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TITLE: VELOCITY REQUIREMENTS FOR ONE-DIMENSIONAL TARGETS

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VELOCITY REQUIREMENTS FOR ONE-DIMENSIONAL TARGETS

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ABSTRACT

A simple zero dimensional model which includes thermal conduction, Bremsstrahlung, compressional heating, alpha heating, and wall movement losses is used to estimate the velocity necessary for a fusion reactor based on impact fusion. Simple 1D impact and spherical 3D shock heating and compression are considered. The results are that an absolute minimum of 6E7 cm/s is needed for the 1D case while 0.85E7 cm/s is needed in the 3D case. However 7E7 cm/s and 1.3E7 cm/s respectively look like good operating points.

INTRODUCTION

The purpose of this paper is to give an estimate of the minimum velocity needed for a projectile which is to shock heat and compressionally heat, in a simple one-dimensional manner, a column of DT gas to temperatures and densities necessary for a fusion reactor. The same model will also be applied to spherical implosions. The physical phenomena taken into account in the 1D estimates are thermal conduction, Bremsstrahlung, compressional heating, alpha heating, and losses due to motion of the containing back wall. In the 3D estimate the same effects are included, however there is no back wall but compression ratios and transfer efficiencies are discussed. These calculations are of the temperature at the center of the plasma and analytic equations are used to estimate the rate of change of this temperature due to each of the physical effects. Thus, there is no zoning of the plasma and its pressure is assumed uniform and acts on a slug (or spherical shell) which is assumed to have a mass per unit area but no thickness. Its velocity is determined by F = ma and the initial velocity.

DISCUSSION AND RESULTS

A. General

The basic equation for the normalized rate of change of the temperature is as follows:

$$\frac{1}{T}\frac{dT}{dt} = -\frac{[3](\gamma-1)v_p}{x} + 2.75E{-}4\ f_\alpha n T^{-5/3}\exp(-211.1/T^{1/3}) - 3.2E{-}14\ n/T^{1/2} - \left[\frac{3}{4}\right]\frac{1.4E21}{\ell n\Lambda}\frac{T^{5/2}}{nx^2} \qquad (1)$$

The square bracket factors are needed when compression is 3D. The x which is the length of the plasma in 1D becomes the radius of the shell in 3D. T is in eV, n is in cm^{-3}, and v_p is the velocity of plasma compression. A γ of 5/3 is used in this calculation. The first term on the right is the compressional heating term. The second term is the alpha heating term.[1] Where f_α is the fraction of alpha energy being absorbed

$$f_\alpha \equiv \frac{<\ell>/\lambda_\alpha}{1 + <\ell>/\lambda_\alpha}.$$

Where $<\ell>$ = 4x Volume/Area and λ_α is the range of α particles given by Spitzer[2] due to energy absorption by only the electrons. The equation is good only for temperatures up to about 20 keV. The third term on the right is for Bremsstrahlung and is derived from the equation of Boyd and Sanderson.[3] The last term is the thermal conduction loss term. The coefficient of thermal conductivity of an unmagnetized plasma is given by Spitzer.[2] The term is found by considering a system of contained plasma with thermal conduction in only one direction. To get this equation one uses the fact that the pressure and its time derivative are uniform over the plasma and the density profile is time independent.

In the calculation the plasma's initial temperature is found by assuming that it is equal to that of the DT in a one-dimensional shock where the piston has the velocity of the imploding wall. The energy which is needed for shock heating is subtracted from the plug energy and the remaining velocity is the initial velocity for the calculation and is used to find the initial temperature. This temperature for DT is:

$$T_i = v^2/2.4E12 \qquad (eV, cm/s)$$

The final approximation is that the mass of the plasma is ignored.

Before discussing the methods of optimization for minimum velocity and the calculational results a discussion of Eq. (1) is in order. Multiplying it by x and rearranging yields:

$$[3] \ (\gamma - 1) \left| v_p \right| > \frac{C(t)}{y} + [B(T) - A(T)]y \qquad (2)$$

when

$$\frac{1}{T}\frac{dT}{dt} > 0,\ f_\alpha = 1,\ \text{and}\ y \equiv nx.$$

A(T), B(t) and C(T) are the Alpha heating, Bremsstrahlung, and thermal conduction temperature dependent parts. Note that the velocity requirement for a given T depends only on y which can be chosen to minimize the v_p requirement. However in the 1D case Bremsstrahlung is worse early in time since $B(T) \alpha 1/T^{1/2}$. This gives another velocity requirement namely

$$(\gamma - 1)\ \ v_p\ \ > B(T_i)y. \tag{3}$$

Since both C(T) and A(T) have strong temperature dependence they are negligible early in time. Thus Eq. (2) and (3) give the velocity requirement for achieving any given T in 1D. Besides the obvious factor of 3 in Eq. (2) another advantage of 3D compression is that the velocity requirements for both Bremsstrahlung and thermal conduction are greater at higher compression because y is time dependent in 3D. Thus, an optimum y can be picked for Eq. (2) further reducing the velocity requirements in 3D. Figure 1 shows the 1D velocity requirement as a function of temperature. In Fig. 1 the mass per unit area is infinite and hence it does not give information about Q. Q is the ratio of thermonuclear energy divided by the initial kinetic energy.

B. 1D Q Calculations

The fact that the back wall motion is included in these calculations adds a loss mechanism which does not depend on the nl product but more on nT. In these calculations the back wall moves according to:

$$p = \rho_o\ v_w\ (v_s + 4/3\ v_w)$$

where v_w is the wall speed and p is the plasma pressure. ρ_0 = 20 gm/cm^3 and v_s = 5.E5 cm/s. These are the density and sound speed of the wall material. The initial length of the system is set at 10 cm. The mass unit area and n are varied (20% stop size) to find the optimum Q for each velocity. The results are shown in Table I. Since fuel depletion is not calculated Q's over 100 are not accurate, but these calculations show when alpha heating dominates Eq. (1). Also shown in Table I is the minimum energy required to achieve the Q's shown. The table shows the initial Bremsstrahlung cooling time divided by the time needed to shock-heat the gas to its initial temperature. The fact that this ratio is about 1 shows that some cooling will occur during the shock heating process especially in the gas that is shocked first. Thus the actual initial temperature may be some lower than used in the calculation. However, if it is large enough to satisfy Eq. (3) then the plasma will heat and the same Q's will be achieved but with a larger compression ratio.

Figure 2 shows the plasma length, plasma temperature and Q versus time for the v = 7E7 cm/s case. It can be seen in Fig. 2 that the compresssional heating ignites the fuel and most of the energy is released during the expansion. The piston in this case has a mass of 0.86 gm/cm and an energy of 230 MJ/cm^2. The 1D system also has the other two undiscussed dimensions which can cause added thermal conduction losses. However, it appears that in the v = 7E7 case the diameter need only be about 1 cm so that radial thermal conduction losses even at L = 10 cm will be small compared to the compressional heating. The reason that the diameter can be this small is due to the strong temperature dependence of the thermal conduction. Thus, a copper slug for the 7E7 cm/s case could be 1 cm in diameter and 1 mm thick which is about the thickness of a penny and half as large in diameter.

In this example the total energy is rather large. However, the system can be made smaller provided that a) the values of y, the velocity, and mass per unit area are kept the same, b) the back wall movement doesn't rob significantly more energy, and c) the thickness of the slug does not exceed the final plasma length. The last condition is necessary for the model to be applicable and will be necessary for efficient transfer of liner energy into plasma energy in any case. This last condition puts the largest lower bound on the system size. Thus if the plug were tungsten then it could be 0.5 mm thick and the system could be made half as large in all dimensions giving a peak compression length of 0.6 mm which is acceptable. The area of the plug would be about 0.2 cm^2 with an energy of about 50 MJ.

C. 3D Q Calculations

The optimization in this case is done by varying y and the mass per unit area divided by y. The maximum Q for a given velocity is shown in Table II. The energy in the model thus far can be arbitrarily small but what is shown is from the following considerations. In order for the shell to efficiently transfer its energy to the plasma it cannot have a thickness much greater than the radius of the plasma. If its thickness is too great, it will transfer too much of its kinetic energy into its own internal energy. This is a consequence of the fact that the speeds involved here are well above the speed of sound in the shell material. From this we have that at peak compression

$$f_o \, \varepsilon \, \frac{1}{2} \rho_o v_i^2 = 3 \, n_f \, kT_f.$$

Here f_o is the ratio of shell volume to plasma volume and ε is the efficiency of transfer of shell energy to plasma energy. From this the initial energy in the shell can be written as

$$\begin{aligned} E &= f \, \frac{4}{3} \, \pi \left[\frac{3kT_f \; (n_f r_f)}{f \, \varepsilon \, \frac{1}{2} \rho_o \, v_i^2} \right]^3 \frac{1}{2} \rho_o \, v_i^2 \\ &= 35 \text{ E41}/v_i^4 \quad \text{(ergs)} \end{aligned} \tag{4}$$

where $n_f r_f$ is the final value of 3E22/cm^2. T_f is 4000 eV, ρ_o is 20, and v_i is the initial shell velocity. Values from Eq. (4) are shown in Table II when $f_o = 7$ and $\varepsilon = 1/4$.

Another consideration is that radial compression ratio limitations also limit the minimum velocity. Figure 3 shows the velocity requirements necessary for each compression ratio. It seems that a good velocity would be 1.3E7 cm/s. It will give a high Q for a modest amount of shell energy while requiring a radial compression of about 20:1.

CONCLUSION

It appears that a projectile with an energy of 50 MJ and a velocity of about 7E7 cm/s will be required for simple 1D impact fusion and that an imploding shell of about 12 MJ at a speed of 1.3E7 cm/s could be used for a 3D implosion. In 1D the velocity is much higher but the geometry is simpler. The ability to achieve high velocities compared to the ability to produce symmetrical 3D implosions will determine which geometry is most desirable.

REFERENCES

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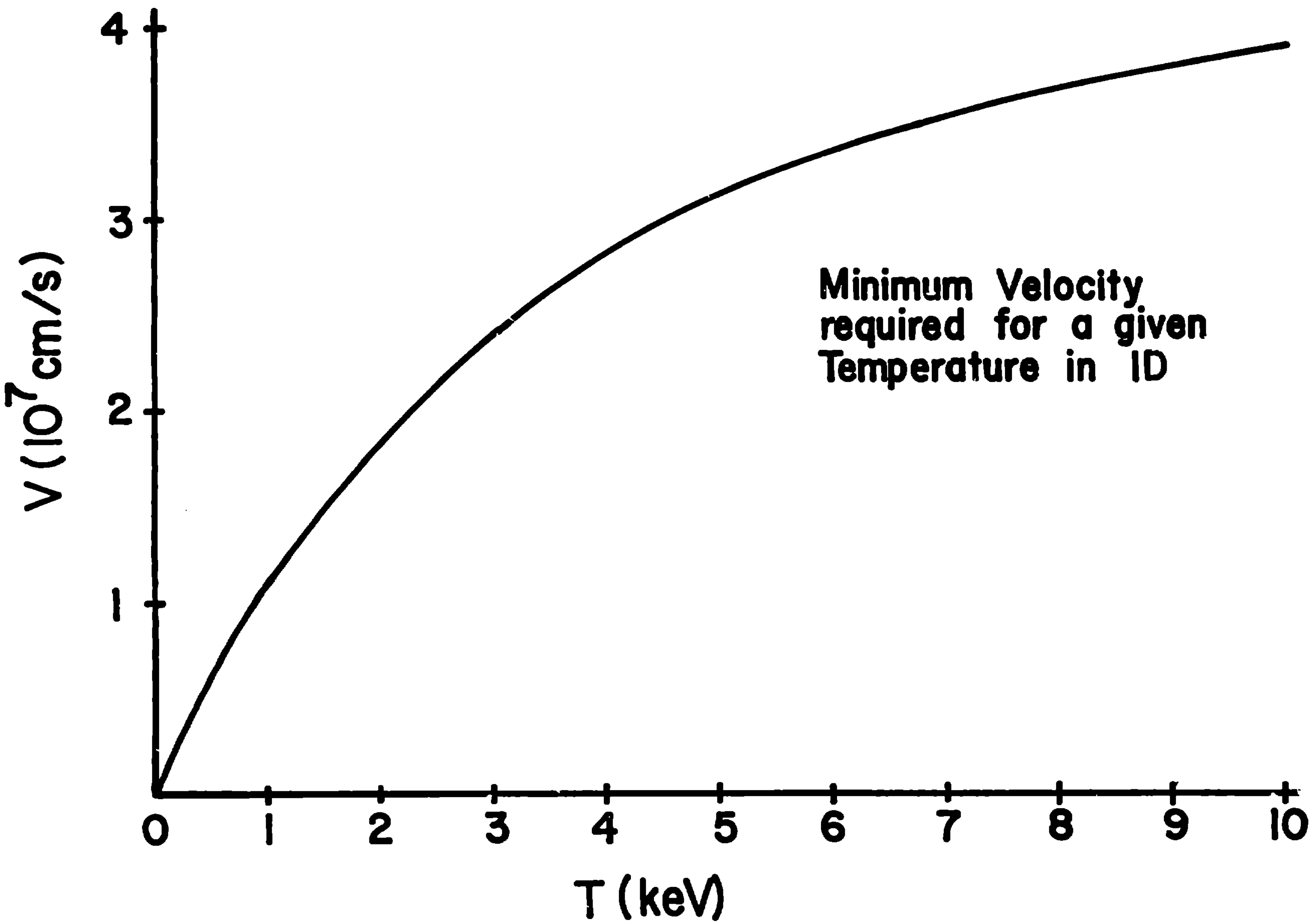

Fig. 1. Minimum impact velocity in 1D needed to achieve a given temperature.

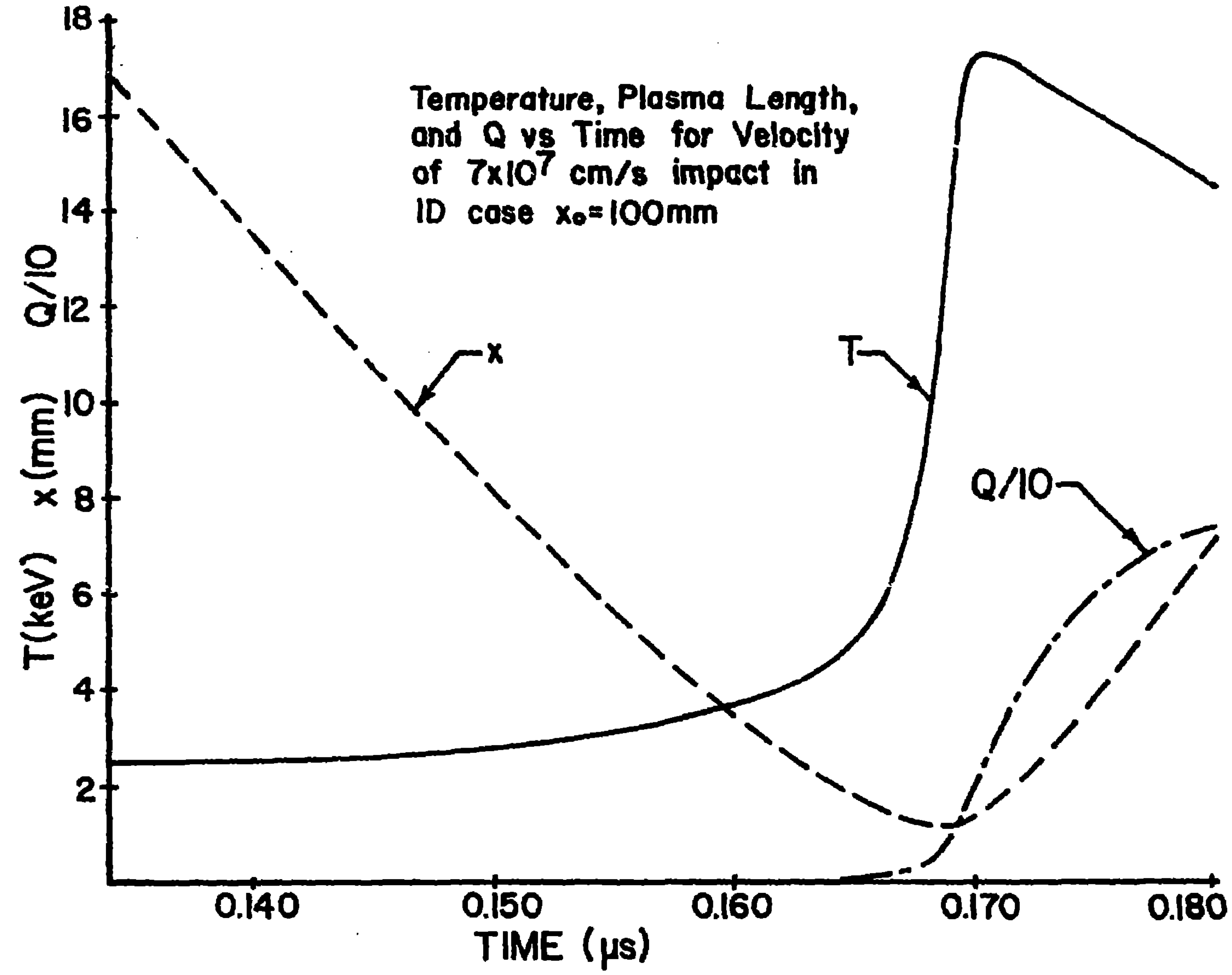

Fig. 2. Plasma length, temperature, and Q vs time for the 1D impact in the 7E7 cm/s velocity case of Table I.

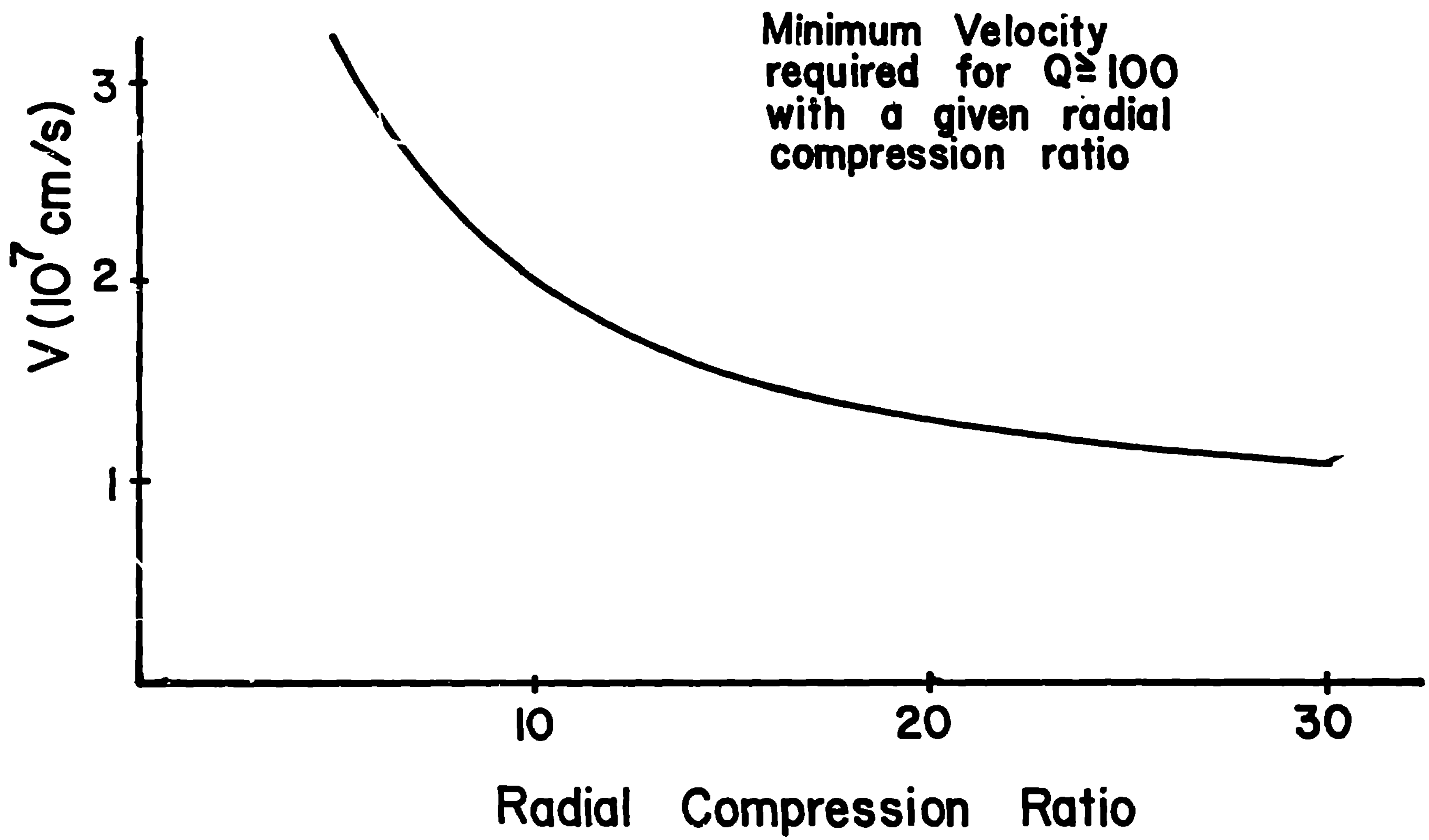

Fig. 3. Minimum velocity requirements as a function of the maximum allowable compression ratio to achieve $Q \geq 100$ in 3D compression.

TABLE I

Optimum parameters for 1-D impact

Velocity	$T_{INITIAL}$	Q	$\frac{MJ}{cm^2}$	$\frac{mass}{cm^2}$	nx	Initial $\frac{\tau_{BREM}}{\tau_{SHOCK\ HEAT}}$
1×10^7	41eV	.000007	1.1	.22gm	$6.7\times10^{20}cm^{-2}$	1.0
2×10^7	160	.0021	8.0	.40	2.6×10^{21}	1.0
3×10^7	360	.028	26	.58	5.0×10^{21}	1.2
4×10^7	640	.15	69	.84	8.7×10^{21}	1.1
5×10^7	1000	.64	150	1.2	1.5×10^{22}	1.1
5.5×10^7	1200	2.5	630	4.2	2.4×10^{22}	.82
6×10^7	1500	>100	1100	6.0	3.4×10^{22}	.71
6.5×10^7	1600	>100	360	1.7	3.6×10^{22}	.75
7×10^7	1800	>100	230	.96	3.6×10^{22}	.86
8×10^7	2100	>100	190	.60	4.1×10^{22}	.93
9×10^7	2400	>100	170	.43	4.5×10^{22}	1.0
10×10^7	2600	>100	150	.30	4.3×10^{22}	1.2

TABLE II

Optimum parameters for 3-D impact

Velocity	$T_{INITIAL}$	Q	Energy (MJ)
$.5\times10^7$	10eV	.010	--
.6	15	.029	--
.7	20	.068	--
.8	27	.15	--
.85	30	>100	67
.9	34	>100	54
1.1	50	>100	24
1.3	60	>100	12
1.5	81	>100	6.9
2.0	167	>100	2.2
3.0	375	>100	.43
4.0	667	>100	.014