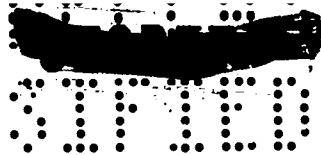


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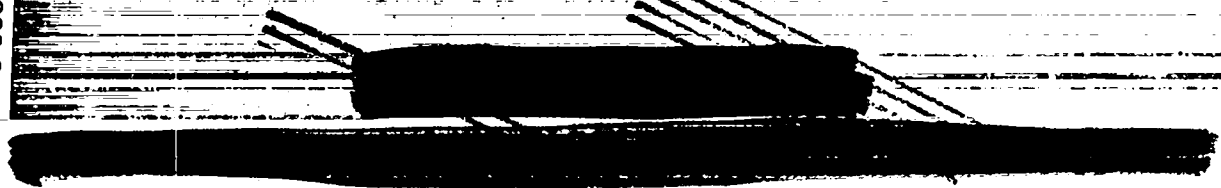
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By Marion Bailey 1-17-96

THEORETICAL SPECIFIC IMPULSES OF HYDROGEN
AND HYDROGEN-METHANE NUCLEAR PROPELLANT SYSTEMS

(Title ~~Confidential~~ RB)

EHS
SPECIAL RE-REVIEW
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THEORETICAL SPECIFIC IMPULSES OF HYDROGEN
AND HYDROGEN-METHANE NUCLEAR PROPELLANT SYSTEMS

(Title [REDACTED])

Work done by:

David G. Clifton
Lawrence R. Sitney

Report written by:

Lawrence R. Sitney

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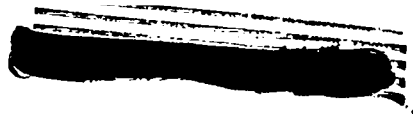
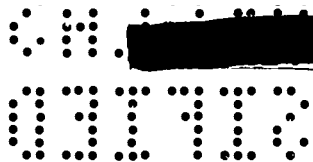
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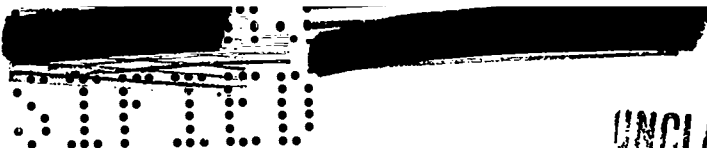
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ABSTRACT

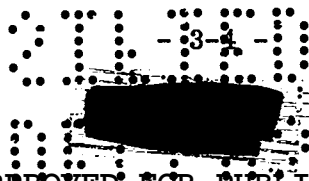
The theoretical specific impulses obtainable with pure hydrogen and with four hydrogen-methane mixtures (99 v/o H_2 - 1 v/o CH_4 ; 97 v/o H_2 - 3 v/o CH_4 ; 95 v/o H_2 - 5 v/o CH_4 ; 90 v/o H_2 - 10 v/o CH_4) have been calculated with an IBM 704 computer for the cases of frozen and of shifting equilibrium. All permutations obtainable with chamber pressures of 300, 500, 700, and 1100 psi and gas temperatures of 2200°K, 2366.5°K, 2588.9°K, and 2866.5°K were used as initial conditions for one series of calculations. In a second set of computations, the chamber pressure was held constant at 700 psi while the initial gas temperature was increased from 2673°K to 3573°K in 100° increments.

For a given propellant composition and initial temperature, the higher the pressure is, the higher the specific impulse at 1 atmosphere exhaust pressure will be. The specific impulse increases with higher initial gas temperature if the chemical composition and the chamber pressure are fixed. The specific impulse is higher for a given set of initial conditions if shifting equilibrium occurs than if the equilibrium is frozen, the difference increasing as the initial gas temperature is raised.

Methods of improving the performance of a nuclear rocket with a hydrogen-methane propellant system are suggested.

ACKNOWLEDGEMENTS

Wildon Fickett and Henry Koppel substantially eased the load of the authors by providing them with an IBM 704 code to calculate the equilibrium composition of a chemical system by means of Brinkley's method.

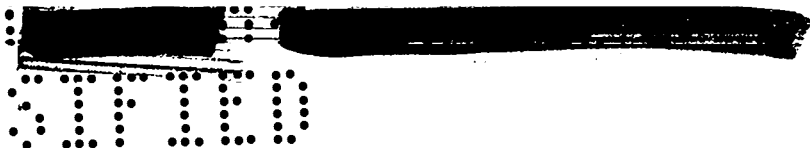


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1. INTRODUCTION

The results presented in this report are the outgrowth of a request for data giving the specific impulses obtainable in a hydrogen-methane nuclearly propelled rocket. The performance data for pure hydrogen and the data demonstrating the effect of temperature on the specific impulses of hydrogen and of hydrogen-methane mixtures were computed in order to show the substantial improvement in specific impulse which is obtainable if the operating temperature of the reactor can be increased a few hundred degrees above the present operating condition of the Kiwi-A or Kiwi-B reactor or if the methane content of the propellant at the present operating temperature of these two reactors can be reduced by some technique, such as coating the graphite reactor with a protective coating of a nonreactive refractory carbide.

The IBM 704 code "Nozzle", which computes the specific impulse of a propellant expanding isentropically with shifting equilibrium through a nozzle, was already in existence when the request arrived. Minor modifications were made in this code to permit the calculation of specific impulses when the composition of the propellant system was "frozen" at its initial conditions. A general description of this code will be given in Section 3.

The results given in this report will permit one to replace with an exact value the somewhat inexact values of the specific impulses of hydrogen-methane systems which were calculated according to the formula


$$I_{sp} = I_{sp}(\text{H}_2) \sqrt{\frac{M(\text{H}_2) T}{M(\text{CH}_4) 2773}} \quad (1.1)$$

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where

I_{sp} = the specific impulse of the hydrogen-methane propellant mixture at a temperature T in degrees Kelvin,

$I_{sp}(H_2)$ = the specific impulse of hydrogen at a temperature of 2773°K,

$\bar{M}(H_2)$ = the mean molecular weight of hydrogen at a temperature of 2773°K (= 2.0052 at 700 psi chamber pressure),

$\bar{M}(CH_4)$ = the mean molecular weight of the hydrogen-methane propellant at a temperature T in degrees Kelvin.

The exact value is calculated according to the equation

$$I_{sp} = \sqrt{2\Delta H/g}, \quad (1.2)$$

where

g = the acceleration of gravity in cm/sec^2 ,

and

ΔH = the change in enthalpy, expressed in ergs, experienced by 1 gram of the propellant in passing from its initial state in the reactor to the final state determined by the isentropic expansion process through the nozzle.


These more exact values for the specific impulse will permit a more reliable systems study for the purpose of optimizing the performance of a hydrogen-methane nuclearly propelled rocket. Moreover, one will be able to select an appropriate operating temperature for the propellant and reactor compatible with the specific impulse which would be necessary to perform a designated mission.


2. CALCULATION OF THERMODYNAMIC DATA

Most of the thermodynamic data used in the equilibrium calculations were computed at LASL. A rigid rotator, harmonic oscillator model was

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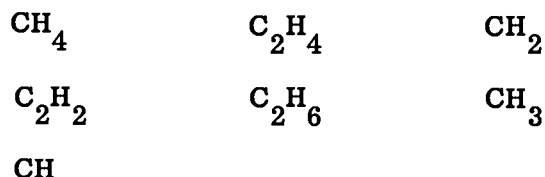




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used for polyatomic molecules, and a nonrigid rotator, anharmonic oscillator model which included the four lowest electronic levels was used for the CH molecule. Other data were obtained from tables published by the National Bureau of Standards.¹ The following list gives the source of thermodynamic data for each of the eleven chemical species considered in the equilibrium calculations.

Computed at LASL



From National Bureau of Standards

C (solid)

C (gas)

H

From A. S. Friedman, NBS (personal communication)

H_2

The spectroscopic data used in the computation of the thermodynamic quantities of the seven molecules are given in Table 2.1. The complete data for each molecule are given, rather than a literature reference, since they are, with the exception of CH, a collection of what seemed to be the "best" values appearing in the literature and not the data from a single reference in the literature.

Thermodynamic data were obtained for each of the eleven molecules over the temperature interval 300°K to 5000°K. The data for each molecule then were separated into two groups, one covering the range from 300°K to 900°K and the other extending from 800°K to 4000°K. The enthalpy function, $(H - H_0)/RT$, and the heat capacity, C_p , then were fitted over each temperature interval by a least-squares quartic fit of the form

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TABLE 2.1

SPECTROSCOPIC DATA USED IN STATISTICAL
THERMODYNAMIC CALCULATIONS

Molecule	Frequency, cm ⁻¹	Degeneracy	Rotational Constants, cm ⁻¹
CH ₄	$\nu_1 = 2916.5$	$g_1 = 1$	A = B = C = 5.241
	$\nu_2 = 1535.0$	$g_2 = 2$	
	$\nu_3 = 3018.9$	$g_3 = 3$	
	$\nu_4 = 1301.0$	$g_4 = 3$	
C ₂ H ₂	$\nu_1 = 3373.7$	$g_1 = 1$	B = 1.17684
	$\nu_2 = 1973.8$	$g_2 = 1$	A = C = 0
	$\nu_3 = 3281.93$	$g_3 = 1$	
	$\nu_4 = 612.66$	$g_4 = 2$	
	$\nu_5 = 726.76$	$g_5 = 2$	
C ₂ H ₄	$\nu_1 = 810.3$	$g_1 = 1$	A = 4.8669
	$\nu_2 = 943.0$	$g_2 = 1$	B = 0.99625
	$\nu_3 = 949.2$	$g_3 = 1$	C = 0.82697
	$\nu_4 = 1027.0$	$g_4 = 1$	
	$\nu_5 = 1236.0$	$g_5 = 1$	
	$\nu_6 = 1342.4$	$g_6 = 1$	
	$\nu_7 = 1443.5$	$g_7 = 1$	
	$\nu_8 = 1623.3$	$g_8 = 1$	
	$\nu_9 = 2989.5$	$g_9 = 1$	
	$\nu_{10} = 3019.3$	$g_{10} = 1$	
	$\nu_{11} = 3105.5$	$g_{11} = 1$	
	$\nu_{12} = 3272.3$	$g_{12} = 1$	

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TABLE 2.1 (Continued)

Molecule	Frequency, cm ⁻¹	Degeneracy	Rotational Constants, cm ⁻¹
C ₂ H ₆ *	$\nu_1 = 2899.2$	$g_1 = 1$	A = 0.66261
	$\nu_2 = 1375.0$	$g_2 = 1$	B = 0.66261
	$\nu_3 = 993.0$	$g_3 = 1$	C = 2.5888
	$\nu_4 = 2954.0$	$g_4 = 1$	
	$\nu_5 = 1379.14$	$g_5 = 1$	
	$\nu_6 = 2995.5$	$g_6 = 2$	
	$\nu_7 = 1472.2$	$g_7 = 2$	
	$\nu_8 = 821.52$	$g_8 = 2$	
	$\nu_9 = 2963.0$	$g_9 = 2$	
	$\nu_{10} = 1460.0$	$g_{10} = 2$	
	$\nu_{11} = 1190.0$	$g_{11} = 2$	
CH ₂	$\nu_1 = 2944.0$	$g_1 = 1$	A = 79.969
	$\nu_2 = 1472.0$	$g_2 = 1$	B = 7.7964
	$\nu_3 = 3149.0$	$g_3 = 1$	C = 7.1038
CH ₃	$\nu_1 = 2923.0$	$g_1 = 1$	A = B = 9.3343
	$\nu_2 = 1379.0$	$g_2 = 1$	C = 4.6672
	$\nu_3 = 3025.0$	$g_3 = 2$	
	$\nu_4 = 1602.0$	$g_4 = 2$	
CH	Values from G. Herzberg, <u>Molecular Spectra and Molecular Structure, Vol. I, Spectra of Diatomic Molecules</u> , p. 518, D. Van Nostrand Company, Inc., New York, 1950.		

*For C₂H₆, E(barrier) = 3050 cal/mole and I(reduced) = 2.651×10^{-40} g cm².

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$$Y = a + bT + cT^2 + dT^3 + eT^4, \quad (2.1)$$

where Y represents either the heat capacity or enthalpy and T represents the temperature in degrees Kelvin.

The free energy functions, $-(F^\circ - H_0^\circ)/RT$, which were actually used in the equilibrium calculations were obtained for each of the eleven molecules by the method of Fickett and Cowan.² In this method the coefficients from the least-squares fit of the enthalpy from equation (2.1) are substituted into the equation

$$-\frac{(F - H_0^\circ)}{RT} = a \ln T + bT + \frac{cT^2}{2} + \frac{dT^3}{3} + \frac{eT^4}{4} + k, \quad (2.2)$$

and the value of k is determined so that the free energy function evaluated by equation (2.2) coincides with the value of the free energy function obtained by statistical thermodynamic methods. The evaluation of k is carried out at even 100° temperature increments within the temperature intervals, and the average value of the k's so determined is used for the free energy function over the entire temperature interval. The value of k in the low temperature range, in general, is quite different from the value in the 800°K to 4000°K range.

The actual expression used for the evaluation of the free energy in the Brinkley method³ of computing the equilibrium composition of a chemical system is as follows:

$$-\frac{F^\circ}{RT} = a \ln T + bT + \frac{cT^2}{2} + \frac{dT^3}{3} + \frac{eT^4}{4} + k - \frac{H_0^\circ}{RT} - \ln P, \quad (2.3)$$

where

H_0° = standard heat of formation of the molecule at 0°K,

P = pressure of the system in atmospheres.

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Integration of the heat capacity quartic equation (2.1) with respect to the temperature yields the enthalpy function. This enthalpy equation is used with equation (2.3) to obtain values for the entropy in the "Nozzle" calculations.


3. CALCULATION OF SPECIFIC IMPULSES


Before the details of the specific impulse calculations are presented, certain of the features of the "Nozzle" code will be described. The code actually consists of three distinct parts identified as "Nozzle 4", "Nozzle 5", and "Nozzle 6". The "4" code is used only for chemical rockets or nuclear rockets with chemical afterburning. It computes the proper combustion temperature for the propellant system based upon the propellant-oxidizer mole ratio and upon the initial temperatures and pressures of the propellant and of the oxidizer; this combustion temperature and the chamber pressure are used as input data for either the "Nozzle 5" or "Nozzle 6" codes, which compute the specific impulse of the propellant system. For a purely nuclear rocket, the chamber temperature and pressure are read directly into the IBM 704 by these codes. The "5" code is used to compute the specific impulse for systems which undergo shifting equilibrium while the "6" code is used in the case of frozen equilibrium.

The section of the code which computes the equilibrium composition of the propellant system, at a specified temperature and pressure, is identical in each of the three parts of the code and can handle either a one or two phase system with as many as fourteen chemical species present in the system. The capacity of the codes can be increased to twenty species, if necessary, by expanding certain sections of the codes. Within a short period of time an improved version of the equilibrium code which will permit five distinct chemical phases and twenty-five chemical species to be considered in the equilibrium calculations will be available. In practice, however, it is not

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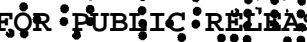
believed that such complicated systems will be of much interest in specific impulse calculations for nuclear propellant systems.

The calculation of specific impulses will be described in a stepwise fashion patterned after the flow diagram of the actual IBM 704 code. The sequence of events is as follows for the shifting equilibrium case:

- (1) Calculate the equilibrium composition of the system at the initial temperature, T_1 , and pressure, P_1 , by means of Brinkley's method.
- (2) Compute the entropy, S_1 , of the equilibrium composition of the system at its initial conditions, and the enthalpy, H_1 , of this system.
- (3) Calculate the equilibrium composition of the system at a specified lower pressure, P_2 , and a guessed temperature, T_2 .
- (4) Compute the entropy, S_2 , associated with the composition of step 3.
- (5) Change the guessed temperature, T_2 , by a predetermined amount, ΔT , to decrease the difference $S_1 - S_2$.
- (6) Solve for the equilibrium composition of the system at temperature $T_2 \pm \Delta T$ and at pressure P_2 .
- (7) Recompute the entropy, S_3 , associated with the conditions of step 6.
- (8) Use a linear iterative procedure based on entropies S_2 and S_3 and temperatures T_2 and $T_2 \pm \Delta T$ to converge on the initial entropy, S_1 . This will give the correct temperature, T_f , associated with the isentropic expansion of the propellant from the initial pressure and temperature within the reactor to the final pressure, P_2 , when shifting equilibrium can occur.
- (9) Compute the enthalpy, H_f , of the equilibrium composition of the system at pressure P_2 and temperature T_f .
- (10) Evaluate the change of enthalpy, $\Delta H = H_1 - H_f$, experienced in the expansion process.
- (11) Multiply ΔH by 2, multiply by 4.184×10^7 to convert ΔH in calories to

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ΔH in ergs, divide by the mass of the system, take the square root of the result, and divide by g , the acceleration of gravity. The result is the specific impulse, I_{sp} , in units of seconds, as defined by equation (1.2).

For the case of frozen equilibrium, the composition of the system is held fixed at the initial equilibrium composition and the temperature is iterated until the final entropy, S_f , agrees with the initial entropy, S_i . The calculation of the specific impulse is performed in the same manner as in step 11 above.

All calculations of the specific impulse have been carried out at the following five exhaust pressures:

$P_e = 1.0$ atmospheres
 0.333
 0.1
 0.01
 0.001.

4. RESULTS

Tables 4.1 through 4.9 contain the complete results of the specific impulse calculations for both shifting and frozen equilibrium. Each section of the tables is composed of two columns, the first giving the results for shifting equilibrium and the second, enclosed in parentheses, giving the results of the frozen equilibrium calculations. The symbols used in these tables have the following meanings:

T_c = chamber temperature in degrees Kelvin,
 P_c = chamber pressure in psi,
 P_e = nozzle exit pressure in atmospheres.

Tables 4.1 through 4.5 represent the results of the eighty permutations

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of the following sets of initial conditions:

Composition	Chamber Pressure	Chamber Temperature
100 v/o H ₂	300 psi	3500°F (2200°K)
99 v/o H ₂ - 1 v/o CH ₄	500 psi	3800°F (2366.5°K)
97 v/o H ₂ - 3 v/o CH ₄	700 psi	4200°F (2588.9°K)
95 v/o H ₂ - 5 v/o CH ₄	1100 psi	4700°F (2866.5°K)
90 v/o H ₂ - 10 v/o CH ₄		

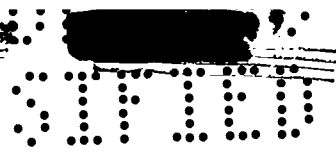
Tables 4.6 through 4.9 demonstrate the dependence of the specific impulse upon the chamber temperature if the chamber pressure is held constant.

Figures 4.1 through 4.4 show the variation of specific impulse with chamber temperature and propellant composition at chamber pressures of 300, 500, 700, and 1100 psi, respectively. Figures 4.5 and 4.6 represent the change in specific impulse with chamber temperature at a constant chamber pressure of 700 psi; Figure 4.5 shows the results for the case of shifting equilibrium while Figure 4.6 covers the frozen equilibrium case. In Figures 4.1 through 4.4 the solid lines represent the shifting equilibrium results and the dotted lines, the frozen equilibrium results. The specific impulses plotted in these six figures are those at 1 atmosphere exhaust pressure. It must be realized, however, that the actual takeoff specific impulses will be about 3 to 4% lower due to the fact that overexpansion of the propellant within the nozzle will occur before separation of the propellant jet stream from the nozzle wall takes place. Moreover, the theoretical specific impulses in the tables will be higher than the actual specific impulses because of either overexpansion or underexpansion of the propellant.

(Text continues on page 30)

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TABLE 4.1
SPECIFIC IMPULSES OF PURE HYDROGEN

$T_c = 2200.0^\circ K$

P_e	$P_c = 300$ psi	$P_c = 500$ psi	$P_c = 700$ psi	$P_c = 1100$ psi
1.000	634.6 (633.6)	666.4 (665.6)	684.5 (683.8)	705.5 (704.8)
0.333	697.1 (695.9)	718.5 (717.6)	730.7 (729.9)	745.1 (744.4)
0.100	742.9 (741.6)	757.2 (756.1)	765.4 (764.4)	775.1 (774.4)
0.010	793.6 (792.1)	800.3 (799.2)	804.2 (803.3)	808.9 (808.1)
0.001	818.4 (816.9)	821.6 (820.3)	823.4 (822.3)	825.6 (824.7)

$T_c = 2366.5^\circ K$

P_e	$P_c = 300$ psi	$P_c = 500$ psi	$P_c = 700$ psi	$P_c = 1100$ psi
1.000	661.2 (658.9)	694.3 (692.3)	712.9 (711.2)	734.8 (733.4)
0.333	726.8 (724.2)	748.9 (746.8)	761.6 (759.7)	776.5 (774.9)
0.100	775.0 (772.0)	789.5 (787.1)	797.9 (795.9)	807.9 (806.2)
0.010	828.2 (824.9)	834.9 (832.2)	838.8 (836.5)	843.5 (841.6)
0.001	854.5 (850.9)	857.3 (854.5)	859.0 (856.6)	861.0 (859.1)

$T_c = 2588.9^\circ K$

P_e	$P_c = 300$ psi	$P_c = 500$ psi	$P_c = 700$ psi	$P_c = 1100$ psi
1.000	697.4 (691.8)	731.8 (727.0)	751.1 (746.9)	773.8 (770.3)
0.333	767.4 (760.7)	790.2 (784.6)	803.1 (798.2)	818.3 (814.3)
0.100	819.1 (811.5)	833.6 (827.5)	841.9 (836.6)	851.8 (847.5)
0.010	876.1 (867.6)	882.0 (875.3)	885.5 (879.7)	889.8 (885.1)
0.001	904.3 (895.2)	906.1 (898.9)	907.2 (901.1)	908.6 (903.7)

$T_c = 2866.5^\circ K$

P_e	$P_c = 300$ psi	$P_c = 500$ psi	$P_c = 700$ psi	$P_c = 1100$ psi
1.000	745.7 (732.1)	781.1 (769.2)	800.9 (790.2)	824.0 (814.8)
0.333	822.3 (805.6)	844.6 (830.6)	857.4 (845.0)	872.3 (862.0)
0.100	879.1 (859.9)	892.1 (876.5)	899.7 (886.1)	908.7 (897.5)
0.010	941.8 (919.7)	945.1 (927.5)	947.2 (932.1)	949.9 (937.7)
0.001	972.9 (949.1)	971.5 (952.8)	970.9 (955.0)	970.4 (957.6)

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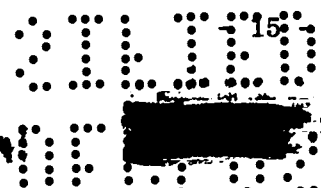




TABLE 4.2

SPECIFIC IMPULSES OF 99 v/o H₂ - 1 v/o CH₄ $T_c = 2200.0^\circ\text{K}$

P_e	$P_c = 300$ psi	$P_c = 500$ psi	$P_c = 700$ psi	$P_c = 1100$ psi
1.000	619.4 (615.5)	649.5 (646.4)	666.4 (663.9)	686.0 (684.3)
0.333	681.2 (676.4)	700.9 (697.2)	711.9 (709.1)	725.0 (723.2)
0.100	726.6 (721.1)	739.1 (735.0)	746.1 (743.0)	754.6 (752.6)
0.010	777.0 (770.7)	781.9 (777.4)	784.6 (781.2)	788.0 (785.8)
0.001	801.8 (795.1)	802.9 (798.2)	803.5 (800.0)	804.4 (802.2)

 $T_c = 2366.5^\circ\text{K}$

P_e	$P_c = 300$ psi	$P_c = 500$ psi	$P_c = 700$ psi	$P_c = 1100$ psi
1.000	646.2 (640.5)	678.1 (672.9)	695.8 (691.1)	716.2 (712.5)
0.333	711.4 (704.3)	732.4 (726.1)	744.0 (738.6)	757.4 (753.2)
0.100	759.4 (751.1)	772.8 (765.7)	780.1 (774.1)	788.6 (784.0)
0.010	812.6 (803.0)	818.0 (810.0)	820.8 (814.1)	823.9 (818.9)
0.001	838.9 (828.6)	840.4 (831.9)	840.9 (833.8)	841.3 (836.1)

 $T_c = 2588.9^\circ\text{K}$

P_e	$P_c = 300$ psi	$P_c = 500$ psi	$P_c = 700$ psi	$P_c = 1100$ psi
1.000	681.2 (672.8)	715.3 (707.0)	734.2 (726.3)	756.0 (748.8)
0.333	751.0 (740.1)	773.5 (763.4)	785.9 (776.6)	800.3 (792.1)
0.100	802.8 (789.9)	816.9 (805.3)	824.7 (814.2)	833.7 (824.7)
0.010	860.1 (844.8)	865.5 (852.3)	868.4 (856.6)	871.6 (861.7)
0.001	888.4 (872.0)	889.6 (875.5)	890.1 (877.6)	890.4 (880.0)

 $T_c = 2866.5^\circ\text{K}$

P_e	$P_c = 300$ psi	$P_c = 500$ psi	$P_c = 700$ psi	$P_c = 1100$ psi
1.000	727.3 (712.1)	762.5 (748.3)	782.4 (768.7)	805.3 (792.6)
0.333	803.4 (783.9)	826.0 (808.3)	838.7 (822.4)	853.5 (838.9)
0.100	860.4 (837.0)	873.7 (853.3)	881.3 (862.6)	890.0 (873.7)
0.010	923.6 (895.6)	927.0 (903.3)	929.1 (907.8)	931.4 (913.2)
0.001	955.0 (924.6)	953.7 (928.2)	952.9 (930.3)	952.1 (932.8)




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TABLE 4.3

SPECIFIC IMPULSES OF 97 v/o H₂ - 3 v/o CH₄

T_c = 2200.0°K

P _e	P _c = 300 psi	P _c = 500 psi	P _c = 700 psi	P _c = 1100 psi
1.000	590.9 (586.2)	621.4 (615.5)	638.0 (631.9)	656.2 (650.5)
0.333	652.0 (644.8)	672.2 (664.5)	683.0 (675.5)	694.6 (688.1)
0.100	697.1 (687.9)	710.1 (701.0)	716.9 (708.3)	723.8 (716.6)
0.010	747.4 (735.8)	752.7 (742.0)	755.2 (745.3)	756.9 (748.8)
0.001	772.2 (759.5)	773.9 (762.3)	774.1 (763.6)	773.2 (764.8)

T_c = 2366.5°K

P _e	P _c = 300 psi	P _c = 500 psi	P _c = 700 psi	P _c = 1100 psi
1.000	617.1 (609.8)	649.3 (640.6)	667.2 (657.9)	687.5 (677.8)
0.333	681.3 (671.1)	703.2 (691.9)	715.1 (703.6)	728.4 (717.1)
0.100	729.5 (716.2)	743.6 (730.1)	751.2 (738.0)	759.4 (747.0)
0.010	783.0 (766.4)	788.9 (773.0)	792.0 (776.7)	794.7 (780.8)
0.001	809.5 (791.3)	811.5 (794.3)	812.2 (796.0)	812.3 (797.6)

T_c = 2588.9°K

P _e	P _c = 300 psi	P _c = 500 psi	P _c = 700 psi	P _c = 1100 psi
1.000	654.2 (640.3)	687.1 (673.0)	705.8 (691.4)	727.4 (712.8)
0.333	722.4 (704.9)	745.1 (727.2)	757.8 (739.8)	771.8 (754.5)
0.100	774.7 (752.8)	789.2 (767.6)	797.0 (776.1)	805.5 (786.1)
0.010	833.3 (805.9)	838.7 (813.1)	841.4 (817.2)	843.9 (822.0)
0.001	862.4 (832.3)	863.4 (835.7)	863.6 (837.6)	863.1 (839.8)

T_c = 2866.5°K

P _e	P _c = 300 psi	P _c = 500 psi	P _c = 700 psi	P _c = 1100 psi
1.000	696.8 (677.8)	731.2 (712.4)	750.5 (732.0)	773.2 (754.9)
0.333	771.0 (746.7)	793.3 (770.1)	806.5 (783.6)	821.9 (799.4)
0.100	827.2 (797.8)	841.7 (813.5)	849.8 (822.5)	859.0 (833.1)
0.010	892.2 (854.5)	896.4 (861.9)	898.7 (866.3)	901.2 (871.4)
0.001	924.7 (882.6)	923.9 (886.1)	923.3 (888.1)	922.5 (890.5)


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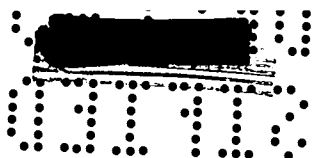


TABLE 4.4

SPECIFIC IMPULSES OF 95 v/o H₂ - 5 v/o CH₄

$$T_c = 2200.0^\circ\text{K}$$

P_e	$P_c = 300$ psi	$P_c = 500$ psi	$P_c = 700$ psi	$P_c = 1100$ psi
1.000	566.2 (562.0)	596.5 (590.3)	613.4 (606.1)	632.2 (624.1)
0.333	626.2 (618.5)	647.1 (637.6)	658.3 (648.3)	670.4 (660.5)
0.100	671.6 (660.3)	685.1 (673.0)	692.3 (680.2)	699.5 (688.2)
0.010	722.3 (707.0)	728.1 (713.0)	730.7 (716.2)	732.8 (719.7)
0.001	747.6 (730.1)	749.4 (732.8)	749.9 (734.1)	749.3 (735.3)

$$T_c = 2366.5^\circ\text{K}$$

P_e	$P_c = 300$ psi	$P_c = 500$ psi	$P_c = 700$ psi	$P_c = 1100$ psi
1.000	591.4 (584.6)	622.3 (614.3)	640.3 (631.0)	661.0 (650.3)
0.333	653.4 (643.7)	675.8 (663.9)	688.1 (675.2)	701.9 (688.4)
0.100	701.7 (687.5)	716.4 (701.0)	724.4 (708.6)	733.0 (717.4)
0.010	755.9 (736.3)	762.2 (742.8)	765.5 (746.4)	768.6 (750.4)
0.001	782.9 (760.7)	785.2 (763.7)	786.1 (765.3)	786.3 (766.9)

$$T_c = 2588.9^\circ\text{K}$$

P_e	$P_c = 300$ psi	$P_c = 500$ psi	$P_c = 700$ psi	$P_c = 1100$ psi
1.000	628.2 (613.6)	660.4 (645.1)	678.8 (662.8)	700.9 (683.4)
0.333	694.1 (676.0)	716.7 (697.5)	730.1 (709.6)	745.6 (723.8)
0.100	745.4 (722.4)	761.2 (736.8)	769.9 (745.0)	779.8 (754.5)
0.010	805.1 (774.1)	811.6 (781.1)	815.2 (785.0)	818.9 (789.5)
0.001	835.0 (800.0)	837.0 (803.2)	837.9 (805.0)	838.5 (806.9)

$$T_c = 2866.5^\circ\text{K}$$

P_e	$P_c = 300$ psi	$P_c = 500$ psi	$P_c = 700$ psi	$P_c = 1100$ psi
1.000	671.9 (649.3)	705.6 (682.7)	724.4 (701.5)	746.4 (723.6)
0.333	744.4 (715.8)	766.3 (738.4)	779.0 (751.5)	794.6 (766.7)
0.100	799.3 (765.3)	814.0 (780.4)	822.8 (789.2)	832.7 (799.5)
0.010	865.6 (820.4)	870.6 (827.6)	873.4 (831.8)	876.3 (836.8)
0.001	899.5 (847.8)	899.2 (851.2)	899.0 (853.2)	898.3 (855.5)

TABLE 4.5

SPECIFIC IMPULSES OF 90 v/o H₂ - 10 v/o CH₄

$$T_c = 2200.0^\circ\text{K}$$

P_e	$P_c = 300$ psi	$P_c = 500$ psi	$P_c = 700$ psi	$P_c = 1100$ psi
1.000	519.3 (515.8)	547.3 (542.2)	563.5 (556.9)	583.1 (573.9)
0.333	575.0 (568.6)	596.0 (586.6)	608.4 (596.6)	621.9 (608.2)
0.100	620.1 (608.0)	635.2 (620.0)	643.3 (626.8)	651.9 (634.5)
0.010	573.4 (652.3)	680.2 (658.0)	683.5 (661.2)	686.5 (664.6)
0.001	700.3 (674.5)	702.9 (677.1)	703.9 (678.4)	703.9 (679.6)

$$T_c = 2366.5^\circ\text{K}$$

P_e	$P_c = 300$ psi	$P_c = 500$ psi	$P_c = 700$ psi	$P_c = 1100$ psi
1.000	542.3 (536.5)	571.0 (564.2)	587.6 (579.8)	607.6 (597.9)
0.333	599.8 (591.6)	620.8 (610.6)	633.5 (621.4)	648.7 (633.8)
0.100	645.7 (632.9)	661.9 (645.7)	671.0 (653.0)	681.0 (661.3)
0.010	702.7 (679.4)	710.3 (685.6)	714.2 (689.0)	718.2 (692.9)
0.001	731.8 (702.7)	734.9 (705.6)	736.2 (707.2)	737.1 (708.8)

$$T_c = 2588.9^\circ\text{K}$$

P_e	$P_c = 300$ psi	$P_c = 500$ psi	$P_c = 700$ psi	$P_c = 1100$ psi
1.000	575.8 (563.1)	605.7 (592.4)	622.8 (609.0)	643.3 (628.2)
0.333	637.1 (621.3)	658.0 (641.5)	670.5 (652.9)	686.0 (666.3)
0.100	684.8 (665.0)	700.3 (678.6)	710.0 (686.4)	721.4 (695.5)
0.010	745.6 (714.2)	753.6 (720.8)	757.9 (724.6)	762.7 (729.0)
0.001	778.0 (739.0)	781.0 (742.4)	782.5 (743.9)	783.8 (745.9)

$$T_c = 2866.5^\circ\text{K}$$

P_e	$P_c = 300$ psi	$P_c = 500$ psi	$P_c = 700$ psi	$P_c = 1100$ psi
1.000	622.9 (595.3)	655.4 (626.2)	673.7 (643.7)	695.1 (664.3)
0.333	691.9 (657.2)	713.3 (678.3)	725.5 (690.5)	740.7 (704.8)
0.100	744.3 (703.7)	758.4 (717.9)	767.1 (726.1)	778.2 (735.8)
0.010	808.6 (755.9)	816.5 (762.8)	820.9 (766.8)	825.9 (771.4)
0.001	847.5 (782.2)	848.7 (785.5)	849.7 (787.3)	850.6 (789.5)

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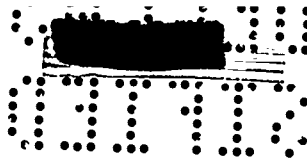


TABLE 4.6

SPECIFIC IMPULSES OF PURE HYDROGEN AT 700 PSI

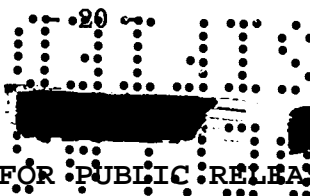
P_e	$T_c = 2673^\circ\text{K}$		$T_c = 2773^\circ\text{K}$		$T_c = 2873^\circ\text{K}$	
1.000	765.9	(760.1)	783.7	(775.7)	802.1	(791.2)
0.333	819.1	(812.5)	838.6	(829.4)	858.7	(846.1)
0.100	858.9	(851.8)	879.7	(869.6)	901.1	(887.3)
0.010	903.7	(895.8)	925.8	(914.6)	948.7	(933.3)
0.001	925.9	(917.6)	948.8	(937.0)	972.5	(956.2)

P_e	$T_c = 2973^\circ\text{K}$		$T_c = 3073^\circ\text{K}$		$T_c = 3173^\circ\text{K}$	
1.000	821.1	(806.6)	840.7	(822.0)	861.2	(837.5)
0.333	879.4	(862.8)	901.1	(879.3)	923.8	(895.9)
0.100	923.3	(904.8)	946.6	(922.3)	971.0	(939.8)
0.010	972.6	(951.9)	997.6	(970.4)	1024.0	(988.8)
0.001	997.2	(975.3)	1023.1	(994.3)	1050.5	(1013.1)

P_e	$T_c = 3273^\circ\text{K}$		$T_c = 3373^\circ\text{K}$		$T_c = 3473^\circ\text{K}$	
1.000	882.5	(853.1)	904.7	(868.8)	927.7	(884.8)
0.333	947.6	(912.6)	972.5	(929.5)	998.6	(946.6)
0.100	996.8	(957.4)	1023.9	(975.1)	1052.3	(992.9)
0.010	1051.9	(1007.3)	1081.5	(1025.8)	1112.9	(1044.4)
0.001	1079.5	(1032.0)	1110.4	(1050.8)	1143.2	(1069.8)

P_e	$T_c = 3573^\circ\text{K}$	
1.000	951.5	(901.1)
0.333	1025.8	(963.9)
0.100	1082.3	(1011.0)
0.010	1146.1	(1063.1)
0.001	1178.0	(1088.8)

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TABLE 4.7

SPECIFIC IMPULSES OF 99 v/o H₂ - 1 v/o CH₄ at 700 PSI

P _e	T _c = 2673°K		T _c = 2773°K		T _c = 2873°K	
1.000	748.6	(739.3)	765.9	(754.5)	783.5	(769.6)
0.333	801.7	(790.6)	820.7	(807.1)	840.0	(823.4)
0.100	841.6	(829.0)	861.8	(846.5)	882.6	(863.7)
0.010	886.4	(872.3)	908.2	(890.7)	930.5	(909.0)
0.001	908.8	(893.8)	931.3	(912.7)	954.5	(931.5)

P _e	T _c = 2973°K		T _c = 3073°K		T _c = 3173°K	
1.000	801.6	(784.7)	820.3	(799.8)	839.8	(814.8)
0.333	859.9	(839.7)	880.7	(855.8)	902.3	(872.0)
0.100	904.1	(880.9)	926.4	(898.0)	949.8	(915.0)
0.010	953.7	(927.1)	977.9	(945.2)	1003.3	(963.1)
0.001	978.5	(950.1)	1003.7	(968.6)	1030.1	(987.1)

P _e	T _c = 3273°K		T _c = 3373°K		T _c = 3473°K	
1.000	860.2	(830.0)	881.4	(845.3)	903.3	(860.9)
0.333	924.9	(888.3)	948.6	(904.7)	973.6	(921.3)
0.100	974.4	(932.1)	1000.2	(949.3)	1027.4	(966.7)
0.010	1030.2	(981.1)	1058.6	(999.2)	1088.7	(1017.3)
0.001	1058.2	(1005.4)	1087.9	(1023.8)	1119.4	(1042.4)

P _e	T _c = 3573°K	
1.000	926.0	(876.8)
0.333	999.6	(938.2)
0.100	1055.9	(984.3)
0.010	1120.6	(1035.5)
0.001	1153.0	(1060.8)

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TABLE 4.8

SPECIFIC IMPULSES OF 97 v/o H₂ - 3 v/o CH₄ at 700 PSI

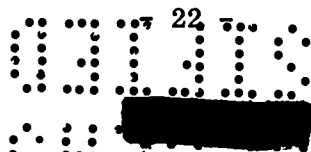
P_e	$T_c = 2673^\circ\text{K}$	$T_c = 2773^\circ\text{K}$	$T_c = 2873^\circ\text{K}$
1.000	719.2 (703.9)	735.2 (718.5)	751.5 (732.9)
0.333	772.4 (753.2)	789.9 (769.0)	807.6 (784.6)
0.100	812.9 (790.4)	831.8 (807.0)	851.0 (823.5)
0.010	858.6 (832.2)	879.2 (849.9)	900.1 (867.4)
0.001	881.5 (853.1)	902.9 (871.3)	924.8 (889.3)

P_e	$T_c = 2973^\circ\text{K}$	$T_c = 3073^\circ\text{K}$	$T_c = 3173^\circ\text{K}$
1.000	768.4 (747.3)	785.8 (761.6)	803.8 (776.0)
0.333	825.8 (800.2)	844.9 (815.5)	864.9 (830.9)
0.100	870.8 (939.9)	891.3 (856.2)	912.7 (872.5)
0.010	921.7 (884.7)	944.2 (901.9)	967.8 (919.1)
0.001	947.3 (907.1)	970.9 (924.8)	995.6 (942.4)

P_e	$T_c = 3273^\circ\text{K}$	$T_c = 3373^\circ\text{K}$	$T_c = 3473^\circ\text{K}$
1.000	822.6 (790.4)	842.1 (805.0)	862.3 (819.9)
0.333	885.9 (846.4)	908.0 (862.1)	931.1 (877.9)
0.100	935.0 (888.8)	958.7 (905.2)	983.9 (921.8)
0.010	992.6 (936.3)	1018.9 (953.5)	1046.7 (970.8)
0.001	1021.7 (959.9)	1049.4 (977.5)	1078.7 (995.1)

P_e	$T_c = 3573^\circ\text{K}$
1.000	883.2 (835.0)
0.333	955.2 (894.0)
0.100	1010.5 (938.5)
0.010	1076.0 (988.2)
0.001	1109.9 (1012.8)

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TABLE 4.9

SPECIFIC IMPULSES OF 95 v/o H₂ - 5 v/o CH₄ at 700 PSI

P _e	T _c = 2673°K		T _c = 2773°K		T _c = 2873°K	
1.000	694.8	(674.5)	710.0	(688.5)	725.4	(702.4)
0.333	747.2	(722.2)	763.5	(737.4)	780.1	(752.5)
0.100	788.5	(758.3)	806.2	(774.3)	823.9	(790.2)
0.010	835.6	(799.1)	855.0	(816.1)	874.7	(832.9)
0.001	859.3	(819.5)	879.7	(837.0)	900.3	(854.3)

P _e	T _c = 2973°K		T _c = 3073°K		T _c = 3173°K	
1.000	741.2	(716.2)	757.5	(729.9)	774.3	(743.7)
0.333	797.4	(767.2)	815.4	(782.0)	834.2	(796.8)
0.100	842.1	(805.9)	861.0	(821.5)	880.9	(837.2)
0.010	894.9	(849.5)	915.9	(866.1)	937.8	(882.6)
0.001	921.6	(871.4)	943.7	(888.4)	966.9	(905.3)

P _e	T _c = 3273°K		T _c = 3373°K		T _c = 3473°K	
1.000	791.7	(757.5)	809.8	(771.5)	828.6	(785.7)
0.333	853.9	(811.7)	874.5	(826.7)	896.1	(841.9)
0.100	902.0	(852.8)	924.4	(868.5)	948.1	(884.4)
0.010	960.9	(899.1)	985.3	(915.6)	1011.0	(932.2)
0.001	991.4	(922.2)	1017.3	(939.1)	1044.8	(956.0)

P _e	T _c = 3573°K	
1.000	847.9	(800.2)
0.333	918.6	(857.3)
0.100	973.1	(900.5)
0.010	1038.2	(948.9)
0.001	1073.9	(972.9)

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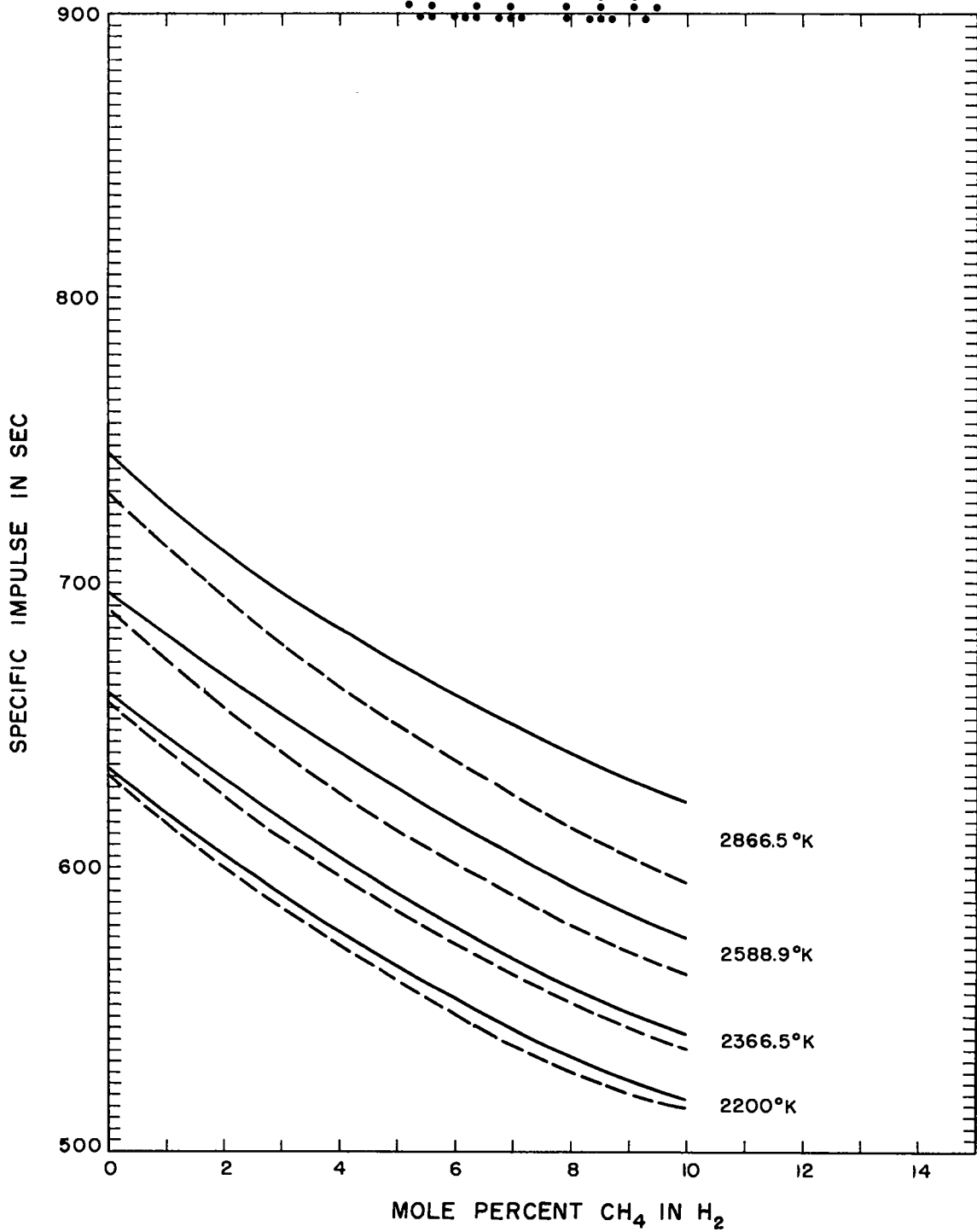


Fig. 4.1 Variation of specific impulse with temperature and propellant composition at 300 psi chamber pressure.

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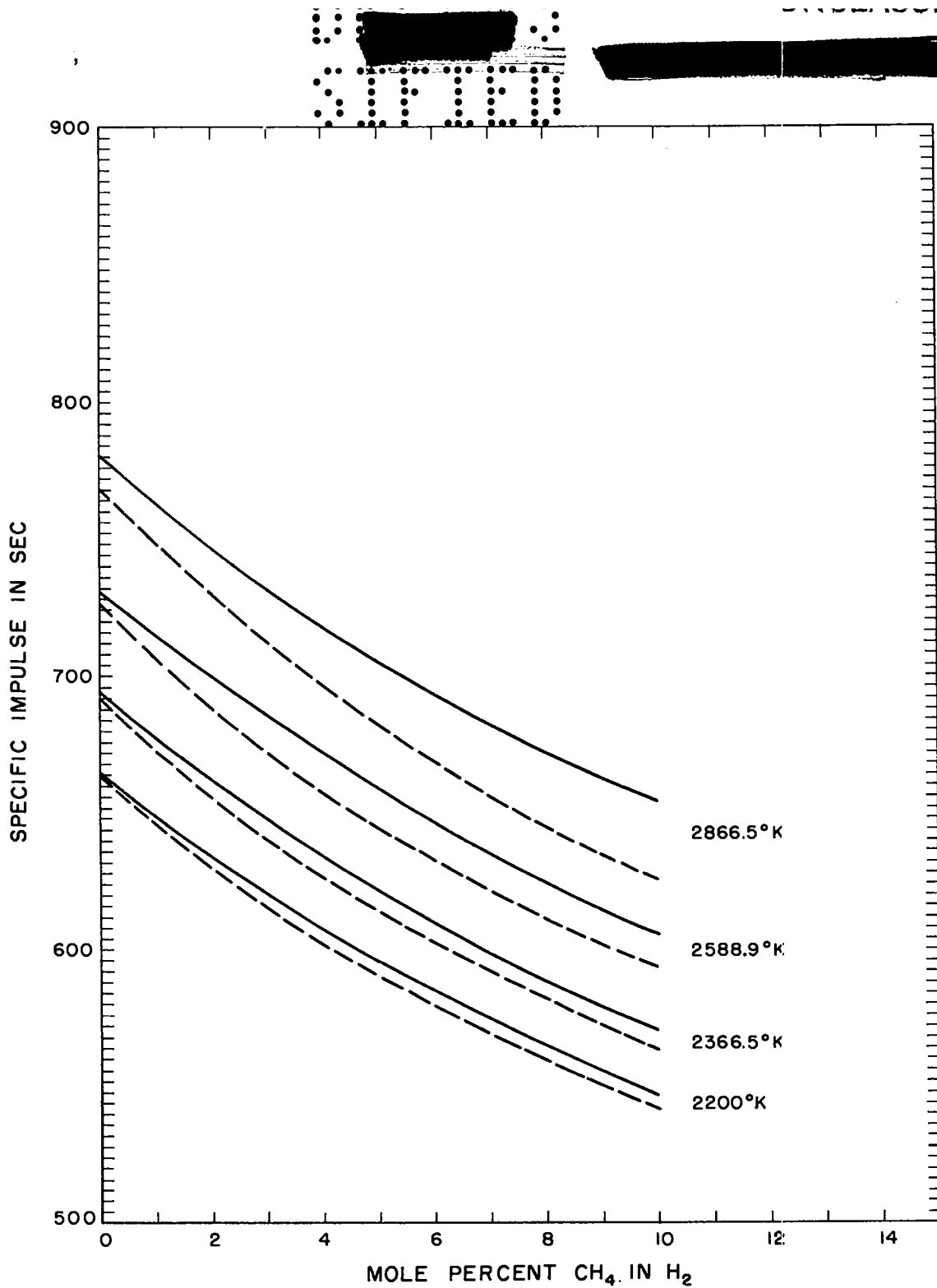


Fig. 4.2 Variation of specific impulse with temperature and propellant composition at 500 psi chamber pressure.

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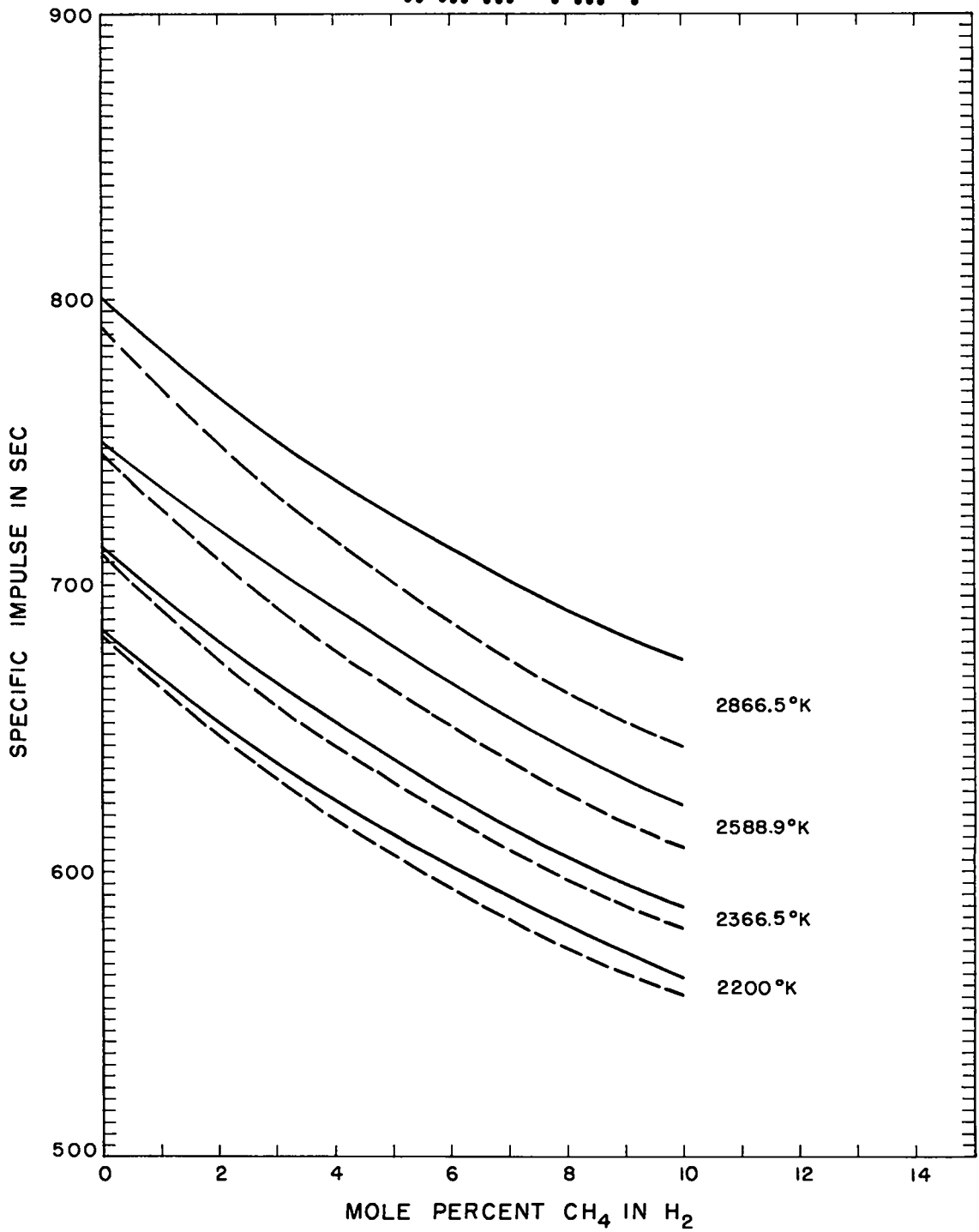


Fig. 4.3 Variation of specific impulse with temperature and propellant composition at 700 psi chamber pressure.

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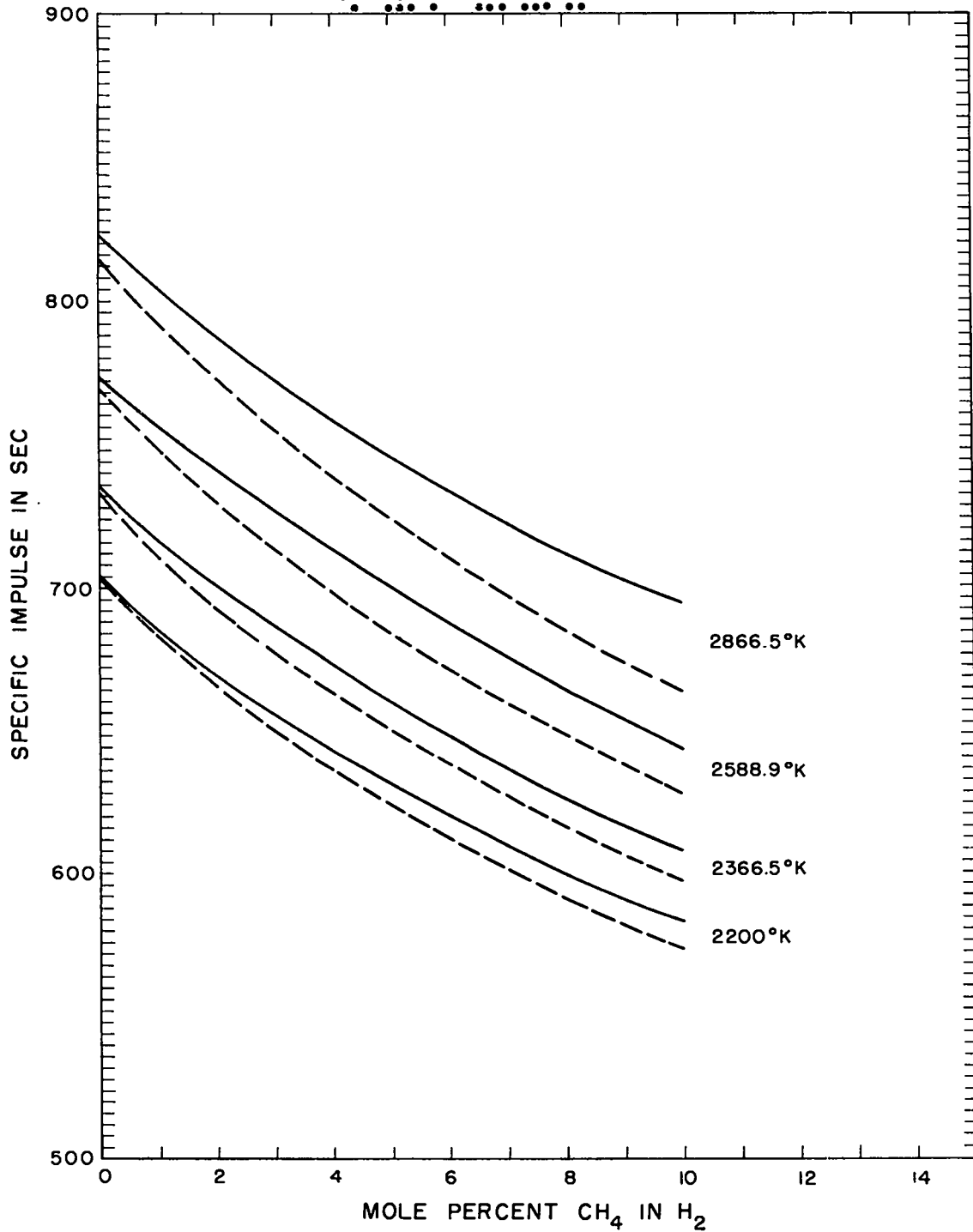


Fig. 4.4 Variation of specific impulse with temperature and propellant composition at 1100 psi chamber pressure.

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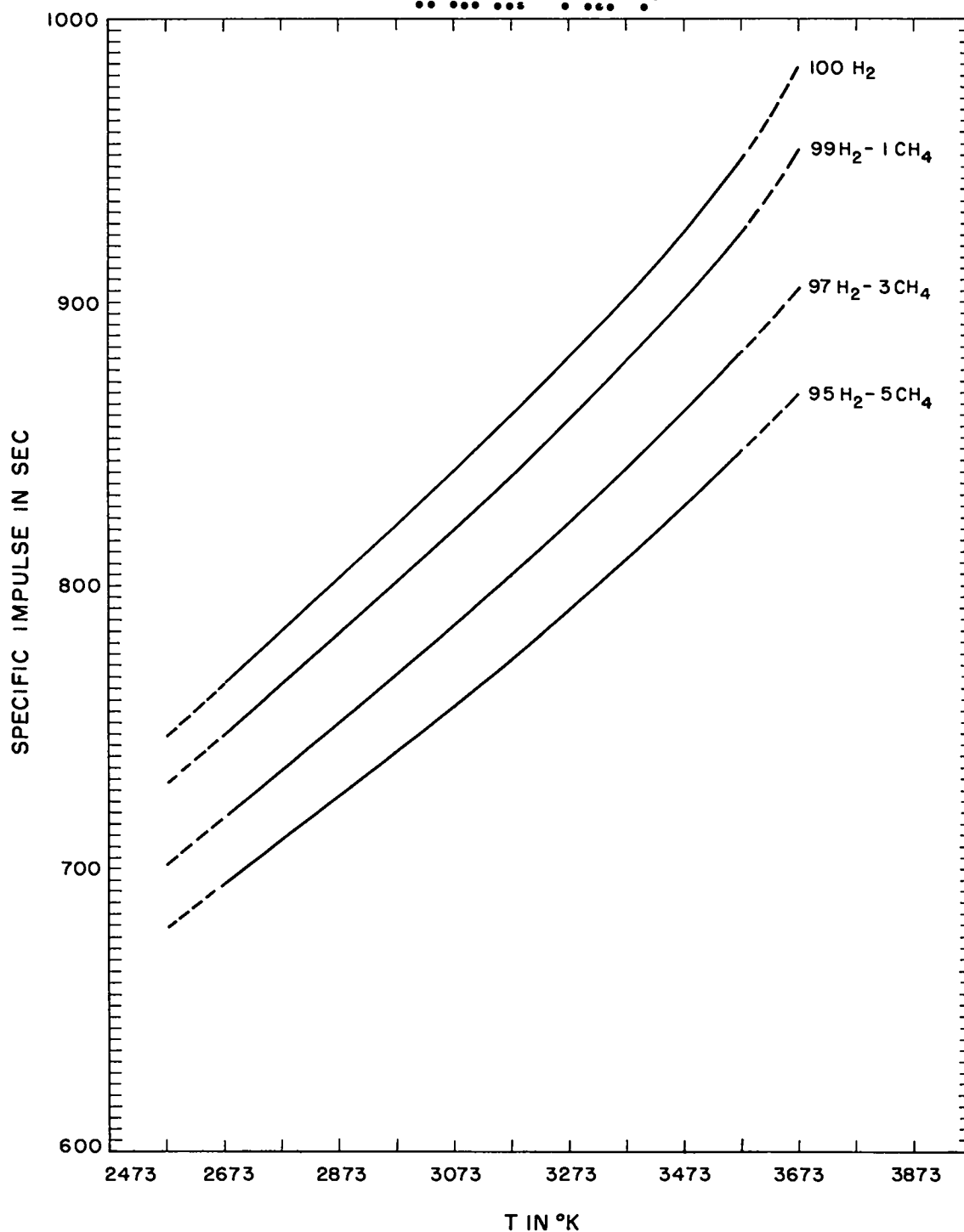


Fig. 4.5 Dependence of specific impulse upon chamber temperature at 700 psi for case of shifting equilibrium.

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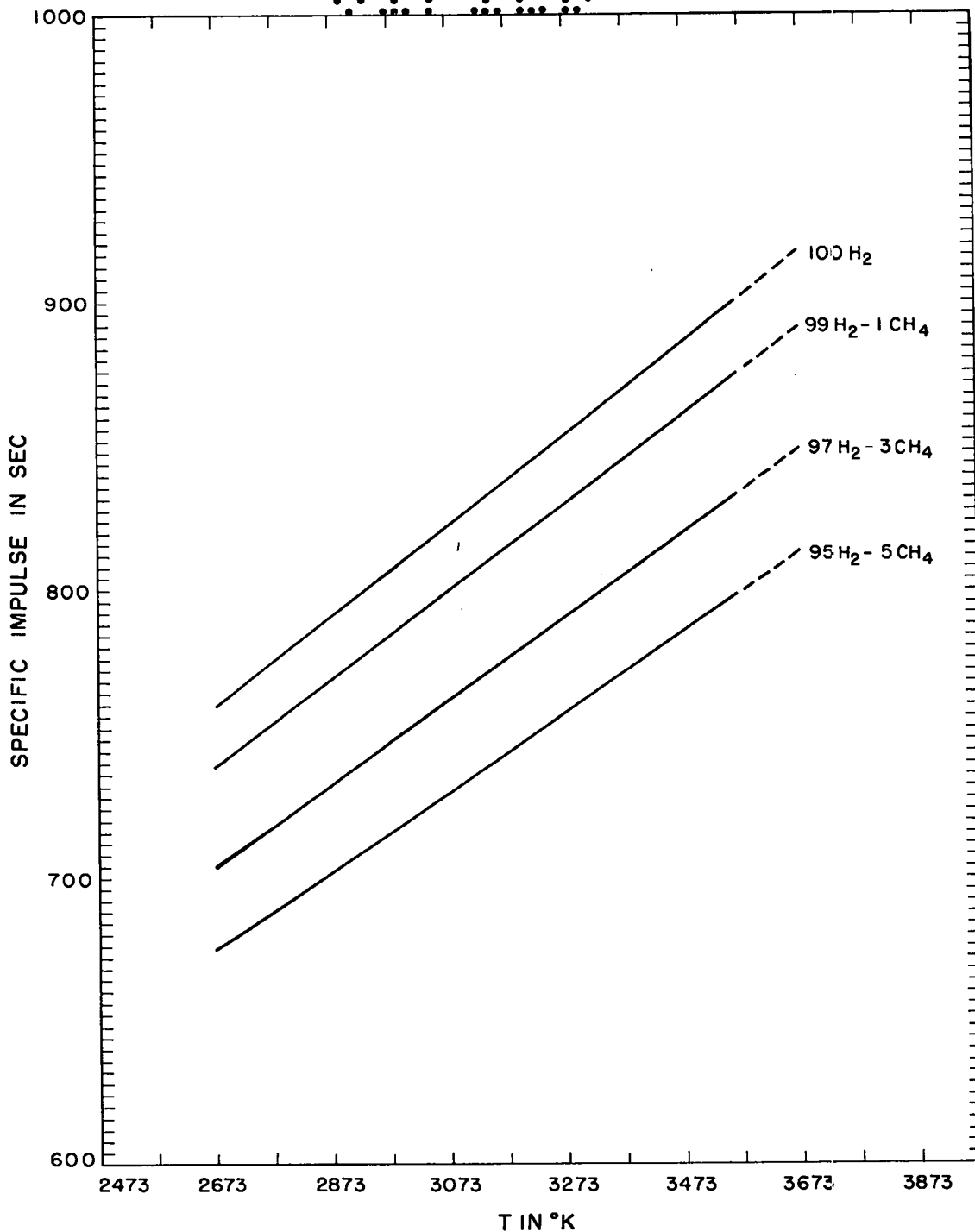
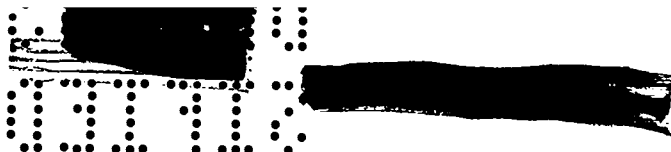


Fig. 4.6 Dependence of specific impulse upon chamber temperature at 700 psi for case of frozen equilibrium.

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5. DISCUSSION

Since the specific impulse of a propellant improves as the temperature, T , is increased and as the mean molecular weight, \bar{M} , of the propellant is decreased, in accordance with the following naive relation

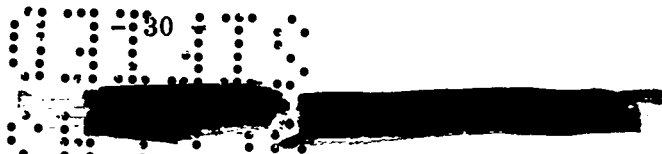
$$I_{sp} = k \sqrt{\frac{T}{M}}, \quad (5.1)$$

it is obvious that the addition of methane to hydrogen will reduce the specific impulse of the propellant system by increasing the mean molecular weight of propellant system. On the other hand, the safe operating temperature of a graphite reactor and probably also of a carbide reactor can be increased as the propellant is changed from pure hydrogen to hydrogen-methane mixtures with higher and higher methane contents.

Experimentally, the upper limit of the methane mole fraction seems to be about 0.05 due to the onset of heavy carbon deposition in the cooler regions of the cylindrical graphite specimens used in LASL tests. These specimens are approximately 3/8 inch OD, 1/16 inch ID, and 30 inches long. However, the deleterious effects of carbon deposition which have been observed to date may not be as serious in specimens with a smaller surface-to-volume ratio. If one accepts the 0.05 mole fraction as an approximate upper limit for the methane content of the propellant, he then is faced with the problem of optimizing the specific impulse of the propellant system within the range of propellant composition 100 v/o H_2 to 95 v/o H_2 - 5 v/o CH_4 . If a reliable experimental correlation between permissible propellant temperature and the methane content of the propellant were available, one could use the data contained in this report to perform this optimization for graphite reactors. In the absence of a complete correlation, these data still are useful as a guide to higher propellant performance.

The following facts are self-evident from the data in Tables 4.1 to 4.9:

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- (1) For a given propellant composition and gas temperature, the specific impulse at 1 atmosphere exhaust pressure will be higher as the initial pressure within the reactor is increased. At 10^{-3} atmosphere exhaust pressure the specific impulse is almost independent of the initial pressure.
- (2) If the propellant composition and reactor pressure are fixed, the specific impulse increases with increasing gas temperature.
- (3) At a given initial gas temperature and pressure, the specific impulse is highest for pure hydrogen and lowest for the hydrogen-methane mixture containing the most methane. The difference between the specific impulse of hydrogen and that of the mixture is proportional to the amount of methane in the mixture.
- (4) Starting at the same initial conditions, the specific impulse can be increased by expanding to lower exhaust pressures.
- (5) The specific impulses computed for the case of shifting equilibrium are higher than those for the case of frozen equilibrium; the difference between these two specific impulses increases as the initial gas temperature is raised for a given propellant composition and as the methane content is increased.

The preceding statements lead to the following obvious methods of improving the performance of rockets having a hydrogen-methane propellant mixture.

- (1) Increase the reactor temperature and hence the propellant temperature.
- (2) Decrease the methane content of the propellant for a given gas temperature.
- (3) Design a variable area ratio nozzle to permit expansion of the propellant to lower exhaust pressures as the ambient pressure drops during the period of powered flight.

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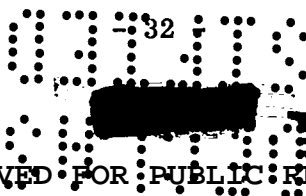
Means of accomplishing these aims will be discussed briefly.

If one is in the position of having to use a hydrogen-based propellant system, he would prefer to get by with as little methane in the propellant as possible, preferably none, on the basis of the values for the dependence of the specific impulse upon the methane content of the propellant. With a bare graphite reactor, the specific impulse attainable experimentally when some methane is added to the hydrogen in order to get higher gas temperatures without corrosion of the graphite by the propellant is higher than it would be with pure hydrogen at a temperature low enough to avoid corrosion of the graphite by the hydrogen. The following two approaches to solving this problem are suggested for nonmetallic reactors.

The graphite can be protected by a coating which is inert to hydrogen at present gas temperatures (2273°K to 2473°K) or which will permit even higher gas temperatures with or without a decrease in the methane content of the propellant. Refractory carbide coatings such as NbC or TaC appear to offer a possibility of reducing the methane content of the propellant while maintaining or raising the present gas temperature. Laboratory tests have been made at LASL upon NbC-coated graphite with a 99 v/o H₂ - 1 v/o CH₄ propellant mixture at a gas temperature of 2773°K; no sign of attack upon the graphite was evident. The specific impulse of this propellant mixture at the test conditions is 820 seconds while the specific impulse of the 97 v/o H₂ - 3 v/o CH₄ propellant mixture at a temperature of 2453°K is only 705 seconds.

The same effect can be accomplished by designing a carbide reactor as an advanced replacement for the graphite reactors now under consideration. Based upon material tests carried out on the NEPA project and upon thermodynamic calculations, these carbide reactors would be capable of operating with hydrogen or with hydrogen containing only a small amount of

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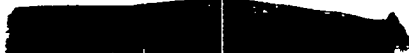


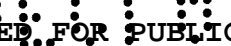
methane at gas temperatures in the neighborhood of 3273°K, provided that the uranium can be retained within the fuel element. A solid solution of either ZrC-UC₂ or TaC-UC₂ would have a high enough melting point in the UC₂-poor portion of the phase diagram to attain these temperatures if the reactor is able to go critical with the uranium loadings to which the high melting portions of the phase diagrams are restricted. Criticality calculations are being performed to determine the required uranium loadings for the two types of carbide fuel elements mentioned above. A limited number of experiments should then be carried out to ascertain the maximum temperatures at which uranium is retained in the two fuel element materials. If the retention of the uranium at sufficiently high temperatures is demonstrated, the design of a carbide reactor should be considered. A pebble bed design would probably be capable of withstanding temperature cycling if the testing program required such cycling; if this capability is not necessary, tubular carbide fuel elements within structural graphite members may be feasible.

The variable area ratio nozzle appears to be feasible in nuclear rockets; two methods of attack are deemed possible. The most straightforward proposal would be for a nozzle with a detachable false liner extending from the vicinity of the throat to the exit end of the nozzle. This liner should be so contoured that the effective area ratio of the nozzle would be approximately 5.5:1 with the liner in position; the area ratio would be of the order of 25:1 for the true nozzle based upon present ideas about the dimensions of a nuclear rocket with a hydrogen-methane propellant system. The liner should be mechanically attached to the main nozzle structure in such a way that it would be capable of detachment in flight when the ambient pressure was of the order of 10⁻¹ to 10⁻² atmosphere.

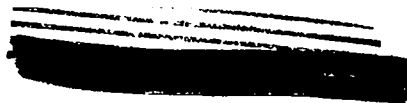
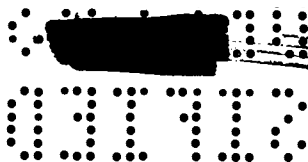
The same goal also might be attained by designing a continuously variable area ratio nozzle although this would seem to be a more difficult







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task. This could be accomplished by using a liner material which would sublime away at a predetermined rate or which would be corroded by the effluent propellant at a known rate. Programming the thrust of a rocket with a continuously variable area ratio probably would be extremely difficult and might force one to accept the slightly lower performance of a nozzle whose area ratio was changed only once but whose performance characteristics were known. Figure 5.1 schematically represents this nozzle concept.

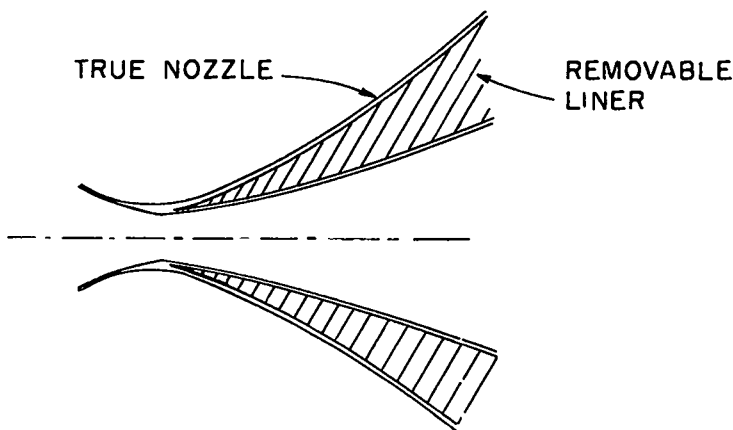


Fig. 5.1 Concept of a variable area ratio nozzle

Since there is a practical limit to the maximum nozzle exit area if the diameter of the nozzle is not to exceed that of the missile, it will be necessary to use a different scheme to attain optimum nozzle performance at high altitudes. It seems feasible to increase the nozzle diameter when the rocket has reached high altitudes by mechanically extending a cowling beyond the rear of the original nozzle. This cowling could be constructed of several overlapping longitudinal sections to permit the downstream end of the cowling to have a larger diameter in the extended position than the upstream end.

A 25:1 nozzle would give optimum performance at about 0.1 atmosphere

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ambient pressure (55,000 feet); if the extension of the cowling were initiated at this pressure, the cowling would not have a greater diameter than the missile until the altitude reached approximately 115,000 feet. At this altitude the density of the ambient air would be about 10^{-2} of the sea level density and the resultant increased cross-sectional area of the nozzle would not appreciably affect the drag of the missile. At 170,000 foot altitude the ambient air density would be 10^{-3} of the sea level density; the nozzle diameter would now be about 2.3 as large as the missile diameter. The decrease in the air density should more than compensate for the drag increase associated with the increase in the nozzle area, and therefore it should not be particularly detrimental to the missile performance to have a nozzle with a larger diameter than the missile. The difference between the optimum thrust at 10^{-3} atmosphere and the thrust into a vacuum is about 3500 pounds per second; if the nozzle diameter could be increased to give optimum performance at 10^{-4} atmosphere, this difference would decrease to about 900 pounds per second. It therefore seems unlikely that any worthwhile gain could be achieved by increasing the nozzle diameter more than a factor of five over the missile diameter.

The actual permissible increase in the nozzle diameter would depend upon the weight increase associated with any given increase in the diameter. The temperature of the propellant will be sufficiently low at ambient pressures below 0.1 atmosphere to permit fiberglass reinforced plastic to be used as the cowling material. Since its density is of the order of 1, a cowling constructed of fiberglass reinforced plastic would weigh about 2600 pounds if it were 0.5 inch thick and had a maximum diameter of 46 feet. This extra weight is quite permissible since the extra thrust would be of the order of 5,000,000 pounds for the total flight.

The concept of a variable area ratio nozzle is not original but it is presented here since it offers the possibility of raising the specific impulse

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of a nuclear rocket with a hydrogen-methane propellant system by about 3 to 5% without a major breakthrough in the "state of the art".

The data in Tables 4.6 and 4.7 indicate that specific impulses of 900 or 1000 seconds are not a figment of the imagination for nuclear rockets with hydrogen-methane propellant systems. It would be possible to attain a specific impulse of 900 seconds with hydrogen at a gas temperature of 3373°K or with 99 v/o H₂ - 1 v/o CH₄ at a temperature of 3473°K. To achieve the I_{sp} of 1000, it would be necessary to raise the gas temperatures of the two propellant systems to 3700°K and 3800°K, respectively. If the final exhaust pressure were 0.1 atmosphere instead of 1 atmosphere, specific impulses of 900 seconds would be attainable at gas temperatures which would be 400° lower than those reported above while a specific impulse of 1000 seconds would be possible at gas temperatures 450° lower than the previously mentioned values. All these specific impulse values are based upon shifting equilibrium since it appears from statements in the open literature that shift-equilibrium does indeed occur in hydrogen-rich propellant systems.

In conclusion, it is thought that a substantial increase in the specific impulse of a hydrogen-based nuclear propellant system can be attained as a result of present know-how and does not require a major breakthrough for its accomplishment.

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3. S. R. Brinkley, Jr., J. Chem. Phys. 14, 563 (1946); 15, 107 (1947).

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