LIQUID METAL TARGET DEVELOPMENT FOR THE GERMAN NEUTRON SOURCE (SNQ)

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1. INTRODUCTION

The heat released in the target of the German neutron source (1100 MeV; 5 mA) amounts to several MW and must be continuously transported to a heat sink. Two different target systems are under consideration:

. A solid lead target system designed as rotating wheel with internal cooling passages /1/ and
. a liquid lead or lead bismuth target system provided with a flowing liquid metal circulated through a heat transport loop.

This contribution concentrates on the work performed for the liquid metal target system. The target system can be designed in different ways, for example:

. As a vertical cylinder with a free liquid surface at the top of the target (in analogy to /2/. The proton beam enters this target vertically.
. As horizontal curved channel of rectangular cross section in which the flowing metal forms a nearly free liquid surface at the inner curvature of the channel. The proton beam enters this target horizontally.

Most theoretical and experimental work was carried out for the vertical cylinder target, only theoretical investigations have been performed up to now for the horizontal arranged flat channel target. In the following the main results will be summarized subdivided in the topics:

. The liquid metal heat transport system.
. The liquid metal targets and their main fluid dynamic and thermodynamic characteristics.
. The proof of the operation of a liquid metal system.

2. THE LIQUID METAL HEAT TRANSPORT SYSTEM

An eutectic mixture of lead bismuth was chosen as target material. It is contained and circulated in a coolant circuit. The heat released in the target is transported from the primary coolant system via heat exchangers to a secondary alkali metal coolant circuit and finally to air. The primary system can be connected to a purification loop if necessary. The total PbBi inventory can be drained into a dump tank. The overall liquid metal target heat transport system is shown in Fig. 1. Both target versions can in general be connected to the heat transport loop.

Using lead bismuth as target material, two temperature limits must be taken into account due to corrossion effects /3,4/:

. The maximum temperature of structural materials should be $\leq 450^{\circ}C$ and
. the maximum temperature difference within the heat transport system should be $\leq 125^{\circ}C$.

For these conditions low alloy ferritic steels can be used as structural materials. In addition, the minimum fluid temperatures should be kept well about the liquid metal freezing point.

The basic thermodynamic and fluiddynamic data of the primary heat transport system were calculated for a variety of operational conditions /5,6/ assuming a maximum temperature of the structural materials of $450^{\circ}C$, which is identical to the averaged maximum fluid temperature. Fig. 1 shows the main characteristics of the heat transport system for a target power of 4.2 MW and fluid temperature increases of $125^{\circ}C/20^{\circ}C$ for the cylindrical/flat channel target respectively. The minimum temperatures of the primary circuit of $325^{\circ}C/430^{\circ}C$ then provide an excellent safety margin over the eutectic Pb Bi freezing point which is $125^{\circ}C$. The mean temperature level of the primary system is large enough to allow a good heat transport from the primary via the secondary circuit to air without requiring too large dimensions of the circuit components /6/. Instead of lead bismuth pure lead could be chosen as target material. In this case the overall operation conditions of the primary and alkali metal heat transport circuit must be increased at last by $50^{\circ}C$ for the cylinder target due to the Pb freezing point of $327^{\circ}C$. The corrosion determined temperature limits however are less stringent in comparison to PbBi as target material.

From these considerations it follows that the heat transport from the target to the heat sink is feasible and that the components of the heat transport system (pumps, heat exchangers, etc.) seem manufacturable.

3. THE LIQUID METAL TARGET AND ITS MAIN FLUID DYNAMIC AND THERMODYNAMIC CHARACTERISTICS

3.1 The Vertical Cylinder Target

This target consists of two coaxial tubes connected by a hollow jet nozzle at the top of the target (Fig.1). In this case the cooled liquid from the heat exchanger flows upward through the annulus. At the top of the annulus the flow is reversed and forms a rotational symmetric hollow jet which at an appropriate axial level coalesces forming the beginning of the free falling cylindrical target (Fig. 2b). The proton beam enters the hollow jet nozzle and reaches the target surface at the point of coalescence. The heat is released along the cylindrical target and transported by circulating back the liquid target material via a pump to the heat exchanger. This target design is characterized by:

- a vertical arrangement,
- a free liquid surface (without fluid guiding walls within the proton beam),
- a flow direction where the lowest fluid temperatures prevail at the target, section with the highest thermal load,
- an axisymmetric temperature distribution with maximum values in the axial center and minimum values at the periphery of the flow,
- high flow velocities (several m/s) and small target diameters.

Essential parameters determining the flow and heat transport characteristics of the jet nozzle and the target were investigat theoretically /7/ - /9/. Experiments were performed in water and are in preparation for liquid metal flow to support the theoretical calculations.

The main fluid dynamic results are:

- The flow characteristic of the hollow jet is determined by the nozzle contour. The point of coalescence is mainly a function of the Froude-Number ($Fr = u_0/\sqrt{g \cdot r_0}$, where u_0 is the flow velocity at and r_0 the radius of the nozzle entrance, and g the gravity). In addition the Euler- as well as the Weber-Numbers are of influence. Fig. 2a shows the axial position of the point of coalescence for various Froude-Numbers plottet versus the x/r_0-ratio of a typical nozzle geometry. Theoretical and experimental data are in good agreement. In addition a photograph of a typical hollow jet contour measured in a water flow is reproduced (Fig. 2b).

  Measured velocity profiles in front of and behind the point of coalescence lead to the conclusion that a small velocity decrease together with high turbulence may prevail at the point of coalescence. The first effect stimulates the existence of a possible hot spot, the second diminishes this possibility. To describe these effects quantitatively the velocity profiles will be determined at the point of coalescence in detail by us of a Laser-Doppler-Anemometer.

Thermodynamic characteristics of the vertical cylinder target were determined. Due to the global calculations of the basic fluid dynamic and thermodynamic characteristics of the primary heat transport system the liquid metal mass flow rates are known. Demands of target neutronics call for a target diameter of about 10 cm. Both magnitudes determine the flow velocity of the target and the hollow jet nozzle contour. For the characteristics shown in Fig. 1 the point of coalescence is reached approximately 35 cm downstream of the nozzle inlet. the target velocity being about 3 m/s.
For these flow parameters the temperature fields were calculated assuming an exponential power decrease in axial target direction and a radial Gaussian (variance σ = 2.5 cm) power distribution. Based on these power distributions, Fig. 2c indicates the calculated radial temperature distributions at different axial target positions. These calculations assume slug flow, steady state conditions and neglect turbulent heat conduction within the fluid. It can be seen that

- the radial temperature variations across different axial target sections (Z) take a Gaussian curve, and that
- the maximum temperature increase ΔT is calculated to be 440 ^{o}C at the end of the target axis while the target periphery remains at inlet temperature.

These main fluid dynamic and thermodynamic design data are extreme values. The calculations result in a high local temperature at the end of the target axis. Despite this high temperature, a flow instability must not be expected. Evaporation at the axis of a free falling liquid metal jet can be excluded taking notice of surface tension effects, by guiding the flow in a liner or by reducing the temperature level of the primary coolant circuit (in case of PbBi). In addition future calculations must be based on more realistic power distributions, taking into account turbulence effected radial heat exchange (measurements are in progress).

3.2 The Horizontal, Rectangular, Curved Channel Target

This target consists of a horizontal channel curved about 180 degree. The liquid enters the channel and is forced to flow at right angle to the proton beam which penetrates the liquid horizontally at the inner curvature of the channel. Here the fluid is enclosed only on three sides. A free liquid metal surface can be stabilized by the centrifugal forces acting in direction to the outer curvature of the channel. After passing the proton beam the liquid reaches a diffuser and a dump tank. The heat released by the proton beam across the longer aspect of the flow channel is transported by circulating back the liquid target material via a pump to the heat exchanger (Fig. 1). This target features

- a horizontal arrangement,
- a free liquid surface (without fluid guiding walls at the proton entrance to the target),
- high flow velocities and small target diameters.

Essential parameters determining the flow and heat transport characteristics of the target were investigated theoretically /11/, and experiments are in preparation to support the calculations.

The main fluid dynamic results are:

- A minimum flow velocity must be generated to get centrifugal forces able to realize a free surface contour in the vacuum approximately vertical to the proton beam. Calculated results (not taking into account wall friction) are shown in Fig. 3a. It can be seen that the flow velocities must reach approximately 2 m/s to keep the fluid well stabilized at the outer curved channel wall. This does also impose that at the beam entrance a valve must be forseen to avoid voiding of the flow channel in cases of flow reduction and start ups.
- This flow velocity must be sufficiently high to support the axial fluid transport. Due to the fact that there exists no pressure gradient in flow direction between the vacuum system at the free liquid surface and the dump tank the driving forces for the fluid flow can only be achieved by the kinetic energy of the fluid. Calculations taking into account wall friction show that a velocity reduction of approximately 10 % is needed to avoid flow reversal and to maintain the fluid motion along a proper designed diffuser of about 2 m length before it flows vertically into the dump.

The main thermodynamic results are:

- The flow velocity should be high enough to avoid local temperature increases within the fluid which are too large. Fig. 3b shows as example the calculated temperature increases in flow direction for a fluid velocity of 2 m/s for different axial proton beam sections. It can be seen that about 150 °C temperature increase are to be expected along the free flow surface center line ($z = 0$).
- A minimum flow velocity - acceptable from the thermodynamic and fluiddynamic points of view - should be realized to avoid large mass flow rates ($\dot{m}$) and to keep the operational and design parameters of the heat transport circuit in a realistic range (heat exchanger, pumps etc.). In comparison to the cylinder target, an increase in mass flow rate must be taken into account due to the enlarged flow area of the flat channel and the necessary flow stabilizing velocities. An increase in mass flow rate by a factor of 3 to 5 seems reasonable, yielding flow velocities in the range of working liquid metal systems i. e. between 2 and 4 m/s, dependent mainly on the axial energy released by the proton beam, the target length, and the target thickness /11/.

These fluid dynamic and thermodynamic design data are assumed conservative. The main facts must be supported by model experiments in water flow which are in preparation.

4. OPERATION OF A LIQUID METAL SYSTEM

The manufacturing and handling of the liquid PbBi system must be investigated. In this respect great advantage can be drawn from liquid alkali metal circuits, where experience with loops of up to 100.000 hours of individual operation time is available. It seems that all components (instruments, pumps heat exchangers) may be manufactured satisfactorily in low-alloy ferritic steel in a temperature range up to 450 °C without raising too severe problems.

To get the special know how of a liquid PbBi system a small model circuit (mass flow rate 5 m^3/h) was built and a large one (mass flow rate 100 m^3/h; target scale 1:1) is under construction. These loops mainly serve to investigate the different liquid metal targets in PbBi flow, to support the results gained in water flow and to investigate the influence of a vacuum on the flow behavior. In addition the design, manufacturing, construction and operation of these loops will be of great use to collect experiences of a PbBi system and to define additional needs.

5. SUMMARY

From the fluid dynamic and thermodynamic point of view liquid metal can be used as target for a spallation neutron source. The heat generated in the target can be transfered to a heat exchanger and via an intermediate heat circuit to a heat sink. Vertically as well as horizontally arranged liquid metal targets seem possible. To support the design calculations for these targets model experiments in water and lead bismuth circuits were and are carried out. The operation of PbBi circuits should demonstrate that liquid metals can be reliably and safely used as targets for an advanced spallation neutron source.

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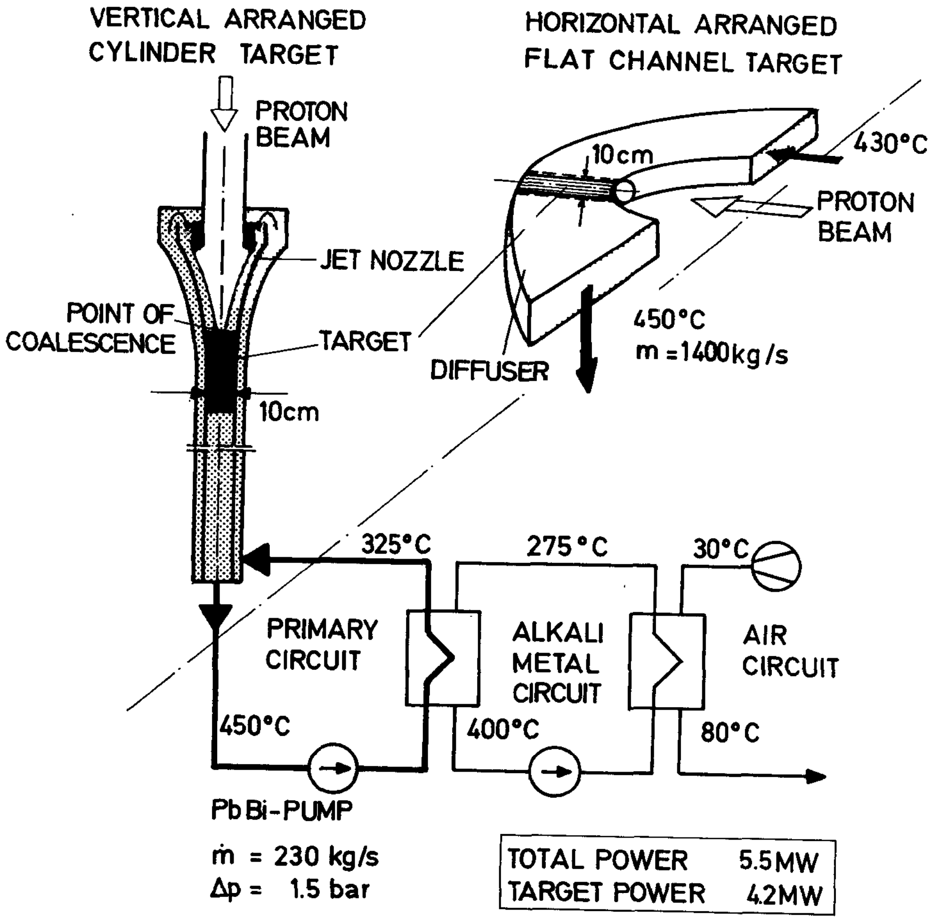
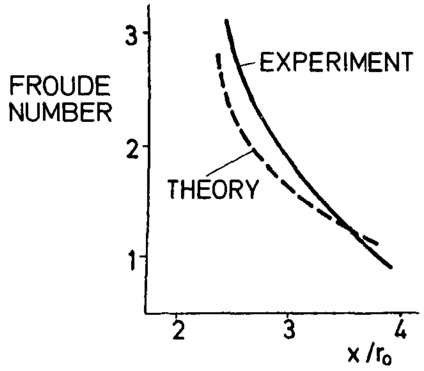
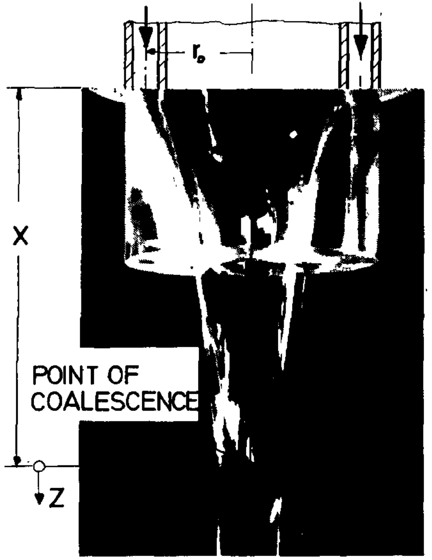


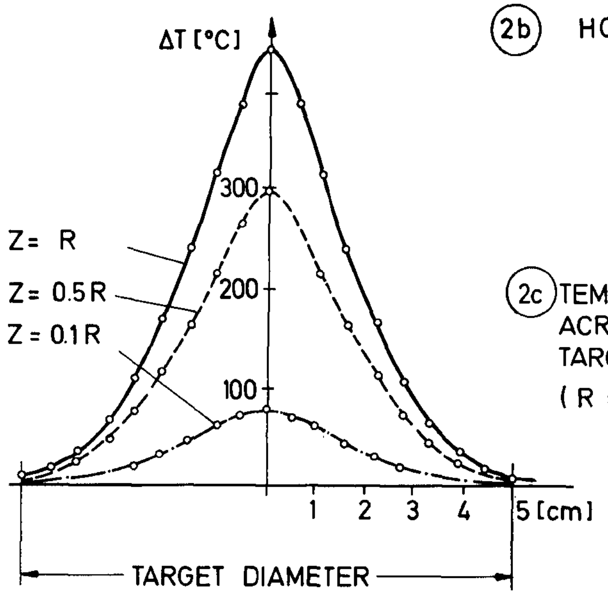
Fig. 1 HEAT TRANSPORT LOOP AND TARGET ARRANGEMENTS



(2a) POINT OF COALESCENCE VS. FROUDE NUMBER

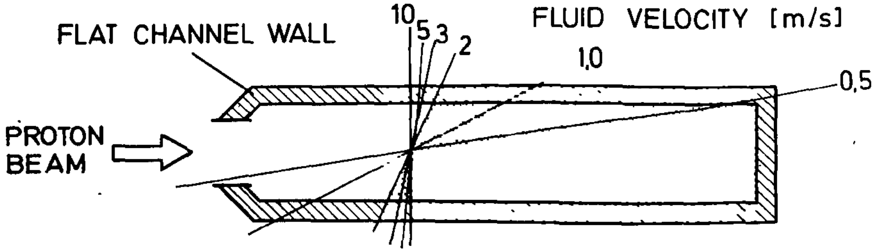


(2b) HOLLOW JET

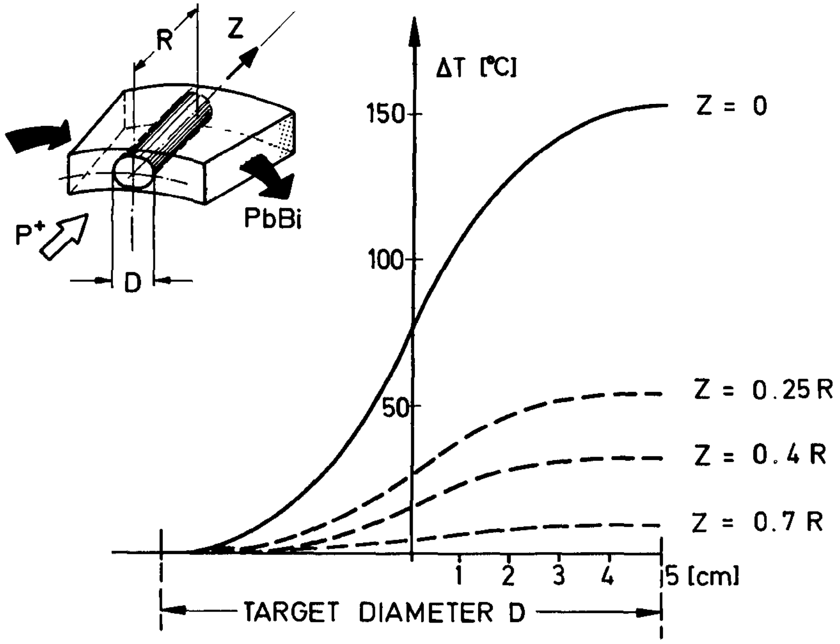


(2c) TEMPERATURE INCREASE ACROSS DIFFERENT TARGET SECTIONS Z
(R = BEAM PENETRATION)

Fig. 2 FLOW CONTOURS AND FLUID TEMPERATURES



(3a) FREE TARGET SURFACE CONTOURS FOR DIFFERENT FLOW VELOCITIES



(3b) TEMPERATURE INCREASE ACROSS DIFFERENT TARGET SECTIONS Z (R = BEAM PENETRATION)

Fig. 3 FLOW CONTOURS AND FLUID TEMPERATURES