NASA TECHNICAL NOTE

NASA TN D-2080

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NASA TN D-2080

COMPILATION OF THEORETICAL ROCKET PERFORMANCE FOR THE CHEMICALLY FROZEN EXPANSION OF HYDROGEN

by Ernie W. Spisz

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • DECEMBER 1963

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SUMMARY

Theoretical performance data are presented for the isentropic expansion of hydrogen through a converging-diverging nozzle with the composition chemically frozen at stagnation conditions. The performance data presented are weight fraction of molecular hydrogen dissociated, flow rate per unit throat area per unit stagnation pressure, specific impulse, power requirements, and efficiency. The ranges of stagnation temperature and pressure considered are 2000° to 5000° K and 0.1 to 500 pounds per square inch absolute, respectively, for nozzle area ratios from 5 to ∞. The data are presented primarily in tabular form with a limited number of figures to illustrate graphical presentations that have been found to be useful.

INTRODUCTION

Hydrogen has been established as one of the most suitable propellants for nuclear and electrothermal space-propulsion devices. For these devices, the advantages of hydrogen are high heat capacity and the corresponding ability to store adequate thermal energy to achieve specific impulse levels of 1000 seconds at temperatures below the melting point of available refractory materials. This characteristic somewhat simplifies the design of the units by eliminating the need for separate cooling systems and makes possible operation at overall efficiencies that are compatible with certain space-mission applications.

Hydrogen, however, begins to dissociate at temperatures at which its application for space-propulsion purposes just begins to have merit. With respect to efficiency, dissociation is significant because of the energy required and the questionable conversion of this energy into directed kinetic energy for propulsion purposes. If the expansion of hydrogen through the exhaust nozzle proceeds with thermochemical equilibrium so that the dissociation energy is converted into directed kinetic energy, dissociation is desirable and should be promoted to obtain the maximum performance attainable at a given temperature level. If the expansion process proceeds in a chemically frozen manner, however, so that the dissociated energy is not converted into kinetic energy, dissociation represents an inefficiency mechanism in the thermodynamic cycle and should be suppressed.

At the present time, it has not been definitely established whether the expansion process for hydrogen for the conditions and nozzle geometries presently being used proceeds in a frozen or an equilibrium manner. The calculated performance data of reference 1 and the experimental data of reference 2 indicate that the expansion process is probably more frozen than in equilibrium. Much more experimental data, however, are required to conclusively establish the degree to which the expansion process of hydrogen departs from chemically frozen conditions. At the present, it is generally accepted that equilibrium expansion represents the maximum performance level attainable, while frozen expansion represents the minimum level for uniform flows.

Some literature is available on the equilibrium performance characteristics of hydrogen (e.g., ref. 3). Very little data are available, however, on the frozen expansion of hydrogen that can be used conveniently for design, evaluation, or optimization purposes. The frozen performance of hydrogen over a wide range of conditions similar to those of reference 3 are therefore presented herein. These data are presented in both tabular and graphic forms for stagnation temperatures and pressures from 2000° to 5000° K and 0.1 to 500 pounds per square inch absolute, respectively, and nozzle area ratios from 5 to ∞.

CALCULATION PROCEDURE

The calculation of the data for the isentropic frozen expansion of hydrogen is based upon the method and computer program of reference 4. The output data of this program are utilized as input data to an accessory computer program for calculating more specific performance parameters that have been found by experience to be useful for the design and evaluation of thrustor systems.

When the computer program of reference 4 is used, it must be recognized that the data are based on the assumption of an expanding gas that is chemically frozen at stagnation conditions. Reference 5 indicates that the composition of the hydrogen gas is probably frozen at, or slightly downstream of, the nozzle throat region rather than at stagnation conditions. These data, therefore, can be considered to be somewhat conservative in that any recombination that may occur downstream of the stagnation region will improve the performance as presented herein.

The performance parameters calculated by the accessory computer program are weight fraction of molecular hydrogen dissociated, flow rate per unit throat area per unit stagnation pressure, and various power requirements and efficiencies.

The weight fraction of molecular hydrogen dissociated α_H and the flow rate per unit throat area parameter $\dot{w}/A^*p_0$ are calculated from equations (1) and (2), respectively:

$$\alpha_H = \frac{X_H}{2 - X_H} \tag{1}$$

$$\frac{\dot{w}}{A^*p_0} = \frac{g_c}{C^*} \tag{2}$$

The mole fraction of atomic hydrogen X_H, the characteristic velocity C^*, and all other parameters required in subsequent equations are obtained from the computer program of reference 4.

The power requirements are calculated in terms of kilowatts of gas power required per unit weight flow rate and in kilowatts of gas power required per pound of thrust (eqs. (3) and (4), respectively):

$$\frac{P_g}{\dot{w}} = 1.899\ (H_O + H_{ref}) \tag{3}$$

$$\frac{P_g}{F} = \frac{1.899\ (H_O + H_{ref})}{I_{vac}} \tag{4}$$

As obtained from the computer program, H_O is based upon the reference temperature at 298° K. In order to incorporate 0° K as the reference temperature in the calculations for power requirements (and subsequent efficiencies), H_{ref} is introduced as the absolute enthalpy of hydrogen at 298° K. The parameter P_g/F is generally used as a mission parameter, and, therefore, it is based upon the vacuum specific impulse I_{vac}, which corresponds to space environment operation for a finite area-ratio nozzle.

The calculated efficiencies are based upon the power-balance method presented in reference 6 with the following equation:

$$P_g = P_j + P_f + P_q + P_e \tag{5}$$

The gas power P_g is the power required to achieve the desired nozzle stagnation conditions. The power terms P_j, P_f, and P_e represent the distribution of the power in the gas at the nozzle exit plane; P_q is the power exchanged between the gas and the nozzle walls while the gas is expanding through the nozzle. The jet power P_j is the thermal power converted to useful thrust power. The "frozen" power P_f represents the influence of dissociation caused by the chemically frozen assumption and this power is not available for conversion to thrust power. The term P_e is the thermal power other than P_f remaining in the gas at the nozzle exit plane that can be utilized for thrust if more complete expansion were provided.

The overall nozzle efficiency η is the ratio of jet power to gas power:

$$\eta = \frac{P_j}{P_g} = 1 - \frac{P_f + P_q + P_e}{P_g} \tag{6}$$

In terms of power loss mechanisms, the overall efficiency can be represented by

$$\eta = \eta_f \eta_q \eta_e \tag{7}$$

where

$$\eta_f = \frac{P_g - P_f}{P_g} \tag{8}$$

$$\eta_q = \frac{P_g - P_f - P_q}{P_g - P_f} \tag{9}$$

$$\eta_e = \frac{P_g - P_f - P_q - P_e}{P_g - P_f - P_q} \tag{10}$$

For the idealized isentropic frozen-expansion process considered here, heat-transfer effects are neglected, and, therefore, $P_q = 0$; thus $\eta_q = 1.0$. This assumption is significant especially for low-power systems and can impose a severe limitation on the data. This assumption, however, was justified on the basis of the generality of the results. The P_q term can be determined only after a specific configuration and an operating condition have been defined. With this assumption, the efficiency expressions reduce to

$$\eta_e = \frac{P_g - P_f - P_e}{P_g - P_f} \tag{11}$$

$$\eta = \eta_f \eta_e = \frac{P_g - P_f - P_e}{P_g} \tag{12}$$

In evaluating the efficiency terms, only the overall nozzle efficiency η and the frozen-flow efficiency η_f are calculated. (The term η_e can be obtained from the ratio η/η_f.) The computer calculations of these terms are based upon the following energy forms of equations (8) and (12) with the reference temperature taken as absolute zero:

$$\eta_f = \frac{H_O + H_{ref} - 11,440\ E_D \alpha_H}{H_O + H_{ref}} \tag{13}$$

$$\eta = \frac{H_O - H_E - 11,440\ E_D \alpha_H}{H_O + H_{ref}} \tag{14}$$

Within the limitations of the two principal assumptions used ((1) constituents frozen at stagnation conditions, and (2) $P_q = 0$, therefore, $\eta_q = 1.0$), the calculation of the data in this manner has been found to predict nozzle performance to a reasonable degree of accuracy for gas temperatures up to 2800° K at stagnation pressures of 1 atmosphere (ref. 7).

PRESENTATION OF DATA

The data are presented in both tabular and graphic form. The tabulated data include all the necessary parameters for a preliminary evaluation of the overall performance of a given thermal propulsion device. These data are presented in table I for stagnation pressures from 0.1 to 500 pounds per square inch absolute. Each part of the table presents the data at a specific stagnation pressure for stagnation temperatures from 2000° to 5000° K and nozzle area ratios from 5 to ∞. Performance data are not presented for temperatures below 2000° K because negligible dissociation occurs, and, therefore, the performance for frozen expansion is identical to equilibrium expansion and can be obtained from reference 3. No data are presented for temperatures above 5000° K because ionization of hydrogen occurs, and the computer is not programmed to handle ionization. The ranges of stagnation pressure and area ratio chosen correspond to those anticipated for space-propulsion devices utilizing hydrogen as the propellant. The tabulated data include the following stagnation parameters: enthalpy, weight fraction of molecular hydrogen dissociated, flow rate per unit throat area per unit stagnation pressure, frozen-flow efficiency, and gas-power requirements per unit propellant weight flow. For each nozzle area ratio associated with a given stagnation temperature and pressure, the performance parameters presented are specific impulse I, vacuum specific impulse I_{vac}, overall nozzle efficiency η, and power requirements per pound of thrust P_g/F for an ambient pressure of zero.

A sufficient number of points are tabulated to provide accurate interpolation in the specific-impulse range of 900 to 1200 seconds. This range corresponds to the present area of interest for nuclear and electrothermal propulsion devices.

The graphic presentation of the data is limited to a number of typical curves that have been found useful for analyzing the performance of electrothermal-propulsion devices. These curves are presented in figures 1 and 2. No attempt has been made to present figures from which general conclusions could be drawn. It is recommended that, for a specific application, the appropriate curves be generated from the tabulated data.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, September 6, 1963

APPENDIX - SYMBOLS

A^* nozzle flow area at throat section, sq in.

A_e nozzle exit area, sq in.

C^* characteristic velocity, $g_c p_0/(\dot{w}/A^*)$, ft/sec

E_D dissociation potential, ev (taken as 4.476 ev for molecular hydrogen)

F thrust, lb

g_c gravitational constant, (lb mass/lb force)(ft/sec^2)

H_e nozzle-exit enthalpy, cal/g

H_0 stagnation enthalpy (referenced to 298° K), cal/g

H_{ref} reference enthalpy level taken as 1009 cal/g to provide power requirements and efficiencies with 0° K as reference level

I specific impulse for $p_e = p_a$, sec

I_{vac} vacuum specific impulse for zero ambient pressure, sec

P_e thermal power remaining in gas at nozzle exit, kw

P_f power frozen into gas, kw

P_g gas power, kw

P_j jet power, kw

P_q power exchanged between gas and nozzle walls, kw

p_a ambient pressure, lb/sq in. abs

p_e nozzle-exit pressure, lb/sq in. abs

p_0 stagnation pressure, lb/sq in. abs

$\dot{w}$ propellant weight flow rate, lb/sec

X_H mole fraction of atomic hydrogen

α_H weight fraction of molecular hydrogen dissociated

η overall nozzle efficiency, $\eta_f \eta_e$

η_e nozzle-expansion efficiency

η_f frozen-flow efficiency

η_q heat-transfer efficiency

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TABLE I. - ISENTROPIC FROZEN EXPANSION OF HYDROGEN FOR AREA RATIOS FROM 5 TO ∞

(a) Stagnation pressure, p_0, 0.1 pound per square inch absolute

Performance parameter	Stagnation temperature, °K										
	2000	2500	2800	3000	3200	3400	3600	3800	4000	4500	5000
	Stagnation enthalpy, H_0, cal/g										
	6808	16482	33708	48092	58412	63829	66619	68337	69635	72331	74840
	Weight fraction of molecular hydrogen dissociated, α_H										
	0.0098	0.1500	0.4426	0.6896	0.8612	0.9425	0.9755	0.9889	0.9946	0.9989	0.9997
	Flow rate per unit throat area per unit stagnation pressure, $\dot{w}/A^*p_0$										
	0.002288	0.001932	0.001669	0.001519	0.001422	0.001359	0.001313	0.001275	0.001242	0.001170	0.001110
	Gas power per unit propellant weight flow rate, $P_g/\dot{w}$										
	14,830	33,200	65,910	93,230	112,800	123,100	128,400	131,700	134,100	139,300	144,000
	Frozen flow efficiency, η_f										
	0.936	0.561	0.347	0.280	0.257	0.255	0.261	0.269	0.278	0.302	0.324
	Area ratio, ∞										
Specific impulse, I	798	924	1023	1094	1153	1199	1239	1274	1308	1388	1464
Vacuum specific impulse, I_{vac}	798	924	1023	1094	1153	1199	1239	1274	1308	1388	1464
Nozzle efficiency, η	0.936	0.561	0.347	0.280	0.257	0.255	0.261	0.269	0.278	0.302	0.324
Power/lb thrust, P_g/F	18.6	36.0	64.4	85.2	97.9	102.7	103.7	103.3	102.6	100.3	98.4
Stagnation press./nozzle exit press., p_0/p_e	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
	Area ratio, 500										
Specific impulse, I	779	907	1014	1089	1150	1197	1236	1272	1306	1386	1459
Vacuum specific impulse, I_{vac}	784	912	1017	1091	1152	1199	1238	1274	1308	1388	1461
Nozzle efficiency, η	0.891	0.541	0.340	0.277	0.256	0.254	0.260	0.268	0.277	0.301	0.323
Power/lb thrust, P_g/F	18.9	36.4	64.8	85.5	98.0	102.7	103.7	103.4	102.6	100.4	98.6
Stagnation press./nozzle exit press., p_0/p_e	40415	51618	92035	137975	175507	194842	203042	206438	207913	209021	204883
	Area ratio, 100										
Specific impulse, I	760	889	1000	1077	1139	1186	1225	1261	1295	1374	1448
Vacuum specific impulse, I_{vac}	771	900	1008	1083	1145	1192	1231	1267	1300	1380	1455
Nozzle efficiency, η	0.848	0.519	0.331	0.271	0.251	0.249	0.255	0.263	0.273	0.296	0.318
Power/lb thrust, P_g/F	18.3	36.9	65.4	86.1	98.6	103.3	104.3	104.0	103.2	100.9	99.0
Stagnation press./nozzle exit press., p_0/p_e	3817	4583	7015	9699	11862	12968	13435	13630	13714	13778	13777
	Area ratio, 50										
Specific impulse, I	746	875	988	1067	1130	1178	1217	1252	1286	1364	1438
Vacuum specific impulse, I_{vac}	762	891	1001	1078	1140	1187	1226	1262	1295	1374	1449
Nozzle efficiency, η	0.818	0.503	0.323	0.267	0.247	0.246	0.252	0.260	0.269	0.292	0.313
Power/lb thrust, P_g/F	19.5	37.3	65.9	86.5	99.0	103.8	104.8	104.4	103.6	101.3	99.4
Stagnation press./nozzle exit press., p_0/p_e	1393	1629	2352	3127	3743	4058	4190	4245	4269	4287	4291
	Area ratio, 25										
Specific impulse, I	727	855	971	1052	1116	1164	1203	1238	1272	1349	1422
Vacuum specific impulse, I_{vac}	749	877	990	1068	1131	1179	1218	1253	1287	1366	1439
Nozzle efficiency, η	0.778	0.480	0.312	0.259	0.241	0.240	0.246	0.254	0.263	0.285	0.307
Power/lb thrust, P_g/F	19.8	37.9	66.6	87.3	99.8	104.5	105.4	105.1	104.3	102.0	100.1
Stagnation press./nozzle exit press., p_0/p_e	507	577	788	1006	1177	1263	1299	1314	1321	1326	1327
	Area ratio, 10										
Specific impulse, I	691	815	934	1018	1084	1132	1171	1205	1238	1314	1385
Vacuum specific impulse, I_{vac}	724	851	967	1048	1112	1160	1199	1234	1267	1345	1418
Nozzle efficiency, η	0.701	0.4364	0.289	0.243	0.227	0.227	0.233	0.241	0.249	0.270	0.291
Power/lb thrust, P_g/F	20.5	39.0	68.2	89.0	101.5	106.2	107.1	106.7	105.9	103.6	101.6
Stagnation press./nozzle exit press., p_0/p_e	131	144	183	221	250	265	271	274	275	275	276
	Area ratio, 5										
Specific impulse, I	648	767	887	973	1040	1088	1126	1160	1191	1264	1332
Vacuum specific impulse, I_{vac}	696	821	938	1021	1087	1135	1174	1208	1240	1316	1388
Nozzle efficiency, η	0.617	0.387	0.261	0.222	0.209	0.210	0.215	0.223	0.231	0.250	0.269
Power/lb thrust, P_g/F	21.3	40.5	70.3	91.3	103.8	108.5	109.4	109.0	108.2	105.8	103.8
Stagnation press./nozzle exit press., p_0/p_e	45.3	48.5	58.7	68.3	75.4	78.9	80.3	80.9	81.2	81.4	81.4

TABLE I. - Continued. ISENTROPIC FROZEN EXPANSION OF HYDROGEN FOR AREA RATIOS FROM 5 TO ∞

(b) Stagnation pressure, 0.5 pound per square inch absolute

Performance parameter	Stagnation temperature, ^{o}K										
	2000	2500	2800	3000	3200	3400	3600	3800	4000	4500	5000
	Stagnation enthalpy, H_0, cal/g										
	6516	12023	21364	31868	44372	55140	62103	66095	68501	72080	74767
	Weight fraction of molecular hydrogen dissociated, α_H										
	0.0044	0.0677	0.2155	0.3918	0.6040	0.7836	0.8931	0.9481	0.9740	0.9943	0.9983
	Flow rate per unit throat area per unit stagnation pressure, $\dot{w}/A^{*}p_0$										
	0.002293	0.001991	0.001782	0.001632	0.001498	0.001400	0.001332	0.001284	0.001246	0.001171	0.001111
	Gas power per unit propellant weight flow rate, $P_g/\dot{w}$										
	14,270	24,730	42,470	62,410	86,160	106,600	119,800	127,400	132,000	138,800	143,900
	Frozen flow efficiency, η_f										
	0.970	0.734	0.506	0.389	0.318	0.285	0.275	0.276	0.282	0.303	0.325
	Area ratio, ∞										
Specific impulse, I	797	912	0.993	1055	1120	1180	1228	1269	1306	1388	1463
Vacuum specific impulse, I_{vac}	797	912	0.993	1055	1120	1180	1228	1269	1306	1388	1463
Nozzle efficiency, η	0.970	0.734	0.506	0.389	0.318	0.285	0.275	0.276	0.282	0.303	0.325
Power/lb thrust, P_g/F	17.9	27.1	42.8	59.2	76.9	90.4	97.6	100.4	101.1	100.0	98.3
Stagnation press./nozzle exit press., p_0/p_e	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
	Area ratio, 500										
Specific impulse, I	778	893	977	1044	1113	1175	1225	1266	1303	1385	1459
Vacuum specific impulse, I_{vac}	783	898	982	1048	1116	1177	1227	1268	1305	1387	1461
Nozzle efficiency, η	0.924	0.703	0.491	0.381	0.314	0.283	0.273	0.275	0.281	0.302	0.323
Power/lb thrust, P_g/F	18.3	27.6	43.2	59.5	77.2	90.6	97.7	100.5	101.2	100.1	98.5
Stagnation press./nozzle exit press., p_0/p_e	39910	42931	57413	80665	119307	156883	182335	195823	202467	207784	204505
	Area ratio, 100										
Specific impulse, I	758	872	959	1028	1100	1163	1214	1255	1292	1373	1448
Vacuum specific impulse, I_{vac}	770	884	970	1038	1108	1170	1220	1261	1298	1379	1454
Nozzle efficiency, η	0.879	0.670	0.472	0.370	0.306	0.277	0.268	0.270	0.276	0.296	0.318
Power/lb thrust, P_g/F	18.6	28.0	43.8	60.2	77.8	91.2	98.3	101.0	101.7	100.6	98.9
Stagnation press./nozzle exit press., p_0/p_e	3782	4004	4967	6431	8609	10782	12245	13021	13400	13706	13755
	Area ratio, 50										
Specific impulse, I	745	857	944	1016	1089	1153	1205	1246	1283	1364	1438
Vacuum specific impulse, I_{vac}	761	874	960	1030	1101	1164	1214	1256	1392	1374	1449
Nozzle efficiency, η	0.847	0.647	0.458	0.360	0.300	0.272	0.264	0.266	0.272	0.292	0.314
Power/lb thrust, P_g/F	18.8	28.3	44.2	60.6	78.3	91.6	98.7	101.5	102.1	101.0	99.3
Stagnation press./nozzle exit press., p_0/p_e	1382	1451	1746	2182	2814	3436	3853	4073	4180	4267	4285
	Area ratio, 25										
Specific impulse, I	726	836	924	997	1073	1138	1190	1232	1268	1349	1422
Vacuum specific impulse, I_{vac}	748	860	947	1018	1091	1155	1206	1247	1284	1365	1439
Nozzle efficiency, η	0.805	0.616	0.439	0.347	0.291	0.265	0.258	0.260	0.266	0.286	0.307
Power/lb thrust, P_g/F	19.1	28.8	44.9	61.4	79.0	92.3	99.4	102.2	102.8	101.7	100.0
Stagnation press./nozzle exit press., p_0/p_e	503	523	612	739	919	1092	1207	1267	1297	1320	1327
	Area ratio, 10										
Specific impulse, I	689	794	882	957	1036	1104	1156	1198	1234	1313	1384
Vacuum specific impulse, I_{vac}	723	832	920	993	1068	1134	1186	1228	1264	1344	1417
Nozzle efficiency, η	0.726	0.556	0.400	0.320	0.272	0.249	0.244	0.246	0.252	0.271	0.291
Power/lb thrust, P_g/F	19.8	29.8	46.2	62.9	80.7	99.0	101.1	103.8	104.4	103.3	101.5
Stagnation press./nozzle exit press., p_0/p_e	130	133	150	174	206	236	255	266	271	274	275
	Area ratio, 5										
Specific impulse, I	647	745	832	907	988	1007	1110	1152	1187	1263	1332
Vacuum specific impulse, I_{vac}	695	800	888	962	1040	1107	1159	1201	1237	1316	1388
Nozzle efficiency, η	0.638	0.490	0.355	0.288	0.247	0.229	0.224	0.227	0.233	0.251	0.269
Power/lb thrust, P_g/F	20.6	30.9	47.8	64.9	82.9	963	1034	106.1	106.7	105.5	103.7
Stagnation press./nozzle exit press., p_0/p_e	45.1	45.6	49.9	56.1	64.4	71.8	76.5	79.0	80.2	81.1	81.3

TABLE I. - Continued. ISENTROPIC FROZEN EXPANSION OF HYDROGEN FOR AREA RATIOS FROM 5 TO ∞

(c) Stagnation pressure, 1.0 pound per square inch absolute

Performance parameter	Stagnation temperature, °K										
	2000	2500	2800	3000	3200	3400	3600	3800	4000	4500	5000
	Stagnation enthalpy, H_0, cal/g										
	6447	10952	18029	26230	37185	48689	57797	63649	67179	71772	74676
	Weight fraction of molecular hydrogen dissociated, α_H										
	0.0031	0.0479	0.1542	0.2884	0.4723	0.6656	0.8144	0.9034	0.9499	0.9887	0.9967
	Flow rate per unit throat area per unit stagnation pressure, $\dot{w}/A^*p_0$										
	0.002295	0.002006	0.001819	0.001681	0.007547	0.001433	0.001547	0.001294	0.001251	0.001172	0.001110
	Gas power per unit propellant weight flow rate, $P_g/\dot{w}$										
	14,140	22,700	36,140	51,710	72,510	94,360	111,700	122,800	129,500	138,200	143,700
	Frozen flow efficiency, η_f										
	0.979	0.795	0.585	0.457	0.366	0.313	0.290	0.284	0.286	0.304	0.325
	Area ratio, ∞										
Specific impulse, I	797	910	984	1041	1103	1165	1219	1264	1303	1387	1463
Vacuum specific impulse, I_{vac}	797	910	984	1041	1103	1165	1219	1264	1303	1387	1463
Nozzle efficiency, η	0.979	0.795	0.585	0.457	0.366	0.314	0.290	0.284	0.286	0.304	0.325
Power/lb thrust, P_g/F	17.8	25.0	36.7	49.7	65.7	81.0	91.6	97.2	99.4	99.6	98.2
Stagnation press/nozzle exit press., p_0/p_e	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
	Area ratio, 500										
Specific impulse, I	777	889	967	1027	1093	1158	1214	1260	1300	1384	1459
Vacuum specific impulse, I_{vac}	783	895	972	1032	1097	1161	1217	1263	1302	1386	1461
Nozzle efficiency, η	0.932	0.759	0.564	0.445	0.360	0.310	0.288	0.282	0.285	0.303	0.323
Power/lb thrust, P_g/F	18.1	25.4	37.2	50.1	66.1	81.3	91.8	97.2	99.5	99.7	98.4
Stagnation press/nozzle exit press., p_0/p_e	39790	41028	50228	6553	92487	130849	163397	184571	196174	206252	204036
	Area ratio, 100										
Specific impulse, I	758	868	946	1009	1078	1145	1202	1249	1288	1372	1448
Vacuum specific impulse, I_{vac}	770	880	959	1020	1087	1153	1209	1255	1294	1379	1454
Nozzle efficiency, η	0.886	0.723	0.541	0.430	0.350	0.303	0.282	0.277	0.280	0.297	0.318
Power/lb thrust, P_g/F	18.4	25.8	37.7	50.7	66.7	81.9	92.4	97.8	100.0	100.3	98.8
Stagnation press/nozzle exit press., p_0/p_e	3774	3874	4499	5490	7156	9278	11152	12370	13337	13617	13728
	Area ratio, 50										
Specific impulse, I	745	852	931	995	1066	1134	1192	1240	1279	1363	1438
Vacuum specific impulse, I_{vac}	760	870	949	1011	1080	1146	1203	1250	1289	1373	1448
Nozzle efficiency, η	0.854	0.698	0.524	0.418	0.342	0.298	0.278	0.273	0.276	0.293	0.314
Power/lb thrust, P_g/F	18.6	26.1	38.1	51.2	67.2	82.4	92.8	98.3	100.5	100.7	99.2
Stagnation press/nozzle exit press., p_0/p_e	1379	1410	1603	1903	2395	3007	3542	3888	4077	4242	4277
	Area ratio, 25										
Specific impulse, I	726	831	910	975	1048	1118	1177	1225	1264	1348	1422
Vacuum specific impulse, I_{vac}	747	855	934	998	1068	1136	1194	1241	1280	1364	1439
Nozzle efficiency, η	0.812	0.663	0.500	0.401	0.330	0.289	0.271	0.267	0.269	0.287	0.307
Power/lb thrust, P_g/F	18.9	26.6	38.7	51.8	67.9	83.1	93.5	99.0	101.1	101.3	99.9
Stagnation press/nozzle exit press., p_0/p_e	503	511	568	658	800	973	1121	1216	1268	1313	1323
	Area ratio, 10										
Specific impulse, I	689	789	867	933	1008	1081	1142	1190	1230	1312	1384
Vacuum specific impulse, I_{vac}	723	827	906	971	1043	1114	1173	1220	1260	1343	1417
Nozzle efficiency, η	0.732	0.598	0.454	0.368	0.306	0.270	0.255	0.252	0.255	0.272	0.291
Power/lb thrust, P_g/F	19.6	27.5	39.9	53.3	69.5	84.7	95.2	100.6	102.8	102.9	101.4
Stagnation press/nozzle exit press., p_0/p_e	130	130	141	158	185	215	241	257	266	273	275
	Area ratio, 5										
Specific impulse, I	646	740	815	882	958	1032	1095	1143	1182	1262	1332
Vacuum specific impulse, I_{vac}	695	795	873	939	1013	1085	1145	1193	1233	1315	1387
Nozzle efficiency, η	0.644	0.525	0.401	0.328	0.276	0.246	0.234	0.232	0.236	0.251	0.269
Power/lb thrust, P_g/F	20.4	28.6	41.4	55.1	71.6	87.0	97.5	102.9	105.0	105.1	103.6
Stagnation press/nozzle exit press., p_0/p_e	45.1	44.9	47.7	52.1	58.9	66.6	73.0	76.9	79.0	80.8	81.2

TABLE I. - Continued. ISENTROPIC FROZEN EXPANSION OF HYDROGEN FOR AREA RATIOS FROM 5 TO ∞

(d) Stagnation pressure, 5 pounds per square inch absolute

Performance parameter	Stagnation temperature, ^{o}K										
	2000	2500	2800	3000	3200	3400	3600	3800	4000	4500	5000
	Stagnation enthalpy, H_0, cal/g										
	6355	9519	13430	17791	24125	32554	42313	51718	59250	69477	73964
	Weight fraction of molecular hydrogen dissociated, α_H										
	0.0014	0.0214	0.0696	0.1335	0.2331	0.3705	0.5316	0.6858	0.8054	0.9470	0.9838
	Flow rate per unit throat area per unit stagnation pressure, $\dot{w}/A^*p_0$										
	0.002296	0.002026	0.001876	0.001768	0.001654	0.001539	0.001434	0.001348	0.001283	0.001180	0.001113
	Gas power per unit propellant weight flow rate, $P_g/\dot{w}$										
	13,790	19,990	27,420	35,700	47,730	63,740	82,270	100,100	114,400	133,900	142,400
	Frozen flow efficiency, η_f										
	0.990	0.896	0.753	0.636	0.525	0.434	0.371	0.333	0.315	0.311	0.327
	Area ratio, ∞										
Specific impulse, I	797	906	973	1020	1071	1126	1183	1237	1285	1382	1462
Vacuum specific impulse, I_{vac}	797	906	973	1020	1071	1126	1183	1237	1285	1382	1462
Nozzle efficiency, η	0.990	0.896	0.753	0.636	0.525	0.434	0.371	0.333	0.315	0.311	0.327
Power/lb thrust, P_g/F	17.6	22.1	28.2	35.0	44.5	56.6	69.6	81.0	89.0	96.8	97.4
Stagnation press/nozzle exit press., p_0/p_e	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
	Area ratio, 500										
Specific impulse, I	777	884	951	1001	1055	1113	1173	1230	1280	1379	1457
Vacuum specific impulse, I_{vac}	78.3	890	958	1007	1060	1118	1177	1232	1283	1381	1459
Nozzle efficiency, η	0.943	0.853	0.720	0.612	0.509	0.425	0.365	0.330	0.313	0.310	0.325
Power/lb thrust, P_g/F	17.9	22.5	28.6	35.5	45.0	57.0	69.9	81.3	89.2	96.9	97.6
Stagnation press/nozzle exit press., p_0/p_e	39632	38540	41449	46788	37146	74802	100423	130025	160052	194998	200388
	Area ratio, 100										
Specific impulse, I	758	862	929	979	1035	1096	1158	1216	1267	1366	1446
Vacuum specific impulse, I_{vac}	769	875	942	992	1047	1106	1167	1224	1279	1373	1453
Nozzle efficiency, η	0.896	0.811	0.686	0.585	0.489	0.411	0.356	0.323	0.306	0.304	0.321
Power/lb thrust, P_g/F	18.2	22.9	29.1	36.0	45.6	57.6	70.5	81.8	89.8	97.5	98.0
Stagnation press/nozzle exit press., p_0/p_e	3763	3705	3910	4277	495.6	6074	7645	9405	10950	12963	13516
	Area ratio, 50										
Specific impulse, I	744	846	912	963	1019	1082	1146	1205	1257	1357	1436
Vacuum specific impulse, I_{vac}	760	864	931	981	1037	1097	1159	1217	1268	1367	1447
Nozzle efficiency, η	0.864	0.781	0.662	0.566	0.475	0.401	0.348	0.317	0.301	0.300	0.316
Power/lb thrust, P_g/F	18.4	23.1	29.5	36.4	46.0	58.1	71.0	82.2	90.2	97.9	98.4
Stagnation press/nozzle exit press., p_0/p_e	1376	1357	1420	1533	1741	2076	2537	3046	3485	4057	4217
	Area ratio, 25										
Specific impulse, I	725	824	890	940	997	1061	1127	1188	1241	1341	1420
Vacuum specific impulse, I_{vac}	747	849	916	966	1022	1084	1148	1207	1258	1358	1437
Nozzle efficiency, η	0.821	0.742	0.630	0.540	0.455	0.386	0.337	0.308	0.294	0.293	0.309
Power/lb thrust, P_g/F	18.7	23.5	30.0	37.0	46.7	58.8	71.7	83.0	90.9	98.6	99.1
Stagnation press/nozzle exit press., p_0/p_e	502	494	512	546	609	708	840	983	1105	1263	1307
	Area ratio, 10										
Specific impulse, I	689	782	844	894	952	1017	1086	1149	1203	1304	1382
Vacuum specific impulse, I_{vac}	722	821	886	936	993	1056	1122	1183	1236	1336	1415
Nozzle efficiency, η	0.740	0.667	0.567	0.489	0.414	0.354	0.313	0.288	0.276	0.277	0.293
Power/lb thrust, P_g/F	19.4	24.4	31.0	38.2	48.1	60.3	73.3	84.6	92.6	100.2	100.6
Stagnation press/nozzle exit press., p_0/p_e	130	127	130	136	148	167	191	217	238	265	272
	Area ratio, 5										
Specific impulse, I	646	732	791	839	897	963	1032	1097	1153	1254	1329
Vacuum specific impulse, I_{vac}	694	788	851	900	958	1023	1090	1153	1207	1307	1385
Nozzle efficiency, η	0.651	0.585	0.498	0.431	0.368	0.317	0.283	0.262	0.253	0.256	0.271
Power/lb thrust, P_g/F	20.1	25.4	32.2	39.7	49.8	62.3	75.5	86.8	94.8	102.4	102.8
Stagnation press/nozzle exit press., p_0/p_e	45.0	44.0	44.7	46.3	49.4	54.2	60.5	66.9	72.2	78.7	80.6

TABLE I. - Continued. ISENTROPIC FROZEN EXPANSION OF HYDROGEN FOR AREA RATIOS FROM 5 TO ∞

(e) Stagnation pressure, 10 pounds per square inch absolute

Performance parameter	Stagnation temperature, °K										
	2000	2500	2800	3000	3200	3400	3600	3800	4000	4500	5000
	Stagnation enthalpy, H_0, cal/g										
	633.3	9178	12325	15684	20524	27140	35417	44519	53072	66980	73112
	Weight fraction of molecular hydrogen dissociated, α_H										
	0.00098	0.0152	0.0493	0.0948	0.1671	0.2714	0.4057	0.5545	0.6929	0.9016	0.9683
	Flow rate per unit throat area per unit stagnation pressure, $\dot{w}/A^* p_0$										
	0.002297	0.002032	0.001890	0.001792	0.001689	0.001583	0.001480	0.001387	0.001311	0.001189	0.001115
	Gas power per unit propellant weight flow rate, $P_g/\dot{w}$										
	13,940	19,350	25,320	31,700	40,890	53,450	69,170	86,460	102,700	129,100	140,800
	Frozen flow efficiency, η_f										
	0.993	0.924	0.810	0.709	0.602	0.506	0.429	0.376	0.343	0.320	0.330
	Area ratio, ∞										
Specific impulse, I	797	905	970	1015	1062	1113	1166	1220	1271	1377	1460
Vacuum specific impulse, I_{vac}	797	905	970	1015	1062	1113	1166	1220	1271	1377	1460
Nozzle efficiency, η	0.993	0.924	0.810	0.709	0.602	0.506	0.429	0.376	0.343	0.320	0.330
Power/lb thrust, P_g/F	17.5	21.4	26.1	31.2	38.5	48.0	59.3	70.9	80.8	93.8	96.4
Stagnation press./nozzle exit press., p_0/p_e	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
	Area ratio, 500										
Specific impulse, I	770	883	947	994	1043	1097	1154	1211	1264	1373	1455
Vacuum specific impulse, I_{vac}	783	889	954	1000	1049	1102	1158	1214	1267	1375	1457
Nozzle efficiency, η	0.945	0.879	0.774	0.680	0.581	0.492	0.420	0.370	0.339	0.319	0.328
Power/lb thrust, P_g/F	17.8	21.8	26.5	31.7	39.0	48.5	59.7	71.2	81.1	93.9	96.6
Stagnation press./nozzle exit press., p_0/p_e	39595	38030	39555	42868	49342	60878	79034	103638	130637	183008	196057
	Area ratio, 100										
Specific impulse, I	758	860	924	970	1021	1077	1136	1195	1250	1360	1444
Vacuum specific impulse, I_{vac}	769	874	938	984	1034	1089	1147	1205	1258	1367	1450
Nozzle efficiency, η	0.899	0.835	0.736	0.648	0.557	0.474	0.407	0.361	0.332	0.313	0.323
Power/lb thrust, P_g/F	18.1	22.1	27.0	32.2	39.5	49.1	60.3	71.8	81.6	94.5	97.0
Stagnation press./nozzle exit press., p_0/p_e	3761	3661	3778	4009	4450	5198	6338	7833	9440	12268	13265
	Area ratio, 50										
Specific impulse, I	744	845	907	954	1005	1062	1122	1183	1239	1350	1434
Vacuum specific impulse, I_{vac}	760	863	927	973	1024	1079	1138	1197	1251	1361	1445
Nozzle efficiency, η	0.867	0.805	0.710	0.626	0.539	0.460	0.397	0.353	0.326	0.308	0.319
Power/lb thrust, P_g/F	18.4	22.4	27.3	32.6	40.0	49.5	60.8	72.3	82.07	94.9	97.4
Stagnation press./nozzle exit press., p_0/p_e	1375	1345	1378	1450	1586	1814	2154	2592	3056	3860	4146
	Area ratio, 25										
Specific impulse, I	725	823	884	930	982	1039	1102	1164	1221	1334	1418
Vacuum specific impulse, I_{vac}	747	848	911	957	1008	1065	1125	1185	1241	1351	1435
Nozzle efficiency, η	0.823	0.764	0.674	0.596	0.514	0.441	0.383	0.342	0.317	0.301	0.312
Power/lb thrust, P_g/F	18.7	22.8	27.8	33.1	40.6	50.2	61.5	72.9	82.8	95.6	98.1
Stagnation press./nozzle exit press., p_0/p_e	501	490	499	520	561	630	730	856	986	1209	1287
	Area ratio, 10										
Specific impulse, I	688	780	839	883	935	993	1057	1122	1181	1296	1379
Vacuum specific impulse, I_{vac}	722	819	880	926	977	1035	1097	1159	1216	1329	1412
Nozzle efficiency, η	0.742	0.686	0.606	0.537	0.466	0.403	0.352	0.318	0.296	0.284	0.295
Power/lb thrust, P_g/F	19.3	23.6	28.8	34.2	41.8	51.7	63.1	74.6	84.4	97.1	99.7
Stagnation press./nozzle exit press., p_0/p_e	130	126	127	131	139	152	171	194	217	256	269
	Area ratio, 5										
Specific impulse, I	646	730	785	828	878	936	1001	1067	1128	1244	1326
Vacuum specific impulse, I_{vac}	694	787	846	890	941	999	1062	1126	1185	1299	1382
Nozzle efficiency, η	0.652	0.602	0.531	0.472	0.411	0.358	0.316	0.287	0.270	0.262	0.273
Power/lb thrust, P_g/F	20.1	24.6	30.0	35.6	43.5	53.5	65.1	76.8	86.7	99.4	101.8
Stagnation press./nozzle exit press., p_0/p_e	45.0	43.8	43.9	44.9	46.9	50.3	55.2	61.1	66.9	76.5	79.7

TABLE I. - Continued. ISENTROPIC FROZEN EXPANSION OF HYDROGEN FOR AREA RATIOS FROM 5 TO ∞

(f) Stagnation pressure, 14.7 pounds per square inch absolute

Performance parameter	Stagnation temperature, $^{\circ}K$										
	2000	2500	2800	3000	3200	3400	3600	3800	4000	4500	5000
	Stagnation enthalpy, H_0, cal/g										
	6324	9034	11856	14786	18961	24688	32029	40526	49136	64935	72347
	Weight fraction of molecular hydrogen dissociated, α_H										
	0.0008	0.0125	0.0407	0.0783	0.1384	0.2266	0.3438	0.4817	0.6212	0.8644	0.9544
	Flow rate per unit throat area per unit stagnation pressure, $\dot{w}/A^*p_0$										
	0.002298	0.002035	0.001897	0.001804	0.001707	0.001606	0.001506	0.001424	0.001332	0.001197	0.001118
	Gas power per unit propellant weight flow rate, $P_g/\dot{w}$										
	13,290	19,070	24,430	29,990	37,920	48,800	62,740	78,880	95,230	125,200	139,300
	Frozen flow efficiency, η_f										
	0.994	0.936	0.838	0.746	0.645	0.548	0.467	0.406	0.365	0.328	0.333
	Area ratio, ∞										
Specific impulse, I	797	905	969	1013	1059	1107	1158	1211	1262	1372	1458
Vacuum specific impulse, I_{vac}	797	905	969	1013	1059	1107	1158	1211	1262	1372	1458
Nozzle efficiency, η	0.994	0.936	0.838	0.746	0.645	0.548	0.467	0.406	0.365	0.328	0.333
Power/lb thrust, P_g/F	17.5	21.1	25.2	29.6	35.8	44.1	54.2	65.1	75.4	91.3	95.5
Stagnation press./nozzle exit press., p_0/p_e	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
	Area ratio, 500										
Specific impulse, I	777	882	946	990	1038	1090	1144	1200	1254	1367	1453
Vacuum specific impulse, I_{vac}	783	889	953	997	1045	1095	1149	1204	1257	1369	1456
Nozzle efficiency, η	0.946	0.891	0.799	0.714	0.620	0.531	0.455	0.398	0.860	1320	0.331
Power/lb thrust, P_g/F	17.8	21.5	25.6	30.1	36.3	44.6	54.6	65.5	75.8	91.5	95.7
Stagnation press./nozzle exit press., p_0/p_e	39579	37795	38775	41282	46277	55127	69682	90458	115618	167517	192205
	Area ratio, 100										
Specific impulse, I	758	860	922	967	1015	1068	1125	1183	1239	1355	1442
Vacuum specific impulse, I_{vac}	769	873	936	981	1029	1081	1137	1193	1248	1362	1449
Nozzle efficiency, η	0.900	0.846	0.760	0.680	0.593	0.510	0.440	0.387	0.352	0.320	0.325
Power/lb thrust, P_g/F	18.1	21.8	26.1	30.6	36.9	45.1	55.2	66.1	76.3	92.0	96.2
Stagnation press./nozzle exit press., p_0/p_e	3759	3650	3724	3899	4243	4834	5757	7038	8550	11701	13041
	Area ratio, 50										
Specific impulse, I	744	844	905	950	998	1052	1110	1170	1227	1344	1432
Vacuum specific impulse, I_{vac}	760	862	925	969	1018	1070	1127	1185	1240	1356	1443
Nozzle efficiency, η	0.868	0.815	0.732	0.656	0.574	0.495	0.429	0.379	0.345	0.315	0.321
Power/lb thrust, P_g/F	18.3	22.1	26.4	30.9	37.3	45.6	55.7	66.6	76.8	92.4	96.6
Stagnation press./nozzle exit press., p_0/p_e	1375	1340	1361	1415	1521	1703	1981	2360	2800	3702	4082
	Area ratio, 25										
Specific impulse, I	725	822	882	926	975	1029	1088	1149	1208	1328	1415
Vacuum specific impulse, I_{vac}	747	847	909	953	1002	1055	1113	1172	1229	1346	1433
Nozzle efficiency, η	0.824	0.773	0.695	0.624	0.547	0.474	0.412	0.366	0.335	0.307	0.314
Power/lb thrust, P_g/F	18.6	22.5	26.9	31.5	37.9	46.2	56.4	67.3	77.5	93.1	97.2
Stagnation press./nozzle exit press., p_0/p_e	501	489	494	510	541	596	679	789	914	1165	1270
	Area ratio, 10										
Specific impulse, I	688	779	836	879	927	981	1042	1105	1166	1289	1377
Vacuum specific impulse, I_{vac}	722	818	878	922	970	1024	1083	1144	1203	1323	1410
Nozzle efficiency, η	0.743	0.695	0.625	0.502	0.494	0.431	0.378	0.338	0.312	0.290	0.297
Power/lb thrust, P_g/F	19.3	23.3	27.8	32.5	39.1	47.6	57.9	68.9	79.1	94.7	98.8
Stagnation press./nozzle exit press., p_0/p_e	130	126	126	129	135	145	161	182	204	248	266
	Area ratio, 5										
Specific impulse, I	646	729	783	823	870	924	985	1049	1112	1236	1323
Vacuum specific impulse, I_{vac}	694	786	843	886	933	988	1048	1110	1171	1292	1380
Nozzle efficiency, η	0.653	0.609	0.547	0.493	0.435	0.381	0.337	0.305	0.283	0.266	0.274
Power/lb thrust, P_g/F	20.1	24.3	29.0	33.9	40.6	49.4	59.9	71.0	81.3	96.9	101.0
Stagnation press./nozzle exit press., p_0/p_e	0.45	43.7	43.6	44.3	45.9	48.6	52.7	57.9	63.7	74.6	79.0

TABLE I. - Continued. ISENTROPIC FROZEN EXPANSION OF HYDROGEN FOR AREA RATIOS FROM 5 TO ∞

(g) Stagnation pressure, 30 pounds per square inch absolute

Performance parameter	Stagnation temperature, °K										
	2000	2500	2800	3000	3200	3400	3600	3800	4000	4500	5000
	Stagnation enthalpy, H_0, cal/g										
	6310	8831	11193	13510	16719	21086	26796	33803	41669	59691	70066
	Weight fraction of molecular hydrogen dissociated, α_H										
	0.000565	0.00876	0.0285	0.0549	0.0974	0.1607	0.2482	0.3590	0.4851	0.7691	0.913
	Flow rate per unit throat area per unit stagnation pressure, $\dot{w}/A^*p_0$										
	0.002294	0.002037	0.001905	0.001819	0.001731	0.001641	0.001548	0.001458	0.001374	0.001217	0.001125
	Gas power per unit propellant weight flow rate, $P_g/\dot{w}$										
	13,900	18,690	23,170	27,570	33,670	41,960	52,800	66,110	81,050	115,300	135,000
	Frozen flow efficiency, η_f										
	0.996	0.954	0.880	0.806	0.718	0.627	0.542	0.471	0.417	0.351	0.342
	Area ratio, ∞										
Specific impulse, I	797	904	967	1009	1053	1098	1146	1195	1245	1361	1454
Vacuum specific impulse, I_{vac}	797	904	967	1009	1053	1098	1146	1195	1245	1361	1454
Nozzle efficiency, η	0.996	0.954	0.880	0.806	0.718	0.627	0.542	0.471	0.417	0.351	0.342
Power/lb thrust, P_g/F	17.4	20.7	24.0	27.3	32.0	38.2	46.1	55.3	65.1	84.7	92.9
Stagnation press./nozzle exit press., p_0/p_e	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
	Area ratio, 500										
Specific impulse, I	777	881	943	986	1031	1078	1128	1181	1234	1354	1448
Vacuum specific impulse, I_{vac}	783	888	950	993	1037	1084	1134	1186	1238	1357	1451
Nozzle efficiency, η	0.948	0.907	0.838	0.769	0.688	0.604	0.526	0.460	0.410	0.347	0.339
Power/lb thrust, P_g/F	17.8	21.0	24.4	27.8	32.5	38.7	46.6	55.8	65.5	85.0	93.0
Stagnation press./nozzle exit press., p_0/p_e	39556	37465	37693	39115	42156	47643	56711	70786	89948	145867	180916
	Area ratio, 100										
Specific impulse, I	758	859	919	962	1006	1055	1107	1162	1217	1341	1436
Vacuum specific impulse, I_{vac}	769	873	934	976	1021	1069	1120	1173	1227	1349	1443
Nozzle efficiency, η	0.901	0.862	0.796	0.732	0.656	0.578	0.506	0.445	0.399	0.340	0.334
Power/lb thrust, P_g/F	18.1	21.4	24.8	28.2	33.0	39.3	47.2	56.4	66.1	85.5	93.5
Stagnation press./nozzle exit press., p_0/p_e	3758	3627	3647	3748	3960	4336	4939	5828	7008	10337	12384
	Area ratio, 50										
Specific impulse, I	744	843	902	944	989	1037	1090	1146	1203	1329	1426
Vacuum specific impulse, I_{vac}	760	862	922	964	1009	1057	1109	1163	1218	1342	1437
Nozzle efficiency, η	0.869	0.830	0.767	0.705	0.634	0.560	0.491	0.434	0.389	0.335	0.329
Power/lb thrust, P_g/F	18.3	21.7	25.1	28.6	33.4	39.7	47.6	56.8	66.5	85.9	93.9
Stagnation press./nozzle exit press., p_0/p_e	1374	1332	1337	1367	1432	1548	1733	2002	2351	3313	3696
	Area ratio, 25										
Specific impulse, I	725	821	879	920	964	1013	1066	1121	1182	1312	1409
Vacuum specific impulse, I_{vac}	747	847	906	948	992	1041	1093	1149	1205	1331	1427
Nozzle efficiency, η	0.826	0.788	0.728	0.670	0.603	0.534	0.470	0.417	0.376	0.326	0.321
Power/lb thrust, P_g/F	18.6	22.1	25.6	29.1	33.9	40.3	48.3	57.6	67.3	86.6	94.6
Stagnation press./nozzle exit press., p_0/p_e	501	486	486	494	514	549	604	684	786	1057	1219
	Area ratio, 10										
Specific impulse, I	688	778	833	872	915	963	1017	1076	1136	1271	1369
Vacuum specific impulse, I_{vac}	722	818	875	916	960	1008	1062	1118	1177	1306	1404
Nozzle efficiency, η	0.744	0.707	0.653	0.602	0.543	0.483	0.428	0.382	0.348	0.306	0.303
Power/lb thrust, P_g/F	19.3	22.9	26.5	30.1	35.1	41.7	49.7	59.1	68.9	88.2	96.2
Stagnation press./nozzle exit press., p_0/p_e	129	125	125	126	129	136	147	162	181	229	257
	Area ratio, 5										
Specific impulse, I	646	728	779	816	857	904	958	1017	1078	1216	1314
Vacuum specific impulse, I_{vac}	694	785	840	879	921	970	1024	1082	1141	1274	1372
Nozzle efficiency, η	0.654	0.620	0.521	0.527	0.476	0.425	0.379	0.341	0.313	0.280	0.279
Power/lb thrust, P_g/F	20.0	23.8	27.6	31.4	36.5	43.2	51.6	61.1	71.0	90.4	98.4
Stagnation press./nozzle exit press., p_0/p_e	45.0	43.5	43.2	43.5	44.4	46.2	48.9	52.8	57.6	69.9	76.8

TABLE I. - Continued. *ISENTROPIC FROZEN EXPANSION OF HYDROGEN FOR AREA RATIOS FROM 5 TO ∞*

(h) Stagnation pressure, 50 pounds per square inch absolute

Performance parameter	Stagnation temperature, °K										
	2000	2500	2800	3000	3200	3400	3600	3800	4000	4500	5000
	Stagnation enthalpy, H_0, cal/g										
	6304	8724	10844	12837	15529	19141	23865	29775	36712	54891	67489
	Weight fraction of molecular hydrogen dissociated, α_H										
	0.0004	0.0068	0.0221	0.0426	0.0756	0.1251	0.1947	0.2856	0.3948	0.6818	0.8662
	Flow rate per unit throat area per unit stagnation pressure, $\dot{w}/A^*p_0$										
	0.002257	0.002039	0.001910	0.001828	0.001745	0.001661	0.001575	0.001488	0.001406	0.001238	0.001134
	Gas power per unit propellant weight flow rate, $P_g/\dot{w}$										
	13,890	18,480	22,510	26,290	31,410	38,260	37,240	58,460	71,630	106,200	130,100
	Frozen flow efficiency, η_f										
	0.997	0.964	0.905	0.842	0.766	0.682	0.599	0.524	0.463	0.375	0.352
	Area ratio, ∞										
Specific impulse, I	797	904	966	1008	1050	1093	1139	1186	1234	1350	1448
Vacuum specific impulse, I_{vac}	797	904	966	1008	1050	1093	1139	1186	1234	1350	1448
Nozzle efficiency, η	0.997	0.964	0.905	0.842	0.766	0.682	0.599	0.524	0.463	0.375	0.352
Power/lb thrust, P_g/F	17.4	20.4	23.3	26.1	29.9	35.0	41.5	49.3	58.1	78.6	89.8
Stagnation press./nozzle exit press., p_0/p_e	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
	Area ratio, 500										
Specific impulse, I	777	881	942	984	1026	1071	1119	1169	1220	1342	1442
Vacuum specific impulse, I_{vac}	782	888	949	991	1034	1078	1125	1174	1225	1345	1445
Nozzle efficiency, η	0.949	0.917	0.861	0.803	0.732	0.655	0.578	0.510	0.453	0.370	0.349
Power/lb thrust, P_g/F	17.8	20.8	23.7	26.5	30.4	35.5	42.0	49.8	58.5	78.9	90.0
Stagnation press./nozzle exit press., p_0/p_e	39545	37262	37135	38011	40096	43959	50402	60416	75098	126067	168542
	Area ratio, 100										
Specific impulse, I	758	859	918	959	1001	1047	1096	1147	1200	1328	1430
Vacuum specific impulse, I_{vac}	769	872	932	974	1016	1062	1110	1160	1212	1336	1437
Nozzle efficiency, η	0.902	0.870	0.817	0.763	0.697	0.625	0.555	0.491	0.439	0.362	0.343
Power/lb thrust, P_g/F	18.1	21.2	24.1	27.0	30.9	36.0	42.6	50.4	59.1	79.4	90.5
Stagnation press./nozzle exit press., p_0/p_e	3757	3615	3608	3669	3816	4084	4521	5180	6097	9170	11663
	Area ratio, 50										
Specific impulse, I	744	843	901	941	983	1029	1078	1131	1185	1315	1419
Vacuum specific impulse, I_{vac}	760	861	921	961	1004	1050	1098	1149	1202	1329	1430
Nozzle efficiency, η	0.870	0.838	0.787	0.735	0.672	0.604	0.537	0.477	0.428	0.356	0.338
Power/lb thrust, P_g/F	18.3	21.5	24.5	27.4	31.3	36.5	43.0	50.9	59.6	79.9	90.9
Stagnation press./nozzle exit press., p_0/p_e	1374	1328	1324	1342	1387	1469	1605	1806	2082	2978	3691
	Area ratio, 25										
Specific impulse, I	725	821	877	917	959	1004	1053	1107	1163	1296	1401
Vacuum specific impulse, I_{vac}	747	846	905	945	987	1033	1082	1134	1188	1317	1420
Nozzle efficiency, η	0.826	0.795	0.746	0.697	0.638	0.575	0.513	0.457	0.412	0.345	0.329
Power/lb thrust, P_g/F	18.6	21.9	24.9	27.8	31.8	37.1	43.7	51.6	60.3	80.6	91.6
Stagnation press./nozzle exit press., p_0/p_e	501	485	482	487	499	524	565	625	707	964	1162
	Area ratio, 10										
Specific impulse, I	688	778	831	868	909	953	1003	1057	1114	1253	1360
Vacuum specific impulse, I_{vac}	722	817	873	912	954	999	1048	1102	1157	1291	1396
Nozzle efficiency, η	0.745	0.714	0.669	0.626	0.574	0.518	0.465	0.417	0.378	0.323	0.310
Power/lb thrust, P_g/F	19.2	22.6	25.8	28.8	32.9	38.3	45.1	53.1	61.9	82.2	93.2
Stagnation press./nozzle exit press., p_0/p_e	129	125	124	124	127	131	139	150	166	213	247
	Area ratio, 5										
Specific impulse, I	646	728	777	812	850	893	942	996	1054	1195	1304
Vacuum specific impulse, I_{vac}	694	784	838	875	916	960	1010	1064	1120	1257	1364
Nozzle efficiency, η	0.655	0.625	0.585	0.547	0.502	0.455	0.410	0.370	0.339	0.294	0.285
Power/lb thrust, P_g/F	20.0	23.6	26.9	30.0	34.3	39.8	46.8	55.0	63.9	84.5	95.4
Stagnation press./nozzle exit press., p_0/p_e	45.0	43.5	43.0	43.1	43.7	44.9	46.9	49.9	53.8	65.7	74.4

TABLE I. - Continued. ISENTROPIC FROZEN EXPANSION OF HYDROGEN FOR AREA RATIOS FROM 5 TO ∞

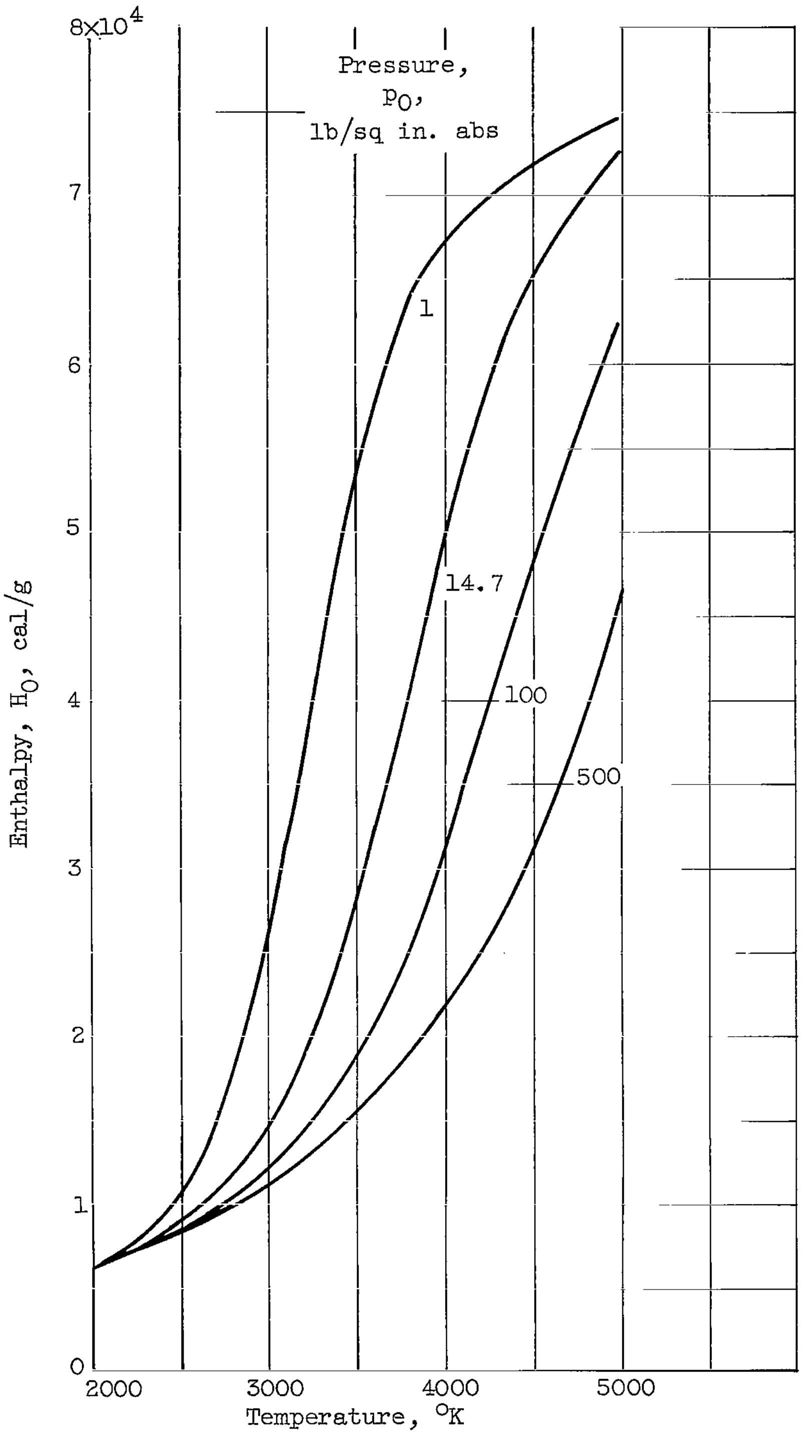
(1) Stagnation pressure, 100 pounds per square inch absolute

Performance parameter	Stagnation temperature, °K										
	2000	2500	2800	3000	3200	3400	3600	3800	4000	4500	5000
	Stagnation enthalpy, H_0, cal/g										
	6297	8616	10493	12159	14325	17156	20815	25423	31000	47656	62457
	Weight fraction of molecular hydrogen dissociated, α_H										
	0.0003	0.0048	0.0156	0.0301	0.0535	0.0888	0.1390	0.2062	0.2907	0.5503	0.7748
	Flow rate per unit throat area per unit stagnation pressure, $\dot{w}/A^*p_0$										
	0.00230	0.00204	0.00191	0.00184	0.00176	0.00168	0.00160	0.00153	0.00145	0.00127	0.00115
	Gas power per unit propellant weight flow rate, $P_g/\dot{w}$										
	13,860	18,260	21,830	24,990	29,100	34,480	41,430	50,190	60,790	92,400	120,500
	Frozen flow efficiency, η_f										
	0.998	0.974	0.930	0.883	0.821	0.749	0.674	0.600	0.534	0.420	0.374
	Area ratio, ∞										
Specific impulse, I	797	904	965	1006	1047	1089	1131	1175	1220	1334	1438
Vacuum specific impulse, I_{vac}	797	904	965	1006	1047	1089	1131	1175	1220	1334	1438
Nozzle efficiency, η	0.998	0.974	0.930	0.883	0.821	0.749	0.674	0.600	0.534	0.420	0.374
Power/lb thrust, P_g/F	17.4	20.2	22.6	24.8	27.8	31.7	36.6	42.7	49.8	69.2	83.8
Stagnation press./nozzle exit press., p_0/p_e	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
	Area ratio, 500										
Specific impulse, I	777	881	941	981	1022	1064	1109	1155	1203	1324	1430
Vacuum specific impulse, I_{vac}	782	887	948	988	1030	1072	1116	1162	1209	1328	1423
Nozzle efficiency, η	0.950	0.926	0.884	0.840	0.783	0.717	0.647	0.580	0.520	0.414	0.371
Power/lb thrust, P_g/F	17.7	20.6	23.0	25.3	28.3	32.2	37.2	43.2	50.3	69.6	84.1
Stagnation press./nozzle exit press., p_0/p_e	39533	37090	36580	36927	38102	40452	44456	50756	60092	99230	145608
	Area ratio, 100										
Specific impulse, I	758	858	916	956	996	1039	1084	1131	1181	1306	1416
Vacuum specific impulse, I_{vac}	769	872	931	971	1012	1054	1099	1146	1194	1317	1425
Nozzle efficiency, η	0.903	0.879	0.839	0.797	0.744	0.683	0.618	0.556	0.501	0.403	0.363
Power/lb thrust, P_g/F	18.0	21.0	23.5	25.8	28.8	32.7	37.7	43.8	50.9	70.2	84.6
Stagnation press./nozzle exit press., p_0/p_e	3756	3602	3568	3592	3674	3839	4116	4544	5159	7571	10320
	Area ratio, 50										
Specific impulse, I	744	842	899	938	978	1020	1065	1113	1164	1292	1404
Vacuum specific impulse, I_{vac}	760	861	919	959	999	1042	1086	1134	1183	1308	1418
Nozzle efficiency, η	0.871	0.847	0.808	0.768	0.717	0.659	0.598	0.539	0.486	0.394	0.357
Power/lb thrust, P_g/F	18.3	21.2	23.8	26.1	29.1	33.1	38.2	44.3	51.4	70.7	85.0
Stagnation press./nozzle exit press., p_0/p_e	1374	1325	1311	1317	1341	1392	1478	1610	1798	2515	3308
	Area ratio, 25										
Specific impulse, I	725	820	876	913	953	994	1039	1087	1139	1271	1385
Vacuum specific impulse, I_{vac}	747	846	903	942	982	1024	1069	1117	1167	1294	1406
Nozzle efficiency, η	0.827	0.803	0.766	0.728	0.680	0.625	0.569	0.514	0.466	0.381	0.348
Power/lb thrust, P_g/F	18.6	21.6	24.2	26.6	29.7	33.7	38.8	44.9	52.1	71.4	85.7
Stagnation press./nozzle exit press., p_0/p_e	501	484	478	479	485	500	326	566	622	832	1056
	Area ratio, 10										
Specific impulse, I	688	777	829	865	902	942	987	1035	1087	1224	1342
Vacuum specific impulse, I_{vac}	722	817	872	909	948	990	1034	1082	1134	1265	1380
Nozzle efficiency, η	0.745	0.721	0.687	0.652	0.610	0.562	0.513	0.466	0.425	0.354	0.326
Power/lb thrust, P_g/F	19.2	22.4	25.06	27.5	30.7	34.9	40.1	46.4	53.6	73.0	87.3
Stagnation press./nozzle exit press., p_0/p_e	129	125	123	123	124	126	131	139	150	189	229
	Area ratio, 5										
Specific impulse, I	645	727	775	808	843	882	925	972	1024	1163	1284
Vacuum specific impulse, I_{vac}	694	784	836	872	910	950	994	1042	1094	1229	1346
Nozzle efficiency, η	0.655	0.631	0.600	0.570	0.533	0.492	0.450	0.411	0.377	0.319	0.298
Power/lb thrust, P_g/F	20.0	23.3	26.1	28.7	32.0	36.3	41.7	48.2	55.6	75.2	89.5
Stagnation press./nozzle exit press., p_0/p_e	45	43.4	42.8	42.7	42.9	43.6	44.9	46.8	49.6	39.6	69.7

TABLE I. - Concluded. ISENTROPIC FROZEN EXPANSION OF HYDROGEN FOR AREA RATIOS FROM 5 TO ∞

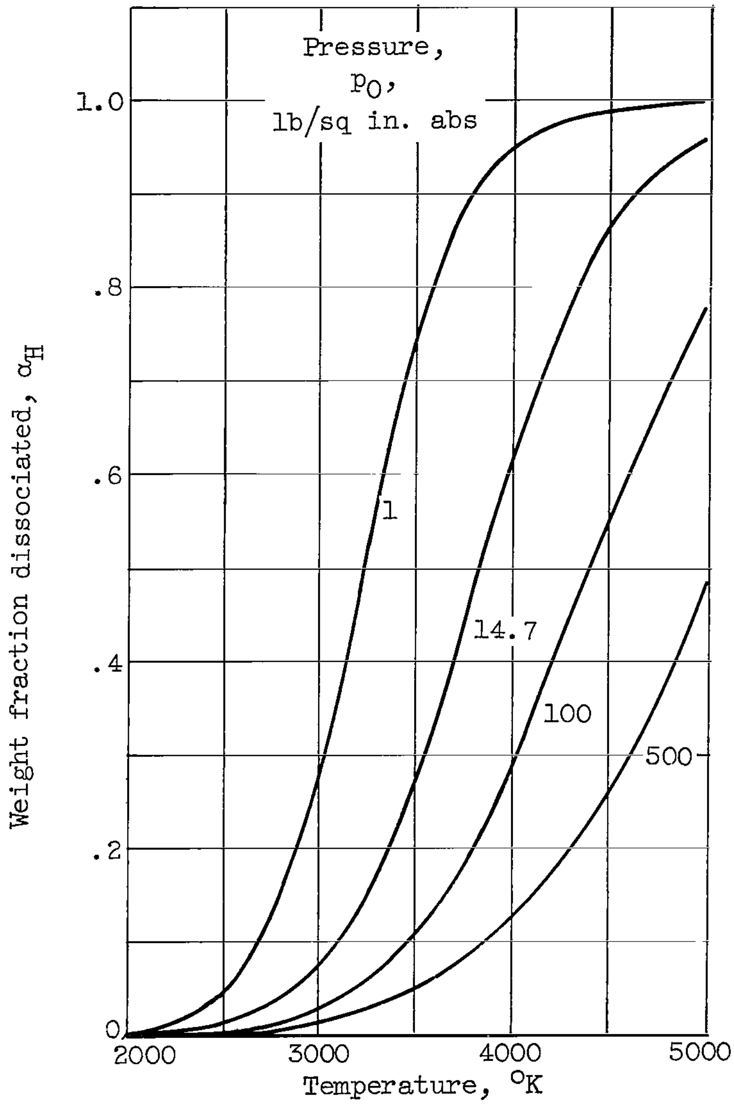
(j) Stagnation pressure, 500 pounds per square inch absolute

Performance parameter	Stagnation temperature, ^{o}K										
	2000	2500	2800	3000	3200	3400	3600	3800	4000	4500	5000
	Stagnation enthalpy, H_0, cal/g										
	6288	8473	10024	11252	12712	14478	16635	19262	22433	32936	46254
	Weight fraction of molecular hydrogen dissociated, α_H										
	0.0001	0.0021	0.0070	0.0135	0.0240	0.0399	0.0626	0.0938	0.135	0.283	0.481
	Flow rate per unit throat area per unit stagnation pressure, $\dot{w}/A^*p_0$										
	0.002298	0.002042	0.001921	0.001849	0.001780	0.001714	0.001650	0.001586	0.001521	0.001365	0.001226
	Gas power per unit propellant weight flow rate, $P_g/\dot{w}$										
	13,860	18,010	20,950	23,280	26,060	29,410	33,490	38,500	44,520	64,470	89,750
	Frozen flow efficiency, η_f										
	0.999	0.988	0.968	0.944	0.910	0.868	0.818	0.763	0.706	0.573	0.479
	Area ratio, ∞										
Specific impulse, I	797	903	964	1004	1043	1082	1121	1160	1200	1301	1403
Vacuum specific impulse, I_{vac}	797	903	964	1004	1043	1082	1121	1160	1200	1301	1403
Nozzle efficiency, η	0.997	0.988	0.968	0.944	0.910	0.868	0.818	0.763	0.706	0.573	0.479
Power/lb thrust, P_g/F	17.9	20.5	22.3	33.8	26.0	27.9	30.7	34.0	37.9	50.4	64.8
Stagnation press./nozzle exit press., p_0/p_e	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
	Area ratio, 500										
Specific impulse, I	777	880	939	978	1016	1055	1094	1134	1175	1282	1390
Vacuum specific impulse, I_{vac}	782	887	946	985	1024	1063	1102	1142	1183	1288	1395
Nozzle efficiency, η	0.951	0.939	0.919	0.896	0.865	0.826	0.780	0.729	0.677	0.556	0.470
Power/lb thrust, P_g/F	17.7	20.3	22.1	23.6	25.4	27.7	30.4	33.7	37.6	50.0	64.3
Stagnation press./nozzle exit press., p_0/p_e	39517	36861	35850	35520	35567	36105	37283	39292	92372	56797	83911
	Area ratio, 100										
Specific impulse, I	758	857	914	952	989	1027	1066	1106	1148	1257	1369
Vacuum specific impulse, I_{vac}	769	871	929	967	1006	1044	1083	1123	1164	1272	1382
Nozzle efficiency, η	0.904	0.891	0.871	0.849	0.820	0.783	0.740	0.694	0.646	0.535	0.456
Power/lb thrust, P_g/F	18.0	20.7	22.5	24.1	25.9	28.2	30.9	34.3	38.2	50.7	65.0
Stagnation press./nozzle exit press., p_0/p_e	3755	3586	3516	3490	3491	3526	3608	3748	3963	4940	6665
	Area ratio, 50										
Specific impulse, I	744	841	897	934	971	1008	1046	1086	1127	1239	1355
Vacuum specific impulse, I_{vac}	760	860	917	955	992	1030	1069	1109	1151	1260	1371
Nozzle efficiency, η	0.872	0.858	0.838	0.817	0.789	0.754	0.713	0.669	0.623	0.519	0.445
Power/lb thrust, P_g/F	18.2	20.9	22.8	24.4	26.3	28.5	31.3	34.7	38.7	51.2	65.5
Stagnation press./nozzle exit press., p_0/p_e	1373	1319	1295	1284	1282	1291	1315	1358	1425	1726	2246
	Area ratio, 25										
Specific impulse, I	725	820	873	909	944	981	1018	1058	1099	1211	1329
Vacuum specific impulse, I_{vac}	747	845	901	938	975	1012	1050	1090	1132	1242	1356
Nozzle efficiency, η	0.828	0.814	0.794	0.774	0.747	0.714	0.676	0.634	0.592	0.497	0.429
Power/lb thrust, P_g/F	18.6	21.3	23.3	24.8	26.7	29.1	31.9	35.3	39.3	51.9	66.2
Stagnation press./nozzle exit press., p_0/p_e	501	482	473	468	467	468	475	487	507	598	752
	Area ratio, 10										
Specific impulse, I	688	776	827	860	893	927	963	1001	1042	1155	1275
Vacuum specific impulse, I_{vac}	722	816	869	905	940	976	1013	1053	1094	1206	1323
Nozzle efficiency, η	0.746	0.731	0.712	0.693	0.668	0.638	0.604	0.568	0.532	0.451	0.396
Power/lb thrust, P_g/F	19.2	22.1	24.1	25.7	27.7	30.1	33.1	36.6	40.7	53.5	67.9
Stagnation press./nozzle exit press., p_0/p_e	129	124	122	127	120	120	121	123	127	144	173
	Area ratio, 5										
Specific impulse, I	645	726	772	803	834	866	900	936	975	1086	1208
Vacuum specific impulse, I_{vac}	694	783	834	867	901	936	972	1010	1050	1162	1282
Nozzle efficiency, η	0.656	0.640	0.621	0.604	0.582	0.556	0.527	0.497	0.466	0.399	0.355
Power/lb thrust, P_g/F	20.0	23.0	25.1	26.9	28.9	31.4	34.5	38.1	42.4	55.5	70.0
Stagnation press./nozzle exit press., p_0/p_e	45.0	43.3	42.5	42.1	41.9	41.9	42.2	42.8	43.8	38.3	55.6



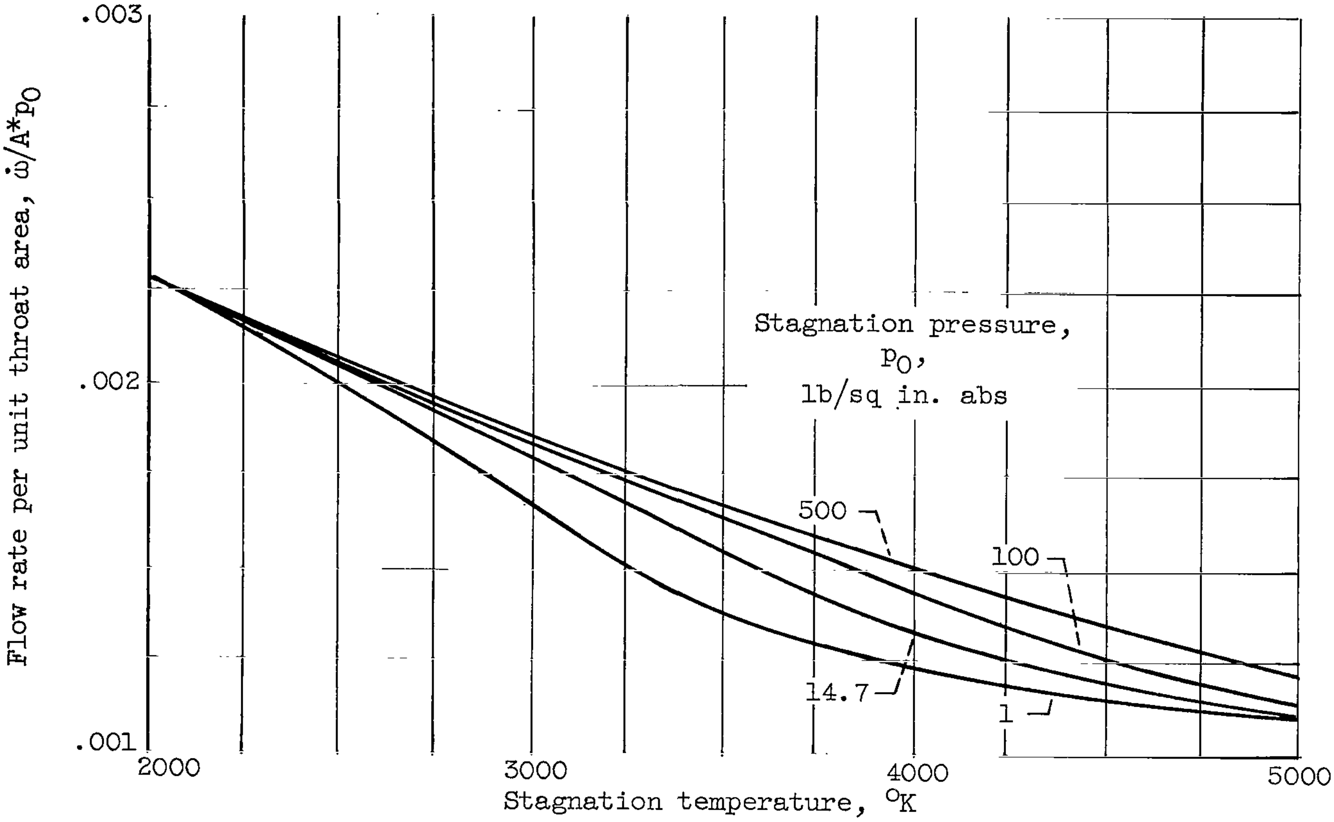
(a) Enthalpy. Reference temperature, 298° K.

Figure 1. - Stagnation parameters of hydrogen.



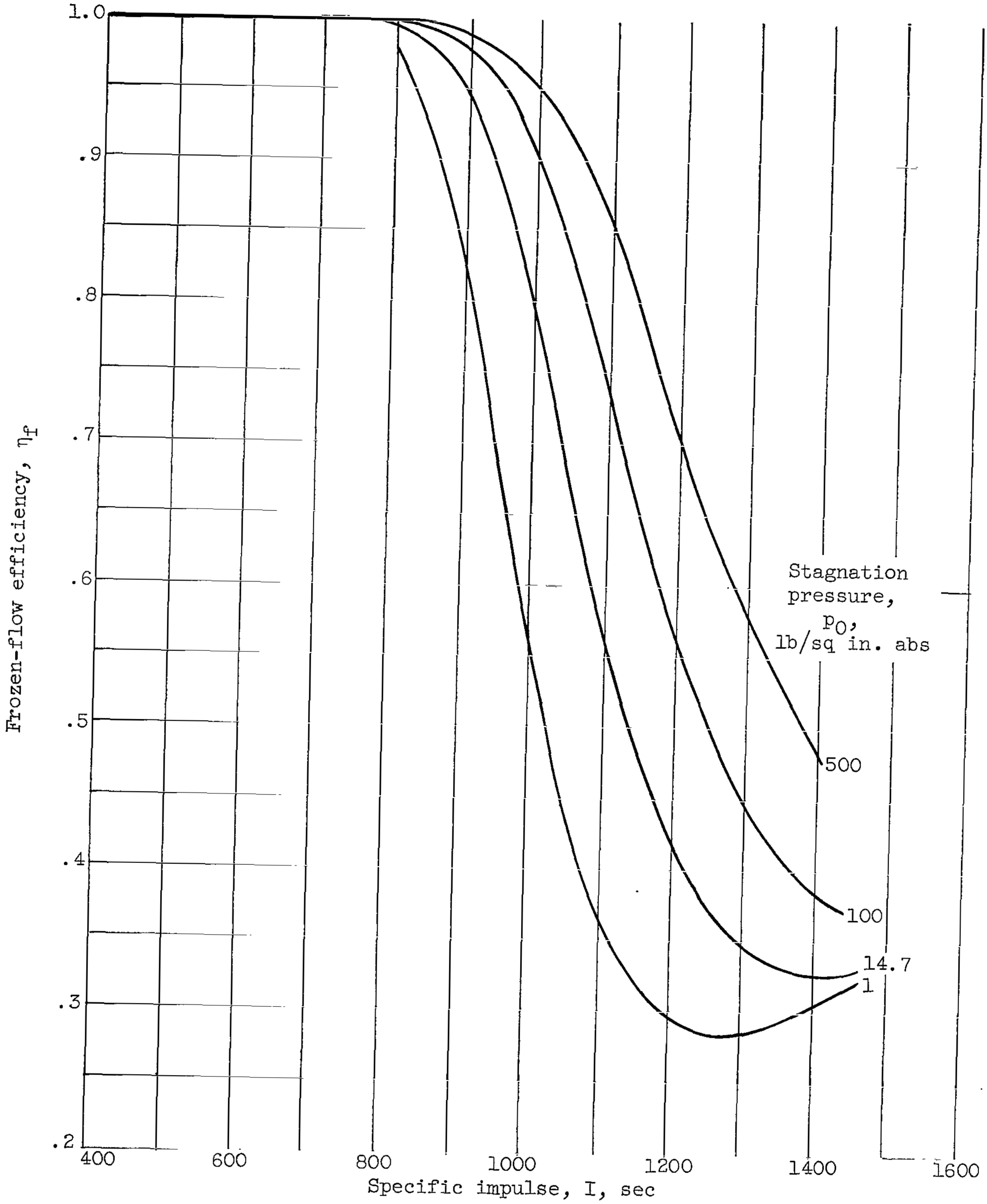
(b) Weight fraction of molecular hydrogen dissociated.

Figure 1. - Continued. Stagnation parameters of hydrogen.



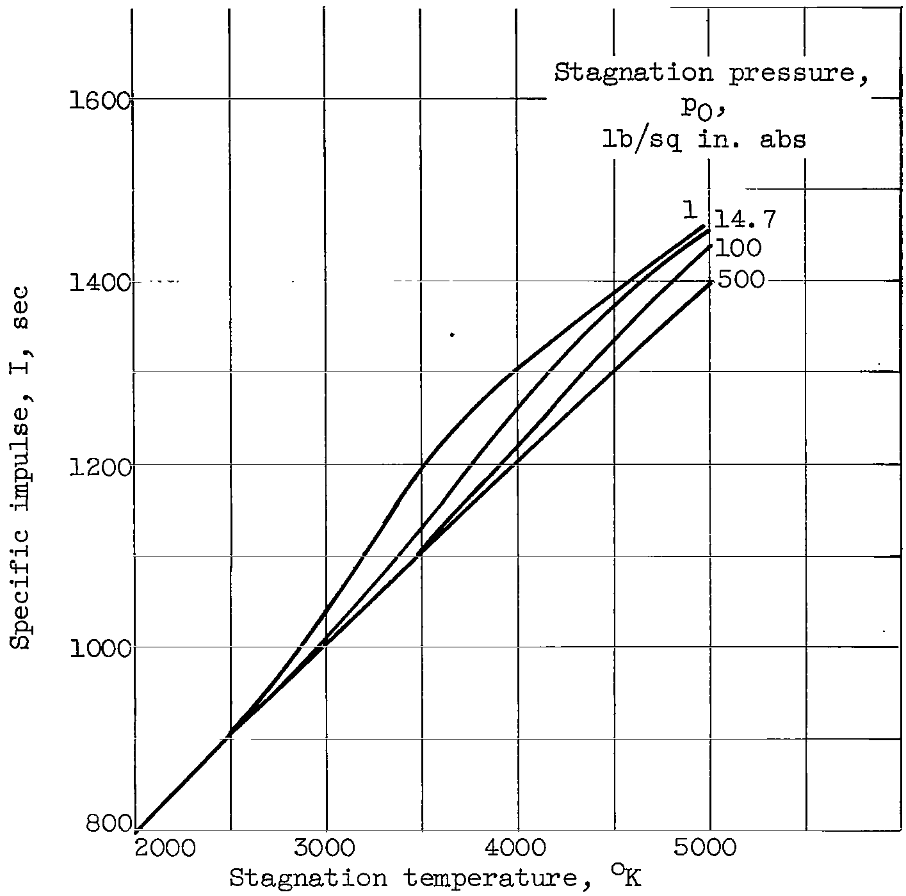
(c) Flow rate per unit throat area.

Figure 1. - Concluded. Stagnation parameters of hydrogen.



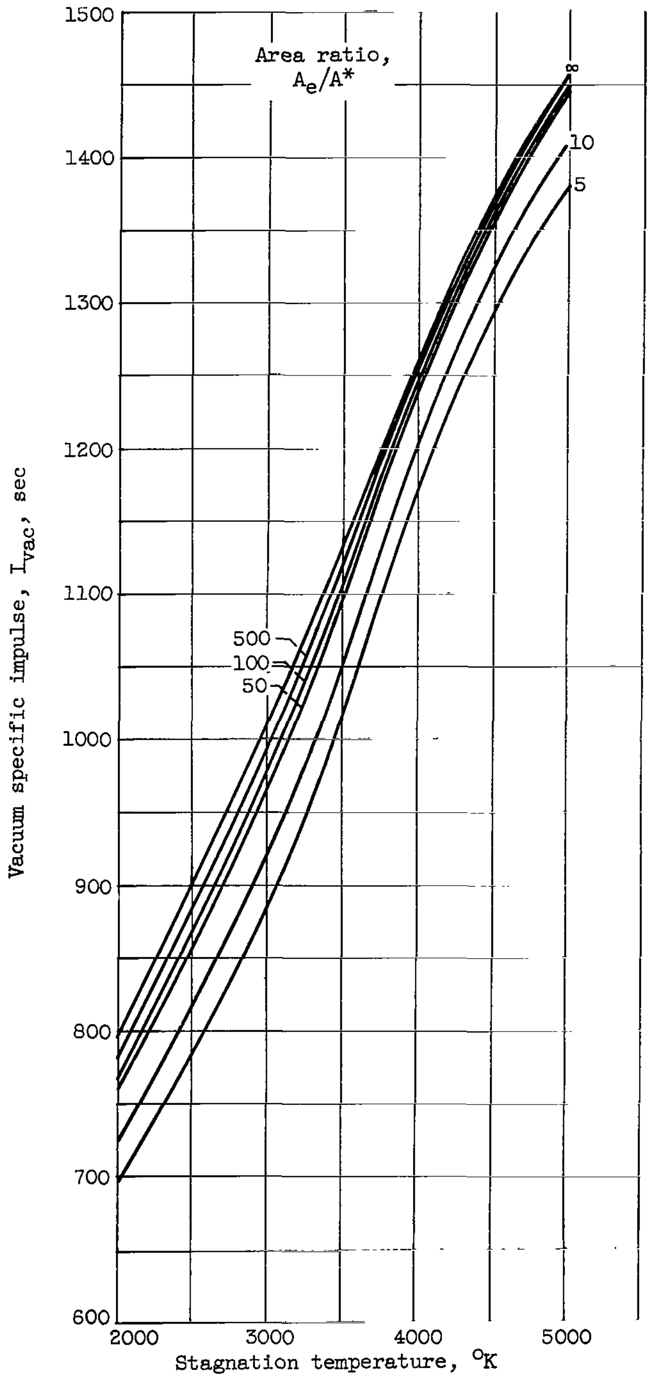
(a) Frozen flow efficiency; infinite area and pressure ratios.

Figure 2. - Performance characteristics of hydrogen for frozen expansion.



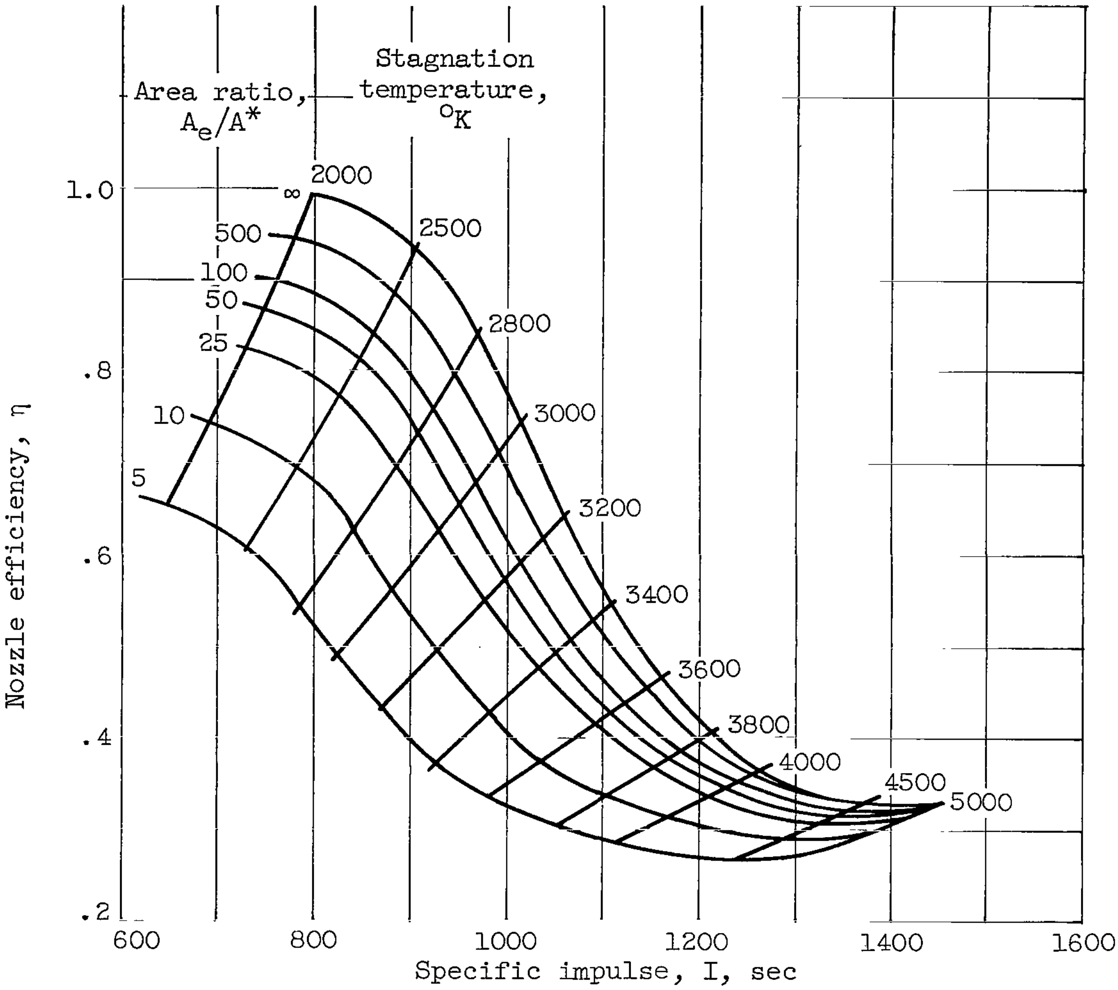
(b) Specific impulse; infinite area and pressure ratios.

Figure 2. - Continued. Performance characteristics of hydrogen for frozen expansion.



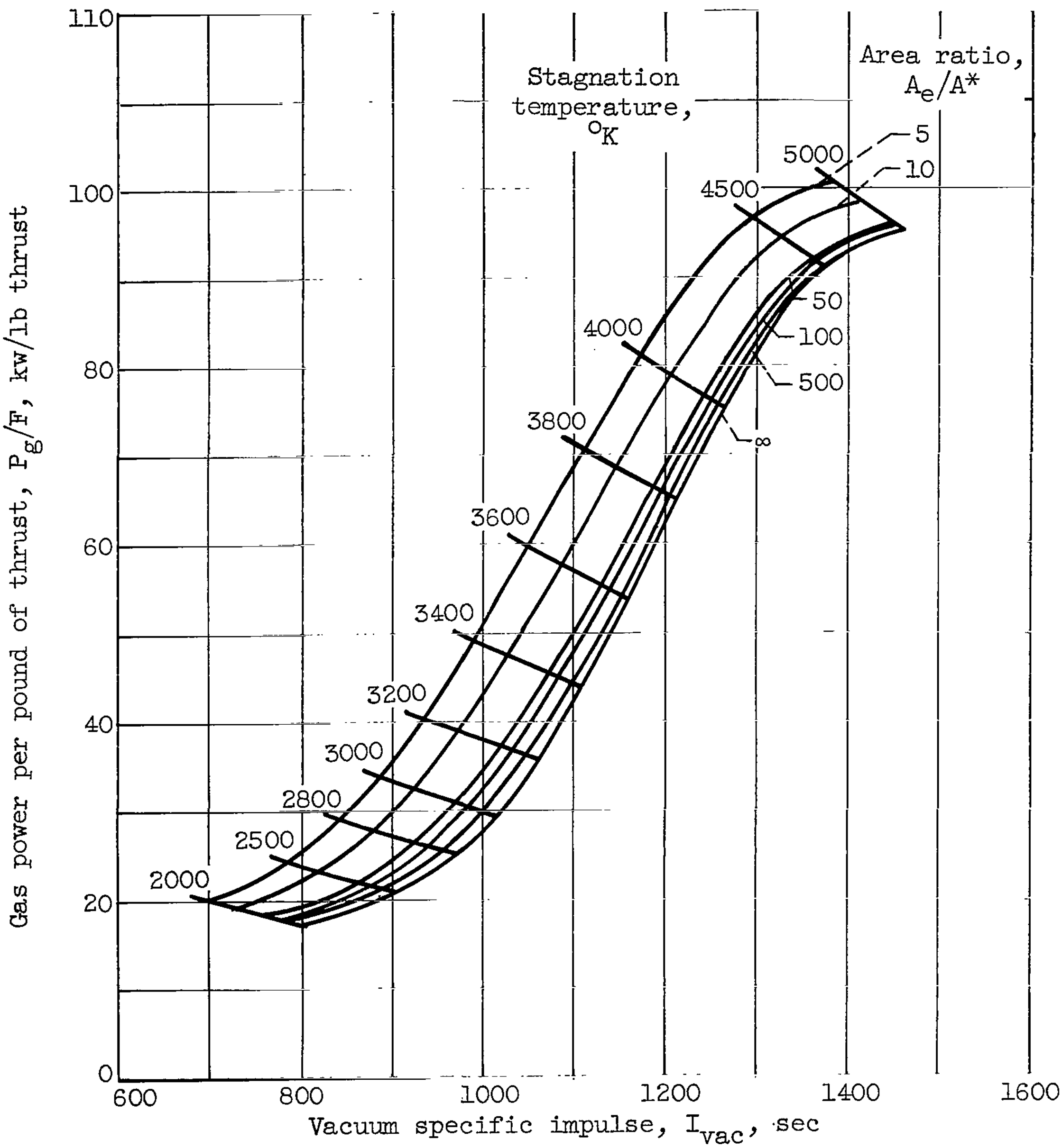
(c) Vacuum specific impulse; finite area ratio; ambient pressure, 0; stagnation pressure, 14.7 pounds per square inch absolute.

Figure 2. - Continued. Performance characteristics of hydrogen for frozen expansion.



(d) Nozzle efficiency; finite area ratio; stagnation pressure, 14.7 pounds per square inch absolute.

Figure 2. - Continued. Performance characteristics of hydrogen for frozen expansion.



(e) Gas power per pound of thrust; finite area ratio; ambient pressure, 0; stagnation pressure, 14.7 pounds per square inch absolute.

Figure 2. - Concluded. Performance characteristics of hydrogen for frozen expansion.

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