# A HIGH-POWER WINDOWLESS GAS TARGET*

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A high density free-jet has a combination of properties that lend themselves well to the design of a high efficiency, high power beam target. We discuss below one possible application of a free jet target--a 14.2 Mev neutron source with $10^{14}/cm^2$ sec surface flux.

## A. Introduction

This design of a high-power windowless target is motivated by questions raised in a study of the feasibility of using controlled thermonuclear (D-T) fusion as the heat source for the economical generation of electrical power.[1] These studies show that the plasma density and temperature will be limited by the total radiant and particulate flux at the surface facing the plasma at a point that corresponds to a 14.2 Mev neutron flux of $10^{14}/cm^2$ sec. For these conditions, a reasonable reactor lifetime (10 to 20 years or so) requires that the vacuum interface maintain its structural integrity for a cumulative fast neutron dose of $> 10^{22}/cm^2$. Because present theories of radiation damage cannot be reliably extended to predict material property changes at this dose level, we would like to determine experimentally the effects of intense 14.2 Mev neutron radiation. This requires a continuously operating neutron source of at least $10^{15}$/sec with small spatial extent ($\sim 1\ cm^3$). The particular target design to be discussed here is designed for use with a relatively low energy ($\sim 250$ kev), high current ($\sim 1$ amp) tritium ion beam, but the efficiency and power handling capacity of the target make its use interesting for higher energy, lower current beams as well.

D-T neutron sources usually consist of a $D^+$ ion beam incident on a tritium bearing target. The targets may be either a gas-loaded solid (e.g., Ti over Cu) or atmospheric density $T_2$ gas confined by a thin (30μ) "window". The window serves the dual purpose of confining the gas and maintaining a low pressure in the beam tube and accelerator. The solid targets provide a localized source, but suffer from two severe disadvantages:

(i) They are very inefficient as measured by fusions/incident ion. The $D^+$ ions lose most of their energy to the high Z materials that must be used in the target.

(ii) They have very low power handling capacity. The adsorbed gas is boiled from the surface at relatively low temperatures.

The disadvantages of the gas target are inherent in the use of a window which introduces similar disadvantages:

(i) They are inefficient as measured by $D^+$ injection energy/$D^+$ reaction energy. In a typical target with a 30μ thick Al window, one must produce a 2.3 Mev beam to ensure that the ions possess 110 kev energy corresponding to the peak of the fusion cross section after traversing the window.

(ii) They have very low power-handling capacity, because the window must be thin, unsupported, cooled from only one side, and yet must withstand almost one atmosphere differential pressure.

Obviously, it is desirable to find some means of generating a high gas density gradient without the use of a window. Transonic and hypersonic flows allow the generation of such gradients.

## B. Free-Jet Expansion

The flow of gas through a nozzle is described in the one-dimensional approximation by the well-known area relationship[2]

$$\left(\frac{A}{A^*}\right)^2 = \frac{1}{M^2}\left[\frac{2}{\gamma+1}\left(1+\frac{\gamma-1}{2}M^2\right)\right]^{(\gamma+1)/(\gamma-1)} \tag{1}$$

where M is the Mach Number, $\gamma$ the ratio of specific heats, A the cross-sectional area of the flow, and $A^*$ the area corresponding to sonic flow. In a supersonic nozzle, $A^*$ is the throat area.

Eq. (1) is double-valued for all values of $A^*/A$. (See Fig. 1.) The upper branch is followed if the flow in the throat of the nozzle attains sonic velocity. Once sonic velocity is reached in the throat, downstream pumping can have no further effect on upstream conditions. Thus the flow is always exactly sonic at the throat and is accelerated in the expanding section of the duct. Because the gas density is inversely proportional to duct area and flow velocity, the sharpest gradient is attained by the most rapid possible expansion of the cross-section downstream of the nozzle. The limiting case of rapid expansion is reached by allowing the gas to stream from a sharp edged orifice into a vacuum. Eventually, the stream will be so expanded that the internal pressure falls below the ambient pressure. Although the expansion through the nozzle is isentropic, it can be shown that it is thermodynamically impossible for the over-expanded jet to return to ambient pressure in a reversible fashion. Thus, the pressure recovery is accomplished in the so-called "normal shock". The external dynamics of free-jet expansion have been extensively studied. Figure 2 illustrates such an expansion. We will be concerned with higher expansion ratios--corresponding, for example, to one torr ambient pressure for atmospheric density in the throat. The jet velocity in Fig. 2 reaches a velocity corresponding to M = 5.0. The velocity is, of course, subsonic after the shock.

It appears, at first, that the normal shock itself contains density gradients steep enough for use in a target, but the Rankine-Hugoniot relations for the density ratio, $\rho_2/\rho_1$, across the shock yield

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma+1)M^2}{(\gamma-1)M^2 + 2} \qquad (2)$$

For a normal shock in diatomic gases, the density ratio across the shock is, at most, 6.0. This is not large enough for our purposes although some possibilities exist in the combination of directed flow upstream of the shock with the moderate density jump across the shock itself. The behavior in the transonic region near the sonic line is more complicated, primarily because of the analytic complexity of the defining equations in this region, but some of the major features are known for the case of zero energy addition. In particular, the transition region is narrow and roughly parabolic in shape. The sonic line density is known in terms of the reservoir conditions.

C. Free-Jet Expansion Target

We propose to inject a $T^+$ ion beam upstream into the throat of a freely-expanding $D_2$ gas jet whose reservoir conditions are so adjusted that the gas density at the sonic line after deposition of the beam energy is $3 \times 10^{19}/cm^3$. This density is sufficient to stop a 230 kev tritium beam within 0.6 cm and will, with a 1.0 amp. beam, satisfy our original requirements on intensity and active volume. The results of two representative computations are shown in Figs. 3 and 4. The exterior pressure in both cases is low enough to allow for operation of a beam tube with minimal differential pumping. The beam energy was chosen by using the criterion that the tritium energy at the sonic line be 230 kev, the energy corresponding to the maximum fusion cross section. Note that very little energy is lost in traversing the supersonic region of the flow by virtue of its extremely low density. The nozzle diameter, 2.0 cm, was chosen on the basis of several considerations--it must be large enough to furnish a reasonable target for a high current beam, and the total gas flow through the orifice must be large enough so that the temperature of the gas is not raised inordinately.

The conditions noted in Fig. 3 correspond to a maximum flow velocity of M = 9 and a mass flow rate of 32 g/sec. The beam energy divided by the mass flow rate predicts a gas temperature at the sonic line of $T = 2600^\circ K$, but this temperature will be reduced somewhat by dissociation of the gas. This high temperature serves quite a useful purpose in driving the expansion, because the sonic velocity varies at $T^{1/2}$. The bulk of the beam energy is not removed in the nozzle, but rather when the beam is slowed and recompressed. If the recompression takes place gradually, the energy may be removed through a much larger surface area than that of the nozzle with resulting very high power handling capacity.

D. Preliminary Target Design

A rough sketch of the proposed target is shown in Fig. 5. The diameter of the vacuum chamber is chosen large enough so as not to impede the expansion.

A large saving in the power necessary to operate what is effectively a Mach 9 hypersonic wind tunnel can be made by using a supersonic diffusor to recompress the gas in the stream and thus to reconvert its directed motion into pressure. This serves the dual purpose of reducing the pressure ratio across the pump (and thus reducing the pump work) and reducing the required low pressure pump speed. A practical fixed orifice diffusor will lead to an overall tunnel pressure ratio, $\lambda$, of $\sim$ 100. An adjustable throat diffusor would improve this ratio to $\sim$ 50, but it is probably best to avoid moving parts in the high radiation environment near the target. In terms of the throat area, $A^*_o$, stagnation pressure $p_o$, pressure ratio, $\lambda$, and stagnation sound speed, $a_o$, the power required to operate the tunnel (neglecting mechanical losses in the compressor and associated systems) is[3]

$$P = \frac{\gamma}{\gamma-1}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} p_o a_o A^* \left(\lambda^{\frac{\gamma-1}{\gamma}} - 1\right) \quad (3)$$

For the example of Fig. 5, the requisite, thermodynamic minimum, tunnel power is 300 kw which may be compared to the ion beam power of 230 kw. The system shown has not been optimized with respect to total power or cost, and it is reasonable to assume that substantial savings could be made--most probably by operating under conditions of lower pressure ratio and higher beam energy.

The tritium input rate for 1.0 amp beam current is $10^{-6}$ that of the deuterium atom flow rate through the nozzle. The tritium contaminant in the flow gas could be held at constant level by complete isotopic separation of a $10^{-4}$% side arm of the return flow to the compressor.

## E. Unresolved Problems

We have not yet computed in detail the effects of thermal dissociation of $D_2$ in the nozzle, thermal choking of the flow nor the effect of volumetric heat addition to the shape and gradient scale of the sonic line. It is a relatively simple matter to put upper bounds on the changes resulting from the first two considerations, but the detailed structure of the trans-sonic region must await the numerical solution of the integro-differential equation describing the development of the flow. The major source of difficulty stems from the fact that the addition of entropy by the beam leads to vorticity, and the flow can no longer be described by the simpler irrotational flow theory. The problem is further complicated by the fact that the upstream boundary conditions are known for the $D_2$ flow, but only the downstream conditions are fixed for the tritium beam. Our understanding of the first two phenomena listed is summarized below.

Thermal Dissociation. The energy input represented by the tritium beam is large enough so that, neglecting the energy of dissociation or excitation of the vibrational levels of the deuterium molecules, the exit temperature would be raised to temperatures high enough that $D_2$ dissociation would become an important consideration. The gas would be completely dissociated with resulting undesirable decrease in $\gamma$. In fact, the dissociation process serves as an energy sink with the result that the exit temperature is limited to 2500°K. This number is based on the assumption of local thermodynamic equilibrium in the nozzle and represents the worst possible situation.

Thermal Choking. It is well known to gas dynamicists that the additions of relatively small increments of energy to gas flowing in a channel can lead to very large reductions in the gas flow rate ("choking"). This arises from the requirement that the flow satisfy simultaneously momentum and energy conservation conditions during the addition of only one of these entities. In our case, the energy addition will take place at the duct exit which allows the system an extra degree of freedom. The net effect, based on the example of arc-heated hypersonic wind tunnels, will be that the reservoir pressure might need to be increased from one to three or four atmospheres to yield the desired exit conditions. This change will not be of great consequence, because the high pressure gas pumps need have relatively small volumetric capacity.

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References

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2. H. W. Liepmann and A. Roshko, Elements of Gas Dynamics, John Wiley and Sons, Inc. (1957), p. 126.

3. Ibid., p. 139.

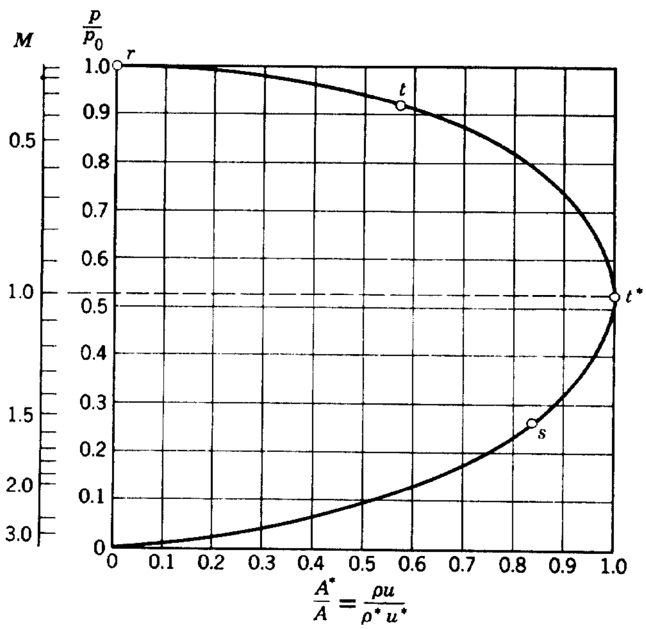
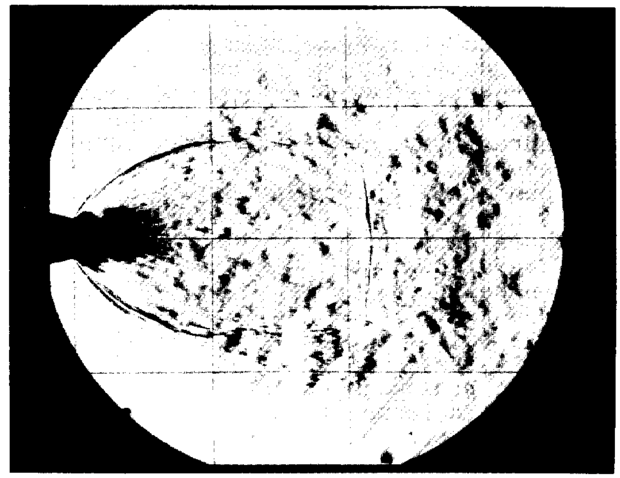



Fig. 1. Velocity as a function of normalized nozzle area for isentropic flow in the one-dimensional approximation. The flow in the expanding region of the nozzle is described by the lower half of the curve if sonic conditions are reached in the throat. (Ref. 2.).



(f) $M_j = 1.0$; $\theta_N = 0°$; $p_j/p_\infty = 87.7$.

Fig. 2. Free jet expansion at moderate pressure ratio. The light dots outlining the flow are computed jet boundaries. (NASA Technical Note D-2327).

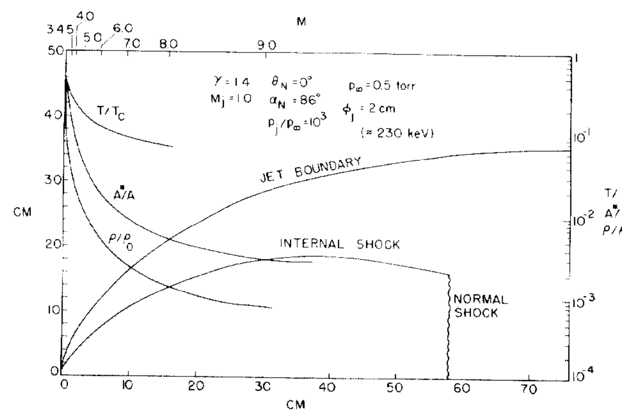



Fig. 3. Flow field for a freely expanding jet from a sonic nozzle ($M_j = 1.0$) of 2 cm. diameter ($\phi_j$ = 2 cm) and a pressure ratio, $p_j/p_\infty$, of $10^3$. The left hand scale refers to the flow field boundary dimensions; the right hand scale to the gas properties normalized to the values at the nozzle. The required ion beam energy is ~ 230 kev.

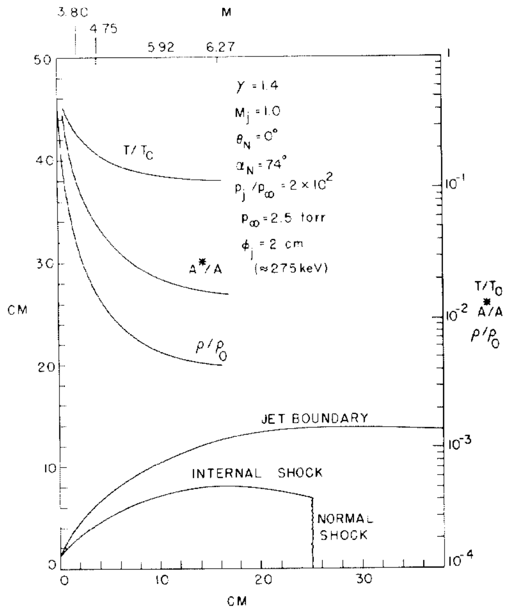



Fig. 4. The flow field for a pressure ratio, $p_j/p$ , of $2 \times 10^2$. Note that the beam energy in this case is ~ 275 kev.

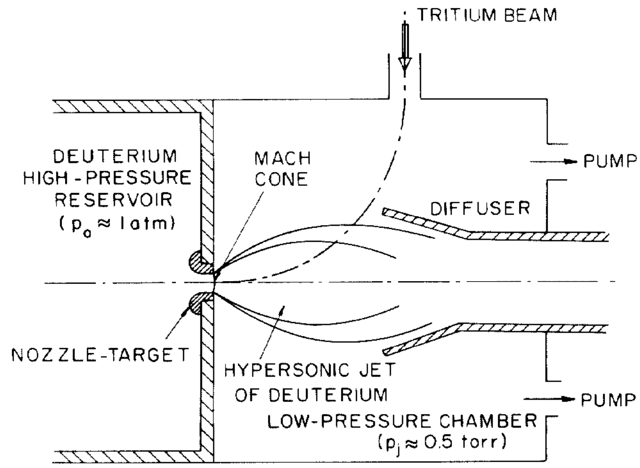



Fig. 5. Highly schematized configuration of a free-jet target. For the conditions used in computing Fig. 3 the nozzle to diffuser distance ~ 50 cm, and the diameter of the low pressure chamber ~ 100 cm.