LIQUID GALLIUM COOLING OF A HIGH-POWER BERYLLIUM TARGET FOR USE IN ACCELERATOR BORON NEUTRON CAPTURE THERAPY (ABNCT).

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Ongoing research at MIT's Laboratory for Accelerator Beam Applications (LABA) is dedicated to developing the components necessary to make Accelerator-based Boron Neutron Capture Therapy (ABNCT) (1,2,3) and Boron Neutron Capture Synovectomy (BNCS) (4,5) viable clinical modalities for the treatment of cancerous tumors and arthritic synovium respectively. Both BNCT and BNCS involve the administration of a boronated pharmaceutical followed by irradiation with a neutron beam which allows for killing of the targeted cells via the 10B(n,α)7Li reaction. Production of the needed neutron flux can be accomplished by bombarding low Z elements such as lithium and beryllium with energetic protons or deuterons. Depending on therapy type, beam powers required for treatment could range from 2.5-10 kW. Targets must be housed in a moderator/reflector assembly which is used to tailor the neutron energy to the specific treatment. The moderator/reflector is typically cylindrical in cross section and contains liquid D20 moderator in a lead or graphite reflector. In order to limit the diameter of the final neutron beam targets are limited in size. Depending on charged particle beam size, power densities of 2-20 MW/rn^2 can be encountered in targets which currently have areas of 10-15 cm^2.

Liquid gallium metal has been tested as the working fluid in a heat removal system for a neutron producing beryllium target which will be capable of operating under conditions which would be beyond the critical1 heat flux of water under similar flow rates. Liquid gallium possesses thermo-physical properties which make it ideal for applications with heat fluences as high as 20 MW/rn^2. Table 1 compares the pertinent properties of liquid gallium and water.

TABLE 1 THERMO-PHYSICAL PROPERTIES OF LIQUID GALLIUM AND WATER

	Gallium	**Water**
Density (kg/rn^3)	6100	1000
Melting point (^{0}C)	29.8	0.0
Boiling point (^{0}C)	2205	100
Thermal conductivity (W/mK)	40	0.6
Specific heat (Id/kg)	0.396	4.2
Viscosity (kg mis)	0.00196	0.000855
Kinematic viscosity (m^2/s)	3.2e-7	8.5 5*e*-7

Initial tests using water coolant illustrated that heat fluences of 15 MW/rn^2 could be removed from a *0.254* cm thick beryllium target with high velocities in a submerged jet impingement configuration. These tests found that heat removal was due to forced convective boiling and required jet velocities of 24 m/s and flow rates of 87 GPM which were provided by a 15hp centrifugal pump. Because the target relied on boiling for the heat transfer, critical heat flux (CHF) was a major concern at high heat fluences. During tests with water, in fact, CHF failure of the target was witnessed (6). As an alternative to using water at large flow rates and velocities, a working fluid was sought which could be used at similar heat fluences at a greatly reduced flowrate. Liquid gallium can be melted and pumped near room temperature and because of its low kinematic viscosity, Reynold’s numbers (Re) are generated which are over a factor of 2 higher than those of water at similar flow velocities. Because it is a liquid metal, gallium possesses a thermal conduction coefficient which is over 50 times higher than water. Standard Nusselt number correlations which can be used to predict heat transfer coefficients for many fluids cannot be used for liquid metals, however, because of their high conductivity which competes with convection in heat transfer.

Experiments to illustrate the effectiveness of gallium cooling were conducted using LABA’s 4.1 MeV tandem accelerator to heat a 0.254 cm thick beryllium target which was cooled with either water or liquid gallium. Temperatures were measured at various target locations and at power loadings of 0-500 Watts with coolant flowrates of 1 L/min and coolant temperatures of 50 ^{0}C. Because it was difficult to determine the size of the beam striking the target, three separate tests were run using first water and then gallium as the cooling fluid. Temperature measurements versus power loadings were made at similar optical settings to ensure that beam sizes and associated heat fluences were similar. Temperature measurements were then used with the numeric code Adina (7) to estimate the average heat transfer coefficient and beam size. Results of the temperature measurements indicate that for equal flow rates, gallium lowers the temperature interface between the fluid and the target by as much as 30%. At a flow rate of 1 L/min gallium was able remove 490 Watts with an interface temperature increase of 25 ^{0}C compared to a 40 ^{0}C increase with water. Even at low flowrates gallium generates a convective heat transfer coefficient of up to 6.0e4 W/m2K. Unlike water which would boil at 100 ^{0}C, heat transfer from gallium would be linear up to the melting point of the target at 1200 ^{0}C. CHF begins to be a problem with water cooling when the target surface temperature is higher than the saturation temperature by about 30 ^{0}C. This is not the case with gallium, however, since it has a low vapor pressure and does not boil below 2200 ^{0}C.

Gallium provides the means to remove large heat fluences with low flow rates without the danger of exceeding the critical heat flux. Because it is a liquid near room temperature, it does not require excessive heating or insulation. Unlike other liquid metal coolants like sodium or lithium it is not reactive with moisture, and it presents no toxicity concerns like mercury or lead-bismuth eutectics.

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DISCUSSION:

Syed Qaim: You have presented several parameters in the trials of gallium. Tucker said one more parameter should be considered and that would be the activation formation of long-lived activation products in gallium as well as in other metals which one can use for cooling. Did you consider this?

Brandon Blackburn: Yes, actually we did. We have done some MCNP calculations because not only do we have to worry about the thermal properties, but the neutronics. What kind of added neutronics does gallium introduce? Gallium actually has a very low neutron cross-section it activates a little bit. What we found is basically, what it adds to the problem is it increases the photon dose to the patient by about 10%; but because it’s Z is 31, you don’t lose any in moderation and it’s cross section is very low.