LIGHT PRODUCED BY COMPRESSION OF GAS BETWEEN TWO PLATES CLOSING AT HIGH VELOCITY

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1. Qualitative Aspects

In order to measure the optical absorption properties of condensed materials in the shocked state, light is customarily brought into the specimen through an unshocked surface parallel to the shock front, reflected from a mirror which is also parallel to the shock front, and transmitted out through the same surface by which it entered. The light thus passes twice through the specimen and is reflected from a mirror which has been shocked. There have been very few such experiments reported. The principal barrier appears to be loss of reflection from the internal mirror. This can happen either through tilt or destruction of the specular surface by shock.

Paul Bellamy has suggested that it might be possible to put a light source behind the specimen, i.e., on the impact side, thereby avoiding the mirror problem. The idea is to mount behind the impactor a second plate, separated from the impactor by a gap, x_2-x_1 in Fig. 1. This gap would be filled with argon or xenon. When the impactor has struck the target, velocity of the impactor has been reduced, while the back plate continues forward, compressing the gas in the gap. This gives rise to a series of shocks which heat and compress the gas. If the difference between impactor and plate velocities is great enough, the gas will ultimately be heated to incandescence. If the temperature is

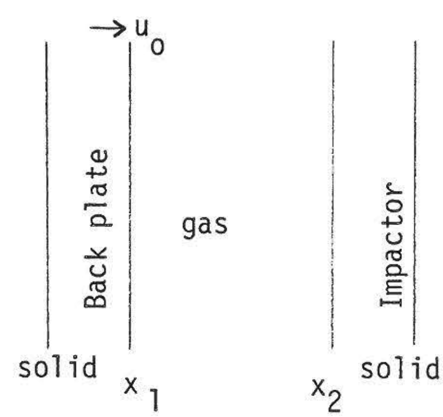


Figure 1

great enough, the hot gas will provide enough light passing through the specimen to be recorded by the diagnostic instrument.

In the following pages attempts to estimate the temperature history of the gas are described. The early history can be described by plotting the course of successive shots. Late history is calculated by assuming that the compression continues adiabatically.

2. Equations of State

The gas is assumed to be ideal with P,V,T related by the equation

$$PV = R'T \tag{1}$$

where P is measured in megabars, V in cc/g, and T in °K. R' is then the gas constant per unit mass. If P_o, V_o, T_o describe a reference state, adiabatic deviations from this state are described by

$$PV^{\gamma} = P_oV_o^{\gamma} \tag{2}$$

where γ is the ratio of specific heats. Referring again to Fig. 1, let the separation between plates be

$$y = x_2 - x_1 . \tag{3}$$

Then V is proportional to y and the adiabatic relation is

$$P = P_o(y_o/y)^{\gamma} . \tag{4}$$

Temperature is

$$T = PV/R' \tag{5}$$

and for adiabatic compression

$$T = T_o(y_o/y)^{\gamma-1} . \tag{6}$$

The (P,V) R-H curve for an ideal gas is

$$V/V_o = (P_o + \mu^2 P)/(P + \mu^2 P_o) \; . \tag{7}$$

The (u,P) relation is

$$(u - u_o)^2 = (P - P_o)^2 (1 - \mu^2) V_o / (P + \mu^2 P_o) \tag{8}$$

where $\mu^2 = (\gamma-1)/(\gamma+1)$.

Argon has atomic weight 39.4. Assuming it to be monatomic, $\gamma = 5/3$, $\mu^2 = 1/4$. The gas constant is

$$R' = 0.2110 \times 10^{-5} \text{ megabar cc/g deg} \tag{9}$$

A reference state is required, and this is taken as

$$P_r = 1 \text{ bar} = 10^{-6} \text{ megabar}$$

$$T_r = 265°K$$

$$V_r = 560 \text{ cc/g}$$

$$c_r = \sqrt{P_r V_r / \gamma} = 0.018 \text{ cm/}\mu\text{sec, reference sound velocity}$$

With the above numerical values, the gas equations are

$$T = 4.739 \times 10^5 \, PV \tag{10.1}$$

$$\text{Adiabat:} \quad T = T_o (y_o/y)^{2/3} \tag{10.2}$$

$$\text{R-H:} \quad \frac{V}{V_o} = \frac{P_o + .25P}{P + .25P_o} \tag{10.3}$$

$$\text{R-H:} \quad u = u_o \pm \{.75 V_o (P - P_o)^2 / (P + .25P_o)\}^{1/2} \tag{10.4}$$

3. Initial Shock Waves

In the simplest case the impactor of Fig. 1 is at rest, having struck a target of the same material and thickness. With the backplate and gas in the gap having velocity u_o, a stopping shock travels backward in the gap, reflects from the backplate and returns to the impactor, reflects again, etc. Pressures and volumes and temperatures in the successive shocks are calculated from Eqs. (10.1), (10.3), and (10.4) assuming that the impactor remains at rest and the backplate retains its velocity u_o. This is a very good approximation in the early stages because the shock pressures in the gaps are too small to significantly change impactor and backplate velocities.

For the first shock, $P_o, V_o = P_r, V_r$. For later shocks they are given the values calculated for the previous shock. The impedance of sapphire is so great compared to the gas that the bounding plates can be treated as rigid. Then the flow consists of a sequence of shocks propagating through the closing gap. Behind a backward facing shock, particle velocity is zero. Behind a forward facing shock, particle velocity is u_o. Values of P are substituted into Eq. (10.4) and u is calculated. P is varied until u has the proper value: u = .08 for forward facing shocks, u = 0 for backward facing shocks. The results for the first seven shocks are given:

$$u_o = .08 \text{ cm/}\mu\text{sec}$$

First shock: $P_o = 10^{-6}$Mb, $V_o = 560$ cc/g, $T_o = 265$°K, $P = 17.4 \times 10^{-6}$Mb, $V = 170$ cc/g, $T = 1430$°K, $u_s = .115$ cm/μsec, $u_s - u_o = .035$ cm/μsec

Second shock: $P_o = 17.4 \times 10^{-6}$Mb, $V_o = 170$ cc/g, $T_o = 1430$°K, $P = 84 \times 10^{-6}$Mb $V = 74$ cc/g, $T = 3000$°K, $u_s = .141$ cm/μsec, $u_s - u_o = u_s$

Third shock: $P_o = 84 \times 10^{-6}$Mb, $V_o = 74$ cc/g, $P = 265 \times 10^{-6}$Mb, $V = 39$ cc/g, $T = 4976$°K, $u_s = .168$ cm/μsec, $u_s - u_o = .088$ cm/μsec

Fourth shock: $P_o = 265 \times 10^{-6}$Mb, $V_o = 39$ cc/g, $P = 660 \times 10^{-6}$Mb, $V = 23$ cc/g, $T = 7364°K$, $u_s = .1945$ cm/μsec, $u_s - u_o = u_s$

Fifth shock: $P_o = 660 \times 10^{-6}$Mb, $V_o = 23$ cc/g, $P = 1420 \times 10^{-6}$Mb, $V = 14.8$ cc/g, $T = 10{,}145°K$, $u_s = .2214$ cm/μsec

Sixth shock: $P_o = 1420 \times 10^{-6}$Mb, $V_o = 14.8$ cc/g, $P = 2750 \times 10^{-6}$Mb, $V = 10.0$ cc/g, $T = 13{,}342°K$, $u_s = .246$ cm/μsec

Seventh shock: $P_o = 2750 \times 10^{-6}$Mb, $V_o = 10.0$ cc/g, $P = 4900 \times 10^{-6}$Mb, $V = 7.1$ cc/g, $T = 16{,}837°K$, $u_s = .272$ cm/μsec

Paths of backplate, impactor, and gas shocks are shown in the x,t plane in Fig. 2 for an assumed initial gap of 3 mm. When pressure in the gas shock is large enough, it will begin to slow the rate of closure of the two plates. With $y = x_2 - x_1$ and the mass per unit area of each plate denoted m,

$$\frac{d\dot{y}}{dt} = \frac{2P}{m}$$

For example let the plate be of sapphire 6 mm thick: $m/2 = 1.2$ g/cm^2 and $d\dot{y}/dt = .01$ mm/μsec^2 for a pressure of 1.2 kbars. This suggests that the above shock calculations, in which it is assumed that impactor is stationary and back plate velocity is constant, are quite good through the fifth shock and worsen progressively after that.

Times and positions at which the shock in the gas reflects from back plate and impactor are obtained as the intersections of shock paths with plate paths.

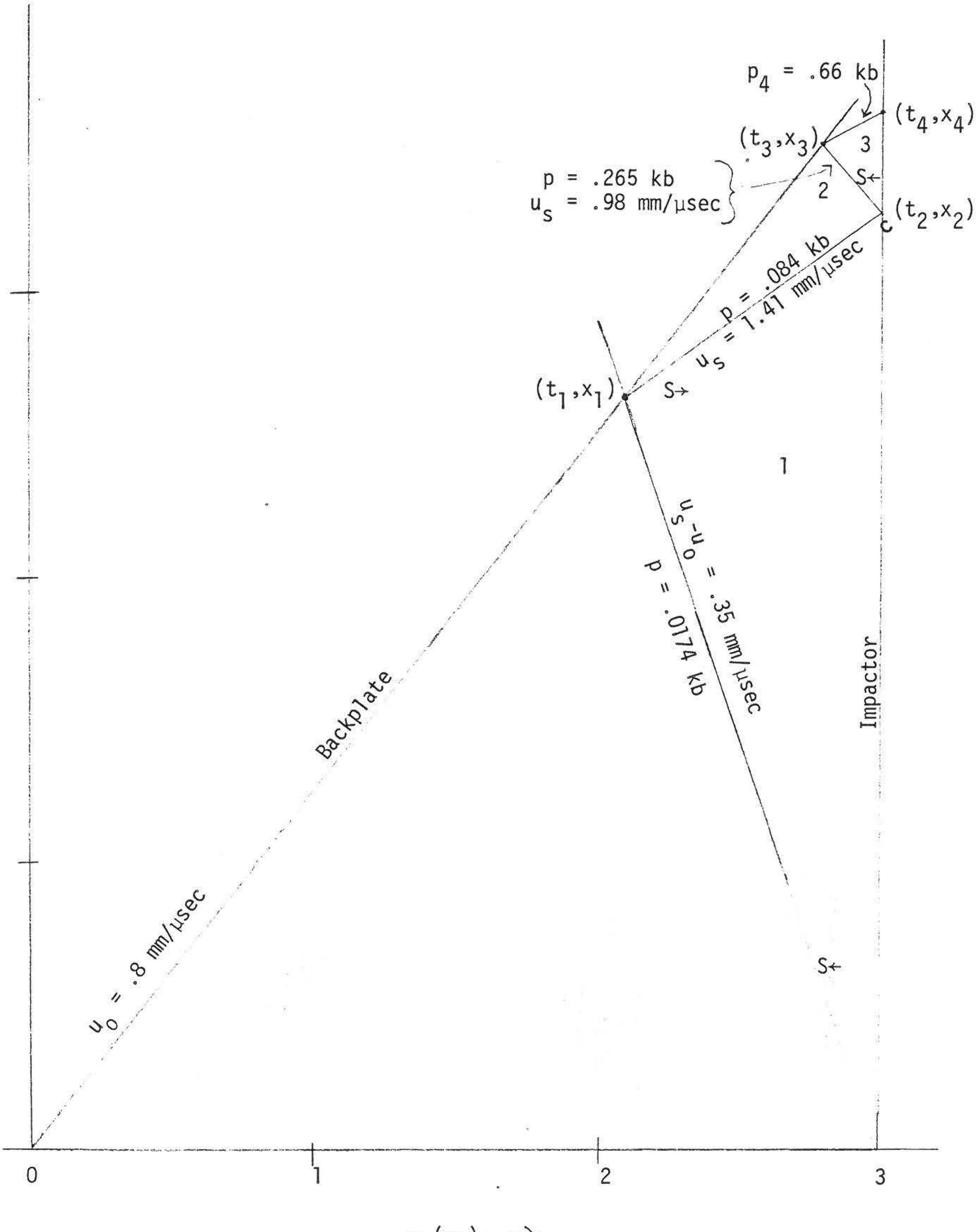
$t_1 = 2.61$ μsec, $x_1 = 2.09$ mm; $y_1 = 3 - x_1 = .91$ mm

$t_2 = 3.26$ μsec, $x_2 = 3$ mm

$t_3 = 3.49$ μsec, $x_3 = 2.79$ mm; $y_3 = .21$ mm

$t_4 = 3.60$ μsec, $x_4 = 3$ mm

Figure 2. Gas shocks produced by rigid backplate closing on a rigid and stationary impactor.



The gap at this time has become so small that accelerations of backplate and impactor have significant influence. At (t_3, x_3) the gas between plate and impactor is at rest and in a uniform pressure and temperature state

$$P_3 = .265 \times 10^{-3} \text{Mb}$$

$$T_3 = 4976°\text{K}, \quad V_3 = 39 \text{ cc/g}$$

Take this as the initial state for an adiabatic compression which heats the gas further and brings the plates to a relative stop.

4. Late Stage Adiabatic Compression

The plates bounding the gas gap are neither very thick nor very thin. If the former condition were true, the pressure-particle velocity relation at the sapphire gas interface would be satisfied by assuming simple waves are being propagated into the plates. For the latter condition the plates could be assumed to be planar masses and Newton's second law applied. The correct behavior should lie between these extremes, so both are calculated. Initial conditions for both cases are those existing at x_3, t_3:

at $t = 0$: impactor position is $Z \equiv Z_2^o = .30$ cm

back plate position is $Z \equiv Z_1^o = .279$ cm

$P_o = .265 \times 10^{-3}$ Mb

$V_o = 39$ cc/g

$y_o = Z_2^o - Z_1^o = .021$ cm

$T_o = 4976°$K

$u_o = .08$ cm/μsec

For the simple wave in the impactor, assumed elastic

$$P = \rho_o c_o \dot{Z}_z \quad (11.1)$$

$$\rho_o c_o = 4.45 \text{ Mb μsec/cm for sapphire}$$

For the simple wave in the back plate

$$P = \rho_o c_o (u_o - \dot{Z}_1) \tag{11.2}$$

$$\dot{y} = \dot{Z}_2 - \dot{Z}_1 = \frac{2P}{\rho_o c_o} - u_o \tag{11.3}$$

For adiabatic expansion of the gas, Eq. (6) applies, giving

$$\dot{y} = by^{-\gamma} - u_o \tag{12}$$

where

$$b = 2P_o y_o^{\gamma}/\rho_o c_o = 1.904 \times 10^{-7} \tag{12.1}$$

The left hand side of Eq. (12) vanishes at

$$y = (b/u_o)^{1/\gamma} = 4.226 \times 10^{-4} \text{cm} \tag{12.2}$$

Since $b/y^{\gamma} = u_o$ at $\dot{y} = 0$, it is less than unity at earlier times. It is consequently possible to integrate Eq. (12) approximately by expanding the integrand in a series in $y^{-\gamma}$. An alternative is to directly integrate Eq. (12) numerically. In either procedure the result is closely represented in Table 1.

If impactor and back plate are assumed to be plane masses, each with mass $\dot{m}$ per unit area, their equations of motion are

$$m\ddot{Z}_2 = P$$

$$m\ddot{Z}_1 = -P$$

$$m(\ddot{Z}_2 - \ddot{Z}_1) = m\ddot{y} = 2P .$$

For adiabatic compression in the gas

$$\ddot{y} = 2y_o^{\gamma} P_o/my^{\gamma} = ay^{-\gamma} . \tag{13}$$

TABLE 1. SIMPLE WAVE APPROXIMATION

t (μsec)	y (cm/μsec)	y (cm)	V (cc/g)	P (Mb)	T (°K)
3.49	-.0800	.021	39	.000265	4,976
3.502	-.0799	.020	37.14	.000287	5,140
3.540		.017	31.57	.000377	5,729
3.590	-.0797	.013	24.14	.000589	6,851
3.640		.009	16.71	.00109	8,754
3.680	-.0790	.00586	10.88	.00222	11,653
3.720	-.0765	.00274	5.09	.00790	19,343
3.740		.00127	2.36	.0284	32,297
3.744	-.0610	.00100	1.86	.0424	37,876
3.748	-.0524	.0008	1.49	.0614	43,951
3.750	-.0429	.00067	1.24	.0826	49,467
- - -	- - -	- - -	- - -	- - -	- - - **
3.752	-.0354	.0006	1.11	.0992	53,243
3.754	-.0196	.0005	0.93	.1344	60,124
3.757	0	.0004226	0.78	.178	67,258

** Calculations uncertain below this line, except for $\dot{y}$.

The first integral of Eq. (13) is

$$\dot{y}^2 = u_o^2 - \frac{2a}{\gamma-1}(y^{-\gamma+1} - y_o^{-\gamma+1}) \tag{13.1}$$

$$\dot{y} = -\sqrt{e - fy^{-\gamma+1}} \tag{13.2}$$

$$e = \frac{2a}{\gamma-1} y_o^{-\gamma+1} + u_o^2 \tag{13.3}$$

$$f = \frac{2a}{\gamma-1} \tag{13.4}$$

Take the plates to be 6 mm thick. Then $m = 4 \times .6 = 2.4$ g/cm^2 and

$$a = 3.53 \times 10^{-7}$$

$\dot{y} = 0$ at $y = 2.12 \times 10^{-6}$ cm. The inertia of the plates is much greater in this approximation than for the simple wave.

Eq. (13.2) can be written as

$$t = t_o + \int_y^{y_o} y^{(\gamma-1)/2}(ey^{\gamma-1} - f)^{-1/2}\, dy \tag{14}$$

With $\gamma = 5/3$, $q = y^{1/3}$ and $R \equiv q^2 e - f$, Eq. (14) becomes

$$t = t_o + \int_y^{y_o} 3q^3 R^{-1/2}\, dq$$

$$= t_o + \frac{1}{e}\left[R^{1/2}\left(q^2 + \frac{2f}{e}\right)\right]_y^{y_o}$$

$$= t_o + \frac{1}{e}\left[R_o^{1/2}\left(q_o^2 + \frac{2f}{e}\right) - R^{1/2}\left(q^2 + \frac{2f}{e}\right)\right] \tag{15}$$

where $R_o = q_o^2 e - f = ey_o^{2/3} - f$.

Using the same constants as in the previous problem, $y_o = .021$ cm, $P_o = .265 \times 10^{-3}$ Mb, $m = 2.4$ g/cm^2, $u_o = .08$ cm/μsec,

$$e = 6.414 \times 10^{-3}$$

$$f = 1.059 \times 10^{-6}$$

$$R_0^{1/2} (q_0^2 + 2f/e) = .07645$$

Evaluation of Eq. (15) gives the results in Table 2.

TABLE 2. PLANE MASS APPROXIMATION

t (μsec)	y (cm)	V (cc/g)	P (Mb)	T (°K)
3.49	.021	39.0	.000265	4,976
3.565	.015	27.9	.000464	6,227
3.628	.010	18.6	.000913	8,160
3.703	.004	7.43	.00420	15,031
3.740	.001	1.86	.0424	37,876
3.752	.0001	0.19	1.97	175,805

Rate of deceleration is somewhat slower for the second case than the first, and the gap is much thinner when $\dot{y} = 0$. In both cases $\dot{y} = 0$ at approximately 3.752 μsec and the temperature reaches 15,000 at about 3.70 μsec.

5. Discussion

The gas is not ideal at high temperatures and densities. Corrections for this deficiency will reduce temperatures significantly, particularly above 10,000°K. Cooling by radiation and conduction have not been considered.

The power lost by radiation is

$$Pr = \sigma T^4$$

where σ is the Stefan Boltzmann constant:

$$\sigma = 5.7 \quad 10^{-5} \text{ erg/cm}^2\text{deg}^4\text{sec}$$

$$= 5.7 \quad 10^{-12} \text{ watts/cm}^2\text{deg}^4$$

TABLE 3.

T,°K:	10^4	1.5×10^4	2×10^4	3×10^4
Pr, watts/cm^2:	5.7×10^4	2.9×10^5	9.1×10^5	4.6×10^6

The total energy delivered to the gas by the closing plates is equal to their kinetic energy at t_o. The back plate is moving with speed u_o; the front plate is stationary. Mass per cm^2 of the quarter inch thick back plate is $m = \rho_o \times .6 = 2.4$ g/cm^2. At $\dot{y} = 0$, all of this energy has been delivered to the gas; the time required to do this is approximately .26 μsec (Table 1 or 2). So the mean rate at which power is delivered to the gas is

$$\overline{P}_D = \frac{1}{2} m u_o^2 / .26\times10^{-6}$$

$$= \frac{1}{2} \times 2.4 \times (8\times10^4)^2/.26\times10^{-6}$$

$$= 2.95 \times 10^{16} \text{ ergs/cm}^2\text{sec}$$

$$= 2.95 \times 10^9 \text{ watts/cm}^2$$

The instantaneous rate of energy delivery is

$$P_D = -P \frac{dV}{dt} = -P_o y_o{}^{\gamma} y^{-\gamma} \cdot V_o \dot{y}/y_o$$

$$= -P_o V_o \dot{y} y_o{}^{\gamma-1} y^{-\gamma} \qquad (16)$$

For the example treated here $P_o = .265 \times 10^{-3}$ megabars, $V_o = 39$ cc/g, $y_o = .021$ cm. Since $\dot{y}$ changes slowly during most of the compression period, it can be set equal to $-u_o = -.08$ cm/μsec. Eq. (16) gives P_D in megabar cc per gram. The quantity of interest is power per cm^2, and this is obtained if (16) is multiplied by $m = 2.4$ g/cm^2. Then for $\gamma = 5/3$

$$P_D = 2.4 \times .265\times10^{-3} \times 39 \times .08 \times (.021)^{2/3} y^{-5/3}$$

$$= 1.51\times10^{-4}\ y^{-5/3}\ \text{megabar cc/cm}^2\mu\text{sec}$$

$$= 1.51\times10^{7}\ y^{-5/3}\ \text{watts/cm}^2 \qquad (17)$$

TABLE 4.

y, cm:	.021	.01	.005
P_D, watts/cm^2:	9.45×10^9	3.25×10^{10}	1.03×10^{11}

Comparison of Tables 3 and 4 shows that radiation losses are not significant.

The simplest expression for thermal conductivity of a gas is

$$\kappa = \frac{k}{\pi d^2}\left(\frac{kT}{\pi m}\right)^{1/2}$$

where d is atomic diameter. For argon this gives, approximately

$$\kappa = 90 \text{ ergs/ cm sec deg}$$

$$= .9\times10^{-5} \text{ watts/cm deg}$$

For a temperature difference of 10^4 degrees across a gap of .005 cm, this gives a heat flux of 18 watts/cm^2. This too is much smaller than the rate at which work is done on the gas. Unless the above conductivity estimate is off by many orders of magnitude, conduction is ineffective in cooling the gas.

When argon flash gaps are used in shock experiments, the light output cuts off very abruptly. The reason is not known. The calculations of section five show that about 70 nsec elapse from the time gas temperature reaches 10^4 degrees until the plates are brought to rest. If the sapphire impactor remains transparent, illumination should continue until the gas subsequently cools by expansion. It appears that an intense light flash of about 70 nsec should be observed, and it might last twice this long. Use of lower impedance windows will reduce the time, as will thinner gaps and greater projectile velocities. The duration might be increased by introducing argon under pressure.

Some Useful Numbers for the Example of Section 4

m	$2.4\ g/cm^2$
P_o	$.265 \times 10^{-3}$ megabars
y_o	$.021$ cm
u_o	$.08$ cm/μsec
γ	$5/3$
$\gamma-1$	$2/3$
a	3.530×10^{-7}
e	$64.16 \times 10^{-4} = 6.414 \times 10^{-3}$
f	$10.59 \times 10^{-7} = 1.059 \times 10^{-6}$
u_o^2	
$y_o^{2/3}$	$.076116$
$y_o^{-2/3}$	13.1379
z_o	4.871×10^{-4}
$z_o^{1/2}$	$.02207$
$y_o^{5/3}$	1.59842×10^{-3}
$2f/e$	3.302×10^{-4}