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NAVORD REPORT 3748

IGNITION ENERGIES OF SOLID PROPELLANTS

29 APRIL 1954

U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

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IGNITION ENERGIES OF SOLID PROPELLANTS

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ABSTRACT: This is a progress report on an investigation to test the theory of Lewis and von Elbe (1) for the ignition of propellants.

Information from two types of experiments was utilized to calculate ignition energies per unit area and "linear" surface temperatures. At the University of Michigan (2,3) M2 propellant was ignited by hot gas under forced convection, while at the Franklin Institute (4,5) ignition occurred by free convection (including radiative) heat transfer. From these experiments it is shown that, for constant gas flow rate (forced convection) and constant gas pressure (free and radiative convection), the ignition energy per unit area decreases with increasing gas temperature, which is in accordance with the theory. The ignition times are too long to allow determination of whether a minimum ignition energy per unit area exists. It is proposed to extend the investigation to the short ignition times provided by the adiabatic compression technique developed at NOL.

Explosives Research Department
U.S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

54WC-2645I

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NAVORD Report 3748 29 April 1954

Under Task NOL B2d-2-1-54 the Naval Ordnance Laboratory is charged with conducting research on the fundamentals of ignition and combustion. This report is concerned with the amount of energy per unit area necessary to ignite a propellant under given conditions.

JOHN T. HAYWARD
Captain, USN
Commander

PAUL M. FYE
By direction

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TABLES AND ILLUSTRATIONS

IGNITION ENERGIES OF SOLID PROPELLANTS

I. TABLE OF SYMBOLS

A	arbitrary constant	dimensionless
c	constant pressure heat capacity	any units
D	diameter of propellant grain	any units
f	energy flux	any units
G	gas mass flow rate	$lbs/hr\ ft^2$
h	reduced heat transfer coefficient	1/cm
H	heat transfer coefficient	any units
k	thermal conductivity of gas	any units
K	thermal conductivity of propellant	any units
n	arbitrary exponent	dimensionless
q	ignition energy per unit area	cal/cm^2
t	time	any units
T_g	gas temperature	^oK
T_o	ambient temperature	^oK
T_s	surface temperature	^oK
T'_s	assumed surface temperature	^oK
v	temperature above ambient at x and t	^oK
v_s	surface temperature above ambient at t	^oK
V	gas temperature above ambient	^oK
$\bar{V}$	fictituous gas "temperature"	^oK
x	distance from surface into propellant	any units
	diffusivity of propellant	any units

I. TABLE OF SYMBOLS (contd.)

τ	ignition time	any units
μ	gas viscosity	any units

Subscripts:

G	"greatest"
L	"least"

II. INTRODUCTION

The ignition theory advanced by Lewis and von Elbe states that the amount of energy per unit area, q, necessary to ignite a propellant surface depends upon the energy source temperature. The lower that temperature, the greater must q be. Also as the temperature increases, q approaches a minimum value. This minimum q is thought to be approximately equal to the excess enthalpy associated with the combustion wave.

The purpose of this investigation has been to test the theory and to demonstrate the conditions under which it is valid.

The equations for the local heat transfer coefficients for forced convection, derived by the University of Michigan (6), enabled us to test this theory under conditions which are similar to those found in practical ignition systems. Because of the type of dependence of these coefficients upon the assumed surface temperature of the grain, it is possible to calculate "greatest" and "least" coefficients for every experimental run. Hence, for every run, this permits the calculations of "greatest" and "least" value of q and surface temperature, T_s.

III. MATHEMATICAL MODEL

To calculate T_s and q at the time of ignition, τ , it is necessary to solve the classical heat conduction equation for a cylinder being heated by convection. To simplify the problem a little, one can substitute a semi-infinite solid for a semi-infinite cylinder. This is possible because the diffusivity of the class of solid propellants is extremely small and the order of ignition times involved does not allow for any appreciable temperature rise much below the surface. Hence, to a temperature wave propagating into the solid from the surface, the solid appears to be of infinite depth i.e. a semi-infinite solid. The problem is reduced to that of finding v_s, the surface temperature above ambient, and q as functions of t for a semi-infinite solid being heated by convection and/or radiation from a medium at temp V above ambient; the initial temperature of the solid is zero.

The equation to be solved is

(1) $$\frac{\partial v}{\partial t} = \kappa \frac{\partial^2 v}{\partial x^2}$$

for the boundary conditions

(2) $$-\frac{\partial v}{\partial x} + h v = V \quad \text{at } x = 0$$
$$v(x,0) = 0$$

The solution (8) is

(3) $$\frac{v(x,t)}{V} = \operatorname{erfc} \frac{x}{2\sqrt{\kappa t}} - \epsilon^{hx + h^2 \kappa t} \operatorname{erfc}\left(\frac{x}{2\sqrt{\kappa t}} + h\sqrt{\kappa t}\right)$$

where $$\operatorname{erfc} \xi = \frac{2}{\sqrt{\pi}} \int_{\xi}^{\infty} \epsilon^{-u^2} du$$

Putting x = 0 and t = τ , one gets for the surface temperature rise at the ignition time,

(4) $$v_s(\tau) = V \left\{ 1 - \epsilon^{h^2 \kappa \tau} \operatorname{erfc} h\sqrt{\kappa \tau} \right\}$$

To calculate q we integrate the flux over the ignition interval, and this is

(5) $$q(0,\tau) = \int_0^{\tau} f(0,t)\, dt$$

where $$f(x,t) = -K \frac{\partial v(x,t)}{\partial x}$$

We have

(6) $$\frac{\partial v(x,t)}{\partial x} = -hV \epsilon^{hx + h^2 \kappa t} \operatorname{erfc}\left(\frac{x}{2\sqrt{\kappa t}} + h\sqrt{\kappa t}\right)$$

The surface flux is

(7) $$f(0,t) = KhV \epsilon^{h^2 \kappa t} \operatorname{erfc} h\sqrt{\kappa t}$$

Substituting (7) into (5) yields

$$(8)\qquad \frac{q(0,\tau)}{K\,h\,V} = \int_0^\tau \epsilon^{h^2\kappa t}\,dt - \frac{2}{\sqrt{\pi}}\int_0^\tau \epsilon^{h^2\kappa t}\,dt \int_0^{h\sqrt{\kappa t}} \epsilon^{-u^2}\,du$$

After evaluating the second integral by parts we finally get

$$(9)\qquad q = \frac{KV}{h\kappa}\left\{\epsilon^{h^2\kappa\tau}\,\mathrm{erfc}\,h\sqrt{\kappa\tau} - 1 + \frac{2}{\sqrt{\pi}}\,h\sqrt{\kappa\tau}\right\}$$

where q will replace $q(o,\tau)$ and v_s will replace $v_s(\tau)$ from now on.

(9) can be rewritten, by substituting (4) into it, giving (9')

$$q = \frac{KV}{h\kappa}\left\{\frac{2}{\sqrt{\pi}}\,h\sqrt{\kappa\tau} - \frac{v_s}{V}\right\}$$

IV. EXPERIMENTAL AND CALCULATED RESULTS

It is desired to evaluate v_s and q for the Michigan and the Franklin Institute data.

The Michigan equation for the heat transfer coefficient, H, between a moving gas stream and a right circular cylinder where axis is normal to the gas flow is

$$(10)\qquad H = A\,\frac{k}{D}\left(\frac{c\mu}{k}\right)^{\frac{1}{3}}\left(\frac{GD}{\mu}\right)^{n}\left(\frac{T_g}{T_s'}\right)^{0.12}$$

The h used is eq(2) is defined by

$$(11)\qquad h = \frac{H}{K}$$

Hence

$$(12)\qquad h = \frac{A}{K}\,\frac{k}{D}\left(\frac{c\mu}{k}\right)^{\frac{1}{3}}\left(\frac{GD}{\mu}\right)^{n}\left(\frac{T_g}{T_s'}\right)^{0.12}$$

For any one experimental run all the constants of (12) are known except T'_s which increases from ambient temperature, T_o. Therefore h depends upon our knowledge of T'_s. But by eq(4), we must know h in order to calculate $T_s = T_o + v_s$! This does not make the situation hopeless, for by the following method we can demonstrate that the indeterminancy in v_s is very small compared to the actual v_s.

For a given τ during any one experiment, the values of v_s and q will be greatest when h is greatest. Similarly, the values of v_s and q will be smallest when h is least. From (12) it is easily seen that

$$(13) \qquad h_G \sim \left(\frac{1}{T'_{s_L}}\right)^{0.12}$$

and

$$(14) \qquad h_L \sim \left(\frac{1}{T'_{s_G}}\right)^{0.12}$$

By replacing T'_{s_L} by T_o in (13) we get h_G and hence v_{s_G} and q_G by (4) and (9). Then replacing T'_{s_G} by $T_o + v_{s_G}$ in (14) we obtain h_L and hence v_{s_L} and q_L. We now have

$$(15) \qquad \begin{array}{c} v_{s_L} < v_s < v_{s_G} \\ q_L < q < q_G \end{array}$$

Analysis of the data shows that

$$(16) \qquad \begin{array}{c} v_{s_G} - v_{s_L} << v_s \\ q_G - q_L << q \end{array}$$

In their report, the Franklin Institute had calculated the surface temperatures for the Michigan work using the latter's equation for the local heat transfer coefficient. Since their values of v_s must obey (15) and (16), we have used these values in (9') to calculate the q's which also obey (15) and (16). For the range investigated q_G and q_L differ by 0.1 - 0.2 cal/cm^2. The lower limit is for shorter ignition times.

At this point it must be pointed out that the ignition time, in all cases, was determined by actuation of a photocell by the propellant flame.

In Table 1 are given the calculated q's for forced convection using an 80% N_2 - 20% O_2 gas.

In Tables 2, 3, and 4 are given the calculated q's for free convection for H_e N_2, and air, respectively. The v_s's shown are those previously calculated (5).

In Table 5 are given q_G, q_L, v_{s_G}, v_{s_L} and the experimental conditions for a different set of forced convection experiments (3). These are characterized by much shorter ignition times. The values of A = 0.81 and n = 0.54 were used in (10).

Figures 1, 2, 3, and 4 are the plots of data in Tables 1, 2, 3, and 4, respectively.

Tables 2, 3, and 4 are plotted in such a manner in Figures 5, 6, and 7 that each Figure represents a constant pressure level.

The physical constants used are reported in the Michigan and Franklin Institute reports.

V. INTERPRETATION AND CONCLUSIONS

Since the model used allowed for energy transfer only from a hot gas to a propellant, the values of v_s and q represent those quantities at the end of the ignition interval, τ, if no chemical reaction had taken place in the propellant.

From Figures 1, 2, 3, and 4 and Table 5, one can see that for all runs at constant flow rate or constant pressure, the values of q decrease with increasing gas temperature. Here we see that the q necessary to ignite the propellant surface must depend not only upon the energy source temperature, as stated in Reference 1, but also upon the flow rate or pressure level for convective processes.

The effect of pressure upon q varies markedly between the three gases for natural convection. In Figures 2, 3, and 4 it is seen that if we consider the gas at constant temperature an increase in pressure gives rise to an increase in q for helium but a decrease in q for nitrogen and the 80% N_2 - 20% O_2 mixture. This inversion cannot be explained at the present moment. We can, however, speculate as to the cause.

Suppose propellant ignition was determined, in addition to the assumed convective heat transfer, by a gas-solid phase chemical reaction. Since ignition times are determined by photocell activation due to the propellant flame radiation, any phenomenon which would cause the delay of the flame reaction would increase τ and, by (9), q. The degree of diffusion of the inert gases, H_e and N_2, into the gas reaction zone next to the propellant surface would vary according to the pressure levels, and the mobility of the inert molecules compared to those of the gas products at any particular level. Thus, one may suppose that the diffusion process could cause the inversion. It must be admitted that this is a very sketchy description of the hypothesis.

On many of the plots in Figures 2, 3, and 4 the 300 psig curves tend to fall out of place when compared with the other pressure levels. The experimenters (5) feel that due to experimental difficulties it is not possible to determine with certainty whether or not any apparent exceptions in their calculations (hence in our's) are significant.

It is important to note that within the range of experimental results used the lowest value of q is 1.7 cal/cm^2. This value is in agreement with minimum ignition energies obtained from previous (9) steady state burning results. These gave a value of 2.55 cal cm^2 for the excess enthalpy associated with a combustion wave as measured by integrating under the temperature-distance curve of steady state burning of nitrocellulose strands. The value of 2.0 cal/cm^2 for the energy associated with the combustion wave was obtained (9) by measuring the heat drain from a burning powder strand to a copper strip cemented to the bottom of the strand. However, there is no evidence to indicate that if the gas temperature is increased, the value of q at ignition could not continue to decrease with shorter ignition times.

VI. FUTURE WORK

At NOL (10) we have been igniting various propellants by adiabatic compression since this method bears close resemblence to practical gun and rocket ignition conditions. We can obtain ignition of equivalent semi-infinite propellant cylinders in the order of two or three milliseconds. Attempts are being made to calculate the ignition energies and a "linear" surface temperatures for such very short ignition times under conditions of continuously varying gas temperature and pressure, and mass flow rate. It is hoped that these conditions will allow us to ascertain whether there exists a critical minimum ignition energy per unit area. The computations are necessarily very complex.

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TABLE 1

IGNITION ENERGIES PER UNIT AREA FOR M2 PROPELLANT USING 80% N_2-20% O_2

OBTAINED FROM UNIVERSITY OF MICHIGAN DATA FOR FORCED CONVECTION

5.0 SCFM

V	τ	h*	v_s*	q
290	7.65	15.36	185	8.88
391	3.05	16.79	210	6.23
516	1.14	18.85	224	4.01
540	0.768	19.04	208	3.00
585	0.767	19.87	234	3.25
628	0.608	20.47	234	3.02
646	0.535	20.68	232	2.81
712	0.413	21.45	238	2.55

3.5 SCFM

V	τ	h*	v_s*	q
296	9.25	12.89	182	9.63
403	3.10	14.04	197	5.85
529	1.26	15.75	211	3.93
635	0.687	17.08	218	2.95
751	0.447	18.43	233	2.56
764	0.456	18.42	238	2.65

2.0 SCFM

V	τ	h*	v_s*	q
322	8.82	9.66	171	8.63
405	4.47	10.72	188	6.73
501	2.07	11.53	191	4.59
632	0.873	12.70	191	2.93

*Calculated by Franklin Institute (5)

TABLE 2

IGNITION ENERGIES PER UNIT AREA FOR M2 PROPELLANT USING He

OBTAINED FROM FRANKLIN INSTITUTE DATA FOR FREE CONVECTION AND RADIATION

P	V	$\bar{V}$**	τ	h*	v_s*	q
0	420	599	9.12	3.57	168	8.38
	495	767	5.82	3.61	182	7.21
	570	957	3.52	3.69	188	5.77
	645	1186	2.41	3.72	199	5.12
	795	1746	1.08	3.85	213	3.55
50	420	532	8.54	5.73	205	9.88
	495	665	4.41	5.78	204	7.04
	570	815	3.22	5.82	223	6.52
	645	986	2.02	5.90	227	5.28
	720	1178	1.28	6.00	228	4.18
	795	1406	0.90	6.00	234	3.61
100	395	473	8.20	7.08	206	9.80
	495	633	4.30	7.12	223	7.72
	570	768	2.46	7.20	223	5.79
	645	922	{1.96	7.24	{247	{5.60
			{1.20		{203	{3.62
	720	1095	1.23	7.32	245	4.47
	795	1295	0.92	7.32	258	3.99
200	420	490	7.10	9.16	238	10.67
	495	601	4.33	9.24	253	8.75
	570	724	2.70	9.26	263	6.95
	645	861	1.73	9.31	266	5.71
	720	1014	1.20	9.34	273	4.87
	795	1183	0.86	9.42	282	4.21
300	420	479	5.32	10.83	235	9.20
	495	585	3.50	10.90	256	7.92
	570	700	2.06	11.00	259	6.14
	645	828	1.38	10.96	265	5.13
	720	969	1.00	11.02	276	4.55
	795	1128	0.67	11.00	275	3.66

*Calculated by Franklin Institute (5)

**$\bar{V}$ is a "temperature" which includes the radiation boundary condition. To calculate v_s and q, $\bar{V}$ is substituted for V in equations 4 and 9. See Reference (4) for details on calculating $\bar{V}$.

TABLE 3

IGNITION ENERGIES PER UNIT AREA
FOR M2 PROPELLANT USING N_2

OBTAINED FROM FRANKLIN INSTITUTE
DATA FOR FREE CONVECTION AND RADIATION

P	V	$\overline{V}$**	τ	h*	v_s*	q
0	420	895	30.50	1.35	187	16.77
	495	1207	15.40	1.38	192	12.44
	570	1588	8.90	1.40	202	9.33
	645	2062	5.50	1.42	213	7.68
	720	2625	3.70	1.44	228	7.40
	795	3306	2.60	1.46	247	6.40
50	420	722	17.50	2.53	200	13.60
	495	941	9.30	2.56	205	8.43
	570	1201	5.60	2.60	214	8.12
	645	1514	3.70	2.63	227	7.17
	720	1886	2.45	2.65	238	5.86
	795	2314	1.80	2.69	257	5.57
100	420	677	12.30	3.33	202	11.53
	495	870	6.80	3.37	208	8.88
	570	1097	4.10	3.41	215	7.17
	645	1369	2.70	3.42	226	5.91
	720	1688	1.85	3.44	237	5.14
	795	2053	1.40	3.49	257	5.05
200	420	631	8.80	4.52	208	10.17
	495	799	5.00	4.59	216	7.89
	570	995	3.10	4.62	224	6.36
	645	1223	2.10	4.66	235	5.59
	720	1488	1.50	4.68	249	4.99
	795	1791	1.10	4.72	264	4.53
300	420	615	5.40	5.43	194	7.44
	495	771	3.10	5.55	200	5.81
	570	952	2.00	5.60	210	4.74
	645	1162	1.35	5.64	218	4.11
	720	1406	1.00	5.64	232	3.77
	795	1676	0.75	5.72	247	3.46

*Calculated by Franklin Institute (5)
**See note in Table 2

TABLE 4

IGNITION ENERGIES PER UNIT AREA
FOR M2 PROPELLANT USING AIR

OBTAINED FROM FRANKLIN INSTITUTE
DATA FOR FREE CONVECTION AND RADIATION

P	V	$\overline{V}$**	τ	h*	v_s*	q
0	420	878	25.80	1.40	177	14.38
	495	1178	11.84	1.43	173	9.54
	570	1547	7.69	1.46	191	8.34
	645	2009	5.22	1.47	211	6.91
	720	2546	3.36	1.50	223	5.39
	795	3187	2.17	1.53	231	4.66
100	420	664	12.02	3.50	204	11.57
	495	851	5.84	3.56	200	7.84
	570	1073	3.62	3.57	208	6.39
	645	1337	2.41	3.59	219	5.47
	720	1646	1.57	3.60	223	4.59
	795	2008	1.25	3.62	247	4.56
300	420	607	4.40	5.66	184	6.20
	495	761	2.94	5.77	200	5.54
	570	939	1.80	5.81	204	4.40
	645	1143	1.36	5.85	223	4.07
	720	1377	1.00	5.89	237	3.76
	795	1644	0.74	5.93	249	3.44

*Calculated by Franklin Institute (5)
**See note in Table 2

TABLE 5

"GREATEST" AND "LEAST" SURFACE TEMPERATURE INCREASES AND IGNITION ENERGIES PER UNIT AREA FOR M2 PROPELLANT USING 80% N2-20% O_2

OBTAINED FROM UNIVERSITY OF MICHIGAN DATA FOR FORCED CONVECTION

G	V	τ	h_G	h_L	v_{s_G}	v_{s_L}	q_G	q_L
1220	920	0.593	12.33	11.50	235	222	2.90	2.78
3360	923	0.278	21.22	19.35	267	249	2.30	2.10
3360	1164	0.150	23.80	21.54	291	268	1.78	1.65

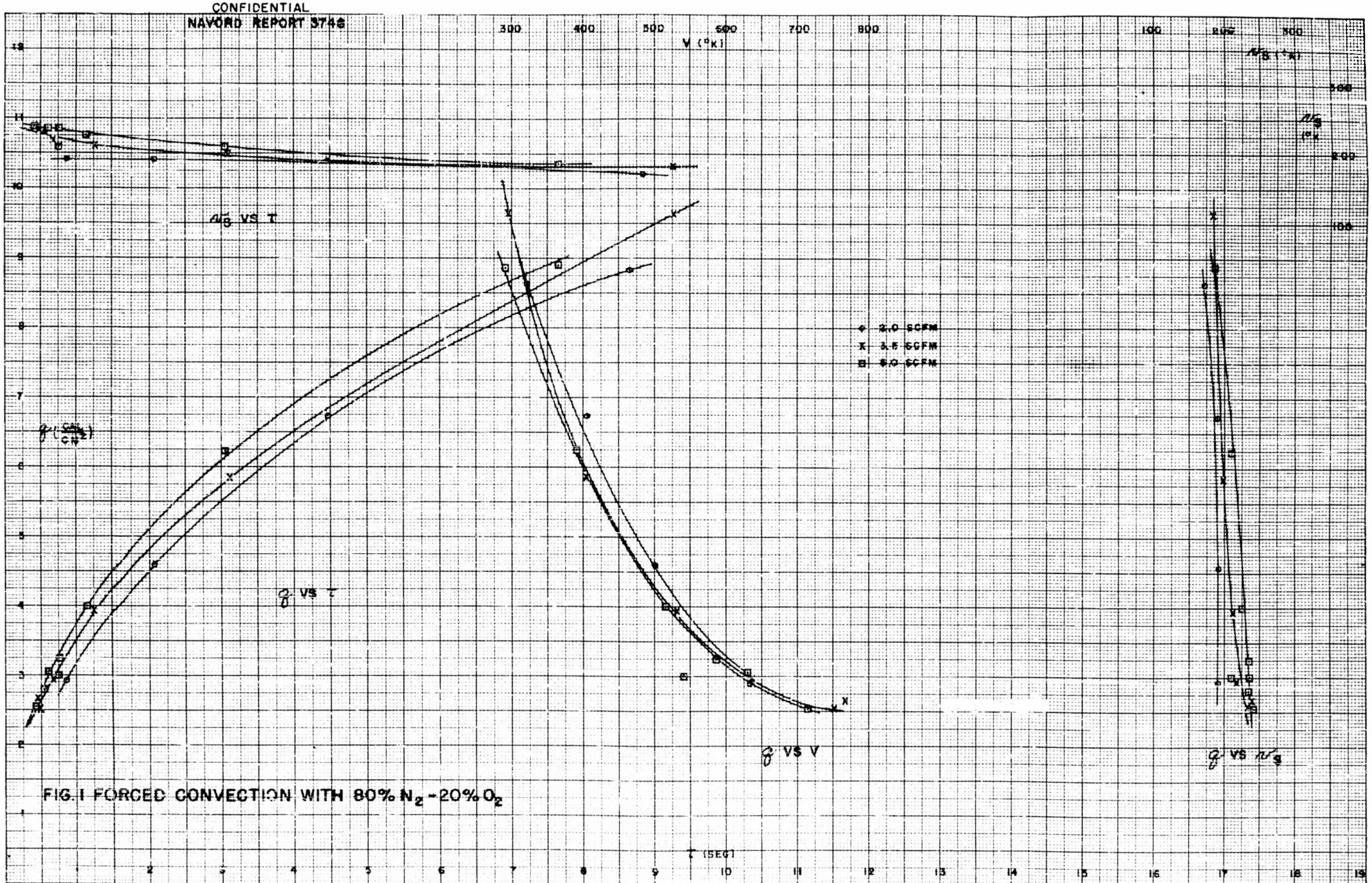

FIG. I FORCED CONVECTION WITH 80% N_2 - 20% O_2

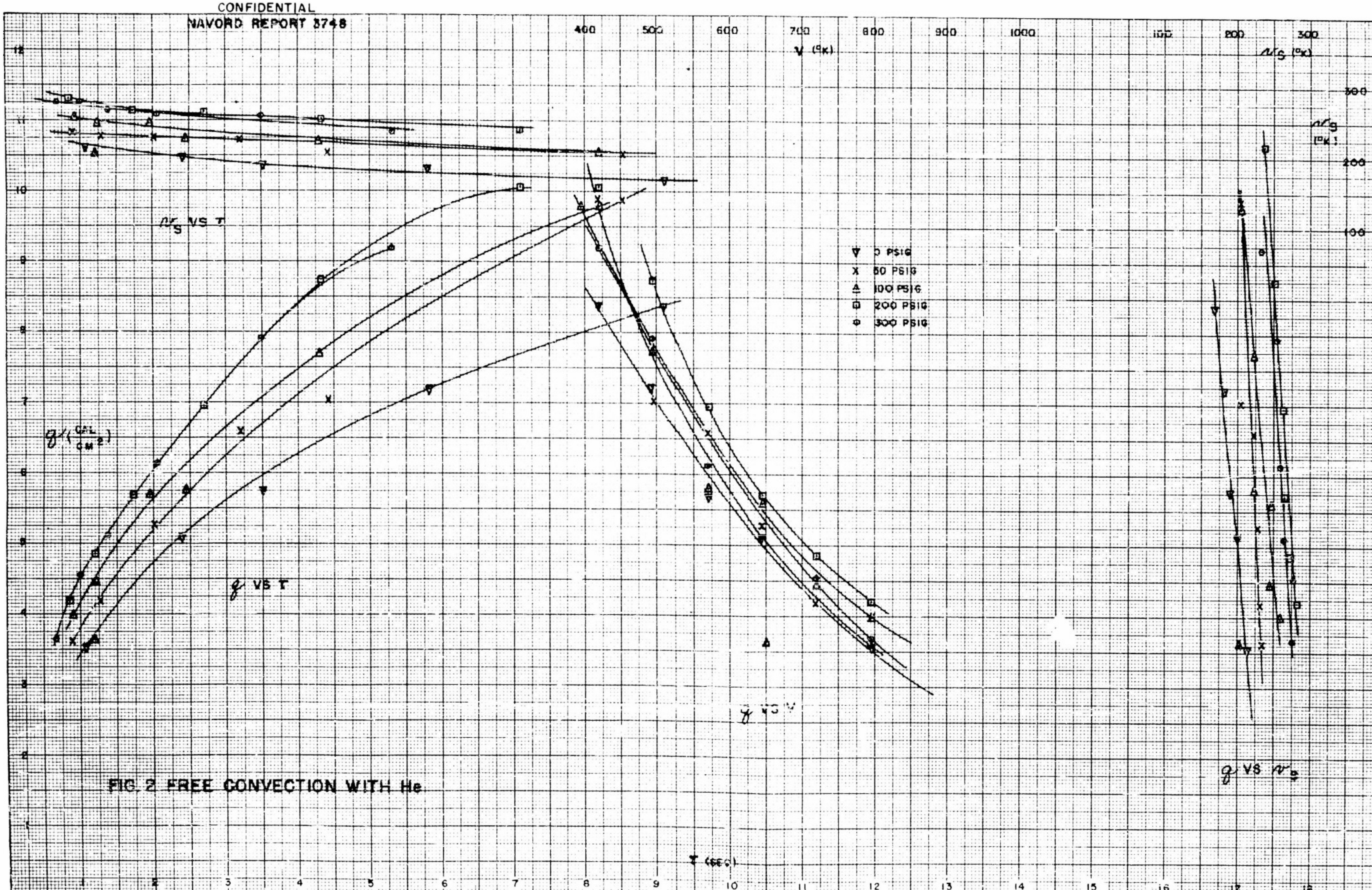

FIG. 2 FREE CONVECTION WITH He

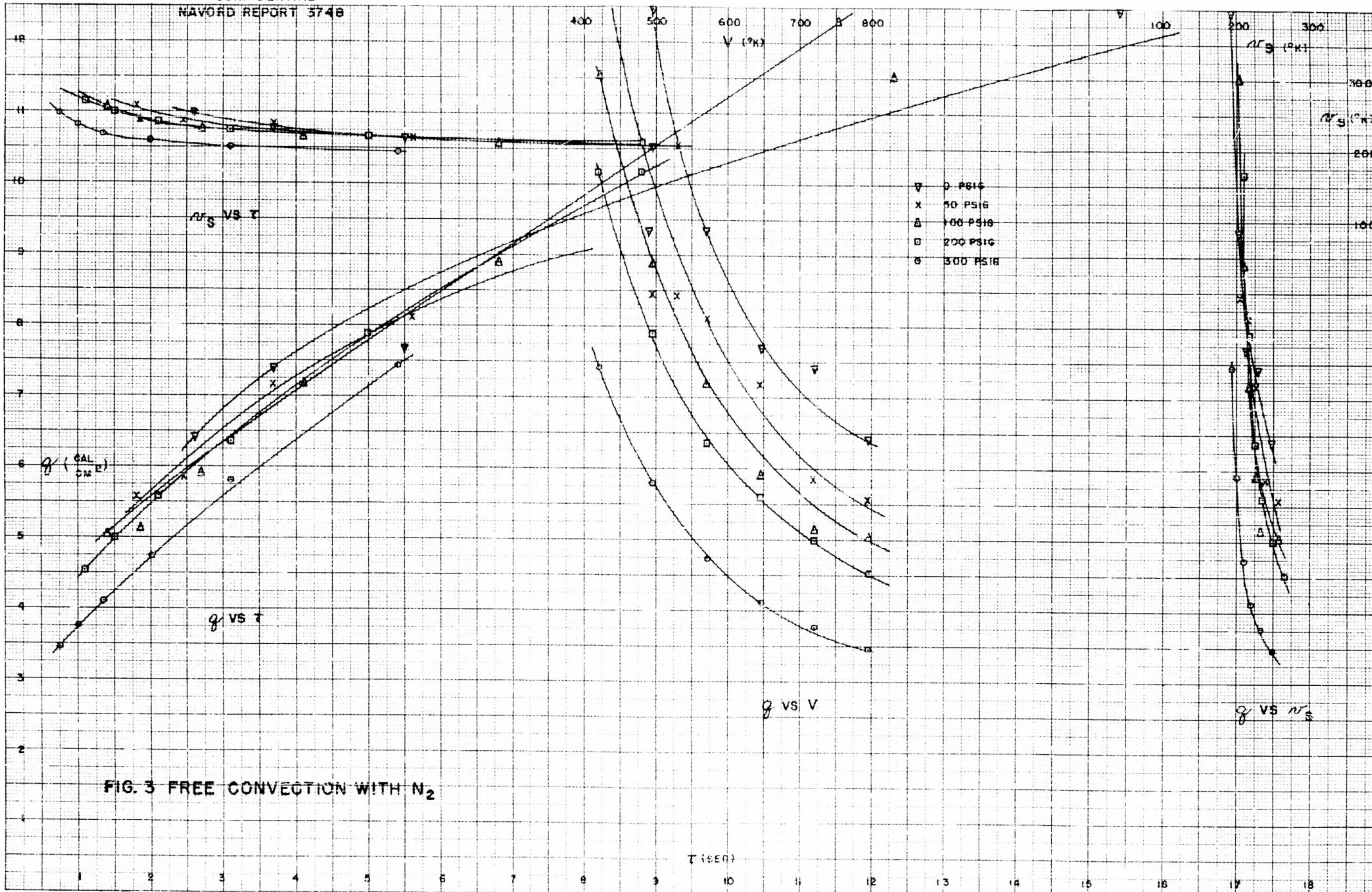

FIG. 3 FREE CONVECTION WITH N_2

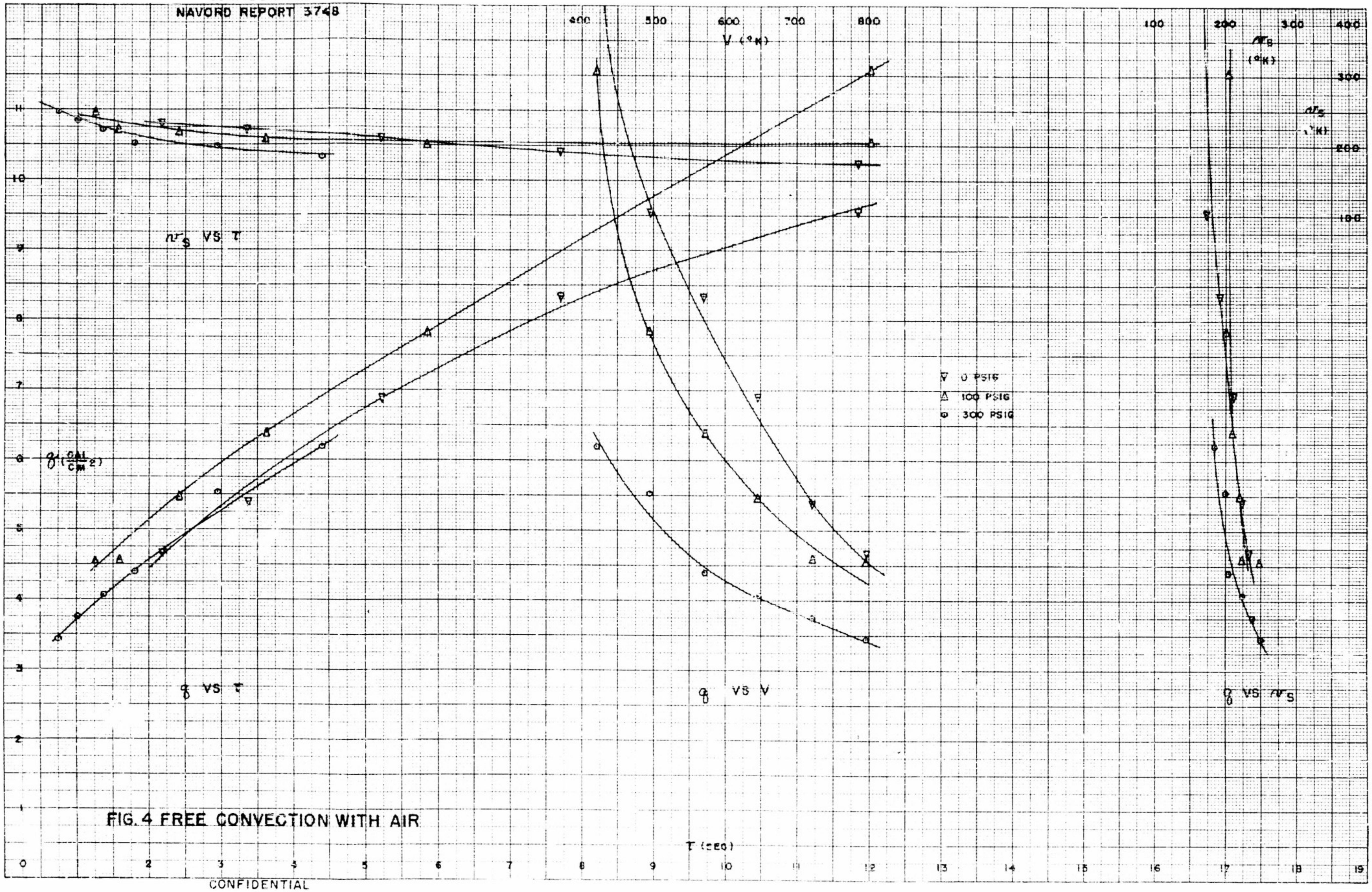

FIG. 4 FREE CONVECTION WITH AIR

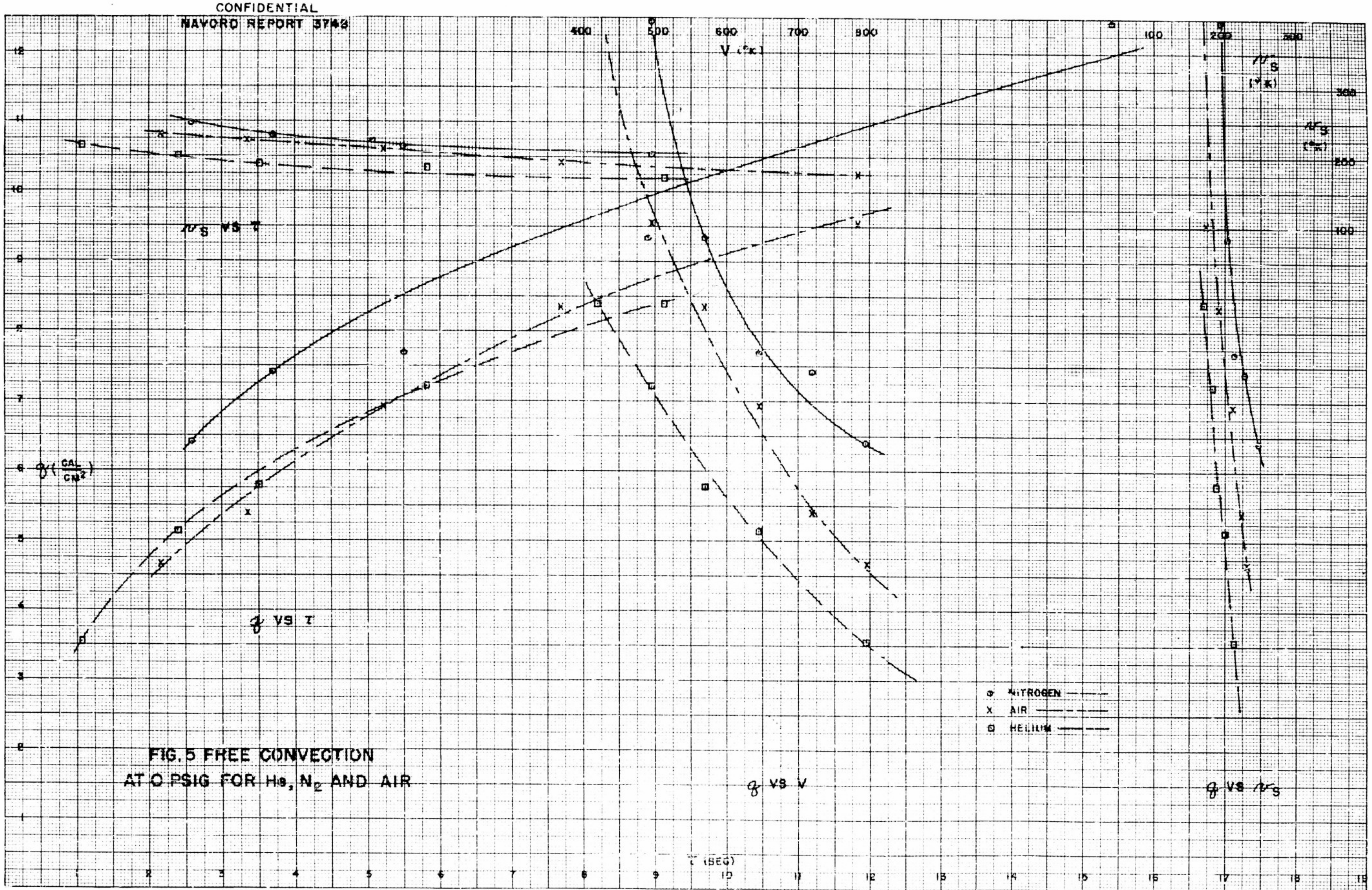

FIG. 5 FREE CONVECTION
AT O PSIG FOR He, N_2 AND AIR

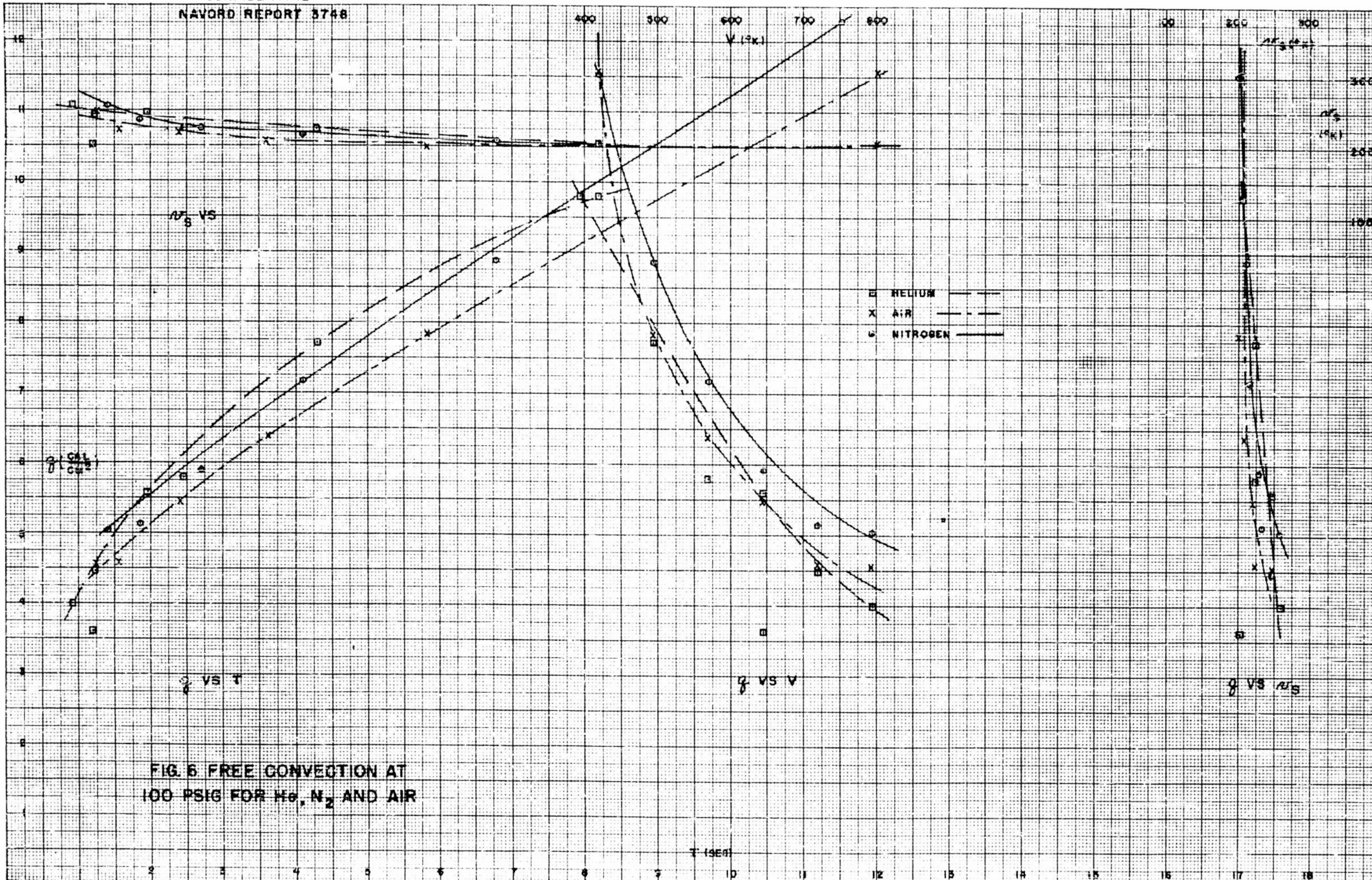

FIG. 6 FREE CONVECTION AT 100 PSIG FOR He, N_2 AND AIR

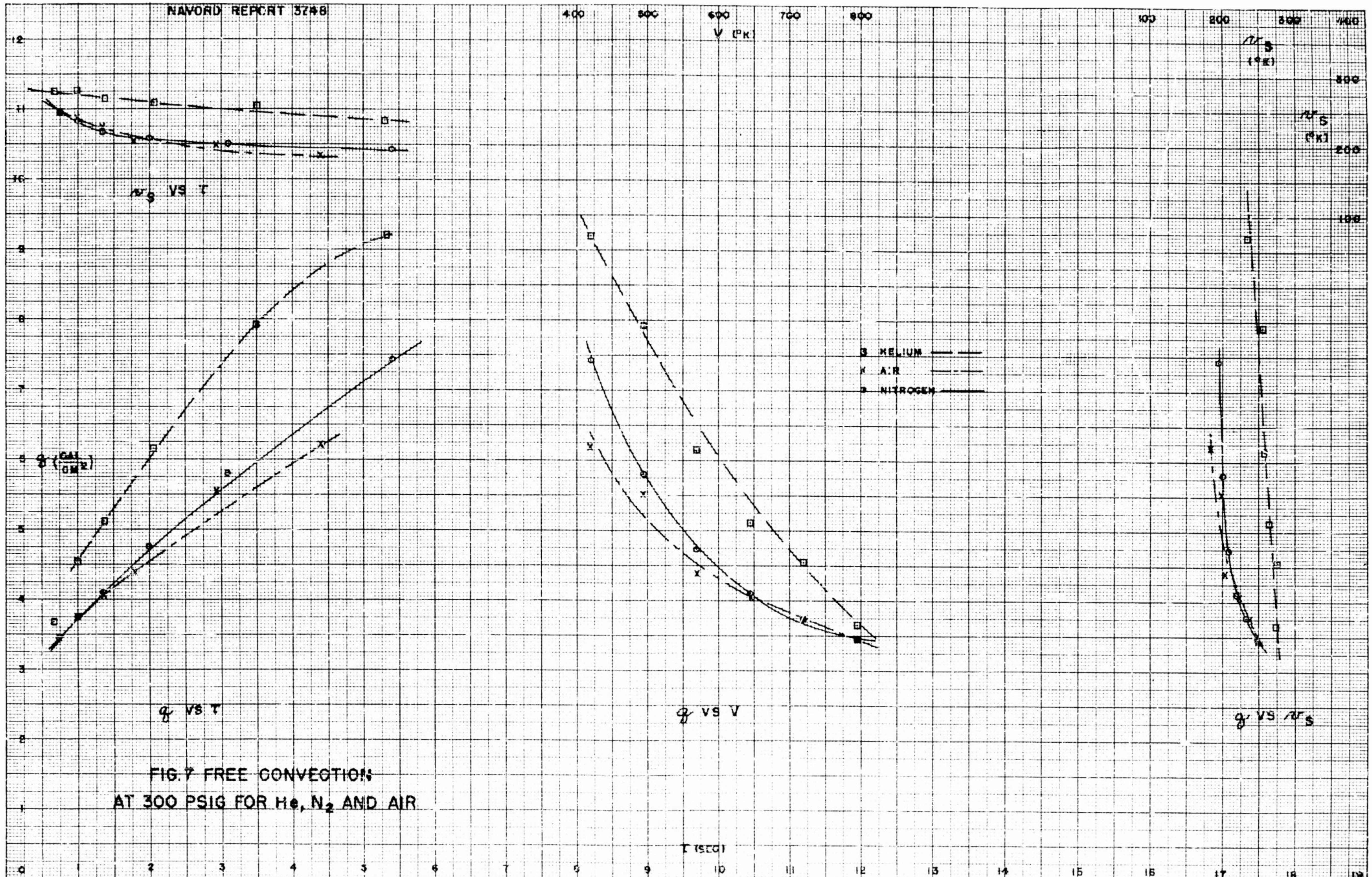

FIG. 7 FREE CONVECTION AT 300 PSIG FOR He, N_2 AND AIR

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