WATER COOLED TARGETS FOR INTENSE ION BEAMS

P. R. Hanley, A. W. Haberl, and A. Taylor
Accelerator Facility- Nuclear Reactor Laboratory
Cornell University, Ithaca, New York

Summary

Target backings cooled by water in linear flow have proven capable of dissipating heat loads from 2 kW ion beams focused to about 20 mm^2 for extended periods without structural failure. In addition to the more obvious modes of failure by plastic deformation and melting, metallographic studies of damaged targets have revealed deep void penetrations along grain boundaries. The targetry limitations imposed on maximum usable beam power by heat transfer from the backing to the cooling fluid have been investigated. Neutron producing lifetimes of LiF targets have been compared for different proton beam and coolant flow conditions.

Introduction

Intense hydrogen ion beams with energies up to a few MeV and several kW of maximum power are easily focused to power densities of the order of 10kW/cm^2, imposing extreme thermal loading on target backings. A design for a target backing cooled by water in linear flow has been evaluated by examining backing surface temperature as a function of beam power and beam power density. These experiments were undertaken both to provide a quantitative measure of target cooling capability under actual beam conditions and to identify the phenomena that induce structural failure during thermal loading.

Experimental Apparatus

Target Description

Cooling systems employing water in vortex flow have demonstrated power density capabilities of the required order of magnitude.[1] When backings are used to support neutron producing target materials, the additional design requirements listed by Coon[2] favor the simplicity of a linear coolant flow configuration. Such a system was designed at Brookhaven a decade ago.[3]

Recently, Wegner[4] has redesigned this device for use with intense ion beams. A section of a cylindrical tube of backing material about 1 mm thick is flattened by forming in a jig to provide a water channel 1 mm x 36 mm x 38 mm long. The flattened area forms the backing surface and seals to the vacuum system with an elastomer O-ring. Here the essential feature of the design is the thin, short channel that forces the coolant into a high velocity linear flow across the heated area. This feature has been used successfully in target backings, beam stops, and defining slits designed for the Cornell Dynamitron (Radiation Dynamics Model PEA-3). During routine operations over the past year, ion beams with powers up to 8 kW have been handled by this equipment without a single failure.

In the 44 mm nominal diameter target system shown in Figure 1, we have designed a new mechanical structure while retaining the thin coolant channel concept. We feel the flat, circular target backing design offers the following advantages: (1) the choice of material and thickness is not limited to that which is available in tubing; (2) no forming of the target material is required; (3) both surfaces can be easily inspected before and after bombardment; (4) treatment of both surfaces is facilitated (plating and roughening of coolant side); and, (5) the water channel wall on the atmospheric side can be easily varied (steel for low ratio of neutron scattering to strength, glass for target cooling studies). Modification for use with a glass back is shown in Figure 1, section (b).

Instrumentation

Three experimental parameters must be measured with modest precision to provide a quantitative evaluation of target performance. They are:

Ion Beam Power (q) in kW. Energy of the ions in the beam is inferred from terminal potential, measured on a voltmeter calibrated by threshold reactions. Current of the ion beam is measured at the target, guarded by a grounded aperture. A guard ring, biased - 500 Vdc with respect to ground, is used to suppress secondary electrons.

Ion Beam Power Density (q/A) in kW/cm^2. By defocusing the beam on a small aperture ($A = 0.20$ cm^2 or 1.00 cm^2), a section of reasonably uniform power density is selected to fall on the target. In the strictest sense, this measurement is an averaged value, and we should indicate that numbers obtained in this way are minimum values only ($q/A >$ measured value).

Target Surface Temperature An Ircon model 300S infrared radiometer is used to probe target surface temperature. This system was chosen for its ability to probe small surface areas without perturbing the temperature distribution. Absolute measurements of temperature are difficult, as calibration of the unit depends on the emissivity of the surface, and this will change due to carbon contamination during bombardment. Emissivity calibration is obtained at two known temperatures: first, at the boiling point of water, and second, at a high temperature produced by reducing the water flow during beam thermal loading. In the second case, the target glows and the infrared value can be compared to that obtained from a calibrated optical pyrometer.

Remote visual observation of target face and coolant channel is provided by a closed circuit television system. Neutrons are monitored by a conventional long counter similar to the type described by McTaggart.[5]

Target Backing Evaluation

Failure Mechanisms

Some qualitative observations of cooling system behavior near the point of structural failure indicate the phenomena involved. Failure is a sudden, almost threshold type of effect. Visual observations of the target face and coolant channel indicate a very strong temperature dependence on beam power input in the region of red heat. At this point, a notable sound level is observed at the target, and a small increase of input power or power density will result in puncture of the backing. Puncture appears to be a result of melting through the backing, caused by severe boiling of the coolant.

Metallographic Studies

A metallographic study was made on target blanks which were sectioned through the zone where the beam impinged. The effect of the beam could be readily assessed by comparing the microstructure both within and remote from the heated zone. Grain growth, and deformation of the target backing due to coolant pressure forces, are visible. Figure 2a illustrates grain boundary erosion produced on a target blank formed by flattening of commercial copper tubing. It is believed that rapid failure of this target would have resulted from the propagation through the sample of the grain boundary cracks ahead of the eroded fissures. This type of failure appears to be caused by the reaction of hydrogen with the Cu_2O particles to form steam bubbles in the grain boundaries. Failure is accelerated by the stress multiplication at the grain boundary notches. Even at modest power densities, small water leaks due to grain boundary damage may develop. Clearly oxygen bearing copper should be avoided.

A partially melted O.F.H.C. copper target is shown in Figure 2b. Liquid copper was retained in situ by the high surface tensional forces, and subsequently solidified forming large copper grains. The curved striations suggest successive positions of the liquid-solid interface during solidification. Appearance of the striations on the micrograph may be due to the precipitation of hydrogen gas at the moving interface. There is no evidence of grain boundary cracking although it is clear that the initial material contained impurities which were removed during the melting. In spite of the melting, such a blank appears to be resuable.

A target puncture induced by reducing coolant flow under severe beam loading, is shown in Figure 2c.

Thermal Analysis

Simple heat conduction arguments can be used to show that the temperature difference from target surface to water channel wall will be of the order of 100C°. With the target face at the melting point, the driving potential for boiling will be $\simeq$ 800C° (i.e., the channel wall temperature less the saturation temperature of water at the channel pressure). At these temperature levels there will be an extreme boiling condition.

The general problem of heat transfer to a liquid by forced convection with boiling has been considered in detail by Tong.[6] Three regimes of boiling are outlined:

a) nucleate boiling - generation of small vapor bubbles at the heated wall that are swept away by shear forces of the flow before they can coalesce.

b) film boiling - creation of a stable, continuous film of vapor that insulates the wall surface from the flow stream.

c) transition region - regions of the wall oscillate from nucleate to film boiling leading to wall temperature variations between broad limits.

These three regions can be recognized on the plot of target surface temperature as a function of beam power, shown in Figure 3. (Here we reduced the volume flow of coolant to enable the entire boiling region to be examined at modest power inputs). On the portion of the boiling curve marked (a), surface temperature data can be correlated as a linear function of input power for a fixed area. This relationship can then be characterized by two quantities: $(\partial T_s/\partial q)$, and T_{DNB}. T_s is the target backing surface temperature, and T_{DNB} is defined as the temperature at departure from nucleate boiling (arbitrarily chosen as the point where the random variation in T_s is 10% of its value).

If a target system is operating at power levels such that T_{DNB} is near the melting point of the backing, then oscillations of the transition region may be sufficient to melt the target suddenly for little or no increase in power input. Alternately, if T_{DNB} is considerably less than $T_{=}$ melting, the coolant will stabilize in the film boiling regime. For this case, $(\partial T_s/\partial q)_{FILM} \gg (\partial T_s/\partial q)_{NUCLEATE}$. Thus the rapid increase in surface temperature for a small increase in power or power density could drive the backing to melting failure quite rapidly.

The transition from nucleate to film boiling can be visually observed through the glass water channel backing. This provides striking confirmation of our analysis, again at reduced flow as for Figure 3. During region (a), small bubbles are formed and swept away by the coolant flow. In the transition region (c), large bubbles cover the surface for a few seconds before being swept into the stream. Film boiling in region (b) covers the wall with a stable film as predicted. As the coolant velocity is increased, the turbulence and speed of the flow complicate the visual observations. A high speed stop action camera would be necessary to adequately examine this region.

Given these interpretations of target and coolant behavior, a consistent approach to target evaluation can now be formulated.

Performance Results

A correlation of target surface temperature as a linear function of beam input power is shown in Figure 4, for A = 1.0 cm^2. Temperature data points were obtained at different beam energies and focal conditions to identify possible errors that could be introduced by inadequate defocusing. Here the glass back was used and the coolant pressure drop was adjusted to give a volume flow = 150 cm^3/sec. In addition, the temperature data from Figure 3 in the region of nucleate boiling has been included. A slope of $\partial T/\partial q$ = 185C°/kW fits the data, with temperature limits of ±20C° enclosing all data points. Above target powers $\simeq$ 2.5kW, heating of the aperture caused infrared interference that complicated the temperature measurements. Visual observations of the target face indicate the absence of glow at 1.30 mA and 2.6 MeV, and subsequent inspection of this target reveals that no melting or damage had occurred, as expected.

In Figure 5, a similar correlation is shown for the case A = 0.2 cm^2. We find that $\partial T/\partial q$ = 294C°/kW, with a spread of ±20C° again enclosing the data points. Problems with infrared interference limit this data to 1.25 kW(6.25 kW/cm^2). Visual observations were utilized to determine that glow does not occur at our maximum transmission point, 820µA and 2.6 MeV (10.6 kW/cm^2).

Some qualitative observations were made at higher total powers by removing the small aperture and passing the beam through the 38 mm diameter guard aperture. This data was taken on an earlier version of the design shown in Figure 1, which had a different coolant flow configuration. We obtained:

	Energy	Current	Observations
1.	1.5 MeV	3.4 mA	no glow or damage for all focal conditions.
2.	2.0	3.4	defocused, no glow
		2.7	focused, dull red glow.
3.	2.5	1.5	focused, intense glow.

LiF Neutron Targets

LiF targets, ranging in thickness from 100 to 1000 µg/cm^2, were vacuum evaporated on gold plated target backings, formed from a flattened copper tube. During the past year, these targets have been used as thick target threshold calibrators and as neutron sources for solid state damage experiments. Under proton beams of 500 µA at 2.25 MeV, targets about 200 µg/cm^2 thick retain the same specific neutron output for at least eight hours of continuous operation (i.e., 4 mA-hours exposure). At these power levels, a drastic reduction of the volume flow to the point where the coolant boils in free convection had no apparent effect on the neutron producing lifetime of the target.

Qualitative indications of neutron lifetime were obtained early in the study with hydrogen ion beams of 1.5 mA at 2.25 MeV. When these beams were focused to spots estimated to be from 5 to 10 mm diameter, halflife for neutron production ranged from 1/2 to 3 hours. By magnetically steering the spot over a 2 cm target diameter, useful lifetimes were increased to about 10 hours. We expect to obtain quantitative information on neutron lifetimes using proton beams in this power density range in the near future.

Discussion

For a flowing coolant with nucleate boiling, heat transfer by forced convection is thought to be negligible (ref. (6), pg. 117-118). Hence there should be little dependence on volume flow rate. Experimental agreement with this prediction is demonstrated by the common temperature correlation for two quite different flow rates as shown in Figure 4. Increasing the flow by a factor of twenty does not affect $(\partial T_s/\partial q)$, but suppresses the transition to film boiling.

If the correlation is extrapolated to a surface temperature equal to the melting point of Cu, then 5.3 kW would be the maximum power that this target could hold on a 1.0 cm^2 area. A similar extrapolation of $(\partial T_s/\partial q)$ for the A = 0.2 cm^2 case gives 3.34 kW (i.e., 16.7 kW/cm^2) as the maximum power point, subject to the requirement that T_{DNB} can be suppressed to temperatures above melting by increasing the flow.

Calculations have been made for the flattened copper tube target that predict a power capability of 7 kW/cm^2, using a shape independent, multilayer plane wall model.[4,7] Although our results indicate a strong shape dependence when A < 1 cm^2, convergence to the one dimensional result should be quite rapid for beam diameter to target thickness ratios > 10. Two dimensional conduction in the copper is significant for thin backings because the thermal resistance of the boiling liquid interface dominates the series heat flow circuit. Extrapolations of our data on backings $\simeq$ 1 mm thick indicate that the one dimensional calculation overestimates the power capability for 1 cm^2 areas, and underestimates for 0.2 cm^2. Shape dependent calculations could be expected to yield the same result as our extrapolations if the wall to water film coefficient is determined for nucleate boiling coolant conditions, and if the transition from nucleate to film boiling can be suppressed.

Experiments are now in progress at this laboratory to determine the exact form of the shape dependence for copper, tungsten, and tantalum backings. Additional work at high powers is being directed at investigation the suppression of T_{DNB}. These results shall be reported elsewhere.

In conclusion, we have found a linear correlation such that two parameters are required to specify the power dissipating capability of a fixed area of our target backing: $(\partial T_s/\partial q)_N$, and T_{DNB}. Although high coolant flow rates may be necessary, they do not materially effect the value of $(\partial T_s/\partial q)$ in nucleate boiling. With present techniques, 2 kW ion beams can be focused to a 5 mm diameter spot on target with impunity. As beam size is increased, target power capability does not scale directly with area. For beams of 1 cm^2 area, these targets may well have an effective limitation of <5 kW on maximum useable ion beam power. Finally, sudden failures of pure, flaw free target backings can be avoided by limiting target temperatures below the nucleate to film boiling transition of the coolant, and below the melting point of the backing materials.

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Figure 1. High Power Target Design
a./ Partial disassembly, steel back.
b./ Glass back.

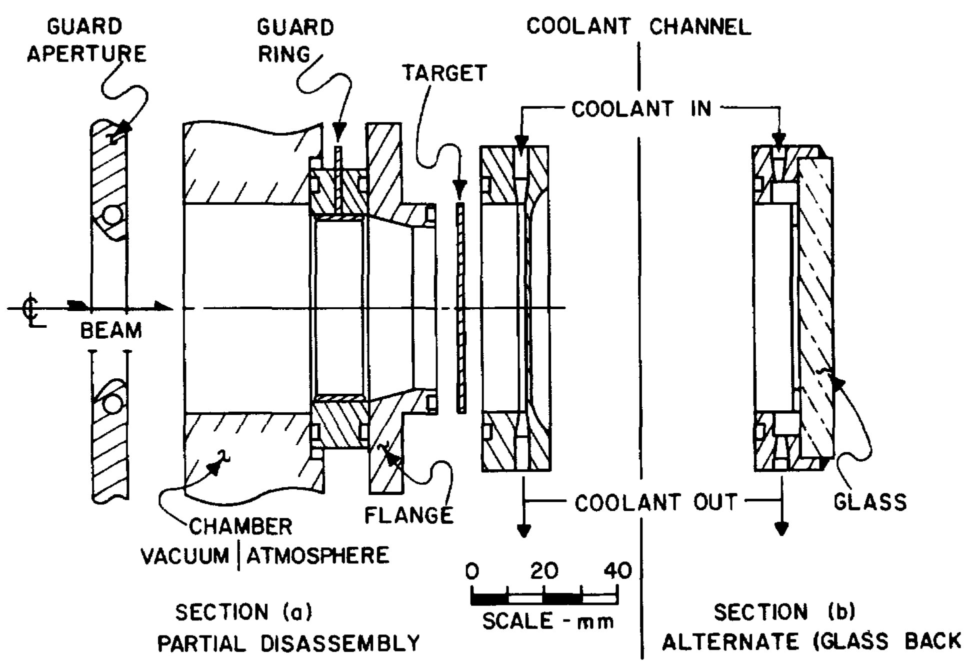

Figure 2. Transverse Cross Sections of Cu Target Backings Showing Modes of Failure.
a./ Fissures in impure copper.
b./ Partial melting in OFHC copper.
c./ Puncture by melting.

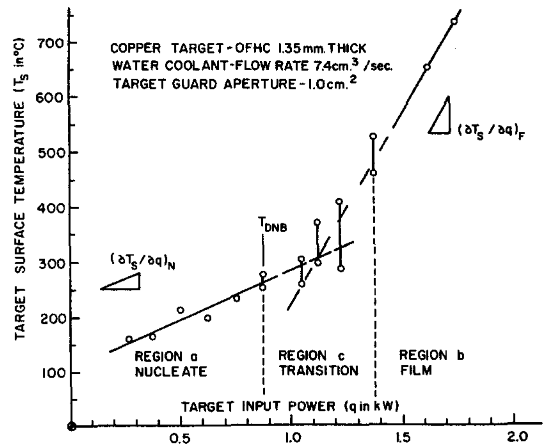

Figure 3. Boiling Regimes. Shown by target surface temperature as a function of target input power at reduced coolant flow rate.
a./ Nucleate boiling.
b./ Film boiling.
c./ Transition from nucleate to film boiling.

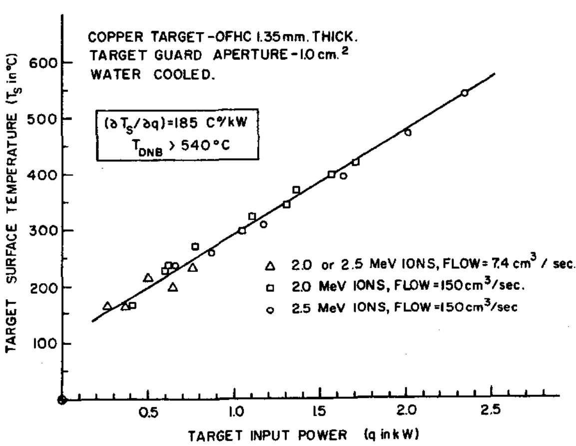

Figure 4. Correlation of target surface temperature data as a linear function of target input power for 1.0 square centimeter beam area.

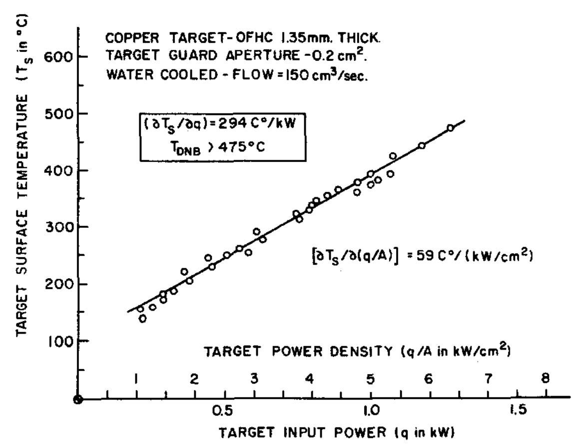

Figure 5. Correlation of target surface temperature data as a linear function of target input power for 0.2 square centimeter beam area.