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PROPULSIVE POTENTIAL OF RESIDUAL ROCKET MOTOR HEAT

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Joseph L. Ansell
Delta Project Office

February 1968

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Greenbelt, Maryland

ABSTRACT

This paper presents an analytical study on how to use the residual motor heat of a solid-propellant rocket for propulsion purposes in full vacuum, through the introduction of an inert quenching fluid. Three fluids were considered: water, propane, and Freon 12, with Delta Launch Vehicle third stage rocket motors (X-258 or FW-4). The possibility of using this quenching technique to provide fine velocity control was explored. Water was found to be superior to the other fluids under the conditions assumed, and the method appears to be feasible for velocity-trim within 6 minutes after solid-propellant burnout. The study includes a computer program to predict the effect of introducing the quenching fluid at various times subsequent to the peak motor temperature.

CONTENTS

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INTRODUCTION

Critical injection missions require accurate control of the total impulse generated by the stages of a launch vehicle, especially the final stage. If an error occurs in the terminal injection velocity, the velocity can be corrected by a fine-trim control system. If the final stage is a solid-propellant motor, one method of fine velocity control is to inject a cold, inert fluid into the hot, expended motor (see Figure 1). While the motor is cooling and losing its energy, the inert fluid gains heat energy from the motor. Allowing the fluid to vaporize and flow through the rocket nozzle provides an advantage by use of its residual propulsive potential. The velocity gain can be adjusted to ensure a fine control over final velocity. The fineness of the control is determined by choice of a velocity-sensing system and the system of valves that permit only the required amount of inert fluid to enter the hot motor shell.

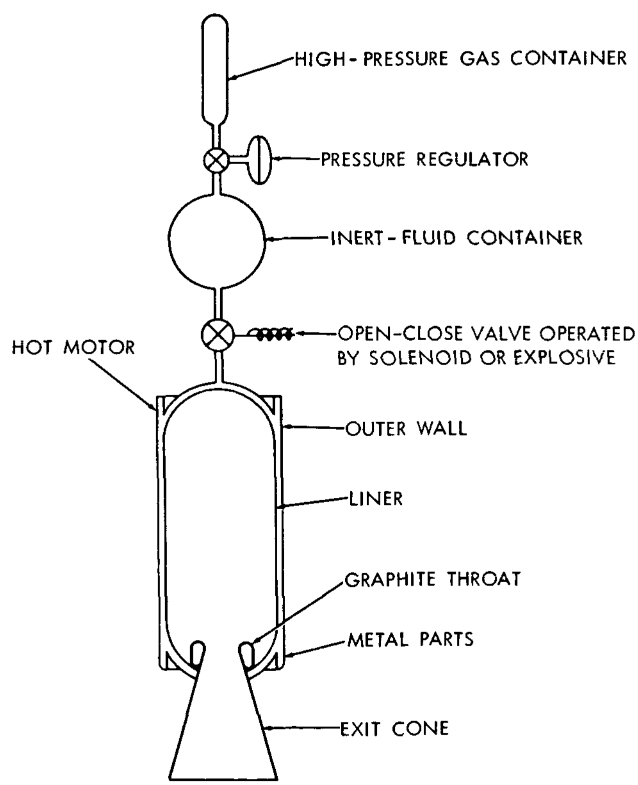

Figure 1—Schematic of a system for the injection of an inert fluid into a hot, solid-propellant motor at a constant injection pressure.

This approach also mitigates outgassing (Reference 1), which often contributes to an error in total impulse. Outgassing causes two problems after the solid main grain burnout. First, the total impulse of the solid-propellant stage may be greater or less than that predicted on the basis of static tests (Reference 2). Second, any outgassing that occurs after separation of the motor from the payload may cause the final-stage motor to collide with the payload, possibly damaging it or changing its attitude or course. A method of quenching a hot motor with an inert fluid to eliminate outgassing has been successfully used in ground testing (Reference 2).

The purpose of this study is: (1) to find the weight penalty and velocity loss due to carrying an inert fluid velocity fine-trim system, (2) to find the potential velocity that can be recovered from using such a system, and (3) to compare the velocity loss with the velocity recovered. A trade-off comparison will show whether it is feasible to carry an inert-fluid, velocity-trim system on a space vehicle that requires close control of the injection velocity.

Appendix A gives the calculations of comparative values for three selected substances; Appendix B lists motor-temperature measurements; Appendix C lists required motor specific heats. Appendix D is a reproduction of a computer program to predict the effect of introducing the quenching fluid at various times. Appendix E gives the calculations of equilibrium conditions for the three substances. Appendix F is a symbol list.

ANALYSIS

A solid-fuel motor retains, after firing, an amount of heat energy Q_0. Since no convection occurs in a vacuum, subtracting the amount of heat Q_{rad} radiated from the motor's surface gives the amount of heat energy available from the hot motor at the peak motor temperature.

$$H = Q_0 - Q_{rad} \tag{1}$$

$$Q_0 = W_3 C_p (T - T_0) . \tag{2}$$

The heat radiated from the motor's surface per unit area per unit time is

$$Q_{rad} = \epsilon\sigma(T^4 - T_1^4) \tag{3}$$

and the total heat radiated is:

$$Q_{rad} = \epsilon\sigma(T^4 - T_1^4)At . \tag{4}$$

Therefore, the heat remaining in the motor at time t after maximum motor temperature is reached is given by:

$$H = W_3 C_p (T - T_0) - \epsilon\sigma A(T^4 - T_1^4)t \tag{5}$$

and, since T_1 is very much smaller than T,

$$H = W_3 C_p (T - T_0) - \epsilon\sigma A T^4 t . \tag{6}$$

Differentiating with respect to time (in order to obtain the time decay of heat from the motor) gives

$$dH/dt = -\epsilon\sigma A T^4 + \left(W_3 C_p - 4\epsilon\sigma A T^3 t\right)dT/dt \ . \tag{7}$$

The heat remaining in the motor is now available for heating the inert propellant fluid; this heat, prior to the fluid flow through the hot motor, is

$$\bar{H} = H + \frac{dH}{dt} \times t \tag{8}$$

$$\bar{H} = \left[W_3 C_p \left(T - T_0\right)\right] - 2\left[\epsilon\sigma A T^4 t\right] + \left[\left(W_3 C_p t - 4\epsilon\sigma A T^3 t^2\right)dT/dt\right] \ . \tag{9}$$

The drop in temperature caused by the flow of inert fluid may be found by equating the heat lost by the motor to the heat gained by the inert fluid:

$$\dot{W}(\Delta t)C_{p6}\left(T_B - T_0\right) + \dot{W}(\Delta t)\lambda + \dot{W}(\Delta t)C_{p7}\left\{\left[T + dT/dt - t + \frac{dT_m}{dt}(\Delta t)\right] - T_B\right\} = W_3 C_p \left[- dT/dt - t - dT_m/dt(\Delta t)\right] \cdot \tag{10}$$

Solving for dT_m/dt gives

$$dT_m/dt = \frac{\dot{W}(\Delta t)C_{p6}\left(T_B - T_0\right) + \dot{W}(\Delta t)\lambda + W_3 C_p dT/dt - t + \dot{W}(\Delta t)C_{p7} T + \dot{W}(\Delta t)C_{p7} dT/dt - t - \dot{W}(\Delta t)C_{p7} T_B}{-\dot{W}(\Delta t)^2 C_{p7} - W_3 C_p (\Delta t)} \cdot \tag{11}$$

To determine the heat available in the motor at any time for a given flow of inert fluid into it,

$$\bar{H} = W_3 C_p \left(T - T_0\right) - 2\epsilon\sigma A T^4 t + \left(W_3 C_p t - 4\epsilon\sigma A T^3 t^2\right)dT/dt + W_3 C_p \frac{dT_m}{dt}(\Delta t) \ . \tag{12}$$

For any given time of injection of fluid into the hot motor and at any flow rate, the time after maximum temperature when the available heat falls to zero may be determined from Equation 12. A computer program helped determine this value (see Appendix D). To find the amount of fluid that can be injected, multiply $t(\bar{H} = 0)$ by the fluid weight flow rate.

$$m = t(\bar{H} = 0)\dot{W} \ . \tag{13}$$

Equation 13 assumes immediate (flash) vaporization of the quenching fluid on entry into the motor chamber. This mass of inert fluid will supply a total impulse

$$I_{tot} = mI_{vac} \tag{14}$$

and, since m and I_{vac} decrease with time, I_{tot} is a maximum when $t = 0$.

Velocity penalty and boost:

$$\Delta V_1 = gI_{vaco} \ln \frac{W_1 + W_2}{W_1 + W_3} \tag{15}$$

$$\Delta V_2 = gI_{vaco} \ln \frac{W_1 + W_2 + W_4 + W_5}{W_1 + W_3 + W_4 + W_5} \tag{16}$$

$$\text{Velocity penalty} = \Delta V_p = \Delta V_1 - \Delta V_2 \tag{17}$$

$$\Delta V_3 (t) = \text{velocity regained} = gI_{vac}(t) \ln \frac{W_1 + W_3 + W_4 + W_5}{W_1 + W_3 + W_4 + W_5 - m_0} \tag{18}$$

ΔV_3 is maximum at time $t = 0$.

COMPARISON WITH THEORETICAL RESULTS

An analysis of this type of quenching system was made with the X-258 and FW-4 Delta third-stage solid rocket motors (References 3, 4, and 5). Actually, given the appropriate data, the derived relationships can be applied to any solid-fuel motor to which a quenching fluid is to be applied after burnout. For the X-258 (S/N RH-47) motor (Figure 2) using estimated values for specific heat, mass, maximum temperature, and motor surface area, the approximate values for incremental velocity increase have been calculated. In this study it is assumed that maximum motor temperature does not exceed chamber outer wall-temperature measurements. This gives conservative values, since the maximum inner wall temperature is considerably higher than that estimated from outer wall-temperature measurements.

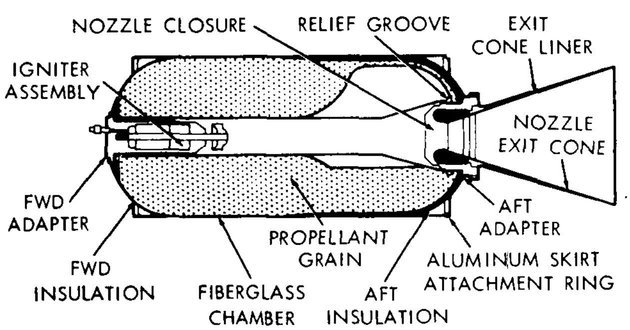

Figure 2—Allegheny Ballistics Laboratory X-258 B-1 rocket motor.

The following results were obtained by calculating propulsive potential for three different inert quenching fluids. Carbon dioxide has previously been used experimentally (Reference 2) in simulated altitude tests for quenching, and water has been proposed repeatedly. Theoretical studies have provided criteria for the selection of a cold-gas propulsion system (Reference 6). Water, propane, and Freon-12 were selected for this study; the choice was dictated by their molecular weight, heat of vaporization, and specific impulse.

Water as a Coolant and Propellant

Water (References 7 and 8), with its low molecular weight and high specific impulse, is an excellent coolant and propellant in spite of its extremely high heat of vaporization. Also, it costs nothing and is readily available (Reference 1). An analysis of a quenching system that uses water as the inert material with an X-258 (S/N RH-47) motor gave the following quantities for the derived relations (for constants and calculations, see Appendix A, part 1):

$$H(t = 0) = 7800 \text{Btu}.$$

Figure 3 shows the heat radiation vs time from the motor. The maximum quenching fluid mass for water for the flow rates used was

$$W_5(t = 0) = 8.89 \text{ lbm for a flow rate of } 0.6 \text{ lbm/sec}.$$

Figure 4 shows the effect of water flow for flow rates of 0.03 to 0.6 lbm/sec. The maximum amount of fluid permits the total impulse recovery of

$$I_{tot}(t = 0) = 1261.49 \text{ lbf-sec}.$$

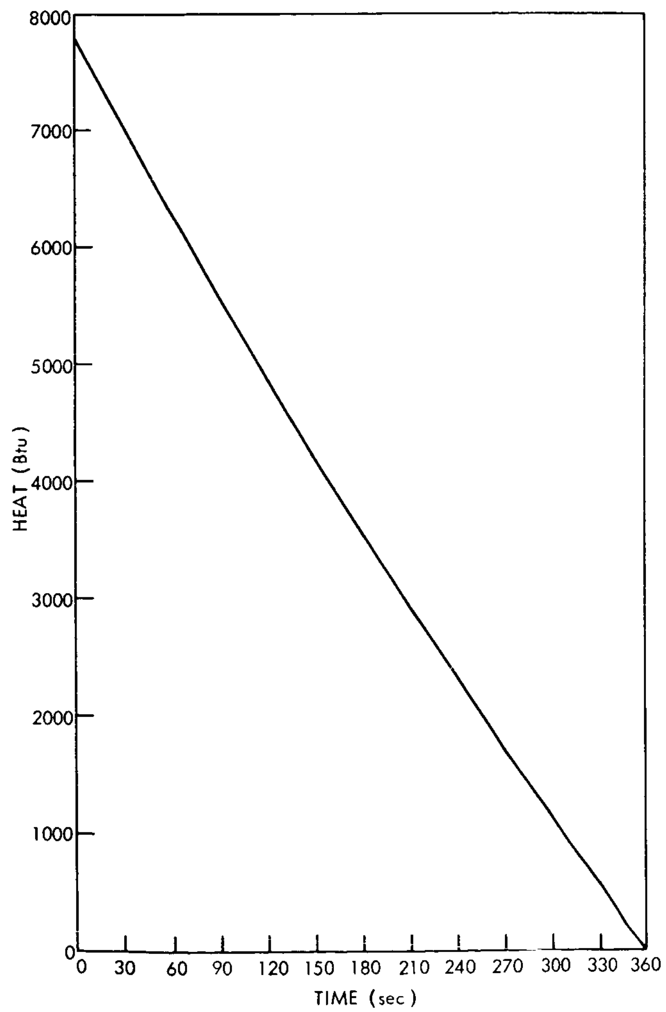

Figure 3—Heat radiation versus time.

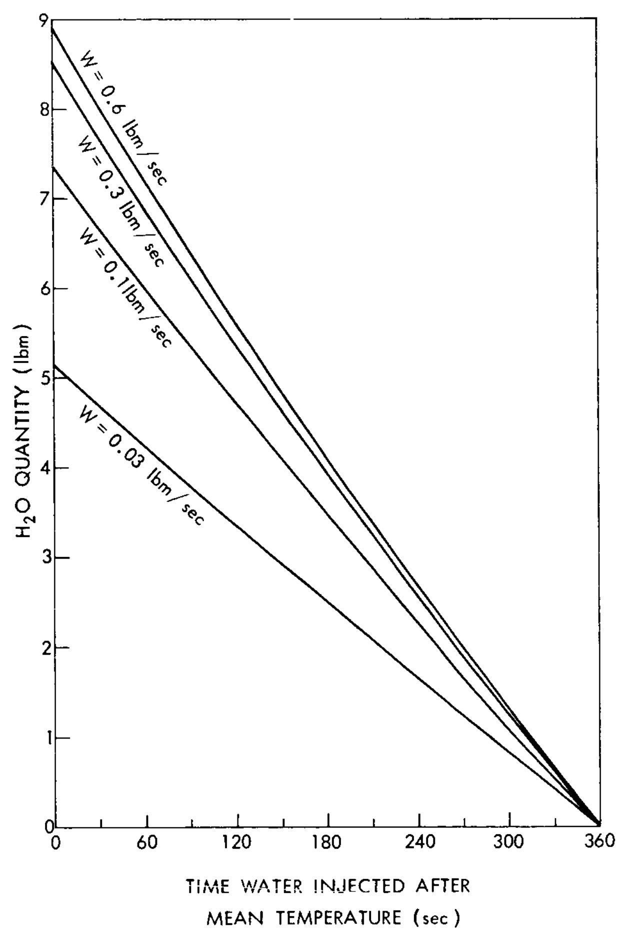

Figure 4—Available H_2O mass versus time.

from specific impulses calculated by the method of References 9, 10, and 11. Figure 5 shows the total impulse recoverable with time for various water-flow rates. The velocity penalty for an X-258 motor carrying water in addition to a 300-lbm payload is obtained from Equation 17.

V_1 = 7362.80 ft/sec, no water carried

V_2 = 7218.46 ft/sec, water carried and not used, with a carrying structure equal to 20 percent of the fluid weight

V_p = 144.34 ft/sec, velocity penalty

$V_3 (t = 0)$ = 113.94 ft/sec, maximum recoverable velocity from the quenching fluid.

Figure 6 shows the recoverable velocity as a function of time and flow rate, with the greatest velocity recovered at the highest flow rate. The above values show that the maximum attainable velocity occurs when no quenching system is carried. However, the recoverable-velocity

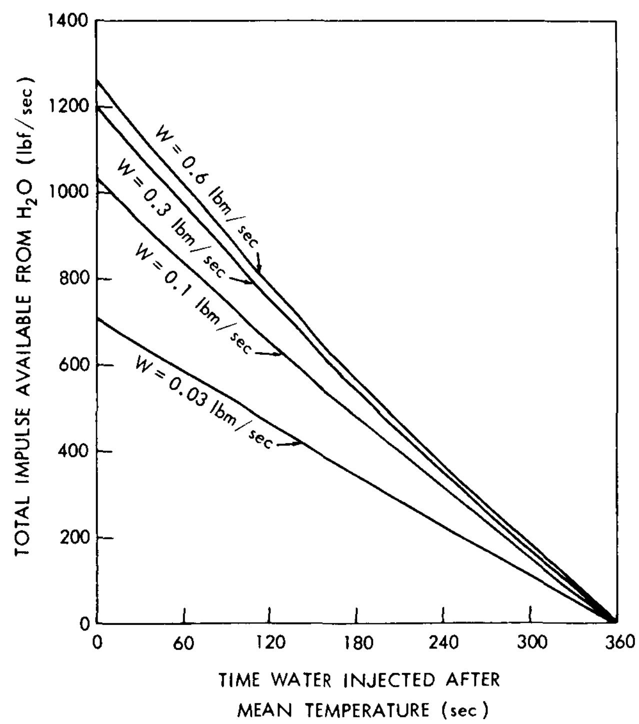

Figure 5—Total impulse available from H_2O versus time.

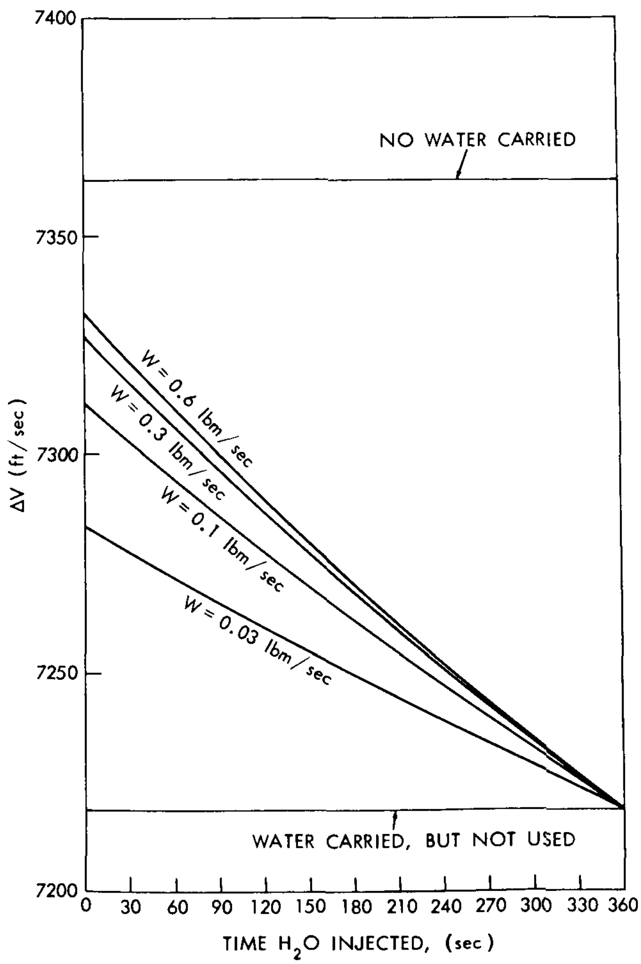

Figure 6—Recoverable velocity versus time and flow rate.

gain when a quenching system is carried and used incurs a relatively small loss (31 ft/sec in 7300 ft/sec or 0.4 percent of ΔV); the control of total impulse error must be assessed against this loss when a mission requires very low injection-velocity error.

Comparison of Water, Propane, and Freon-12

Table 1 shows the values for the same calculations as water (above) for Freon-12 and propane. For constants and calculations, see Appendix A, parts 2 and 3. Of the three substances studied for this report, water proved to give the best velocity recovery; propane was a very close second. Both Freon-12 and propane had a higher specific impulse at the high initial temperature of the motor than is shown in Reference 8, a low temperature study. However, their specific-impulse values relative to each other agreed fairly well with the referenced literature.

Table 1*

Comparison of Three Different Materials for Theoretical Maximum Values at t = 0.

Measured Quantity	Water	Propane	Freon-12
H(t = 0) (Btu)	7800.00	7800.00	7800.00
M(t = 0) (lbm)	8.89	17.72	40.19
I_{tot} (t = 0) (lbf sec)	1261.49	2507.07	2655.59
ΔV_1 (ft/sec)	7362.80	7362.80	7362.80
ΔV_2 (ft/sec)	7218.46	7081.49	6753.61
ΔV_p (ft/sec)	144.34	281.31	609.19
ΔV_3 (t = 0) (ft/sec)	113.94	222.62	226.17
$\Delta V_3 - V_p$ (ft/sec)	-30.40	-58.69	-363.02

*The last line $(\Delta V_3 - V_p)$ represents the net profit (+) or loss (−) in incremental velocity upon expending all the fluid. Zero corresponds to the break-even point.

ANALYSIS OF SYSTEM

In this study, it has been noted that the final attainable velocity depends mainly on the solid-propellant motor residual heat and the choice of a few important inert-fluid properties. When water is used as a quenching agent, its high heat of vaporization is a definite shortcoming. A substance with a low heat of vaporization gives more efficient use of the motor heat, but the molecular weight of the substance should not be high enough to give an unduly low I_{sp}. Another factor required is high specific impulse for the available peak temperature. Appendix E lists theoretical rocket performances for equilibrium conditions, with these inert fluids. The specific heat of the motor shell must also be considered (see Appendix C). So must its mass; the higher the mass, the more energy does it provide for a given maximum temperature and specific heat, but the more velocity penalty does it incur. The ΔT, and therefore the maximum temperature of the motor, should be as great as possible. Insulation such as the foil used on the X-258 (S/N RH-47) works well for two reasons: it allows a high maximum temperature, and it retains the heat longer than without insulation. Surface area and emissivity of the motor shell have a slight (almost negligible) effect on heat leakage after time $t = 0$; the smaller they are, the more slowly will the heat be radiated from the motor's surface.

Finally, the time that elapses following maximum temperature is very important; if a quenching fluid is not used quickly enough, the system may not allow the recovery of any velocity.

CONCLUSIONS AND RECOMMENDATIONS

The results of this study show that although the velocity lost by carrying the weight of an inert quenching fluid cannot be fully regained, the penalty is fairly small for water (30 ft/sec), somewhat higher for propane (59 ft/sec) and considerably higher for Freon 12 (363 ft/sec). From a theoretical standpoint, the residual rocket motor heat constitutes a feasible source of energy for potential application to a propulsive system. For those launch conditions that require close control of the injection velocity, injecting an inert fluid into the hot post-burnout combustion chamber should be a way to adjust the final velocity until the motor has lost its heat from radiation. The results are considered conservative because, for a slight increase in either the chamber temperature or the heat capacity, there might be a velocity gain instead of a penalty.

It would be advisable to follow this theoretical study by experimental measurements of: (1) the actual residual heat energy after firing, and (2) the effect of introducing an inert quenching fluid at various flow rates (using adequate thrust and pressure instrumentation). It should then be possible to establish the efficiency of the propulsive system under realistic conditions, to determine the resolution in fine velocity control with existing hardware, and to generate the criteria for selecting competitive velocity-correcting techniques.

ACKNOWLEDGMENTS

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Greenbelt, Maryland, December 12, 1967
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APPENDIX A

CALCULATION OF COMPARATIVE VALUES FOR WATER, PROPANE, AND FREON-12, AS COOLANT AND PROPELLANT

1. X-258 (S/N RH-47) motor: water as coolant and propellant

(a) Constants:

$W_3 \approx$ 50 lbm

$C_p \approx$ 0.30 Btu/lbm°R

$T \approx$ 600°F = 1060°R = 590°K

$T_0 \approx$ 80°F = 540°R

$\epsilon \approx$ 0.7

$\sigma =$ 5.672×10^{-5} erg/°K^4 sec cm^2

$\sigma =$ 3.30×10^{-15} Btu/°R^4 sec in^2

$T_1 \approx$ 0°K

$A \approx$ 3700 in^2

$dT/dt \approx$ 0.25°R/sec (see Figure A1)

$C_{p_5} =$ 1 Btu/lbm°R

$C_{p_6} =$ 0.48 Btu/lbm°R

$\lambda =$ 540 Btu/lbm

$T_B =$ 212°F = 672°R (this assumes that the injection pressure is constant at 1 atmosphere)

$I_{vac} =$ 142.1 lbf sec/lbm at t = 0 (T = 590°K, A_E/A_T = 53.2)

$dI_{vac} =$ -0.0181 lbf/lbm (see Figure A2)

$W_1 \approx$ 300 lbm

$W_2 \approx$ 550 lbm

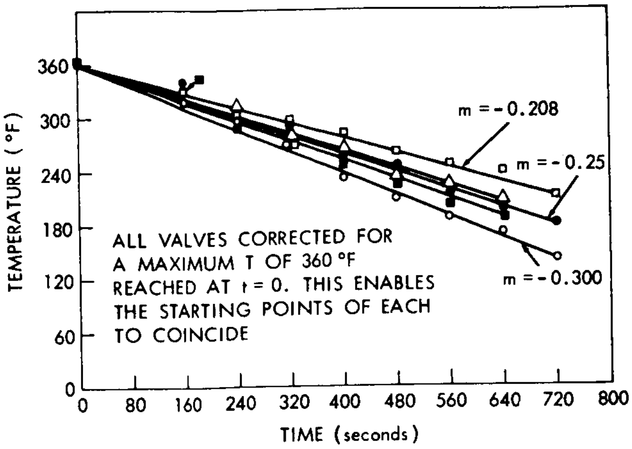

Figure A1—Radiant-body residual temperature versus time.

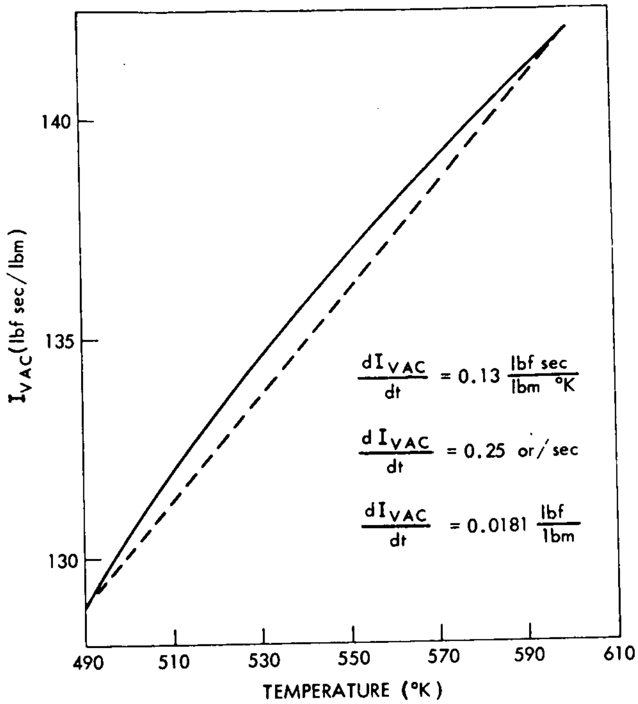

Figure A2—I_{vac} versus temperature for chamber pressure of 100 psia.

$W_3 \approx$ 50 lbm

$W_4 =$ 0.2 W_5 (max.)

$W_5 =$ m(t)

Assumed: 20 percent of total fluid weight is needed for the structure, tankage, etc.,

When:

$\dot{W}_1$ = 0.03 lbm/sec then dT_m/dt = -1.47°R/sec
$\dot{W}_2$ = 0.1 lbm/sec then dT_m/dt = -5.46°R/sec
$\dot{W}_3$ = 0.3 lbm/sec then dT_m/dt = -16.7°R/sec
$\dot{W}_4$ = 0.6 lbm/sec then dT_m/dt = -33.4°R/sec
$I_{vaco} \approx$ 258 lbf sec/lbm

(b) Calculations:

Total heat available:

$\bar{H}(t = 0)$ = 50 lbm × 0.30 Btu/lbm°R × 520°R

$\bar{H}(t = 0)$ = 7800 Btu (see other values in Figure 3)

Total possible mass:

m(t = 0, $\dot{W}$ = 0.6) = 8.89 lbm (see other values in Figure 4)

Total impulse:

I_{tot} (t = 0, $\dot{W}$ = 0.6) = 1261.49 lbf/sec (see other values in Figure 5)

Velocity penalty and boost:

$$\Delta V_1 = (32.174)\ (258)\ \ln \frac{300 + 550}{300 + 50}$$

$$\Delta V_1 = 7362.80 \text{ ft/sec}$$

$$\Delta V_2 = (32.174)\ (258)\ \ln \frac{300 + 550 + 1.78 + 8.89}{300 + 50 + 1.78 + 8.89}$$

$$\Delta V_2 = 7218.46 \text{ ft/sec}$$

$$\Delta V_p = 144.34 \text{ ft/sec}$$

$$\Delta V_3\ (t = 0) = (32.174)(142.1 - 0.0181 \times 0.6)\ \ln \frac{300 + 50 + 1.78 + 8.89}{300 + 50 + 1.78}$$

$$\Delta V_3\ (t = 0) = 113.94 \text{ ft/sec}$$

2. X-258 (S/N RH-47) motor: Freon-12 as coolant and propellant

(a) Constants:

$C_{p5} = 0.22$ Btu/lbm°R

$C_{p6} = 0.15$ Btu/lbm°R

$\lambda = 60.5$ Btu/lbm

$T_B = 028$°C $= -18.5$°F $= 441.5$°R (6.72 atmosphere at 80°F)

$I_{vac} = 66.7$ lbf sec/lbm at $t = 0$ ($T = 590$°K $A_E/A_T = 53.2$)

$dI_{vac} = -0.0093$ lbf/lbm

When:

$\dot{w}_1 = 0.03$ lbm/sec then $dT_m/dt = -0.07$°R/sec

$\dot{W}_2 = 0.1$ lbm/sec then $dT_m/dt = -0.82$°R/sec

$\dot{W}_3 = 0.3$ lbm/sec then $dT_m/dt = -2.94$°R/sec

$\dot{W}_4 = 0.6$ lbm/sec then $dT_m/dt = -6.12$°R/sec

(b) Calculations:

Total possible mass:

$m(t = 0, \dot{W} = 0.6) = 40.19$ lbm

Total impulse:

I_{tot} ($t = 0, \dot{W} = 0.6$) = 2655.59 lbf-sec

Velocity penalty and boost:

$$\Delta V_2 = (32.174)(258) \ln \frac{300 + 550 + (1.2 \times 40.19)}{300 + 50 + (1.2 \times 40.19)}$$

$\Delta V_2 = 6753.61$ ft/sec

$\Delta V_p = 609.19$ ft/sec

$$V_3 (t = 0) = (32.174)(66.7 - 0.0093 \times 0.6) \ln \frac{300 + 50 + (1.2 \times 40.19)}{300 + 50 + (0.2 \times 40.19)}$$

$V_3 (t = 0) = 226.17$ ft/sec

3. X-258 (S/N RH-47) motor: Propane as coolant and propellant

(a) Constants:

C_{p5} = 0.58 Btu/lbm°R

C_{p6} = 0.40 Btu/lbm°R

λ = 146 Btu/lbm

T_B = -42°C = -43.5°F = 416.5°R (9.72 atmosphere at 80°F)

I_{vac} = 142.2 lbf-sec/lbm at $t = 0$ ($T = 590°K$ $A_E/A_T = 53.2$)

dI_{vac}/dt = -0.0239 lbf/lbm

When:

$\dot{W}_1$ = 0.03 lbm/sec then dT_m/dt = -0.57°R/sec

$\dot{W}_2$ = 0.1 lbm/sec then dT_m/dt = -2.48°R/sec

$\dot{W}_3$ = 0.3 lbm/sec then dT_m/dt = -5.01°R/sec

$\dot{W}_4$ = 0.6 lbm/sec then dT_m/dt = -15.94°R/sec

(b) Calculations:

Total usable mass:

$m(t = 0, \dot{W} = 0.6)$ = 17.72 lbm

Total impulse:

$$I_{tot}\ (t = 0,\ \dot{W} = 0.6) = 2507.07\ \text{lbf/sec}$$

Velocity penalty and boost:

$$\Delta V_2 = (32.174)\ (258)\ \ln \frac{300 + 550 + (1.2 \times 17.72)}{300 + 50 + (1.2 \times 17.72)}$$

$$\Delta V_2 = 7081.49\ \text{ft/sec}$$

$$V_p = 281.31\ \text{ft/sec}$$

$$V_3\ (t = 0) = (32.174)\ (142.2 - 0.0239 \times 0.6)\ \ln \frac{300 + 50 + (1.2 \times 17.72)}{300 + 50 + (0.2 \times 17.72)}$$

$$V_3\ (t = 0) = 222.62\ \text{ft/sec}$$

APPENDIX B

MEASUREMENT OF MAXIMUM MOTOR TEMPERATURE AFTER FIRING

Maximum temperatures were measured at nine separate points around the motor shell during and after firing (Reference 3). The temperatures at all points were averaged at different times after ignition to give the time of maximum motor temperature and the temperature average at that time. (See Table B1.)

Table B1

Averages of Maximum Motor Temperatures* of the X-258 RH-47 Motor at Different Times After Ignition (Reference 3).

t, sec**	T, °F
200	576
250	596
300	603
350	602
400	599

*Maximum average motor temperature: Approximately 600°F at 300 seconds after ignition.
Initial motor temperature = 80°F
T = 600°F - 80°F = 520°F

**Note: This time should not be confused with the t used in developing the thermodynamic equations. *That* t is the number of seconds past maximum motor temperature. *This* t = 300 + x.

Change in temperature (ΔT) is the difference between initial motor temperature and maximum temperature. Table B2 gives a comparison of maximum temperatures and ΔT's for different motors and insulation. Figure A1 gives values for the time decrease of heat from the motor's surface, plotted against temperature starting with a fixed temperature of 360°F.

Table B2

Maximum Motor Temperatures of Different Type Motors.

	Motor Type		
Measured Quantity	X-258 (References 3 and 4)	FW-4 (Reference 5)	
Insulation	Foil	No Foil	No Foil
Max T, °F	570°, 600°	425°, 440°	340°, 390°
ΔT, °F	490°, 520°	345°, 360°	265°, 315°

APPENDIX C

EFFECT OF SPECIFIC HEAT OF MOTOR SHELL ON ΔV_3 FOR WATER

As can be seen from Appendix A, part 1, Figure 6, and Table C1, the specific heat c_p of 0.30 which was estimated for the motor shell will not provide the motor with enough heat energy to allow enough water to be used to recoup the velocity penalty for carrying the water. A separate study gives the relation between increase in c_p, increase in fluid mass, and consequently increase in ΔV_3. The data from this study can be seen in Table C1, and Figure C1. It shows that to return just the velocity penalty at time $t = 0$, a motor shell with a c_p of at least 0.37 Btu/lbm °R must be used.

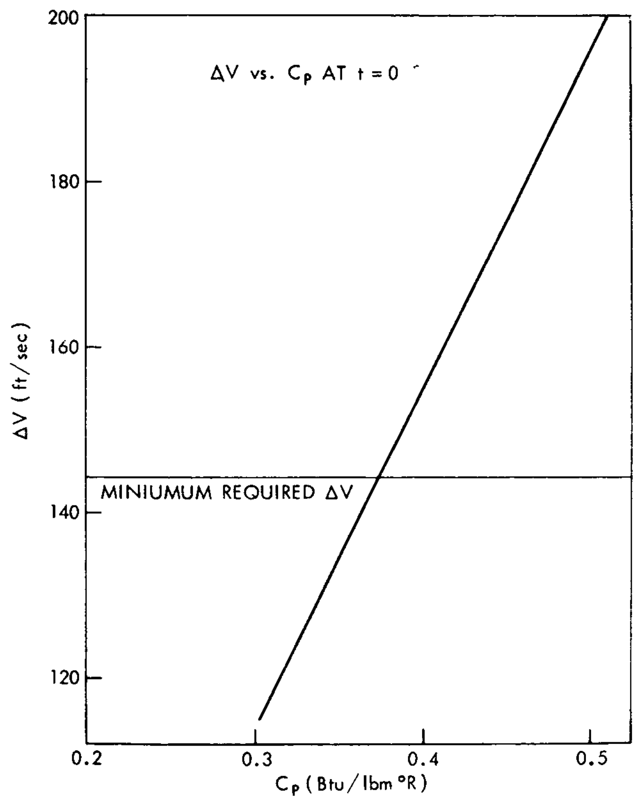

Figure C1—ΔV versus C_p at $t = 0$.

Table C1

C_p's of Motor Shell and Masses at H_2O Required for Certain Velocities.

V_3, ft/sec	H_2O Mass Required (lbm)	Necessary Motor C_p (Btu/lbm °R)
113.94	8.89	0.30
144.34	11.35	0.37
160.00	12.33	0.41
180.00	14.11	0.46
200.00	15.89	0.52

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APPENDIX D

PROGRAM LISTING

```
C    WATER  ROCKET
C    ENERGY  REMAINING  IN  HOT  MOTOR
C    TOTAL  MASS,  IMPULSE,  AND  INCREMENTAL  VELOCITY  AVAILABLE
C    HIGH  TEMPERATURE  PROGRAM
C    FOR THOSE MATERIALS WHOSE BOILING POINTS ARE ABOVE STARTING TEMPERATURE
      DIMENSION  H(14),AM(14),TIMP(14),VEL(14),T(14)
      DIMENSION  DELT(14,14),TT(14),TTD(14),HH(14),HDUM(14,14)
      READ(5,76) NCASE
   76 FORMAT(I5)
      DO 3 L=1,NCASE
      READ(5,77) SIG,EM,CP,TEM,TEMO,EP,AREA,DTDT
   77 FORMAT(8(F10.5))
      READ(5,78) DIDT,DTWDT,TEMB,CP1,CP2,ALAM,VACIO,G
   78 FORMAT(8(F10.4))
      READ(5,80) FLOW
   80 FORMAT(F10.3)
      WRITE(6,79) L
   79 FORMAT(13H1CASE  NUMBER,I5///110H                    TIME              DELTA
     1 T           ENERGY                MASS            IMPULSE           VELOCITY
     2       TEST H////)
      DO 1 I=1,13
      T(1)=-30.
      DO 2 J=1,13
      T(J+1)=T(J)+30.
      DD=I
      DELT(I,J)=T(J+1)-((30.*DD)-30.)
      IF (DELT(I,J)) 5,10,10
    5 DELT(I,J)=0.
   10 H1=(EM*CP*(TEM-TEMO))
      H2=(2.*EP*SIG*AREA*(TEM**4)*T(J+1))
      H3=(EM*CP*T(J+1)*DTDT)
      H4=(4.*EP*SIG*AREA*(TEM**3)*DTDT*(T(J+1)**2))
      H5=(EM*CP*DTWDT*DELT(I,J))
      HDUM(I,J)=H1-H2+H3-H4+H5
      IF (HDUM(I,J)) 15,15,2
   15 VV=32.
      TT(I)=T(J+1)
      TTD(I)=DELT(I,J)
   18 VV=VV/2.
      H1=(EM*CP*(TEM-TEMO))
      H2=(2.*EP*SIG*AREA*(TEM**4)*TT(I))
      H3=(EM*CP*TT(I)*DTDT)
      H4=(4.*EP*SIG*AREA*(TEM**3)*DTDT*(TT(I)**2))
      H5=(EM*CP*DTWDT*TTD(I))
      HH(I)=H1-H2+H3-H4+H5
      IF (HH(I)) 30,17,32
   30 IF (HH(I)+.01) 31,17,17
```

```
31 TT(I)=TT(I)-VV
   TTD(I)=TTD(I)-VV
   GO TO 18
32 IF (HH(I)-.01) 17,17,33
33 TT(I)=TT(I)+VV
   TTD(I)=TTD(I)+VV
   GO TO 18
17 AM(I)=FLOW*TTD(I)
 8 H(I)=AM(I)*(CP1*(TEMB-TEMO)+ALAM+CP2*(TEM+(DTDT*TT(I))+(DTWDT*TTD(
  1I))-TEMB))
 9 TIMP(I)=AM(I)*(VACIO+(DIDT*TT(I)))
   V1=ALOG((350.+(1.2*AM(I)))/(350.+(.2*AM(I))))
   VEL(I)=G*(VACIO+(DIDT*TT(I)))*V1
   GO TO 1
 2 CONTINUE
 1 CONTINUE
   WRITE(6,81)(TT(I),TTD(I),H(I),AM(I),TIMP(I),VEL(I),HH(I),I=1,13)
81 FORMAT(5X,7F15.3/)
 3 CONTINUE
55 STOP
   END
```

TERM DEFINITIONS

H	ENERGY REMAINING IN THE HOT MOTOR
AM	MASS OF WATER THAT CAN BE ADDED TO THE HOT MOTOR
TIMP	IMPULSE AVAILABLE FROM THE WATER
VEL	ADDITIONAL VELOCITY AVAILABLE FROM THE WATER
T	TIME ELAPSED SINCE MAXIMUM MOTOR TEMPERATURE
DELT	TIME ELAPSED FOR WATER FLOW
SIG	STEPHAN-BOLTZMANN CONSTANT
EM	TOTAL MOTOR MASS
CP	AVERAGE MOTOR SPECIFIC HEAT
TEM	MAXIMUM MOTOR TEMPERATURE
TEMO	INITIAL MOTOR TEMPERATURE
EP	MOTOR SHELL EMISSIVITY
AREA	MOTOR SURFACE AREA
DTDT	MOTOR TEMPERATURE LOSS PER TIME TO SPACE
DIDT	IMPULSE LOSS PER TEMPERATURE FROM THE WATER
DTWDT	MOTOR TEMPERATURE LOSS PER TIME TO WATER
TEMB	BOILING POINT OF WATER AT ATMOSPHERIC PRESSURE
CP1	SPECIFIC HEAT OF WATER LIQUID
CP2	SPECIFIC HEAT OF WATER VAPOR
ALAM	HEAT OF VAPORIZATION FOR WATER
VACIO	VACUUM SPECIFIC IMPULSE OF WATER AT THE MAXIMUM MOTOR TEMPERATURE
G	GRAVITY CONSTANT

APPENDIX E

EQUILIBRIUM CALCULATIONS FOR WATER, PROPANE, AND FREON-12

THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION
FROM AN ASSIGNED TEMPERATURE AND AT VARIOUS CHAMBER PRESSURES

WATER

PARAMETERS

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT
PC/P	1.000	1.838	40.200	52.720	100.000	463.000	1000.000	10000.00	100000.0
P, ATM	6.805	3.703	0.1693	0.1291	0.0680	0.0147	0.0068	0.0007	0.0001
T, DEG K	590	512	241	225	192	131	108	61	35
H, CAL/G	-3073.4	-3110.3	-3233.2	-3240.2	-3254.9	-3281.8	-3292.0	-3312.9	-3324.8
S, CAL/(G)(K)	2.6052	2.6052	2.6052	2.6052	2.6052	2.6052	2.6052	2.6052	2.6052
M, MOL WT	18.017	18.017	18.017	18.017	18.017	18.017	18.017	18.017	18.017
(DLM/DLP)T	0.	0.	0.	0.	0.	0.	0.	0.	0.
(DLM/DLT)P	-0.0000	-0.0000	-0.0000	-0.0000	-0.0000	-0.0000	-0.0000	-0.0000	-0.0000
CP, CAL/(G)(K)	0.4800	0.4686	0.4425	0.4421	0.4417	0.4432	0.4445	0.4487	0.4521
GAMMA	1.2984	1.3078	1.3320	1.3325	1.3329	1.3314	1.3300	1.3250	1.3227
MACH NUMBER	0.	1.000	3.004	3.174	3.586	4.655	5.247	7.309	9.937
CSTAR, FT/SEC		2563	2563	2563	2563	2563	2563	2563	2563
CF		0.712	1.480	1.512	1.577	1.690	1.731	1.812	1.856
AE/AT		1.000	4.950	5.939	9.205	27.13	47.26	255.8	1421.
IVAC,LB-SEC/LB		100.0	127.7	129.4	133.0	139.3	141.7	146.4	149.0
I, LB-SEC/LB ,		56.7	117.9	120.5	125.7	134.7	137.9	144.4	147.9

DERIVATIVES

(DLI/DLPC)PC/P		0.00000	0.00000	-0.00000	0.00000	0.00000	0.00000	0.00000	-0.00000
(DLT/DLPC)PC/P	0.00000	-0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	-0.00000	0.00000
(DLAR/DLPC)PC/P		-0.	0.00000	0.00000	0.00000	0.00000	0.00000	-0.00000	0.00000
(DLCS/DLPC)PC/P		-0.00000	-0.00000	-0.00000	-0.00000	-0.00000	-0.00000	-0.00000	-0.00000
(DLI/DHC)PC/P*		1.78703	1.85064	1.85326	1.85859	1.86609	1.86811	1.87094	1.87114
(DLT/DHC)PC/P*	3.53104	3.61665	3.83008	3.83418	3.83747	3.82447	3.81308	3.77763	3.74929
(DLAR/DHC)PC/P*		0.	0.14983	0.15131	0.14926	0.12876	0.11536	0.07707	0.04855
(DLCS/DHC)PC/P*		1.82962	1.82962	1.82962	1.82962	1.82962	1.82962	1.82962	1.82962
*(HC IN KCAL/G)									
(DLI/DLPCP)S		0.76484	0.08320	0.07450	0.05836	0.03467	0.02731	0.01412	0.00766
(DLT/DLPCP)S	-0.22979	-0.23536	-0.24925	-0.24952	-0.24973	-0.24889	-0.24815	-0.24584	-0.24400
(DLAR/DLPCP)S,		0.	0.66755	0.67597	0.69191	0.71644	0.72455	0.74004	0.74835

MOLE FRACTIONS

H2O1(G)	0.99995	0.99995	0.99995	0.99995	0.99995	0.99995	0.99995	0.99995	0.99994
O2(G)	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005	0.00006

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.000005 FOR ALL ASSIGNED CONDITIONS

H1(G) H2(G) O1(G) O1H1(G)

THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION FROM AN ASSIGNED TEMPERATURE AND AT VARIOUS CHAMBER PRESSURES

WATER

PARAMETERS

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT
PC/P	1.000	1.838	40.200	52.720	100.000	463.000	1000.000	10000.00	100000.0
P, ATM	34.02	18.51	0.8463	0.6454	0.3402	0.0735	0.0340	0.0034	0.0003
T, DEG K	590	512	241	225	192	131	108	61	35
H, CAL/G	-3073.4	-3110.3	-3233.2	-3240.2	-3254.9	-3281.8	-3292.0	-3312.9	-3324.8
S, CAL/(G)(K)	2.4277	2.4277	2.4277	2.4277	2.4277	2.4277	2.4277	2.4277	2.4276
M, MOL WT	18.017	18.017	18.017	18.017	18.017	18.017	18.017	18.017	18.017
(DLM/DLP)T	0.00000	0.	0.	0.	0.	0.	0.	0.	0.
(DLM/DLT)P	-0.0000	-0.0000	0.0000	0.0000	-0.0000	-0.0000	0.0000	0.0000	-0.0000
CP, CAL/(G)(K)	0.4800	0.4686	0.4426	0.4422	0.4417	0.4431	0.4446	0.4485	0.4494
GAMMA	1.2984	1.3078	1.3320	1.3324	1.3328	1.3314	1.3299	1.3252	1.3253
MACH NUMBER	0.	1.000	3.004	3.174	3.586	4.654	5.247	7.309	9.927
CSTAR, FT/SEC		2563	2563	2563	2563	2563	2563	2563	2563
CF		0.712	1.480	1.512	1.577	1.690	1.731	1.812	1.856
AE/AT		1.000	4.950	5.940	9.205	27.14	47.27	255.8	1421.
IVAC,LB-SEC/LB		100.0	127.7	129.4	133.0	139.3	141.7	146.4	149.0
I, LB-SEC/LB ,		56.7	117.9	120.5	125.7	134.7	137.9	144.4	147.9

DERIVATIVES

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT
(DLI/DLPC)PC/P		0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	-0.00000	0.00000
(DLT/DLPC)PC/P	0.00000	-0.00000	-0.00000	-0.00000	0.00000	-0.00000	-0.00000	0.00000	-0.00000
(DLAR/DLPC)PC/P		-0.	0.00000	0.00000	0.00000	0.00000	-0.00000	0.00000	-0.00000
(DLCS/DLPC)PC/P		-0.00000	-0.00000	-0.00000	-0.00000	-0.00000	-0.00000	-0.00000	-0.00000
(DLI/DHC)PC/P*		1.78710	1.85069	1.85345	1.85861	1.86614	1.86823	1.87070	1.87147
(DLT/DHC)PC/P*	3.53108	3.61662	3.82966	3.83308	3.83704	3.82479	3.81207	3.77927	3.77156
(DLAR/DHC)PC/P*		0.	0.14945	0.15011	0.14892	0.12915	0.11432	0.07905	0.07064
(DLCS/DHC)PC/P*		1.82952	1.82952	1.82952	1.82952	1.82952	1.82952	1.82952	1.82952
*(HC IN KCAL/G)									
(DLI/DLPCP)S		0.76464	0.08320	0.07451	0.05836	0.03467	0.02731	0.01411	0.00766
(DLT/DLPCP)S	-0.22979	-0.23536	-0.24922	-0.24945	-0.24971	-0.24891	-0.24808	-0.24595	-0.24544
(DLAR/DLPCP)S,		0.	0.66757	0.67604	0.69193	0.71642	0.72461	0.73994	0.74689

MOLE FRACTIONS

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT
H2O1(G)	0.99995	0.99995	0.99995	0.99995	0.99995	0.99995	0.99995	0.99995	0.99995
O2(G)	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.000005 FOR ALL ASSIGNED CONDITIONS

H1(G) H2(G) O1(G) O1H1(G)

THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION
FROM AN ASSIGNED TEMPERATURE AND AT VARIOUS CHAMBER PRESSURES

WATER

PARAMETERS

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT
PC/P	1.000	1.838	40.200	52.720	100.000	463.000	1000.000	10000.00	100000.0
P, ATM	68.05	37.02	1.693	1.291	0.6805	0.1470	0.0680	0.0068	0.0007
T, DEG K	590	512	241	225	192	131	108	61	35
H, CAL/G	-3073.4	-3110.4	-3233.2	-3240.2	-3254.9	-3281.8	-3292.0	-3312.9	-3324.8
S, CAL/(G)(K)	2.3512	2.3512	2.3512	2.3512	2.3512	2.3512	2.3512	2.3512	2.3512
M, MOL WT	18.017	18.017	18.017	18.017	18.017	18.017	18.017	18.017	18.017
(DLM/DLP)T	0.00000	0.	0.	0.	0.	0.	0.	0.	0.
(DLM/DLT)P	-0.0000	0.0000	-0.0000	-0.0000	-0.0000	-0.0000	0.0000	-0.0000	-0.0000
CP, CAL/(G)(K)	0.4800	0.4686	0.4425	0.4421	0.4417	0.4431	0.4446	0.4488	0.4510
GAMMA	1.2934	1.3078	1.3320	1.3324	1.3328	1.3314	1.3299	1.3259	1.3237
MACH NUMBER	0.	1.000	3.004	3.174	3.586	4.654	5.247	7.310	9.934
CSTAR, FT/SEC		2563	2563	2563	2563	2563	2563	2563	2563
CF		0.712	1.480	1.512	1.577	1.690	1.731	1.812	1.856
AE/AT		1.000	4.950	5.939	9.204	27.13	47.26	255.8	1421.
IVAC,LB-SEC/LB		100.0	127.7	129.4	133.0	139.3	141.7	146.4	149.0
I, LB-SEC/LB ,		56.7	117.9	120.5	125.7	134.7	137.9	144.4	147.9

DERIVATIVES

(DLI/DLPC)PC/P		0.00000	0.00000	-0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
(DLT/DLPC)PC/P	0.00000	-0.00000	-0.00000	0.00000	-0.00000	-0.00000	-0.00000	0.00000	0.00000
(DLAR/DLPC)PC/P		-0.	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00001
(DLCS/DLPC)PC/P		-0.00000	-0.00000	-0.00000	-0.00000	-0.00000	-0.00000	-0.00000	-0.00000
(DLI/DHC)PC/P*		1.78725	1.85077	1.85333	1.85864	1.86620	1.86821	1.87075	1.87106
(DLT/DHC)PC/P*	3.53108	3.61661	3.83008	3.83357	3.83692	3.82475	3.81181	3.77672	3.75792
(DLAR/DHC)PC/P*		0.	0.14996	0.15089	0.14893	0.12921	0.11424	0.07664	0.05757
(DLCS/DHC)PC/P*		1.82935	1.82935	1.82935	1.82935	1.82935	1.82935	1.82935	1.82935
*(HC IN KCAL/G)									
(DLI/DLPCP)S		0.76466	0.08321	0.07451	0.05836	0.03467	0.02731	0.01412	0.00766
(DLT/DLPCP)S	-0.22979	-0.23536	-0.24925	-0.24948	-0.24970	-0.24891	-0.24806	-0.24578	-0.24456
(DLAR/DLPCP)S,		0.	0.66754	0.67601	0.69194	0.71642	0.72463	0.74010	0.74778

MOLE FRACTIONS

H2O1(G)	0.99995	0.99995	0.99995	0.99995	0.99995	0.99995	0.99995	0.99995	0.99995
O2(G)	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.000005 FOR ALL ASSIGNED CONDITIONS

H1(G) H2(G) O1(G) O1H1(G)

THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION
FROM AN ASSIGNED TEMPERATURE AND AT VARIOUS CHAMBER PRESSURES

WATER

PARAMETERS

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT
PC/P	1.000	1.838	40.200	52.720	100.000	463.000	1000.000	10000.00	100000.0
P, ATM	102.1	55.54	2.539	1.936	1.021	0.2205	0.1021	0.0102	0.0010
T, DEG K	590	512	241	225	192	131	108	61	35
H, CAL/G	-3073.4	-3110.3	-3233.2	-3240.2	-3254.9	-3281.9	-3292.0	-3312.9	-3324.8
S, CAL/(G)(K)	2.3065	2.3065	2.3065	2.3065	2.3065	2.3065	2.3065	2.3065	2.3065
M, MOL WT	18.017	18.017	18.017	18.017	18.017	18.017	18.017	18.017	18.017
(DLM/DLP)T	0.	0.	0.00000	0.	0.	0.	0.	0.	0.
(DLM/DLT)P	0.0000	-0.0000	-0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000	0.0000
CP, CAL/(G)(K)	0.4800	0.4686	0.4425	0.4422	0.4417	0.4432	0.4445	0.4489	0.4534
GAMMA	1.2984	1.3078	1.3320	1.3324	1.3328	1.3313	1.3300	1.3257	1.3214
MACH NUMBER	0.	1.000	3.004	3.174	3.586	4.655	5.248	7.310	9.941
CSTAR, FT/SEC		2563	2563	2563	2563	2563	2563	2563	2563
CF		0.712	1.480	1.512	1.577	1.690	1.731	1.812	1.856
AE/AT		1.000	4.950	5.939	9.204	27.13	47.26	255.8	1421.
IVAC,LB-SEC/LB		100.0	127.7	129.4	133.0	139.3	141.7	146.4	149.0
I, LB-SEC/LB ,		56.7	117.9	120.5	125.7	134.7	137.9	144.4	147.9

DERIVATIVES

(DLI/DLPC)PC/P		0.00000	0.00000	0.00000	-0.00000	-0.00000	0.00000	0.00000	0.00000
(DLT/DLPC)PC/P	-0.00000	-0.00000	0.00000	-0.00000	0.00000	0.00000	0.00000	-0.00000	-0.00000
(DLAR/DLPC)PC/P		-0.	0.00000	-0.00000	0.00000	0.00000	0.00000	0.00000	-0.00000
(DLCS/DLPC)PC/P		-0.00000	-0.00000	-0.00000	-0.00000	-0.00000	-0.00000	-0.00000	-0.00000
(DLI/DHC)PC/P*		1.78706	1.85065	1.85337	1.85836	1.86603	1.86801	1.87074	1.87148
(DLT/DHC)PC/P*	3.53105	3.61665	3.83015	3.83312	3.83685	3.82420	3.81266	3.77563	3.73799
(DLAR/DHC)PC/P*		0.	0.14992	0.15016	0.14890	0.12857	0.11506	0.07530	0.03690
(DLCS/DHC)PC/P*		1.82959	1.82959	1.82959	1.82959	1.82959	1.82959	1.82959	1.82959
*(HC IN KCAL/G)									
(DLI/DLPCP)S		0.76471	0.08320	0.07451	0.05835	0.03467	0.02730	0.01411	0.00766
(DLT/DLPCP)S	-0.22979	-0.23536	-0.24926	-0.24945	-0.24969	-0.24887	-0.24812	-0.24571	-0.24325
(DLAR/DLPCP)S,		0.	0.66754	0.67604	0.69195	0.71646	0.72458	0.74018	0.74909

MOLE FRACTIONS

H2O1(G)	0.99995	0.99995	0.99995	0.99995	0.99995	0.99995	0.99995	0.99995	0.99995
O2(G)	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.000005 FOR ALL ASSIGNED CONDITIONS

H1(G) H2(G) O1(G) O1H1(G)

THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION
FROM AN ASSIGNED TEMPERATURE AND AT VARIOUS CHAMBER PRESSURES

WATER

PARAMETERS

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT
PC/P	1.000	1.838	40.200	52.720	100.000	463.000	1000.000	10000.00	100000.0
P, ATM	204.1	111.1	5.078	3.872	2.041	0.4409	0.2041	0.0204	0.0020
T, DEG K	590	512	241	225	192	131	108	61	35
H, CAL/G	-3073.4	-3110.3	-3233.2	-3240.2	-3254.9	-3281.8	-3292.0	-3312.9	-3324.8
S, CAL/(G)(K)	2.2300	2.2300	2.2300	2.2300	2.2300	2.2300	2.2301	2.2300	2.2300
M, MOL WT	18.017	18.017	18.017	18.017	18.017	18.017	18.017	18.017	18.017
(DLM/DLP)T	0.	0.00000	0.	0.	0.	0.	0.00000	0.	0.
(DLM/DLT)P	-0.0000	-0.0000	-0.0000	-0.0000	-0.0000	-0.0000	0.0000	-0.0000	-0.0000
CP, CAL/(G)(K)	0.4800	0.4686	0.4426	0.4422	0.4417	0.4432	0.4449	0.4482	0.4508
GAMMA	1.2984	1.3078	1.3320	1.3324	1.3329	1.3313	1.3297	1.3264	1.3240
MACH NUMBER	0.	1.000	3.004	3.174	3.585	4.655	5.248	7.309	9.932
CSTAR, FT/SEC		2563	2563	2563	2563	2563	2563	2563	2563
CF		0.712	1.480	1.512	1.577	1.690	1.731	1.812	1.856
AE/AT		1.000	4.950	5.939	9.205	27.13	47.27	255.8	1421.
IVAC,LB-SEC/LB		100.0	127.7	129.4	133.0	139.3	141.7	146.4	149.0
I, LB-SEC/LB ,		56.7	117.9	120.5	125.7	134.7	137.9	144.4	147.9

DERIVATIVES

(DLI/DLPC)PC/P		0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
(DLT/DLPC)PC/P	0.00000	-0.00000	0.00000	-0.00000	0.00000	0.00000	-0.00000	0.00000	-0.00000
(DLAR/DLPC)PC/P		-0.	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
(DLCS/DLPC)PC/P		-0.00000	-0.00000	-0.00000	-0.00000	-0.00000	-0.00000	-0.00000	-0.00000
(DLI/DHC)PC/P*		1.78706	1.85068	1.85338	1.85864	1.86612	1.86808	1.87053	1.87128
(DLT/DHC)PC/P*	3.53108	3.61664	3.82970	3.83331	3.83745	3.82394	3.81004	3.78166	3.76008
(DLAR/DHC)PC/P*		0.	0.14944	0.15034	0.14923	0.12824	0.11237	0.08147	0.05923
(DLCS/DHC)PC/P*		1.82958	1.82958	1.82958	1.82958	1.82958	1.82958	1.82958	1.82958
*(HC IN KCAL/G)									
(DLI/DLPCP)S		0.76464	0.08320	0.07451	0.05836	0.03467	0.02731	0.01411	0.00766
(DLT/DLPCP)S	-0.22980	-0.23536	-0.24923	-0.24946	-0.24973	-0.24885	-0.24795	-0.24610	-0.24470
(DLAR/DLPCP)S,		0.	0.66757	0.67603	0.69190	0.71648	0.72475	0.73978	0.74765

MOLE FRACTIONS

H2O1(G)	0.99995	0.99995	0.99995	0.99995	0.99995	0.99995	0.99995	0.99995	0.99994
O2(G)	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005	0.00006

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.000005 FOR ALL ASSIGNED CONDITIONS

H1(G)   H2(G)   O1(G)   O1H1(G)

THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION
FROM AN ASSIGNED TEMPERATURE AND AT VARIOUS CHAMBER PRESSURES

PROPANE

PARAMETERS

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT
PC/P	1.000	1.744	40.200	52.720	100.000	483.000	1000.000	10000.00	100000.0
P, ATM	6.805	3.901	0.1693	0.1291	0.0680	0.0147	0.0068	0.0007	0.0001
T, DEG K	590	551	337	320	280	197	164	90	49
H, CAL/G	-638.9	-667.9	-793.8	-801.8	-819.1	-851.9	-864.4	-890.1	-904.1
S, CAL/(G)(K)	2.2650	2.2650	2.2650	2.2650	2.2650	2.2650	2.2650	2.2650	2.2650
M, MOL WT	21.687	21.784	22.043	22.045	22.048	22.049	22.049	22.048	22.049
(DLM/DLP)T	0.00819	0.00599	0.00012	0.00007	0.00001	0.00000	0.	0.	0.
(DLM/DLT)P	-0.1387	-0.1074	-0.0034	-0.0019	-0.0004	-0.0000	0.	-0.0000	-0.0000
CP, CAL/(G)(K)	0.8704	0.8002	0.4672	0.4517	0.4219	0.3758	0.3619	0.3439	0.3425
GAMMA	1.1472	1.1545	1.2409	1.2504	1.2719	1.3155	1.3317	1.3552	1.3571
MACH NUMBER	0.	1.000	2.867	3.008	3.352	4.265	4.793	6.742	9.373
CSTAR, FT/SEC		2442	2442	2442	2442	2442	2442	2442	2442
CF		0.662	1.529	1.569	1.650	1.793	1.845	1.947	2.001
AE/AT		1.000	6.029	7.308	11.54	34.69	60.31	316.1	1678.
IVAC,LB-SEC/LB		93.8	127.5	129.6	134.0	141.8	144.6	150.2	153.2
I, LB-SEC/LB ,		50.2	116.1	119.1	125.2	136.1	140.1	147.8	151.9

DERIVATIVES

(DLI/DLPC)PC/P		0.00388	0.00161	0.00146	0.00116	0.00070	0.00054	0.00027	0.00014
(DLT/DLPC)PC/P	0.01460	0.01173	-0.00251	-0.00291	-0.00347	-0.00400	-0.00415	-0.00437	-0.00439
(DLAR/DLPC)PC/P		-0.	-0.00737	-0.00756	-0.00777	-0.00781	-0.00782	-0.00776	-0.00765
(DLCS/DLPC)PC/P		0.00312	0.00312	0.00312	0.00312	0.00312	0.00312	0.00312	0.00312
(DLI/DHC)PC/P*		1.13901	1.38375	1.40671	1.45826	1.56196	1.60283	1.68554	1.72741
(DLT/DHC)PC/P*	1.94724	2.11816	3.62796	3.75222	4.01687	4.51037	4.68400	4.92918	4.94829
(DLAR/DHC)PC/P*		0.	1.04992	1.14621	1.35367	1.74184	1.87459	2.03706	2.01430
(DLCS/DHC)PC/P*		1.20658	1.20658	1.20658	1.20658	1.20658	1.20658	1.20658	1.20658
*(HC IN KCAL/G)									
(DLI/DLPCP)S		0.86620	0.09806	0.08838	0.06998	0.04178	0.03269	0.01623	0.00839
(DLT/DLPCP)S	-0.11987	-0.12625	-0.19363	-0.19995	-0.21370	-0.23985	-0.24908	-0.26212	-0.26314
(DLAR/DLPCP)S,		0.	0.70778	0.71136	0.71625	0.71837	0.71823	0.72165	0.72848

MOLE FRACTIONS

C1H4(G)	0.64131	0.64810	0.66628	0.66645	0.66663	0.66667	0.66667	0.66667	0.66667
H2(G)	0.02173	0.01592	0.00033	0.00018	0.00003	0.00000	0.	0.	0.
C1(S)	0.33696	0.33599	0.33339	0.33336	0.33334	0.33333	0.33333	0.33333	0.33333

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.000005 FOR ALL ASSIGNED CONDITIONS

C1(G) C2(G) C3(G) C1H1(G) C1H2(G) C1H3(G) C2H2(G) C2H4(G) H1(G)

THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION
FROM AN ASSIGNED TEMPERATURE AND AT VARIOUS CHAMBER PRESSURES

PROPANE

PARAMETERS

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT
PC/P	1.000	1.749	40.200	52.720	100.000	463.000	1000.000	10000.00	100000.0
P, ATM	34.02	19.45	0.8463	0.6454	0.3402	0.0735	0.0340	0.0034	0.0003
T, DEG K	590	548	326	309	270	189	157	86	47
H, CAL/G	-647.2	-676.0	-799.0	-806.8	-823.4	-854.9	-866.9	-891.4	-904.9
S, CAL/(G)(K)	2.1042	2.1042	2.1042	2.1042	2.1042	2.1042	2.1042	2.1042	2.1042
M, MOL WT	21.885	21.935	22.047	22.048	22.048	22.048	22.049	22.048	22.049
(DLM/DLP)T	0.00370	0.00257	0.00004	0.00002	0.00000	0.00000	0.	0.	0.
(DLM/DLT)P	-0.0626	-0.0462	-0.0010	-0.0005	-0.0001	-0.0000	-0.0000	-0.0000	-0.0000
CP, CAL/(G)(K)	0.7492	0.6958	0.4536	0.4408	0.4147	0.3722	0.3594	0.3434	0.3425
GAMMA	1.1536	1.1627	1.2486	1.2574	1.2777	1.3196	1.3347	1.3559	1.3571
MACH NUMBER	0.	1.000	2.877	3.021	3.370	4.295	4.880	6.801	9.454
CSTAR, FT/SEC		2426	2426	2426	2426	2426	2426	2426	2426
CF		0.665	1.525	1.563	1.643	1.783	1.834	1.934	1.986
AE/AT		1.000	5.929	7.180	11.32	33.91	58.90	308.3	1638.
IVAC,LB-SEC/LB		93.2	126.1	128.1	132.4	140.0	142.7	148.1	151.0
I, LB-SEC/LB ,		50.1	114.9	117.8	123.8	134.4	138.3	145.8	149.7

DERIVATIVES

(DLI/DLPC)PC/P		0.00196	0.00071	0.00065	0.00051	0.00031	0.00024	0.00012	0.00006
(DLT/DLPC)PC/P	0.00759	0.00573	-0.00127	-0.00141	-0.00160	-0.00180	-0.00187	-0.00196	-0.00196
(DLAR/DLPC)PC/P		-0.	-0.00349	-0.00353	-0.00358	-0.00357	-0.00357	-0.00354	-0.00349
(DLCS/DLPC)PC/P		0.00146	0.00146	0.00146	0.00146	0.00146	0.00146	0.00146	0.00146
(DLI/DHC)PC/P*		1.23657	1.47391	1.49445	1.54066	1.63460	1.67188	1.74720	1.78516
(DLT/DHC)PC/P*	2.2624(	2.43589	3.73668	3.84544	4.08676	4.55430	4.71616	4.93545	4.94794
(DLAR/DHC)PC/P*		0.	0.95447	1.04110	1.23456	1.60773	1.73231	1.87629	1.85081
(DLCS/DHC)PC/P*		1.31197	1.31197	1.31197	1.31197	1.31197	1.31197	1.31197	1.31197
*(HC IN KCAL/G)									
(DLI/DLPCP)S		0.86002	0.09674	0.08714	0.06892	0.04108	0.03212	0.01595	0.00824
(DLT/DLPCP)S	-0.12879	-0.13622	-0.19892	-0.20461	-0.21735	-0.24219	-0.25079	-0.26246	-0.26312
(DLAR/DLPCP)S,		0.	0.70419	0.70816	0.71371	0.71674	0.71709	0.72160	0.72864

MOLE FRACTIONS

C1H4(G)	0.65519	0.65869	0.66656	0.66661	0.66666	0.66667	0.66667	0.66667	0.66667
H2(G)	0.00984	0.00684	0.00009	0.00005	0.00001	0.00000	0.	0.	0.
C1(S)	0.33497	0.33447	0.33335	0.33334	0.33333	0.33333	0.33333	0.33333	0.33333

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.000005 FOR ALL ASSIGNED CONDITIONS

C1(G) C2(G) C3(G) C1H1(G) C1H2(G) C1H3(G) C2H2(G) C2H4(G) H1(G)

THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION
FROM AN ASSIGNED TEMPERATURE AND AT VARIOUS CHAMBER PRESSURES

PROPANE

PARAMETERS

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT
PC/P	1.000	1.751	40.200	52.720	100.000	463.000	1000.000	10000.00	100000.0
P, ATM	68.05	38.86	1.693	1.291	0.6805	0.1470	0.0680	0.0068	0.0007
T, DEG K	590	547	323	306	267	187	155	85	47
H, CAL/G	-649.2	-678.0	-800.2	-807.9	-824.4	-855.6	-867.5	-891.8	-905.1
S, CAL/(G)(K)	2.0380	2.0380	2.0380	2.0380	2.0380	2.0380	2.0380	2.0380	2.0380
M, MOL WT	21.933	21.969	22.048	22.048	22.048	22.049	22.049	22.049	22.049
(DLM/DLP)T	0.00262	0.00179	0.00002	0.00001	0.00000	0.00000	0.	0.	0.
(DLM/DLT)P	-0.0444	-0.0323	-0.0006	-0.0003	-0.0001	-0.0000	-0.0000	-0.0000	-0.0000
CP, CAL/(G)(K)	0.7204	0.6720	0.4509	0.4385	0.4132	0.3713	0.3588	0.3433	0.3427
GAMMA	1.1555	1.1650	1.2502	1.2589	1.2791	1.3205	1.3354	1.3560	1.3569
MACH NUMBER	0.	1.000	2.880	3.024	3.374	4.302	4.838	6.815	9.473
CSTAR, FT/SEC		2421	2421	2421	2421	2421	2421	2421	2421
CF		0.665	1.523	1.562	1.641	1.781	1.831	1.930	1.983
AE/AT		1.000	5.906	7.151	11.27	33.74	58.58	306.6	1628.
IVAC,LB-SEC/LB		93.1	125.7	127.7	132.0	139.5	142.2	147.6	150.4
I, LB-SEC/LB ,		50.1	114.7	117.5	123.5	134.0	137.8	145.3	149.2

DERIVATIVES

(DLI/DLPC)PC/P		0.00143	0.00050	0.00046	0.00036	0.00022	0.00017	0.00008	0.00004
(DLT/DLPC)PC/P	0.00558	0.00413	-0.00092	-0.00101	-0.00114	-0.00128	-0.00132	-0.00138	-0.00139
(DLAR/DLPC)PC/P		-0.	-0.00249	-0.00252	-0.00254	-0.00254	-0.00253	-0.00251	-0.00247
(DLCS/DLPC)PC/P		0.00104	0.00104	0.00104	0.00104	0.00104	0.00104	0.00104	0.00104
(DLI/DHC)PC/P*		1.26370	1.49608	1.51596	1.56081	1.65235	1.68875	1.76232	1.79934
(DLT/DHC)PC/P*	2.35267	2.52212	3.75916	3.86512	4.10235	4.56424	4.72337	4.93672	4.94612
(DLAR/DHC)PC/P*		0.	0.92544	1.01048	1.20182	1.57190	1.69463	1.83442	1.80679
(DLCS/DHC)PC/P*		1.33999	1.33999	1.33999	1.33999	1.33999	1.33999	1.33999	1.33999
*(HC IN KCAL/G)									
(DLI/DLPCP)S		0.85836	0.09643	0.08685	0.06868	0.04091	0.03199	0.01588	0.00821
(DLT/DLPCP)S	-0.13135	-0.13896	-0.20004	-0.20561	-0.21817	-0.24271	-0.25118	-0.26252	-0.26302
(DLAR/DLPCP)S,		0.	0.70343	0.70748	0.71314	0.71637	0.71684	0.72160	0.72877

MOLE FRACTIONS

C1H4(G)	0.65853	0.66109	0.66660	0.66663	0.66666	0.66667	0.66667	0.66667	0.66667
H2(G)	0.00698	0.00478	0.00006	0.00003	0.00001	0.00000	0.	0.	0.
C1(S)	0.33450	0.33413	0.33334	0.33334	0.33333	0.33333	0.33333	0.33333	0.33333

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.000005 FOR ALL ASSIGNED CONDITIONS

C1(G) C2(G) C3(G) C1H1(G) C1H2(G) C1H3(G) C2H2(G) C2H4(G) H1(G)

THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION
FROM AN ASSIGNED TEMPERATURE AND AT VARIOUS CHAMBER PRESSURES

PROPANE

PARAMETERS

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT
PC/P	1.000	1.751	40.200	52.720	100.000	463.000	1000.000	10000.00	100000.0
P, ATM	102.1	58.28	2.539	1.936	1.021	0.2205	0.1021	0.0102	0.0010
T, DEG K	590	547	322	305	266	187	154	85	46
H, CAL/G	-650.0	-678.8	-800.8	-808.4	-824.9	-855.9	-867.7	-891.9	-905.1
S, CAL/(G)(K)	1.9998	1.9998	1.9998	1.9998	1.9998	1.9998	1.9998	1.9998	1.9998
M, MOL WT	21.954	21.984	22.048	22.048	22.048	22.048	22.049	22.048	22.049
(DLM/DLP)T	0.00214	0.00146	0.00002	0.00001	0.00000	0.00000	0.	0.	0.
(DLM/DLT)P	-0.0363	-0.0263	-0.0005	-0.0003	-0.0000	-0.0000	-0.0000	0.	-0.0000
CP, CAL/(G)(K)	0.7077	0.6616	0.4497	0.4376	0.4125	0.3710	0.3586	0.3433	0.3427
GAMMA	1.1564	1.1661	1.2509	1.2596	1.2796	1.3209	1.3357	1.3560	1.3568
MACH NUMBER	0.	1.000	2.881	3.026	3.376	4.305	4.842	6.821	9.481
CSTAR, FT/SEC		2420	2420	2420	2420	2420	2420	2420	2420
CF		0.666	1.523	1.561	1.640	1.780	1.830	1.929	1.981
AE/AT		1.000	5.896	7.138	11.25	33.66	58.44	305.8	1624.
IVAC,LB-SEC/LB		93.0	125.6	127.6	131.8	139.3	142.0	147.4	150.2
I, LB-SEC/LB ,		50.1	114.5	117.4	123.4	133.9	137.6	145.1	149.0

DERIVATIVES

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT
(DLI/DLPC)PC/P		0.00118	0.00041	0.00037	0.00029	0.00018	0.00014	0.00007	0.00004
(DLT/DLPC)PC/P	0.00464	0.00340	-0.00076	-0.00083	-0.00093	-0.00104	-0.00108	-0.00113	-0.00113
(DLAR/DLPC)PC/P		-0.	-0.00204	-0.00206	-0.00208	-0.00207	-0.00207	-0.00205	-0.00202
(DLCS/DLPC)PC/P		0.00085	0.00085	0.00085	0.00085	0.00085	0.00085	0.00085	0.00085
(DLI/DHC)PC/P*		1.27629	1.50599	1.52559	1.56981	1.66027	1.69629	1.76904	1.80569
(DLT/DHC)PC/P*	2.39501	2.56178	3.76878	3.87360	4.10914	4.56868	4.72654	4.93728	4.94566
(DLAR/DHC)PC/P*		0.	0.91183	0.99624	1.18674	1.55562	1.67745	1.81544	1.78717
(DLCS/DHC)PC/P*		1.35280	1.35280	1.35280	1.35280	1.35280	1.35280	1.35280	1.35280
*(HC IN KCAL/G)									
(DLI/DLPCP)S		0.85756	0.09630	0.08673	0.06858	0.04084	0.03193	0.01585	0.00820
(DLT/DLPCP)S	-0.13255	-0.14022	-0.20052	-0.20605	-0.21852	-0.24295	-0.25135	-0.26255	-0.26300
(DLAR/DLPCP)S,		0.	0.70310	0.70718	0.71289	0.71621	0.71673	0.72160	0.72880

MOLE FRACTIONS

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT
C1H4(G)	0.66001	0.66214	0.66661	0.66664	0.66666	0.66667	0.66667	0.66667	0.66667
H2(G)	0.00570	0.00388	0.00005	0.00002	0.00000	0.00000	0.	0.	0.
C1(S)	0.33428	0.33398	0.33334	0.33334	0.33333	0.33333	0.33333	0.33333	0.33333

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.000005 FOR ALL ASSIGNED CONDITIONS

C1(G) C2(G) C3(G) C1H1(G) C1H2(G) C1H3(G) C2H2(G) C2H4(G) H1(G)

THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION
FROM AN ASSIGNED TEMPERATURE AND AT VARIOUS CHAMBER PRESSURES

PROPANE

PARAMETERS	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT
PC/P	1.000	1.752	40.200	52.720	100.000	463.000	1000.000	10000.00	100000.0
P, ATM	204.1	116.5	5.078	3.872	2.041	0.4409	0.2041	0.0204	0.0020
T, DEG K	590	546	321	303	265	186	153	85	46
H, CAL/G	-651.2	-679.9	-801.5	-809.1	-825.5	-856.3	-868.1	-892.1	-905.2
S, CAL/(G)(K)	1.9352	1.9352	1.9352	1.9352	1.9352	1.9352	1.9352	1.9352	1.9352
M, MOL WT	21.982	22.003	22.048	22.048	22.048	22.048	22.048	22.049	22.049
(DLM/DLP)T	0.00152	0.00102	0.00001	0.00001	0.00000	0.	0.	0.	0.
(DLM/DLT)P	-0.0257	-0.0184	-0.0003	-0.0002	-0.0000	-0.0000	0.	0.	-0.0000
CP, CAL/(G)(K)	0.6911	0.6482	0.4483	0.4363	0.4116	0.3705	0.3583	0.3432	0.3427
GAMMA	1.1575	1.1675	1.2519	1.2605	1.2804	1.3214	1.3361	1.3561	1.3569
MACH NUMBER	0.	1.000	2.883	3.027	3.378	4.309	4.847	6.828	9.491
CSTAR, FT/SEC		2417	2417	2417	2417	2417	2417	2417	2417
CF		0.666	1.522	1.560	1.639	1.779	1.829	1.927	1.979
AE/AT		1.000	5.883	7.122	11.22	33.56	58.26	304.8	1619.
IVAC,LB-SEC/LB		92.9	125.4	127.4	131.6	139.1	141.8	147.1	149.9
I, LB-SEC/LB ,		50.1	114.4	117.2	123.2	133.6	137.4	144.8	148.7
DERIVATIVES									
(DLI/DLPC)PC/P		0.00085	0.00029	0.00026	0.00021	0.00012	0.00010	0.00005	0.00002
(DLT/DLPC)PC/P	0.00336	0.00243	-0.00054	-0.00059	-0.00066	-0.00074	-0.00077	-0.00080	-0.00080
(DLAR/DLPC)PC/P		-0.	-0.00146	-0.00146	-0.00147	-0.00147	-0.00147	-0.00145	-0.00143
(DLCS/DLPC)PC/P		0.00060	0.00060	0.00060	0.00060	0.00060	0.00060	0.00060	0.00060
(DLI/DHC)PC/P*		1.29327	1.51902	1.53821	1.58160	1.67068	1.70617	1.77791	1.81399
(DLT/DHC)PC/P*	2.45253	2.61483	3.78101	3.88443	4.11793	4.57437	4.73054	4.93801	4.94618
(DLAR/DHC)PC/P*		0.	0.89342	0.97710	1.16666	1.53390	1.65457	1.79030	1.76240
(DLCS/DHC)PC/P*		1.36979	1.36979	1.36979	1.36979	1.36979	1.36979	1.36979	1.36979
*(HC IN KCAL/G).									
(DLI/DLPCP)S		0.85652	0.09613	0.08657	0.06844	0.04075	0.03186	0.01582	0.00818
(DLT/DLPCP)S	-0.13417	-0.14190	-0.20113	-0.20660	-0.21899	-0.24325	-0.25156	-0.26259	-0.26303
(DLAR/DLPCP)S,		0.	0.70268	0.70680	0.71256	0.71599	0.71659	0.72159	0.72879
MOLE FRACTIONS									
C1H4(G)	0.66195	0.66349	0.66663	0.66665	0.66666	0.66667	0.66667	0.66667	0.66667
H2(G)	0.00404	0.00272	0.00003	0.00002	0.00000	0.	0.	0.	0.
C1(S)	0.33401	0.33379	0.33334	0.33334	0.33333	0.33333	0.33333	0.33333	0.33333

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.000005 FOR ALL ASSIGNED CONDITIONS

C1(G) C2(G) C3(G) C1H1(G) C1H2(G) C1H3(G) C2H2(G) C2H4(G) H1(G)

THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION
FROM AN ASSIGNED TEMPERATURE AND AT VARIOUS CHAMBER PRESSURES

FREON

PARAMETERS

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT
PC/P	1.000	1.778	40.200	52.720	100.000	463.000	1000.000	10000.00
P, ATM	6.805	3.984	0.1693	0.1291	0.0680	0.0147	0.0068	0.0007
T, DEG K	590	565	427	416	391	333	306	231
H, CAL/G	-952.2	-957.3	-983.1	-985.0	-989.3	-998.4	-1002.4	-1012.5
S, CAL/(G)(K)	0.6616	0.6616	0.6616	0.6616	0.6616	0.6616	0.6616	0.6616
M, MOL WT	119.515	119.779	120.770	120.805	120.864	120.918	120.923	120.925
(DLM/DLP)T	0.00579	0.00471	0.00064	0.00049	0.00025	0.00003	0.00001	0.00000
(DLM/DLT)P	-0.1229	-0.1048	-0.0190	-0.0151	-0.0082	-0.0012	-0.0004	-0.0000
CP, CAL/(G)(K)	0.2281	0.2212	0.1761	0.1727	0.1655	0.1512	0.1448	0.1257
GAMMA	1.0942	1.0951	1.1067	1.1082	1.1120	1.1222	1.1281	1.1504
MACH NUMBER	0.	1.000	2.819	2.940	3.220	3.876	4.209	5.254
CSTAR, FT/SEC		1060	1060	1060	1060	1060	1060	1060
CF		0.642	1.575	1.622	1.724	1.924	2.007	2.200
AE/AT		1.000	7.199	8.929	14.96	52.84	100.4	692.6
IVAC,LB-SEC/LB		40.4	57.8	59.0	61.7	67.1	69.4	74.7
I, LB-SEC/LB ,		21.1	51.9	53.4	56.8	63.4	66.1	72.4

DERIVATIVES

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT
(DLI/DLPC)PC/P		0.00272	0.00119	0.00113	0.00098	0.00070	0.00059	0.00037
(DLT/DLPC)PC/P	0.00896	0.00769	0.00079	0.00041	-0.00030	-0.00114	-0.00130	-0.00154
(DLAR/DLPC)PC/P		-0.	-0.00279	-0.00297	-0.00331	-0.00364	-0.00366	-0.00368
(DLCS/DLPC)PC/P		0.00177	0.00177	0.00177	0.00177	0.00177	0.00177	0.00177
(DLI/DHC)PC/P*		4.15918	4.45975	4.48710	4.55453	4.71694	4.79786	5.04191
(DLT/DHC)PC/P*	7.43070	7.66212	9.62613	9.81187	10.24098	11.20843	11.70181	13.48194
(DLAR/DHC)PC/P*		0.	1.08361	1.20749	1.50511	2.23966	2.64250	4.17446
(DLCS/DHC)PC/P*		4.26562	4.26562	4.26562	4.26562	4.26562	4.26562	4.26562
*(HC IN KCAL/G)								
(DLI/DLPCP)S		0.91252	0.11371	0.10440	0.08676	0.05930	0.05005	0.03149
(DLT/DLPCP)S	-0.08186	-0.08286	-0.09523	-0.09667	-0.10016	-0.10882	-0.11350	-0.13072
(DLAR/DLPCP)S.		0.	0.78989	0.79796	0.81251	0.83178	0.83642	0.83779

MOLE FRACTIONS

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT
C1CL4(G)	0.47695	0.48123	0.49745	0.49802	0.49899	0.49987	0.49997	0.50000
C1F4(G)	0.48848	0.49062	0.49872	0.49901	0.49949	0.49994	0.49998	0.50000
CL2(G)	0.02305	0.01877	0.00255	0.00198	0.00101	0.00013	0.00003	0.00000
C1(S)	0.01152	0.00938	0.00128	0.00099	0.00051	0.00006	0.00002	0.00000

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.000005 FOR ALL ASSIGNED CONDITIONS

THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION
FROM AN ASSIGNED TEMPERATURE AND AT VARIOUS CHAMBER PRESSURES

FREON

PARAMETERS

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT
PC/P	1.000	1.710	40.200	52.720	100.000	463.000	1000.000	10000.00
P, ATM	34.02	19.90	0.8463	0.6454	0.3402	0.0735	0.0340	0.0034
T, DEG K	590	563	422	411	385	328	301	227
H, CAL/G	-953.6	-958.7	-984.2	-986.0	-990.2	-999.2	-1003.2	-1013.1
S, CAL/(G)(K)	0.6327	0.6327	0.6327	0.6327	0.6327	0.6327	0.6327	0.6327
M, MOL WT	120.288	120.420	120.867	120.881	120.903	120.922	120.925	120.925
(DLM/DLP)T	0.00263	[illegible]	0.00024	0.00018	0.00009	0.00001	0.00000	0.00000
(DLM/DLT)P	-0.0557	-0.0464	-0.0072	-0.0056	-0.0030	-0.0004	-0.0001	-0.0000
CP, CAL/(G)(K)	0.2044	0.1996	0.1696	0.1672	0.1618	0.1496	0.1435	0.1245
GAMMA	1.0959	1.0970	1.1088	1.1102	1.1137	1.1235	1.1294	1.1521
MACH NUMBER	0.	1.000	2.821	2.943	3.224	3.884	4.217	5.269
CSTAR, FT/SEC		1056	1056	1056	1056	1056	1056	1056
CF		0.642	1.572	1.619	1.721	1.919	2.001	2.193
AE/AT		1.000	7.161	8.879	14.86	52.43	99.63	685.5
IVAC, LB-SEC/LB		40.3	57.5	58.7	61.4	66.7	[illegible]	74.2
I, LB-SEC/LB		21.1	51.6	53.2	56.5	63.0	65.7	72.0

DERIVATIVES

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT
(DLI/DLPC)PC/P		0.00110	0.00055	0.00051	0.00044	0.00031	0.00026	0.00017
(DLT/DLPC)PC/P	0.00450	0.00375	0.00023	0.00007	-0.00022	-0.00053	-0.00059	-0.00070
(DLAR/DLPC)PC/P		-0.	-0.00139	-0.00147	-0.00159	-0.00170	-0.00170	-0.00170
(DLCS/DLPC)PC/P		0.00084	0.00084	0.00084	0.00084	0.00084	0.00084	0.00084
(DLI/DHC)PC/P*		4.41262	4.64811	4.67255	4.72944	4.87090	4.94422	5.17158
(DLT/DHC)PC/P*	8.29305	8.48949	9.99591	10.13747	10.47773	11.33081	11.81049	13.61901
(DLAR/DHC)PC/P*		0.	0.94818	1.05064	1.30808	1.99336	2.39646	3.97629
(DLCS/DHC)PC/P*		4.47119	4.47119	4.47119	4.47119	4.47119	4.47119	4.47119
*(HC IN KCAL/G)								
(DLI/DLPCP)S		0.91142	0.11329	0.10401	0.08637	0.05900	0.04979	0.03126
(DLT/DLPCP)S	-0.08534	-0.08630	-0.09766	-0.09888	-0.10191	-0.10991	-0.11453	-0.13205
(DLAR/DLPCP)S,		0.	0.78859	0.79674	0.81151	0.83106	0.83567	0.83669

MOLE FRACTIONS

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT
C1CL4(G)	0.48952	0.49168	0.49905	0.49928	0.49964	0.49996	0.49999	0.50000
C1F4(G)	0.49476	0.49584	0.49952	0.49964	0.49982	0.49998	0.50000	0.50000
CL2(G)	0.01047	0.00832	0.00095	0.00072	0.00036	0.00004	0.00001	0.00000
C1(S)	0.00524	0.00416	0.00048	0.00036	0.00018	0.00002	0.00000	0.00000

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.000005 FOR ALL ASSIGNED CONDITIONS

THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION
FROM AN ASSIGNED TEMPERATURE AND AT VARIOUS CHAMBER PRESSURES

FREON

PARAMETERS

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT
PC/P	1.000	1.710	40.200	52.720	100.000	463.000
P, ATM	68.05	39.80	1.693	1.291	0.6805	0.1470
T, DEG K	590	563	421	410	384	326
H, CAL/G	-953.9	-959.0	-984.4	-986.3	-990.4	-999.4
S, CAL/(G)(K)	0.6207	0.6207	0.6207	0.6207	0.6207	0.6207
M, MOL WT	120.474	120.569	120.886	120.896	120.911	120.924
(DLM/DLP)T	0.00186	0.00147	0.00016	0.00012	0.00006	0.00001
(DLM/DLT)P	-0.0395	-0.0328	-0.0049	-0.0038	-0.0020	-0.0003
CP, CAL/(G)(K)	0.1987	0.1946	0.1682	0.1660	0.1610	0.1492
GAMMA	1.0963	1.0975	1.1093	1.1106	1.1141	1.1238
MACH NUMBER	0.	1.000	2.822	2.944	3.225	3.886
CSTAR, FT/SEC		1055	1055	1055	1055	1055
CF		0.642	1.572	1.619	1.720	1.918
AE/AT		1.000	7.152	8.867	14.84	52.34
IVAC,LB-SEC/LB		40.2	57.4	58.6	61.3	66.6
I, LB-SEC/LB ,		21.0	51.6	53.1	56.4	62.9

DERIVATIVES

(DLI/DLPC)PC/P		0.00072	0.00039	0.00036	0.00031	0.00022
(DLT/DLPC)PC/P	0.00328	0.00271	0.00014	0.00003	-0.00017	-0.00038
(DLAR/DLPC)PC/P		-0.	-0.00101	-0.00106	-0.00114	-0.00121
(DLCS/DLPC)PC/P		0.00060	0.00060	0.00060	0.00060	0.00060
(DLI/DHC)PC/P*		4.46928	4.69523	4.71777	4.77287	4.90875
(DLT/DHC)PC/P*	8.52987	8.70947	10.07433	10.20746	10.52614	11.35754
(DLAR/DHC)PC/P*		0.	0.90250	1.00290	1.24865	1.92636
(DLCS/DHC)PC/P*		4.52548	4.52548	4.52548	4.52548	4.52548
*(HC IN KCAL/G)						
(DLI/DLPCP)S		0.91147	0.11320	0.10390	0.08629	0.05893
(DLT/DLPCP)S	-0.08630	-0.08747	-0.09819	-0.09937	-0.10228	-0.11015
(DLAR/DLPCP)S,		0.	0.78830	0.79647	0.81129	0.83089

MOLE FRACTIONS

C1CL4(G)	0.49255	0.49413	0.49936	0.49951	0.49976	0.49998
C1F4(G)	0.49628	0.49706	0.49968	0.49976	0.49988	0.49999
CL2(G)	0.00744	0.00587	0.00064	0.00049	0.00024	0.00003
C1(S)	0.00372	0.00294	0.00032	0.00024	0.00012	0.00001

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.000005 FOR ALL ASSIGNED CONDITIONS

THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION
FROM AN ASSIGNED TEMPERATURE AND AT VARIOUS CHAMBER PRESSURES

FREON

PARAMETERS

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT
PC/P	1.000	1.709	40.200	52.720	100.000	463.000	1000.000
P, ATM	102.1	59.72	2.539	1.936	1.021	0.2205	0.1021
T, DEG K	590	563	420	409	383	326	299
H, CAL/G	-954.0	-959.1	-984.5	-986.4	-990.5	-999.5	-1003.4
S, CAL/(G)(K)	0.6138	0.6138	0.6138	0.6138	0.6138	0.6138	0.6138
M, MOL WT	120.556	120.635	120.894	120.902	120.914	120.924	120.925
(DLM/DLP)T	0.00152	0.00120	0.00013	0.00010	0.00005	0.00001	0.00000
(DLM/DLT)P	-0.0323	-0.0267	-0.0039	-0.0030	-0.0016	-0.0002	-0.0001
CP, CAL/(G)(K)	0.1962	0.1924	0.1677	0.1656	0.1607	0.1491	0.1431
GAMMA	1.0965	1.0978	1.1095	1.1108	1.1143	1.1240	1.1298
MACH NUMBER	0.	1.000	2.822	2.944	3.226	3.886	4.220
CSTAR, FT/SEC		1054	1054	1054	1054	1054	1054
CF		0.642	1.572	1.619	1.720	1.919	2.001
AE/AT		1.000	7.153	8.868	14.84	52.34	99.43
IVAC, LB-SEC/LB		40.2	57.4	58.6	61.2	66.6	68.8
I, LB-SEC/LB		21.0	51.5	53.1	56.4	62.9	65.6

DERIVATIVES

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT
(DLI/DLPC)PC/P		0.00060	0.00032	0.00030	0.00026	0.00018	0.00015
(DLT/DLPC)PC/P	0.00271	0.00223	0.00011	0.00002	-0.00014	-0.00031	-0.00034
(DLAR/DLPC)PC/P		-0.	-0.00084	-0.00088	-0.00094	-0.00100	-0.00100
(DLCS/DLPC)PC/P		0.00050	0.00050	0.00050	0.00050	0.00050	0.00050
(DLI/DHC)PC/P*		4.49038	4.71694	4.73933	4.79162	4.92503	4.99542
(DLT/DHC)PC/P*	8.63917	8.81082	10.10905	10.23745	10.54661	11.36988	11.84751
(DLAR/DHC)PC/P*		0.	0.87557	0.97337	1.21584	1.89148	2.29702
(DLCS/DHC)PC/P*		4.55581	4.55581	4.55581	4.55581	4.55581	4.55581
*(HC IN KCAL/G)							
(DLI/DLPCP)S		0.91113	0.11318	0.10389	0.08625	0.05890	0.04970
(DLT/DLPCP)S	-0.08674	-0.08792	-0.09842	-0.09958	-0.10243	-0.11027	-0.11488
(DLAR/DLPCP)S,		0.	0.78815	0.79632	0.81121	0.83081	0.83541

MOLE FRACTIONS

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT
C1CL4(G)	0.49392	0.49521	0.49949	0.49961	0.49981	0.49998	0.50000
C1F4(G)	0.49696	0.49761	0.49974	0.49980	0.49990	0.49999	0.50000
CL2(G)	0.00608	0.00479	0.00051	0.00039	0.00019	0.00002	0.00001
C1(S)	0.00304	0.00239	0.00026	0.00020	0.00010	0.00001	0.00000

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.000005 FOR ALL ASSIGNED CONDITIONS

THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION
FROM AN ASSIGNED TEMPERATURE AND AT VARIOUS CHAMBER PRESSURES

FREON

PARAMETERS

	CHAMBER	THROAT	EXIT	EXIT	EXIT	EXIT
PC/P	1.000	1.709	40.200	52.720	100.000	463.000
P, ATM	204.1	119.4	5.078	3.872	2.041	0.4409
T, DEG K	590	563	419	408	383	325
H, CAL/G	-954.2	-959.3	-984.7	-986.5	-990.7	-999.6
S, CAL/(G)(K)	0.6020	0.6020	0.6020	0.6020	0.6020	0.6020
M, MOL WT	120.664	120.721	120.903	120.908	120.917	120.924
(DLM/DLP)T	0.00108	0.00085	0.00009	0.00007	0.00003	0.00000
(DLM/DLT)P	-0.0229	-0.0189	-0.0027	-0.0021	-0.0011	-0.0001
CP, CAL/(G)(K)	0.1929	0.1895	0.1679	0.1650	0.1603	0.1489
GAMMA	1.0968	1.0981	1.1097	1.1111	1.1145	1.1241
MACH NUMBER	0.	1.000	2.823	2.945	3.226	3.887
CSTAR, FT/SEC		1054	1054	1054	1054	1054
CF		0.642	1.572	1.619	1.719	1.918
AE/AT		1.000	7.145	8.856	14.82	52.27
IVAC,LB-SEC/LB		40.2	57.3	58.5	61.2	66.5
I, LB-SEC/LB ,		21.0	51.5	53.0	56.3	62.8

DERIVATIVES

(DLI/DLPC)PC/P		0.00043	0.00022	0.00021	0.00018	0.00013
(DLT/DLPC)PC/P	0.00195	0.00160	0.00007	0.00001	-0.00010	-0.00022
(DLAR/DLPC)PC/P		-0.	-0.00060	-0.00062	-0.00067	-0.00071
(DLCS/DLPC)PC/P		0.00035	0.00035	0.00035	0.00035	0.00035
(DLI/DHC)PC/P*		4.52919	4.74359	4.76436	4.81687	4.94728
(DLT/DHC)PC/P*	8.78631	8.94517	10.15160	10.27313	10.57375	11.38505
(DLAR/DHC)PC/P*		0.	0.85061	0.94556	1.18370	1.85481
(DLCS/DHC)PC/P*		4.58463	4.58463	4.58463	4.58463	4.58463
*(HC IN KCAL/G)						
(DLI/DLPCP)S		0.91156	0.11309	0.10379	0.08620	0.05887
(DLT/DLPCP)S	-0.08733	-0.08852	-0.09871	-0.09983	-0.10264	-0.11041
(DLAR/DLPCP)S,		0.	0.78802	0.79624	0.81108	0.83071

MOLE FRACTIONS

C1CL4(G)	0.49569	0.49662	0.49965	0.49973	0.49987	0.49999
C1F4(G)	0.49785	0.49831	0.49982	0.49987	0.49993	0.49999
CL2(G)	0.00431	0.00338	0.00035	0.00027	0.00013	0.00001
C1(S)	0.00215	0.00169	0.00018	0.00013	0.00007	0.00001

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.000005 FOR ALL ASSIGNED CONDITIONS

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APPENDIX F

SYMBOL LIST

A = surface area of solid-propellant rocket motor

C_p = average specific heat of motor = $\left(M_1 C_{p1} + M_2 C_{p2} + M_3 C_{p3} + M_4 C_{p4} + M_5 C_{p5}\right)/W_3$

C_{p1} = specific heat of outer wall of motor

C_{p2} = specific heat of metal parts (ring and bolts attached to motor)

C_{p3} = specific heat of graphite throat

C_{p4} = specific heat of motor liner

C_{p5} = specific heat of exit cone

C_{p6} = specific heat of inert fluid

C_{p7} = specific heat of inert fluid vapor

g = gravitational constant

H = total heat in motor at maximum temperature

$\bar{H}$ = available heat from motor at any time

I_{tot} = total impulse available from inert fluid

I_{vac} = vacuum specific impulse of inert fluid at the maximum motor temperature

I_{vaco} = vacuum specific impulse for solid-propellant rocket motor at $t = 0$

M_1 = weight of outer wall of motor

M_2 = weight of metal parts (ring and bolts attached to motor)

M_3 = weight of graphite throat

M_4 = weight of inner motor liner

M_5 = weight of exit cone

m_t = weight of fluid that can be injected into hot motor at any time

m_0 = weight of fluid actually injected into hot motor

Q_0 = energy generated and retained by rocket motor after main grain burnout

Q_{rad} = energy radiated by motor's surface

°R = degrees Rankine

T = maximum temperature of motor shell after firing

T_0 = temperature of motor shell before firing

T_1 = temperature of space outside motor

T_B = boiling point of inert fluid at injection pressure

t = time elapsed after maximum temperature (T) is reached

Δt = time elapsed for flow of fluid into hot motor

ΔV_1 = velocity increment provided by solid-propellant motor without quenching system

ΔV_2 = velocity increment provided by solid-propellant motor when carrying the injection system but not using it

ΔV_3 = incremental velocity increase when using the system at any time

ΔV_p = $V_1 - V_2$ = velocity penalty

$\dot{W}$ = weight flow rate of inert fluid into hot motor

W_1 = weight of payload

W_2 = weight of motor

W_3 = total weight of empty solid propellant motor = $M_1 + M_2 + M_3 + M_4 + M_5$

W_4 = weight of inert-fluid-carrying system without fluid

W_5 = weight of inert fluid to be used

dH/dt = loss of heat from motor with time

dI/dt = loss of specific impulse of inert fluid with time as temperature drops

dT/dT = temperature decay rate from hot motor to space surrounding motor

dT_m/dt = temperature decay rate when inert fluid flows

ϵ = emissivity of motor shell

σ = Stephan-Boltzmann constant

λ = heat of vaporization of inert fluid