

CEW-920792--40

# Liquid Metal Cooling of Synchrotron Optics.\*

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ANL/CP--77509

DE93 002989

September, 1992

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Received by OSTI

NOV 10 1992

\*This work supported by the U.S. Department of Energy, BES-Materials Sciences, under contract no. W-31-109-ENG-38

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# Liquid metal cooling of synchrotron optics

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## ABSTRACT

The installation of insertion devices at existing synchrotron facilities around the world has stimulated the development of new ways to cool the optical elements in the associated x-ray beamlines. Argonne has been a leader in the development of liquid metal cooling for high heat load x-ray optics for the next generation of synchrotron facilities. The high thermal conductivity, high volume specific heat, low kinematic viscosity, and large working temperature range make liquid metals a very efficient heat transfer fluid. A wide range of liquid metals were considered in the initial phase of this work. The most promising liquid metal cooling fluid identified to date is liquid gallium, which appears to have all the desired properties and the fewest number of undesired features of the liquid metals examined. Besides the special features of liquid metals that make them good heat transfer fluids, the very low vapor pressure over a large working temperature range make liquid gallium an ideal cooling fluid for use in a high vacuum environment. A leak of the liquid gallium into the high vacuum and even into very high vacuum areas will not result in any detectable vapor pressure and may even improve the vacuum environment as the liquid gallium combines with any water vapor or oxygen present in the system. The practical use of a liquid metal for cooling silicon crystals and other high heat load applications depends on having a convenient and efficient delivery system. The requirements for a typical cooling system for a silicon crystal used in a monochromator are pumping speeds of 2 to 5 gpm (120 cc per sec to 600 cc per sec) at pressures up to 100 psi. No liquid metal pump with these capabilities was available commercially when this project was started, so it was necessary to develop a suitable pump in house. A number of synchrotron experiments were performed at Cornell University (CHESS) and at Brookhaven (NSLS) where this pump was used to cool the first silicon crystal in a two crystal monochromator. Data from these experiments using different cooling geometries and flow rates are compared with theory and possible future development. An estimate is made for the optimized heat transfer coefficient  $h$  for liquid gallium cooling of silicon diffraction crystals and compared to similar optimized values for water cooling of similar crystals. The main difference in these two optimizations is that, in the case of gallium cooling, the flow remains turbulent, while, in the case of water cooling, it becomes laminar. The flatter velocity profile of the turbulent flow in the cooling channel allows one to obtain higher values for  $h$  and, at the same time, use cooling channels with larger dimensions than were obtained in the water cooling optimization. The larger channels make it possible to obtain higher flow rates in the channels for the liquid gallium than were obtained for the optimized water cooling. This makes the gallium cooling case less sensitive to the increase in cooling fluid temperature and further reduces the surface temperature of the crystal.

## **2. INTRODUCTION**

The high intensity, high brilliance, insertion-device-based x-ray beams of the next generation of synchrotron sources, Argonne's Advanced Photon Source (APS), the European Synchrotron Radiation Facility (ESRF) and the Japanese Synchrotron project (SPring-8) will deliver large thermal loads to various components in the beamlines. The first optical element in the beamline will often absorb nearly all of the full heat of these intense x-ray beams that will range in power from 1 kW to 20 kW. The increased collimation of the next generation sources will increase the concentration of this heat load on the crystal over what is produced by currently available synchrotron beams. This will further increase the seriousness of the heat load problem. Hence, improved methods of cooling the first optical elements, particularly when they are diffraction crystals, are clearly needed to achieve the full potential of these new high intensity x-ray beamlines.

Many new cooling geometries have been developed, as can be seen from the contents of this symposium as well as the recent international SRI (Synchrotron Radiation Instrumentation) meetings in Chester, England, in July 1991, and in Tsububa, Japan, in 1988. In some cases, new cooling fluids have also been investigated. The Advanced Photon Source (APS) at Argonne has pioneered the use of liquid metals as cooling fluids for x-ray optics in high intensity synchrotron beamlines. Of the four or five attractive candidates for use as cooling fluids, liquid gallium appears to have the best combination of desirable properties and the fewest number of undesirable properties. Its high thermal conductivity, high volume specific heat, and low kinematic viscosity make it an efficient heat transfer fluid at the liquid-solid interface. Its very low vapor pressure and large working temperature range make it ideal for cooling applications in a high vacuum environment. In those cooling cases examined to date where water cooling has been replaced by liquid gallium cooling, there has been a considerable improvement in the cooling efficiency, often by a factor of three to five.

The practical use of a liquid metal for cooling silicon crystals and other high heat load applications depends on having a convenient and efficient delivery system. The requirements for a typical cooling system for a silicon crystal used in a monochromator are pumping speeds of 2 to 5 gpm (120 cc per sec to 600 cc per sec) at pressures up to 100 psi. No liquid metal pump with these capabilities was available commercially when this project was started, so it was necessary to develop a suitable pump in house. The latest version of this pump develops a head pressure of 150 psi while delivering 6 gpm. This is more than sufficient for most cooling tasks, even for the very highest heat loads expected from the high intensity beams of the APS.

## **3. LIQUID METAL COOLING FLUIDS**

Liquid metals have been used in nuclear power reactors in high temperature, high heat load conditions with considerable success. Argonne has been a leader in the development of this technology, so it was a relatively easy extension of this technology, to apply liquid metal cooling to the high heat load problems faced in the synchrotron community. Liquid metals tend to have high thermal conductivity, high volume specific

heats, and large working temperature ranges. These qualities make them excellent heat exchange fluids. Table I lists the properties of some of the more likely liquid metal cooling fluids. They are listed in order, by their melting points (high to low). Liquid metals with

**TABLE I FLUID PROPERTIES OF LIQUID METALS**

	M.P. °C	B.P. °C	k W/cm,°K	Cv J/cm <sup>3</sup>	ρ g/cm <sup>3</sup>	μ / ρ cp/g	V.P. mm Hg
Bi	271.	1560.	0.17	1.4	9.7	0.17	10 <sup>-10</sup>
Sn	232.	2270.	0.30	1.4	5.7	0.34	<10 <sup>-10</sup>
Li	186.	1336.	0.47	2.3	0.53	1.12	10 <sup>-10</sup>
In	156.	2000.	0.42	1.9	7.3		<10 <sup>-10</sup>
Na	97.5	880.	0.90	1.34	0.97	0.70	10 <sup>-10</sup>
K	62.3	760.	0.53	0.70	0.87	0.59	6x10 <sup>-7</sup>
Rb	38.5	700.	0.33	0.52	1.53	0.44	6x10 <sup>-6</sup>
Ga	29.8	2071.	0.33	2.4	6.0	0.26	<10 <sup>12</sup> (50°)
Cs	28.5	670.	0.20	0.50	1.87	0.34	10 <sup>-6</sup> (20°)
Hg	-38.9	356.	0.084	1.91	13.5	0.12	0.12 (20°)

melting points above 300°C were not included because they are impractical to work with in the synchrotron environment. The first four, bismuth, tin, lithium, and indium are excellent cooling fluids, especially lithium, with its very high thermal conductivity and very high specific heat per unit volume. However, these four were rejected on the basis of their moderately high melting points. The next two, sodium and potassium, are also very good cooling fluids. Their operating temperature ranges are smaller than the previous candidates but are still quite large. If there were not an even better option, they would be prime candidates for the cooling fluid of choice. Their main drawback is that they react strongly with oxygen and water and are thus a possible fire hazard and require special handling procedures. Liquid rubidium has all the necessary attributes to make an excellent cooling fluid and would have been considered if it were not so expensive. Gallium and cesium have quite acceptable melting points, just above room temperature, and good thermal conductivity. Gallium was chosen over cesium because of its much higher specific heat per unit volume, its better working temperature range, its much lower vapor pressure, and its much less reactive nature when exposed to oxygen and water. The low vapor pressure is very important if one is working in a high vacuum environment. Mercury was rejected because of its poor thermal conductivity, low working temperature range, and very high vapor pressure. A leak in a mercury cooling loop would be serious even at room

temperatures and very serious at elevated temperatures. It could easily contaminate the whole system, and, if any mercury vapor were to reach the main ring of APS, it would attack the aluminum walls of the storage ring. The use of mercury is forbidden in most accelerator environments.

Gallium, with its high thermal conductivity, high volume specific heat, large working temperature range, and very low vapor pressure, is the liquid metal cooling fluid of choice. Gallium has the added attractive feature of being relatively non-toxic. The pure metal as well as most of the compounds it forms in nature are not soluble in water and are, therefore, not absorbed through the skin. This characteristic combined with its very low vapor pressure makes gallium much safer to handle than most of the other liquid metals. Gallium can be alloyed with indium to form a eutectic that melts below room temperature. The indium-gallium combination is also a very good liquid metal cooling fluid and has the important advantage of not freezing at room temperature. The main difficulty with the use of the indium-gallium mixture is that it is much more difficult to clean up if it is spilled. With pure gallium, all one has to do is to pour cold water on it and freeze it, then one can pick it up as a solid lump. The mixture of indium and gallium does not freeze as easily and tends to smear and stick to the surface of most materials.

**TABLE II PROPERTIES OF COOLING FLUIDS**

	M.P. °C	B.P. °C	k W/cm,°K	Cv J/cm <sup>3</sup>	ρ g/cm <sup>3</sup>	μ / ρ cp/g	V.P. mm Hg
Ga	29.8	2071.	0.33	2.4	6.0	0.26	<10 <sup>12</sup> (50°C)
H <sub>2</sub> O	0.0	100.	0.0064	4.12	1.0	1.0	0.17 (20°C)
N <sub>2</sub>	-210.	-196.	0.0014	1.60	0.81	0.21	7x10 <sup>3</sup> (20°C)

Table II compares the properties of gallium with those of water, liquid nitrogen, and liquid propane. Again the major difference between gallium and these other possible cooling fluids is the high thermal conductivity, large working temperature range, and very low vapor pressure.

#### 4. HEAT TRANSFER COEFFICIENT "h"

In calculations for distortions of the diffraction crystal, the major differences for different cooling fluids comes from the different values for the heat transfer coefficient h. This is a model dependent number that describes the amount of heat that is transferred between the solid and the cooling fluid per unit area, per degree of temperature. The value of h is then given in units of watts per cm<sup>2</sup> per degree C or the equivalent and is commonly

written as

$$h = (k/d) Nu, \quad (1)$$

where  $k$  is the coefficient of thermal conductivity,  $d$  is the hydraulic diameter, and  $Nu$  is the Nusselt number, given by

$$Nu = A_1 + A_2 Re^n Pr^m. \quad (2)$$

Substituting in eq. 1,

$$h = (k/d) [A_1 + A_2 Re^n Pr^m], \quad (3)$$

where  $Re$  is the Reynolds number and  $Pr$  is the Prandtl number, given by

$$Re = d V_a / \nu \quad (4)$$

$$Pr = \nu C_v / k, \quad (5)$$

where  $\nu$  is the kinematic viscosity = normal viscosity divided by the density of the fluid,  $C_v$  is the volume specific heat,  $d$  is the hydraulic diameter,  $V_a$  is the average velocity of the fluid, and  $k$  is the thermal conductivity of the fluid. The constants  $A_1$  and  $A_2$  and the exponents  $n$  and  $m$  are experimentally determined. The hydraulic diameter  $d$  is a parameter that takes into account the size and shape of the cooling channels and is just the diameter of a circular cooling channel. In the case of a rectangular cooling channel,  $d$  is approximated by equation (6)

$$d = 4(ab) / (2a + 2b), \quad (6)$$

where  $a$  and  $b$  are the sides of the rectangle. Baker and Tessier<sup>1</sup> recommend using Lyon equation (equation 7) for liquid metal flow when  $Pr$  is less than 0.1. In this equation the exponents  $m$  and  $n$  are both approximately 0.8, and  $A_1$  and  $A_2$  are 7 and 0.025, respectively. Thus,  $h$  is given by

$$h = (k/d) [7 + 0.025 Re^{0.8} Pr^{0.8}]. \quad (7)$$

Substituting for  $Re$  and  $Pr$ ,

$$h = (k/d) [7 + 0.025 (d/\nu)^{0.8} (\nu C_v/k)^{0.8} (V_a)^{0.8}]. \quad (8)$$

Substituting the appropriate values for gallium and  $d = 0.05$  cm, one has:

$$h = 6.6 [ 7 + 0.0104 V_a^{0.8} ]. \quad (9)$$

Substituting 100 cm / sec, 200 cm / sec and 300 cm / sec for  $V_a$  one has

$$\begin{aligned} h &= 6.6 [ 7 + 0.414 ] = 48.9 \text{ W / cm}^2, \text{ }^\circ\text{C} \quad ( 100 \text{ cm / sec} ) \\ &= 6.6 [ 7 + 0.721 ] = 51.0 \text{ W / cm}^2, \text{ }^\circ\text{C} \quad ( 200 \text{ cm / sec} ) \\ &= 6.6 [ 7 + 0.997 ] = 52.8 \text{ W / cm}^2, \text{ }^\circ\text{C} \quad ( 300 \text{ cm / sec} ). \end{aligned}$$

Note that the second term in equation 9 (involving the velocity of the cooling fluid) has only a small effect on the value of  $h$  in this parameter range. This is not consistent with the data taken at the Cornell synchrotron facility CHESS in 1991.<sup>2</sup> Some of this data is shown in figure 1 in which the maximum increase in surface temperature of the silicon crystal under the x-ray beam is plotted versus the flow rate of the liquid gallium in the cooling channels. The change in this temperature is caused by the change in the value of  $h$ , which results in a change in the temperature difference between the cooling fluid and the wall of the channel. The two upper curves are for a core-drilled crystal with circular cooling channels 2.4 mm in diameter, and the lower two curves are for a crystal with rectangular channels with a  $d = 0.121$  cm. The currents labeling each set of curves gives the beam current in the storage ring for that run, which is proportional to the power in the x-ray beam. Both sets of curves vary dramatically with cooling fluid flow and thus with the average velocity of the cooling fluid  $V_a$ . Part of the difference between the dependence of  $h$  in the calculations and the experiments may be related to the different values of  $d$ . When  $d$  is large, the relative importance of the second term increases, giving an increase in the effect of the velocity on  $h$ . Substituting the value of  $d = 0.121$  cm for the rectangular channel case, one obtains

$$h = 2.73 [ 7 + 0.0211 V_a^{0.8} ]. \quad (10)$$

Calculating  $h$  for the same 3 velocities:

$$\begin{aligned} h &= 2.73 [ 7 + 0.840 ] = 21.4 \text{ W / cm}^2, \text{ }^\circ\text{C} \quad ( 100 \text{ cm / sec} ) \\ &= 2.73 [ 7 + 1.463 ] = 23.1 \text{ W / cm}^2, \text{ }^\circ\text{C} \quad ( 200 \text{ cm / sec} ) \\ &= 2.73 [ 7 + 2.023 ] = 24.6 \text{ W / cm}^2, \text{ }^\circ\text{C} \quad ( 300 \text{ cm / sec} ). \end{aligned}$$

A flow of 1 gpm (gallon per minute) is equal to 63 cm<sup>3</sup> per sec and corresponds to a velocity of 84.8 cm per sec in these rectangular channels. Calculating  $h$  for the points on the lower set of curves:

$$\begin{aligned} h &= 2.73 [ 7 + 0.423 ] = 20.3 \text{ W / cm}^2, \text{ }^\circ\text{C} \quad ( 42.8 \text{ cm / sec} ) (0.5 \text{ gpm}) \\ &= 2.73 [ 7 + 0.736 ] = 21.1 \text{ W / cm}^2, \text{ }^\circ\text{C} \quad ( 84.8 \text{ cm / sec} ) (1.0 \text{ gpm}) \\ &= 2.73 [ 7 + 1.018 ] = 21.9 \text{ W / cm}^2, \text{ }^\circ\text{C} \quad (127.2 \text{ cm / sec} ) (1.5 \text{ gpm}) \\ &= 2.73 [ 7 + 1.282 ] = 22.6 \text{ W / cm}^2, \text{ }^\circ\text{C} \quad (169.6 \text{ cm / sec} ) (2.0 \text{ gpm}). \end{aligned}$$

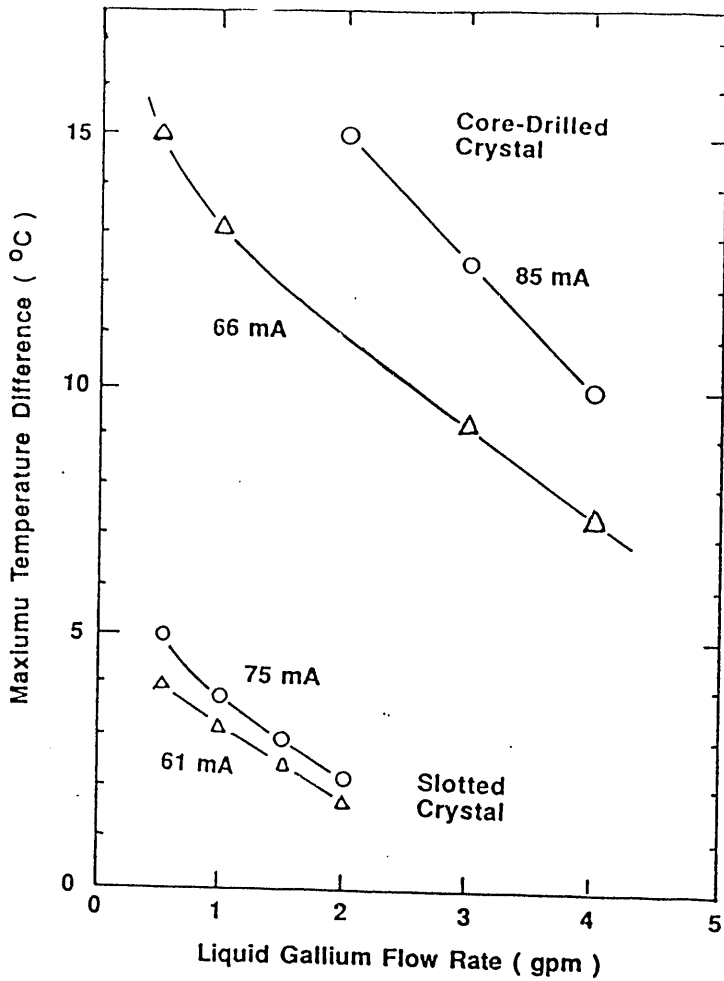


Figure 1. Maximum temperature difference on surface of crystal as a function of flow of the liquid gallium cooling fluid. The upper two curves are for the core-drilled crystal and the lower two curves are for the slotted crystal. Labels in mA refer to the current in the storage ring and are proportional to the power in the photon beam.

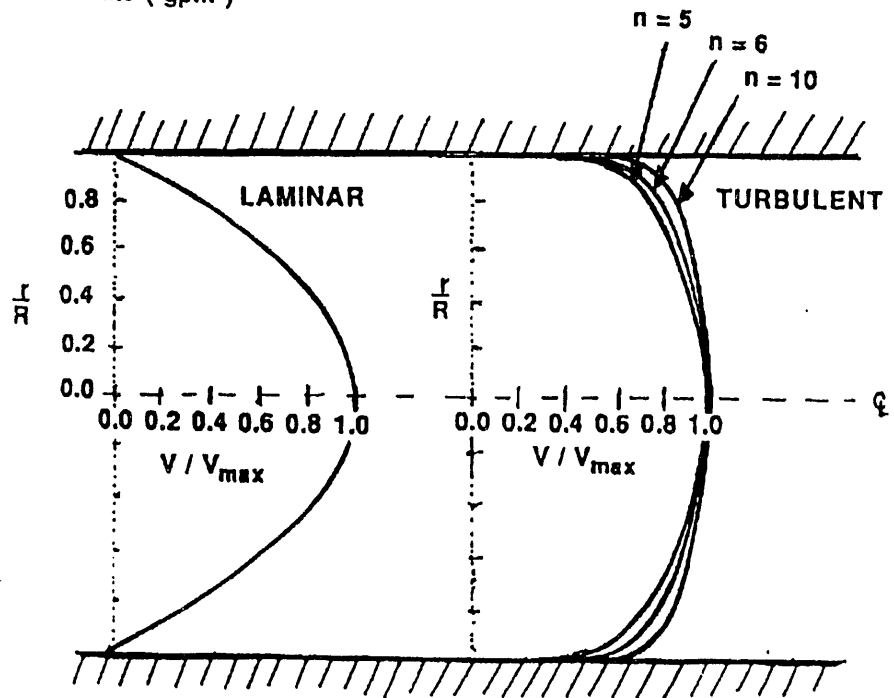


Figure 2. Velocity profile for laminar and turbulent flow as a function of distance from the center of the tube. The label "n" refers to the degree of turbulence present.



Very little change in the value of  $h$  occurs with considerable change in  $V_a$ . This is clearly in disagreement with the data, so either the relative values of the coefficients  $A_1$  and  $A_2$  are wrong, or the values of the exponents,  $n$  and  $m$ , on  $Re$  and  $Pr$ , respectively, are wrong. If one calculates  $h$  for the core-drilled channels in the CHESS experiments, the comparison is just as poor. Substituting  $d = 0.24$  cm in equation 8,

$$h = 1.38 [ 7 + 0.0365 V_a^{0.8} ]. \quad (11)$$

Calculating the values of  $h$  for the 3 points on the upper curve:

$$\begin{aligned} h &= 1.38 [ 7 + 3.053 ] = 13.9 \text{ W / cm}^2, \text{ }^\circ\text{C} \text{ (256 cm / sec) (2 gpm)} \\ h &= 1.38 [ 7 + 4.228 ] = 15.5 \text{ W / cm}^2, \text{ }^\circ\text{C} \text{ (384 cm / sec) (3 gpm)} \\ h &= 1.38 [ 7 + 5.316 ] = 17.0 \text{ W / cm}^2, \text{ }^\circ\text{C} \text{ (512 cm / sec) (4 gpm)}. \end{aligned}$$

This dependence gives some change with flow rate but not nearly enough to match the CHESS data. The Reynolds numbers for the flow rates are  $2.46 \times 10^4$ ,  $3.69 \times 10^4$ , and  $4.92 \times 10^4$  for 2 gpm, 3 gpm, 4 gpm, respectively. All of these values are well into the turbulent flow range. These  $Re$  numbers suggest that one should use the more conventional coefficients,  $m = 0.4$  and  $n = 0.8$ , for  $Pr$  and  $Re$ , that Baker and Tessier<sup>1</sup> suggests for fluids with  $Pr$  greater than 0.7 and  $Re = 10^4$  to  $1.2 \times 10^5$ . Using these values,

$$h = (k / d) [ 7 + 0.025 Re^{0.8} Pr^{0.4} ]. \quad (12)$$

Substituting for  $Re$  and  $Pr$ ,

$$h = (k / d) [ 7 + 0.025 (d / \nu)^{0.8} (\nu C_v / k)^{0.4} (V_a)^{0.8} ]. \quad (13)$$

Substituting  $d = 0.121$  cm for the case of gallium cooling,

$$h = 2.73 [ 7 + 0.228 V_a^{0.8} ]. \quad (14)$$

Calculating  $h$  for the rectangular channel CHESS experiment:

$$\begin{aligned} h &= 2.73 [ 7 + 4.57 ] = 31.6 \text{ W / cm}^2, \text{ }^\circ\text{C} \text{ ( 42.4 cm / sec) (0.5 gpm)} \\ &= 2.73 [ 7 + 7.95 ] = 40.8 \text{ W / cm}^2, \text{ }^\circ\text{C} \text{ ( 84.8 cm / sec) (1.0 gpm)} \\ &= 2.73 [ 7 + 11.02 ] = 49.2 \text{ W / cm}^2, \text{ }^\circ\text{C} \text{ (127.2 cm / sec) (1.5 gpm)} \\ &= 2.73 [ 7 + 13.85 ] = 56.9 \text{ W / cm}^2, \text{ }^\circ\text{C} \text{ (169.6 cm / sec) (2.0 gpm)}. \end{aligned}$$

These values show much more variation but still less than the data. The improvement in the value of  $h$  that is seen in the experimental data comes from the change in the velocity profile

of the cooling fluid in the channel from laminar to turbulent (see figure 2). Calculating  $h$  for the core-drilled case, using eq. 13:

$$h = 1.38 [ 7 + 0.112 V_a^{0.8} ]. \quad (15)$$

Calculating the values of  $h$  for the 3 points on the upper curve in figure 1:

$$\begin{aligned} h &= 1.38 [ 7 + 33.00 ] = 55.2 \text{ W / cm}^2, \text{ }^\circ\text{C} \quad (253 \text{ cm / sec}) (2 \text{ gpm}) \\ h &= 1.38 [ 7 + 45.69 ] = 72.7 \text{ W / cm}^2, \text{ }^\circ\text{C} \quad (380 \text{ cm / sec}) (3 \text{ gpm}) \\ h &= 1.38 [ 7 + 57.44 ] = 88.9 \text{ W / cm}^2, \text{ }^\circ\text{C} \quad (506 \text{ cm / sec}) (4 \text{ gpm}). \end{aligned}$$

This dependence comes close to matching the experimental results. Although the match to the Pr numbers suggested by Baker and Tessier<sup>1</sup> is poor, the Re numbers ( $1.2 \times 10^4$  to  $4.8 \times 10^4$ ) match their suggested turbulent values ( $10^4$  to  $1.2 \times 10^5$ ) quite well. Thus the appropriate turbulent conditions are present in the core-drilled channels for flow rates equal to or greater than 1 gpm.

The Pr value of water (Pr = 6.4) used as a cooling fluid match quite well the condition suggested by Baker and Tessier<sup>1</sup> for equation 13. The Re numbers for flow rates of 2 gpm, 3 gpm, and 4 gpm, are  $6.1 \times 10^3$ ,  $9.1 \times 10^3$ , and  $1.21 \times 10^4$ . These values just overlap the suggested range for Re of  $10^4$  to  $1.2 \times 10^5$  for the use of equation 13. Substituting the appropriate values for water in equation 13, for water in the core-drilled case, one has:

$$h = 0.0267 [ 7 + 0.666 V_a^{0.8} ] : \quad (16)$$

$$\begin{aligned} h &= 0.0267 [ 7 + 55.71 ] = 1.67 \text{ W / cm}^2, \text{ }^\circ\text{C} \quad (253 \text{ cm / sec}) (2 \text{ gpm}) \\ h &= 0.0267 [ 7 + 77.14 ] = 2.25 \text{ W / cm}^2, \text{ }^\circ\text{C} \quad (380 \text{ cm / sec}) (3 \text{ gpm}) \\ h &= 0.0267 [ 7 + 97.01 ] = 2.78 \text{ W / cm}^2, \text{ }^\circ\text{C} \quad (506 \text{ cm / sec}) (4 \text{ gpm}). \end{aligned}$$

The calculated values for  $h$  are much smaller for the water cooling case than for the gallium cooling case. Also, the first term in the brackets is small compared to the second term that varies with velocity and can, to first order, be ignored. The multiplier in front of the brackets ( $k / d$ ) is quite small compared to the gallium case because the value of  $k$ , the coefficient of thermal conductivity, is much smaller for water than for gallium. Reducing the value of  $d$ , the hydraulic diameter, increases the multiplier, but at the same time, reduces the second term in the brackets. Thus, when water is used in the slotted crystal cooling case:

$$h = 0.0529 [ 7 + 0.385 V_a^{0.8} ] : \quad (17)$$

$$\begin{aligned} h &= 0.0529 [ 7 + 7.72 ] = 0.778 \text{ W / cm}^2, \text{ }^\circ\text{C} \quad ( 42.4 \text{ cm / sec}) (0.5 \text{ gmp}) \\ h &= 0.0529 [ 7 + 13.43 ] = 1.081 \text{ W / cm}^2, \text{ }^\circ\text{C} \quad ( 84.8 \text{ cm / sec}) (1.0 \text{ gmp}) \end{aligned}$$

$$h = 0.0529 [ 7 + 18.58 ] = 1.353 \text{ W / cm}^2, \text{ }^\circ\text{C} \text{ ( 127.2 cm / sec ) (1.5 gmp)}$$

$$h = 0.0529 [ 7 + 23.39 ] = 1.608 \text{ W / cm}^2, \text{ }^\circ\text{C} \text{ ( 169.6 cm / sec ) (2.0 gmp)}.$$

Again, the values of  $h$  are much smaller for the water cooling case than the gallium cooling case. Reducing the hydraulic diameter and increasing the velocity of the flow will increase the value of  $h$ , but only slowly. If we substitute the values for water with  $d = 0.05$  cm, in the first case considered for gallium, one has

$$h = 0.128 [ 7 + 0.190 V_a^{0.8} ]: \quad (18)$$

$$h = 0.128 [ 7 + 7.56 ] = 1.86 \text{ W / cm}^2, \text{ }^\circ\text{C} \text{ (100 cm / sec)}$$

$$h = 0.128 [ 7 + 7.56 ] = 2.58 \text{ W / cm}^2, \text{ }^\circ\text{C} \text{ (200 cm / sec)}$$

$$h = 0.128 [ 7 + 7.56 ] = 3.23 \text{ W / cm}^2, \text{ }^\circ\text{C} \text{ (300 cm / sec)}.$$

No major improvement occurs and the value of  $h$  is only moderately higher than the values obtained when the core-drilled crystal was cooled with water and much lower than when the core-drilled crystal was cooled with gallium. In order to obtain a major increase the value of  $h$ , it is necessary to use very narrow channels. Tuckerman<sup>3,4</sup> has developed a formalism for the use of microchannels with water cooling. He optimizes the width of the channel,  $W_c$ , with equation 19,

$$W_c = 2.29 [ \mu k_f / C_v ]^{0.25} [ Nu_\infty ]^{0.25} [ L ]^{0.5} [ P ]^{0.25}, \quad (19)$$

where  $Nu_\infty$  is the Nusselt number with no end effect ( $Nu_\infty = 7$ ),  $L$  is the length of channel, and  $P$  is the pressure drop across the channel. The height of the channel  $H_c$  is calculated from equation 20,

$$H_c = m W_c ( k_s / Nu_\infty k_f )^{0.5} \quad (20)$$

where  $k_s$  is the thermal conductivity and  $m$  is a value between 1 and 2. The optimized value of  $h$  is then given by equation 21,

$$h = 0.125 L^{-0.5} [ k_f C_v / \mu ]^{0.25} [ k_w ]^{0.5} [ Nu ]^{0.25} [ P ]^{0.25}, \quad (21)$$

where  $k_w$  is the thermal conductivity of the wall of the channel and  $L$  is the length of the heated area. This equation assumes fully established laminar flow, thus the pressure drop  $P$  across the channel is given by equation 22,<sup>5</sup>

$$P = 32 \nu L V_a / (d)^2 \quad (22)$$

where  $d$  is given by equation 6. Substituting the values for water and a pressure drop of 35

psi,  $L = 1$  cm,  $W = 1$  cm, and  $W_c = W_w$ , where  $W_w$  is the thickness of the walls between the channels, one obtains:

$$\begin{aligned} W_c &= W_w = 0.0056 \text{ cm} \\ H &= 0.0360 \text{ cm} \\ h &= 30 W / ^\circ\text{C}, \text{ cm}^2. \end{aligned}$$

Assuming laminar flow (one of the requirements for this formalism), one can calculate the volume flow  $q$  through a single channel using equation 23,

$$q \text{ (cm}^3/\text{sec)} = 718 H (W_c)^3 [\mu]^{-1} [\Delta P / \Delta L], \quad (23)$$

where  $W_c$  is the width of the channel in cm,  $H$  is the height of the channel in cm,  $\mu$  is the viscosity in poise, and  $[\Delta P / \Delta L]$  is the pressure change in psi per cm length of the channel. Equation 23 gives  $q = 0.0159 \text{ cm}^3 / \text{sec}$  for a single channel. In a 1 cm width of cooling plate there will be 89 channels, so the total water flow  $q$  (total) through the plate will be  $1.418 \text{ cm}^3 / \text{sec}$ . This means that a 500 Watt load on the cooling plate will raise the temperature of the cooling fluid by  $85.5 \text{ }^\circ\text{C}$ . The  $\Delta T$  between the fluid and wall would be  $500 / 30 = 16.7 \text{ }^\circ\text{C}$ , thus the rise in the cooling fluid temperature is the dominant term. The average velocity of the fluid in the channels can be calculated by dividing  $q$  by the area of the channel,

$$V_a = q / \text{Area} = 79 \text{ cm} / \text{sec}, \quad (24)$$

and

$$\text{Re} = \rho d V_a / \mu = 77. \quad (25)$$

Any value of  $\text{Re}$  below 2000 can be considered laminar flow.

Substituting the values for gallium in the above equations for optimized microchannels, one has  $W_c = W_w = 0.0194$  cm, and  $H = 0.9 m W_c$ . Let  $m = 1.1$  and  $2.0$ , then  $H = 0.0194$  cm and  $0.0349$  cm, and  $h = 34.6 W / ^\circ\text{C}, \text{ cm}^2$ . This value of  $h = 34.6 W / ^\circ\text{C}, \text{ cm}^2$ , gives a  $\Delta T$  between the fluid and the wall of  $14.5^\circ\text{C}$ . Calculating the volume flow per channel from equation 23,  $q = 0.237 \text{ cm}^3 / \text{sec}$  and  $0.662 \text{ cm}^3 / \text{sec}$  for the two values of  $H$ . A cooling plate width of 1 cm will have 25 channels, and the total flow through the cooling plate will be  $25 q = 5.93 \text{ cm}^3 / \text{sec}$  and  $10.7 \text{ cm}^3 / \text{sec}$  for the two values of  $H$ . The average velocity in the channels will then be  $V_a = 630 \text{ cm} / \text{sec}$  and  $978 \text{ cm} / \text{sec}$ , and  $\text{Re} = 4888$  and  $7589$  for the two values of  $H$ . These values are much larger than our limit of  $\text{Re} = 2000$  for laminar flow, so the microchannel formalism of equations 19-21 can not be applied to the gallium case. This suggests that one should use equation 12 to calculate  $h$  for even this microchannel-optimized case. If the average velocities were as high as calculated above for the laminar flow case then the cooling fluid temperature would rise

only 0.0703 and 0.0389 °C / watt / cm<sup>2</sup> of heat load. A 500 W heat load on the cooling plate would raise the temperature of the cooling fluid by 35°C and 19.5°C for the two values of H.

The Re numbers 4888 and 7589 are well into the turbulent flow region so it is necessary to recalculate the average velocity and flow rate for the gallium-cooled "microchannel optimized" cases discussed above. In the turbulent flow case, the pressure drop in the channel can be calculated from equation 26:

$$\Delta P = f L \rho (V_a)^2 / 2 d, \quad (26)$$

where L is the length of the channel, V<sub>a</sub> is the average velocity, d is the hydraulic diameter, ρ is the density of the cooling fluid, and f is the friction factor.<sup>5</sup> Equation 26 can be solved for the average velocity using the Re number suggested by the laminar example given above to obtain approximate values for f, the friction factor. This new value for the average velocity can then be used to obtain a better value for Re and the friction factor, and, after a few reiterations, one can obtain a value for V<sub>a</sub> that when used in equation 26 gives the assumed value of the pressure drop. This value of V<sub>a</sub> can be used to calculate the flow rate in a single channel and then the total flow rate in a cooling plate 1 cm wide. Setting W<sub>c</sub> = H = 0.0194 cm and P = 35 psi, one obtains:

$$\begin{aligned} V_a &= 650 \text{ cm / sec} \\ \text{Re} &= 5037 \\ q &= 0.244 \text{ cm}^3 / \text{sec} \\ q \text{ (total)} &= 6.3 \text{ cm}^3 / \text{sec} , \end{aligned}$$

and for W<sub>c</sub> = 0.0194 cm, H = 0.0349 cm and P = 35 psi, one obtains:

$$\begin{aligned} V_a &= 765 \text{ cm / sec} \\ \text{Re} &= 7428 \\ q &= 0.518 \text{ cm}^3 / \text{sec} \\ q \text{ (total)} &= 13.0 \text{ cm}^3 / \text{sec} . \end{aligned}$$

Substituting these two sets of values in equation 12, the equation that gave the best match to the experimental data for gallium cooling with turbulent flow, one obtains for the case of W<sub>c</sub> = 0.0194 cm, H = 0.0194 cm, and d = 0.0194 cm:

$$h = 17 [ 7 + 0.00489 V^{0.8} ], \quad (27)$$

$$h = 17 [ 7 + 0.870 ] = 133.8 \text{ W / °C, cm}^2 \quad (650 \text{ cm / sec}) ,$$

and for W<sub>c</sub> = 0.0194 cm, H = 0.0349 cm and d = 0.0240 cm:

$$h = 13.1 [ 7 + 0.00601 V_a^{0.8} ], \quad (28)$$

$$h = 13.1 [ 7 + 1.218 ] = 107.7 \text{ W / }^\circ\text{C, cm}^2 \text{ (765 cm / sec) .}$$

These values for  $h$  are three to four times higher than the laminar flow predictions and give a  $\Delta T = 3.7 \text{ }^\circ\text{C}$  and  $4.6 \text{ }^\circ\text{C}$  for the temperature difference between the fluid and the wall, and a  $\Delta T = 34 \text{ }^\circ\text{C}$  and  $16 \text{ }^\circ\text{C}$  for the rise in the temperature of the fluid for the two values of  $H$ . These relative values suggest that the value of  $H$  should be larger than  $0.0349 \text{ cm}$ . Setting  $H = 0.0700 \text{ cm}$  gives  $d = 0.0303 \text{ cm}$ ,  $V_a = 900 \text{ cm / sec}$ ,  $Re = 10900$ ,  $q = 1.22 \text{ cm}^3 / \text{sec}$ , and  $q(\text{total}) = 30.6 \text{ cm}^3 / \text{sec}$ . The value of  $h$  calculated from equation 12 is

$$h = 11 [ 7 + 0.00718 V_a^{0.8} ], \quad (29)$$

$$h = 11 [ 7 + 1.659 ] = 95.2 \text{ W / }^\circ\text{C, cm}^2 \text{ (900 cm / sec) .}$$

Using these values for  $h$ , a heat load of  $500 \text{ W}$  will give a  $\Delta T = 5.3 \text{ }^\circ\text{C}$  for the temperature difference between the fluid and the wall, and a  $\Delta T = 6.8 \text{ }^\circ\text{C}$  for the rise in the temperature of the fluid. The average temperature rise of the gallium relative to the inlet temperature, is  $5.3 + 6.8 / 2 = 8.7 \text{ }^\circ\text{C}$  and the maximum rise is  $12.1 \text{ }^\circ\text{C}$ . This is a factor of 7 lower than the optimized water case given above. Thus, one finds that the optimized values of the channel dimensions for gallium cooling will be calculated using a different formalism than one uses to calculate optimized values for water because one has turbulent flow in the gallium case and laminar flow in the water case. The net effect of the higher thermal conductivity of gallium is to allow one to use wider channels for the optimized gallium case than for the optimized water case. This leads to larger values for both the heat transfer coefficient  $h$  and  $q(\text{total})$ , the flow rate of the cooling fluid in the channels.

The reason that the turbulent flow case is more effective in removing heat is illustrated in figure 2 in which the velocity profile of laminar flow is compared to the velocity profile of turbulent flow in a circular tube. The much flatter velocity profile for the turbulent case is due to faster moving fluid closer to the surface of the channel. This increased velocity of the fluid near the surface carries away the heat more efficiently and increases the thermal gradient near the surface, which increases the heat transfer to the fluid and, at the same time, maintains a high flow rate for the cooling fluid. The turbulence in the fluid also increases the effective thermal conductivity of the fluid. This helps to transport heat to the central region of the channel where the velocity is the highest and improves the heat sink nature of the flowing fluid.

#### **4. THERMAL DISTORTIONS FROM HIGH HEAT LOADS**

Figure 3. illustrates the typical high heat load problem experienced by a two crystal monochromator subjected to a very intense x-ray beam.<sup>6</sup> The diffraction surface of the first

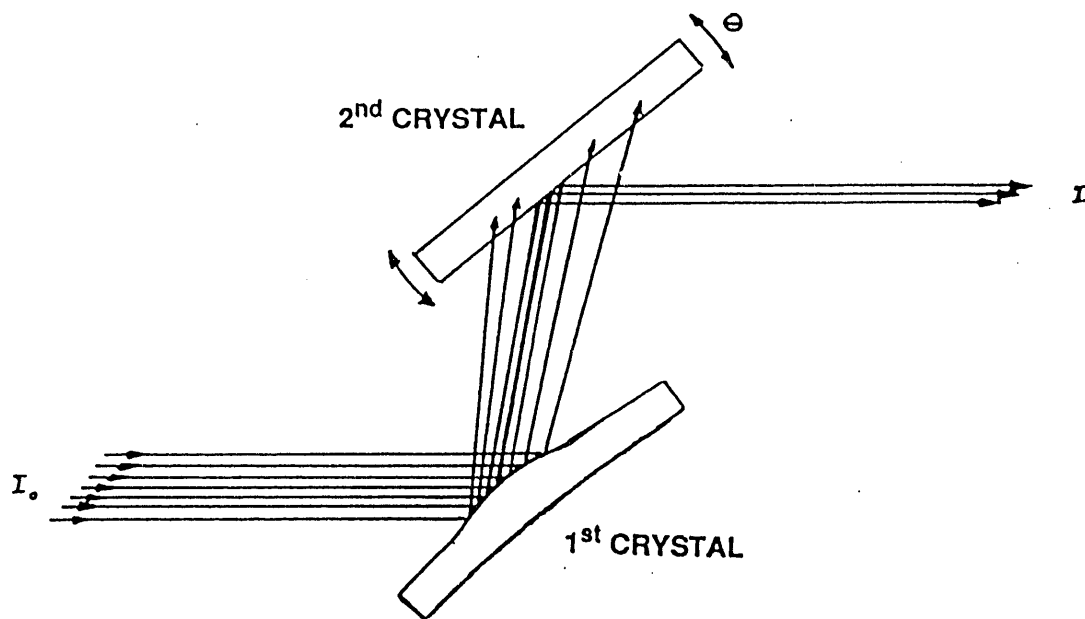


Figure 3. Schematic drawing of the two diffraction crystals in a two-crystal monochromator showing the effects of the heating the surface of the first crystal on the diffracted beam.

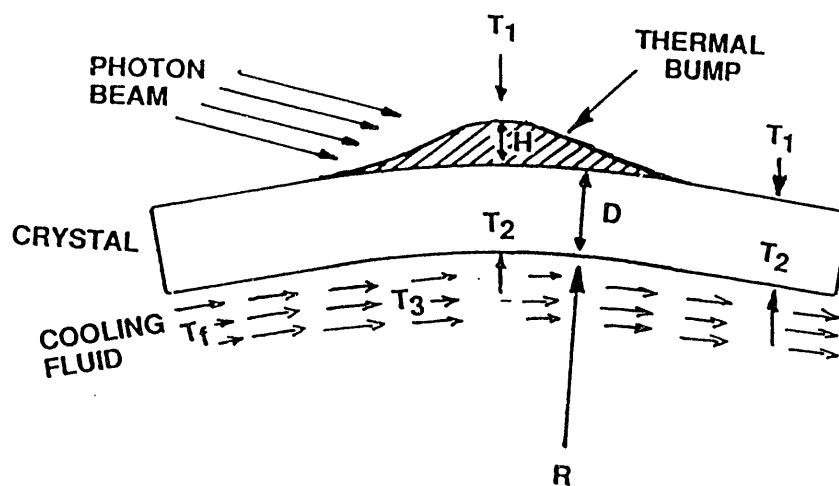


Figure 4. Schematic drawing of a silicon crystal showing distortion resulting from the high heat load of an intense x-ray synchrotron beam.

crystal becomes distorted in such a way that many of the photons that are diffracted by the first crystal do not satisfy the Bragg condition,  $n\lambda = 2d \sin\theta$ , and cannot be diffracted by the second crystal, resulting in a serious loss in intensity in a doubly-diffracted x-ray beam.

A detailed view of the distortions present in the first crystal appears in figure 4. The surface temperature of the crystal is given by equation (30), where the three  $\Delta T$ s are defined by equations 31-34:

$$T_1(\text{surface}) = \Delta T_{12} + \Delta T_{23} + \Delta T_3 + T_f \quad (30)$$

$$\Delta T_{12} = T_1 - T_2 = D Q / k \quad (31)$$

$$\Delta T_{23} = T_2 - T_3 = Q / h \quad (32)$$

$$\Delta T_3 = T_3 - T_f = (1 / H_c V_a C_v) \int Q(x) dx \quad (33)$$

$$\Delta T_1 = T_1 - T_f. \quad (34)$$

$T_1$  is the temperature of the diffraction surface,  $T_2$  is the temperature of the crystal surface in contact with the cooling fluid,  $T_3$  is the average temperature of the cooling fluid at some point as it passes through the crystal, and  $T_f$  is the temperature of the cooling fluid at the inlet.  $D$  is the thickness of the crystal above the cooling channel,  $Q$  is the heat flux per unit area,  $k$  is the thermal conductivity of the crystal,  $h$  is the heat transfer coefficient at the crystal-fluid interface,  $C_v$  is the volume specific heat of the cooling fluid,  $H_c$  is the depth of the cooling channel, and  $V_a$  is the average velocity of the cooling fluid.<sup>2,6</sup> This approximation assumes no spreading of the heat parallel to the surface of the crystal and that the crystal is a plate of uniform thickness cooled from the underside by a uniformly thick cooling channel. Note that  $h$  enters into only the value of  $\Delta T_{23}$ .

The heat load generates three different kinds of distortions in the crystal.<sup>6</sup> There is a general bowing of the crystal caused by the variation of the thermal expansion of the plate as a function of depth into the plate. If the crystal is a uniform plate, the radius of this bowing,  $R$  will be given by eq. (35).

$$R = D / \alpha \Delta T_{12}. \quad (35)$$

Substituting in equation 31 in equation 35,

$$R = k / \alpha Q \quad (36)$$



where  $\alpha$  is the coefficient of thermal expansion of the crystal. Equation 37 gives the interesting result that R does not depend on D, the thickness of the plate. Thus, a heat flux, Q, of 100 Watts per  $\text{cm}^2$  will generate a radius of curvature of 50 m in the surface of a silicon crystal. When the cooling fluid flows through cooling channels just below of the surface of the crystal, the thickness of the crystal below the cooling channels stiffens the crystal and eliminates most of this bowing.<sup>2</sup> The change in the angle of the surface per unit length  $\Delta\theta_s$  for a crystal with cooling channels just below the surface, is given approximately by equation 37,

$$\Delta\theta_s = \alpha [ (\Delta T_{12} / D) + \Delta T_{12} / (D + 0.5C) ] \times [ D^2 / L^2 ] \quad (37)$$

where D is the thickness of the top layer, C is the height of the channel, and L is the thickness of the crystal below the channels. When L is large this distortion becomes small. Thus, this distortion is usually not an important factor.

The second type of distortion, often referred to as the thermal bump, is caused by the expansion of the crystal in the direction perpendicular to the surface. The height of the bump H is given by equation 38,

$$H = \alpha \{ (\Delta T_{12} / 2) + \Delta T_{23} + \Delta T_3 \} D . \quad (38)$$

Substituting equations 31-32 in equation 38 one obtains

$$H = \alpha \{ (Q D^2 / 2k) + (Q D / h) + \Delta T_3 D \} . \quad (39)$$

If the shape of the thermal bump is Gaussian then the maximum slope error will be given by equation 40:

$$\Delta\theta \text{ max} = \pm 1.4 ( H / \text{FWHM} ) . \quad (40)$$

For  $Q = 100 \text{ Watts} / \text{cm}^2$ ,  $\text{FWHM} = 2 \text{ cm}$ ,  $D = 0.2 \text{ cm}$ , cooling fluid flow rate of  $100 \text{ cm}^3 / \text{sec}$  and  $h = 5 \text{ Watts} / \text{cm}^2$  and  $1 \text{ Watt} / \text{cm}^2$ , for gallium and water, respectively, the maximum slopes will be  $\pm 2.3 \text{ arc sec}$  for a liquid-gallium-cooled silicon crystal and  $\pm 9.2 \text{ arc sec}$  for a water-cooled silicon crystal. These slope errors are comparable to the Darwin widths for perfect crystals and would broaden the rocking curves for these energy photons. For large thicknesses of the top layer (large D), the first term will dominate, but for small values of D, as is the case in the example given above, the second term, with h in the denominator, will dominate. Thus, the large value of h for gallium is responsible for the improved cooling with liquid gallium. In both examples, the dominate term is the one containing h. For gallium, it contributes 70 % of the effect, and, for water, it contributes 94 % of the effect.

In practice, one reduces D to the smallest value that one can without disturbing the

surface of the crystal. Experiments have demonstrated that a value of  $D = 0.06$  cm is acceptable. Using this value with a  $Q = 500$  Watts,  $FWHM = 2$  cm, cooling fluid flow =  $100$   $\text{cm}^3 / \text{sec}$  and values of  $h = 25$  and  $5$  for gallium and water, respectively, the maximum slopes will be  $\pm 0.83$  arc sec for a liquid gallium-cooled silicon crystal and  $\pm 2.9$  arc sec for a water-cooled silicon crystal. Again, the term containing  $h$  is the main contributor to the surface distortion. In the gallium case, this term contributes 62 %, and in the water case, the second term contributes 90 % of the effect. The above examples are not meant to be a direct comparison of gallium cooling to water cooling in any single set of conditions because the optimized dimension of the channels will be different in the two cases, but rather, examples of how the value of  $h$  affects the distortion of the cooled crystal.

Decreasing the width of the cooling channel will increase the heat transfer coefficient and reduce the distortion, but this will also reduce the cooling fluid flow rate and increase the importance of the third term in equation 39. In the microchannel case with optimized water cooling, the value of  $h$  was raised to  $30$   $\text{W} / ^\circ\text{C}, \text{cm}^2$ , but the flow was reduced to  $1.42$   $\text{cm}^3 / \text{sec}$ , for a  $1$  cm wide strip of cooled surface,  $1$  cm long. It took  $35$  psi of pressure drop across the channels to achieve even this quite small flow. If this value was used in the above example with a heat load of  $500$  W, the temperature rise of the water would be  $86$   $^\circ\text{C}$  and the distortion from this third term would be comparable to the second term that involves  $h$ . The maximum slope error would increase from  $2.9$  to  $5.1$  arc sec. The optimized values for gallium gave larger channel dimensions and a much larger cooling fluid flow rate of  $30.6$   $\text{cm}^3 / \text{sec}$ . With this flow rate, the temperature of the cooling fluid would rise only  $6.8$   $^\circ\text{C}$ . This increase in temperature would increase the distortion in the crystal surface from  $0.83$  to  $1.15$  arc sec. The optimized gallium case gave a value for  $h = 95.2$   $\text{W} / ^\circ\text{C}, \text{cm}^2$ , which is 3 times the optimized value for water.

The third type of distortion in the crystal is the change in the crystal lattice spacing at the surface of the crystal due to the variation in the thermal expansion of the crystal caused by the variation of the surface temperature. This can be viewed as a variation in the diffraction angle  $\Delta\theta$ , given by equation (41):

$$\Delta\theta_d = \theta \alpha \Delta T_1 = \theta \alpha \left\{ D Q / k + Q / h + (1 / H_c V_a C_v) \int Q(x) dx \right\}. \quad (41)$$

For a silicon crystal (using 111 planes) with  $\Delta T_1 = 50$   $^\circ\text{C}$ ,  $\alpha \Delta T_1 = 1.5 \times 10^{-4}$ , and a photon energy of  $20$  keV, the maximum angular shift is  $3.0$  arc sec, and, at  $8$  keV, the maximum shift is  $7.7$  arc sec. These shifts are similar to the widths of the rocking curves of perfect silicon crystals at these energies and would, therefore, cause a mismatch between the first and second crystal in a double crystal monochromator and result in a loss of flux in the diffracted x-ray beam.

Substituting in equation 41, the slotted crystal example (silicon 111 planes) given above in which  $h$  is calculated from equation 13, with  $Q = 500$  Watts,  $D = 0.06$  cm,  $FWHM = 2$  cm, and a cooling fluid flow rate of  $100$   $\text{cm}^3 / \text{sec}$ ,  $h = 44$   $\text{W} / \text{cm}^2, ^\circ\text{C}$  for gallium and  $1.18$

$W / \text{cm}^2, ^\circ\text{C}$  for water. The maximum temperature rise for the gallium case is  $33.3 ^\circ\text{C}$  and, for the water case, is  $444 ^\circ\text{C}$ . These temperature increases result in angular shifts for the 20 keV case of 2.0 arc sec and 27.0 arc sec for the gallium and water cases, respectively. The angular shifts for the 8 keV case are 5.1 arc sec and 68 arc sec for gallium and water, respectively. The cooling fluid flow rate of  $100 \text{ cm}^3 / \text{sec}$  is large enough so that the effect of the third term in equation 41 is only a few percent of the total in both cases. The major reason for the large temperature rise for the water case is the low value of  $h$ . The channel width needs to be narrower in the water case to achieve a higher value of  $h$  and thus a lower maximum temperature rise.

If one uses the optimized values of  $h$  and the corresponding flow rates given in section 4, where  $h = 95 \text{ W} / \text{cm}^2, ^\circ\text{C}$  and  $q$  (total) =  $30.6 \text{ cm}^3 / \text{sec}$  for the gallium case and  $h = 30 \text{ W} / \text{cm}^2, ^\circ\text{C}$  and  $q$  (total) =  $1.42 \text{ cm}^3 / \text{sec}$  for the water case, and  $D = 0.06 \text{ cm}$  for both cases, then the maximum temperature rise for the gallium case is  $22.1^\circ\text{C}$  and for the water case is  $122.6 ^\circ\text{C}$ . The maximum angular shift is 1.3 and 7.4 arc sec for the gallium and water cases, respectively, for the 20 keV case and 3.4 arc sec and 18.8 arc sec for the gallium and water, respectively, for the 8 keV case. In the gallium-cooling case, the third term associated with the rise in cooling fluid temperature ( $6.8 ^\circ\text{C}$ ) accounts for 31 % of the temperature rise, and, in the water case, the third term ( $85.9 ^\circ\text{C}$ ) accounts for 76 % of the temperature rise.

## 5. SUMMARY

When the cooling channel size and shape are optimized for a liquid metal, such as liquid gallium, the optimum channel width or channel diameter is appreciably larger than those found for water. This results in higher flow rates, higher fluid velocities in the cooling channels, and higher Reynolds numbers. The net effect is that the two cooling fluids operate in different flow regimes. The optimized water cooling is in the laminar flow region, and the optimized gallium cooling is in the transition region between laminar flow and turbulent flow at low flow rates and well into the turbulent flow region at high flow rates. The velocity profiles in a tube or channel are quite different for these two cases, and this leads to the different formulations of the calculations used to determine the heat transfer coefficient. This difference is illustrated in figure 2 where the velocity profile for laminar flow in a tube is compared to the velocity profile for turbulent flow. The laminar flow shows a parabolic-shaped velocity profile, while the turbulent flow case becomes flatter as turbulence develops. Thus, the velocity gradients can be much higher in turbulent flow, and the distance that the heat must flow before it is carried away by the flowing fluid can be much shorter. This occurs because there is additional momentum transfer between the high velocity stream near the center of the tube and slow moving regions near the wall. Thus, the transfer of both heat and momentum is increased in the liquid metal case as compared to the water case. The higher flow rates make it easier to keep the rise in the cooling fluid temperature within acceptable limits and reduce its contribution to the distortion of the crystal surface.

## **6. ACKNOWLEDGMENTS**

The author would like to thank Shawn Rogers and Ali Khounsary for their comments and suggestions on this subject. This work was supported by the Department of Energy, BES-Materials Sciences, under contract No. W-31-109-Eng-38.

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