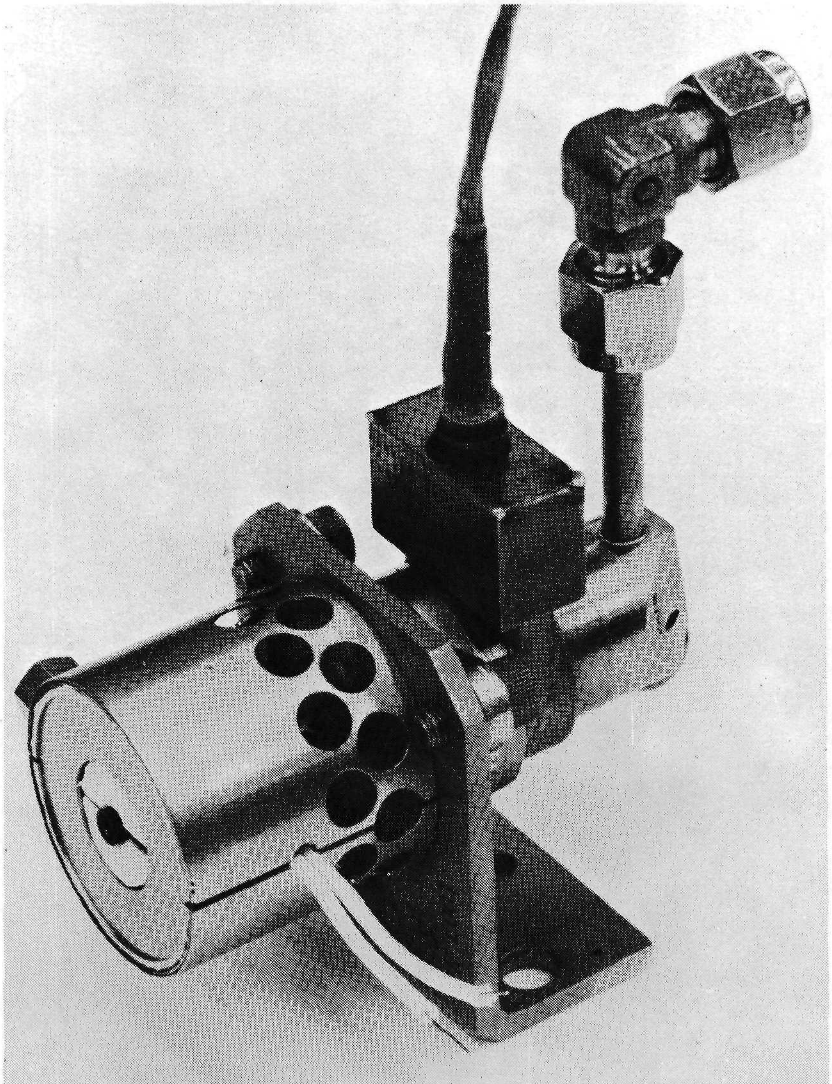

Figure 2. ENGINEERING MODEL EHT

3.0 THRUSTER ANALYSES

The analyses formulated for the Electrothermal Hydrazine Thruster provided mathematical models which were utilized in preliminary design definition, interpretation of test data, and the evaluation of design and operational changes. Three computer programs were formulated to provide the necessary steady-state and transient performance design tools. These included:

1. A program to provide preliminary evaluation of the energy balance characteristics of the thruster.
2. A program to evaluate steady-state performance relative to the configuration and operational parameters.
3. A model of transient (pulse mode) operation of the thruster relative to design and operational parameters.

The steady-state energy balance and performance programs for the EHT were formulated by F. B. Muenzer on the TRW Timeshare digital system to provide a tabular data printout. The transient performance model was formulated on a C15000 active-element analog computer to provide direct time-variant output of the operational characteristics. Complete descriptions of the analyses may be found in Reference 2.

Parameter studies were conducted with both the analog computer transient model and the digital steady-state program. Studies included evaluation of the effects on thruster operation of variations in supply pressure, ammonia dissociation fraction, wall and screen pack surface area, thruster volumes (head-end and chamber), thruster mass, electrical power, holding temperature, throat and injector area, and nozzle thrust coefficient. Thruster performance parameters included: impulse, specific impulse, characteristic velocity, thrust coefficient, wall and chamber temperature, thrust, and flow rate, as well as internal pressures and temperatures.

While three separate analytical models were formulated, the energy balance computer model served only as a preliminary aid in understanding the thruster operation. This model was ultimately replaced as an evaluation tool by the more extensive steady-state and transient performance models.

It should be noted that both the steady-state and transient performance models were based on a lumped-parameter representation of the EHT. In the lumped-parameter method, the pressure, flow rate, heat transfer and other characteristics of the thruster (shown schematically in Figure 3) are analytically described as occurring at a finite number of specified nodes. Thus, the pressure/flow characteristics, for example, are schematically represented as shown in Figure 4. In this figure, R_1, R_2, R_3, and R_4, represent the valve flow resistance, injector flow resistance, screen pack flow resistance and nozzle throat flow resistance, respectively. P_0 represents the supply pressure, and the capacitance effects at P_1, P_2, and P_3 determine the injector inlet pressure, head end pressure, and chamber pressure, respectively.

3.1 Energy Balance Analysis

The energy balance analysis was conducted to provide a general understanding of the nominal energy distribution and performance characteristics for specified thruster operating conditions. In order to provide this preliminary evaluation, an analytical model was formulated and a digital computer program was written to provide rapid iterative solutions.

The energy balance was represented as

$$C_p \dot{w} \Delta T = \Sigma \dot{Q}$$

where

C_p = specific heat of hydrazine decomposition products
$\dot{w}$ = mass flow rate, lb/sec
ΔT = temperature increase above inlet condition
$\Sigma \dot{Q}$ = sum of heat input and losses

The thermal decomposition of hydrazine was assumed to occur in two stages, decomposition and dissociation (see Reference 3), thus

$$3N_2H_4 \rightarrow 4NH_3 + N_2 + 144{,}300 \text{ BTU (exothermic decomposition)}$$

and

$$4NH_3 \rightarrow 2N_2 + 6H_2 - 79{,}200 \text{ BTU (endothermic dissociation)}$$

The heat input and loss terms included the exothermic decomposition heat, the endothermic ammonia dissociation heat, the heat of

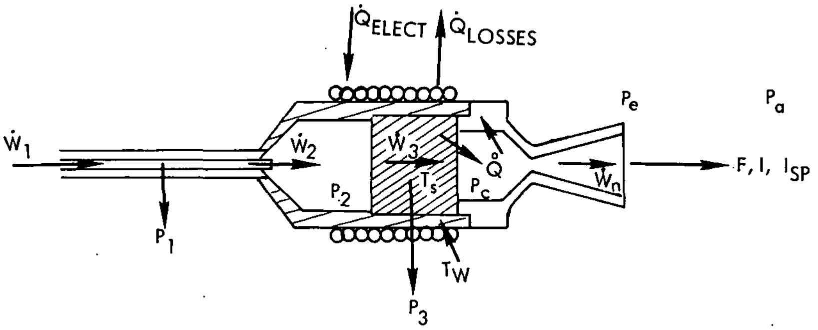

Figure 3. ELECTROTHERMAL HYDRAZINE THRUSTER SCHEMATIC

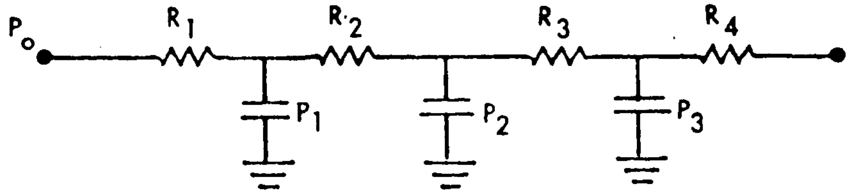

Figure 4. LUMPED PARAMETER PRESSURE/FLOW SCHEMATIC

vaporization, the electrical heat input, and the radiative and conductive heat losses from the thruster.

Program inputs required were chamber pressure, throat area, electrical power, thermal losses, propellant inlet temperature and nozzle thrust coefficient. Specific heat ratio and specific heat were defined as a function of dissociation fraction (from Reference 3). Based on these values, the program calculated chamber temperature, flow rate, thrust, specific impulse, net decomposition and dissociation energy. A typical program output is illustrated in Table 1.

3.2 Steady-State Analysis

The steady-state performance model was formulated to provide a more accurate assessment of thruster steady-state operation relative to design parameters such as chamber size, injector pressure drop, nozzle configuration, screen pack pressure drop and heat transfer areas, as well as supply pressure and temperature, thruster holding power, and thermal losses. This model was utilized to conduct parametric sensitivity and design variation studies to define the effects of the above parameters on chamber temperature, specific impulse, characteristics velocity, and thrust of the EHT.

Equations were developed for the flow rates, pressure drops, and the pertinent heat transfer rates. A combination of analytical and empirical data defined the thruster heat losses and the viscous losses in the nozzle expansion process. These data were entered into the program in tabular form.

The program input parameters and calculated performance variables are summarized in the typical data output shown in Table 2.

3.3 Transient Analysis

The thruster transient computer model was formulated on a C15000 active element analog computer. The analog is particularly amenable to this type of study, since the engineering equations can be simulated in a modular form. This facilitates changing

Table 1. TYPICAL ENERGY BALANCE PROGRAM OUTPUT

```
? PC=76.79,QD0T1=12.,QD0TL=5.41,CF=1.654$

    CHAMBER PRESSURE     =  7.679E+01  PSIA
    THRØAT AREA          =  3.140E-04  INCHES SQUARE
    CHAMBER TEMPERATURE  =  2.566E+03  DEGREES R
    INLET TEMPERATURE    =  5.300E+02  DEGREES R
    FLØWRATE             =  1.760E-04  LBS./SEC.
    SPECIFIC IMPULSE     =  2.266E+02  SEC.
    THRUST               =  3.988E-02  LBS.-F

                          BTU/SEC      WATTS

  ELECTRICAL INPUT   =    1.138E-02    1.200E+01
  DECØMPØSITIØN      =    2.649E-01    2.793E+02
 *VAPØRIZATIØN       =    0.           0.
  DISSØCIATIØN       =    4.356E-02    4.592E+01
  LØSSES             =    5.132E-03    5.410E+00
```

*Vaporization energy term is included in the decomposition energy.

Table 2. TYPICAL STEADY-STATE COMPUTER PROGRAM OUTPUT

INPUTS

SUPPLY PRESSURE	=	2.000E+02	PSIA
SUPPLY TEMPERATURE	=	7.000E+01	DEGREES F
ELECTRICAL POWER INPUT	=	1.200E+01	WATTS
DISSOCIATION FRACTION	=	3.000E-01	
INJECTOR AREA	=	4.480E-06	SQUARE INCHES
THROAT AREA	=	3.140E-04	SQUARE INCHES
EXPANSION RATIO	=	5.000E+01	

---OUTPUT---

INJECTOR INLET PRESSURE	=	1.372E+02	PSIA
HEAD END PRESSURE	=	8.016E+01	PSIA
AVERAGE SCREEN PACK PRESSURE	=	7.848E+01	PSIA
CHAMBER PRESSURE	=	7.681E+01	PSIA
VAPORIZATION TEMPERATURE	=	3.360E+02	DEGREES F
AVERAGE GAS TEMPERATURE	=	1.590E+03	DEGREES F
SCREEN PACK TEMPERATURE	=	1.590E+03	DEGREES F
WALL TEMPERATURE	=	1.595E+03	DEGREES F
CHAMBER TEMPERATURE	=	2.106E+03	DEGREES F
CHEMICAL HEAT INPUT	=	2.332E+02	WATTS
WALL TO SCREEN HEAT FLUX	=	7.926E-01	WATTS
WALL TO GAS HEAT FLUX	=	5.976E+00	WATTS
SCREEN TO GAS HEAT FLUX	=	7.926E-01	WATTS
HEAT LOSSES	=	5.231E+00	WATTS
THRUST COEFFICIENT	=	1.654E+00	
FLOWRATE	=	1.759E-04	LBS./SEC.
THRUST	=	3.988E-02	LBS.-F
SPECIFIC IMPULSE	=	2.268E+02	SEC.
CSTAR	=	4.415E+03	FT./SEC.

the model to include different configurational or operational conditions. The analog program provides time variant analog data such as would be obtained from actual hardware testing. This is particularly useful in evaluating test data since performance parameters not measurable in testing (instantaneous flow rates, etc.) are produced as direct analytical outputs.

As with the steady-state model, the transient thruster model was based on lumped parameter considerations whereby mass, resistance, and temperature were represented by single lumped nodes. The mathematical model was derived from conservatin of mass and energy relationships in time-variant form.

Program inputs included specified thruster dimensions (injector area, head-end and chamber volume, etc.), supply pressure, and temperature. Values for specific heat, specific heat ratio, and gas constant were included tabularly as a function of dissociation fraction. Nozzle efficiency was also entered in tabular form. Calculated parameters included thruster flow rates, thrust, chamber and internal pressures, screen pack, wall and gas bulk temperatures, impulse and specific impulse. A sample of the data output is given in Figure 5.

4.0 CORRELATION OF ANALYTICAL AND EXPERIMENTAL DATA

The results of the analyses described in the preceding section were used to provide preliminary design data for development model thrusters. When experimental data became available from the development hardware, the analyses were "calibrated." This process involved the modification of several previously assumed values for such parameters as heat transfer coefficients and pressure drops. The modified analyses were then used as the basis for the Engineering Model EHT design. One further analytical iteration based on the results of the Engineering Model test data would provide an even more versatile tool for scaling thruster sizes and establishing off-nominal performance. This iteration would also result in closer correlations in many instances between the analytical and Engineering Model test data, since several

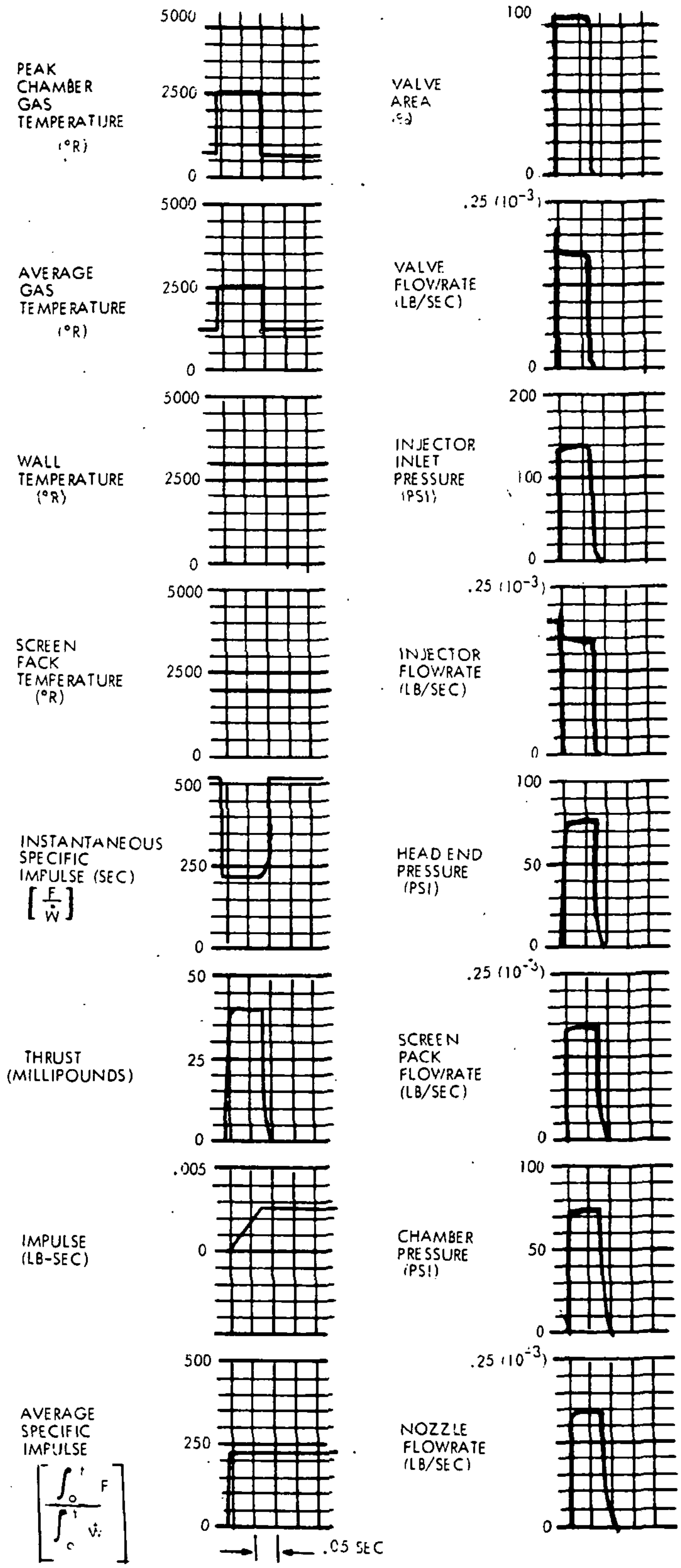

Figure 5. TYPICAL TRANSIENT PERFORMANCE DATA FROM ANALOG MODEL (SUPPLY PRESSURE = 200 psi, 1650°F)

configurational changes were not included in the analytical models. These configurational changes can be seen by comparing Figure 6, a sectioned Engineering Model thruster, with Figure 3, the configuration used in the analyses. Note that the Engineering Model thruster included a thermal barrier tube, a chamber pressure tap and a two layer heater which increased the overall size of the unit.

4.1 Thermal Characteristics

The results of the preliminary thermal loss calculations are shown in Figure 7. Included are separate loss estimates for conduction down the injector tube, losses through the insulation package, and radiative losses from the nozzle. The experimental data marked "Thermal Model" were obtained with hardware which nearly duplicated that assumed by the analysis. As indicated, the analysis is rather optimistic and projects a 1500°R operating (or holding) temperature with about 2.7 watts input. The thermal model required about 3.4 watts. The discrepancy is partially attributable to the heater leads and thermocouple instrumentation which were not included in the analysis. The Engineering Model design, which incorporated a barrier tube for structural support, required 5 watts for operation at 1500°R. The Engineering Model also included a chamber pressure tap and electrical leads which represent heat loss paths.

4.2 Steady-State Operation

Steady-state thrust is shown in Figure 8 as a function of inlet pressure. Both the analysis and the test data indicate that the thrust varies linearly with supply pressure. While the analysis was nearly correct at the 0.025-pound thrust design point for thruster S/N 301, a large discrepancy exists at higher inlet Pressures. This is because the analysis assumed a large valve pressure drop, whereas the pressure drop through the Parker solenoid valve is nearly negligible over the applicable flow rate range. However, the thrust of GSFC 004 at high inlet pressures coincides almost exactly with the analysis. This is the result of an increased injector pressure drop due to the incorporation of the loop in the injector tube.

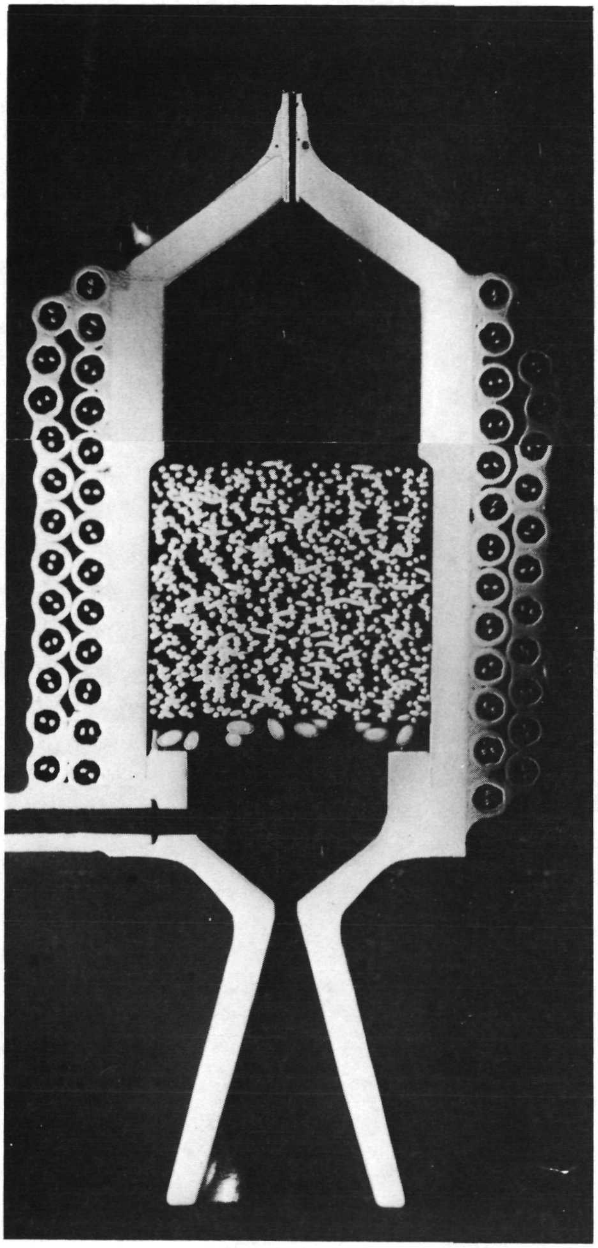

Figure 6. SECTIONED ENGINEERING MODEL THRUSTER

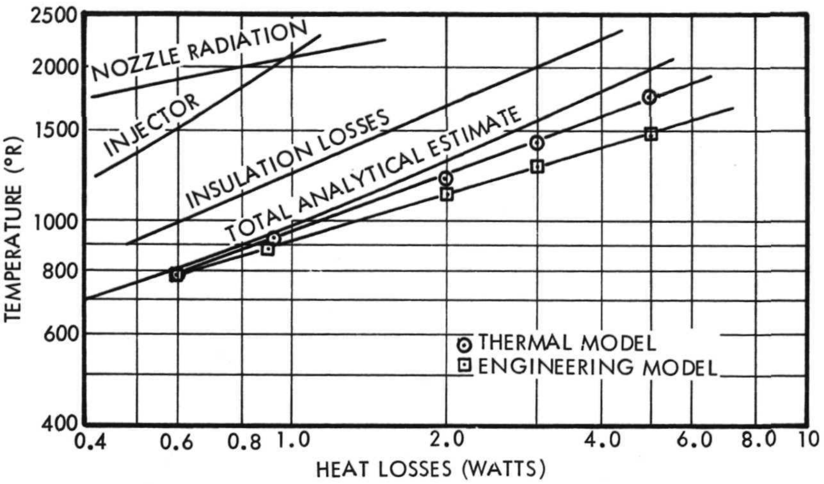

Figure 7. THRUSTER HEAT LOSSES

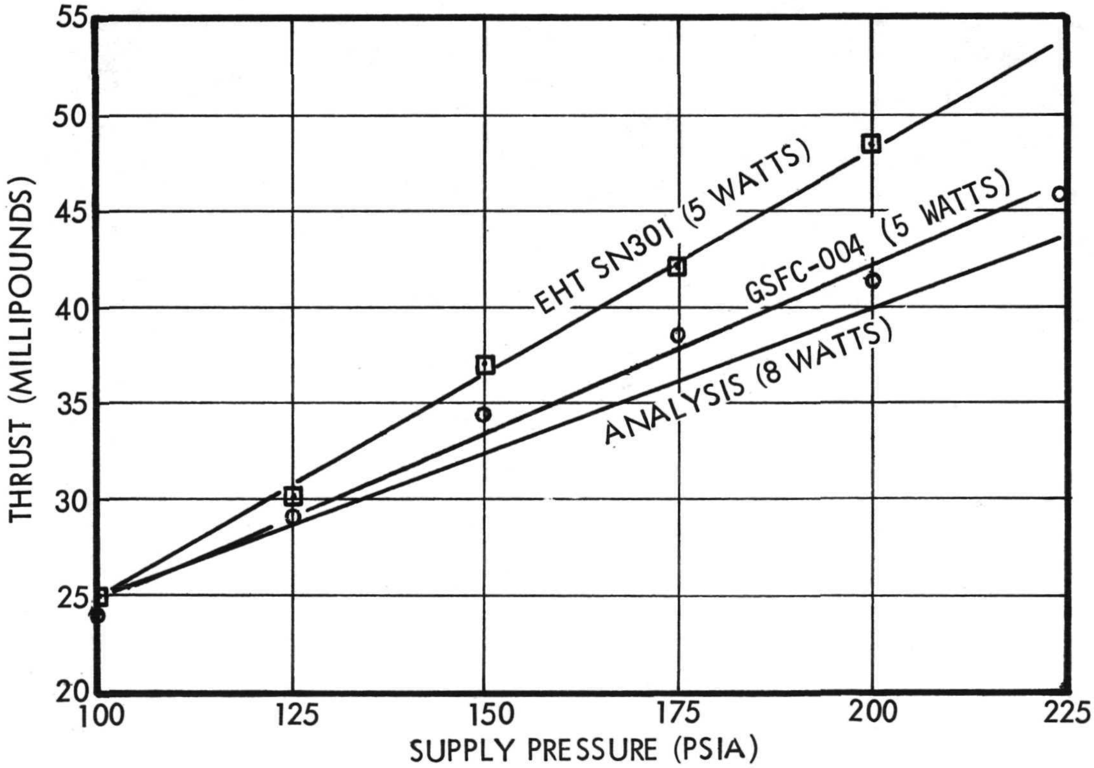

Figure 8. STEADY-STATE THRUST

The analytical prediction of steady-state specific impulse is shown in Figure 9, together with Engineering Model Test data. The analytical model indicates little degradation in specific impulse with decreasing supply pressure. The primary effect considered is a decrease in nozzle efficiency. The experimental data indicate a stronger sensitivity to supply pressure. This results from a change in residence time in the thrust chamber which influences the ammonia dissociation fraction. At low inlet pressures, the residence times are longer, the dissociation fraction is higher, and the net gas entahlpy and specific impulse are reduced.

4.3 Transient Analyses

Under no-flow conditions, the electrical heater of the EHT maintains a nominal temperature of about 1000°F. When propellant flow is initiated and maintained for a sufficient length of time, the exothermic decomposition reaction increases the thruster temperature to about 1650-1750°F. This temperature transient is reflected in both the thrust level and the specific impulse. The thrust transient has been found to be small since the total pressure drop through the thruster is relatively insensitive to temperature. However, the specific impulse transient is significant since it is proportional to the square root of temperature (more correctly, the chamber enthalpy). The transient analysis took into account the thermal mass, heat transfer rates, and energy inputs to the thruster and calculated the instantaneous specific impulse. These data are shown in Figure 10 together with experimental data. As indicated by the figure, the steady-state value is reached about 60 seconds after the initiation of propellant flow.

As shown earlier in Figure 5, the analog computer data output format was selected to coincide as nearly as possible with the output of the EHT data acquisition system. The left-hand side of Figure 11 is a reproduction of a 0.05-second EHT pulse (chamber pressure) taken from the middle of a train of pulses where the thruster temperature was at a nominal value of about 1600°F. The upper curve is solenoid valve current which indicates the times at which

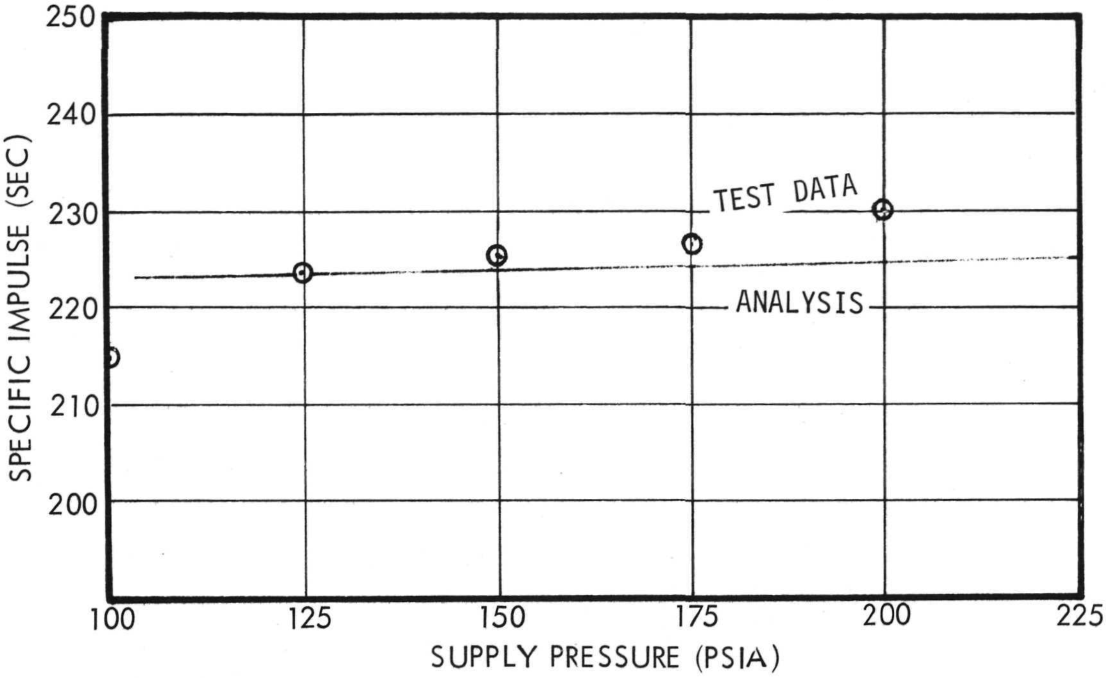

Figure 9. STEADY-STATE SPECIFIC IMPULSE

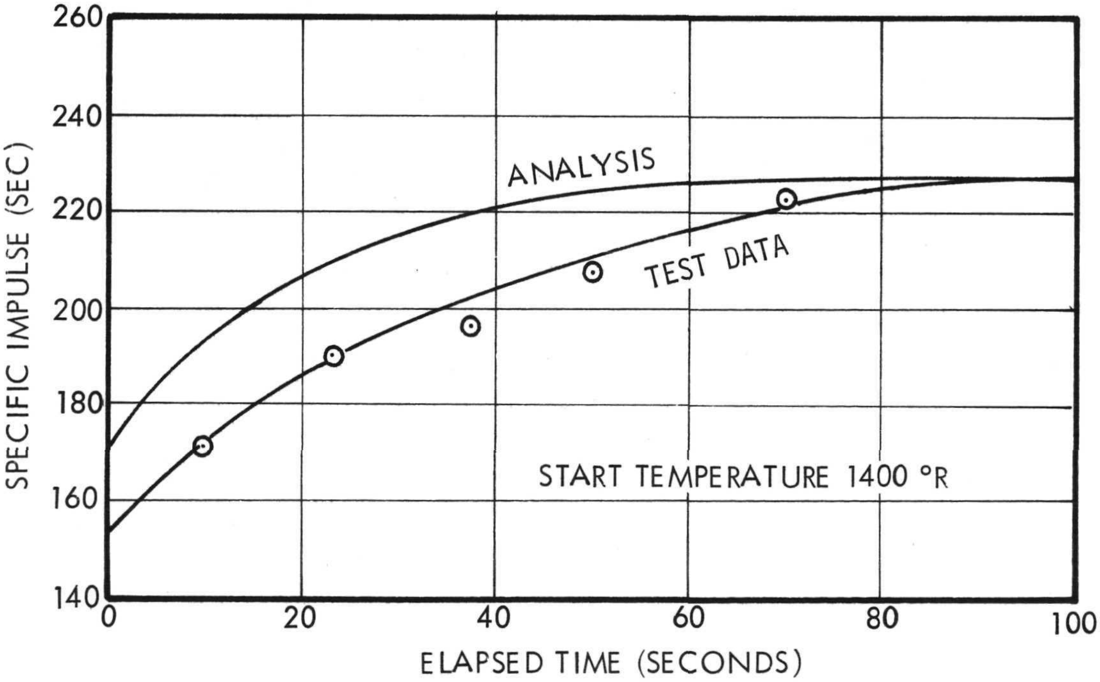

Figure 10. SPECIFIC IMPULSE TRANSIENT

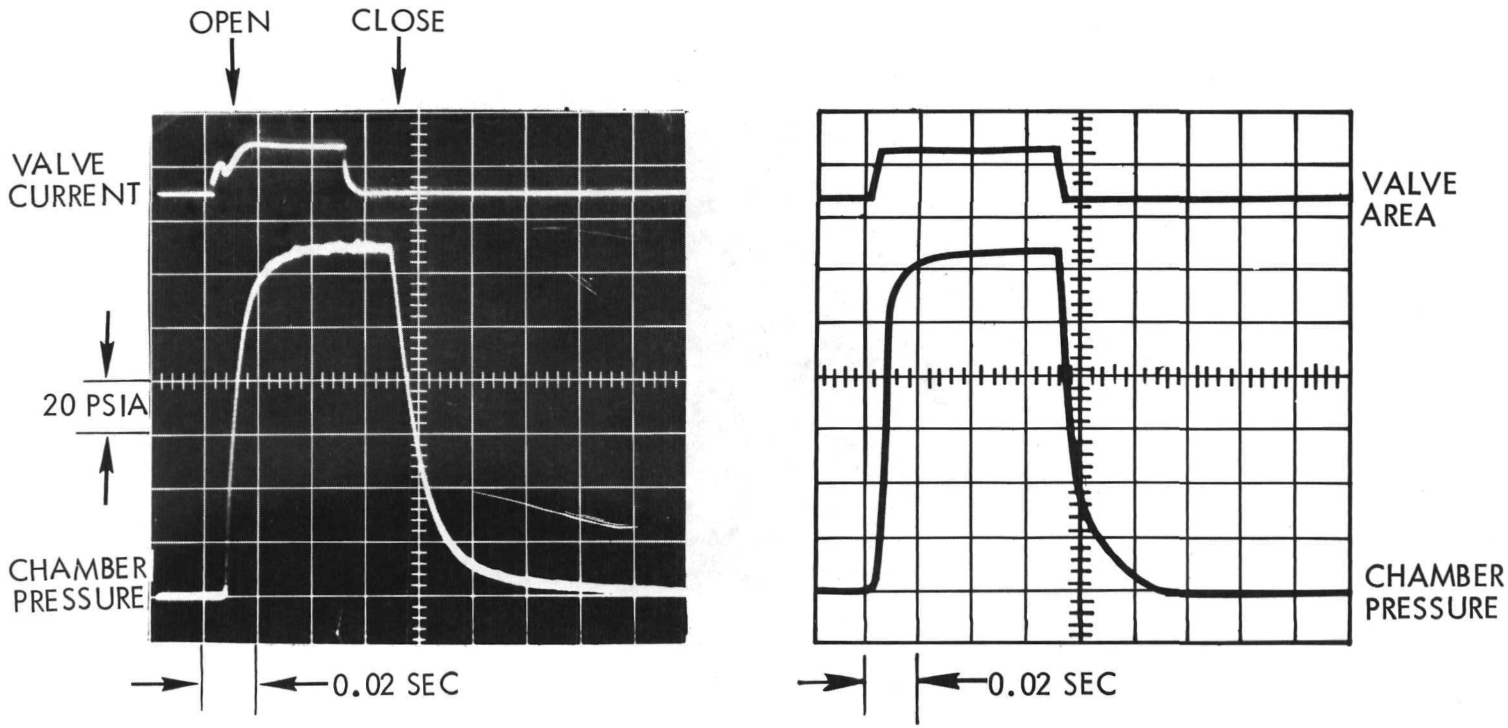

Figure 11. PULSE SHAPE CORRELATION (200 psia)

the valve actually opens and closes. The actual valve open time is about 70 milliseconds. The right-hand side of Figure 11 is a reproduction of the analog computer output with nearly identical boundary conditions. The upper curve is the analog of the valve open time (noted as valve area in Figure 5), in this case 75 milliseconds. The analog model is quite consistent with the actual test data for the pressure increase transient. The initial portion of the decay transient is also accurately modeled. After decay to about 10 percent of chamber pressure is reached, the analytical correlation is less accurate. This is believed to be due to the effect of the liquid hydrazine "stored" within the injector at the time of the valve closure. This liquid is expelled at a slower rate than the decomposed propellant within the chamber. This results in longer decay times than predicted by the analog model. The long decay transient for the EHT also results in a slightly lower delivered specific impulse for short pulses compared with the analog prediction. Since the propellant is expelled somewhat less efficiently than predicted during the transients, the analog specific impulse is about 10 percent too high.

Delivered impulse bit as a function of supply pressure and pulse width is shown in Figure 12. The Engineering Model thruster produced impulse bits of approximately 1 millipound-second near the end of the 300,000-cycle, 30-hour steady-state test. At this time during the test, the steady-state thrust had decreased about 25 percent from the valves shown in Figure 8 due to an increased injector pressure drop. This lower thrust is reflected in the data of Figure 12.

5.0 CONCLUSIONS

The analytical models of the electrothermal hydrazine thrusters have proven to be a valuable tool in the areas of thrust design and data interpretation. While the analytical models have not always correlated with experimental data in absolute magnitude, all of the observed data trends have been projected analytically.

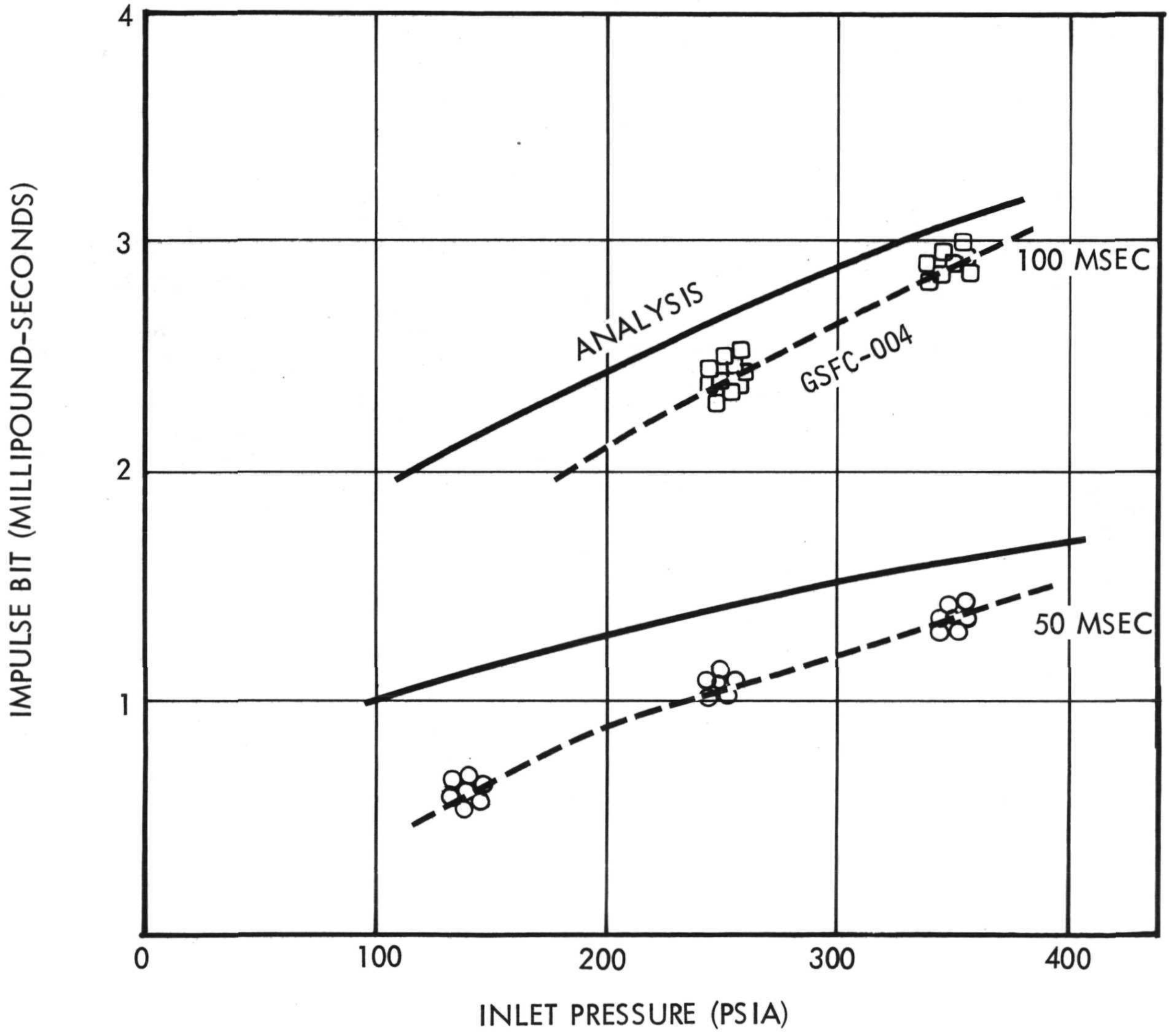

Figure 12. DELIVERED IMPULSE BIT

The ability to accurately assess the fundamental operating parameters of the EHT lends confidence to both the overall design and the ability to successfully comply with the performance specified for the forthcoming Engineering Model tests.

6.0 REFERENCES

1. Murch, C. K. and Hunter, C. R., "Electrothermal Hydrazine Thruster Development," AIAA Paper No. 72-451.

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