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GALLIUM-COOLED TARGET FOR COMPACT ACCELERATOR-BASED NEUTRON SOURCES

UCANS-1,

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Union for Compact

Accelerator-based Neutron Sources

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OUTLINE

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Boiling water heat transfer

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TARGET COOLING

Cooling the beryllium target in compact accelerator-based neutron sources is a considerable challenge at the contemplated proton-beam power densities, although not without precedent. Already at the LENS facility at Indiana University, experience with water cooling seems to be at or to exceed the practical limits of water cooling technology, where conditions approach critical heat flux (CHF) *nucleate boiling limitations* (about 300 W/cm^2, although this can be exceeded using extreme measures).

Liquid metal coolants offer prospects of higher heat fluxes than water, but the most common ones suffer drawbacks.

LIQUID GALLIUM COOLING

Here, I explore the prospects for a liquid gallium (gallium-tin may be eligible)–cooled target, which seems to have few drawbacks.

Gallium remains in single phase even at elevated temperatures. Gallium is practically non-toxic, readily affordable (~$500/kg), and its thermophysical properties are well known. There is adequate engineering experience to support design even though its use in not common. A closely related Ga-cooled prototype has operated (ABNCT at MIT). A gallium test loop exists at ANL.

Gallium is compatible with air and water, and with structural and target materials (SS, Ti, Be, rubber-like elastomers) but corrodes aluminum.

PROPERTIES OF GALLIUM

Atomic number Z = 31

Mass number A = 69.7

Stable isotopes Ga^{69} (60.1%), Ga^{71} (39.9%)

Melting temperature T_m = 29.8 ° C

Boiling temperature T_b = 2403 ° C

Vapor pressure: less than 10^{-19} Pa at temperatures below 500 ° C)

Heat of fusion Q_f = 5.59 kJ/mol

Density @ 30 ° C, ρ = 6.095 gm/cm^3

Thermal conductivity k = 0.406 W/cm-° C

Specific heat C_p = 0.37 J/gm-° C

Viscosity η = 0.019 poise = 0.019 gm/cm-sec

Neutron capture cross section 2.9 barns/atom for thermal neutrons.

resonance integral 21 barns/atom

Activation products Ga^{70} ($T_{1/2}$ = 21 min), Ga^{72} ($T_{1/2}$ = 14 hr)

BOILING WATER HEAT TRANSFER

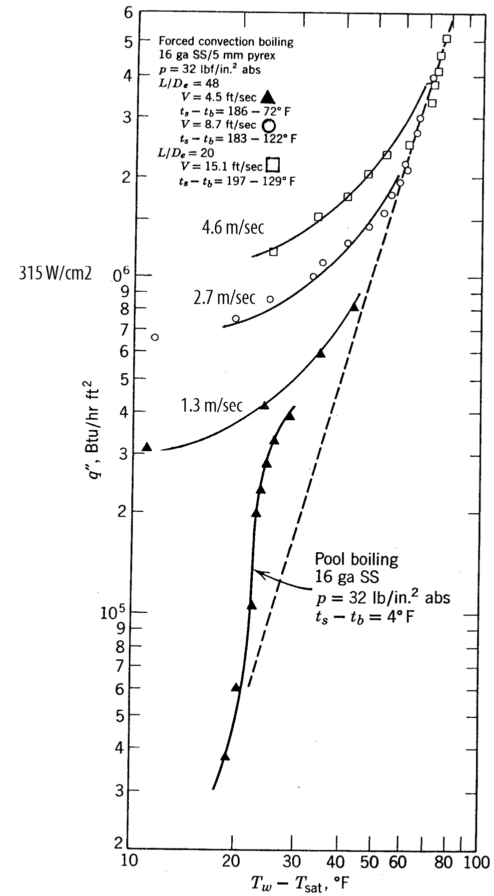


Figure 5-3 Forced convection surface boiling data and pool boiling data for stainles steel tube. From (B30).

The region a-b is the practical, single-phase and nucleate boiling regime at low flow velocities and modest pressures

BOILING WATER HEAT TRANSFER

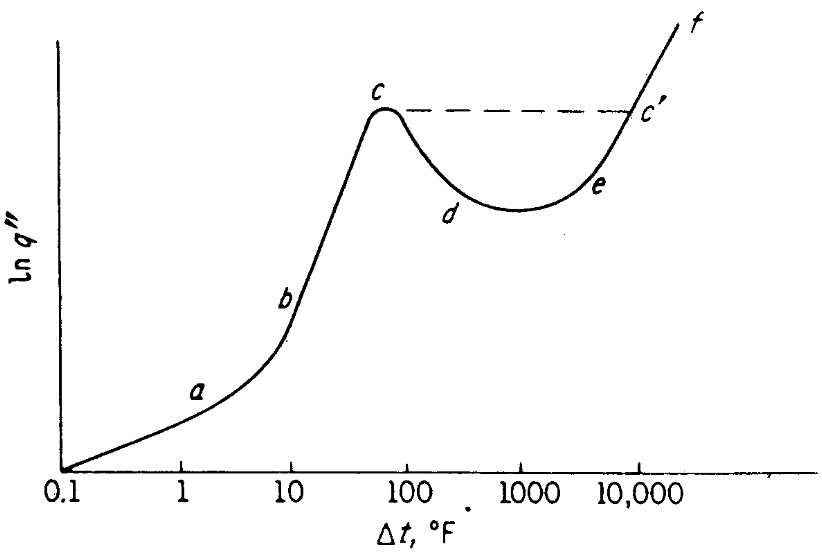


FIG. 11-8. Boiling regimes: Below *a*, liquid natural convection; *a–b*, mixed; *b–c*, nucleate boiling; *c–d*, mixed; *d–e*, film boiling; *e–f*, film boiling and radiation.

The region a-b-c is the practical regime illustrated in the next figure. The heat flux at c is the *critical heat flux*, beyond which the heat flow is unstable, vapor blankets the heated sur-face, and temperatures jump to c’, governed by film boiling and radiation heat transfer, called *burnout*.

The *critical heat flux is* the maximum feasible for given flow conditions . In extreme circumstances, q''_{max} can be as large as l.0 kW/cm^2, but in practice is 300-500 W/cm^2.

ASSESSMENT OF GALLIUM HAZARDS

The Materials Safety Data Sheet for gallium and gallium-containing alloys indicates caution in handling (use gloves), and avoidance of inhalation of powder and contact with eyes (may cause irritation). Liquid gallium metal is corrosive against many metals. A general appraisal of hazards is that gallium is, in most ways, benign.

Gallium metal is not flammable in air or in contact with water.

Gallium is liquid at human body temperature but solid at room temperature (in most climates).

HEAT TRANSPORT AND FLUID FLOW

Heat transport from a heated surface to flowing liquid involves numerous quantities:

The (dimensionless) Prandtl number (a property of the fluid only) is

$$Pr = C_p \eta / k = (0.37)(0.019)/0.406 = 0.0173.$$

The (dimensionless) Nusselt number, $Nu = hD_e/k$, so that

$$h = (k/D_e)Nu, \text{ where}$$

D_e = 4(flow cross sectional area)/(wetted perimeter of the flow channel) is the effective diameter of the channel.

The heat flux q" is

$$q'' = h\,\Delta T.$$

HEAT TRANSPORT AND FLUID FLOW

Seban's correlation gives the Nusselt number for liquid metal coolants

$Nu = 5.8 + 0.02\ Pe^{0.8}$, where Pe is the Peclet number,

$Pe = RePr$, in which Re is the (dimensionless) Reynolds number

$Re = v\ D_e \rho / \eta$, in which v is the channel-averaged fluid velocity.

[The Dittus-Boelter equation for non-metallic coolants like water is

$Nu = 0.023\ Re^{0.8} Pr^n$, where n = 0.4 for heat flow into the fluid.]

The Darcy equation gives the pressure drop Δp in a channel of length L with single-phase fluid,

$\Delta p = f(L/D_e)\ \rho v^2/2$, where f is the Darcy-Weisbach friction factor,

$f \sim 0.184/Re^{0.2}$ (for $Re > 2 \times 10^4$)

A SCOPING CALCULATION

The temperature of the heated surface is the critical quantity for our targets. Beryllium target material and can withstand rather high temperatures.

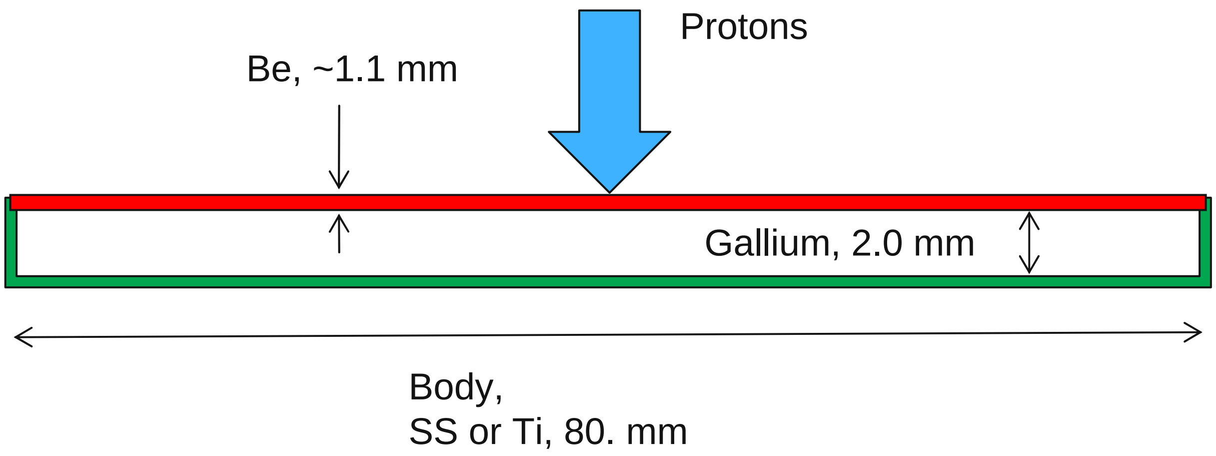
Assuming 20 kW over an 8-cm diameter, the average heat flux is $q'' = 20000/[(\pi/4)(8^2)] = 398.\ W/cm^2$, but the peak heat flux is about twice that because the proton beam is non-uniform, so I calculate for

$$q_{peak}'' = 800\ W/cm^2.$$

This is already considerably beyond common practice for nucleate boiling heat transfer in a water-cooled system, but is in the range considered for CANS.

Proton beamline designers need to provide realistic beam power distributions and peak-to-average power density values to proceed with detailed design.

A SCOPING CALCULATION



Cross sectional view of Target

I assume a rectangular flow channel of cross section 8 cm wide and 2 mm thick, so that the equivalent diameter is

D_e = 4(8)(.2)/[2(8.2)] = 0.390 cm.

Let the flow velocity be v = 100 cm/sec. Then the Reynolds number in the cooled cross section is

Re = (100)(.390)(6.095)/(0.019) = 12511.

A SCOPING CALCULATION (CONTINUED)

The Peclet number is $Pe = (0.0173)(12511) = 216.4$, and the Nusselt number is $Nu = 5.8 + .02(216.4^{0.8}) = 7.28$, so that the heat transfer coefficient is

$$h = (0.406)(7.28)/(0.390) = 7.58 \text{ W/cm}^2\text{-}^\circ\text{C}.$$

Then the wall-fluid temperature difference is

$$\Delta T = 800/7.58 = 105.6\ ^\circ\text{C},$$

which is an acceptable figure.

A SCOPING CALCULATION (CONTINUED)

The frictional pressure drop through the target region, assumed to be 10 cm along the flow path, is

$$\Delta p = (0.028)(10./0.390)(6.095)(100^2)/2 =$$
$$= 2.188 \times 10^4 \text{ gm-cm/sec}^2/\text{cm}^2 =$$
$$= 2.188 \times 10^3 \text{ kg-m/ sec}^2/\text{m}^2 =$$
$$= 2.188 \times 10^3 \text{ N/m}^2 = 0.022 \text{ atm},$$

which is quite small.

The volume flow rate is V'_{tot} = vA = (100)(8)(.2) = 160 cm^3/sec.

The temperature rise in the target channel $\delta T = P/\rho C_p V_{tot}$ is δT = (20000)/[(6.095)(0.37)(160)] = 55 °C, which is acceptable.

A SCOPING CALCULATION (CONTINUED)

Assume that the external cooling circuit consists of D = 2.0-cm-diameter tubing (for circular tubes, $D_e = D$), L = 5 m long. Then the flow velocity in the tube is $v_{tube} = V'_{total}/(\pi 2.0^2/4) = 50.9$ cm/sec.

The frictional pressure drop for the external loop depends on the Reynolds number for the flow in the tube,

Re = (50.9)(2.0)(6.095)/0.019) = 3.266×10^4 , for which the friction factor is f = 0.023. Thus the pressure drop is

$$\Delta p_{external} = (0.023)(500/2.0)(6.095)(50.9^2)/2$$
$$= 4.54 \times 10^4 \text{ gm-cm/sec}^2/\text{cm}^2$$
$$= 4.54 \times 10^3 \text{ N/m}^2 = 0.041 \text{ atm.}$$

This is without accounting for the pressure drop in the heat exchanger except to the extent that it is included in the pressure drop in the assumed 5-meter-long external piping.

A SCOPING CALCULATION (CONTINUED)

The acceleration pressure changes at the entrance and exit from the target region more or less cancel around the loop, but the pressure in the target region is smaller than the pressure in the entry tube according to

$\Delta p_{accel} = \rho v_{target} v_{tube}$ = 3.102 x 10^4 gm-cm/sec^2/cm^2 = 3.102 x 10^3 N/m^2 =

= 0.0282 atm.

The power required to circulate the fluid is

$P_{pump} = V'_{total} \Delta p_{friction}$ = (160 cm^3/sec)x[(4.54 + 2.19)x10^3N/m^2] =

= 1.08 N-m/sec = 1.08 W,

which does not account for the inefficiency of the pump. A centrifugal pump or an electromagnetic pump might suffice for circulating the coolant.

The volume of gallium in the system is approximately that of the 5-m piping, $V_{gallium}$ = 1570. cm^3. The corresponding mass of gallium is $M_{gallium}$ = 9.6 kg.

SUMMARY

The scoping results are based on simple analytical calculations and bulk averages, therefore need detailed analysis using modern thermal-hydraulic codes and more precise data.

<u>Summary</u>:

Water-cooled target systems are suitable for CANS up to a certain power level, but present difficulties at envisioned high levels of power. Critical heat flux limitations in nucleate boiling water coolant limit its use in envisioned CANS applications.

Gallium-cooled systems overcome these limitations, and are compatible with water as coolant. Liquid gallium is a convenient, benign coolant, exceeding heat flux requirements, and compatible with all the components of a CANS.

System components that contact gallium cannot be of aluminum, but SS and/or titanium are suitable.

CONCLUSIONS

The scoping study reveals that a gallium-cooled system maintains target temperatures (~100 ° C above ambient), with modest coolant velocities (~1m/se,. 0.16 l/sec), modest coolant temperature rise (~55 ° C), affordable coolant mass (~10 kg: ~ $5000.), moderate pumping power (~0. atm pressure drop), moderate target coolant pressure (~0.3 atm below system driving pressure).

A recommendation:

Design high-power (>~ 10 kW beam power) CANS for use of gallium coolant, but begin operation with water coolant. Existing systems will need backfitting of some components. New systems will require engineering for the less familiar gallium coolant, but this seems to present no big problems. The ABNCT source, beryllium target and gallium cooled, built and operated at MIT, is a proof-of-principal prototype and source of experience. A windowless x-ray source based on gallium, built at ANL is also a valuable prototype.

THANKS FOR LISTENING