29 ti
25 c/ps
717

UCRL - 76858
PREPRINT
CONF-750723--15

LAWRENCE LIVERMORE LABORATORY
University of California / Livermore, California

A HEAVY WATER JET TARGET AND A BERYLLIUM TARGET FOR PRODUCTION OF FAST NEUTRONS

C. M. LOGAN, J. D. ANDERSON,
H. H. BARSCHALL AND J. C. DAVIS

JULY 1, 1975

THIS PAPER WAS PREPARED FOR SUBMISSION TO
INTERNATIONAL CONFERENCE ON RADIATION TEST
FACILITIES FOR THE CTR SURFACE AND MATERIALS PROGRAM
ARGONNE NATIONAL LABORATORY ERDA - JULY 15-18, 1975

A HEAVY WATER JET TARGET AND A BERYLLIUM TARGET FOR PRODUCTION OF FAST NEUTRONS

C. M. Logan, J. D. Anderson, H. H. Barschall, and J. C. Davis

Lawrence Livermore Laboratory
Livermore, California 94550, U.S.A.

ABSTRACT

A limitation on the neutron flux obtainable from proton or deuteron induced reactions is the heating of the target by the accelerated charged particles. The heat can be removed more easily if the target moves. We have investigated the possibility of using a rotating Be target and a heavy water jet as a target for bombardment by 35-MeV deuterons. In a thick Be metal target moving at 10 m/sec through such a beam of 1 cm diameter a temperature pulse of about 300°C will be produced by the 0.3 MW beam. The Be target should be able to withstand such a temperature pulse. A Be target suitable for 3 MW of power in a 1 cm diameter beam would require internal cooling and a higher velocity. A free jet of heavy water is also a possible target. Laser photographs of water jets in vacuum show small angles of divergence. The effect of heating by a 0.3 MW beam is probably not important because the temperature rise produced by the beam is small compared to the absolute temperature of the unheated jet.

INTRODUCTION

Existing or proposed neutron sources for the CTR materials research program use reactions induced by accelerated hydrogen isotopes. Heating caused by slowing down of the charged particles in the targets of these sources limits the obtainable neutron flux. The allowable power density can be increased if the target moves so that heat is removed from the reaction zone by mass transport as well as convection and conduction. The acceptable temperature depends on the target system. Solid tritides must be kept to relatively low temperatures to prevent decomposition of the compound and diffusive loss of the tritium. Jet systems are generally limited by the stability of the jet. A molten lithium metal or lithium compound target is limited by the stability of the flow and by the acceptable surface vaporization rate. A beryllium target is limited by temperature and stress induced by temperature gradients. This paper describes targets for neutron production by the reactions of deuterium with D_2O and Be.

NEUTRON SPECTRUM

In order to provide a spectrum similar to that on the first wall of a fusion reactor, one can use instead of the D-T reaction the reaction of high energy deuterons with other light nuclides. The targets that appear most suitable both on the basis of ease of preparation and cooling and on the basis of neutron yield are deuterium and beryllium. For a deuterium target a jet D_2O water is considered in this paper, and for beryllium, a metal wheel. We have in addition considered a beryllium metal target with internal D_2O water cooling. The spectrum of neutrons from the deuteron bombardment of a thick Be target has recently been measured by Meulders [1] et al. Their results for a bombarding energy of 33 MeV are shown in Fig. 1. The most probable neutron energy is near 14 MeV. The yield of neutrons of energy greater than 4 MeV is 2.8×10^{-11} μC^{-1} sr^{-1}. The yield of neutrons from the deuteron bombardment of D_2O would be somewhat lower than this value. The spectrum of neutrons from energetic deuterons on a thick D_2O target is not well known, but an extrapolation from lower energies indicates that energetic deuterons on D_2O will produce neutrons with slightly higher average energy than deuterons on beryllium.

It is difficult to compare radiation damage from the d + Be neutrons with that in a fusion reactor because of the lack of knowledge of nuclear cross sections. We have carried out calculations of the effect on Nb of neutrons from the bombardment of a thick Be target by 20-MeV deuterons. For this spectrum, the primary recoil spectrum is deficient in recoils of low energy and extends to slightly higher energies than for the first wall of a fusion reactor. For higher energy deuterons the recoil spectrum will extend to even higher energies. Although pertinent (n, α) cross sections are not well known, we estimate that neutrons from 35-MeV deuterons incident on Be will produce more helium per displaced atom that neutrons at the first wall of a fusion reactor.

ROTATING Be TARGET

We have studied the expected behavior of a rotating Be wheel under bombardment by 8.6 mA and 86 mA of 35-MeV deuterons. In order to stop the deuterons the Be target must be 5 mm thick. We have chosen for this analysis a 1 g/cm^2 thick disk and have calculated the temperature transients produced by the beam in the rotating target. The calculations used the TRUMP [2] computer program with temperature-dependent specific heat and thermal conductivity [3] as shown in Fig. 2. We assumed no heat removal. An initial temperature of 300°C was used.

The deuteron beam was assumed to be cylindrically symmetric with a Gaussian profile. The energy deposited in an element of the target as it moves through the beam is proportional to the total beam power and inversely proportional to both the beam diameter and the linear velocity of the target element.

The energy deposition by 35-MeV deuterons as a function of depth in Be is shown in Fig. 3. The values near the end of the range, i.e., below 3 MeV include the effect of straggling. As a result of straggling, the maximum linear energy transfer by the beam occurs when the average deuteron energy is

2 MeV and it is half that of a deuteron at an energy of 2 MeV. For the calculation the target was divided into 100 layers of 54 μm thicknesses; the deuterons stop before the eighty-second layer.

Calculations were carried out for the following three cases:

Case	Beam Diameter (FWHM) (cm)	Beam Power (MW)	Linear Target Velocity (m/s)
(a)	1	0.3	10
(b)	10	3	10
(c)	10	3	100

The calculations showed that in all cases the depth at which the highest temperature is reached is slightly closer to the surface of entry than the depth of maximum energy deposition. Fig. 4 shows a plot of the temperature versus logarithm of time for the element reaching the highest temperature for case (a). For case (b) the highest temperature is 475°C and for case (c) 330°C.

The target could be cooled by circulating water behind it. The highest beam power density occurs in case (a), i.e., 0.27 MW/cm^2. If the deuteron beam is incident at a radius of 0.5 m from the axis of target rotation, the time averaged heat flux at this radius is 0.85 kW/cm^2. There is no problem in removing this heat by cooling water. This heat flux is comparable to that in the rotating tritium target which has been in use at this laboratory for some time.

Stress on the rotating target wheel caused by centrifugal forces is very small compared to the tensile strength for the 10 m/s case, and even at 100 m/s the tensile strength is at least an order of magnitude greater than the stress. The stress resulting from thermal gradients was estimated by assuming that the beam produced an elliptical heated area on a flat plate. The area was assumed elliptical rather than circular to take into account the rotation of the target. The eccentricity was assumed to be 0.5, and the temperature of the ellipse was taken to be 285°C above the unheated part of the plate. The resulting stress at the tip of the ellipse would be 600 MPa (86 ksi), which is higher than acceptable. A more realistic calculation will result in a reduction of the stress, but this calculation has not yet been performed.

ROTATING Be AND D_2O TARGET

Instead of cooling the back side of the rotating Be target, the cooling water could be circulated inside the Be. A similar internally cooled target made of copper has been designed and tested for use as backing for a tritium target. The large heat transfer coefficient and channel surface area in this design permits the use of a smaller target diameter. Internal cooling at the end of the deuteron range would move the temperature spike into the water and would eliminate the problem caused by deuteron implantation in the Be. If D_2O were used as a coolant instead of H_2O the neutron yield would be increased.

A section through a possible target is shown in Fig. 5. Water would flow radially outward through 0.5 mm wiggly channels picking up heat by direct deposition and by forced convective transport from the Be. Coolant would be returned through the larger channel picking up additional heat and deposited deuterium. In order to calculate the temperature in the Be, a two-dimensional geometry with 132 elements was used. Surface heat removal was included by using a surface heat transfer coefficient of 17 W/cm^2 °C, a value we have measured in similar channels. Water in the small channels was at 100°C while that returning in the larger channel was at 200°C. The variation of temperature with time was calculated for a section of the target moving with a linear velocity of 100 m/s at a radius of 0.16 m. This corresponds to a rate of rotation of 6000 rpm. The heating pulse from the beam was repeated for successive target revolutions until the temperature cycle repeated. For a power of 3 MW and a beam diameter of 1.0 cm (FWHM), the following temperatures were found: maximum temperature in the target = 365°C; temperature variation of target elements ≃ 100°C; maximum temperature difference through the thickness of the target at any point in the cycle = 95°C.

A D_2O JET

The use of the d + D reaction as an intense source of high energy neutrons has the difficulty that there does not appear to be any pure deuterium target available in which the required beam power can be dissipated and in which the deuterons can be stopped in an acceptable distance. For this reason we have considered the possibility of employing a free-standing jet of heavy water as a target for bombardment by energetic deuterons.

Since the beam transport system must be under vacuum, it would be desirable for the region surrounding the jet to be at low pressure. We have measured the pressure in a chamber through which a jet of ordinary water was injected at velocities up to 300 m/s. An opening in the chamber permitted the jet to exhaust into an effluent pipe which was open to the atmosphere. Sufficient pumping effect is provided by the passage of the jet through the chamber to reduce the chamber pressure to the vapor pressure of the water at inlet temperature (~ 9 mm Hg). By pumping on the chamber with a 4 l/s mechanical pump the pressure could be maintained at 670 Pa (5 mm Hg), the vapor pressure of water at 0°C.

We have photographed the jet in vacuum flowing at different rates. At low velocities the flow is laminar. Fig. 6 shows a 2 mm diameter jet flowing at 0.5 m/s. Fig. 7 is a 20 ns exposure of a jet flowing at 200 m/s and having a diameter of 2 mm. The angle of divergence of the jet increases slowly with increasing Reynolds number but remains below 3° included angle for all velocities tested. The driving forces tending to expand the jet are vapor pressure, surface interactions and turbulence. Jets in vacuum diverge less than the same velocity jet in air at one atmosphere. No observable change in divergence occurs as a result of varying inlet temperature between 10°C and 20°C. Jet turbulence seems to be the major influence on the angle of divergence. This is particularly noticable in our tests with 1 cm diameter jets.

We have considered the effect of a 0.3 MW beam of 35-MeV deuterons on a jet with a rectangular cross section 1 cm X 2 cm and flowing with a velocity of 300 m/s. The beam is assumed to be normal to the 2 cm face of the jet and to have a Gaussian profile with a diameter of 1 cm (FWHM). Deuterons of this energy have a range of about 0.7 cm. In the 67 μs required for the water to traverse the deuteron beam (2 X FWHM), heat is conducted through only 6 μm, based on the thermal diffusivity of 1.2 X 10^{-7} m^2/sec for heavy water. This distance is small compared to the width of the Bragg peak so that conduction during the transit time can be neglected. The maximum temperature increase in the temperature of the jet occurs at the depth of the Bragg peak. If straggling is taken into account, the largest rate of energy loss of the deuteron beam is 18 MeV/mm. For a 0.3 MW beam this produces a temperature rise of 26°C in a jet flowing 300 m/s. This actual maximum temperature increase will be smaller than this value because of mixing with cooler water on either side of the zone of maximum energy deposition. The average temperature rise in the water will be much smaller. For the 300 m/s jet the flow is 0.06 m^3/s and the average temperature increase produced by 0.3 MW will be ~ 1°C.

The pressure required to drive the jet at 300 m/s is 45 MPa (7 ksi) and the power required for 2 cm^2 area is 2.7 MW. This power will be converted to heat in the collection system. Fig. 8 shows how the jet velocity and power vary with supply pressure.

SUMMARY

Neutrons from the reaction of deuterons with Be and D_2O appear useful to the CTR materials program. Targets which would utilize 0.3 MW of 35-MeV deuterons to produce a neutron source with dimensions on the order of 1 cm appear feasible. Such targets which would dissipate 3 MW could probably be developed. For larger diameter beams even larger powers could be utilized. In addition to the applications considered in the text, the possibility exists that a jet of D_2O might also be used as a target to neutrons using the D (t,n) reaction.

ACKNOWLEDGMENTS

Rex Booth suggested considering heavy water coolant channels in a Be target. Chet Singleton designed the jet testing apparatus.

This work performed under the auspices of U.S. Energy Research and Development Administration.

REFERENCES

1. J. P. Meulders et al, "Fast Neutron Yields and Spectra from Targets of Varying Atomic Number Bombarded with Deuterons from 16 to 50 MeV," *Phys. Med. Biol.*, 20, 235 (1975)

2. A. L. Edwards, "TRUMP: A Computer Program for Transient and Steady-State Temperature Distributions in Multidimensional Systems," USAEC Rep. UCRL-14754, Lawrence Livermore Laboratory (1972)

3. A. L. Edwards, "A Compilation of Thermal Property Data for Computer Heat-Conduction Calculations," USAEC Rep. UCRL-50589, Lawrence Livermore Laboratory (1969)

Fig. 1 The neutron spectrum and yield at 0° from 33-MeV deuterons incident on Be from Ref. 1.

Fig. 2 Thermal conductivity and specific heat of Be as used in temperature calculations.

Fig. 3 Energy loss versus depth for a beam of 25-MeV deuterons incident on Be. The step variation plotted was used for the calculations and is an approximation of the actual smooth curve.

Fig. 4 Temperature of the hottest point in a thick Be target passed through a 0.3 MJ beam of 35-MeV deuterons with a diameter of 1 cm (FWHM).

Fig. 5 A section through an internally cooled Be target.

Fig. 6 Laminar flow water jet in vacuum.

Fig. 7 Turbulent water jet in vacuum.

Fig. 8 The effect of supply pressure on jet velocity and power for a frictionless incompressible fluid. The power is per dm^2 of jet cross section.

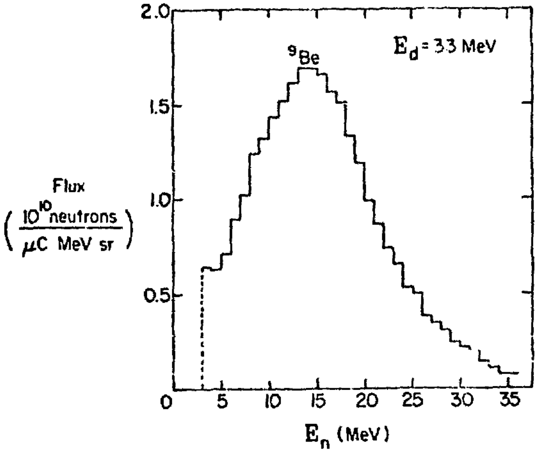
2.0
1.5
1.0
0.5
0
5
10
15
20
25
30
35
Flux
$\left(\frac{10^{10}\text{neutrons}}{\mu\text{C MeV sr}}\right)$
E_n (MeV)
^{9}Be
E_d = 33 MeV

Fig. 1

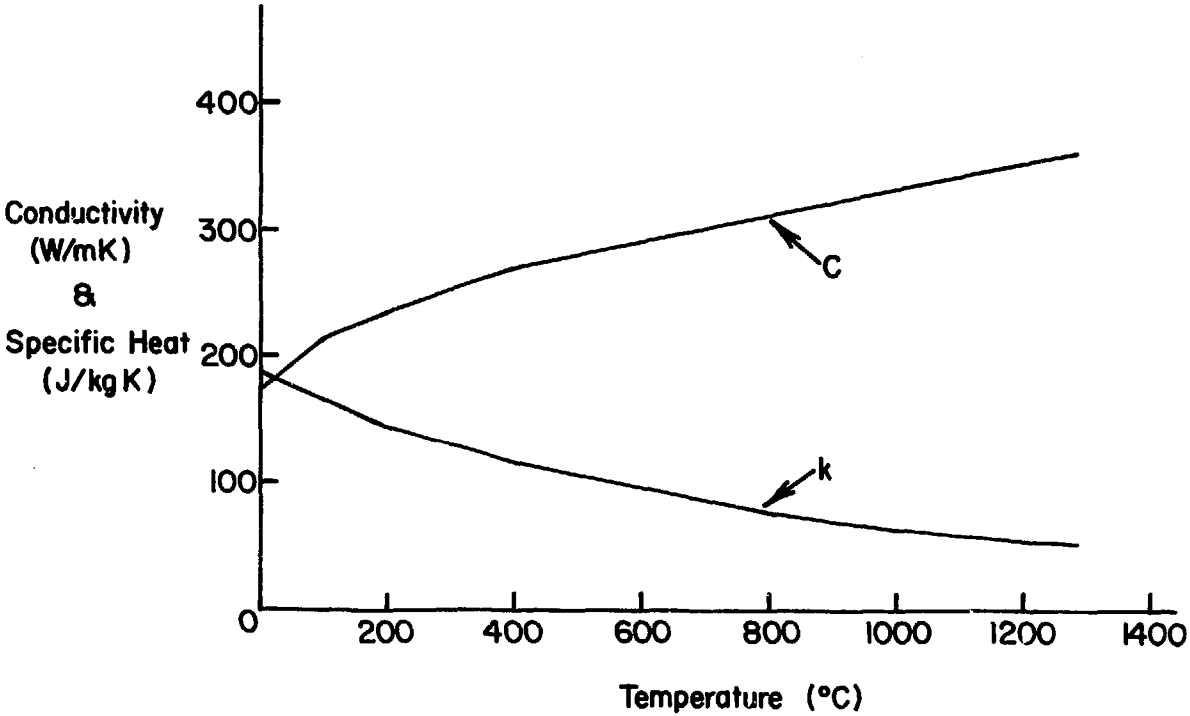
Conductivity (W/mK)
&
Specific Heat (J/kg K)
400
300
200
100
0
200
400
600
800
1000
1200
1400
Temperature (°C)
C
k

Figure 2

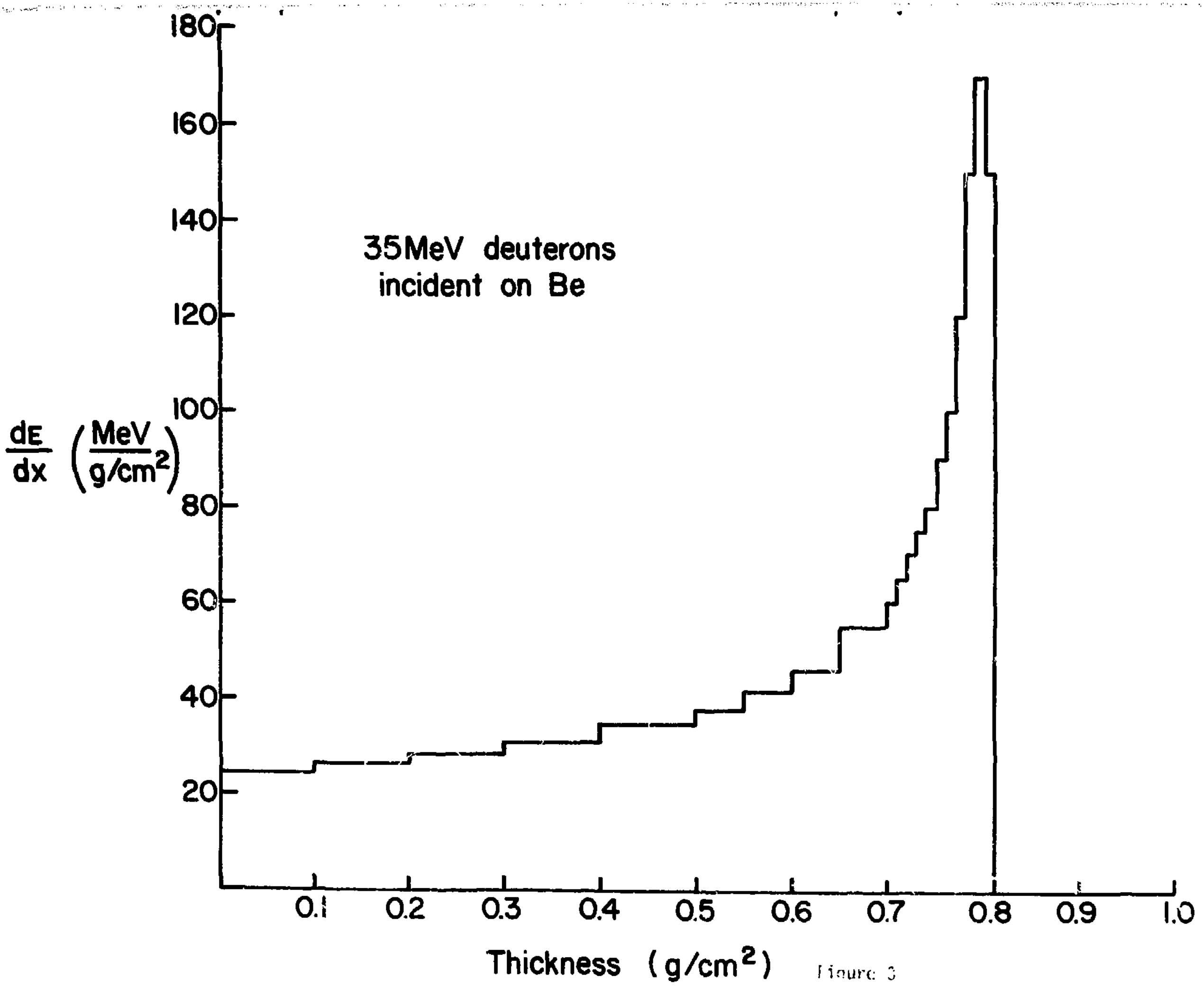
35MeV deuterons
incident on Be
$\frac{dE}{dx}$ $\left(\frac{MeV}{g/cm^2}\right)$
180
160
140
120
100
80
60
40
20
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Thickness (g/cm^2)

Figure 3

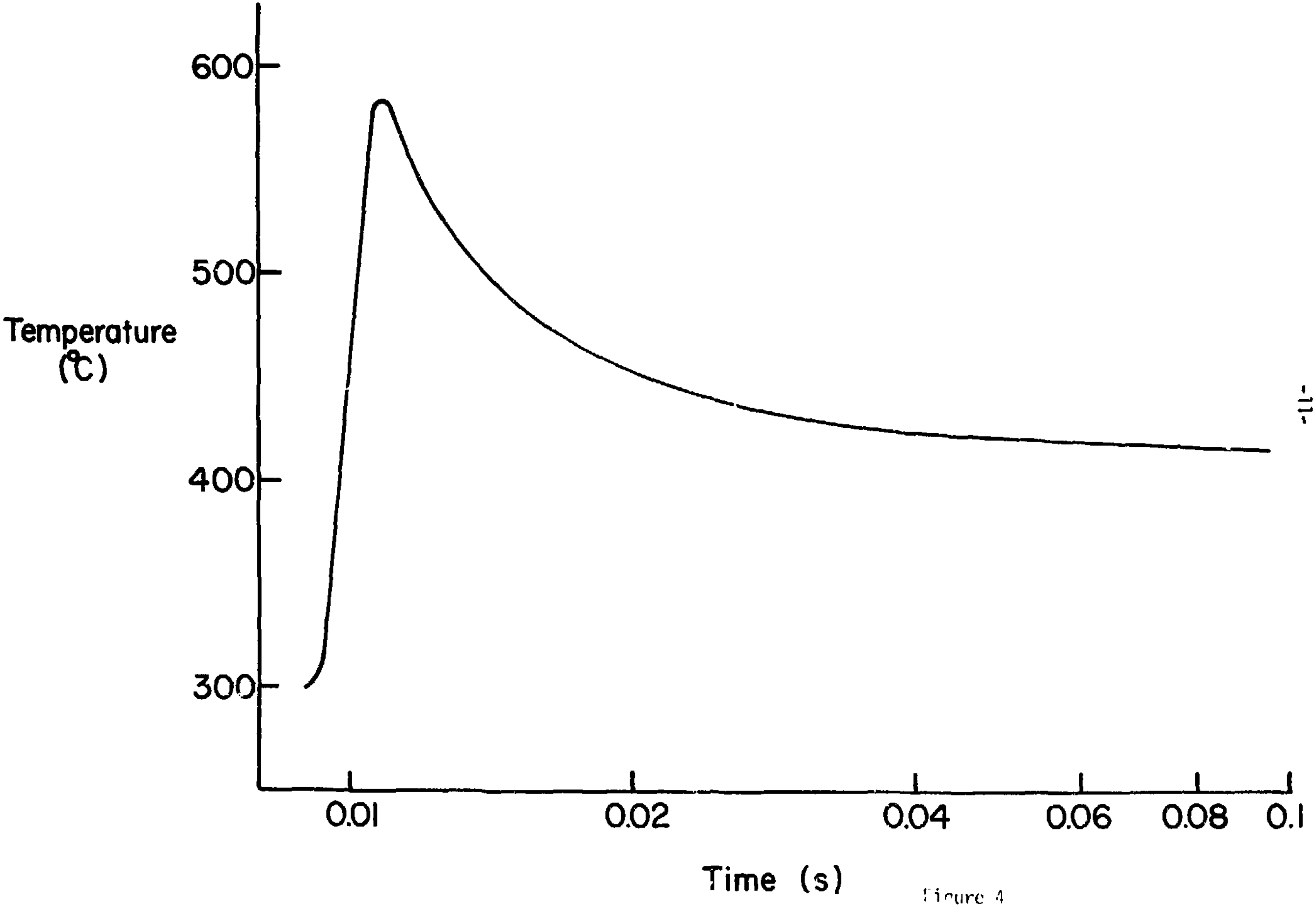

Figure 4

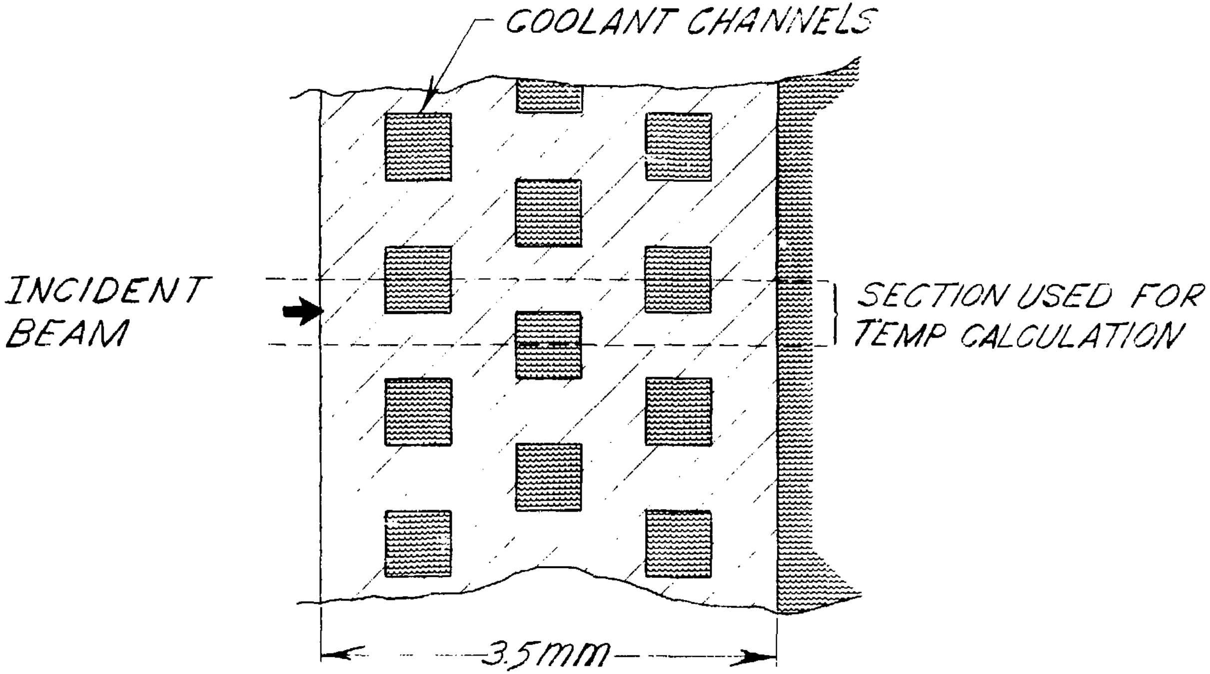
COOLANT CHANNELS
INCIDENT BEAM
SECTION USED FOR TEMP CALCULATION
3.5mm

Figure 5

Figure 6

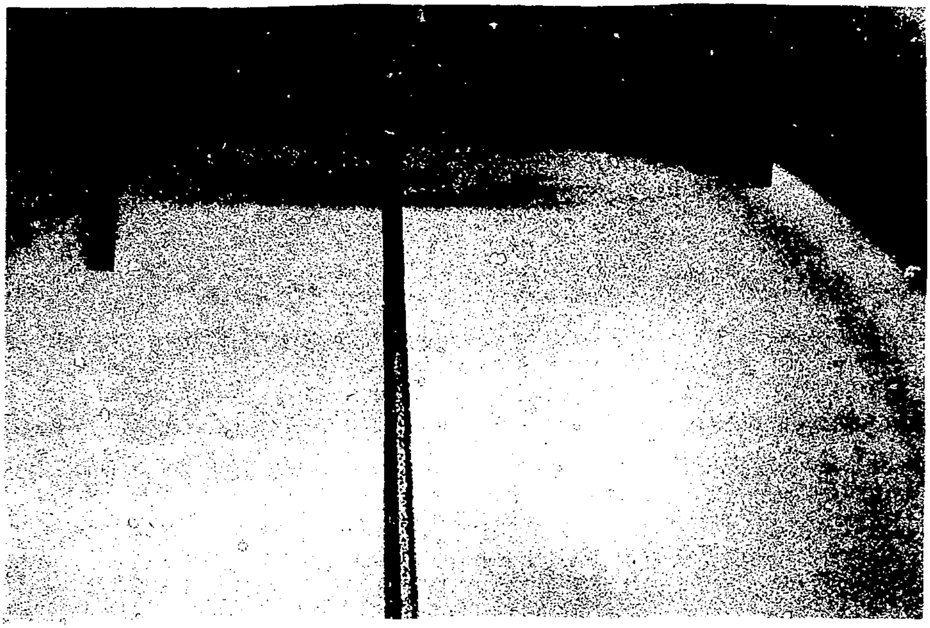

Figure 7

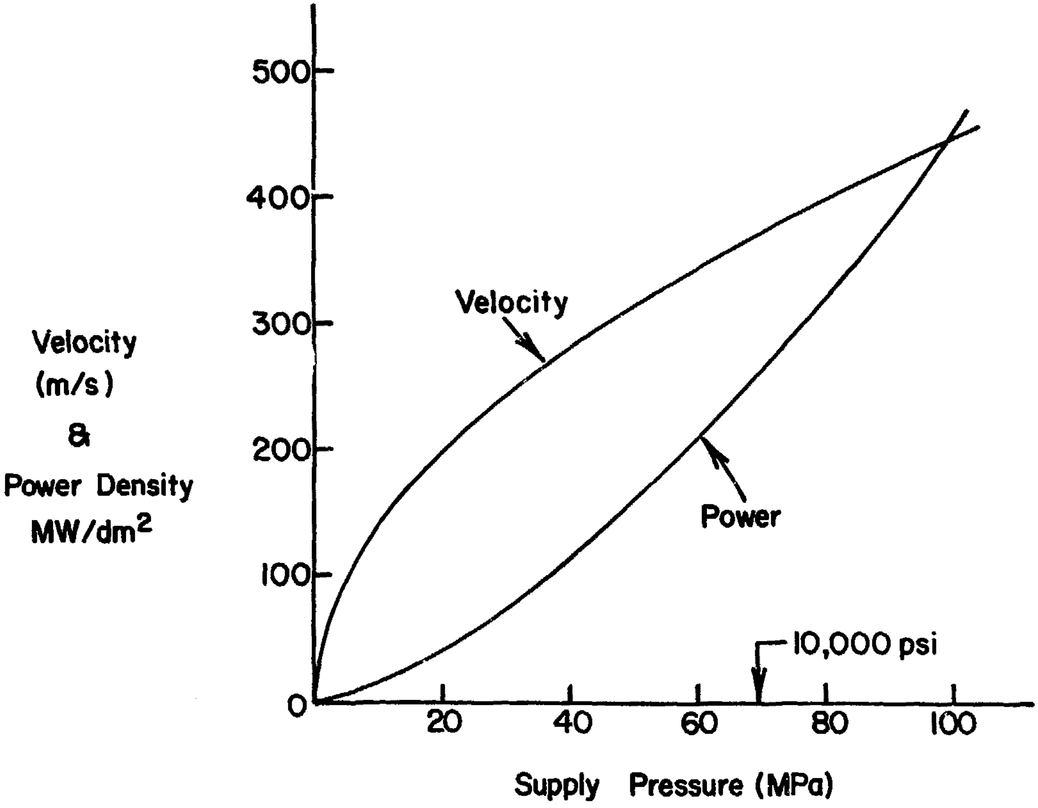
Velocity (m/s) & Power Density MW/dm^2
500
400
300
200
100
0
20
40
60
80
100
Supply Pressure (MPa)
Velocity
Power
10,000 psi

Figure 8