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THERMODYNAMIC AND TRANSPORT PROPERTIES OF AIR AND THE COMBUSTION PRODUCTS OF NATURAL GAS AND OF ASTM-A-1 FUEL WITH AIR

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16. Abstract

The ratio of specific heats, molecular weight, viscosity, specific heat at constant pressure, thermal conductivity, and Prandtl number were calculated for air, the combustion products of natural gas and air, and the combustion products of ASTM-A-1 jet fuel and air. These properties were calculated for temperatures from 300 to 2500 K, pressures of 3 and 10 atm (3.04×10^5 and 10.13×10^5 N/m^2), and fuel-air ratios from zero to stoichiometric. Adiabatic combustion temperatures were also determined. The theoretical data for thermal conductivity and Prandtl number were compared with experimental values of these properties available in the literature. Agreement between the theoretical and experimental data was within 5 percent.

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SUMMARY

The ratio of specific heats, molecular weight, viscosity, specific heat at constant pressure, thermal conductivity, and Prandtl number were calculated for air, the combustion products of natural gas and air, and the combustion products of ASTM-A-1 jet fuel and air. The properties were analytically determined over a temperature range from 300 to 2500 K and for pressures of 3 and 10 atmospheres (3.04×10^5 and 10.13×10^5 N/m^2). The data for natural gas and ASTM-A-1 were calculated for fuel-air ratios from zero to stoichiometric. Adiabatic combustion temperatures over the same range of pressure and fuel-air ratios were also determined for natural gas and ASTM-A-1.

Theoretical values of Prandtl number and thermal conductivity for air and the combustion products of a $(CH_2)_n$ type hydrocarbon jet fuel at the stoichiometric fuel-air ratio were compared with data from an independent experimental investigation. The maximum difference between experimental and theoretical Prandtl numbers and thermal conductivities was less than 5 percent.

INTRODUCTION

An analytical investigation was conducted to determine the thermodynamic and transport properties for air, the combustion products of natural gas and air, and the combustion products of ASTM-A-1 jet fuel and air at the pressures and temperatures encountered in NASA jet engine turbine-cooling studies. Values of these properties were not available in the literature over the full range of interest (e.g., see ref. 1). Accurate values are required when basic heat-transfer correlations are being developed to improve the reliability of predicting turbine blade and vane local temperatures.

The properties determined analytically were the ratio of specific heats γ, molecular weight m, viscosity μ, specific heat at constant pressure c_p, thermal conductivity k, and Prandtl number Pr. Adiabatic combustion temperatures were also determined by assuming an initial fuel and air temperature of 298 K. The calculations were made for (1) air, (2) natural gas burned in air, and (3) ASTM-A-1 jet fuel burned in air. All properties were calculated for temperatures from 300 to 2500 K at pressures of 3 and 10 atmospheres (3.04×10^5 and 10.13×10^5 N/m^2). The properties for the combustion products of both natural gas and ASTM-A-1 were determined for fuel-air ratios up to stoichiometric.

An independent experimental investigation of the Prandtl number and thermal conductivity for hydrocarbon combustion products over a limited temperature range was recently completed at the University of Minnesota under a NASA contract. The experimental techniques and results are described in detail in reference 2. Where applicable, comparisons are made herein to demonstrate the correlation of the theoretical and experimental data.

SYMBOLS

c_p	specific heat at constant pressure, cal/(g)(K); J/(g)(K)
F/A	fuel-air ratio
ΔH_c^o	heat of combustion at 298 K, cal/g; J/g
k	thermal conductivity, cal/(cm)(sec)(K); J/(cm)(sec)(K)
m	molecular weight
P	pressure, atm; N/m^2
Pr	Prandtl number
T	temperature, ^oR, K
γ	ratio of specific heats
μ	viscosity, g/(cm)(sec)

Subscripts:

R	recovery
s	static
T	total

THERMODYNAMIC AND TRANSPORT PROPERTY CALCULATIONS PROGRAM

The program used to calculate the thermodynamic and transport properties is described in reference 3. It is a program which combines the thermodynamic chemical equilibrium calculations program (refs. 4 and 5) with a program which calculates the transport properties. Transport cross-section data used in the calculations for species involving the elements hydrogen, oxygen, and nitrogen were obtained from references 3 and 6, and for species involving carbon and argon were obtained from reference 7. The only change in the program was that rotational relaxation effects were included in the calculation of the thermal conductivity (ref. 8). The rotational collision numbers used in the calculations are given (in parentheses) as follows: methane CH_4 (9), carbon dioxide CO_2 (2.4), hydrogen H_2 (250), water H_2O (2), nitrogen N_2(7), and oxygen O_2 (12). The collision numbers were assumed to be independent of temperature. For the other species, the Eucken approximation was used.

The program was used to determine the combustion temperature of both natural gas and ASTM-A-1 with air at pressures of 3 and 10 atmospheres (3.04×10^5 and 10.13×10^5 N/m^2), and also the thermodynamic and transport properties at these two pressures and temperatures from 300 to 2500 K. The compositions assumed for air, natural gas, and ASTM-A-1 are given in appendix A.

THERMODYNAMIC AND TRANSPORT PROPERTY CALCULATIONS

Calculations of thermodynamic and transport properties were made for air, natural gas burned in air, and ASTM-A-1 burned in air at temperatures from 300 to 2500 K and pressures of 3 and 10 atmospheres (3.04×10^5 and 10.13×10^5 N/m^2). The results of these calculations are presented in tables I to VII and in figures 1 to 27. The data for air are shown in the figures as the curves for a fuel-air ratio, F/A, of zero. For fuel-air ratios greater than zero, the lowest temperature for which data are plotted in figures 1 to 23 corresponds to the point at which water condenses from the combustion products.

The thermodynamic and transport properties γ, m, μ, c_p, k, and Pr of air at a pressure of 3 atmospheres (3.04×10^5 N/m^2) are given in table I and are shown graphically in figures 1 to 6 and 13 to 18 as the data for a fuel-air ratio of zero. The other F/A data in these figures are discussed in the next two sections. The analytical data show that the ratio of specific heats decreases with increasing temperature whereas the viscosity, specific heat at constant pressure, and thermal conductivity increase with increasing temperature. The molecular weight remains constant until dissociation effects become apparent at approximately 2000 K. The Prandtl number is essentially constant until a temperature of approximately 800 K is reached and decreases thereafter.

The properties of air at 10 atmospheres (10.13×10^5 N/m^2) are shown in table II and in figures 7 to 11 and 19 to 23. Since the calculations indicate that the difference in the viscosity of air at 3 and 10 atmospheres (3.04×10^5 and 10.13×10^5 N/m^2) is negligible over the entire temperature range investigated, figure 3 is applicable to both pressure levels for air. Increasing the pressure from 3 to 10 atmospheres (3.04×10^5 to 10.13×10^5 N/m^2) has essentially no effect on the other thermodynamic and transport properties of air at temperatures below approximately 2000 K. Above 2000 K, γ, m, and Pr increase with an increase in pressure, whereas c_p and k decrease at higher pressure. The greatest effect of pressure is in the c_p, k, and Pr data.

Combustion Products of Natural Gas and Air

The adiabatic combustion temperatures for natural gas and air as a function of F/A are shown in table III and in the upper curves of figure 12. The initial temperature of the reactants was assumed to be 298 K. Pressure has no effect on the combustion temperature for fuel-air ratios below 0.04. For fuel-air ratios greater than 0.04, a slight increase in combustion temperature occurs with pressure. The highest combustion temperatures of 2242 and 2262 K are attained at the stoichiometric F/A for pressures of 3 and 10 atmospheres (3.04×10^5 and 10.13×10^5 N/m^2), respectively.

The effect of F/A on the thermodynamic and transport properties at 3 atmospheres (3.04×10^5 N/m^2) is shown in table IV and in figures 1 to 6. The properties were calculated for fuel-air ratios from zero (air) to stoichiometric and for temperatures from 300 to 2500 K. The ratio of specific heats, molecular weight, and viscosity decrease with increasing F/A, while the specific heat at constant pressure and thermal conductivity show the opposite trend. For temperatures lower than approximately 1400 K, the Prandtl number increases with increasing F/A, whereas above 1400 K the effect is reversed.

The corresponding data at 10 atmospheres (10.13×10^5 N/m^2) are given in table V and in figures 7 to 11. Over the range of F/A investigated, the effect of pressure on the properties of the combustion products of natural gas and air is essentially the same as that described for air, with pressure having a negligible effect until the temperature exceeds approximately 1700 K. As was the case for air, the viscosity is essentially independent of pressure, and, thus, figure 3 can be used for the viscosity data at 3 and 10 atmospheres (3.04×10^5 and 10.13×10^5 N/m^2).

Combustion Products of ASTM-A-1 and Air

Table III and the lower curves in figure 12 illustrate the effect of F/A on the adiabatic combustion temperature of ASTM-A-1 for fuel-air ratios from zero to stoichiometric and pressures of 3 and 10 atmospheres (3.04×10^5 and 10.13×10^5 N/m^2). The combustion temperatures for ASTM-A-1 are lower than those for natural gas at a given

F/A with a maximum difference of 87 K at F/A = 0.04. The effect of pressure on the adiabatic combustion temperature is similar to that discussed for natural gas with maximum combustion temperatures of 2307 and 2333 K at 3 and 10 atmospheres (3.04×10^5 and 10.13×10^5 N/m^2), respectively.

The thermodynamic and transport properties of the combustion products of ASTM-A-1 at 3 atmospheres (3.04×10^5 N/m^2) are given in table VI and in figures 13 to 18. The variation of property data with F/A and temperature is similar to that discussed for natural gas with the exception of molecular weight. That is, the ratio of specific heats and viscosity decrease with increasing fuel-air ratio, whereas the specific heat at constant pressure and thermal conductivity increase with increasing fuel-air ratio. However, at temperatures below approximately 1700 K, the molecular weight is essentially independent of fuel-air ratio over the range of fuel-air ratios investigated. Above 1700 K, the molecular weight decreases with increasing fuel-air ratio. The Prandtl number increases with increasing fuel-air ratio below about 1700 K. At temperatures greater than 1700 K, the opposite trend is shown except at the stoichiometric fuel-air ratio above 2200 K.

Similar data for the properties at 10 atmospheres (10.13×10^5 N/m^2) are given in table VII and in figures 19 to 23. The viscosity is essentially independent of pressure over the temperature range investigated, and figure 15 is therefore applicable to 10 atmospheres (10.13×10^5 N/m^2), also. All property variations with pressure are similar to that discussed previously for air and the combustion products of natural gas and air, with the effect of pressure becoming noticeable at temperatures above approximately 1700 K.

COMPARISON OF EXPERIMENTAL AND THEORETICAL DATA

An independent experimental determination of the Prandtl number and the thermal conductivity of air and the combustion products of a simulated hydrocarbon fuel with air was made at the University of Minnesota subsequent to the completion of the theoretical study just described. The experimental investigation was conducted under NASA contract and is summarized in appendix B and described in detail in reference 2.

The values for experimental and theoretical Prandtl numbers for air at temperatures from approximately 800 to 1400 K are shown in figure 24. The experimental data are lower than the NASA theoretical data over the entire temperature range of the experimental investigation. The agreement between experimental and theoretical data is fairly good, with a maximum difference of about 5 percent. Although the experimental data were obtained at 1 atmosphere (1.01×10^5 N/m^2), whereas the theoretical data were calculated for 3 atmospheres (3.04×10^5 N/m^2), the results are comparable since the data presented in tables VI and VII and in figures 18 and 23 indicate no pressure effect on Prandtl number in the temperature range in which the comparison was made.

The experimental and theoretical data for the thermal conductivity of air are presented in figure 25. The agreement between experimental and theoretical thermal conductivities is similar to the agreement in Prandtl number data. The experimental thermal conductivity data fall above the theoretical curve in all cases, with a maximum difference of approximately 5 percent as expected since the experimental thermal conductivities were calculated from the experimental values of Prandtl number.

The experimental and theoretical Prandtl number data for combustion products of a hydrocarbon fuel with a hydrogen- to carbon-atom ratio of 2 ($(CH_2)_n$) and air for a fuel-air ratio of 0.068 are shown in figure 26. The experimental and theoretical data agree within 2.5 percent. Although the simulated fuel was assumed to have a hydrogen- to carbon-atom ratio of 2, whereas ASTM-A-1 has a hydrogen- to carbon-atom ratio of 1.918, the theoretical data for the Prandtl number of the combustion products of natural gas and air and of ASTM-A-1 and air show a negligible difference in the theoretical Prandtl number between ASTM-A-1 and a hydrocarbon fuel with a hydrogen- to carbon-atom ratio of 2. The theoretical data were calculated at a pressure of 3 atmospheres (3.04×10^5 N/m^2) whereas the experimental values were determined at 1 atmosphere (1.01×10^5 N/m^2). However, the pressure effect on theoretical Prandtl number is negligible. Thus, the comparison of the theoretical Prandtl number data of ASTM-A-1 at 3 atmospheres (3.04×10^5 N/m^2) with the experimental data is justified.

A comparison of experimental and theoretical thermal conductivity is shown in figure 27. The correlation of the experimental and theoretical data is good, with all the experimental data falling within 4 percent of the theoretical data. The experimental thermal conductivities are somewhat larger than the theoretical data because the viscosity values used in reference 2 are higher than those calculated with the NASA thermodynamic properties program.

CONCLUDING REMARKS

The ratio of specific heats, molecular weight, viscosity, specific heat at constant pressure, thermal conductivity, and Prandtl number were analytically determined for air, the combustion products of natural gas and air, and the combustion products of ASTM-A-1 and air. These properties were calculated for temperatures from 300 to 2500 K and pressures of 3 and 10 atmospheres (3.04×10^5 and 10.13×10^5 N/m^2). The data for natural gas and ASTM-A-1 were determined for fuel-air ratios from zero to stoichiometric. Adiabatic combustion temperatures of natural gas burned in air and ASTM-A-1 burned in air were also calculated over this range of fuel-air ratios.

The theoretical data presented herein are for the combustion products of the fuels defined in appendix A. However, it is estimated that the difference between calculated thermodynamic and transport properties of the combustion products of natural gas and the properties of any nominal natural gas composition burned in air will be less than 3 percent. Likewise, errors of less than 3 percent will be introduced if the thermodynamic and transport properties of the combustion products of ASTM-A-1 are used for the properties of the combustion products of any of the typical JP fuels.

The effect of pressure on the theoretical properties is negligible for temperatures less than 1700 K since the amount of dissociation of the reaction products does not become a significant factor until the temperature exceeds 1700 K. Even for temperatures exceeding 1700 K, the viscosity was not affected over the pressure range investigated. Of the remaining properties investigated, the specific heat at constant pressure, thermal conductivity, and Prandtl number were the most sensitive to pressure.

The comparison of experimental and theoretical data for the Prandtl number and thermal conductivity for air and for the combustion products of a $(CH_2)_n$ type hydrocarbon fuel at the stoichiometric fuel-air ratio showed good agreement over the limited temperature range of the experimental investigation conducted at the University of Minnesota. The maximum difference between experimental and theoretical Prandtl numbers and thermal conductivities was less than 5 percent.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 17, 1969,
720-03.

APPENDIX A

COMPOSITIONS OF AIR, NATURAL GAS, AND ASTM-A-1

The following data define the compositions that were assumed for air, natural gas, and ASTM-A-1 jet fuel.

The composition of air is given by the following formula:

$$C_{0.00030}N_{1.56176}O_{0.41959}Ar_{0.00932}$$

Natural gas was assumed to consist of the following components:

Component	Composition, wt. %
Nitrogen, N_2	2.648
Methane, CH_4	87.474
Carbon dioxide, CO_2	1.181
Ethane, C_2H_6	6.332
Propane, C_3H_8	1.621
Butane, C_4H_{10}	.576
Pentane, C_5H_{12}	.168

ASTM-A-1 jet fuel has the composition $CH_{1.9184}$ and at 298 K has a heat of combustion ΔH_c^o of -10 333 calories per gram (-43 200 J/g).

APPENDIX B

EXPERIMENTAL MEASUREMENT OF PRANDTL NUMBER AND THERMAL CONDUCTIVITY

An experimental investigation of Prandtl number and thermal conductivity was conducted by the University of Minnesota for a simulated hydrocarbon fuel assumed to have a hydrogen- to carbon-atom ratio of 2. The Prandtl number and thermal conductivity were determined for temperatures from approximately 800 to 1340 K at a pressure of 1 atmosphere (1.01×10^5 N/m^2).

The experimental procedure was based on the fact that the recovery factor for a flat plate is equal to the square root of the Prandtl number for laminar boundary layer flows at high velocity. End effects were eliminated by using a cylinder with its axis parallel to the direction of flow to simulate the conditions on a flat plate. The recovery temperature of the cylinder was conveniently measured by using a differential thermocouple as the cylinder. The combustion products were synthesized by mixing carbon dioxide, water vapor, nitrogen, and air in the required proportions to simulate the reaction products. The gaseous mixture was heated to the required test temperature in a heat exchanger and then accelerated through a nozzle to develop the high velocity flow required for application of the aforementioned relation between recovery factor and Prandtl number. The junctions of the differential thermocouple were positioned so that the difference between total temperature and recovery temperature was read directly. This temperature difference and a measurement of total temperature and static- to total-pressure ratio are sufficient to calculate Prandtl number:

$$(\mathrm{Pr})^{1/2} = 1 - \frac{T_T - T_R}{T_T\left[1 - \left(\dfrac{P_s}{P_T}\right)^{(\gamma-1)/\gamma}\right]}$$

(eq. (7) of ref. 2). The thermal conductivity was derived in the following manner. The specific heat at constant pressure was analytically determined by using a weighted average of specific heats for the individual components of the combustion products. The viscosity of the reaction mixture was calculated by the method of Chapman and Cowling, as described in reference 9. The thermal conductivity was then calculated from the experimental value of the Prandtl number.

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TABLE I. - THERMODYNAMIC AND TRANSPORT PROPERTIES OF AIR

AT 3 ATMOSPHERES (3.04×10^{5} N/m^{2})

Temperature, T, K	Ratio of specific heats, γ	Molecular weight, m	Viscosity μ, g/(cm)(sec)	Specific heat at constant pressure, c_p		Thermal conductivity, k		Prandtl number, Pr
				cal/(g)(K)	J/(g)(K)	cal/(cm)(sec)(K)	J/(cm)(sec)(K)	
300	1.4001	28.967	1.78×10^{-4}	0.2401	1.005	0.61×10^{-4}	2.6×10^{-4}	0.704
400	1.3951		2.24	.2422	1.013	.77	3.2	.705
500	1.3865		2.64	.2461	1.030	.92	3.8	.705
600	1.3759		3.00	.2511	1.051	1.07	4.48	.706
700	1.3646		3.33	.2568	1.074	1.21	5.06	
800	1.3537		3.63	.2626	1.099	1.35	5.65	
900	1.3439		3.92	.2681	1.122	1.49	6.23	
1000	1.3357		4.19	.2730	1.142	1.62	6.78	
1100	1.3288		4.44	.2772	1.160	1.75	7.32	.705
1200	1.3224		4.69	.2814	1.177	1.87	7.82	.705
1300	1.3163		4.93	.2855	1.195	2.00	8.37	.705
1400	1.3103		5.17	.2897	1.212	2.13	8.91	.704
1500	1.3045		5.40	.2939	1.230	2.26	9.46	.704
1600	1.2988		5.63	.2982	1.248	2.39	10.0	.703
1700	1.2932		5.85	.3026	1.266	2.52	10.5	.702
1800	1.2875	28.966	6.07	.3073	1.286	2.66	11.1	.701
1900	1.2818	28.966	6.29	.3124	1.307	2.80	11.7	.700
2000	1.2759	28.965	6.50	.3181	1.331	2.96	12.4	.699
2100	1.2696	28.962	6.72	.3247	1.359	3.13	13.1	.696
2200	1.2628	28.957	6.93	.3327	1.392	3.33	13.9	.693
2300	1.2553	28.948	7.14	.3427	1.434	3.56	14.9	.688
2400	1.2471	28.935	7.35	.3555	1.487	3.84	16.1	.681
2500	1.2381	28.914	7.57	.3718	1.556	4.18	17.5	.673

TABLE II. - THERMODYNAMIC AND TRANSPORT PROPERTIES OF AIR

AT 10 ATMOSPHERES (10.13×10^5 N/m^2)

Temperature, T, K	Ratio of specific heats, γ	Molecular weight, m	Viscosity, μ, g/(cm)(sec)	Specific heat at constant pressure, c_p		Thermal conductivity, k		Prandtl number, Pr
				cal/(g)(K)	J/(g)(K)	cal/(cm)(sec)(K)	J/(cm)(sec)(K)	
300	1.4001	28.967	1.78×10^{-4}	0.2401	1.005	0.61×10^{-4}	2.6×10^{-4}	0.704
400	1.3951		2.24	.2422	1.013	.77	3.2	.705
500	1.3865		2.64	.2461	1.030	.92	3.8	.705
600	1.3759		3.00	.2511	1.051	1.07	4.48	.706
700	1.3646		3.33	.2568	1.074	1.21	5.06	
800	1.3537		3.63	.2626	1.099	1.35	5.65	
900	1.3439		3.92	.2681	1.122	1.49	6.23	
1000	1.3356		4.19	.2730	1.142	1.62	6.78	
1100	1.3288		4.44	.2772	1.160	1.75	7.32	.705
1200	1.3224		4.69	.2814	1.177	1.87	7.82	.705
1300	1.3163		4.93	.2855	1.195	2.00	8.37	.705
1400	1.3103		5.17	.2897	1.212	2.13	8.91	.704
1500	1.3045		5.40	.2939	1.230	2.26	9.46	.704
1600	1.2989		5.63	.2981	1.247	2.39	10.0	.703
1700	1.2933		5.85	.3025	1.266	2.52	10.5	.702
1800	1.2878	28.966	6.07	.3070	1.285	2.66	11.1	.702
1900	1.2823	28.966	6.29	.3118	1.305	2.80	11.7	.701
2000	1.2769	28.966	6.50	.3168	1.325	2.94	12.3	.700
2100	1.2713	28.964	6.72	.3223	1.349	3.10	13.0	.698
2200	1.2656	28.961	6.93	.3285	1.374	3.27	13.7	.696
2300	1.2596	28.957	7.14	.3357	1.405	3.46	14.5	.693
2400	1.2533	28.950	7.35	.3443	1.441	3.67	15.4	.689
2500	1.2466	28.938	7.57	.3548	1.484	3.93	16.4	.684

TABLE III. - ADIABATIC COMBUSTION TEMPERATURES OF NATURAL GAS AND OF ASTM-A-1 BURNED IN AIR AT 3 AND 10 ATMOSPHERES (3.04×10^5 AND 10.13×10^5 N/m^2)

Fuel	Pressure, P, atm	Pressure, P, N/m^2	Fuel-air ratio, F/A	Adiabatic combustion temperature, K	Fuel	Pressure, P, atm	Pressure, P, N/m^2	Fuel-air ratio, F/A	Adiabatic combustion temperature, K
Natural gas	3	3.04×10^5	0	[a]298	ASTM-A-1	3	3.04×10^5	0	[a]298
			.0100	745				.0100	708
			.0200	1130				.0200	1068
			.0400	1770				.0400	1684
			.0600	2242				.0600	2182
								.0682	2307
	10	10.13×10^5	0	[a]298		10	10.13×10^5	0	[a]298
			.0100	745				.0100	708
			.0200	1130				.0200	1068
			.0400	1771				.0400	1684
			.0600	2262				.0600	2192
								.0682	2333

[a]Initial fuel and air temperatures were assumed to be 298 K.

TABLE IV. - THERMODYNAMIC AND TRANSPORT PROPERTIES OF NATURAL GAS BURNED IN AIR

AT 3 ATMOSPHERES (3.04×10^{5} N/m^2)

Temperature, T, K	Fuel-air ratio, F/A	Ratio of specific heats, γ	Molecular weight, m	Viscosity, μ, g/(cm)(sec)	Specific heat at constant pressure, c_p		Thermal conductivity, k		Prandtl number, Pr
					cal/(g)(K)	J/(g)(K)	cal/(cm)(sec)(K)	J/(cm)(sec)(K)	
[a]300	0.0100	1.2287	29.410	1.76×10^{-4}	0.2414	1.010	0.60×10^{-4}	2.5×10^{-4}	0.709
400		1.3888	28.757	2.22	.2469	1.033	.77	3.2	.712
500		1.3796		2.62	.2512	1.051	.93	3.9	.710
600		1.3687		2.98	.2566	1.074	1.08	4.52	.709
700		1.3573		3.30	.2625	1.098	1.22	5.10	.708
800		1.3463		3.61	.2687	1.124	1.37	5.73	.708
900		1.3364		3.89	.2745	1.149	1.51	6.32	.707
1000		1.3280		4.16	.2798	1.171	1.65	6.90	.707
1100		1.3210		4.42	.2844	1.190	1.78	7.45	.706
1200		1.3145		4.67	.2888	1.208	1.91	7.99	.705
1300		1.3084		4.92	.2932	1.227	2.05	8.58	.705
1400		1.3024		5.15	.2976	1.245	2.18	9.12	.704
1500		1.2966		5.39	.3021	1.264	2.31	9.67	.703
1600		1.2908		5.61	.3069	1.284	2.45	10.3	.702
1700		1.2849	28.756	5.84	.3120	1.305	2.60	10.9	.701
1800		1.2787	28.755	6.06	.3177	1.329	2.75	11.5	.699
1900		1.2722	28.752	6.28	.3242	1.356	2.92	12.2	.697
2000		1.2652	28.748	6.49	.3320	1.389	3.11	13.0	.693
2100		1.2575	28.741	6.71	.3416	1.429	3.33	13.9	.688
2200		1.2490	28.730	6.93	.3537	1.480	3.60	15.1	.680
2300		1.2396	28.713	7.14	.3692	1.545	3.95	16.5	.668
2400		1.2295	28.687	7.35	.3892	1.628	4.39	18.4	.652
2500		1.2187	28.648	7.56	.4147	1.735	4.97	20.8	.631
[a]300	0.0200	1.2158	30.213	1.75×10^{-4}	0.2411	1.009	0.60×10^{-4}	2.5×10^{-4}	0.709
400		1.3828	28.554	2.19	.2514	1.052	.77	3.2	.719
500		1.3731		2.59	.2561	1.072	.93	3.9	.715
600		1.3620		2.95	.2619	1.096	1.08	4.52	.712
700		1.3504		3.28	.2682	1.122	1.24	5.19	.711
800		1.3394		3.58	.2746	1.149	1.39	5.82	.710
900		1.3295		3.87	.2808	1.175	1.53	6.40	.709
1000		1.3210		4.14	.2864	1.198	1.68	7.03	.708
1100		1.3139		4.40	.2913	1.219	1.81	7.57	.707
1200		1.3073		4.65	.2960	1.238	1.95	8.16	.706
1300		1.3012		4.90	.3007	1.258	2.09	8.74	.705
1400		1.2954		5.14	.3053	1.277	2.23	9.33	.704
1500		1.2896		5.37	.3100	1.297	2.37	9.92	.703
1600		1.2839		5.60	.3149	1.318	2.51	10.5	.702
1700		1.2781	28.553	5.82	.3203	1.340	2.66	11.1	.700
1800		1.2720	28.551	6.05	.3263	1.365	2.83	11.8	.698
1900		1.2655	28.548	6.27	.3334	1.395	3.01	12.6	.695
2000		1.2583	28.543	6.48	.3421	1.431	3.21	13.4	.690
2100		1.2502	28.534	6.70	.3532	1.478	3.46	14.5	.683
2200		1.2411	28.520	6.92	.3676	1.538	3.78	15.8	.673
2300		1.2309	28.498	7.13	.3866	1.618	4.20	17.6	.657
2400		1.2197	28.465	7.35	.4116	1.722	4.75	19.9	.637
2500		1.2081	28.416	7.56	.4441	1.858	5.49	23.0	.611

[a]Properties at 300 K reflect the effect of the condensation of water from the combustion products.

TABLE IV. - Concluded. THERMODYNAMIC AND TRANSPORT PROPERTIES OF NATURAL GAS BURNED IN AIR

AT 3 ATMOSPHERES (3.04×10^5 N/m^2)

Temperature, T, K	Fuel-air ratio, F/A	Ratio of specific heats, γ	Molecular weight, m	Viscosity, μ g/(cm)(sec)	Specific heat at constant pressure, c_p cal/(g)(K)	Specific heat at constant pressure, c_p J/(g)(K)	Thermal conductivity, k cal/(cm)(sec)(K)	Thermal conductivity, k J/(cm)(sec)(K)	Prandtl number, Pr
[a]300	0.0400	1.1925	31.905	1.73×10^{-4}	0.2406	1.007	0.59×10^{-4}	2.5×10^{-4}	0.709
400		1.3720	28.169	2.14	.2602	1.089	.76	3.2	.733
500		1.3614		2.54	.2657	1.112	.93	3.9	.724
600		1.3499		2.89	.2722	1.139	1.10	4.60	.720
700		1.3382		3.22	.2792	1.168	1.26	5.27	.716
800		1.3271		3.53	.2862	1.197	1.41	5.90	.714
900		1.3171		3.82	.2930	1.226	1.57	6.57	.712
1000		1.3085		4.09	.2993	1.252	1.72	7.20	.710
1100		1.3012		4.35	.3048	1.275	1.87	7.82	.709
1200		1.2946		4.61	.3100	1.297	2.02	8.45	.707
1300		1.2886		4.85	.3150	1.318	2.17	9.08	.706
1400		1.2830		5.10	.3199	1.338	2.31	9.67	.705
1500		1.2776	28.168	5.33	.3248	1.359	2.46	10.3	.703
1600		1.2723	28.168	5.56	.3299	1.380	2.62	11.0	.702
1700		1.2669	28.167	5.79	.3355	1.404	2.78	11.6	.700
1800		1.2612	28.165	6.02	.3419	1.431	2.95	12.3	.697
1900		1.2548	28.161	6.24	.3497	1.463	3.15	13.2	.693
2000		1.2474	28.154	6.46	.3601	1.507	3.39	14.2	.686
2100		1.2386	28.142	6.68	.3741	1.565	3.70	15.5	.675
2200		1.2282	28.123	6.90	.3938	1.648	4.12	17.2	.659
2300		1.2163	28.091	7.11	.4212	1.762	4.70	19.7	.637
2400		1.2032	28.042	7.33	.4586	1.919	5.52	23.1	.609
2500		1.1901	27.969	7.54	.5078	2.125	6.63	27.7	.578
[a]300	0.0600	1.1724	33.723	1.71×10^{-4}	0.2402	1.005	0.58×10^{-4}	2.4×10^{-4}	0.709
400		1.3624	27.807	2.09	.2687	1.124	.75	3.1	.747
500		1.3511		2.48	.2750	1.151	.93	3.9	.734
600		1.3392		2.83	.2821	1.180	1.10	4.60	.727
700		1.3274		3.16	.2897	1.212	1.27	5.31	.722
800		1.3163		3.47	.2974	1.244	1.44	6.02	.718
900		1.3063		3.76	.3048	1.275	1.60	6.69	.715
1000		1.2976		4.03	.3116	1.304	1.76	7.36	.713
1100		1.2903		4.30	.3176	1.329	1.92	8.03	.711
1200		1.2839		4.56	.3232	1.352	2.08	8.70	.709
1300		1.2782		4.81	.3283	1.374	2.23	9.33	.707
1400		1.2731		5.05	.3332	1.394	2.38	9.96	.705
1500		1.2683		5.29	.3379	1.414	2.54	10.6	.704
1600		1.2636	27.806	5.52	.3430	1.435	2.70	11.3	.701
1700		1.2582	27.805	5.75	.3494	1.462	2.89	12.1	.696
1800		1.2512	27.801	5.98	.3587	1.501	3.11	13.0	.688
1900		1.2418	27.792	6.20	.3730	1.561	3.42	14.3	.677
2000		1.2302	27.774	6.42	.3941	1.649	3.81	15.9	.664
2100		1.2171	27.744	6.65	.4226	1.768	4.32	18.1	.650
2200		1.2038	27.697	6.87	.4590	1.920	4.97	20.8	.634
2300		1.1909	27.629	7.08	.5038	2.108	5.80	24.3	.615
2400		1.1792	27.534	7.30	.5574	2.332	6.86	28.7	.593
2500		1.1690	27.409	7.52	.6195	2.592	8.21	34.4	.567

[a]Properties at 300 K reflect the effect of the condensation of water from combustion products.

TABLE V. - THERMODYNAMIC AND TRANSPORT PROPERTIES OF NATURAL GAS BURNED IN AIR AT 10 ATMOSPHERES (10.13×10^5 N/m^2)

Temperature, T, K	Fuel-air ratio, F/A	Ratio of specific heats, γ	Molecular weight, m	Viscosity, μ, g/(cm)(sec)	Specific heat at constant pressure, c_p		Thermal conductivity, k		Prandtl number, Pr
					cal/(g)(K)	J/(g)(K)	cal/(cm)(sec)(K)	J/(cm)(sec)(K)	
[a]300	0.0100	1.2945	29.649	1.77×10^{-4}	0.2403	1.005	0.60×10^{-4}	2.5×10^{-4}	0.705
400		1.3888	28.757	2.22	.2469	1.033	.77	3.2	.712
500		1.3796		2.62	.2512	1.051	.93	3.9	.710
600		1.3687		2.98	.2566	1.074	1.08	4.52	.709
700		1.3573		3.30	.2625	1.098	1.22	5.10	.708
800		1.3463		3.61	.2687	1.124	1.37	5.73	.708
900		1.3364		3.89	.2745	1.149	1.51	6.32	.707
1000		1.3280		4.16	.2798	1.171	1.65	6.90	.707
1100		1.3210		4.42	.2844	1.190	1.78	7.45	.706
1200		1.3145		4.67	.2888	1.208	1.91	7.99	.705
1300		1.3084		4.92	.2932	1.227	2.05	8.58	.705
1400		1.3025		5.15	.2976	1.245	2.18	9.12	.704
1500		1.2967		5.39	.3020	1.264	2.31	9.67	.703
1600		1.2910		5.61	.3067	1.283	2.45	10.3	.702
1700		1.2853	28.756	5.84	.3115	1.303	2.59	10.8	.701
1800		1.2795	28.756	6.06	.3168	1.325	2.74	11.5	.700
1900		1.2736	28.754	6.28	.3225	1.349	2.90	12.1	.698
2000		1.2674	28.751	6.49	.3290	1.377	3.07	12.8	.696
2100		1.2610	28.747	6.71	.3365	1.408	3.26	13.6	.692
2200		1.2541	28.740	6.93	.3454	1.445	3.48	14.6	.688
2300		1.2467	28.729	7.14	.3563	1.491	3.74	15.6	.681
2400		1.2388	28.713	7.35	.3696	1.546	4.05	16.9	.671
2500		1.2304	28.690	7.56	.3860	1.615	4.44	18.6	.658
[a]300	0.0200	1.2697	30.459	1.76×10^{-4}	0.2401	1.005	0.60×10^{-4}	2.5×10^{-4}	0.706
400		1.3828	28.554	2.19	.2514	1.052	.77	3.2	.719
500		1.3731		2.59	.2561	1.072	.93	3.9	.715
600		1.3620		2.95	.2619	1.096	1.08	4.52	.712
700		1.3504		3.28	.2682	1.122	1.24	5.19	.711
800		1.3394		3.58	.2746	1.149	1.39	5.82	.710
900		1.3295		3.87	.2808	1.175	1.53	6.40	.709
1000		1.3210		4.14	.2864	1.198	1.68	7.03	.708
1100		1.3139		4.40	.2913	1.219	1.81	7.57	.707
1200		1.3073		4.65	.2960	1.238	1.95	8.16	.706
1300		1.3012		4.90	.3006	1.258	2.09	8.74	.705
1400		1.2954		5.14	.3052	1.277	2.23	9.33	.704
1500		1.2898		5.37	.3098	1.296	2.37	9.92	.703
1600		1.2842		5.60	.3146	1.316	2.51	10.5	.702
1700		1.2787	28.553	5.82	.3196	1.337	2.66	11.1	.701
1800		1.2730	28.552	6.05	.3251	1.360	2.81	11.8	.699
1900		1.2671	28.550	6.27	.3312	1.386	2.98	12.5	.697
2000		1.2610	28.547	6.48	.3383	1.415	3.16	13.2	.694
2100		1.2543	28.541	6.70	.3467	1.451	3.37	14.1	.690
2200		1.2471	28.532	6.92	.3570	1.494	3.61	15.1	.683
2300		1.2392	28.519	7.13	.3699	1.548	3.91	16.4	.674
2400		1.2306	28.498	7.35	.3862	1.616	4.29	17.9	.662
2500		1.2215	28.469	7.56	.4067	1.702	4.76	19.9	.645

[a]Properties at 300 K reflect the effect of the condensation of water from the combustion products.

TABLE V. - Concluded. THERMODYNAMIC AND TRANSPORT PROPERTIES OF NATURAL GAS BURNED IN AIR AT 10 ATMOSPHERES (10.13×10^5 N/m^2)

Temperature, T, K	Fuel-air ratio, F/A	Ratio of specific heats, γ	Molecular weight, m	Viscosity, μ, g/(cm)(sec)	Specific heat at constant pressure, c_p		Thermal conductivity, k		Prandtl number, Pr
					cal/(g)(K)	J/(g)(K)	cal/(cm)(sec)(K)	J/(cm)(sec)(K)	
a300	0.0400	1.2290	32.165	1.73×10^{-4}	0.2396	1.002	0.59×10^{-4}	2.5×10^{-4}	0.706
400		1.3720	28.169	2.14	.2602	1.089	.76	3.2	.733
500		1.3614		2.54	.2657	1.112	.93	3.9	.724
600		1.3499		2.89	.2722	1.139	1.10	4.60	.720
700		1.3382		3.22	.2792	1.168	1.26	5.27	.716
800		1.3271		3.53	.2862	1.197	1.41	5.90	.714
900		1.3171		3.82	.2930	1.226	1.57	6.57	.712
1000		1.3085		4.09	.2993	1.252	1.72	7.20	.710
1100		1.3012		4.35	.3048	1.275	1.87	7.82	.709
1200		1.2946		4.61	.3100	1.297	2.02	8.45	.707
1300		1.2886		4.85	.3150	1.318	2.17	9.08	.706
1400		1.2830		5.10	.3198	1.338	2.31	9.67	.705
1500		1.2777	28.168	5.33	.3246	1.358	2.46	10.3	.703
1600		1.2726	28.168	5.56	.3295	1.379	2.61	10.9	.702
1700		1.2675	28.167	5.79	.3346	1.400	2.77	11.6	.700
1800		1.2623	28.166	6.02	.3403	1.424	2.93	12.3	.698
1900		1.2568	28.164	6.24	.3467	1.451	3.11	13.0	.696
2000		1.2508	28.159	6.46	.3546	1.484	3.31	13.8	.691
2100		1.2440	28.152	6.68	.3646	1.525	3.56	14.9	.685
2200		1.2362	28.140	6.90	.3777	1.580	3.86	16.2	.675
2300		1.2272	28.120	7.11	.3952	1.654	4.25	17.8	.662
2400		1.2172	28.091	7.33	.4186	1.751	4.77	20.0	.643
2500		1.2064	28.047	7.54	.4492	1.879	5.46	22.8	.621
a300	0.0600	1.1970	33.997	1.71×10^{-4}	0.2391	1.000	0.58×10^{-4}	2.4×10^{-4}	0.706
400		1.3624	27.807	2.09	.2687	1.124	.75	3.1	.747
500		1.3511		2.48	.2750	1.151	.93	3.9	.734
600		1.3392		2.83	.2821	1.180	1.10	4.60	.727
700		1.3274		3.16	.2897	1.212	1.27	5.31	.722
800		1.3163		3.47	.2974	1.244	1.44	6.02	.718
900		1.3063		3.76	.3048	1.275	1.60	6.69	.715
1000		1.2976		4.03	.3116	1.304	1.76	7.36	.713
1100		1.2903		4.30	.3176	1.329	1.92	8.03	.711
1200		1.2839		4.56	.3232	1.352	2.08	8.70	.709
1300		1.2782		4.81	.3283	1.374	2.23	9.33	.707
1400		1.2732		5.05	.3331	1.394	2.38	9.96	.706
1500		1.2685		5.29	.3377	1.413	2.54	10.6	.704
1600		1.2641		5.52	.3423	1.432	2.69	11.3	.702
1700		1.2594	27.806	5.75	.3475	1.454	2.86	12.0	.699
1800		1.2540	27.803	5.98	.3544	1.483	3.05	12.8	.694
1900		1.2470	27.798	6.20	.3644	1.525	3.30	13.8	.686
2000		1.2381	27.787	6.42	.3790	1.586	3.60	15.1	.676
2100		1.2275	27.768	6.65	.3992	1.670	3.99	16.7	.664
2200		1.2161	27.738	6.86	.4252	1.779	4.47	18.7	.652
2300		1.2047	27.692	7.08	.4571	1.913	5.07	21.2	.639
2400		1.1937	27.628	7.30	.4952	2.072	5.80	24.3	.623
2500		1.1838	27.542	7.52	.5394	2.257	6.71	28.1	.604

[a]Properties at 300 K reflect the effect of the condensation of water from the combustion products.

TABLE VI. - THERMODYNAMIC AND TRANSPORT PROPERTIES OF ASTM-A-1 BURNED IN AIR

AT 3 ATMOSPHERES (3.04×10^5 N/m^2)

Temperature, T, K	Fuel-air ratio, F/A	Ratio of specific heats, γ	Molecular weight, m	Viscosity, μ, g/(cm)(sec)	Specific heat at constant pressure, c_p		Thermal conductivity, k		Prandtl number Pr
					cal/(g)(K)	J/(g)(K)	cal/(cm)(sec)(K)	J/(cm)(sec)(K)	
[a]300	0.0100	1.2340	29.210	1.76×10^{-4}	0.2411	1.009	0.60×10^{-4}	2.5×10^{-4}	0.709
400		1.3892	28.968	2.22	.2449	1.025	.77	3.2	.709
500		1.3799		2.62	.2492	1.043	.92	3.8	.709
600		1.3690		2.98	.2545	1.065	1.07	4.48	.708
700		1.3576		3.31	.2605	1.090	1.22	5.10	
800		1.3466		3.61	.2665	1.115	1.36	5.69	
900		1.3368		3.89	.2723	1.139	1.50	6.28	
1000		1.3285		4.16	.2774	1.161	1.63	6.82	.707
1100		1.3216		4.42	.2819	1.179	1.76	7.36	.707
1200		1.3152		4.67	.2863	1.198	1.89	7.91	.706
1300		1.3091		4.91	.2905	1.215	2.02	8.45	.705
1400		1.3032		5.15	.2948	1.233	2.16	9.04	.705
1500		1.2975		5.38	.2993	1.252	2.29	9.58	.704
1600		1.2917	28.967	5.61	.3039	1.272	2.42	10.1	.703
1700		1.2859	28.967	5.83	.3088	1.292	2.57	10.8	.702
1800		1.2800	28.966	6.05	.3142	1.315	2.72	11.4	.701
1900		1.2737	28.964	6.27	.3204	1.341	2.88	12.0	.698
2000		1.2669	28.960	6.49	.3276	1.371	3.06	12.8	.695
2100		1.2595	28.954	6.70	.3366	1.408	3.27	13.7	.691
2200		1.2512	28.944	6.92	.3480	1.456	3.52	14.7	.684
2300		1.2420	28.928	7.13	.3626	1.517	3.84	16.1	.674
2400		1.2320	28.904	7.35	.3814	1.596	4.24	17.7	.661
2500		1.2214	28.868	7.56	.4056	1.697	4.76	19.9	.643
[a]300	0.0200	1.2256	29.800	1.75×10^{-4}	0.2406	1.007	0.59×10^{-4}	2.5×10^{-4}	0.709
400		1.3836	28.969	2.20	.2474	1.035	.76	3.2	.714
500		1.3737		2.60	.2522	1.055	.92	3.8	.712
600		1.3624		2.96	.2579	1.079	1.07	4.48	.711
700		1.3509		3.28	.2641	1.105	1.22	5.10	.710
800		1.3400		3.58	.2704	1.131	1.37	5.73	.710
900		1.3301		3.87	.2764	1.156	1.51	6.32	.709
1000		1.3218		4.14	.2818	1.179	1.65	6.90	.708
1100		1.3148		4.40	.2865	1.199	1.78	7.45	.708
1200		1.3084		4.65	.2910	1.218	1.91	7.99	.707
1300		1.3024		4.89	.2954	1.236	2.05	8.58	.706
1400		1.2967		5.13	.2998	1.254	2.18	9.12	.705
1500		1.2911		5.36	.3043	1.273	2.32	9.71	.705
1600		1.2855	28.968	5.59	.3090	1.293	2.46	10.3	.703
1700		1.2798	28.968	5.82	.3141	1.314	2.60	10.9	.702
1800		1.2739	28.966	6.04	.3197	1.338	2.76	11.5	.700
1900		1.2676	28.964	6.26	.3263	1.365	2.93	12.3	.698
2000		1.2607	28.959	6.47	.3344	1.399	3.12	13.1	.694
2100		1.2528	28.951	6.69	.3447	1.442	3.35	14.0	.688
2200		1.2439	28.939	6.91	.3581	1.498	3.64	15.2	.680
2300		1.2338	28.918	7.12	.3759	1.573	4.01	16.8	.667
2400		1.2228	28.887	7.33	.3994	1.671	4.50	18.8	.651
2500		1.2112	28.840	7.55	.4299	1.799	5.15	21.5	.630

[a]Properties at 300 K reflect the effect of the condensation of water from the combustion products.

TABLE VI. - Continued. THERMODYNAMIC AND TRANSPORT PROPERTIES OF ASTM-A-1 BURNED IN AIR

AT 3 ATMOSPHERES (3.04×10^{5} N/m^{2})

Temperature, T, K	Fuel-air ratio, F/A	Ratio of specific heats, γ	Molecular weight, m	Viscosity, μ, g/(cm)(sec)	Specific heat at constant pressure, c_p, cal/(g)(K)	Specific heat at constant pressure, c_p, J/(g)(K)	Thermal conductivity, k, cal/(cm)(sec)(K)	Thermal conductivity, k, J/(cm)(sec)(K)	Prandtl number,
[a]300	0.0400	1.2101	31.014	1.73×10^{-4}	0.2396	1.002	0.58×10^{-4}	2.4×10^{-4}	0.709
400		1.3732	28.971	2.16	.2524	1.056	.75	3.1	.723
500		1.3622		2.56	.2580	1.079	.92	3.8	.718
600		1.3504		2.91	.2644	1.106	1.07	4.48	.716
700		1.3387		3.23	.2711	1.134	1.23	5.15	.714
800		1.3277		3.54	.2779	1.163	1.38	5.77	.713
900		1.3179		3.82	.2844	1.190	1.53	6.40	.712
1000		1.3095		4.09	.2902	1.214	1.67	6.99	.711
1100		1.3025		4.36	.2953	1.236	1.81	7.57	.710
1200		1.2962		4.61	.3002	1.256	1.95	8.16	.709
1300		1.2904		4.85	.3048	1.275	2.09	8.74	.708
1400		1.2849		5.09	.3094	1.295	2.23	9.33	.707
1500		1.2797		5.32	.3139	1.313	2.37	9.92	.706
1600		1.2745	28.970	5.55	.3187	1.333	2.51	10.5	.704
1700		1.2693	28.969	5.78	.3238	1.355	2.66	11.1	.703
1800		1.2637	28.967	6.00	.3297	1.379	2.83	11.8	.700
1900		1.2575	28.964	6.22	.3369	1.410	3.01	12.6	.697
2000		1.2503	28.958	6.44	.3464	1.449	3.23	13.5	.692
2100		1.2417	28.947	6.66	.3593	1.503	3.50	14.6	.684
2200		1.2315	28.929	6.88	.3773	1.579	3.86	16.2	.672
2300		1.2196	28.899	7.09	.4026	1.684	4.36	18.2	.655
2400		1.2066	28.852	7.31	.4371	1.829	5.04	21.1	.634
2500		1.1934	28.782	7.52	.4824	2.018	5.97	25.0	.608
[a]300	0.0600	1.1959	32.281	1.71×10^{-4}	0.2386	0.998	0.57×10^{-4}	2.4×10^{-4}	0.710
400		1.3637	28.973	2.12	.2572	1.076	.75	3.1	.731
500		1.3518		2.51	.2636	1.103	.91	3.8	.724
600		1.3396		2.86	.2706	1.132	1.07	4.48	.721
700		1.3277		3.19	.2779	1.163	1.23	5.15	.718
800		1.3167		3.49	.2852	1.193	1.39	5.82	.716
900		1.3069		3.77	.2921	1.222	1.54	6.44	.715
1000		1.2985		4.05	.2983	1.248	1.69	7.07	.713
1100		1.2916		4.31	.3038	1.271	1.84	7.70	.712
1200		1.2854		4.56	.3089	1.292	1.98	8.28	.710
1300		1.2799		4.81	.3136	1.312	2.13	8.91	.709
1400		1.2748		5.05	.3182	1.331	2.27	9.50	.708
1500		1.2701	28.972	5.28	.3226	1.350	2.41	10.1	.707
1600		1.2655	28.972	5.51	.3272	1.369	2.56	10.7	.705
1700		1.2607	28.971	5.74	.3322	1.390	2.71	11.3	.703
1800		1.2554	28.969	5.97	.3385	1.416	2.89	12.1	.700
1900		1.2489	28.964	6.19	.3471	1.452	3.09	12.9	.695
2000		1.2404	28.955	6.41	.3599	1.506	3.36	14.1	.687
2100		1.2294	28.937	6.63	.3795	1.588	3.73	15.6	.674
2200		1.2159	28.906	6.85	.4089	1.711	4.26	17.8	.657
2300		1.2008	28.855	7.06	.4504	1.884	5.00	20.9	.637
2400		1.1861	28.775	7.28	.5045	2.111	5.98	25.0	.614
2500		1.1733	28.660	7.50	.5692	2.382	7.23	30.3	.590

[a]Properties at 300 K reflect the effect of the condensation of water from the combustion products.

TABLE VI. - Concluded. THERMODYNAMIC AND TRANSPORT PROPERTIES OF ASTM-A-1 BURNED IN AIR

AT 3 ATMOSPHERES (3.04×10^{5} N/m^{2})

Temperature, T, K	Fuel-air ratio, F/A	Ratio of specific heats, γ	Molecular weight, m	Viscosity, μ, g/(cm)(sec)	Specific heat at constant pressure, c_p		Thermal conductivity, k		Prandtl number, Pr
					cal/(g)(K)	J/(g)(K)	cal/(cm)(sec)(K)	J/(cm)(sec)(K)	
[a]300	0.0682	1.2257	32.813	1.70×10^{-4}	0.2381	0.996	0.57×10^{-4}	2.4×10^{-4}	0.710
400		1.3600	28.974	2.10	.2591	1.084	.74	3.1	.734
500		1.3478		2.49	.2658	1.112	.91	3.8	.727
600		1.3354		2.84	.2731	1.143	1.07	4.48	.722
700		1.3236		3.16	.2806	1.174	1.23	5.15	.720
800		1.3126		3.47	.2880	1.205	1.39	5.82	.717
900		1.3028		3.75	.2951	1.235	1.55	6.49	.716
1000		1.2945		4.03	.3015	1.261	1.70	7.11	.714
1100		1.2876		4.29	.3070	1.284	1.85	7.74	.712
1200		1.2816		4.54	.3121	1.306	1.99	8.33	.711
1300		1.2762	28.973	4.79	.3169	1.326	2.14	8.95	.709
1400		1.2712	28.973	5.03	.3217	1.346	2.29	9.58	.708
1500		1.2662	28.972	5.26	.3267	1.367	2.44	10.2	.706
1600		1.2607	28.970	5.50	.3327	1.392	2.60	10.9	.704
1700		1.2543	28.966	5.72	.3406	1.425	2.78	11.6	.700
1800		1.2464	28.958	5.95	.3514	1.470	3.01	12.6	.696
1900		1.2369	28.944	6.17	.3664	1.533	3.28	13.7	.690
2000		1.2257	28.921	6.39	.3872	1.620	3.63	15.2	.681
2100		1.2132	28.884	6.62	.4149	1.736	4.09	17.1	.671
2200		1.2003	28.830	6.83	.4509	1.887	4.69	19.6	.657
2300		1.1877	28.752	7.05	.4956	2.074	5.46	22.8	.640
2400		1.1762	28.646	7.27	.5489	2.297	6.44	26.9	.620
2500		1.1665	28.507	7.49	.6101	2.553	7.65	32.0	.597

[a]Properties at 300 K reflect the effect of the condensation of water from the combustion products.

TABLE VII. - THERMODYNAMIC AND TRANSPORT PROPERTIES OF ASTM-A-1 BURNED IN AIR

AT 10 ATMOSPHERES (10.13×10^5 N/m^2)

Temperature, T, K	Fuel-air ratio, F/A	Ratio of specific heats, γ	Molecular weight, m	Viscosity, μ, g/(cm)(sec)	Specific heat at constant pressure, c_p		Thermal conductivity, k		Prandtl number, Pr
					cal/(g)(K)	J/(g)(K)	cal/(cm)(sec)(K)	J/(cm)(sec)(K)	
[a]300	0.0100	1.3050	29.449	1.77×10^{-4}	0.2401	1.005	0.60×10^{-4}	2.5×10^{-4}	0.706
400		1.3892	28.968	2.22	.2449	1.025	.77	3.2	.709
500		1.3799		2.62	.2492	1.043	.92	3.8	.709
600		1.3690		2.98	.2545	1.065	1.07	4.48	.708
700		1.3576		3.31	.2605	1.090	1.22	5.10	
800		1.3466		3.61	.2665	1.115	1.36	5.69	
900		1.3368		3.89	.2723	1.139	1.50	6.28	
1000		1.3285		4.16	.2774	1.161	1.63	6.82	.707
1100		1.3216		4.42	.2819	1.179	1.76	7.36	.707
1200		1.3152		4.67	.2863	1.198	1.89	7.91	.706
1300		1.3091		4.91	.2905	1.215	2.02	8.45	.705
1400		1.3033		5.15	.2948	1.233	2.16	9.04	.705
1500		1.2976		5.38	.2992	1.252	2.29	9.58	.704
1600		1.2919		5.61	.3037	1.271	2.42	10.1	.703
1700		1.2863	28.967	5.83	.3084	1.290	2.56	10.7	.702
1800		1.2806	28.967	6.05	.3134	1.311	2.71	11.3	.701
1900		1.2749	28.965	6.27	.3189	1.334	2.86	12.0	.700
2000		1.2689	28.963	6.49	.3250	1.360	3.02	12.6	.698
2100		1.2626	28.959	6.70	.3321	1.390	3.20	13.4	.695
2200		1.2559	28.953	6.92	.3404	1.424	3.41	14.3	.691
2300		1.2487	28.943	7.13	.3506	1.467	3.65	15.3	.685
2400		1.2410	28.929	7.35	.3631	1.519	3.94	16.5	.677
2500		1.2329	28.907	7.56	.3786	1.584	4.30	18.0	.666
[a]300	0.0200	1.2884	30.043	1.76×10^{-4}	0.2396	1.002	0.60×10^{-4}	2.5×10^{-4}	0.706
400		1.3836	28.969	2.20	.2474	1.035	.76	3.2	.714
500		1.3737		2.60	.2522	1.055	.92	3.8	.712
600		1.3624		2.96	.2579	1.079	1.07	4.48	.711
700		1.3509		3.28	.2641	1.105	1.22	5.10	.710
800		1.3399		3.58	.2704	1.131	1.37	5.73	.710
900		1.3301		3.87	.2764	1.156	1.51	6.32	.709
1000		1.3218		4.14	.2818	1.179	1.65	6.90	.708
1100		1.3148		4.40	.2865	1.199	1.78	7.45	.708
1200		1.3084		4.65	.2910	1.218	1.91	7.99	.707
1300		1.3025		4.89	.2954	1.236	2.05	8.58	.706
1400		1.2967		5.13	.2998	1.254	2.18	9.12	.705
1500		1.2912		5.36	.3042	1.273	2.32	9.71	.705
1600		1.2857		5.59	.3088	1.292	2.45	10.3	.704
1700		1.2803	28.968	5.82	.3136	1.312	2.60	10.9	.703
1800		1.2748	28.967	6.04	.3187	1.333	2.74	11.5	.701
1900		1.2691	28.965	6.26	.3244	1.357	2.90	12.1	.699
2000		1.2631	28.963	6.47	.3310	1.385	3.08	12.9	.697
2100		1.2566	28.958	6.69	.3388	1.418	3.27	13.7	.693
2200		1.2496	28.950	6.91	.3484	1.458	3.50	14.6	.688
2300		1.2419	28.937	7.12	.3604	1.508	3.77	15.8	.681
2400		1.2334	28.918	7.33	.3757	1.572	4.11	17.2	.671
2500		1.2244	28.890	7.55	.3949	1.652	4.53	19.0	.658

[a]Properties at 300 K reflect the effect of the condensation of water from the combustion products.

TABLE VII. - Continued. THERMODYNAMIC AND TRANSPORT PROPERTIES OF ASTM-A-1 BURNED IN AIR AT 10 ATMOSPHERES (10.13×10^5 N/m^2)

Temperature, T, K	Fuel-air ratio, F/A	Ratio of specific heats, γ	Molecular weight, m	Viscosity, μ, g/(cm)(sec)	Specific heat at constant pressure, c_p, cal/(g)(K)	Specific heat at constant pressure, c_p, J/(g)(K)	Thermal conductivity, k, cal/(cm)(sec)(K)	Thermal conductivity, k, J/(cm)(sec)(K)	Prandtl number, Pr
[a]300	0.0400	1.2594	31.267	1.73×10^{-4}	0.2386	0.998	0.59×10^{-4}	2.5×10^{-4}	0.706
400		1.3732	28.971	2.16	.2524	1.056	.75	3.1	.723
500		1.3622		2.56	.2580	1.079	.92	3.8	.718
600		1.3504		2.91	.2644	1.106	1.07	4.48	.716
700		1.3387		3.23	.2711	1.134	1.23	5.15	.714
800		1.3277		3.54	.2779	1.163	1.38	5.77	.713
900		1.3179		3.82	.2844	1.190	1.53	6.40	.712
1000		1.3095		4.09	.2902	1.214	1.67	6.99	.711
1100		1.3025		4.36	.2953	1.236	1.81	7.57	.710
1200		1.2962		4.61	.3002	1.256	1.95	8.16	.709
1300		1.2904		4.85	.3048	1.275	2.09	8.74	.708
1400		1.2850		5.09	.3093	1.294	2.23	9.33	.707
1500		1.2798		5.32	.3138	1.313	2.37	9.92	.706
1600		1.2748	28.970	5.55	.3183	1.332	2.51	10.5	.705
1700		1.2698	28.970	5.78	.3231	1.352	2.66	11.1	.703
1800		1.2648	28.969	6.00	.3283	1.374	2.81	11.8	.702
1900		1.2594	28.966	6.22	.3343	1.399	2.98	12.5	.699
2000		1.2535	28.962	6.44	.3415	1.429	3.16	13.2	.696
2100		1.2468	28.956	6.66	.3507	1.467	3.38	14.1	.691
2200		1.2392	28.944	6.88	.3628	1.518	3.65	15.3	.684
2300		1.2303	28.926	7.09	.3789	1.585	3.99	16.7	.674
2400		1.2204	28.898	7.31	.4005	1.676	4.43	18.5	.660
2500		1.2096	28.857	7.52	.4288	1.794	5.02	21.0	.643
[a]300	0.0600	1.2347	32.544	1.71×10^{-4}	0.2376	0.994	0.58×10^{-4}	2.4×10^{-4}	0.707
400		1.3637	28.973	2.12	.2572	1.076	.75	3.1	.731
500		1.3518		2.51	.2636	1.103	.91	3.8	.724
600		1.3396		2.86	.2706	1.132	1.07	4.48	.721
700		1.3277		3.19	.2779	1.163	1.23	5.15	.718
800		1.3167		3.49	.2852	1.193	1.39	5.82	.716
900		1.3069		3.77	.2921	1.222	1.54	6.44	.715
1000		1.2985		4.05	.2983	1.248	1.69	7.07	.713
1100		1.2916		4.31	.3038	1.271	1.84	7.70	.712
1200		1.2855		4.56	.3089	1.292	1.98	8.28	.710
1300		1.2799		4.81	.3136	1.312	2.13	8.91	.709
1400		1.2749		5.05	.3181	1.331	2.27	9.50	.708
1500		1.2702		5.28	.3225	1.349	2.41	10.1	.707
1600		1.2658	28.972	5.51	.3268	1.367	2.55	10.7	.705
1700		1.2614	28.972	5.74	.3314	1.387	2.70	11.3	.704
1800		1.2568	28.970	5.97	.3365	1.408	2.86	12.0	.702
1900		1.2516	28.967	6.19	.3429	1.435	3.04	12.7	.698
2000		1.2453	28.962	6.41	.3517	1.472	3.25	13.6	.693
2100		1.2374	28.951	6.63	.3643	1.524	3.52	14.7	.686
2200		1.2276	28.933	6.85	.3827	1.601	3.88	16.2	.675
2300		1.2158	28.902	7.06	.4090	1.711	4.37	18.3	.660
2400		1.2031	28.854	7.28	.4445	1.860	5.03	21.0	.643
2500		1.1906	28.782	7.50	.4893	2.047	5.88	24.6	.624

[a]Properties at 300 K reflect the effect of the condensation of water from the combustion products.

TABLE VII. - Concluded. THERMODYNAMIC AND TRANSPORT PROPERTIES OF ASTM-A-1 BURNED IN AIR

AT 10 ATMOSPHERES (10.13×10^5 N/m^2)

Temperature, T, K	Fuel-air ratio, F/A	Ratio of specific heats, γ	Molecular weight, m	Viscosity, μ, g/(cm)(sec)	Specific heat at constant pressure, c_p		Thermal conductivity, k		Prandtl number, Pr
					cal/(g)(K)	J/(g)(K)	cal/(cm)(sec)(K)	J/(cm)(sec)(K)	
[a]300	0.0682	1.2257	33.080	1.70×10^{-4}	0.2371	0.992	0.57×10^{-4}	2.4×10^{-4}	0.707
400		1.3600	28.974	2.10	.2591	1.084	.74	3.1	.734
500		1.3478		2.49	.2658	1.112	.91	3.8	.727
600		1.3354		2.84	.2731	1.143	1.07	4.48	.722
700		1.3236		3.16	.2806	1.174	1.23	5.15	.720
800		1.3126		3.47	.2880	1.205	1.39	5.82	.717
900		1.3028		3.75	.2951	1.235	1.55	6.49	.716
1000		1.2945		4.03	.3015	1.261	1.70	7.11	.714
1100		1.2876		4.29	.3070	1.284	1.85	7.74	.712
1200		1.2816		4.54	.3121	1.306	1.99	8.33	.711
1300		1.2763	28.973	4.79	.3168	1.325	2.14	8.95	.709
1400		1.2714	28.973	5.03	.3214	1.345	2.28	9.54	.708
1500		1.2667	28.973	5.26	.3260	1.364	2.43	10.2	.706
1600		1.2618	28.971	5.50	.3312	1.386	2.58	10.8	.704
1700		1.2564	28.968	5.72	.3376	1.413	2.75	11.5	.702
1800		1.2501	28.963	5.95	.3458	1.447	2.95	12.3	.699
1900		1.2425	28.954	6.17	.3569	1.493	3.17	13.3	.694
2000		1.2336	28.938	6.39	.3718	1.556	3.45	14.4	.688
2100		1.2235	28.913	6.61	.3916	1.638	3.80	15.9	.681
2200		1.2126	28.876	6.83	.4169	1.744	4.24	17.7	.672
2300		1.2015	28.823	7.05	.4485	1.877	4.79	20.0	.660
2400		1.1907	28.750	7.27	.4866	2.036	5.47	22.9	.646
2500		1.1810	28.654	7.48	.5307	2.220	6.31	26.4	.630

[a]Properties at 300 K reflect the effect of the condensation of water from the combustion products.

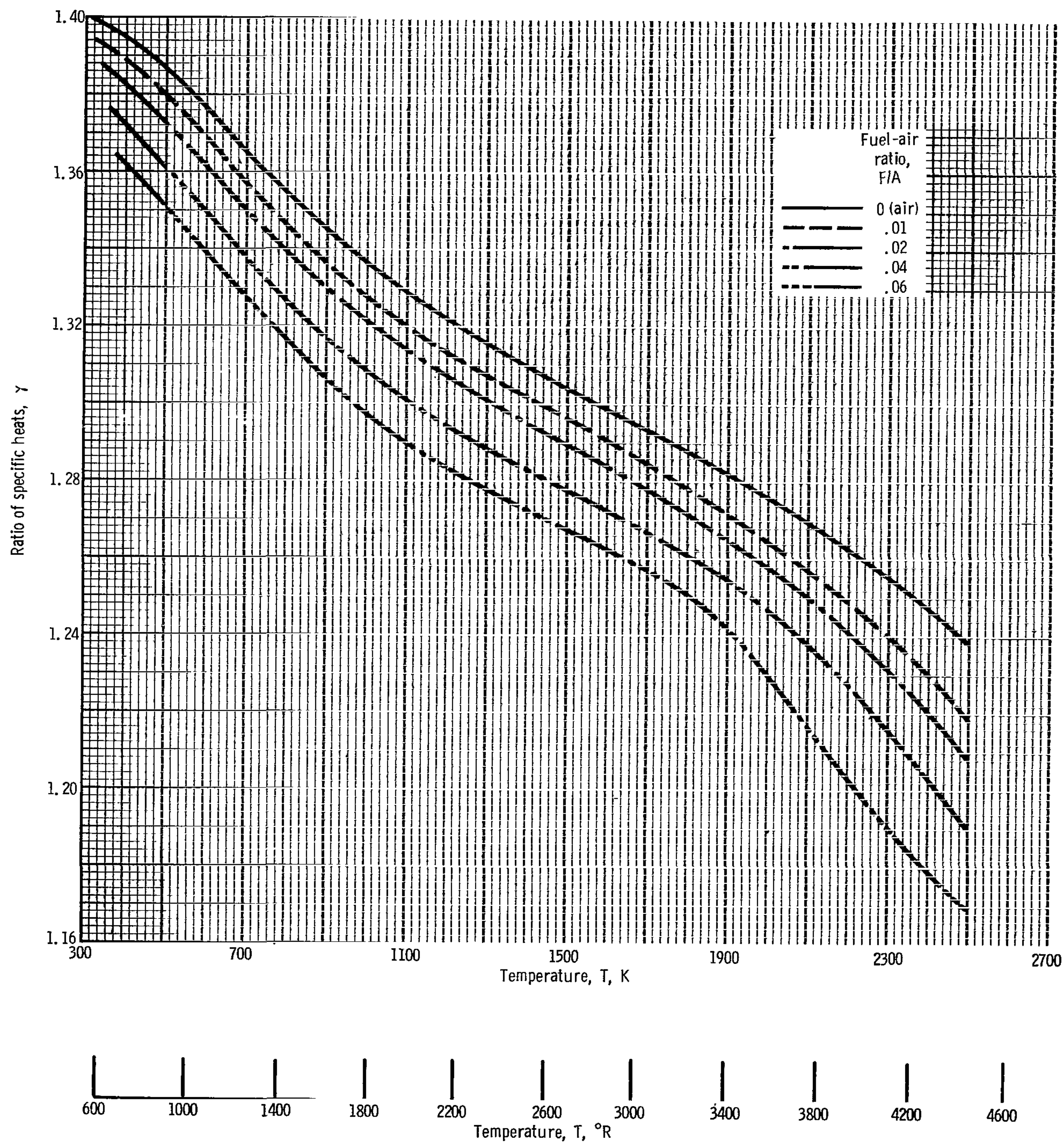

Figure 1. - Ratio of specific heats for combustion products of natural gas and air at pressure of 3 atmospheres (3.04×10^5 N/m^2).

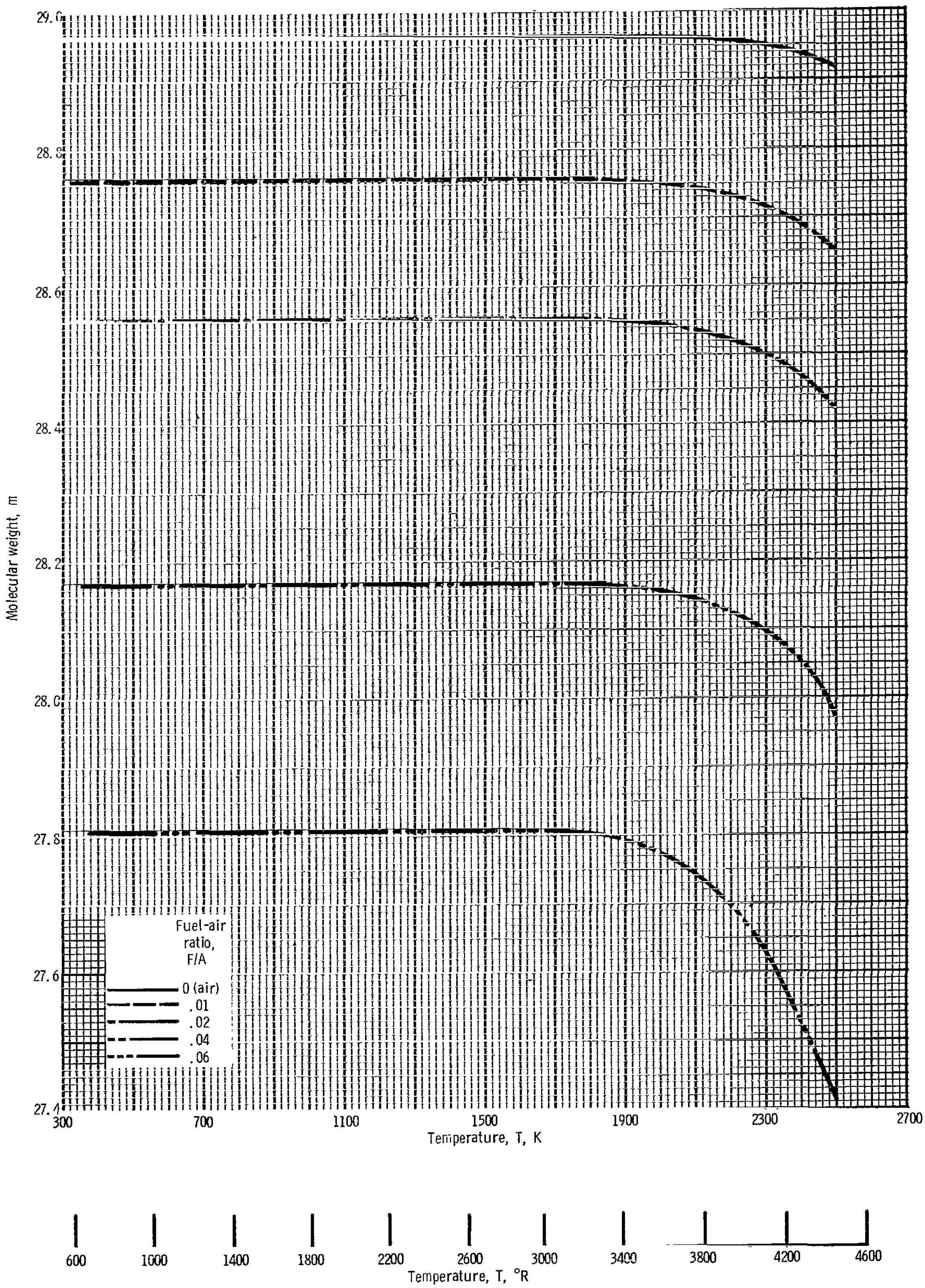

Figure 2. - Molecular weight of combustion products of natural gas and air at pressure of 3 atmospheres (3.04×10^5 N/m^2).

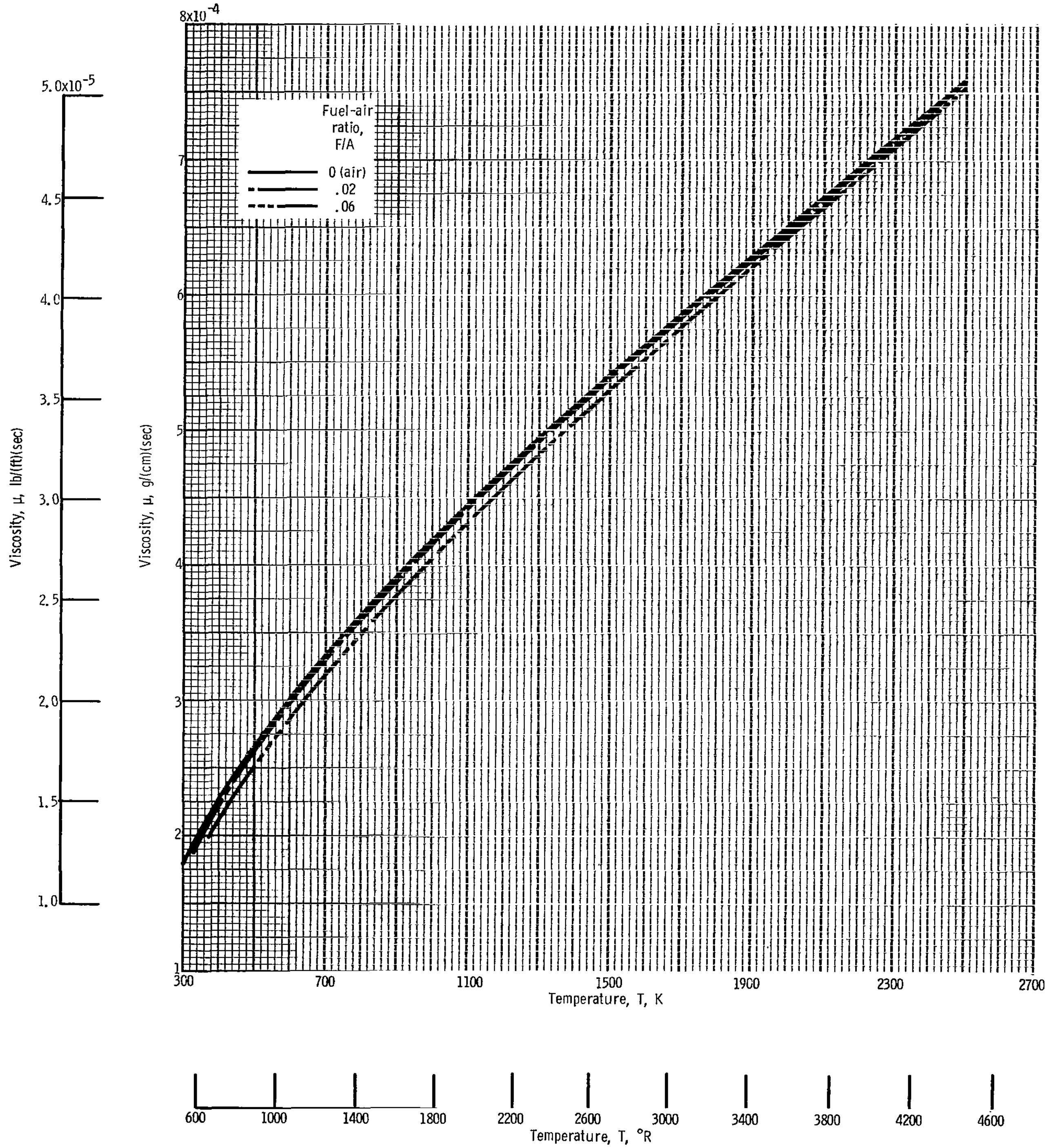

Figure 3. - Viscosity of combustion products of natural gas and air at pressures of 3 and 10 atmospheres (3.04×10^5 and 10.13×10^5 N/m^2).

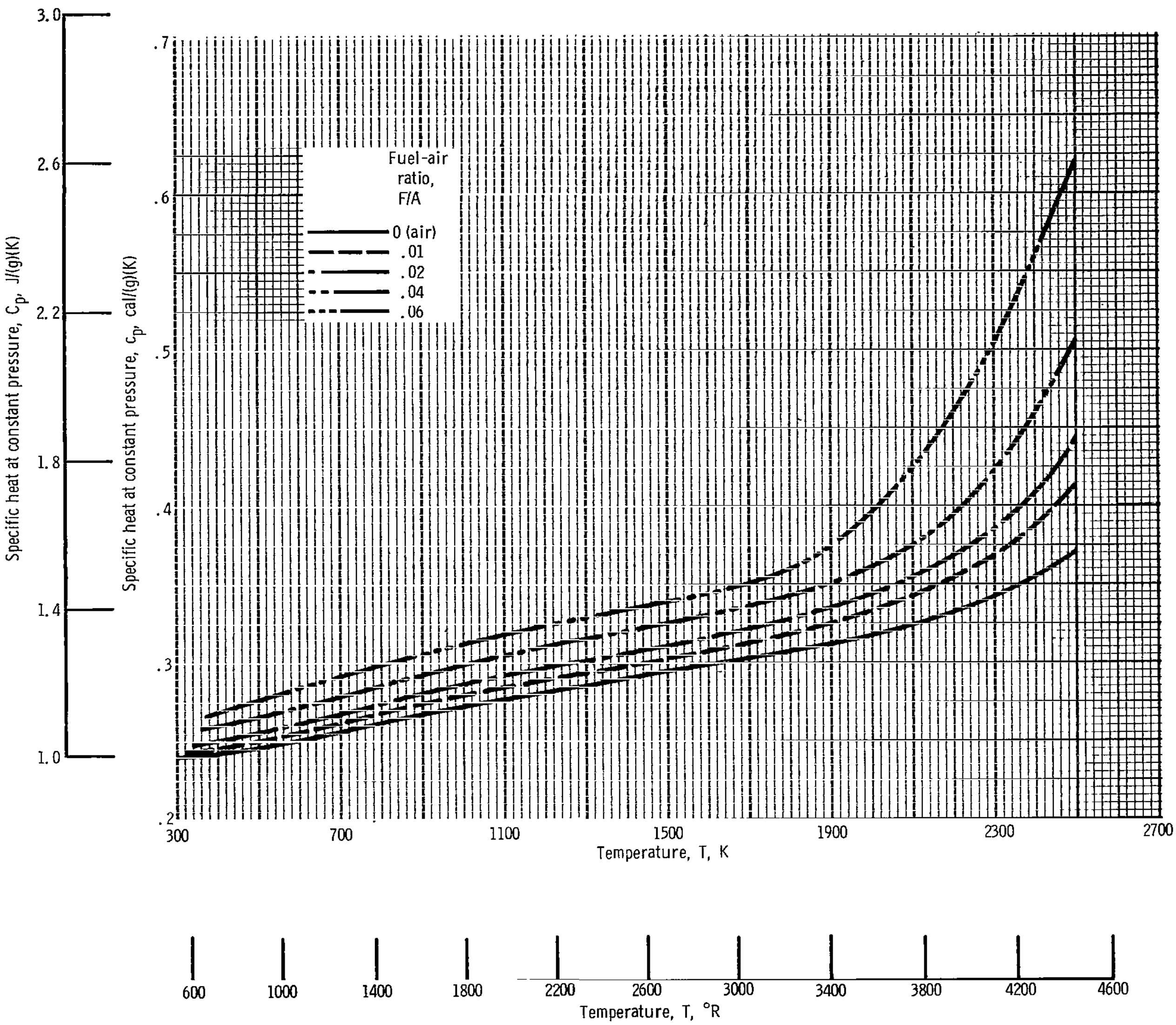

Figure 4. - Specific heat at constant pressure of combustion products of natural gas and air at pressure of 3 atmospheres (3.04×10^5 N/m^2).

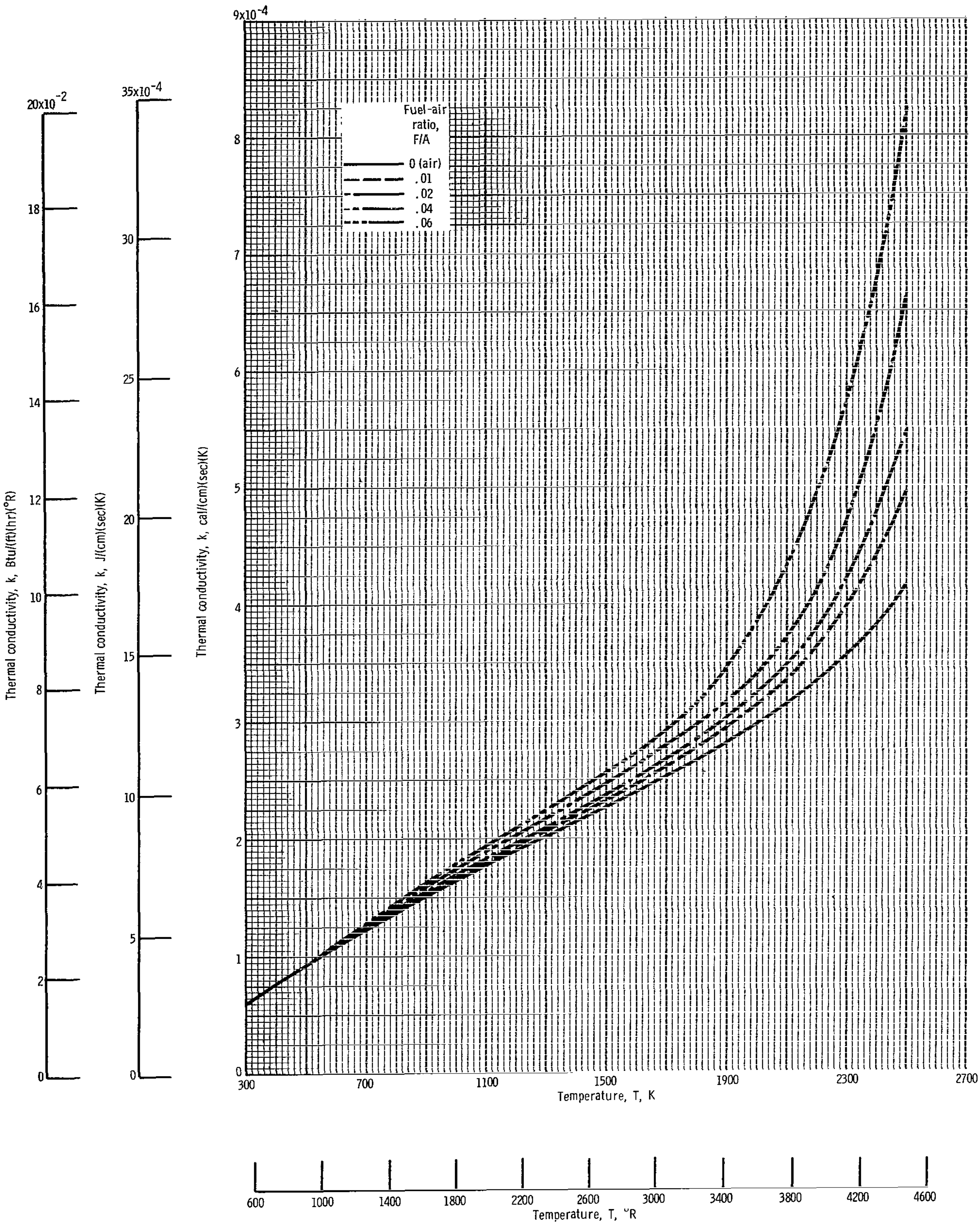

Figure 5. - Thermal conductivity of combustion products of natural gas and air at pressure of 3 atmospheres (3.04×10^5 N/m^2).

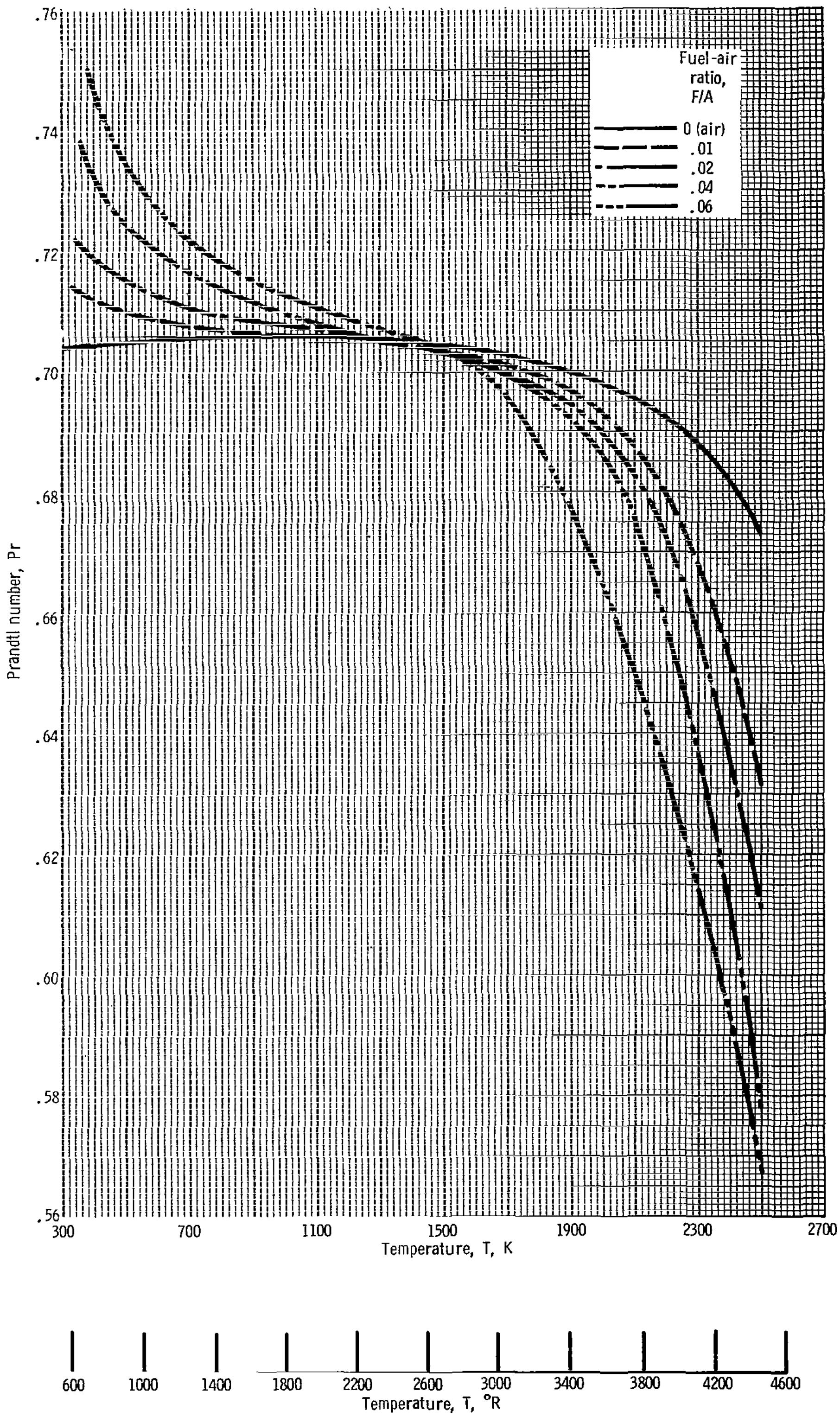

Figure 6. - Prandtl number of combustion products of natural gas and air at pressure of 3 atmospheres (3.04×10^5 N/m^2).

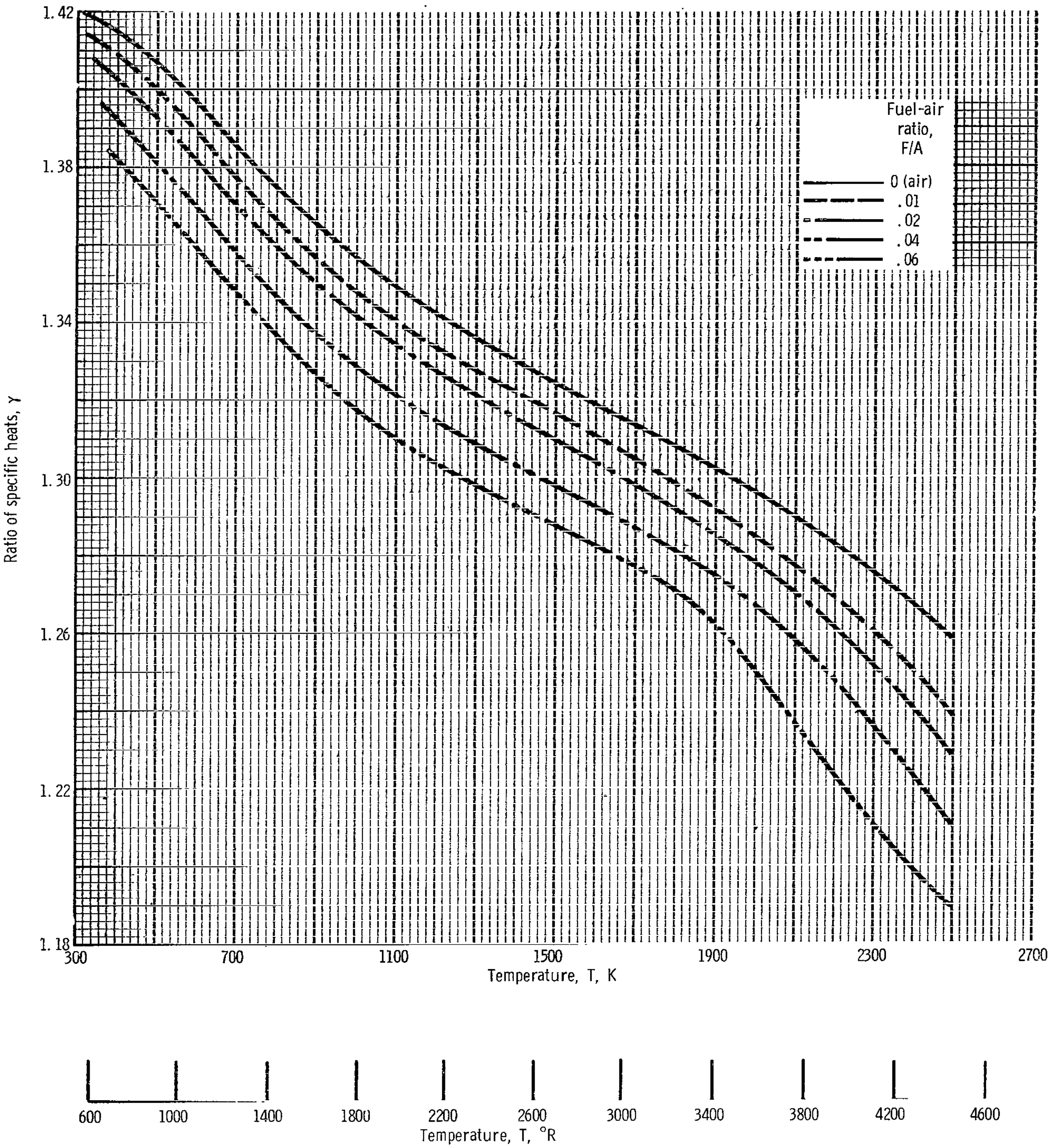

Figure 7. - Ratio of specific heats for combustion products of natural gas and air at pressure of 10 atmospheres (10.13×10^5 N/m^2).

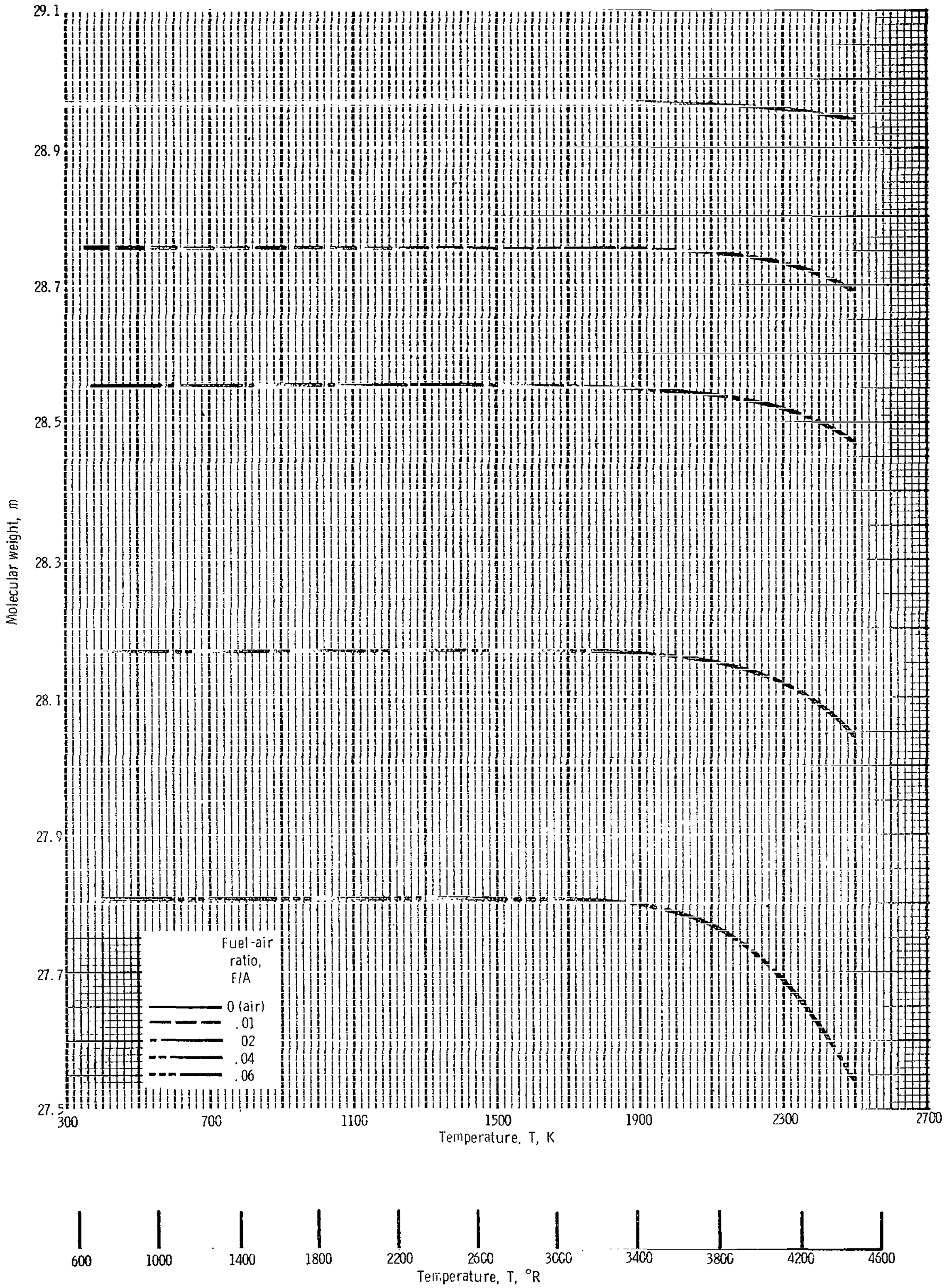

Figure 8. - Molecular weight of combustion products of natural gas and air at pressure of 10 atmospheres (10.13×10^5 N/m^2).

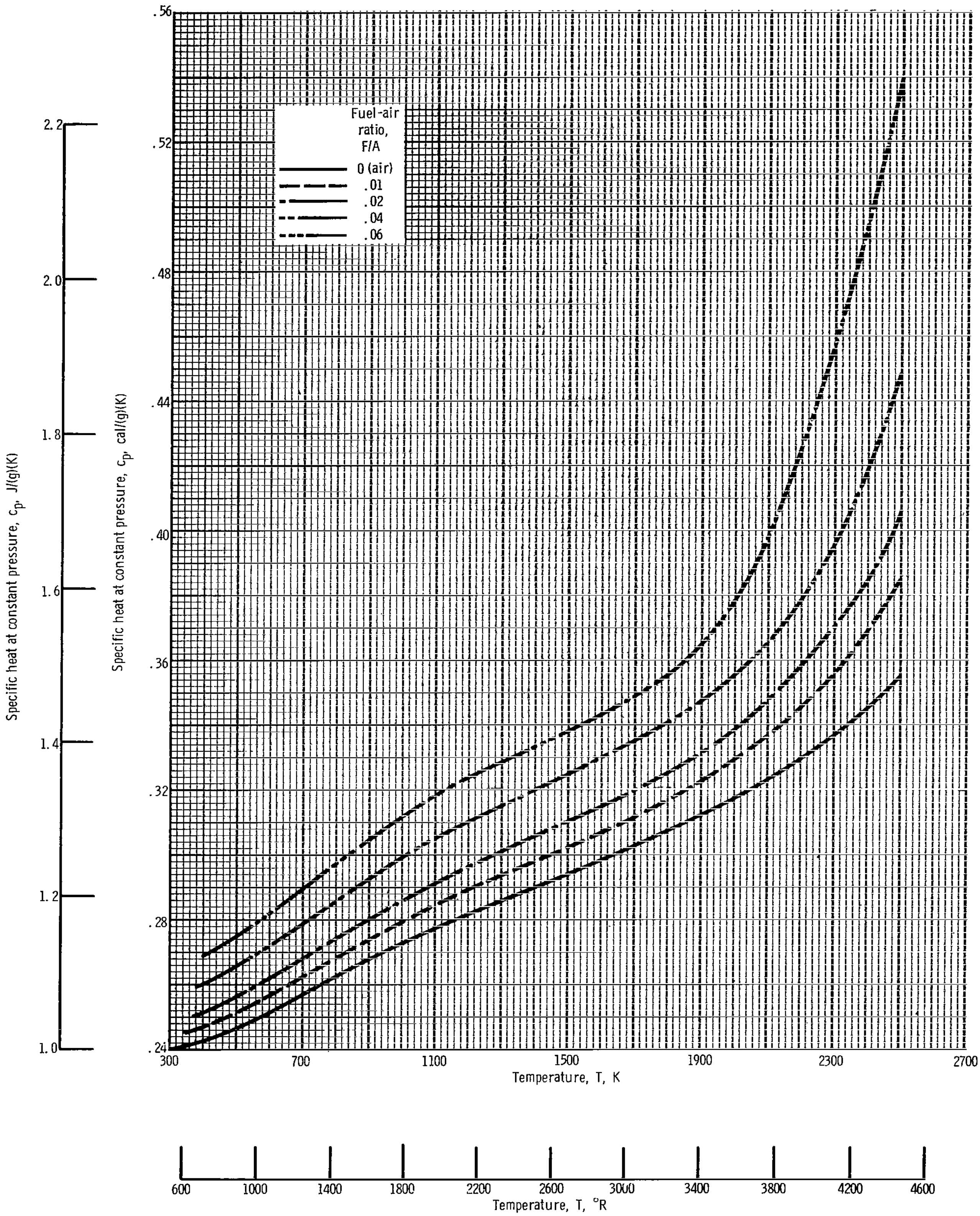

Figure 9. - Specific heat at constant pressure of combustion products of natural gas and air at pressure of 10 atmospheres (10.13×10^5 N/m^2).

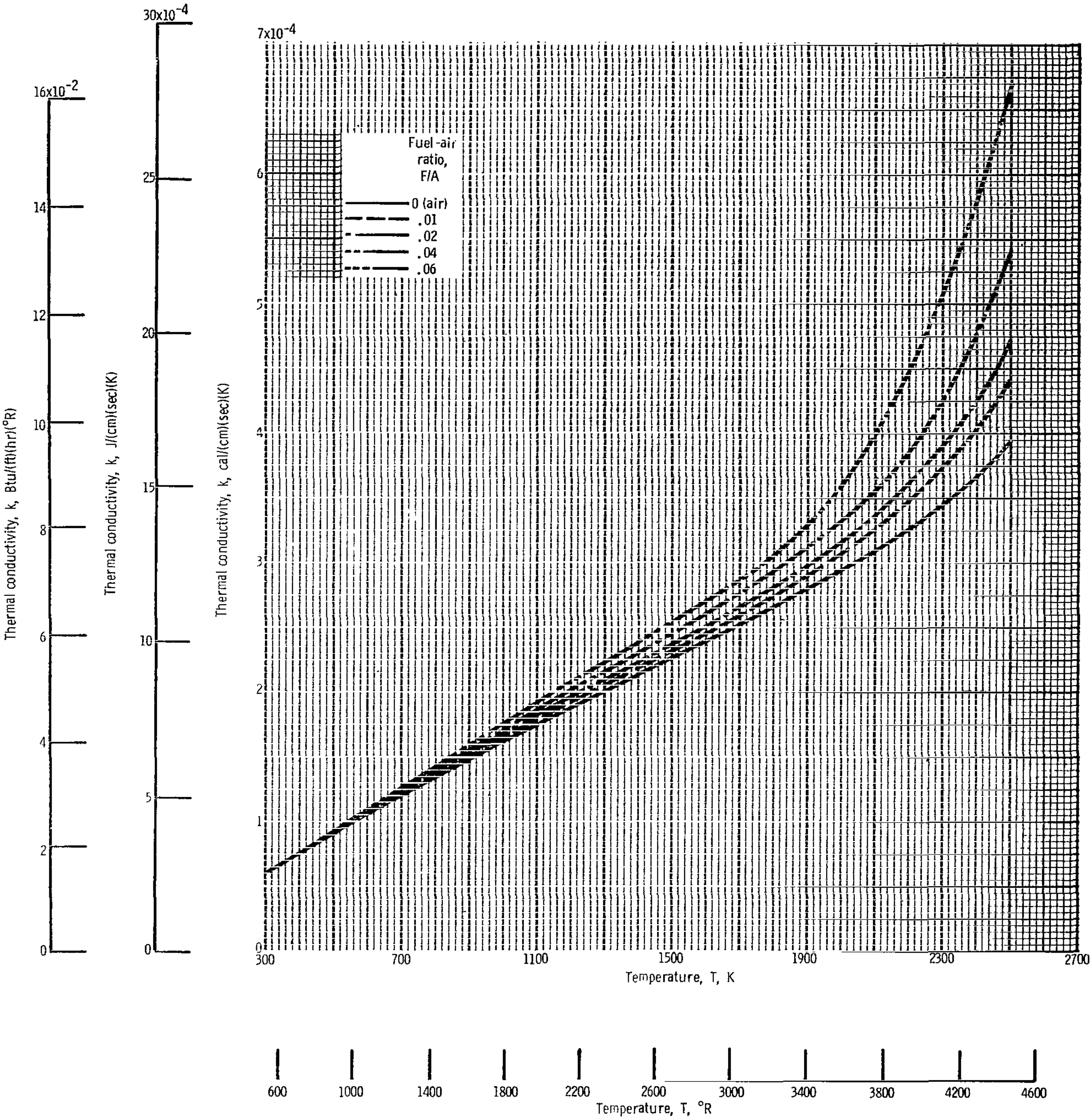

Figure 10. - Thermal conductivity of combustion products of natural gas and air at pressure of 10 atmospheres (10.13×10^5 N/m^2).

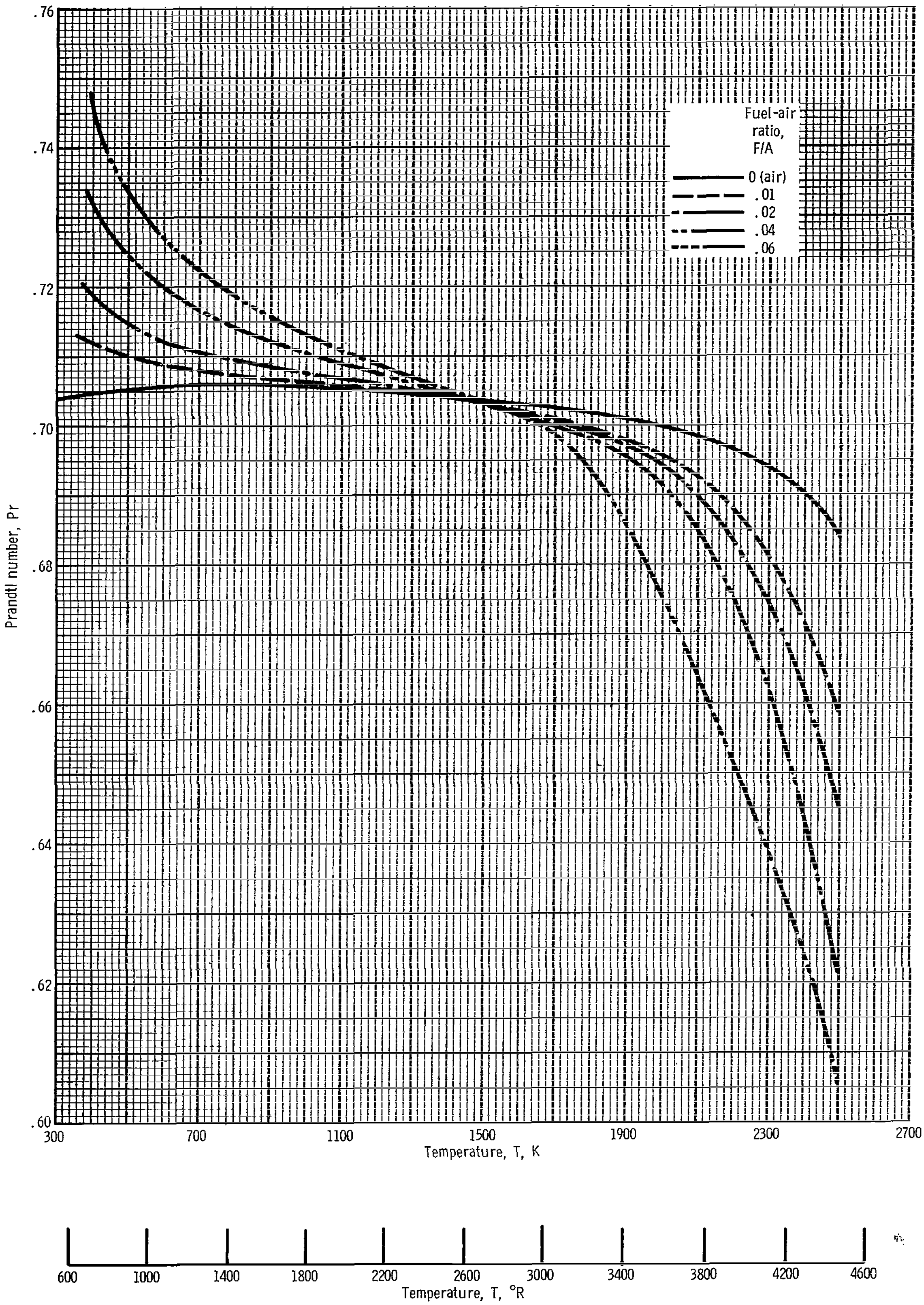

Figure 11. - Prandtl number of combustion products of natural gas and air at pressure of 10 atmospheres (10.13×10^5 N/m^2).

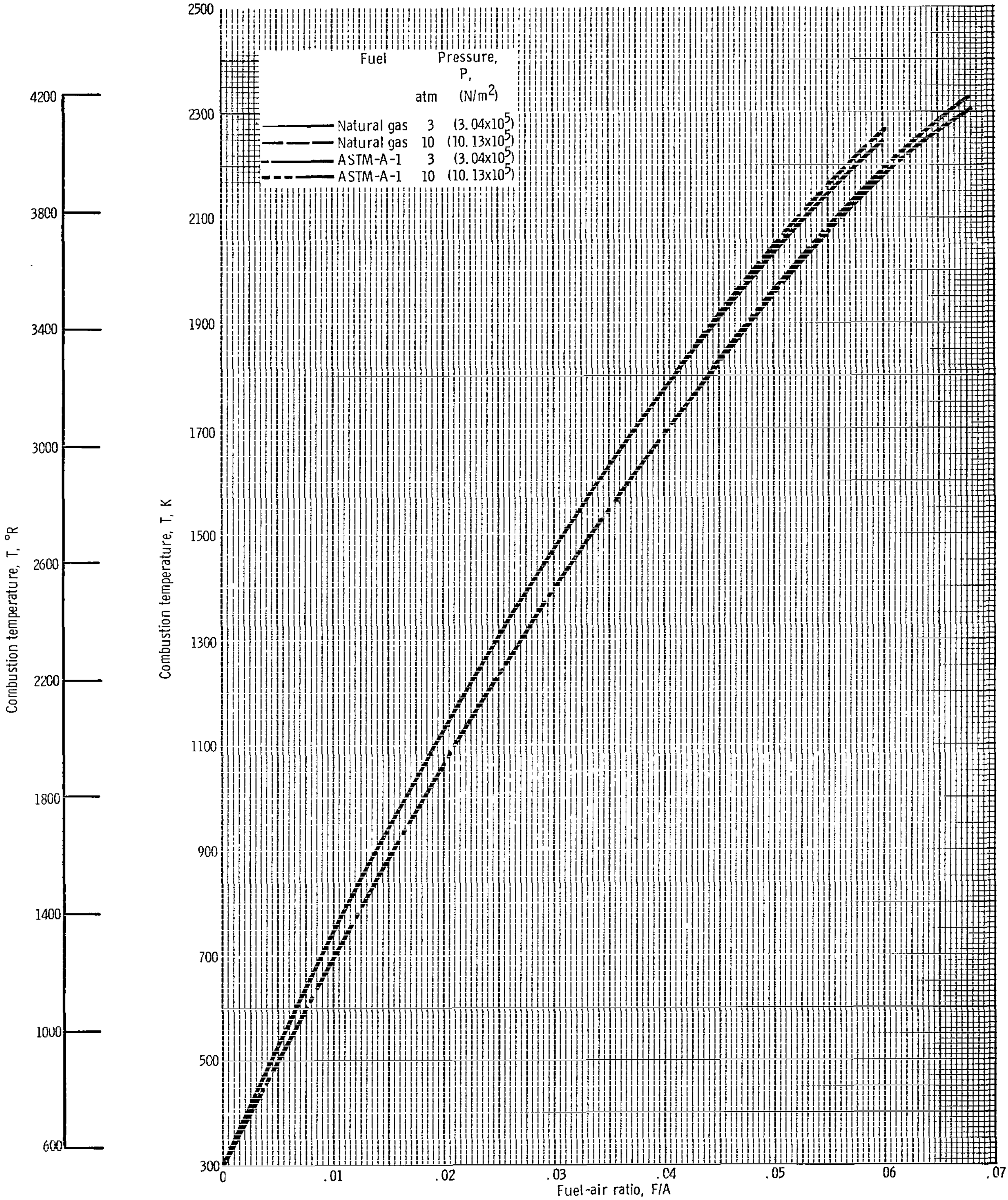

Figure 12. - Adiabatic combustion temperatures of natural gas and of ASTM-A-1 burned in air.

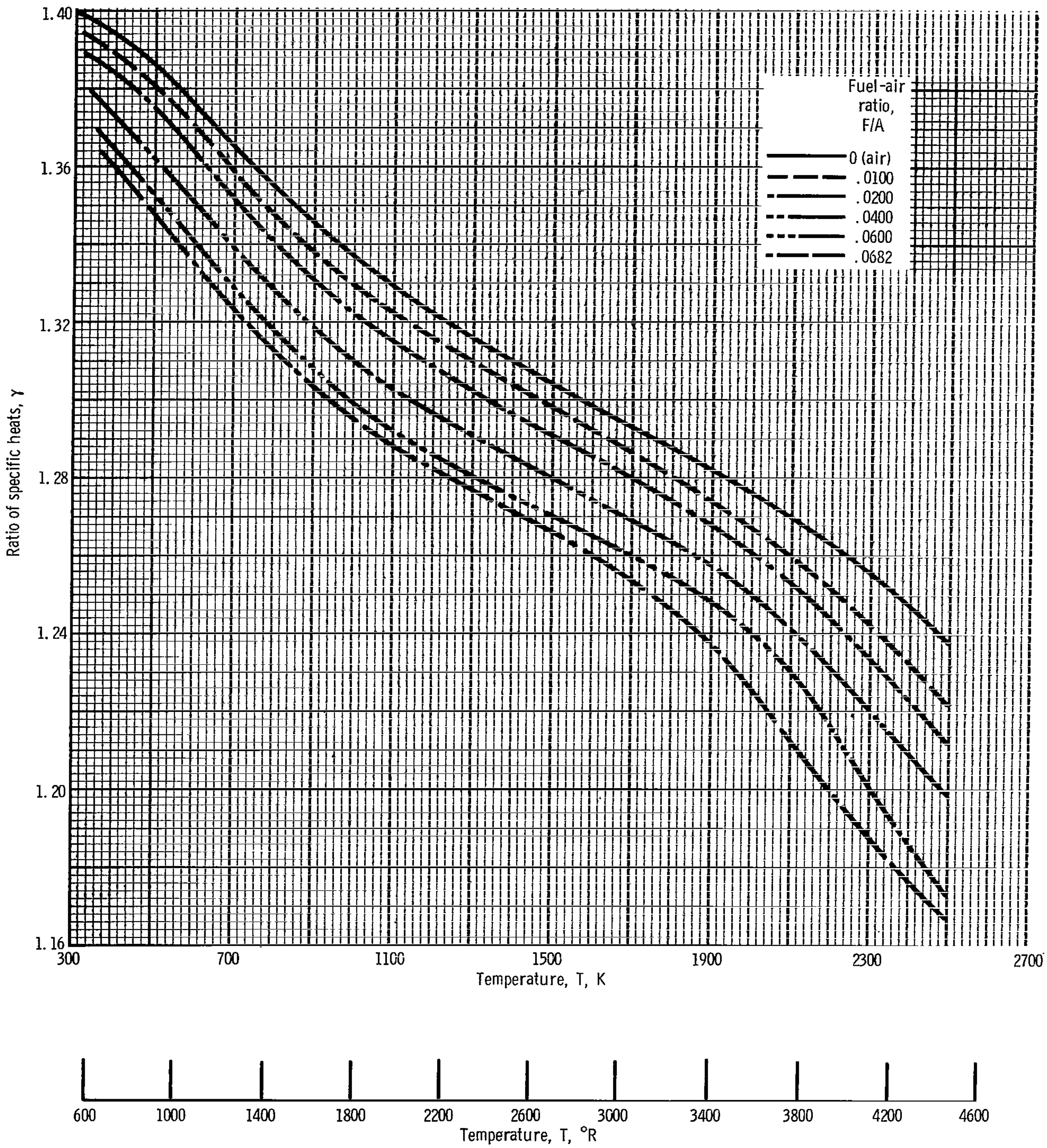

Figure 13. - Ratio of specific heats of combustion products of ASTM-A-1 and air at pressure of 3 atmospheres (3.04×10^5 N/m^2).

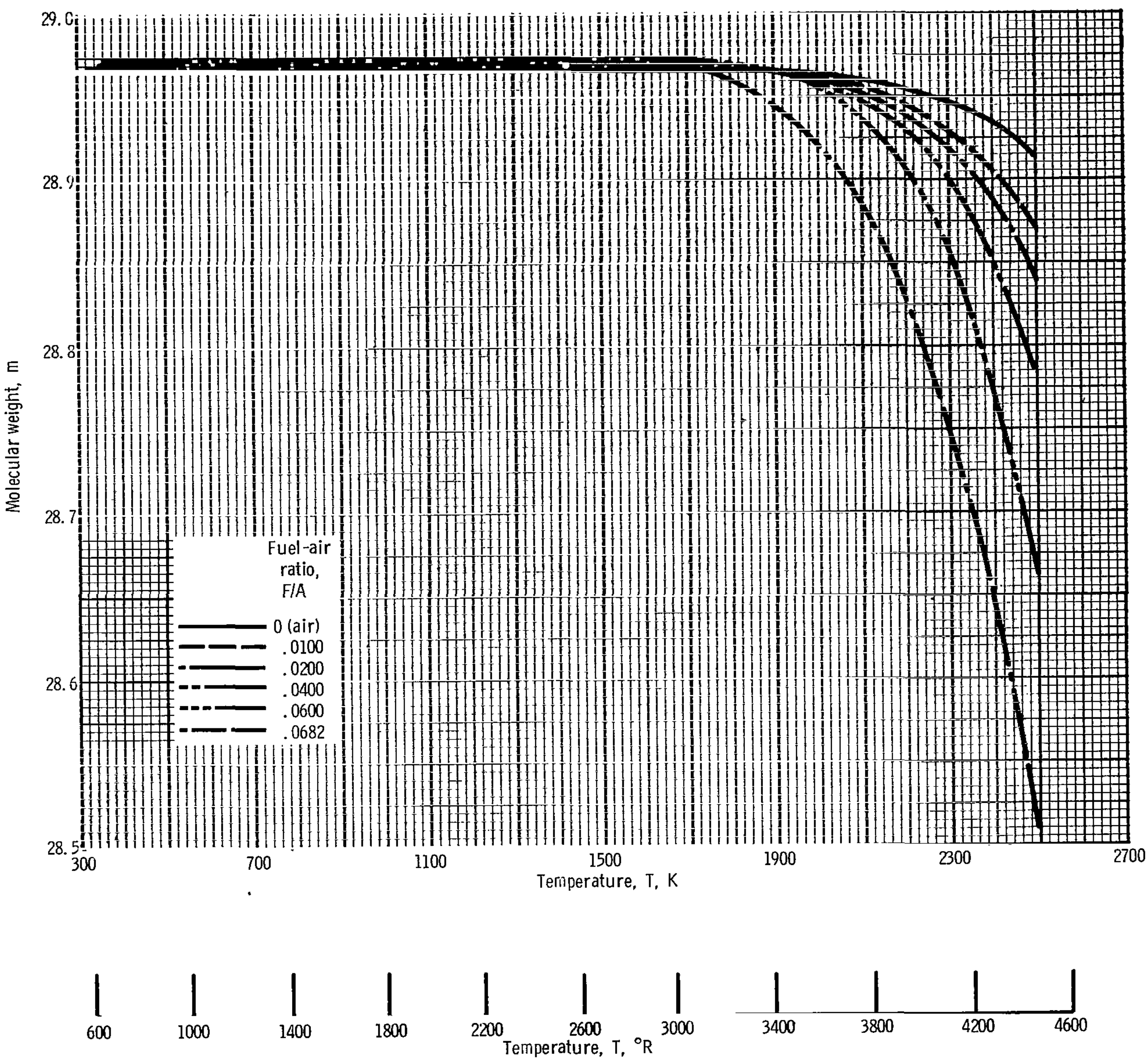

Figure 14. - Molecular weight of combustion products of ASTM-A-1 and air at pressure of 3 atmospheres (3.04×10^5 N/m^2).

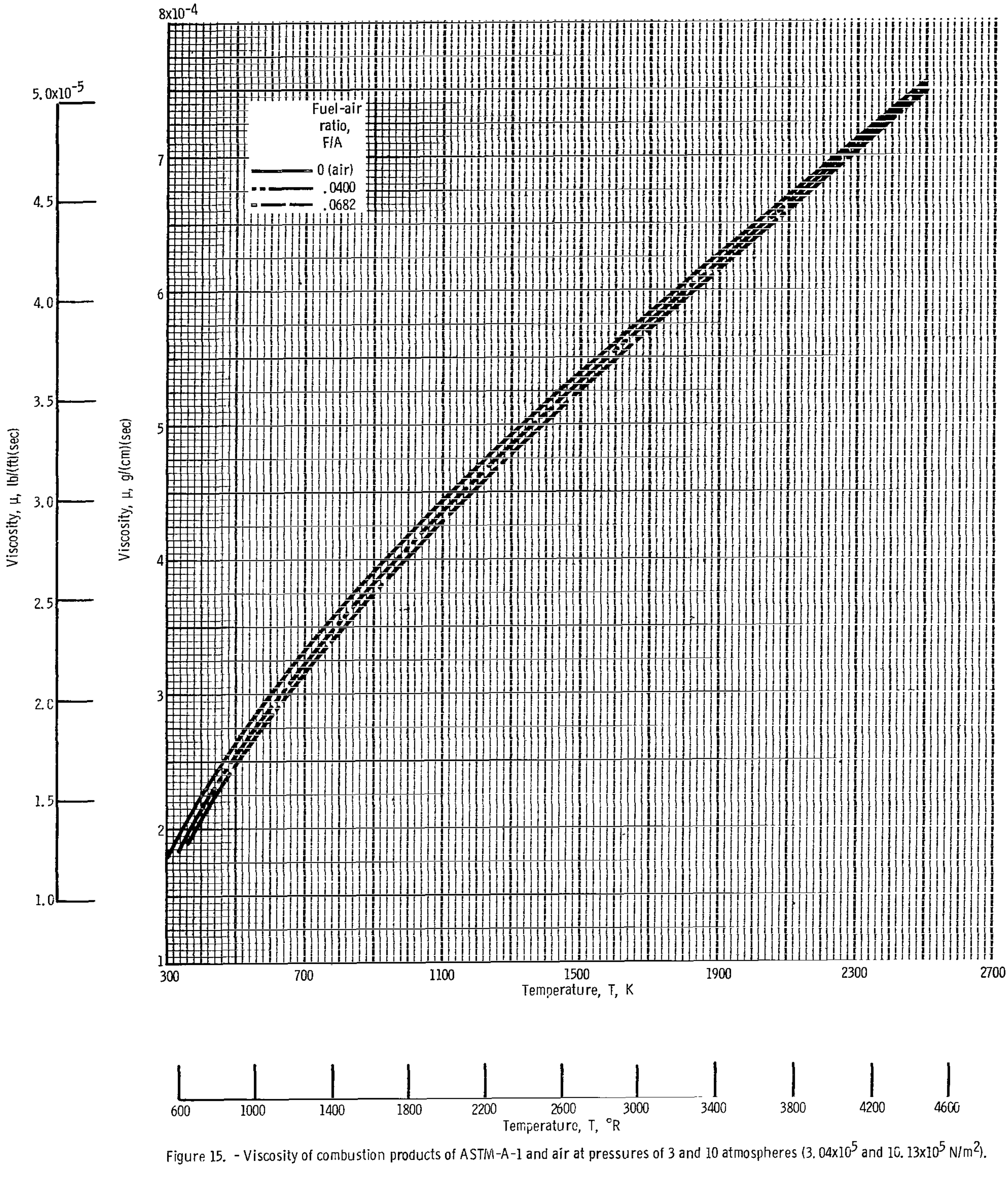

Figure 15. - Viscosity of combustion products of ASTM-A-1 and air at pressures of 3 and 10 atmospheres (3.04×10^5 and 10.13×10^5 N/m^2).

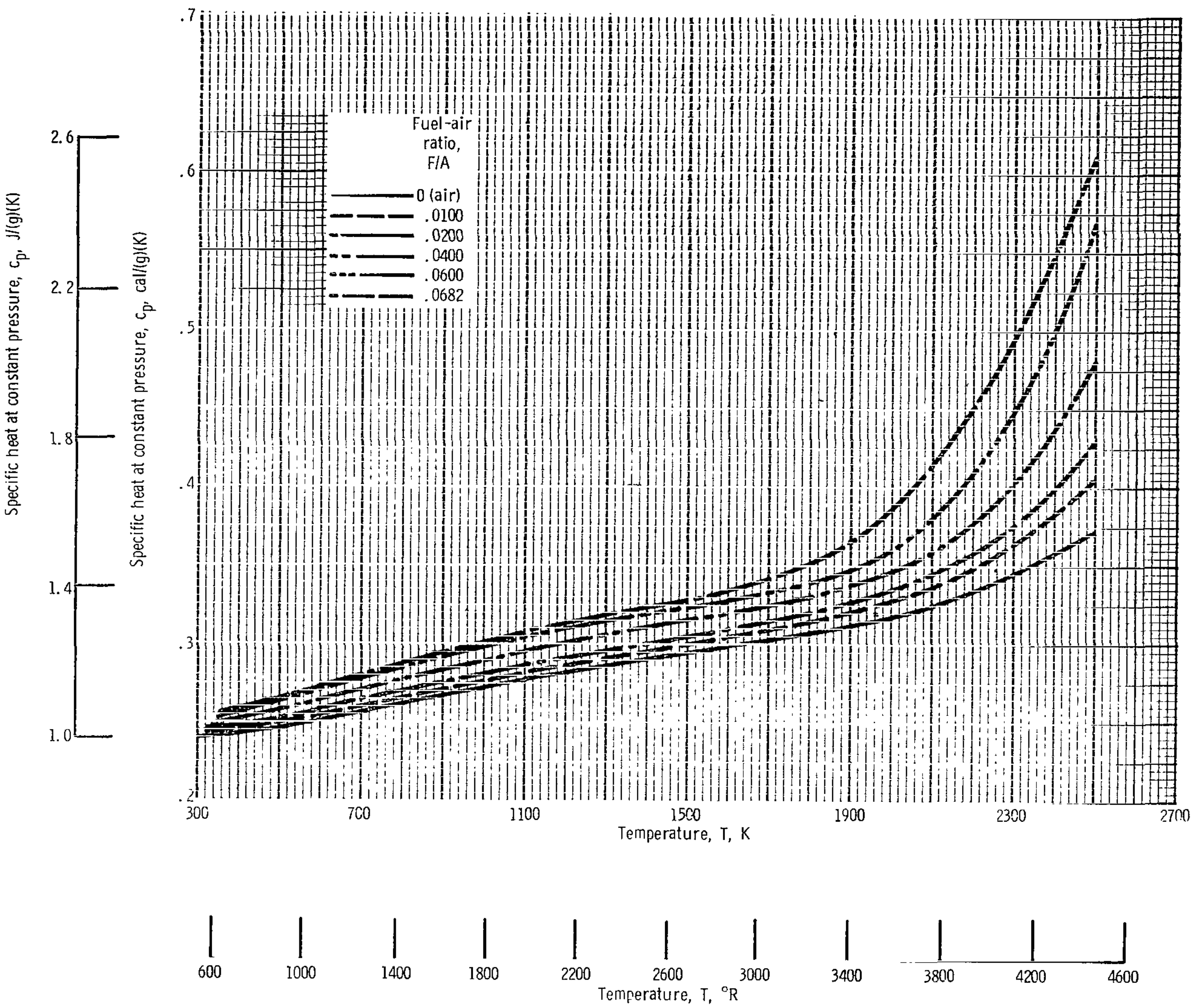

Figure 16. - Specific heat at constant pressure of combustion products of ASTM-A-1 and air at pressure of 3 atmospheres (3.04×10^5 N/m^2).

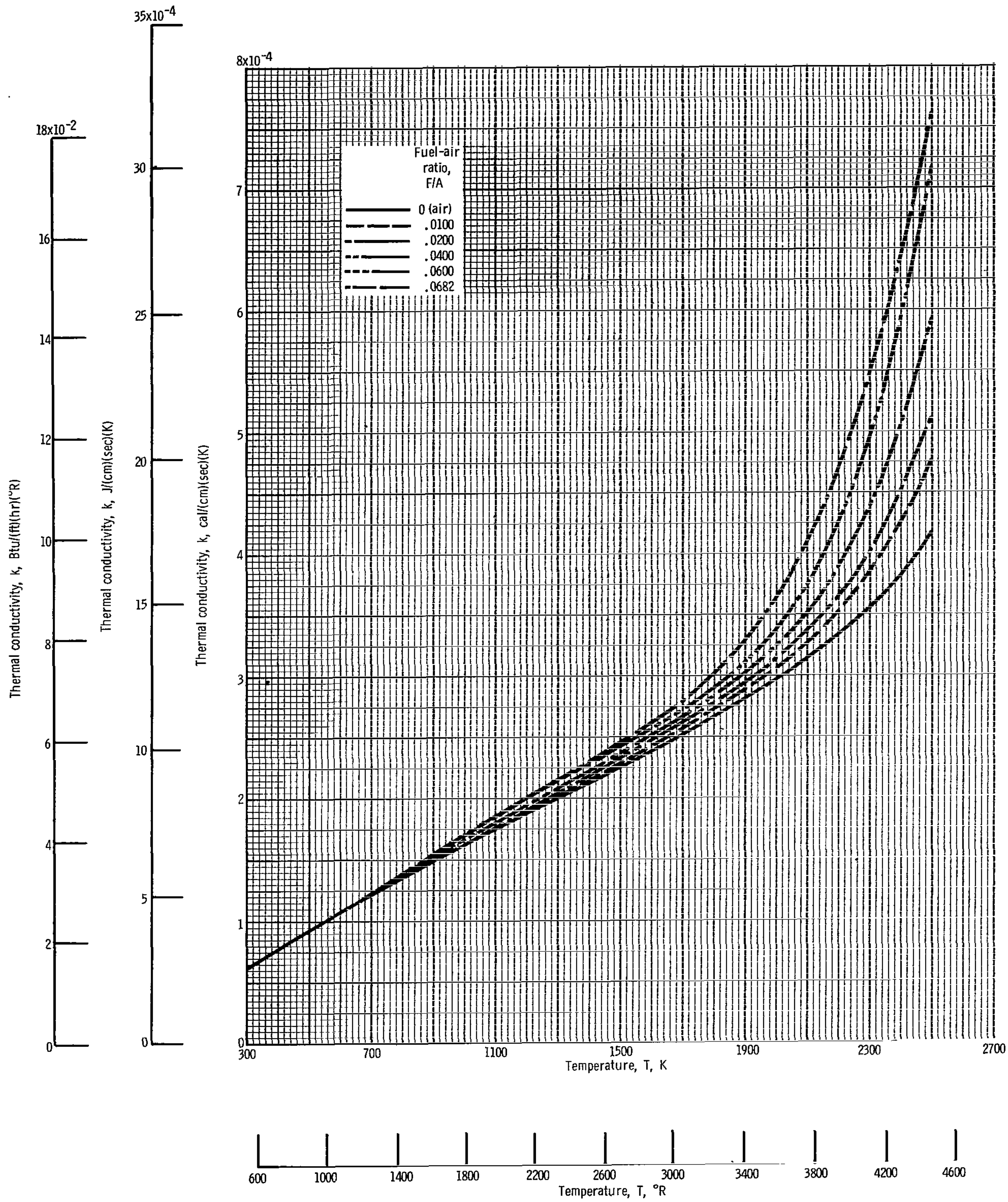

Figure 17. - Thermal conductivity of combustion products of ASTM-A-1 and air at pressure of 3 atmospheres (3.04×10^5 N/m^2).

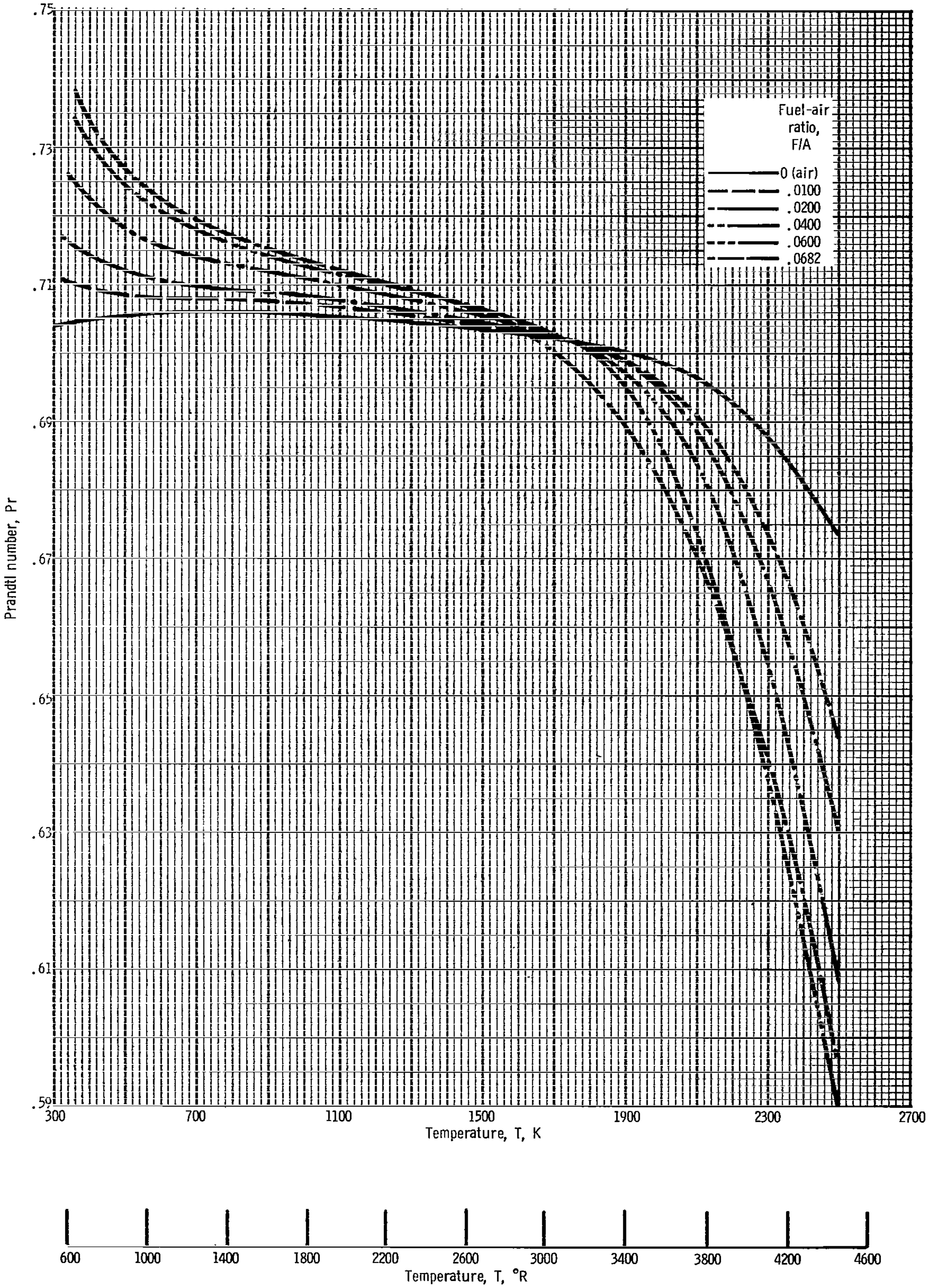

Figure 18. - Prandtl number of combustion products of ASTM-A-1 and air at pressure of 3 atmospheres (3.04×10^5 N/m^2).

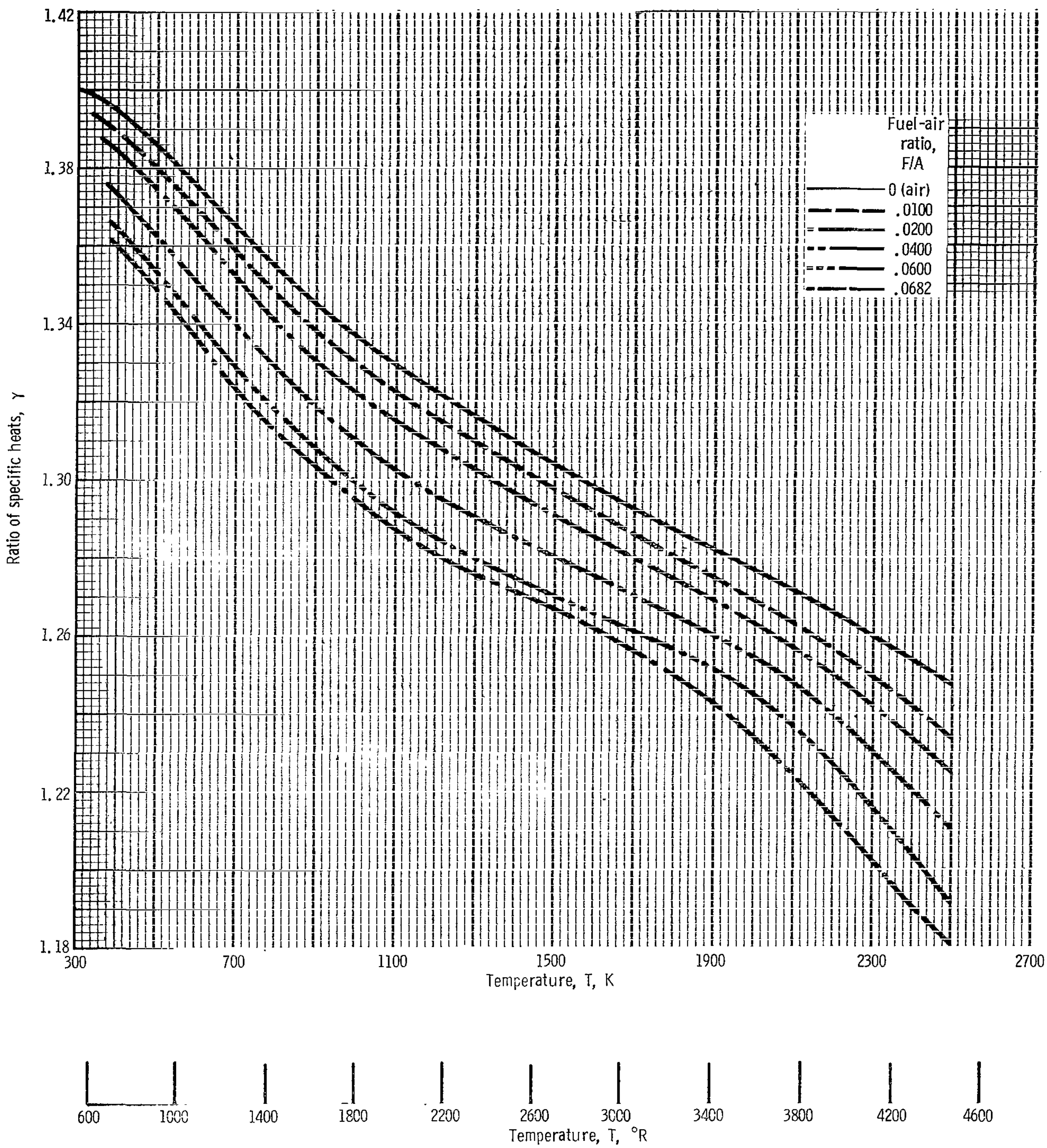

Figure 19. - Ratio of specific heats of combustion products of ASTM-A-1 and air at pressure of 10 atmospheres (10.13×10^5 N/m^2).

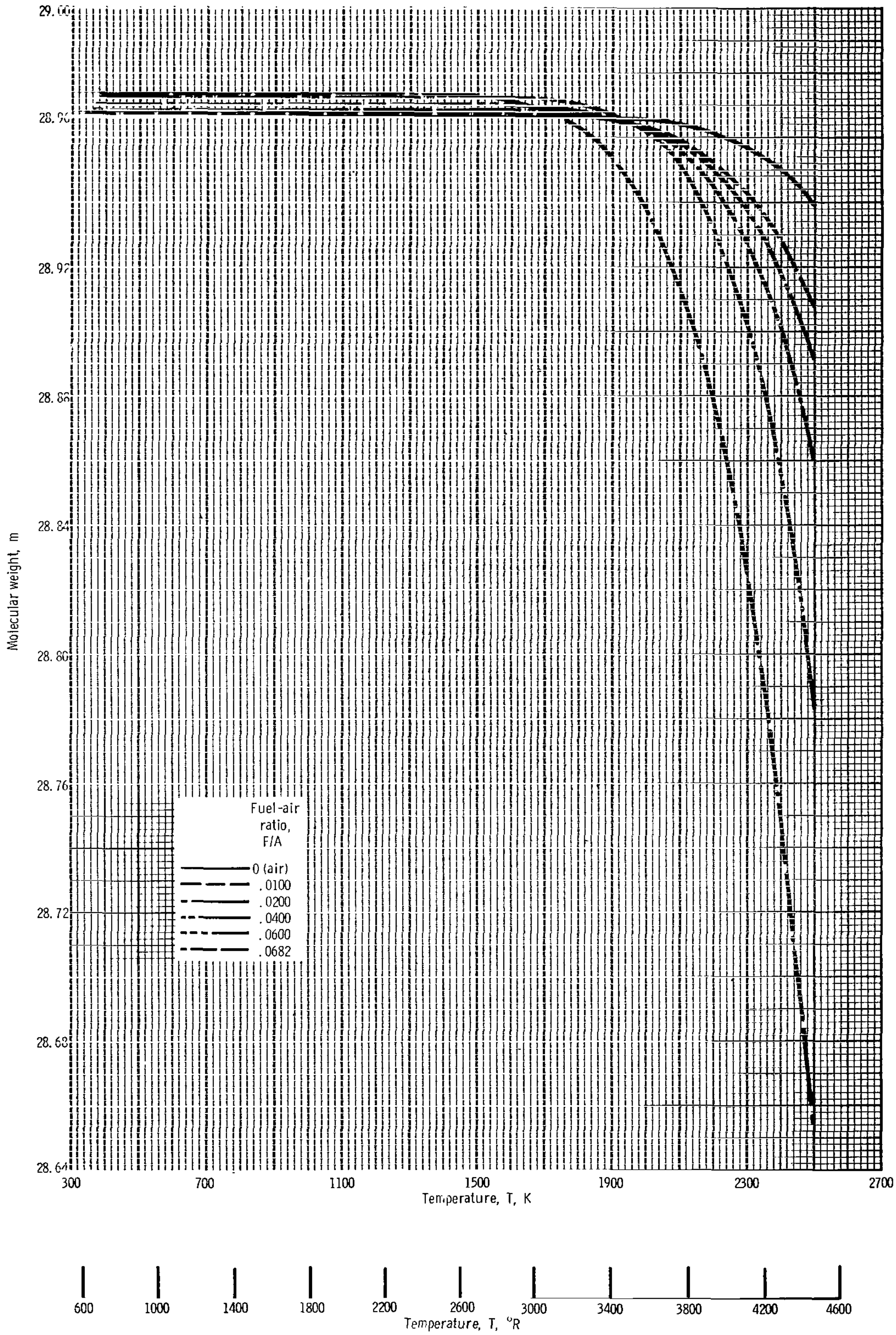

Figure 20. - Molecular weight of combustion products of ASTM-A-1 and air at pressure of 10 atmospheres (10.13×10^5 N/m^2).

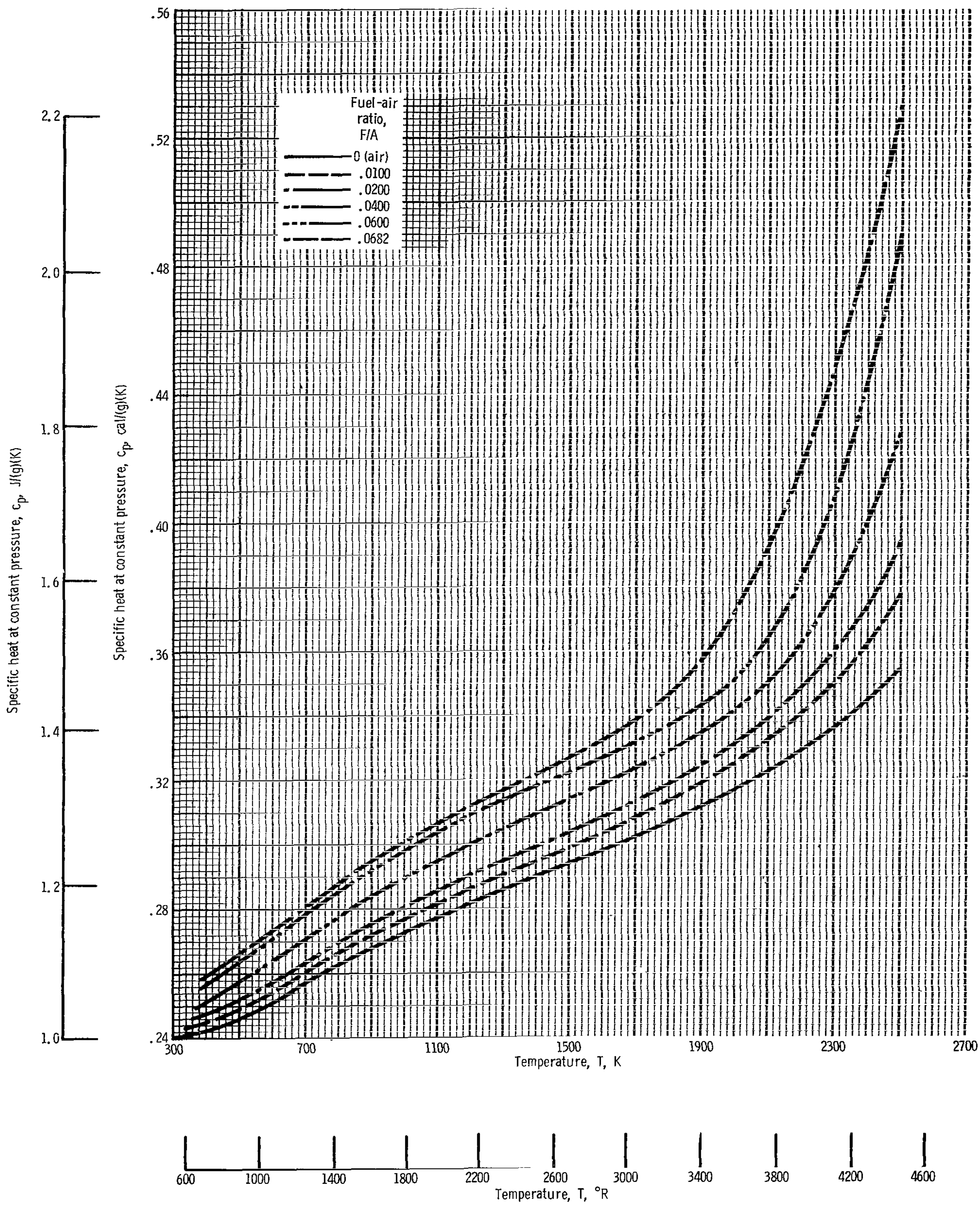

Figure 21. - Specific heat at constant pressure for combustion products of ASTM-A-1 and air at pressure of 10 atmospheres (10.13×10^5 N/m^2).

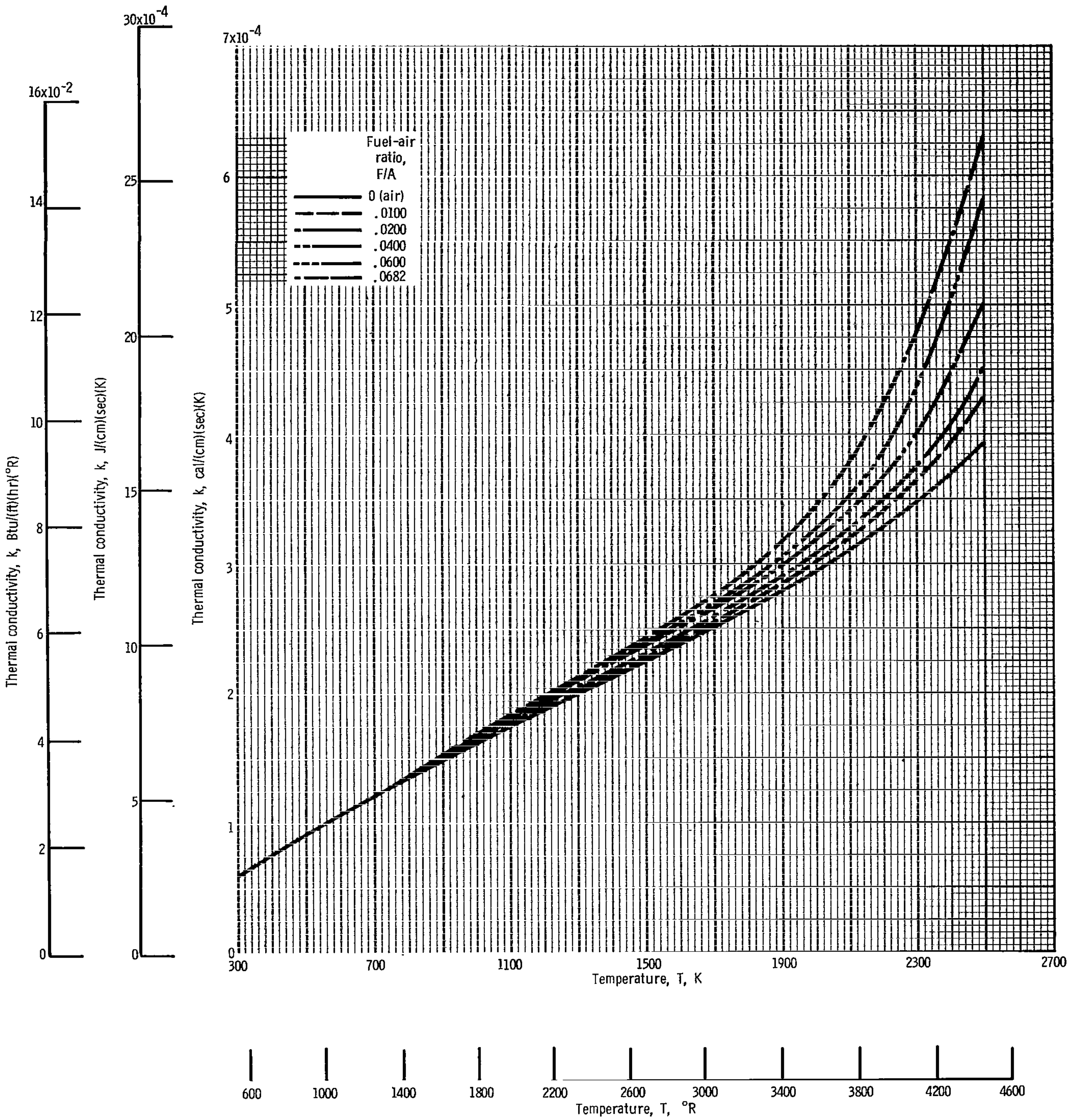

Figure 22. - Thermal conductivity of combustion products of ASTM-A-1 and air at pressure of 10 atmospheres (10.13×10^5 N/m^2).

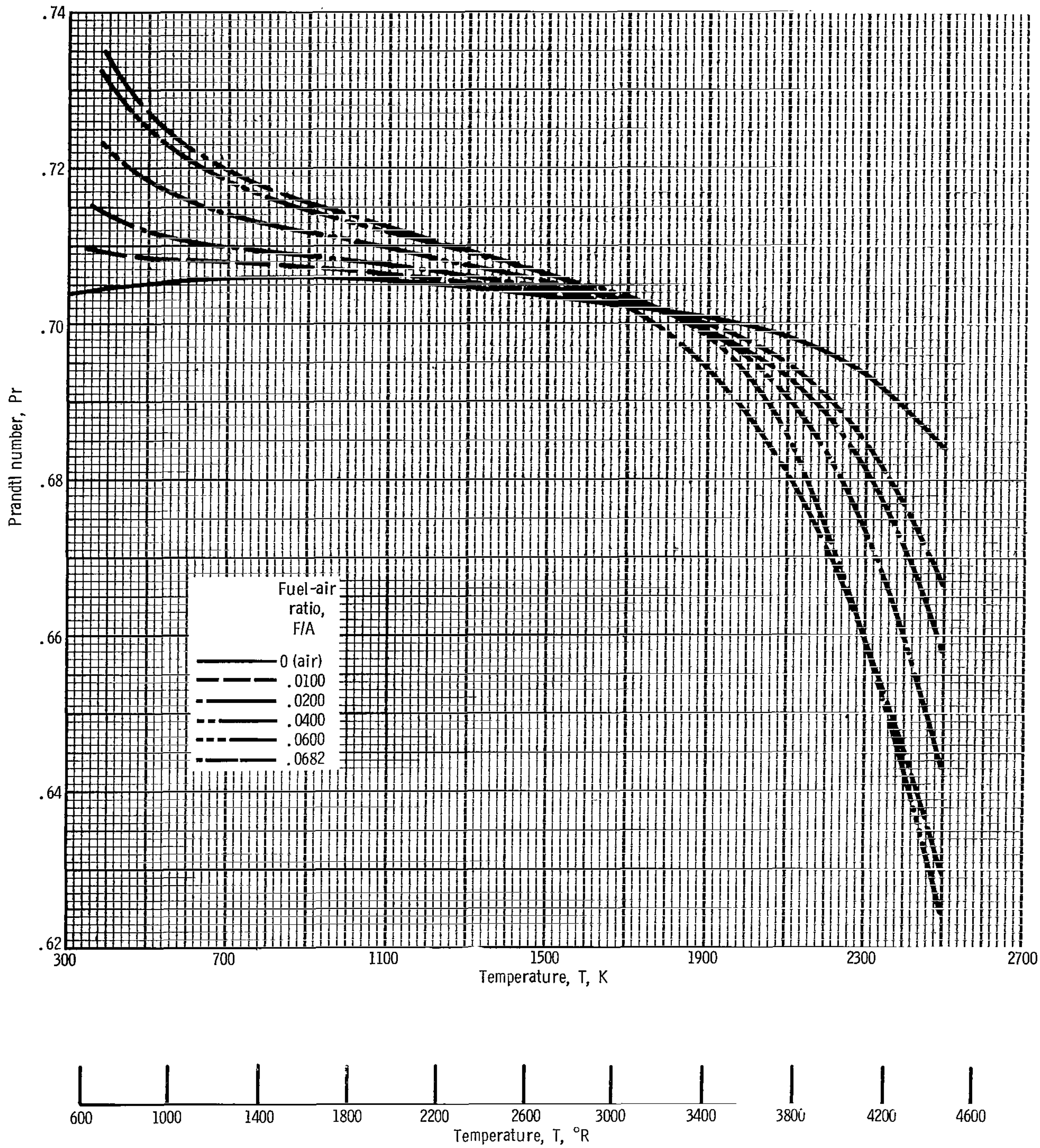

Figure 23. - Prandtl number of combustion products of ASTM-A-1 and air at pressure of 10 atmospheres (10.13×10^5 N/m^2).

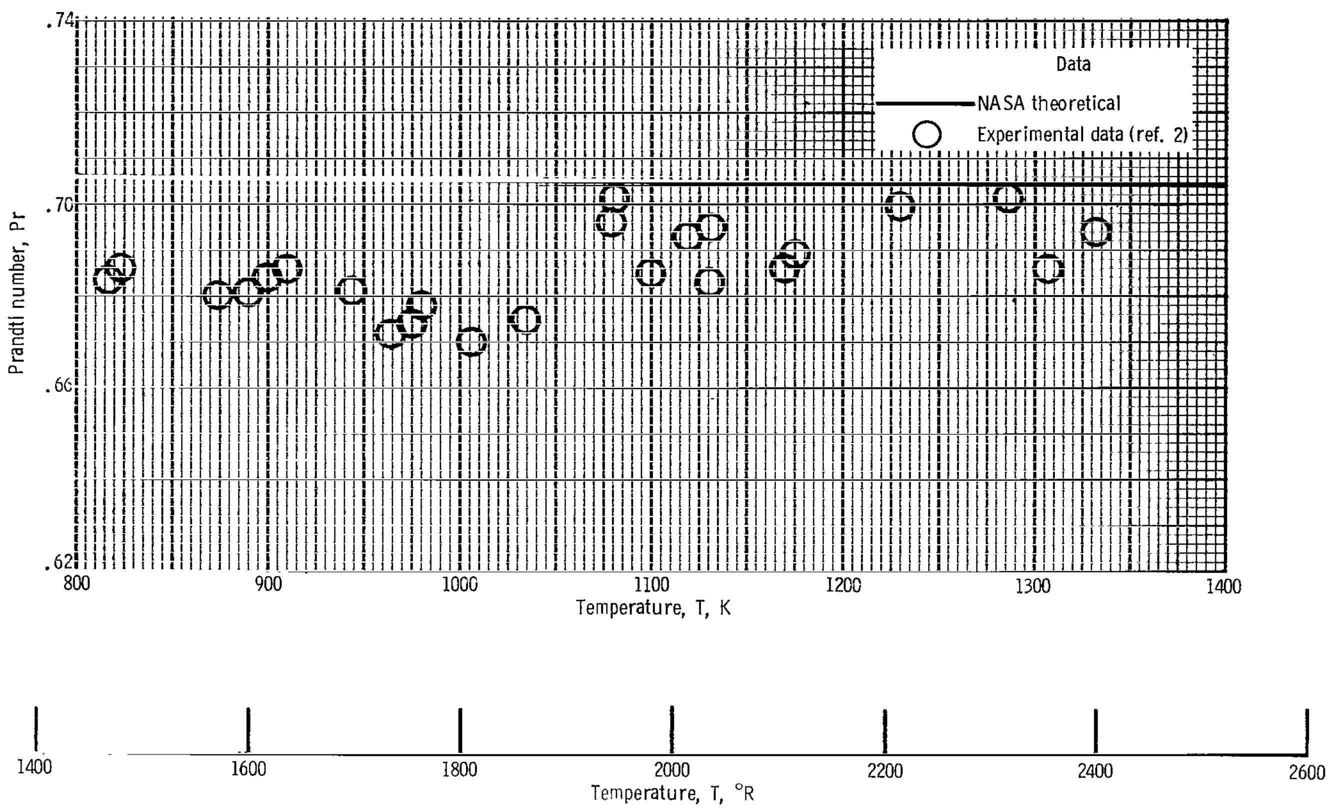

Figure 24. - Comparison of experimental and theoretical values for Prandtl number of air.

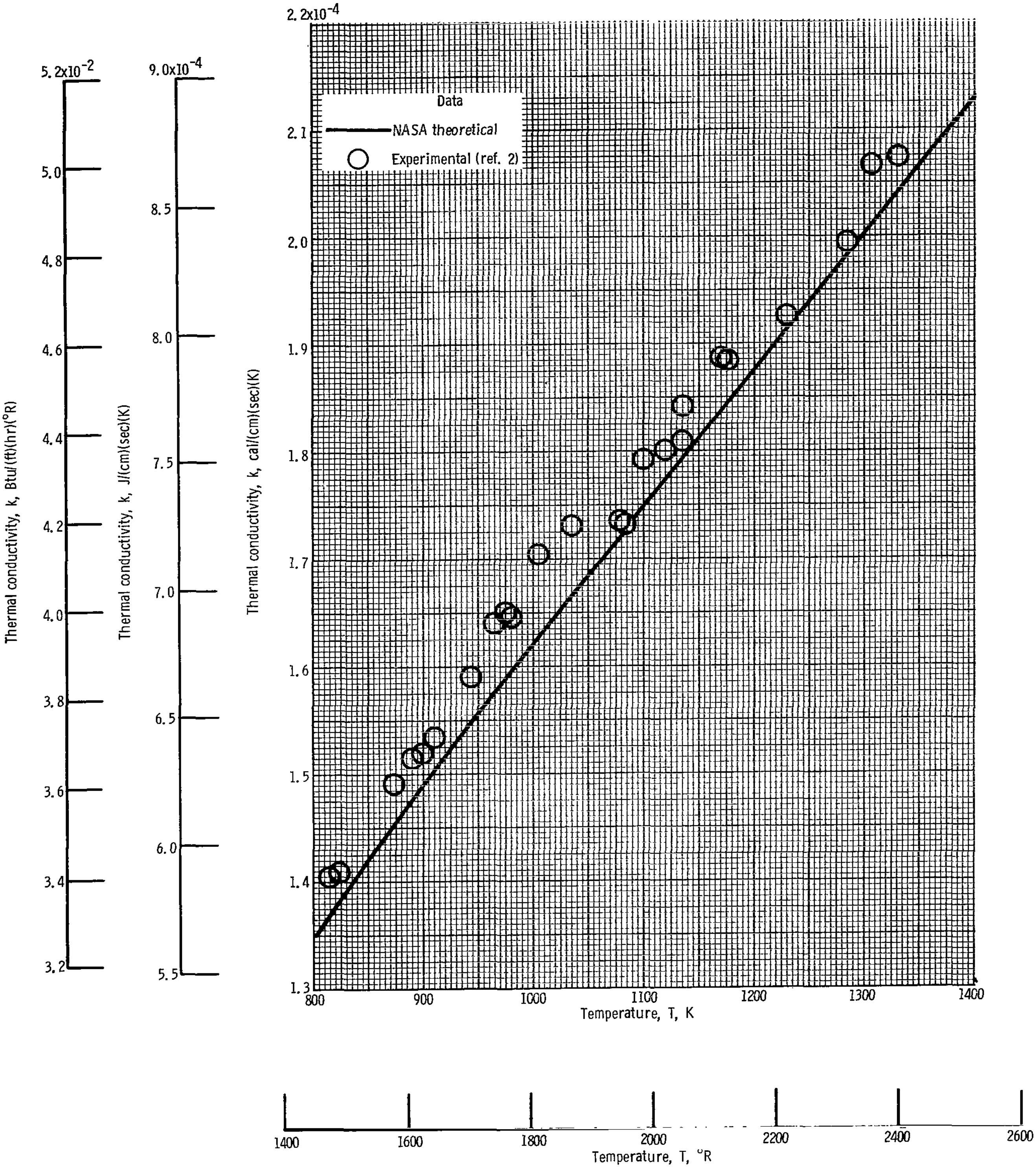

Figure 25. - Comparison of experimental and theoretical values of thermal conductivity for air.

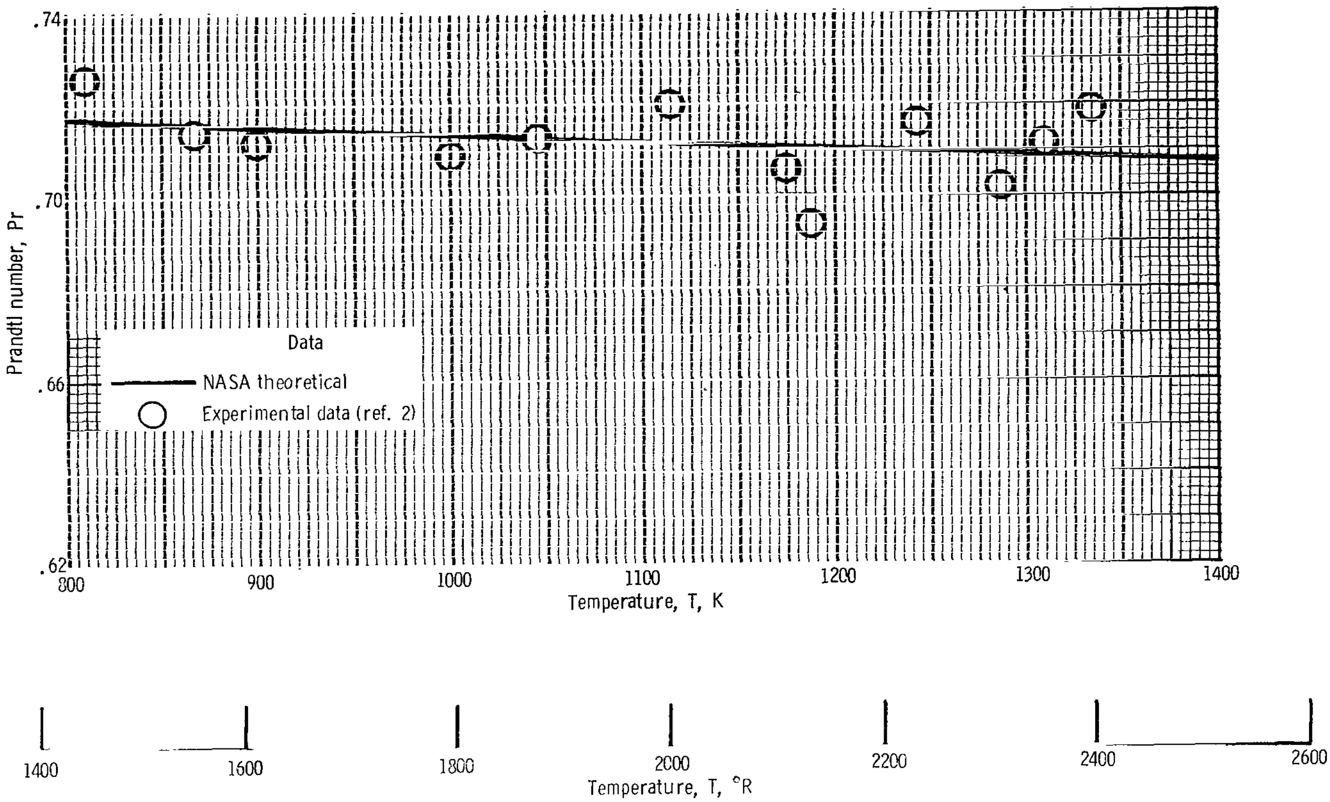

Figure 26. - Comparison of experimental and theoretical values of Prandtl numbers for combustion products of $(CH_2)_n$ type hydrocarbon and air at fuel-air ratio of 0.068.

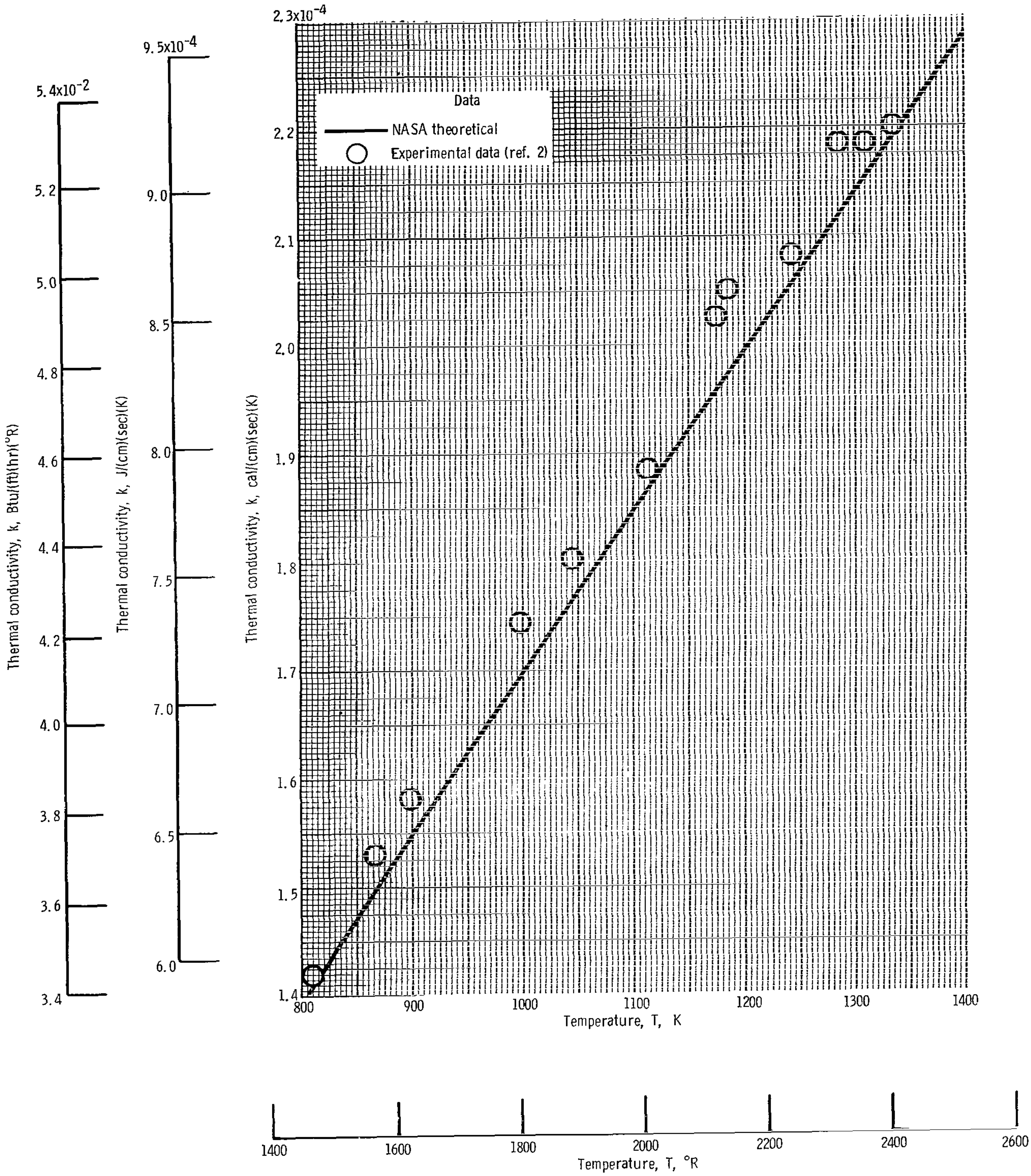

Figure 27. - Comparison of experimental and theoretical values of thermal conductivity for combustion products of $(CH_2)_n$ type hydrocarbon and air at fuel-air ratio of 0.068.

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