

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

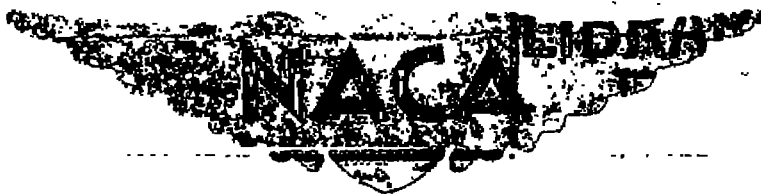
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AN INVESTIGATION OF AIRCRAFT HEATERS

II - PROPERTIES OF GASES

By Myron Tribus and L. M. K. Boelter
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WASHINGTON

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

ADVANCE RESTRICTED REPORT

AN INVESTIGATION OF AIRCRAFT HEATERS

II - PROPERTIES OF GASES

By Myron Tribus and L. M. K. Boelter

A list of properties of the following pure gases and air which are pertinent to airplane heat transfer calculations has been compiled from the literature for the temperature range encountered in airplane operations:

Air

Hydrogen

Nitrogen

Oxygen

Carbon dioxide

Carbon monoxide

The properties of exhaust gases of various compositions are not available to the authors, but it is suggested that the properties of air be utilized for exhaust gas calculations until more exact data are made available.

The reader must be cautioned that when utilizing generalized heat transfer equations or their graphical counterpart, the physical properties which were employed by the experimenter must be substituted into the generalized expressions in order that the proper magnitude of the unit conductance will result.

SYMBOLS

C_p unit heat capacity at constant pressure, Btu/lb °F

C_v unit heat capacity at constant volume, Btu/lb °F

f ratio of $\frac{k}{g_v \mu} = 3600 \text{ g c, ft/hr sec}$

g gravitational force per unit mass, $\frac{lb}{\left(\frac{lb \cdot sec^2}{ft}\right)}$

k thermal conductivity, $\frac{Btu}{hr \cdot ft^2 \left(\frac{^{\circ}F}{ft}\right)}$

T temperature (abs.), $^{\circ}R$

μ absolute viscosity, $lb \cdot sec/ft^2$

Pr Prandtl modulus, $\frac{\mu C_p (3600 \text{ } g)}{k}$

c ratio, $\frac{k}{\mu C_v (3600 \text{ } g)}$

The data presented herein represent the work of many experimenters.

The values for specific heats were taken directly from Heck (reference 1) and converted to the engineering system of units. The original work of Heck extends from 140° to $4940^{\circ} F$ and is probably the best obtainable. It is based upon spectroscopic measurements.

Williams (reference 2) has shown that, if Sutherland's equations (reference 3) for the viscosity of a gas holds, a plot of $T^{3/2}/\mu$ against T should give a straight line. When such plots were constructed, it was found that all the gases except hydrogen yielded straight lines. For hydrogen it was found that the ratio $T^{2/3}/\mu$ was constant within the accuracy of the experimental results. Using the equation $\mu = C T^{2/3}$ for hydrogen, and

$\mu = C \frac{T^{3/2}}{1 + C_2}$ for the other gases, excellent agreement was

obtained between the calculated values and the measured values of the viscosity. In the case of carbon dioxide and oxygen, the deviations from experimental values were nearly all less than 1 percent.

In contrast with the data for unit heat capacity and

viscosity, there is a paucity of accurate data on thermal conductivities of gases. Laby and Nelson (reference 4) found among 19 observers an average deviation of 7 percent in the values reported for the thermal conductivity of air at 32° F. The data for other gases are less plentiful. Only three measurements of the thermal conductivity of carbon monoxide were found, all near 32° F.

In modern engineering practice, however, it is often desired to know thermal conductivities at temperatures other than 32° F. Rather than make an outright guess, the following theoretical relationship was utilized (reference 5):

$$k = (3600 \text{ g cm}) \mu C_v = f \mu C_v$$

From the measured values of k , μ , and C_v , values of f were calculated and plotted against temperature. If a definite variation in f as a function of T could be found, such a variation was used as a basis for predicting k at temperatures at which it has not been measured, using the measured values of μ and C_v . Such a method is subject to many errors, obviously, but it was the best that could be devised. The results are unsatisfactory, but until a better scheme is devised or more data are presented, they will have to serve as the basis for high temperature calculations. The tabulated values of thermal conductivities are based on the derived equations.

The probable errors are based on the average deviation of experimental results from the "best curve." In such a case as k for CO, judgment based on three measured values at 32° F can hardly be considered more than a guess when applied to values at 1000° F.

These properties are all independent of pressure in the range two atmospheres down to 5 millimeters of mercury. Shown below are the temperature ranges for which experimental data were available, and the temperatures for which certain properties were extrapolated as discussed above.

Grateful acknowledgment is due Messrs. E. B. Weinberg and H. F. Brockschmidt for their help in preparing the report.

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TEMPERATURE RANGE OF EXPERIMENTAL DATA

Gas	Range in which data are available (deg F)	Range in which curves were extrapolated (deg F)
Air		
Heat capacity (C_p)	(Calculated from O_2 and N_2 values)	
Viscosity	-109 to 1600	
Thermal conductivity	-109 to 590	590 to 1600
Hydrogen		
Heat capacity (C_p)	-100 to 4940	
Viscosity	-113 to 1517	
Thermal conductivity	-113 to 608	608 to 1600
Nitrogen		
Heat capacity (C_p)	-100 to 4940	
Viscosity	-106 to 1516	
Thermal conductivity	-103 to 212	212 to 1600
Oxygen		
Heat capacity (C_p)	-100 to 4940	
Viscosity	59 to 1524	-100 to 59
Thermal conductivity	-109 to 212	212 to 1600
Carbon dioxide		
Heat capacity (C_p)	-100 to 4940	
Viscosity	30 to 1600	-100 to 30
Thermal conductivity	-109 to 502	602 to 1600
Carbon monoxide		
Heat capacity (C_p)	-100 to 4940	
Viscosity	-109 to 530	530 to 1600
Thermal conductivity	32 to 51	-200 to 32 51 to 1600

REFERENCES

1. Heck, Robert C. H.: The New Specific Heats. Mech. Eng., vol. 62, Jan. 1940, pp. 9-12; vol. 63, Feb. 1941, pp. 126-135 (Addenda).
2. Williams, F. A.: Proc. Roy. Soc., London, A110, 1926, p. 141.
3. Sutherlands: Phil. Mag., vol. 36, 1893, p. 507.
4. Laby and Nelson: ICT, V 213.
5. Loeb, Leonard B.: Kinetic Theory of Gases. McGraw-Hill Book Co., Inc., 1927, p. 215.

BIBLIOGRAPHY

Conductivity

- Archer: k for CO_2 . Phil. Mag., vol. 19, pp. 901-918.
- Archer: Experimental Values of k . Proc. Roy. Soc., A165, pp. 474-485.
- Berg, H. H.: DVL Exhaust Gas Analyzer for Internal Combustion Engines. Automobiltechnische Zeitschr., vol. 41, no. 17, Sept. 10, 1938, p. 455.
- Bolland and Molvillos: Nature, vol. 140, p. 63.
- Mnaskog: A Mathematical Treatment of k . Arkiv. Mat. Astron. Fysik, vol. 16, pp. 1-60.
- Mucken: Measurements of k . Physik. Zeitschr., vol. 14, pp. 324-362.
- Mucken: k for Various Gases. Physik. Zeitschr., vol. 13, pp. 1101-1107.
- Gregory: Experimental Values of k . Proc. Roy. Soc., A149, pp. 35-56.

Gregory and Archer: Experimental Values of k . Proc. Roy. Soc., London, 110A, 1926, pp. 91-122.

Gregory and Archer: Experimental Determination of k . Phil. Mag., vol. 15, 1933, pp. 301-309.

Gregory and Archer: Experimental Determination of k . Proc. Roy. Soc., A121, pp. 285-293.

Gregory and Dock: Review. Phil. Mag., vol. 25, pp. 129-147.

Gregory and Marshall: Proc. Roy. Soc., 114A, pp. 354-366.

Gregory and Marshall: Experimental Values of k . Proc. Roy. Soc., A118, pp. 594-607.

Gruss and Schmick: Siemens Konz., vol. 7, pp. 202-224.

Heindlhofer: Thermal Conductivity. Ann. Physik, vol. 37, pp. 247-256; vol. 45, pp. 259-282, 1914.

Henderson: Experimental Results of Measurements of k . Phys. Rev., vol. 15, 1920, pp. 46-57.

Hercus and Laby: Measurements of k . Phil. Mag., vol. 3 (7), pp. 1061-1064.

Ibbs: Review. Phil. Mag., vol. 21, pp. 508-509.

Ibbs and Hirst: Theoretical Considerations of the Values of k . Proc. Roy. Soc., A123, pp. 134-142.

Kannulwick and Martin: Experimental Determination of k . Proc. Roy. Soc., A144, pp. 496-513.

Knudsen: Ann. Physik, vol. 34, pp. 593-656.

Laby: Review of Data on k . Nature, 137, p. 741.

Milverton: Experimental Results of k . Phil. Mag., vol. 17, pp. 397-422.

Moethdurft: Experimental Values of k . Ann. Physik, vol. 28, pp. 137-156.

- Pauli, E.: Ann. d. Physik, vol. 23, pp. 907-931.
- Pollock, J. A.: κ for Gases. Proc. Roy. Soc., New South Wales, vol. 49, pp. 249-252; Review, vol. 53, pp. 116-119.
- Sherrat and Griffiths: Review and Experimental Data. Phil. Mag., vol. 27, pp. 68-75.
- Soddy and Borry: κ for Gases. Proc. Roy. Soc., vol. 83, pp. 254-264; vol. 84, pp. 576-585.
- Smoluchowski: Theoretical Consideration of κ . Ann. Physik, vol. 35, pp. 983-1004; Review, Phil. Mag., vol. 21, (6), pp. 11-15.
- Todd: Experimental Measurements of κ . Proc. Roy. Soc., vol. 83, pp. 19-39.
- Trautz: Physik regelmass. Ber. 6, pp. 163-80. A Review. 204, References.
- Trautz and Zündel: Ann. Physik, vol. 17, 1933, pp. 345-375.
- Uehling and Uhlenbeck: Theoretical Considerations of κ . Phys. Rev., vol. 43, 1933, pp. 552-561.
- Weber: Experimental Determination of κ . Ann. Physik, vol. 82, pp. 479-503. Experimental Results of Measurements of κ ; vol. 54, pp. 325-326, 437-462, 481-502.

Viscosity

- Bauman: Ann. Physik, vol. 2, 1929.
- Binkley: Ann. Physik, vol. 2, 1929.
- Boomondi, Pierre: Comptes Rendus, vol. 196, 1933, pp. 1472-1474.
- Majumdar and Vajifdar: J. Univ. Bombay, vol. 7, pt. 3.
- Narath: Ann Physik, vol. 2, 1929.
- Stauf: Ann Physik, vol. 2, 1929.

- ten Bosch, M.: *Wärmetübertragung*, 3d. ed., p. 257.
- Trautz and Baumann: *Ann Physik*, vol. 2, 1929, p. 733.
- Trautz and Binkels: *Ann Physik*, vol. 5, 1930, p. 561.
- Trautz and Kurz: Review of Previous Experiments on Viscosity. *Ann Physik*, vol. 9, 1931, pp. 981-1003.
- Trautz and Ludowigs: *Ann. Physik*, vol. 2, 1929, p. 733.
- Trautz and Sorg: *Ann. Physik*, vol. 10, 1931, pp. 81-96.
- Trautz and Stauf: *Ann. Physik*, vol. 2, 1929.
- Trautz and Weizel: *Ann. Physik*, vol. 78, 1925, p. 305.
- Trautz and Zink: *Ann. Physik*, vol. 7, (5), 1930, pp. 427-452.
- Williams, F. A.: *Proc. Roy. Soc., London*, A110, 1926, p. 165.

TABLE I.-- AIR

t (deg F)	c_p (Btu/lb °F)	$\mu \times 10^6$ (lb sec/ft ²)	$k \times 10^2$ (Btu/ft ² hr $\frac{\text{deg F}}{\text{ft}}$)	Pr
-100	0.2393	0.280	1.04	0.743
0	.2398	.343	1.30	.731
100	.2403	.398	1.57	.706
200	.2412	.449	1.82	.690
300	.2427	.498	2.05	.682
400	.2449	.542	2.28	.677
500	.2476	.587	2.50	.672
600	.2505	.630	2.72	.668
700	.2534	.663	2.93	.666
800	.2566	.699	3.14	.663
900	.2598	.732	3.34	.660
1000	.2630	.767	3.55	.658
1100	.2660	.800	3.76	.655
1200	.2690	.832	3.99	.652
1300	.2715	.864	4.19	.650
1400	.2740	.896	4.40	.648
1500	.2766	.928	4.61	.646
1600	.2789	.960	4.84	.643

TABLE II.-- HYDROGEN

t (deg F)	α_p (Btu/lb °F)	$\mu \times 10^6$ (lb sec/ft ²)	$k \times 10^2$ (Btu/ft ² hr $\frac{\text{deg F}}{\text{ft}}$)	Pr
-100	3.393	0.143	7.5	0.870
0	3.413	.169	9.5	.707
100	3.432	.192	11.4	.671
200	3.449	.215	13.1	.654
300	3.359	.235	14.7	.640
400	3.466	.254	15.9	.640
500	3.472	.275	16.9	.654
600	3.476	.294	17.6	.676
700	3.483	.313	18.4	.688
800	3.490	.331	19.4	.687
900	3.501	.347	20.5	.686
1000	3.514	.364	21.6	.685
1100	3.531	.381	22.8	.684
1200	3.551	.397	23.9	.683
1300	3.572	.413	25.2	.681
1400	3.596	.428	26.1	.679
1500	3.621	.443	27.4	.677
1600	3.646	.458	28.7	.675

TABLE III.-- NITROGEN

t (deg F)	q_p (Btu/lb °F)	$\mu \times 10^6$ (lb sec/ft ²)	$k \times 10^2$ (Btu/ft ² hr $\frac{\text{deg F}}{\text{ft}}$)	Pr
-100	0.2478	0.2675	1.03	0.711
0	.2478	.3275	1.32	.711
100	.2484	.3800	1.54	.709
200	.2490	.4285	1.74	.708
300	.2500	.4750	1.94	.707
400	.2515	.5160	2.12	.706
500	.2538	.5560	2.32	.704
600	.2564	.5950	2.52	.701
700	.2592	.6310	2.72	.698
800	.2623	.666	2.91	.695
900	.2655	.700	3.10	.690
1000	.2689	.731	3.30	.688
1100	.2721	.762	3.50	.687
1200	.2751	.792	3.70	.683
1300	.2780	.820	3.88	.681
1400	.2807	.845	4.04	.679
1500	.2835	.871	4.23	.677
1600	.2860	.895	4.40	.674

TABLE IV. - OXYGEN

t (deg F)	α_p (Btu/lb °F)	$\mu \times 10^6$ (lb sec/ft ²)	$k \times 10^2$ (Btu/ft ² hr $\frac{\text{deg F}}{\text{ft}}$)	Pr
-200		0.226		
-100	0.2180	.3051	1.06	0.726
0	.2185	.3772	1.31	.725
100	.2200	.4410	1.59	.724
200	.2228	.500	1.79	.720
300	.2266	.554	2.03	.715
400	.2305	.607	2.28	.709
500	.2350	.654	2.54	.705
600	.2390	.700	2.77	.703
700	.2429	.743	3.01	.698
800	.2465	.785	3.24	.694
900	.2498	.824	3.47	.692
1000	.2528	.861	3.66	.688
1100	.2553	.897	3.90	.686
1200	.2577	.932	4.09	.684
1300	.2599	.965	4.27	.682
1400	.2618	1.000	4.46	.681
1500	.2635	1.030	4.65	.679
1600	.2651	1.060	4.82	.678

TABLE V.- CARBON DIOXIDE

t (deg F)	c_p (Btu/lb °F)	$\mu \times 10^6$ (lb sec/ft ²)	$k \times 10^2$ (Btu/ft ² hr $\frac{\text{deg F}}{\text{ft}}$)	Pr
-100	0.1885	0.2121	0.57	0.796
0	.1976	.2721	.76	.779
100	.2075	.3275	1.00	.773
200	.2175	.3795	1.23	.762
300	.2280	.4285	1.47	.754
400	.2385	.4765	1.74	.746
500	.2480	.5200	1.99	.736
600	.2565	.5625	2.24	.734
700	.2640	.6040	2.50	.726
800	.2700	.6420	2.72	.723
900	.2760	.6790	2.96	.721
1000	.2815	.7165	3.19	.719
1100	.2861	.7520	3.42	.717
1200	.2905	.7850	3.64	.715
1300	.2945	.8160	3.84	.713
1400	.2984	.8450	4.06	.711
1500	.3018	.8760	4.25	.708
1600	.3050	.9100	4.46	.708

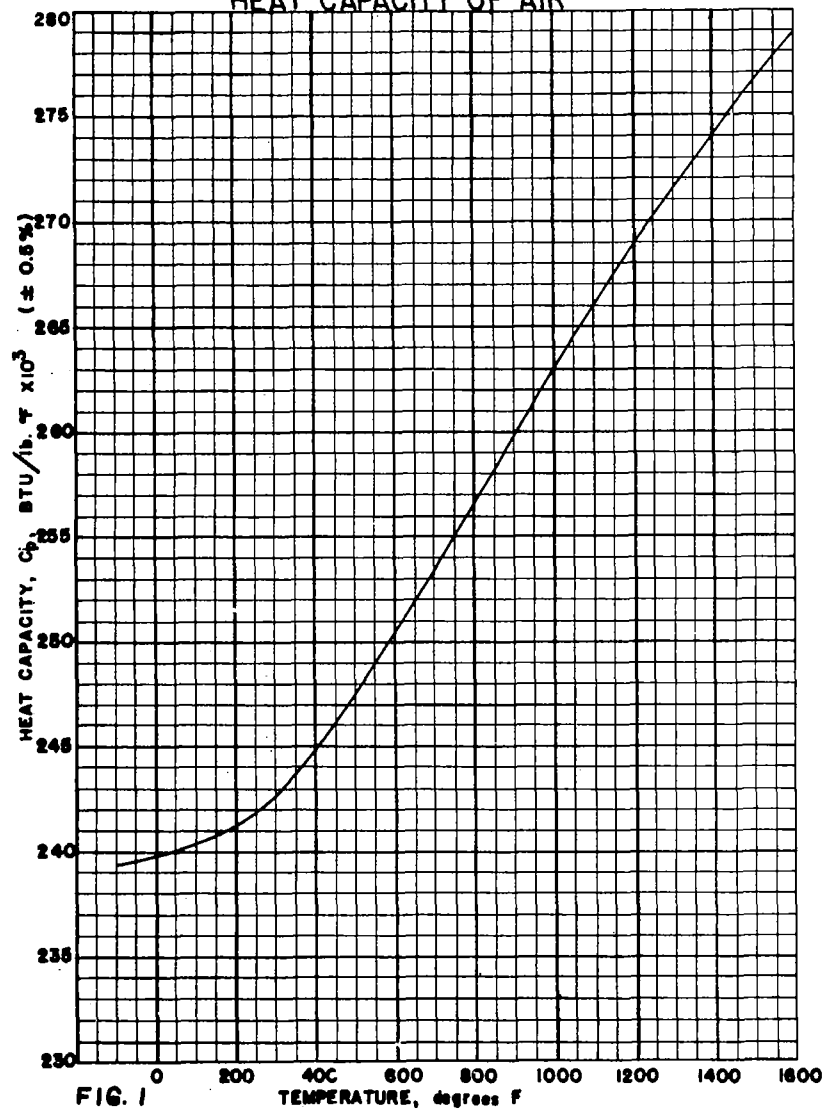
TABLE VI.-- CARBON MONOXIDE

t (deg F)	Q_p (Btu/lb °F)	$\mu \times 10^6$ (lb sec/ft ²)	$k \times 10^2$ (Btu/hr ft ² $\frac{\text{deg F}}{\text{ft}}$)	Pr
-100	0.2480	0.267	1.05	0.716
0	.2482	.331	1.29	.716
100	.2486	.382	1.49	.716
200	.2496	.431	1.69	.716
300	.2512	.475	1.89	.713
400	.2532	.518	2.08	.709
500	.2561	.556	2.27	.708
600	.2592	.593	2.46	.704
700	.2627	.624	2.65	.700
800	.2662	.662	2.85	.698
900	.2696	.694	3.05	.694
1000	.2730	.725	3.22	.690
1100	.2763	.755	3.41	.688
1200	.2793	.784	3.60	.684
1300	.2822	.811	3.78	.682
1400	.2850	.834	3.96	.680
1500	.2878	.865	4.14	.678
1600	.2905	.890	4.30	.676

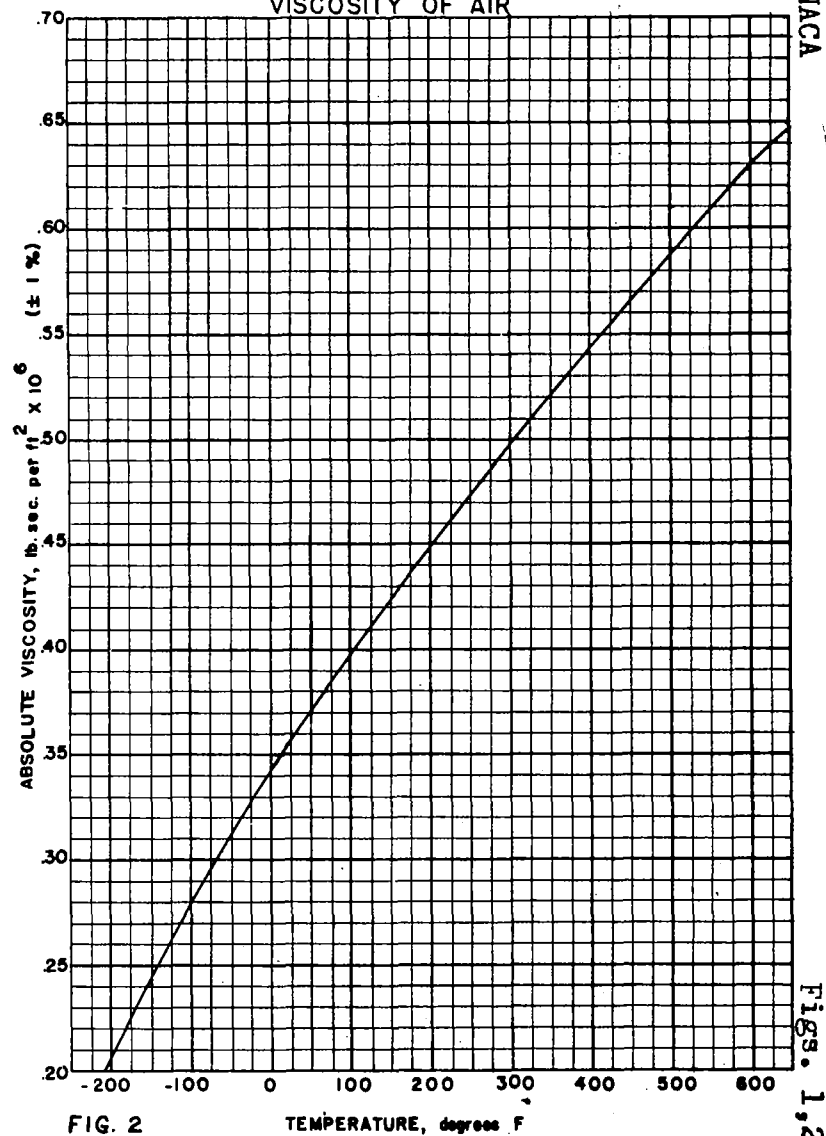
TABLE VI.-- CARBON MONOXIDE

t (deg F)	C_p (Btu/lb °F)	$\mu \times 10^6$ (lb sec/ft ²)	$k \times 10^2$ (Btu/hr ft ² $\frac{\text{deg F}}{\text{ft}}$)	Pr
-100	0.2480	0.267	1.05	0.716
0	.2482	.331	1.29	.716
100	.2486	.382	1.49	.716
200	.2496	.431	1.69	.716
300	.2512	.475	1.89	.713
400	.2532	.518	2.08	.709
500	.2561	.556	2.27	.708
600	.2592	.593	2.46	.704
700	.2627	.624	2.65	.700
800	.2662	.662	2.85	.698
900	.2696	.694	3.05	.694
1000	.2730	.725	3.22	.690
1100	.2763	.755	3.41	.688
1200	.2793	.784	3.60	.684
1300	.2822	.811	3.78	.682
1400	.2850	.834	3.96	.680
1500	.2878	.865	4.14	.678
1600	.2905	.890	4.30	.676

HEAT CAPACITY OF AIR



VISCOSITY OF AIR



VISCOSITY OF AIR

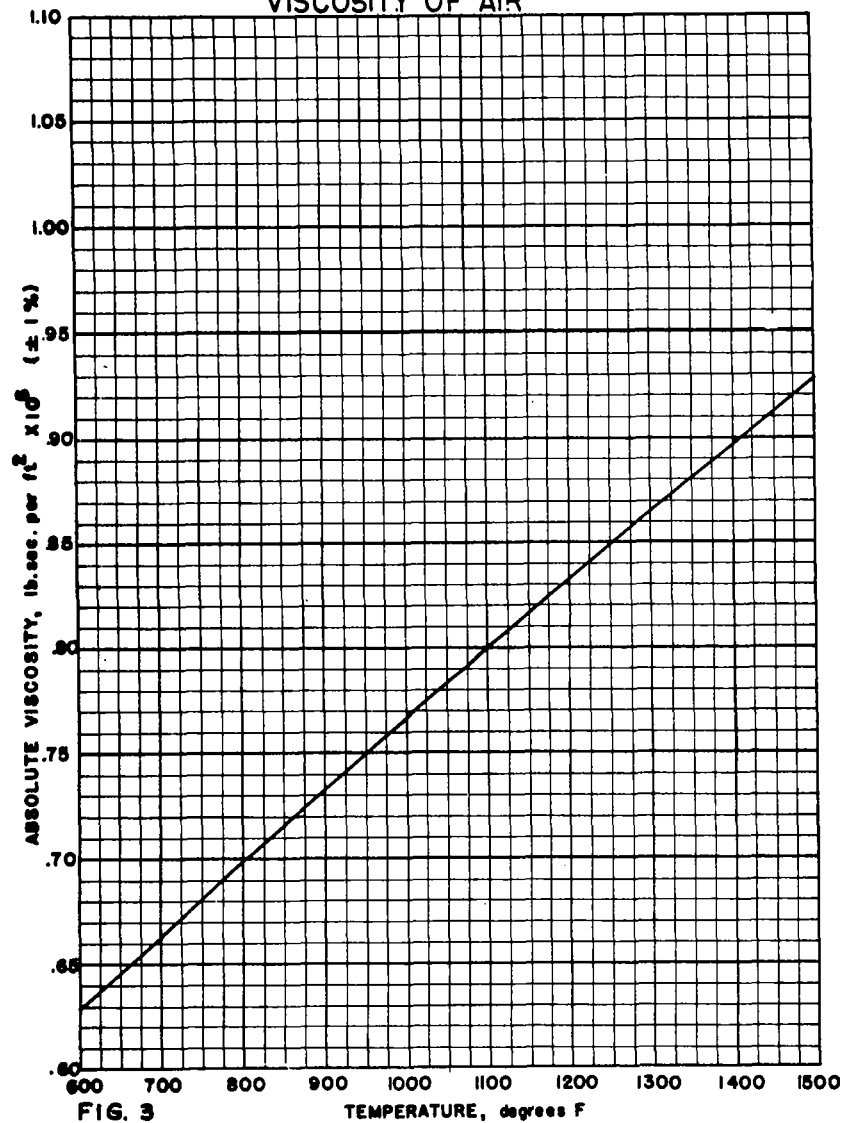


FIG. 3

THERMAL CONDUCTIVITY OF AIR

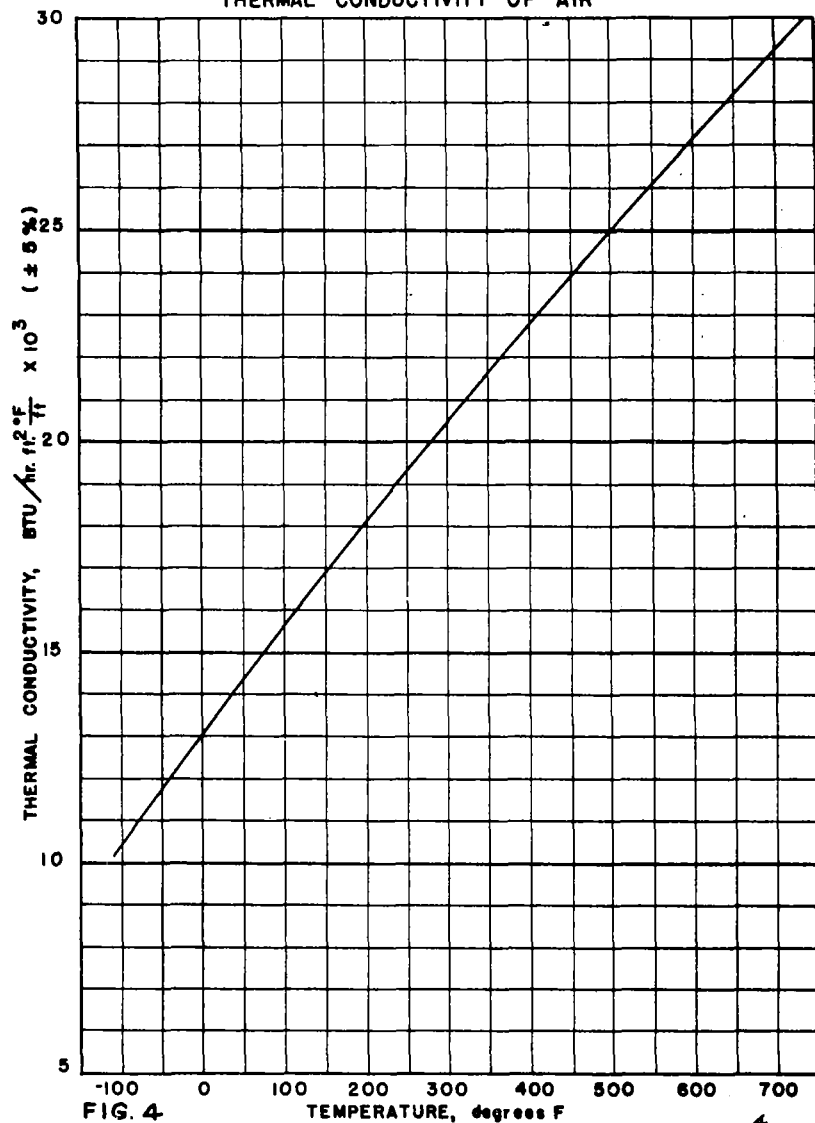
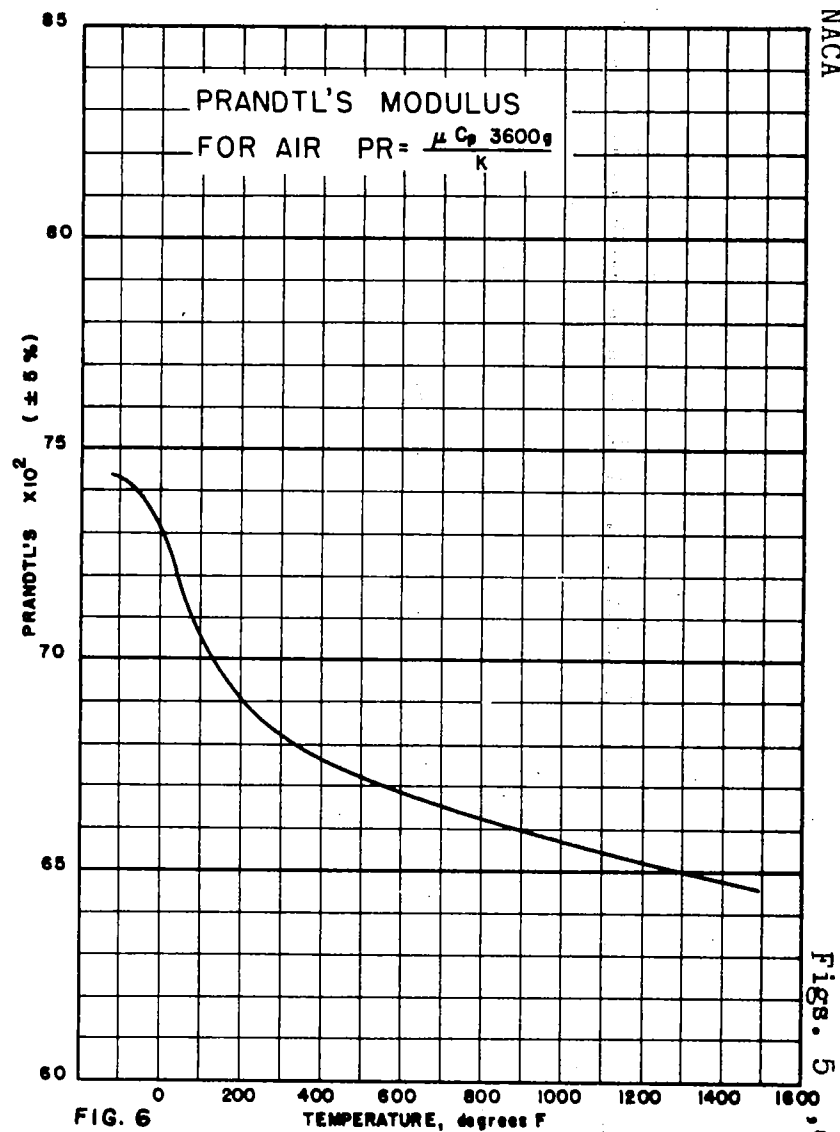
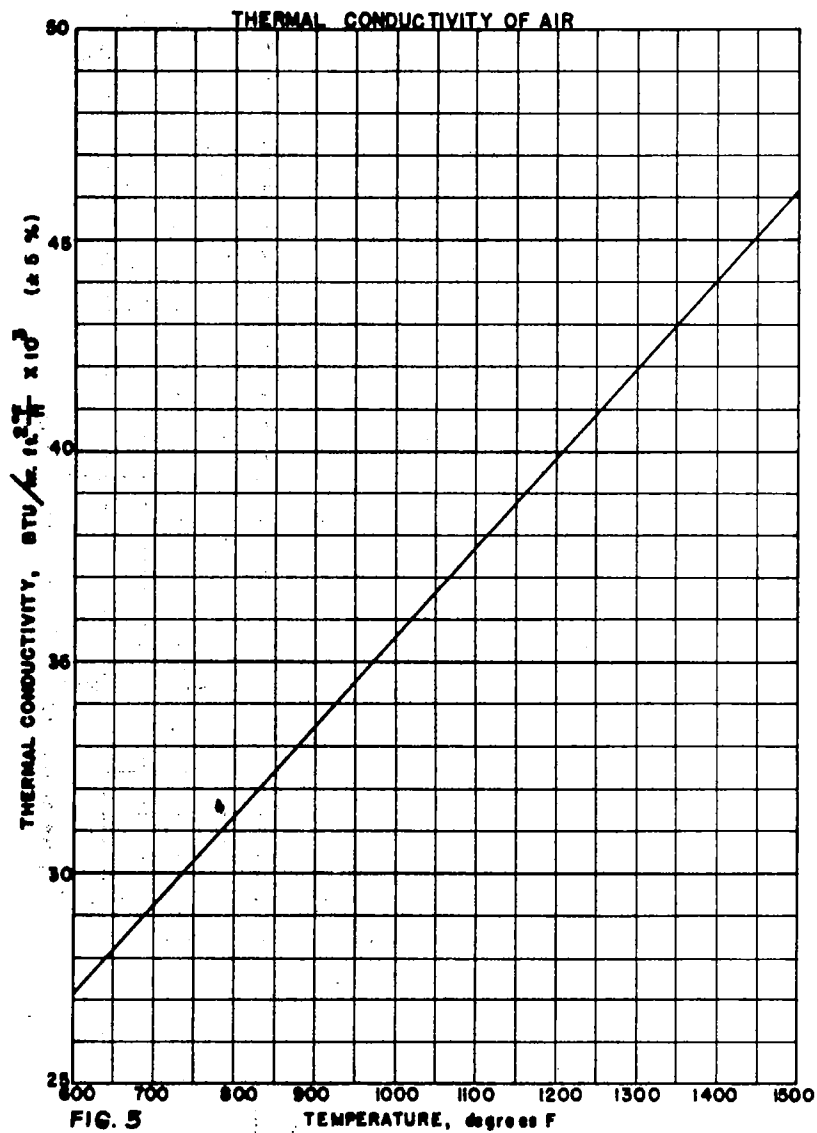
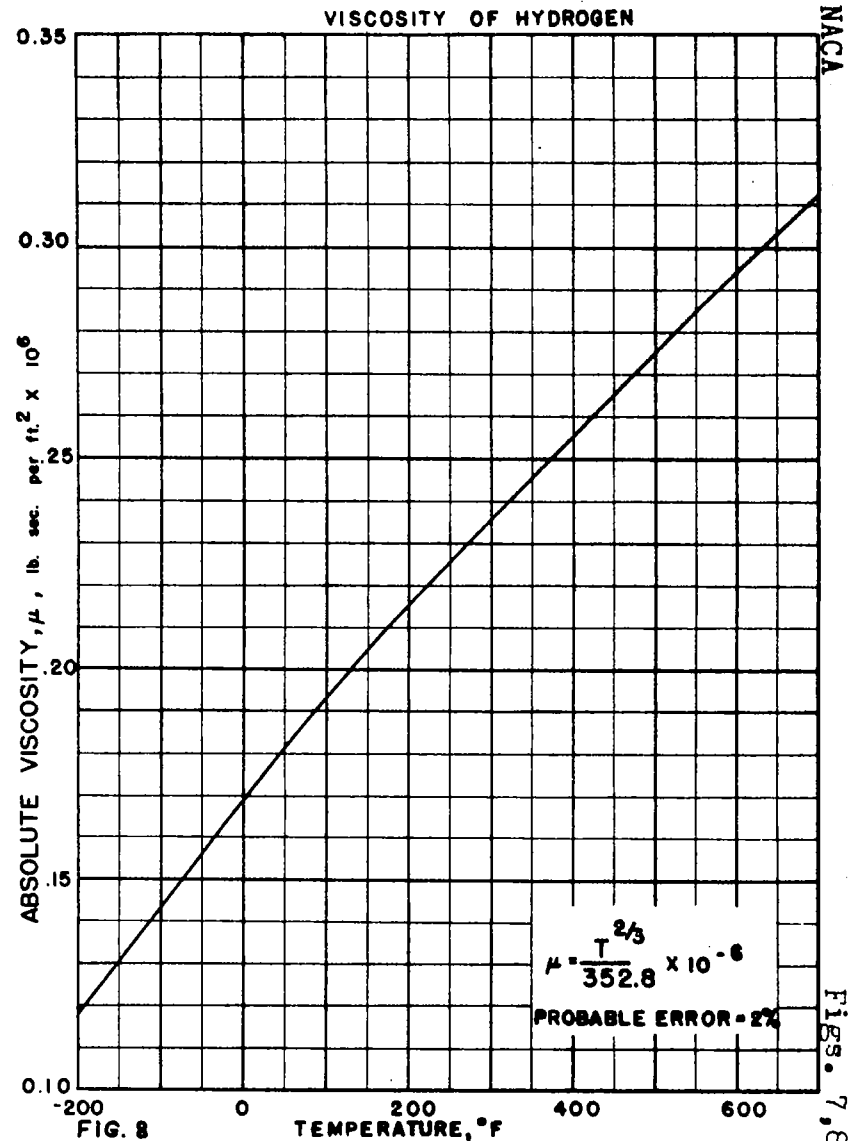
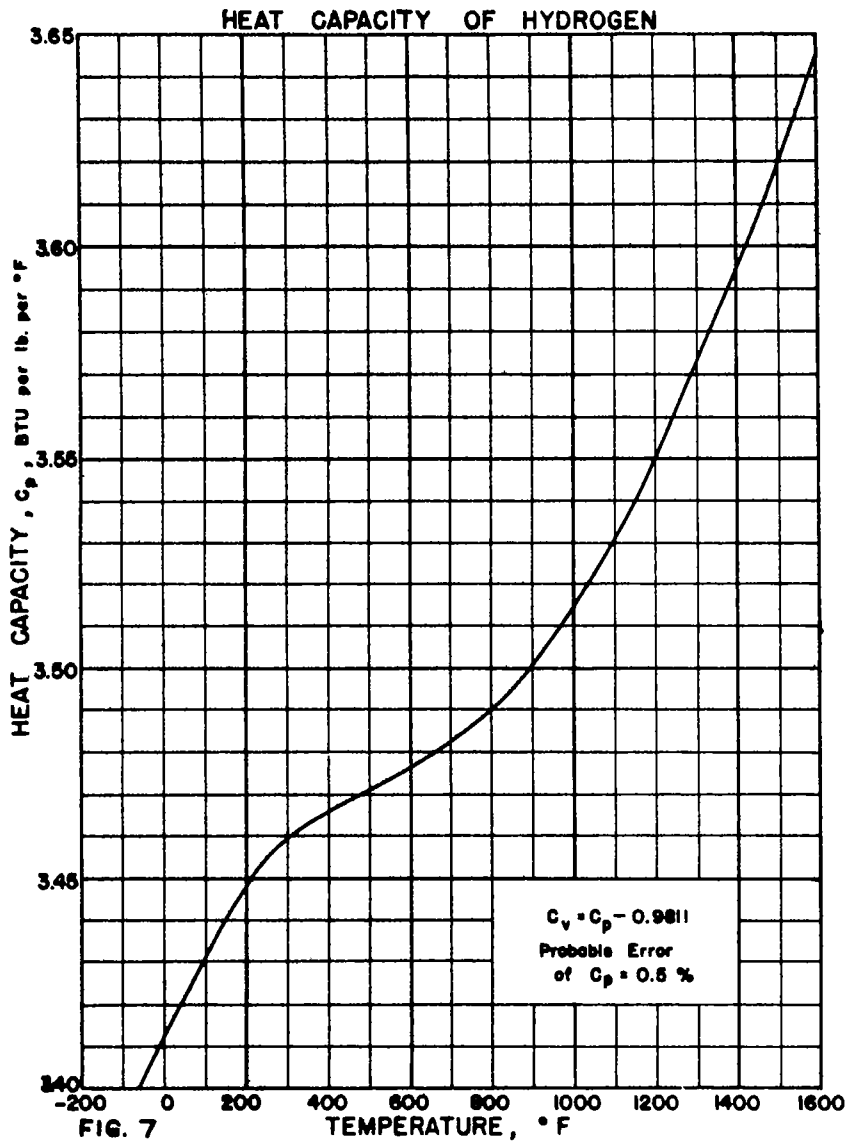


FIG. 4

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Figs. 3, 4





VISCOSITY OF HYDROGEN

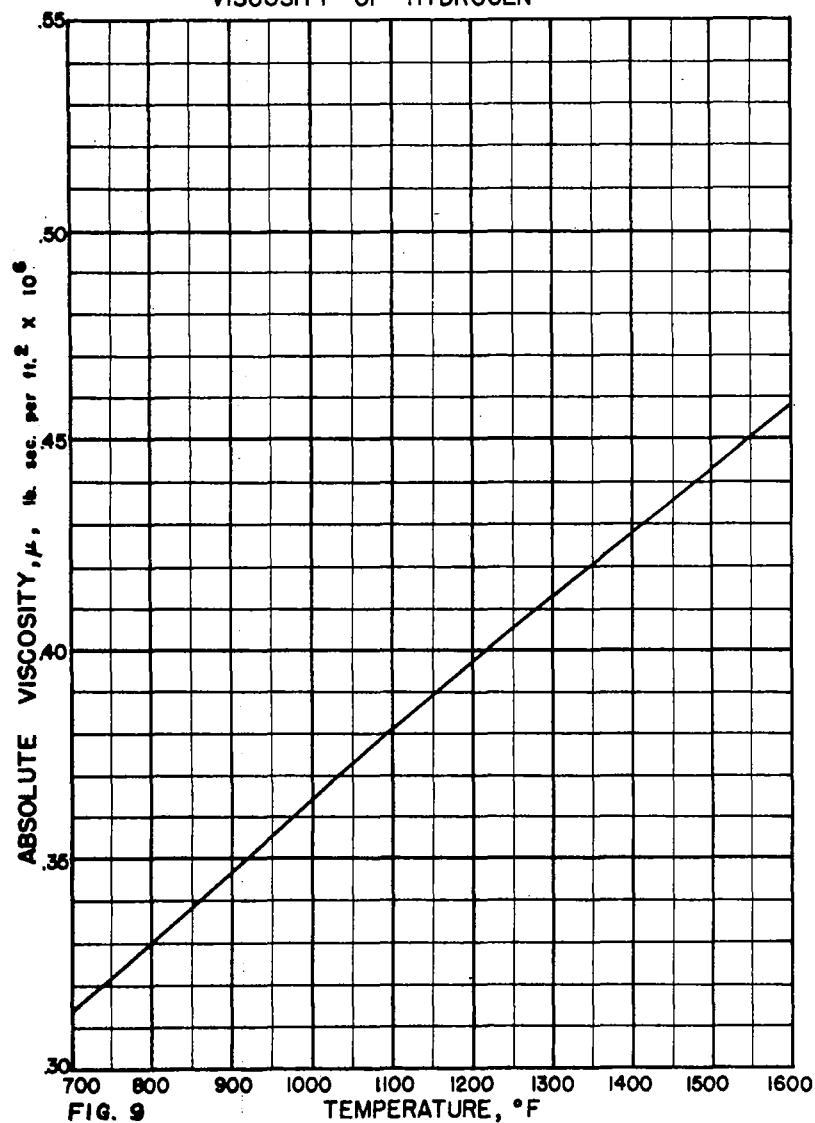


FIG. 9

THERMAL CONDUCTIVITY OF HYDROGEN

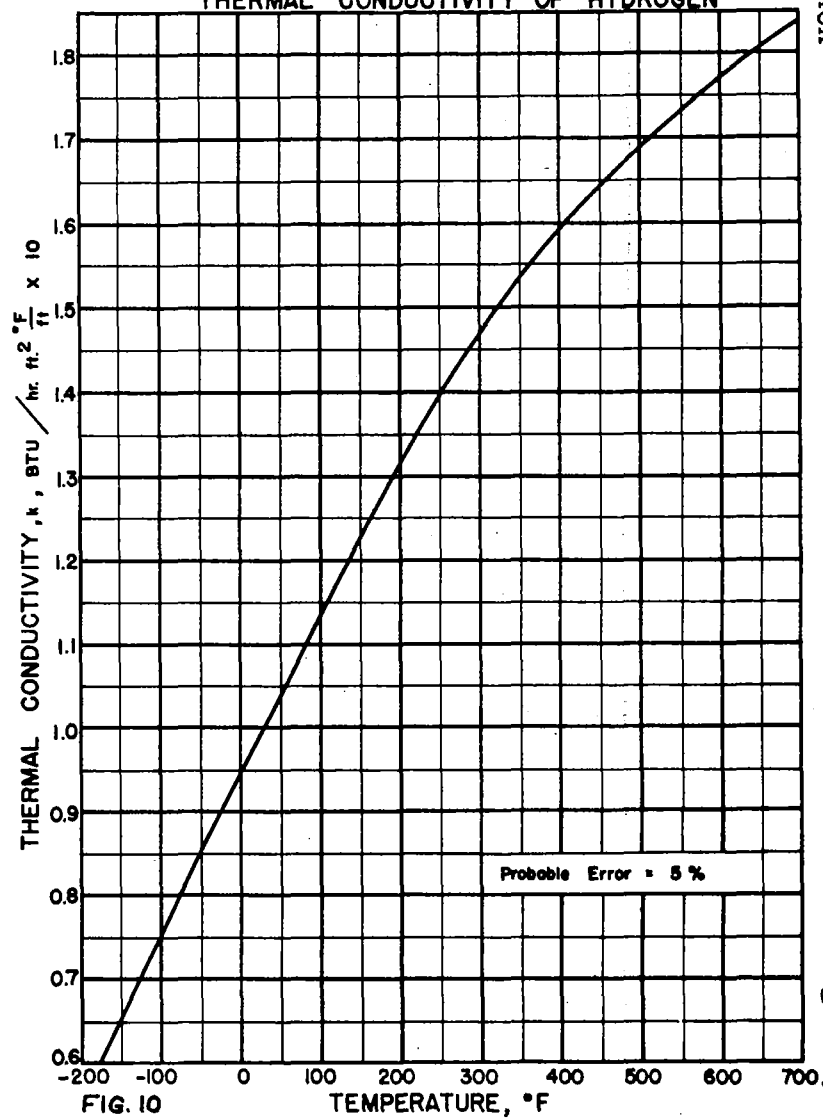
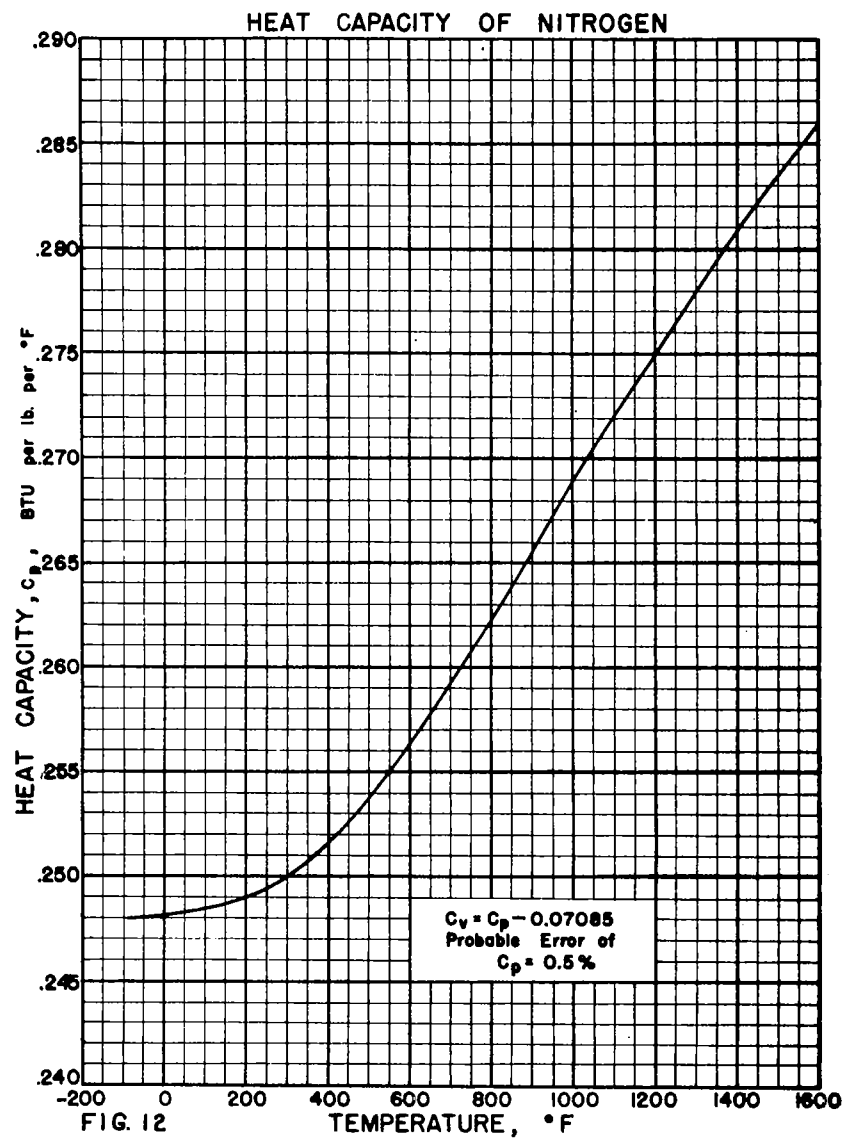
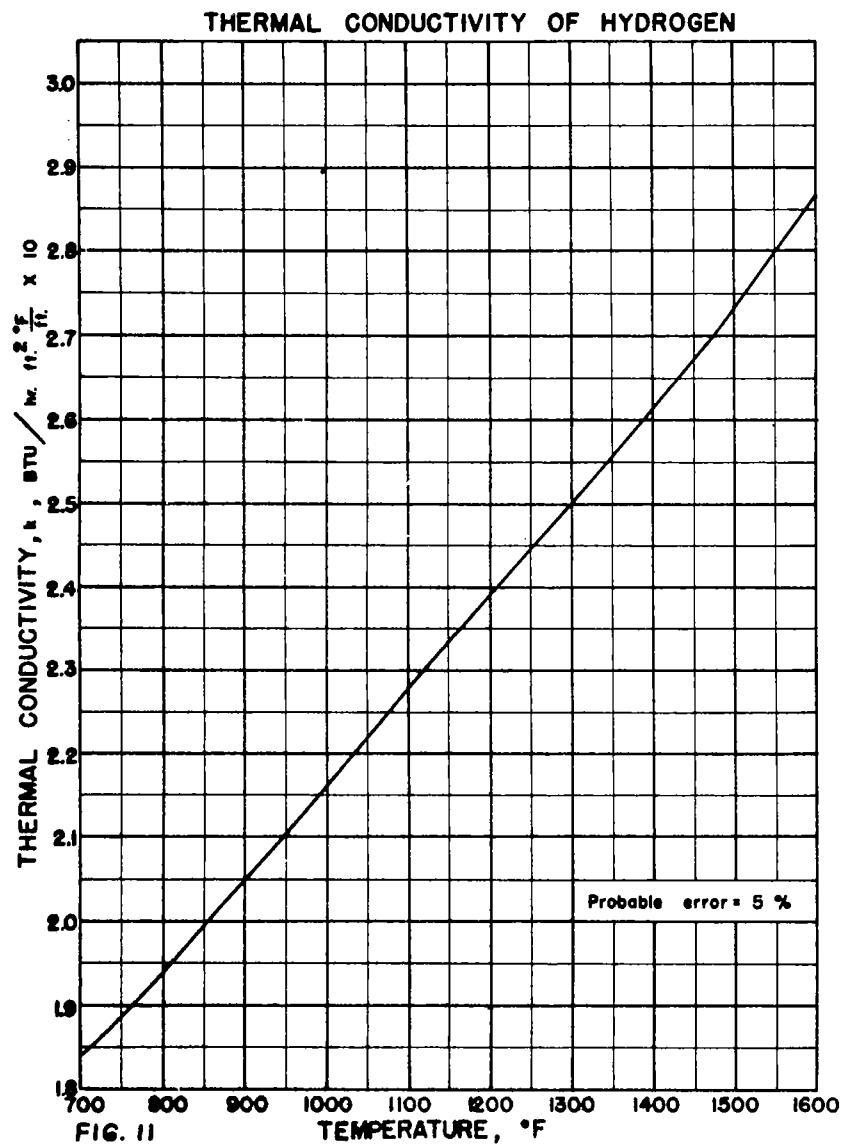
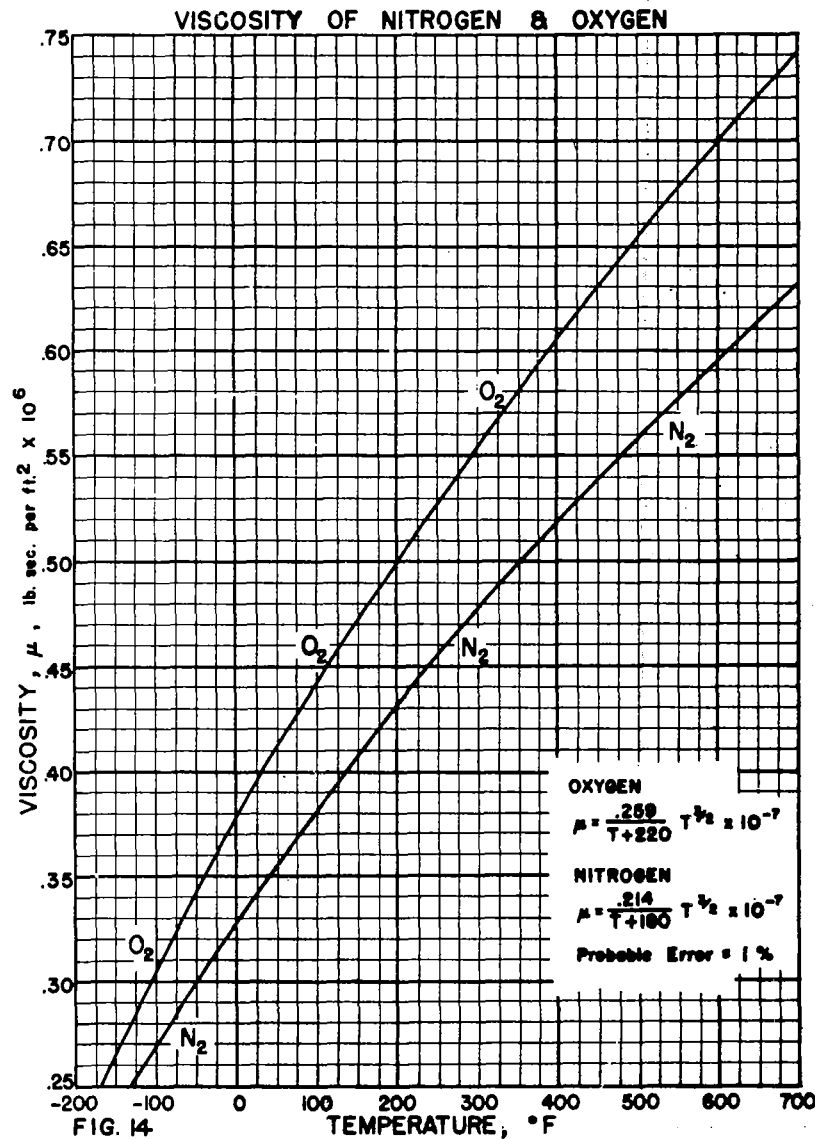
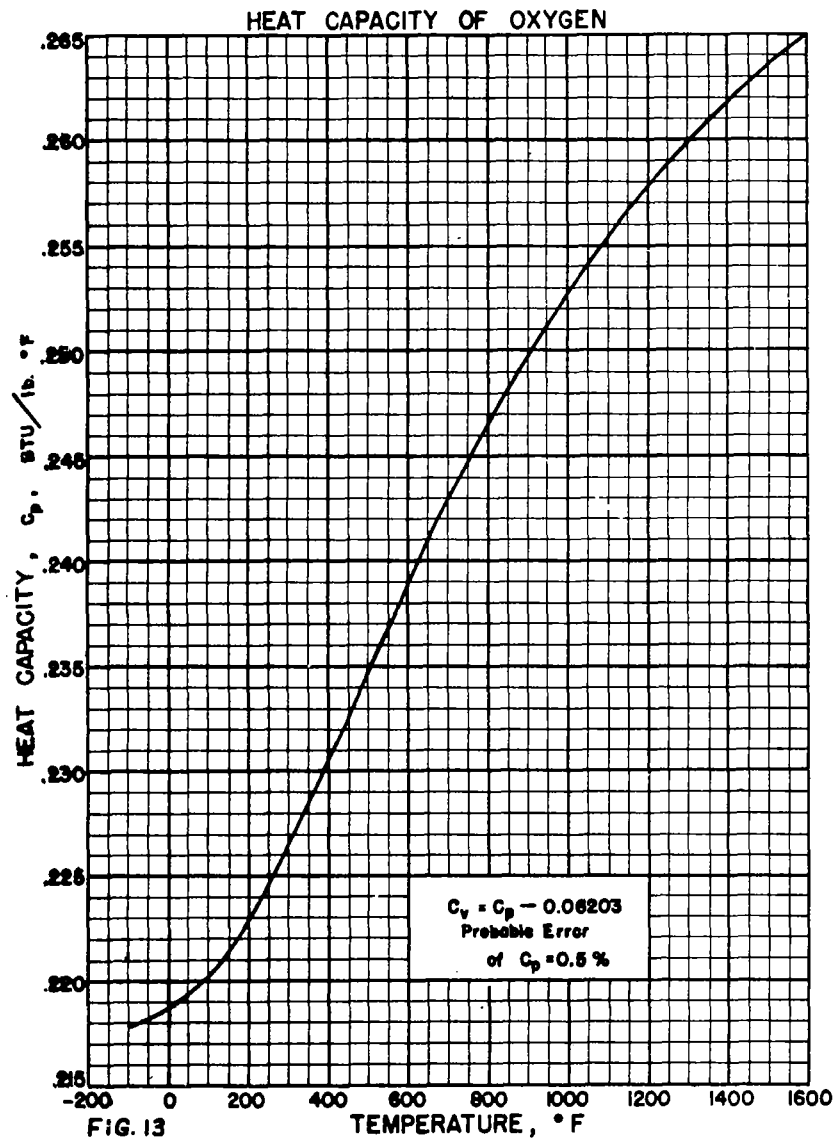


FIG. 10

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Figs. 9, 10





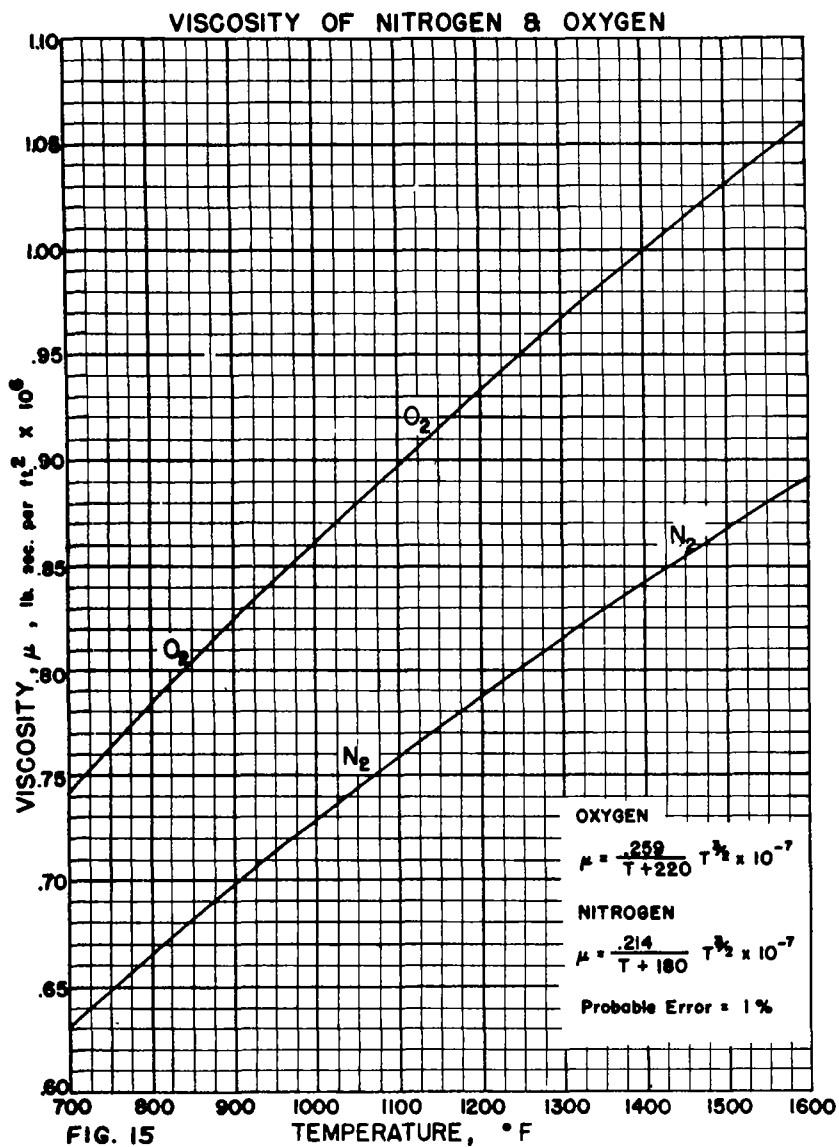


FIG. 15

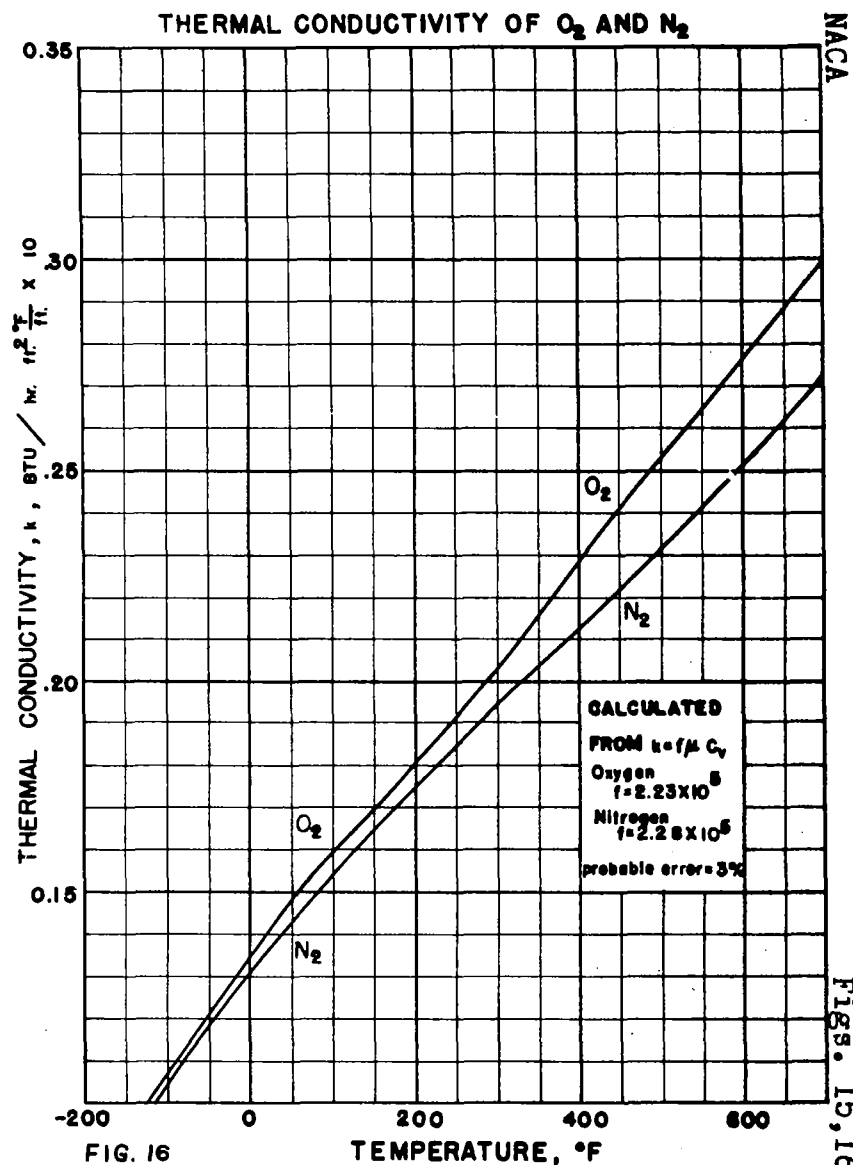


FIG. 16

TEMPERATURE, °F

THERMAL CONDUCTIVITY OF O₂ AND N₂

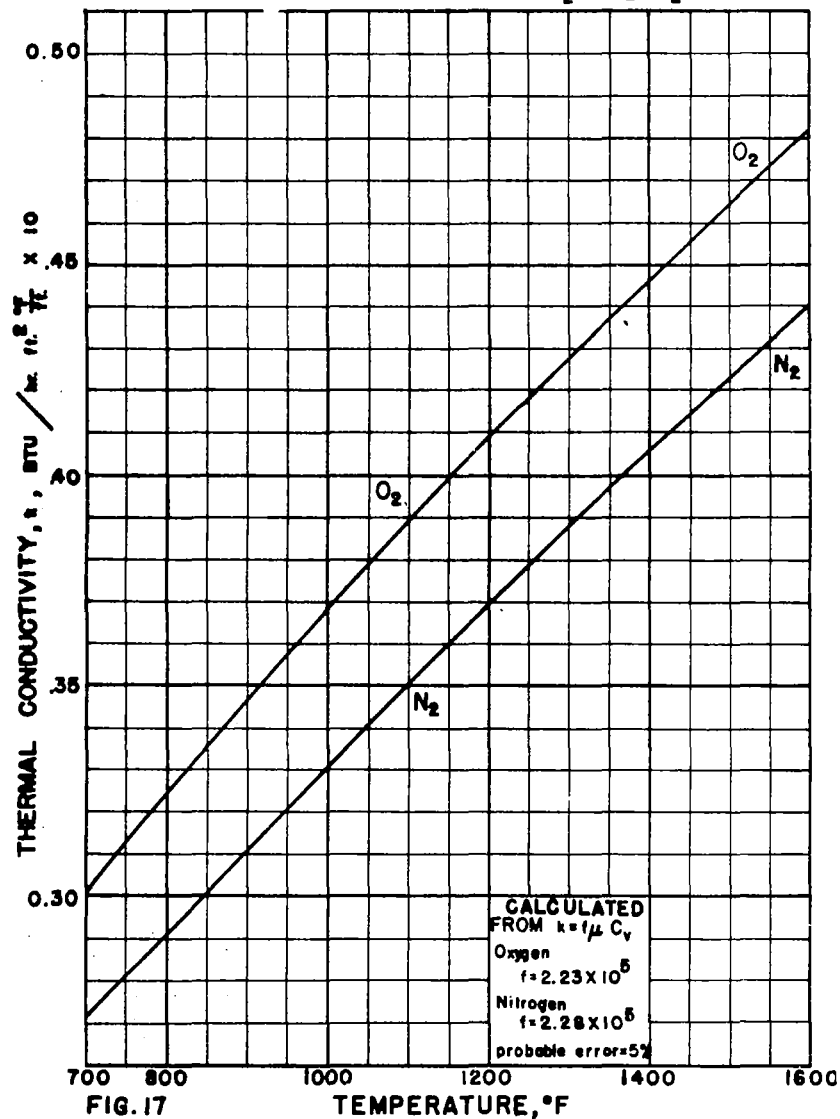


FIG. 17

HEAT CAPACITY OF CO₂

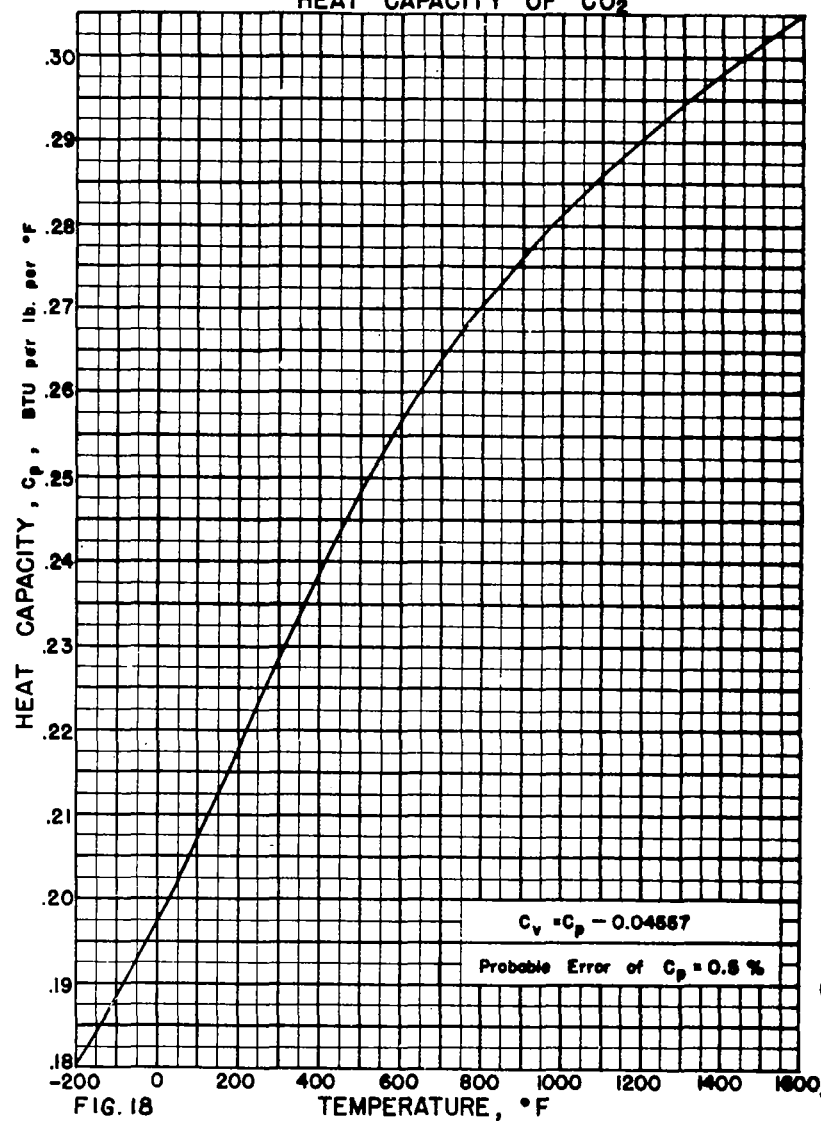
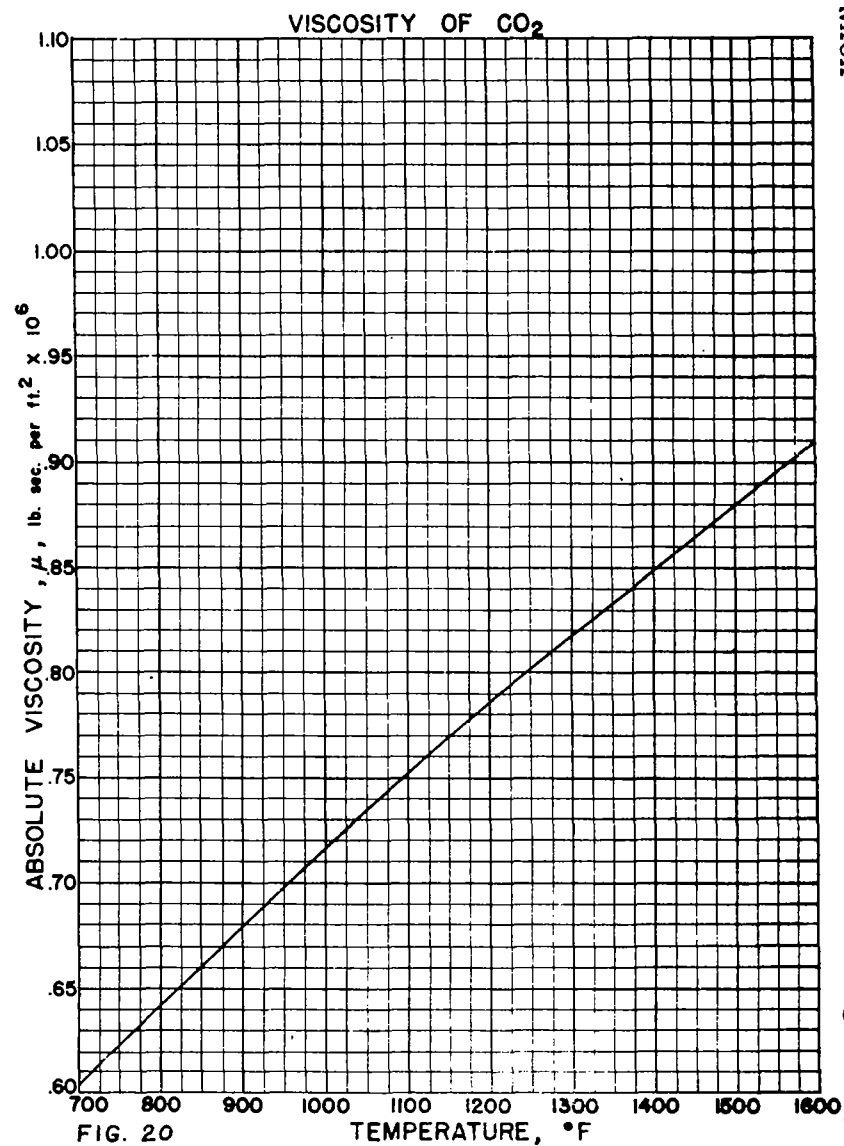
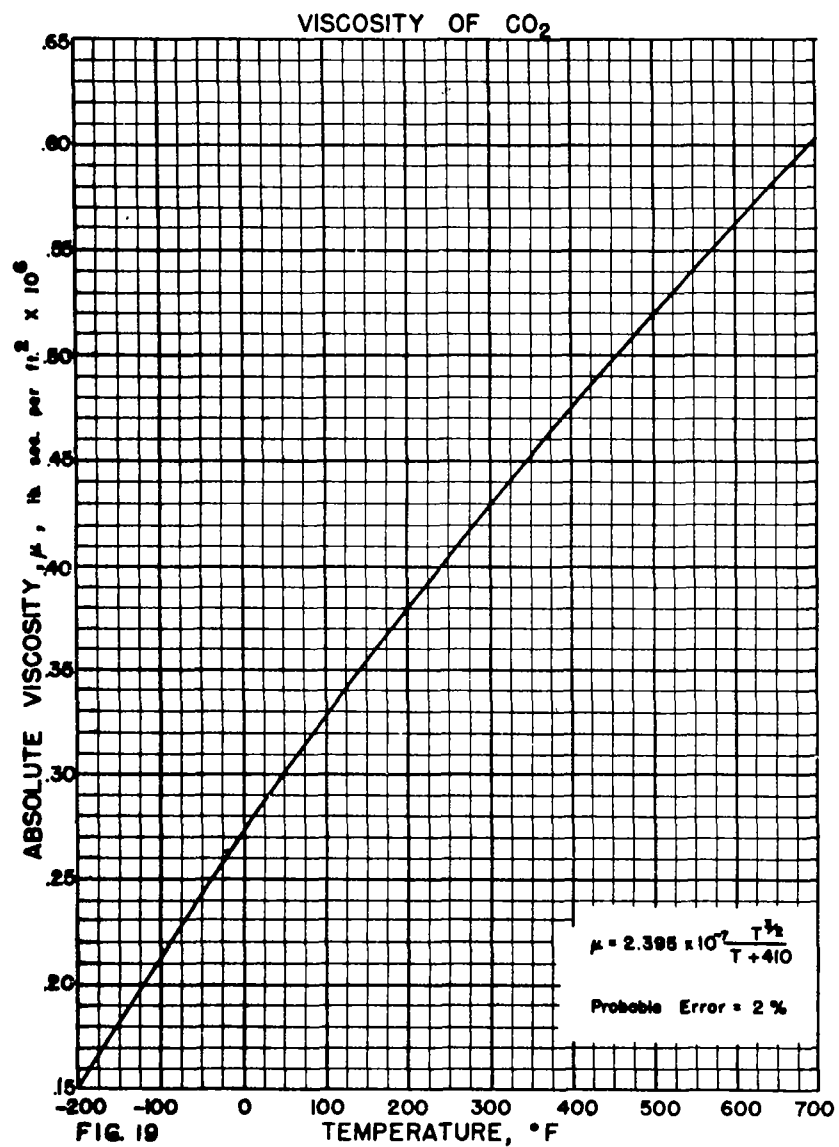
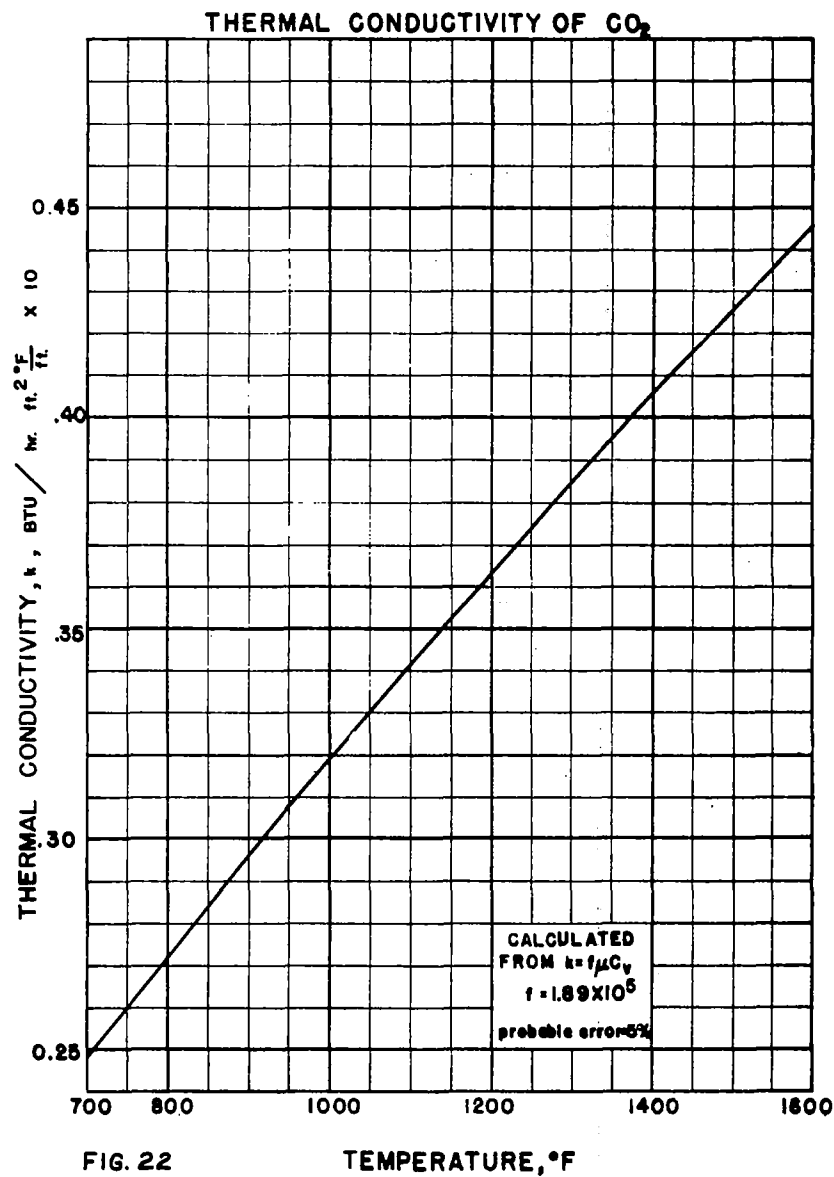
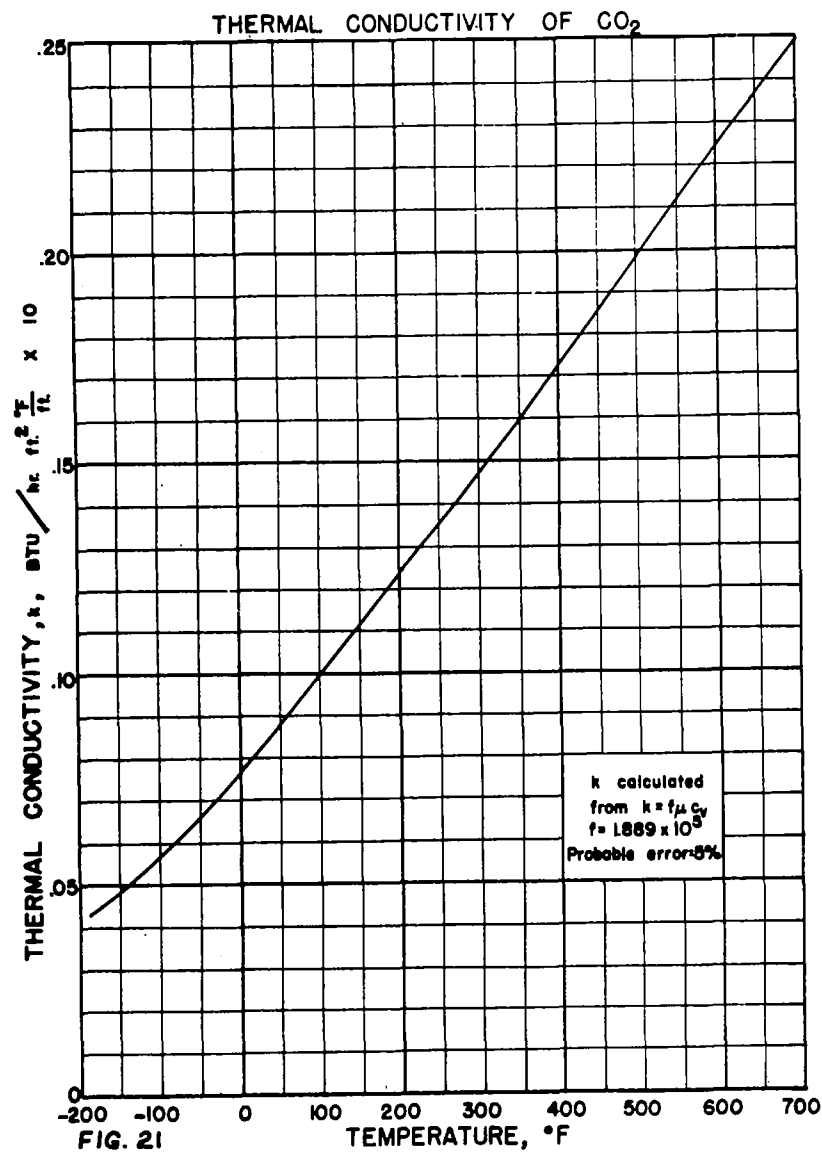
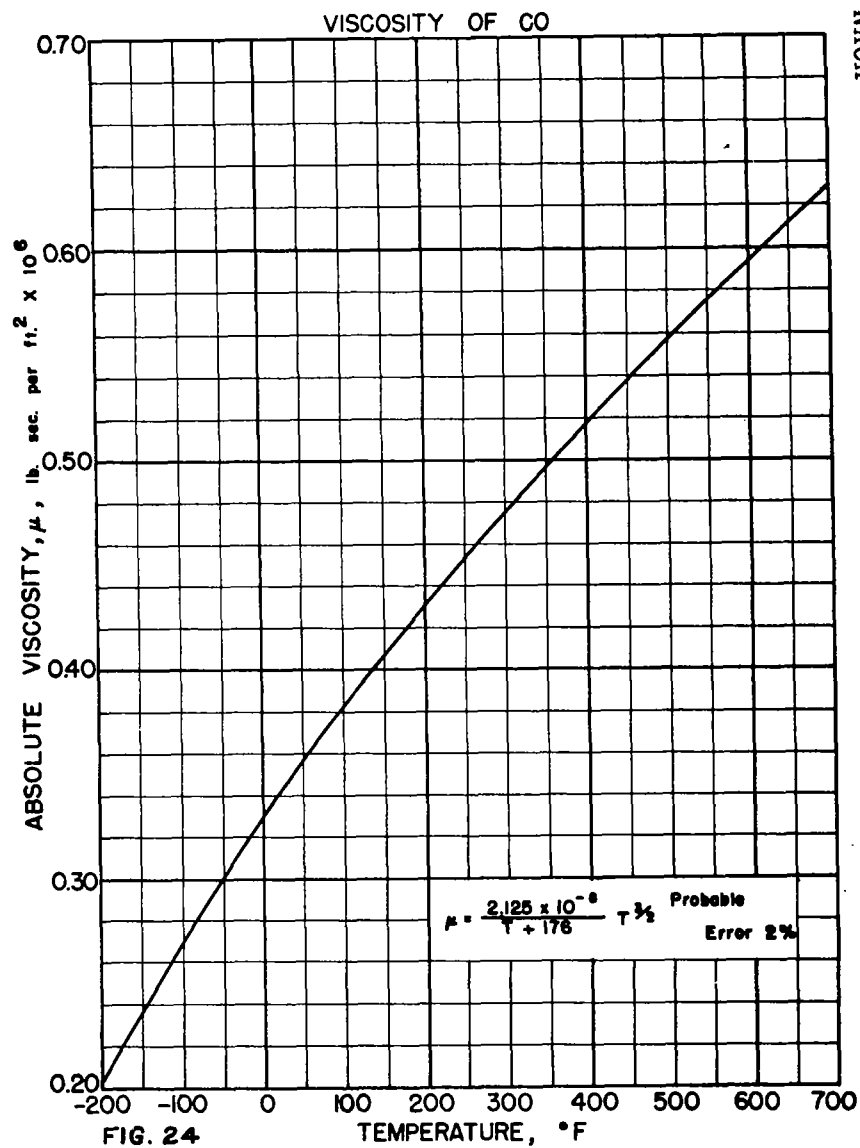
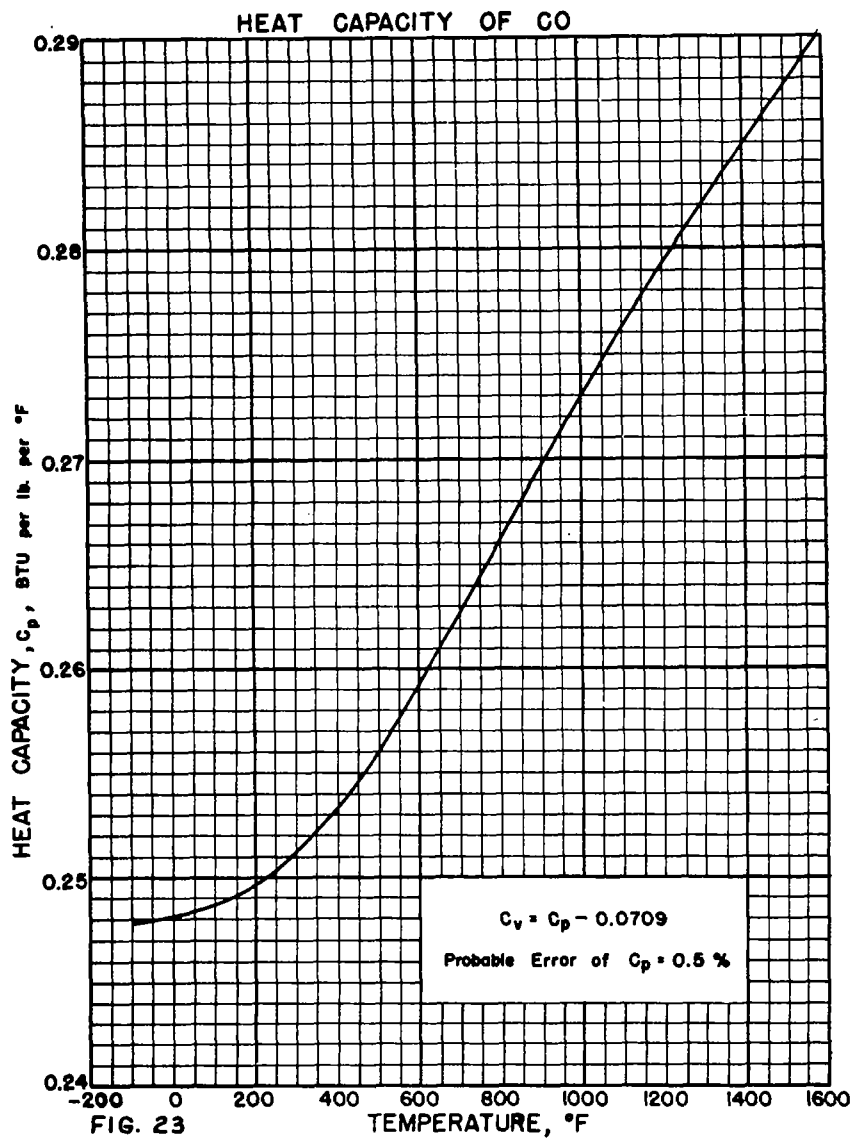
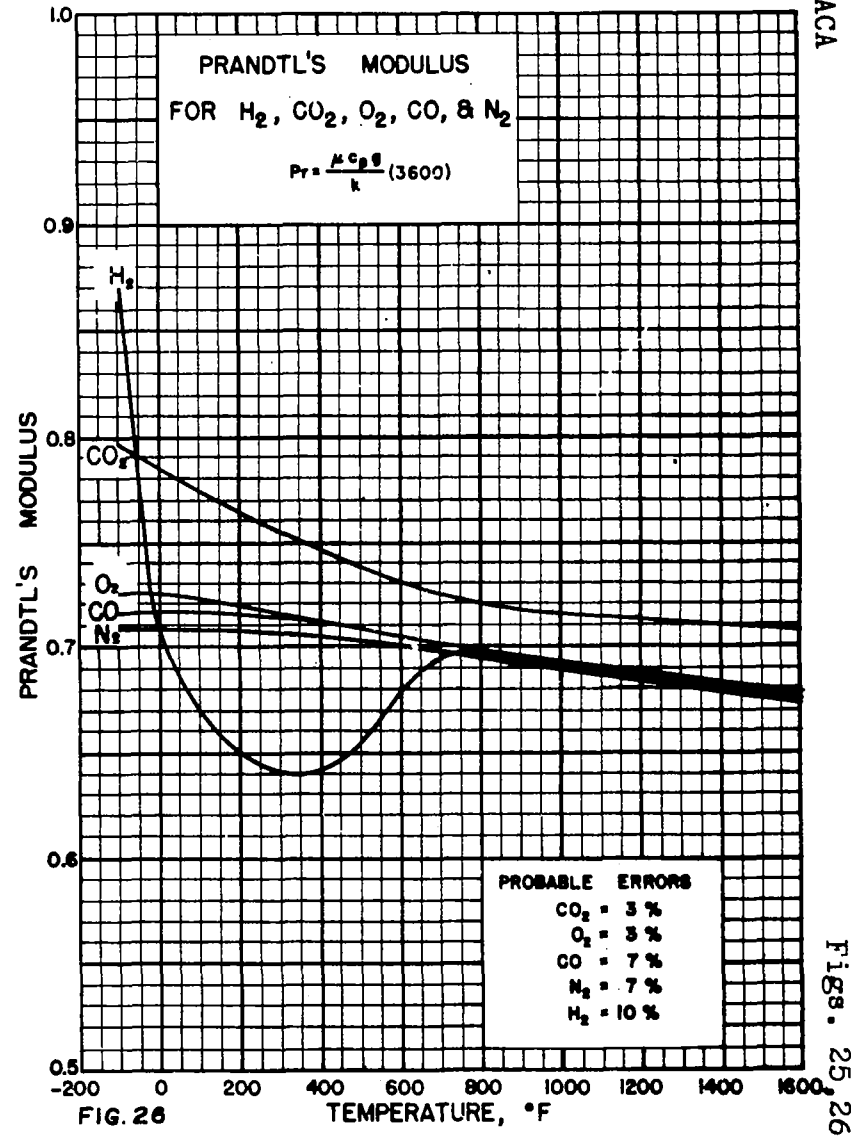
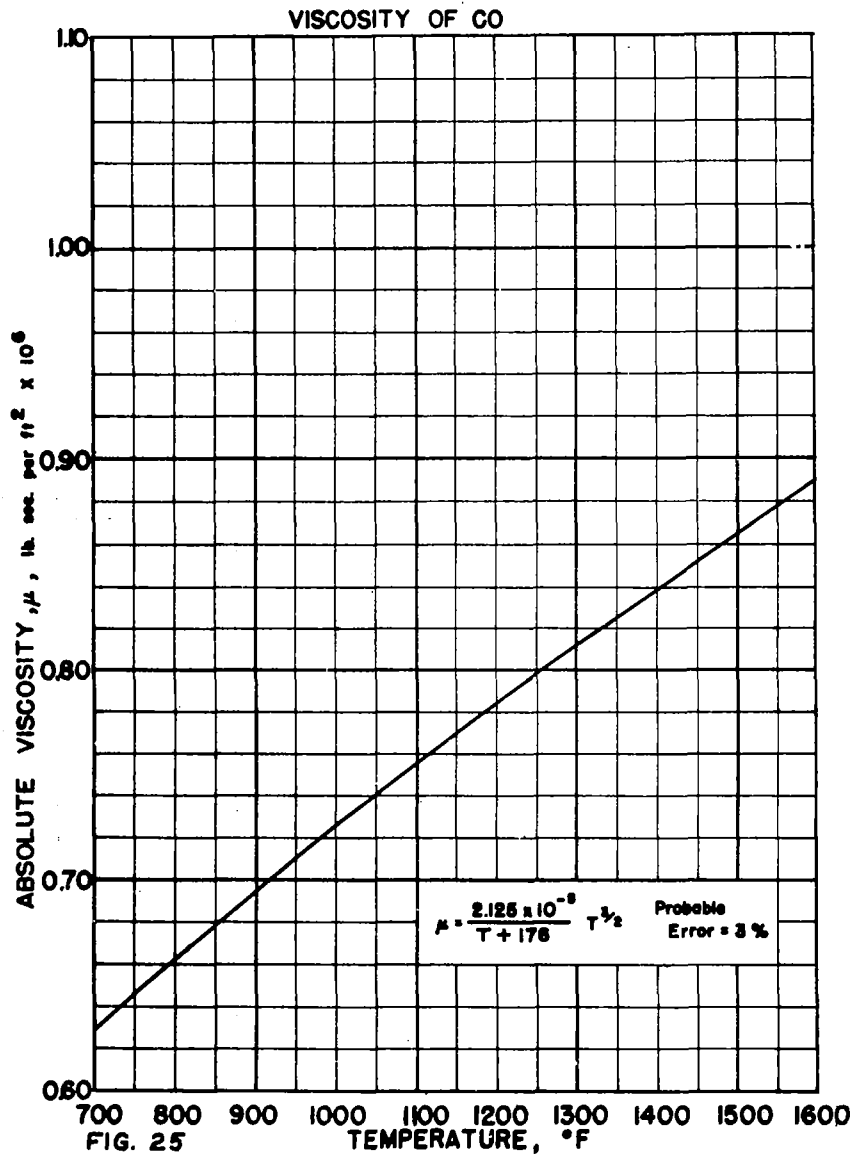


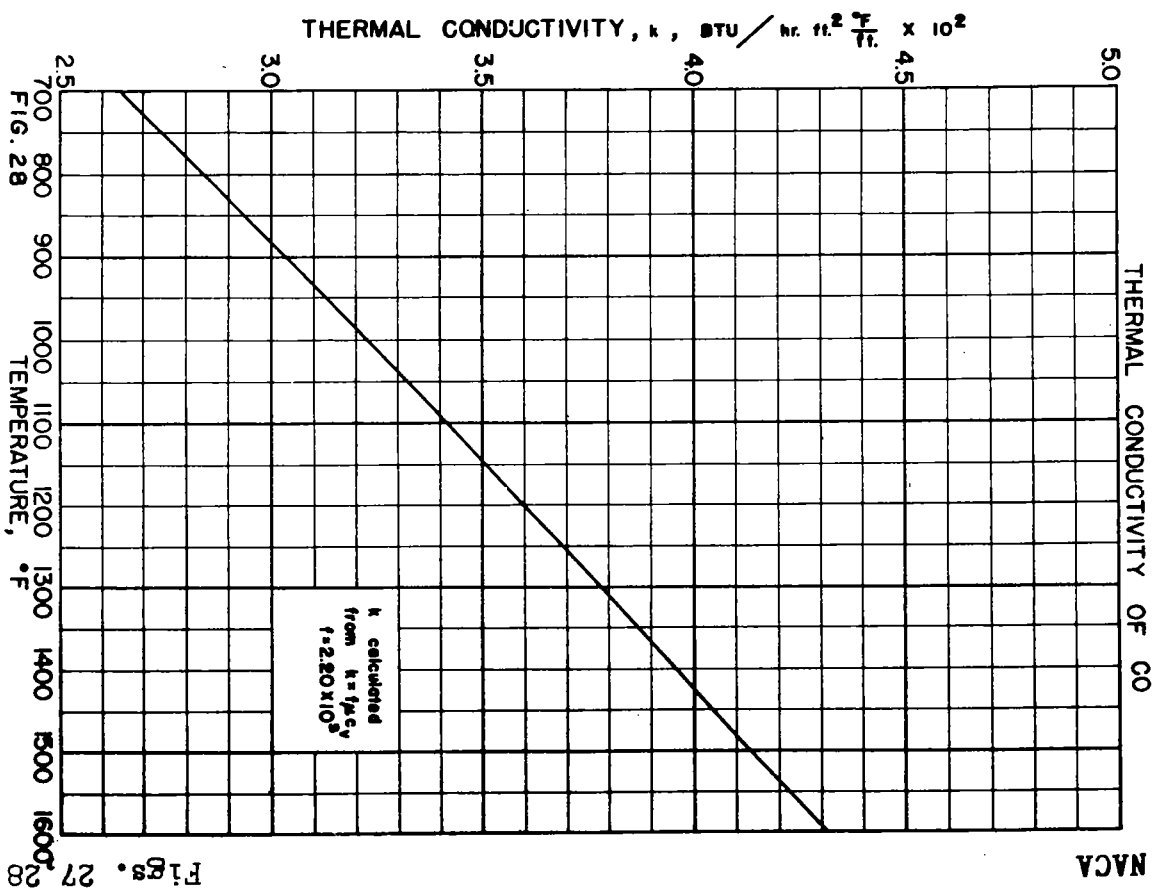
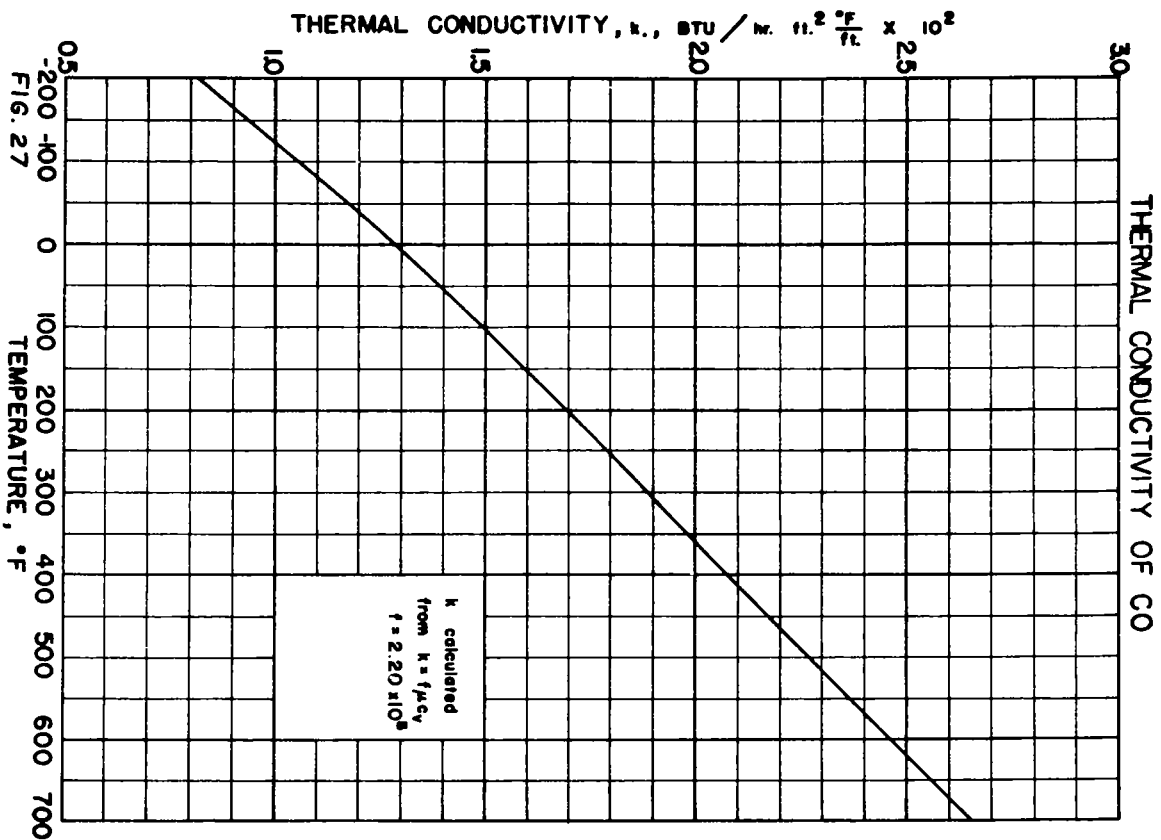
FIG. 18











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TITLE: An Investigation of Aircraft Heaters II - Properties of Gases

AUTHOR(S): Tribus, Myron; Boelter, L.M.K.

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ABSTRACT:

(23) * Aircraft ~~heaters~~ heaters;

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A list of properties of gases which are pertinent to airplane heat transfer calculation is presented. The gases include air, hydrogen, nitrogen, oxygen, carbon dioxide and carbon monoxide. Properties of exhaust gases of various compositions are not listed - on account of their unavailability. It is suggested that, in utilizing generalized heat transfer equations or their graphical pendant, the physical properties employed in experiments be substituted into the generalized expressions in order that the proper magnitude of the unit conductance will result.

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