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REPORT ON GMX-4 ACTIVITIES

I

Shock Waves in Gases

II

Thermal Effects in Metals

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REPORT ON GMX-4 ACTIVITIES

I. Shock Waves in Gases

The study of free surface velocity by means of the pin technique is rendered difficult by reason of premature discharge of the pins. It is believed that the air shock which precedes the metal surface is sufficiently ionized to bring this about, but the mechanism by which this ionization occurs is somewhat obscure. At a surface velocity of 2.7 X 10^5 cm/sec this ionization is present in, H_2, He, N_2, and O_2. A slightly greater velocity serves to ionize CO_2, but CH_4 and C_2H_6 show no detectable ionization, even at velocities in excess of 3.0 X 10^5.

The inference of ionization drawn from pin investigations is confirmed by studies with photo-cells. Intense luminosity is present when ionization is suspected; little or no light is emitted when no preconduction is observed. That these two effects are indeed associated with the shock wave in the gas is demonstrated by the fact that the onset of preconduction precedes metallic conduction by an interval proportional to the distance traveled by the metal surface. Furthermore, in the photo-cell experiments the diaphragm which collimates the light beam fails at the instant when the air shock is believed to reach it, while the light intensity prior to this failure increases more or less linearly with time.

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Penney has calculated temperature and pressure in air shocks for the range in which we are interested. He assumes equilibrium behind the shock, and allows for excitation of various types of molecular energies. It is presumed that the mass-velocity v in our air shocks is equal to the free surface velocity of the moving metallic surface. When $v = 2.7 \times 10^5$ cm/sec, Penney finds:

Air Shock Velocity (cm/sec) $C = 3.113 \times 10^5$

Shock Pressure (Atmospheres) $p = 111$

Temperature (Degrees Kelvin) $T = 3760$

Ratio: $\frac{\text{Shock Velocity}}{\text{Mass Velocity}}$ $\frac{C}{v} = 1.152$

This calculated value of temperatures is certainly sufficient to cause some ionization. But this explanation of ionization would not account for the observed fact that ionization begins suddenly, at a velocity near 2.6×10^5, and is so intense as to obscure metallic conduction when $v = 3.0 \times 10^5$ or more. However, the figure given for $\frac{C}{v}$ is in excellent agreement with observation.

In contemplating extension of Penney's theory to other gases, simplification would be desirable, as the computation of internal energy by his method is laboriously elaborate. Unfortunately, no worthwhile simplification can be more than crudely approximate. We begin by assuming that our gases are ideal, in that their equations of state are:

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1. $\frac{p}{\rho} = \frac{R}{\mu} T$, when μ = molecular weight, so that $C_p - C_v = R$.

For any particular shock, we further assume that there exists an average value of C_v, say $\overline{C_v}$, such that

$$\int_{T_1}^{T_2} C_v \, dT = \overline{C_v} \; (T_2 - T_1)$$

Thus for 1 mole of gas, the differential of internal energy U would be:

$$dU = C_v \, dT + \left[T\left(\frac{\partial p}{\partial T}\right)_v - p \right] dV = C_v \, dT$$

since $T\left(\frac{\partial p}{\partial T}\right)_v - p = 0$, or

2. $\triangle U = \overline{C_v} \; \left(T_2 - T_1\right)$

The equations governing the propagation of the shock are:

$$3. \begin{cases} \rho c = \rho' (c - v) & \text{(mass)} \\ p' - p = \rho c v & \text{(momentum)} \\ p' v = \rho c \triangle u + \frac{1}{2} \rho c v^2 & \text{(energy)} \end{cases}$$

Here

ρ = original density, ρ' = final density, in grams/cc

c = shock velocity, v = mass velocity, in cm/sec

p = original pressure, p' = final pressure, in dynes/cm^2

$\triangle u$ = change of internal energy in ergs/gram.

Now $\triangle u = \frac{\triangle U}{\mu} = \frac{\overline{C_v}}{R} \left(\frac{RT'}{\mu} - \frac{RT}{\mu} \right)$

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Let $\frac{\overline{C_v}}{R} = \frac{1}{\gamma - 1}$ where now γ is an effective ratio of specific heats. Then using 1

$$\Delta u = \frac{1}{\gamma-1}\left(\frac{p'}{\rho'} - \frac{p}{\rho}\right).$$

Our equations now become

$$\left\{\begin{array}{l} \frac{1}{\gamma-1}\left(\frac{p'}{\rho'}-\frac{p}{\rho}\right) = \frac{p'v}{\rho c} - \frac{1}{2} v^2 \\ \frac{p'}{p} = \frac{\rho c v}{p} + 1 \\ \frac{\rho}{\rho'} = 1 - \frac{v}{c} \end{array}\right.$$

4. Set $v = v_0\sqrt{\frac{p}{\rho}}$, $C = C_0\sqrt{\frac{p}{\rho}}$, $\frac{c}{v} = X$

Then

$$\left\{\begin{array}{l} \frac{\rho}{\rho'} = 1 - \frac{1}{X} \\ \frac{p'}{p} = C_0 v_0 + 1 = X v_0^2 + 1 \\ \frac{1}{\gamma-1}\cdot\frac{p}{\rho}\cdot\left(\frac{p'}{p}\frac{\rho}{\rho'} - 1\right) = \frac{p'}{p}\cdot\frac{p}{\rho}\cdot\frac{v}{c} - \frac{1}{2}\frac{p}{\rho}v_0^2 = \Delta u \end{array}\right.$$

$$\frac{1}{\gamma-1}\left[\left(1-\frac{1}{X}\right)\left(Xv_0^2+1\right) - 1\right] = \left(Xv_0^2+1\right)\frac{1}{X} - \frac{1}{2}v_0^2$$

$$\frac{1}{\gamma-1}\left[Xv_0^2 + 1 - v_0^2 - \frac{1}{X} - 1\right] = v_0^2 + \frac{1}{X} - \frac{1}{2}v_0^2 = \frac{1}{2}v_0^2 + \frac{1}{X}$$

$$Xv_0^2 - v_0^2 - \frac{1}{X} + (1-\gamma)\left(\frac{v_0^2}{2} + \frac{1}{X}\right) = 0$$

$$X^2 + \left(\frac{1-\gamma}{2} - 1\right)X + \frac{1-\gamma-1}{v_0^2} = 0$$

5. $$X^2 - \frac{\gamma+1}{2}X - \frac{\gamma}{v_0^2} = 0$$

This equation determines X as a function of v_0, γ.

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6. $$X = \frac{\gamma + 1}{4}\left(1 + \sqrt{1 + \gamma\left[\frac{4}{(\gamma+1)v_o}\right]^2}\right)$$

One may now find the temperature increase:

$$\Delta u = \frac{1}{\gamma - 1} \cdot \frac{R}{\mu}\,(T' - T) = \frac{1}{\gamma - 1} \cdot \frac{p}{\rho T}\,(T' - T) = \frac{p}{\rho}\left(\frac{1}{2}\,v_o{}^2 + \frac{1}{X}\right)$$

7. $$\frac{T'}{T} = 1 + (\gamma - 1)\left(\frac{1}{2}\,v_o{}^2 + \frac{1}{X}\right)$$

Given X, v (as in Penney's report) to find γ, we simply solve (5.), which yields

8. $$\gamma = \frac{X^2 - \frac{X}{2}}{\frac{1}{v_o{}^2} + \frac{X}{2}}$$

Finally, to compute C_o, given γ, p', we set $X = \frac{C_o}{v_o}$ and substitute in (5.)

$$\frac{C_o{}^2}{v_o{}^2} - \frac{\gamma + 1}{2}\,\frac{C_o}{v_o} - \frac{\gamma}{v_o{}^2} = 0$$

$$C_o{}^2 - \frac{\gamma + 1}{2}\,C_o v_o - \gamma = 0 \quad \text{, but } C_o v_o = \frac{p'}{p} - 1$$

9. $$\therefore C_o{}^2 = \gamma + \frac{\gamma + 1}{2}\left(\frac{p'}{p} - 1\right)$$

In Fig. 1, X is plotted as a function of v_o for various values of γ, while Fig. 2 gives T'/T in a similar manner. Fig. 3, give $\frac{v_o}{v}$ as a function of the molecular weight μ, when T = 283° K. It is based on average values of the velocity of sound for typical gases.

It is hardly to be expected that the value of γ will be constant for any particular gas when a wide range of temperature

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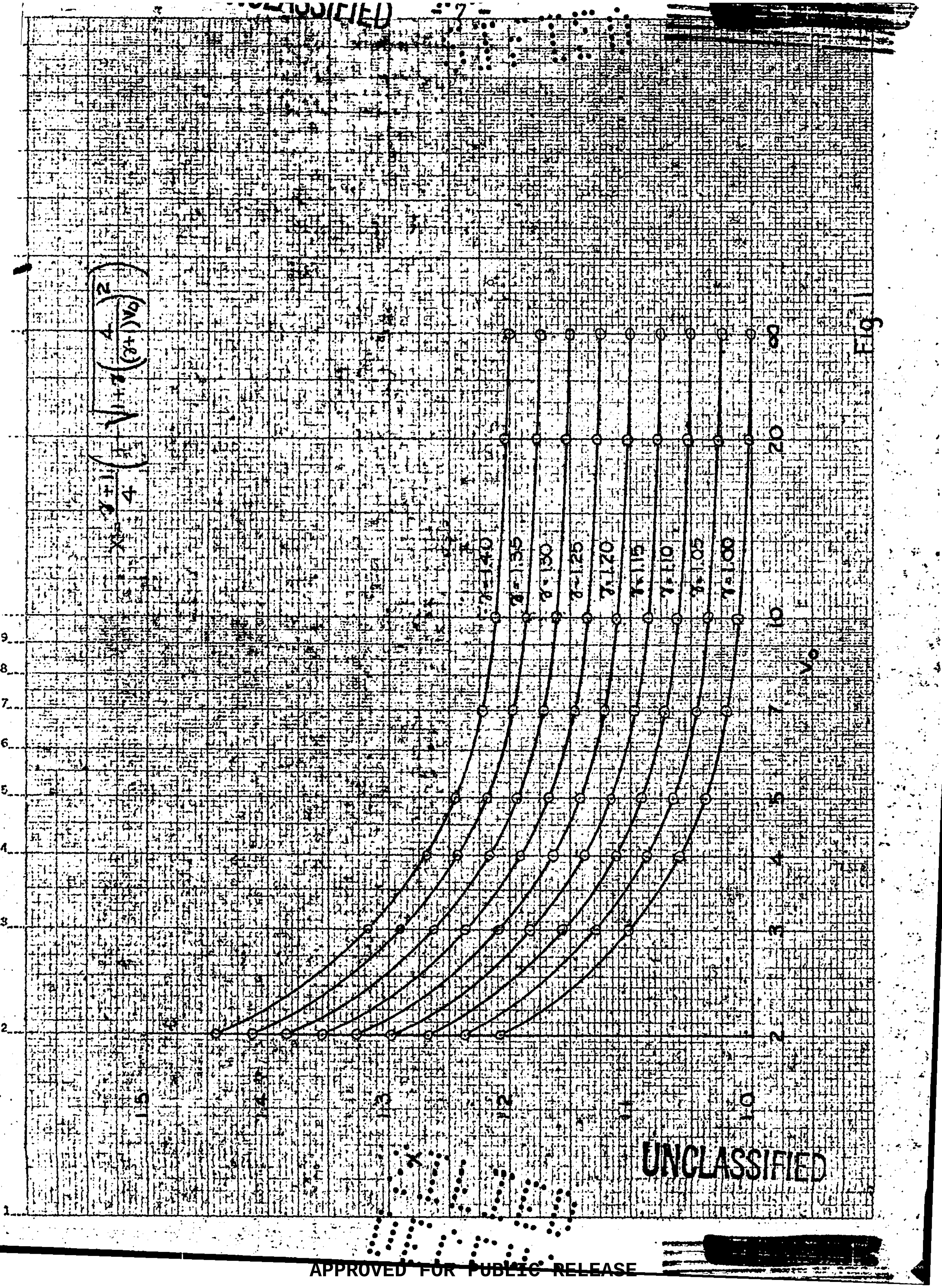

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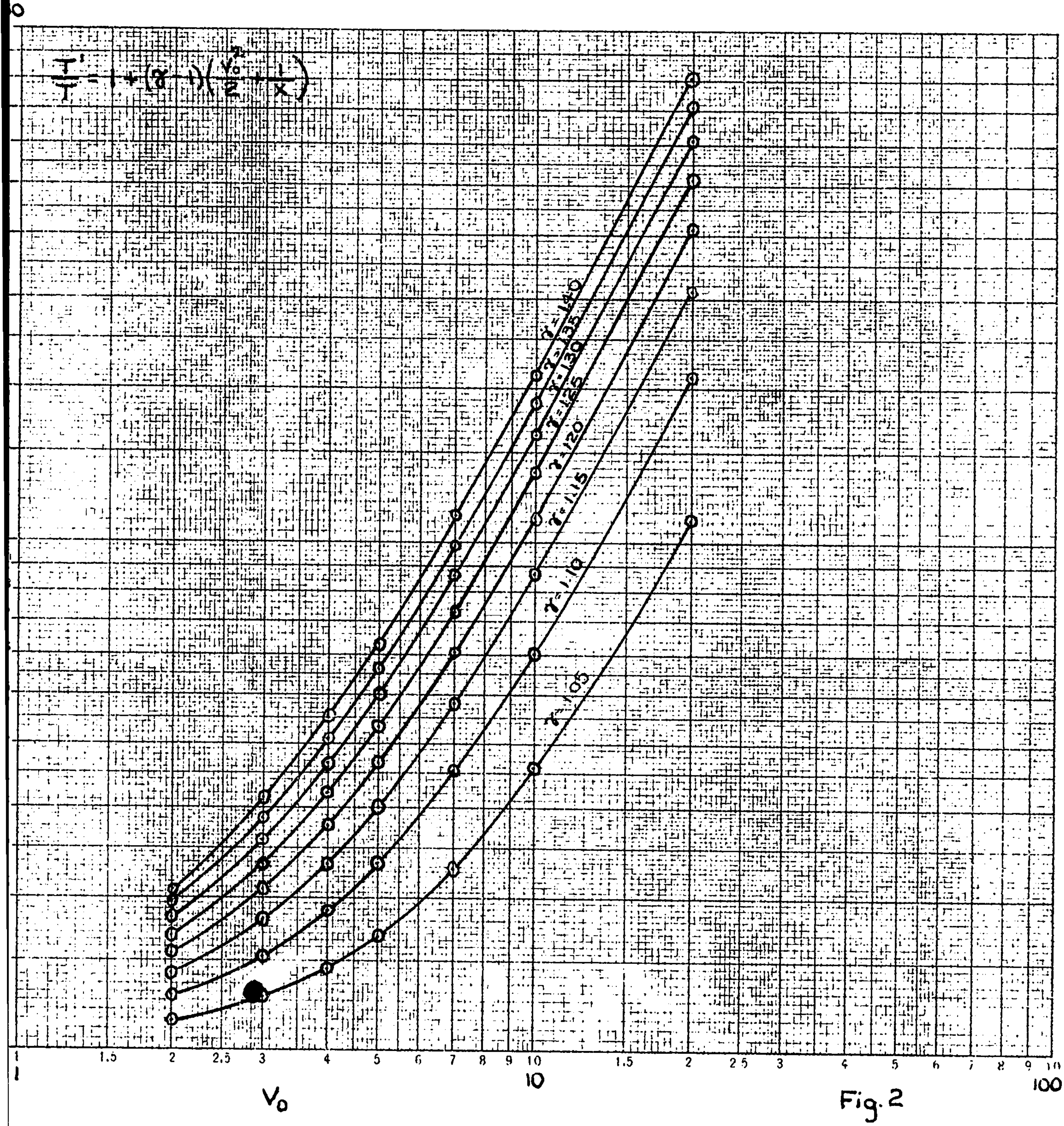

Fig. 2

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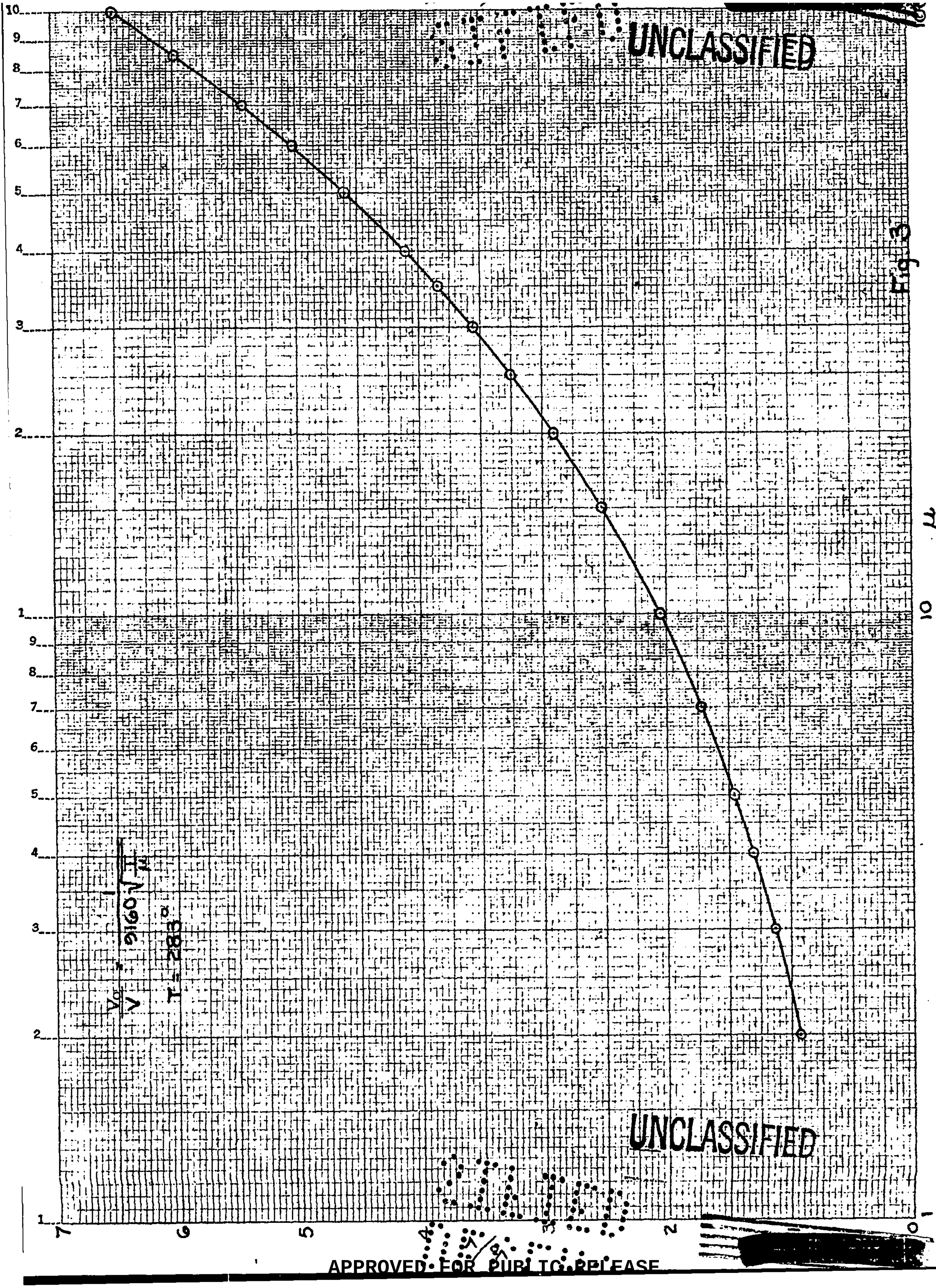

Fig 3

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is to be covered. As an example of this, Fig. 4 shows the variation of our effective value of γ as computed from Eq. 8, using the data of Penney's report. It might be interesting to use such experimental data as are available to check this figure, though it is doubtful if the precision would be sufficient to give a detailed confirmation.

We now proceed to estimate X, T', p' for several gases in which we are interested, taking v = 2.7 x 10^5 cm/sec. In order to do this, it is necessary to guess the effective values of γ ; there appears in the table below: The initial condition is taken to be T = 283° K, p = 1 atmosphere.

TABLE I

Gas	Molecular Weight	γ (estimated)	v_0	X	T' Deg K	$p'/p = Xv_0^2+1$	Ionization Potential (ev)	Maximum Shock Energy(ev)
H_2	2.02	1.40	2.48	1.360	716°	9.4	15.6	0.18
He	4.00	1.65	3.48	1.412	1530°	18.1	24.5	0.32
CH_4	16.0	1.15	6.96	1.097	1340°	54	14.5	1.2
N_2	28.0	1.25	9.29	1.137	3400°	99	15.5	2.1
C_2H_6	30.1	1.12	9.59	1.072	1840°	99	12.8	2.3
O_2	32.0	1.25	9.91	1.166	3820°	116	12.5	2.4
CO_2	44.0	1.20	11.62	1.109	4040°	151	14.4	3.3
Air	29.0	1.28	9.45	1.152	3880°	104		2.2
Air (Penney)	29.0	1.28		1.152	3760°	111		

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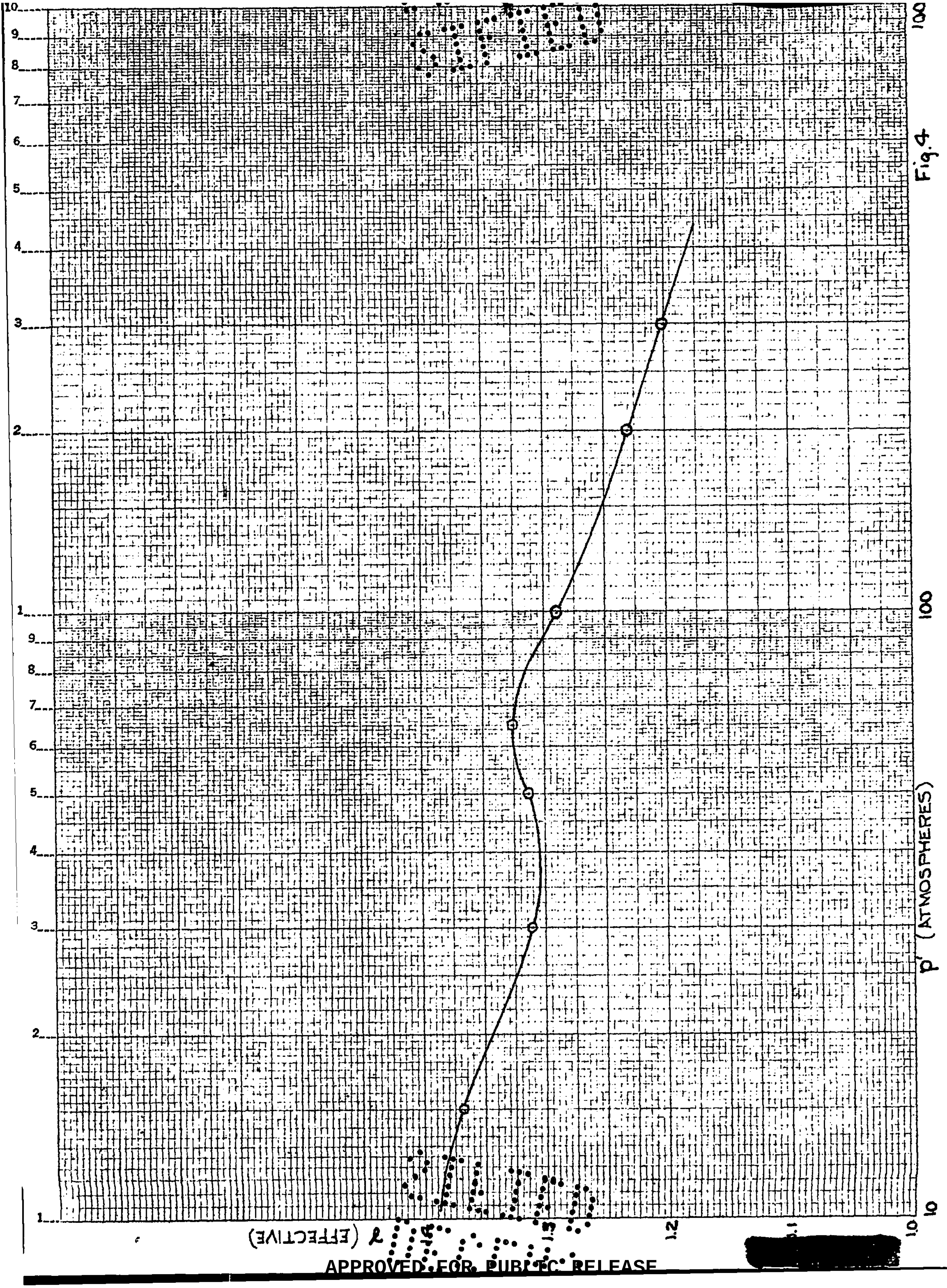

Fig. 4

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It will be seen that the approximate theory gives a pressure and temperature for air in fair agreement with those computed by Penney. The effective value of γ in this case was chosen to give Penney's value for X. In the other cases, adjustment of γ would vary X, T', P', but probably not drastically. Observed values for X may soon permit an estimate of the effective value of γ. For example, Gitting's results on air shock, with a surface velocity of 4.0×10^5 indicate that X = 1.165. This would require an effective value of γ = 1.32.

The production of ions in the gas remains something of a mystery. It is possible to compute the average work done per particle from Eq. 3. $\frac{p'v}{\rho c}$ represents the total work done per unit mass by the shock. To be sure, nearly half of this ultimately appears as kinetic energy, but we can take this figure as representing a basis of comparison for the work available to ionize the different gases. Now:

$$\frac{p'v}{\rho c} = \frac{pv}{\rho c} + v^2 = \frac{v^2}{v_0^2} \cdot \frac{1}{X} = v^2 \left(1 + \frac{1}{Xv_0^2}\right)$$

The number of particles in one gram will be $\frac{6.02 \times 10^{23}}{\mu}$, so we divide by this, also dividing by 1.6×10^{-12} to convert to electron volts. Hence the energy available per molecule is:

$$W = \frac{\mu}{9.6 \times 10^{11}} v^2 \left(1 + \frac{1}{Xv_0^2}\right) \qquad \text{(v in cm/sec)}$$

The values thus computed appear in Table I. Experimentally, one finds air commencing to ionize at 2.7×10^5 cm/sec, while

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methane requires nearly 7 x 10^5 cm/sec. Thus for methane, the critical value is $W = 8.1$ e.v. It is reasonable to suppose that methane can absorb a good part of this energy in vibration and rotation. No doubt oxygen too can absorb energy in the same way. However, it might not be unreasonable to assume that methane could absorb three times as much, because of its diverse degrees of freedom, and the low energies associated with them. Such an assumption makes the ratio of available shock energy to ionization energy nearly equal in the two gases, though clearly the ratio is very small. In fact, if we assume 1/7th the oxygen energy is available, while 1/21st the methane energy is available, we get fractions of the ionization potential not far from that of helium, where no doubt any energy absorbed inelastically must go into energy of the orbital electrons. But this hypothesis fails utterly to account for the ready ionization of hydrogen, where the work available for ionization is much too small by comparison.

A possible source of ionization in H_2 might be the relatively complete ionization of heavy impurities, for example N_2, CO_2, or H_2O. In the shock front these molecules would be brought from rest to the mean shock velocity by means of repeated collisions with H_2 molecules. In the event that these collisions were inelastic, it would require perhaps 14 of them to bring N_2 up to speed; more might occur in directions transverse to the shock. Thus the N_2 molecule might receive up to 15 times the energy of an average H_2 molecule,

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or 1.1 e.v. This is comparable to the energies available for other gases, but it low by a factor of 10 if one is trying to account for complete ionization of the impurity.

Most of the above discussion is obviously little better than conjecture. Certain experimental work would greatly elucidate matters. In the first place, one must discover the critical surface velocity for all gases of interest. To do this, it would be well to standardize (1) pin size and shape, (2) pin voltage, (3) recording circuit, and (4) the signal amplitude which is taken as indicating incipient ionization. It is more difficult to prescribe standardization for the luminosity experiments. In the second place the possibility of effects of impurities in the light gases (H_2 and He) might well be investigated, though this may not be easy. Ionization of .01% is probably ample to account for the observed effects. An impurity present to 0.1% (molar) would require only 10% ionization to be observable. It might be interesting to see if traces of N_2 would increase the luminosity observed with hydrogen.

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II. Thermal Effects in Metals

The equation of state of a metal, together with a knowledge of its specific heat as a function of temperature provides all the information necessary to calculate the temperature in the material which has suffered a Rankine-Hugoniot compression. LA-208 and LA-385 contain the necessary information, but the actual computation of temperature increase in a given case is a bit laborious. We shall proceed to compute the temperature rise in aluminum, for a shock which reduces the volume to 0.8 its initial value. The underlying principle is that the change in internal energy may be computed either from the work done by the shock in a Rankine-Hugoniot compression, or from the equation of state.

The conservation of energy in a Rankine-Hugoniot compression yields:

$$\Delta U = \frac{1}{2} (p_1 + p_2)(v_1 - v_2) \quad * \qquad 1.$$

Here (p_1, v_1) refer to the original pressure and <u>volume</u> respectively, while p_2, v_2 are the final values.

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* This equation is of course derivable from Eq. 3 of the Report on Air Shock, if we distinguish between the two notations. Eq. 3 refers to a 1 gram mass, for which

$$\Delta u = \frac{p'v}{\rho c} - \frac{1}{2} v^2$$

, from which we eliminate v and c using conservation of mass and momentum. Thus one finds

$$\Delta u = \frac{1}{2} (p' + p)\left(\frac{1}{\rho} - \frac{1}{\rho'}\right)$$

, but for mass M, volume V, $\rho = \frac{M}{V}$, $\rho' = \frac{M}{V'}$, $\Delta U = M\Delta u$, so

$$\Delta U = \frac{1}{2} (p' + p)(V - V')$$

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Thermodynamically, one finds

$$du \equiv \left(\frac{\partial u}{\partial T}\right)_v dT + \left(\frac{\partial u}{\partial v}\right)_T dV$$

which becomes, with suitable substitutions,

$$du = C_v dT + T^2 \left[\frac{\partial}{\partial T}\left(\frac{p}{T}\right)\right]_v dv \qquad 2.$$

Now LA-385 makes certain assumptions about the equation of state, $p = p\ (v,T)$, and then deduces the form of the expression for internal energy U. The pertinent statements are:

$$p = p_o(v) + a(v)T + b(v)T^2 \qquad \text{(p.21, Eq. 2.1)}$$

$$U = -\int_1^v p_o dv + T^2 \int_o^v b\,dv + 3RT \qquad \text{(p.23, Eq.2.4a)}$$

This amounts to assuming that

$$3. \quad C_v = \left(\frac{\partial U}{\partial T}\right)_v = 2T \int_o^v b dv + 3R$$

Note here that the inital volume at $T = 0$ is $v_o = 1$, that p is measured in megabars (1 megabar = 10^{12} dynes/cm^2 = 10^6 atmospheres nearly), that T is measured in electron volts (1 e.v. = 11,600 degrees centigrade), and that R, instead of being the gas constant in ergs per mole per degree centigrade is now measured in 10^{12} ergs per cubic centimeter per electron volt, and thus depends on both density and molecular weight. The latter is sufficiently confusing to warrant a whole sentence in LA-385 (p. 23).

In a compression from v_1 to v_2, one now finds:

$$4. \ \triangle U = \int_{v_2}^{v_1} p_o dv + T_2^2 \int_o^{v_2} b dv - T_1^2 \int_o^{v_1} dv + 3R(T_2 - T_1)$$

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This is written down from inspection of Eq. 2.4a of LA-385. It may also be deduced of course by integration of Eq. 2, using C_v as stated in Eq. 3, and any convenient path for evaluating the line integral. In Eq. 1 we now set $p_1 = 0$, $p_2 = p_o(v_2) + a(v_2)T_2 + b(v_2)T_2^2$, and find

$$5. \quad \Delta U = \frac{v_1 - v_2}{2}\left(p_o(v_2) + a(v_2)T_2 + b(v_2)T_2^2\right)$$

Equating 4 and 5 we clearly get a quadratic equation by which T_2 may be determined as a function of v_2.

We have done this for the case mentioned above, viz. $v_2 = 0.8\, v_1$. The functions a(v) and b(v) are given in LA-385, p. 33, but the function b(v) gives a divergent integral in equation 4. Now according to LA-385 the function b for small v is of the form

$$b = Kv^{-1/3}$$

whose integral converges for $v = 0$. In order to evaluate the integral, we have used the latter form for b when $v \leq 0.2$, and have adjusted K to agree with the function on LA-385, p. 33 when $v = 0.2$. Thus for aluminum,

$$\int_0^1 b\,dv = \int_0^{0.2} 0.0425 v^{-1/3}\, dv + \int_{0.2}^1 b\,dv = 0.056812$$

while for iron, by the same technique, $\int_0^1 b\,dv = 0.054090$.

In any event, for the moderate compression considered ($v_2 = 0.8\, v_1$) the terms in T^2 are of little importance.

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The first step is to find v_1 at room temperature, $T_1 = 0.025$ e.v. (17°C.), and zero pressure. This is found by solving for v the equation

$$0 = \frac{0.733\mu + 1.190\mu^2 + 2.380\mu^4}{1 + 1.5\mu^2} + 0.025\left(\frac{0.19290}{v} + 0.38031 - 0.007v\right)$$

$$+ 0.000625\left(\frac{0.005470}{v} + 0.054149 - 0.047703v + 0.017508v^2\right)$$

where $\mu = \frac{1}{v} - 1$. The result is

$$v_1 = 1.02022 \doteq 1.020 \quad , \text{ whence}$$

$$v_2 = 0.816$$

$$v_1 - v_2 = 0.204$$

We must now evaluate

$$\Delta U = \int_{0.816}^{1.020} p_0 dv + T_2^{\,2} \int_0^{0.816} bdv - T_1^{\,2} \int_0^{1.02} bdv + 3R(T_2 - T_1)$$

The integrations were performed graphically, by plotting p_0 and b as a function of v, and then using a planimeter (Figs. 5 and 6). In integrating b(v) one must of course add $.025(v_2 - v_1)$ to the area under the curve in Fig. 6, as well as adding $\int_0^1 bdv$. We find

$$\int_{0.816}^{1.020} p_0 dv = 0.01670$$

$$\int_0^{0.816} bdv = 0.05103$$

$$\int_0^{1.020} bdv = 0.05676$$

$$3R = 0.28970$$

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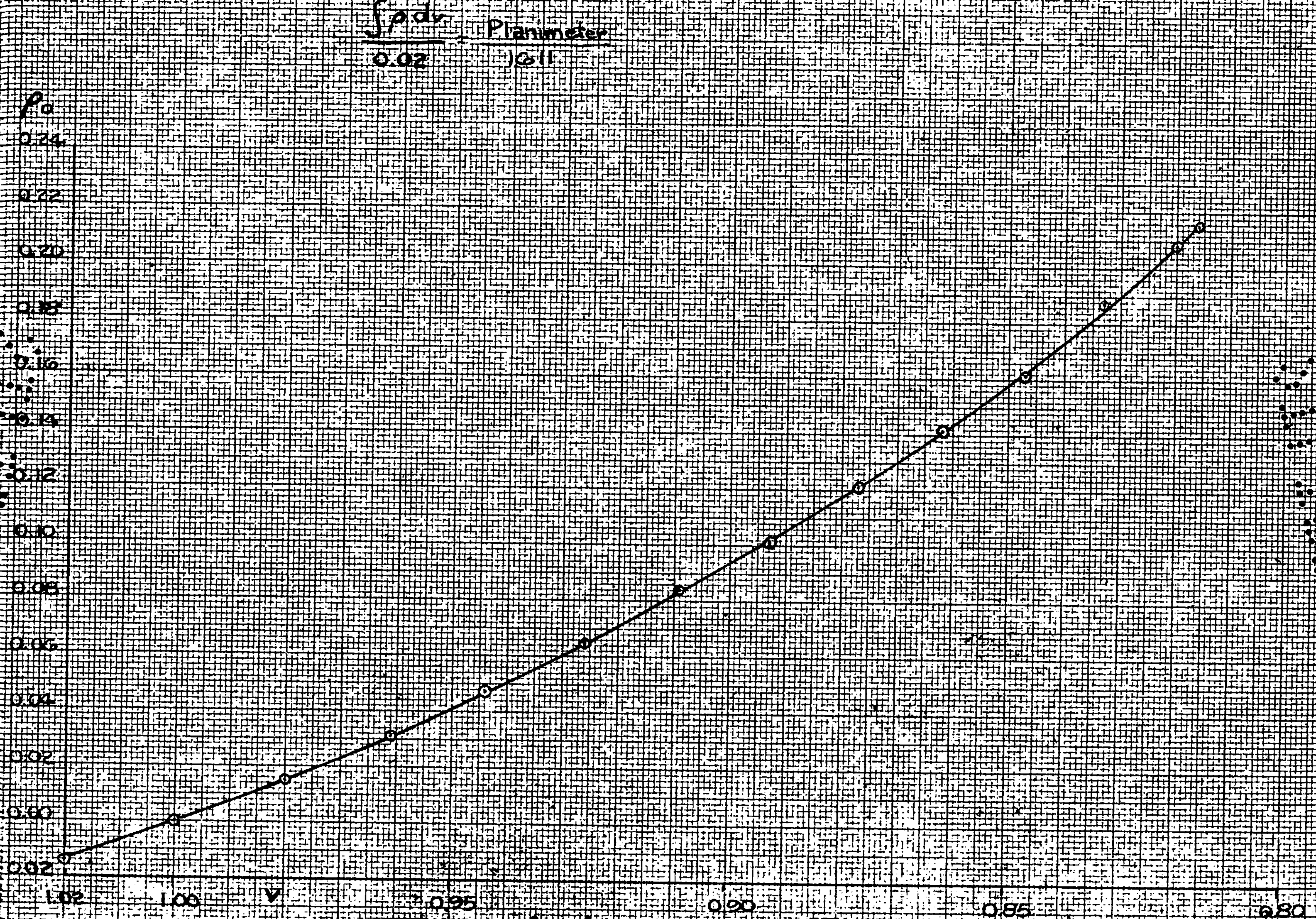
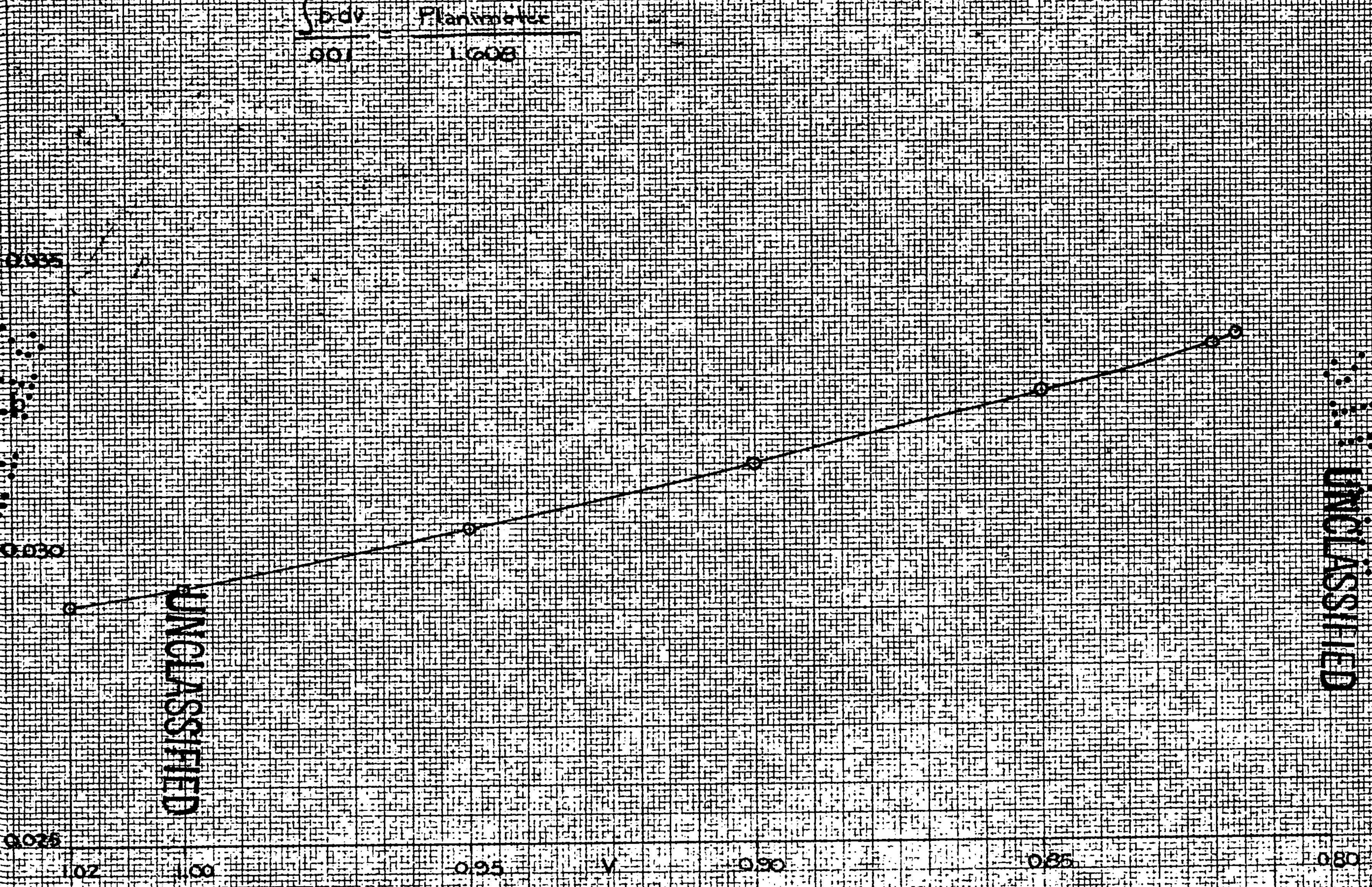


$\rho_0(v)$ for Aluminum

Fig. 5.



b(v) for Aluminum

Fig. 6

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Thus, setting $T_1 = 0.025$

$$\triangle U = 0.05103\ T_2^2 + 0.28970\ T_2 + 0.00942$$

From Eq. 5 we easily find

$$\triangle U = 0.00343\ T_2^2 + 0.062322\ T_2 + 0.02193$$

Since these two expressions must be equal,

$$0.04760\ T_2^2 + 0.2273\ T_2 - 0.01251 = 0$$

Finally,

$$T_2 = 0.0545 = 632^\circ K$$

$$T_1 = 0.0250 = 290^\circ K$$

$$T_2 - T_1 = 0.0295 = 342^\circ C$$

The above procedure, though perfectly straightforward is somewhat laborious. It is of some interest to inquire whether an approximate method could be devised, which would yield nearly the same result. We begin by observing that the terms in T_2^2 are negligible. Suppose then, we take as our equation of state

$p = p_o + aT$ where "a" is constant.

Computing "a" for volume $v = 0.9$, one finds $a = 0.587$.

Taking $C_v = 3R$,

$\left(\frac{\partial u}{\partial v}\right)_T = T^2 \frac{\partial}{\partial T}\left(\frac{p}{T}\right) = T^2 \frac{\partial}{\partial T}\left(\frac{p_o}{T} + a\right) = -p_o$, one finds

$$\begin{cases} \triangle u = \int_{v_2}^{v_1} p_o dv + 3R \triangle T & \text{from the equation of state} \\ \triangle u = \frac{\triangle v}{2}\left[p_o(v_2) + aT\right] \end{cases}$$

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Hence
$$\begin{cases} \Delta u = 0.290(T - T_o) + 0.01670 = 0.290T + 0.00945 \\ \Delta u = 0.0219 + 0.0598T \end{cases}$$

$$0.230T = 0.0125$$

$T = .0544 = 630^{o}K$, in good agreement with the result of the more elaborate method.

It would be convenient if it were possible to compute the temperature increase from the cold equation of state, and the accepted values of the coefficient of thermal expansion. If

$$p = p_o + aT + bT^2$$, one finds

$$\left(\frac{\partial p}{\partial T}\right)_v = a + 2bT$$

$$\left(\frac{\partial p}{\partial V}\right)_T = \left(\frac{\partial p_o}{\partial V}\right)_T + T\left(\frac{\partial a}{\partial V}\right)_T + T^2\left(\frac{\partial b}{\partial v}\right)_T$$

From Ln-385

$$\begin{cases} \frac{\partial p_o}{\partial V} = -\frac{1}{v^2}\frac{\partial p_o}{\partial \mu} = -\left(\frac{\alpha + 2\beta\mu}{1 + 1.5\mu^2} - \frac{\alpha\mu + \beta\mu^2}{(1 + 1.5\mu^2)^2}\cdot 3\mu\right)\left(-\frac{1}{v^2}\right) \\ \frac{\partial a}{\partial v} = -\frac{0.19290}{v^2} - .007 \\ \frac{\partial b}{\partial v} = -\frac{.00547}{v^2} - .0477 + 0.0350v \end{cases}$$

At atmospheric pressure, room temperature, $v = 1.02$, $\mu = -0.02$

$$\begin{cases} \frac{\partial p_o}{\partial V} = -\frac{1}{1.04}\left(\frac{0.733 - 0.048}{1.0006} + \frac{009}{1.001}\right) = -0.666 \\ \frac{\partial a}{\partial v} = -0.192 \\ \frac{\partial b}{\partial v} = -0.0166 \end{cases}$$ which gives

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$$\left(\frac{\partial p}{\partial V}\right)_T = -0.671 \qquad \left(\frac{\partial p}{\partial T}\right)_V = 0.564$$

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Since the thermal expansion coefficient is

$$\frac{1}{v}\left(\frac{\partial v}{\partial T}\right)_p = -\frac{1}{v}\left(\frac{\partial v}{\partial p}\right)_T\left(\frac{\partial p}{\partial T}\right)_V \quad \text{, one finds}$$

$$\frac{1}{v}\left(\frac{\partial v}{\partial T}\right)_p = +0.823$$

The value from the Handbook of Chemistry and Physics is 0.832.

It would now be desirable to deduce from the tabulated values of thermal expansion a value for "a" by which temperature increments could be computed for materials not discussed in LA-385. Unfortunately, this does not seem to be easily possible, since there seems to be no way of inferring from LA-208 an equation of state at room temperature. In any event, we have not thus far succeeded in doing this.

It is, however, easy to compute the shock pressure p_2 corresponding to our compressed material, $v_2 = 0.816$, when $T = 0.0545$ e.v. The result is

$$p_2 = 0.215 + 0.610 \times 0.0545 + 0.0336 \times 0.0030$$

$$p_2 = 0.248 \text{ m.b.}$$

If one simply takes the cold equation of state, the pressure corresponding to $v_2 = 0.8\ v_1$ is 0.240 mb. The pressures inferred from pin measurements are in general higher than those in LA-208. Hence, temperature considerations tend to decrease the observed discrepancy between the equations in LA-208 and experiment.

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