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Target Options for SINQ - A Neutronic Assessment

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Abstract

In order to raise the neutron output of SINQ, now operating with a Zircaloy rod bundle target, several options of varying complexity are conceivable. This includes liquid metal targets as well as lead-based rod targets with different cladding materials, but also composite targets where the highest loaded zone is made from a different material than the bulk of the target, to keep thermal neutron absorption as low as possible.

Using the LAHET code system the neutronic performance of the various target concepts was examined in a first round in order to provide some guidance on the effect of different possible choices on the overall source performance.

This report will summaries some of the investigations for different target concepts and a parameter study related to a composite target with a tungsten core embedded in a lead body.

1. Introduction

Being a continuous neutron source with a large D_2O tank surrounding the target for neutron moderation and reflection, SINQ is particularly sensitive to neutron absorbing materials in or in the vicinity of its target. Different variants of targets for SINQ using solid and liquid target materials were initially studies by Atchison [1], [2], [3]. A thorough neutronic assessment was carried out for the system finally chosen for the commissioning and initial operating phases of the neutron source [4], namely a target made up from Zircaloy rods. These calculations were made with the HETC code for the high energy transport calculations and a locally extensively modified version of the O5R code with ENDF/B-IV cross section data for sub 15 MeV neutron transport. In the mean time the LCS code system [5] is being widely used for such calculations and it was of interest to apply this package to the SINQ case in order to be consistent with other groups and to compare results. First calculations with this system for the SINQ Zircaloy target

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were reported in a different paper [6]. Although results from earlier calculations could generally be confirmed, it was observed that flux values obtained with the LCS package tend to be lower than the earlier results. In cases where measurements on the actual system allowed direct comparison, good agreement with the LCS-result was found [7]. Therefore, in order to study options for the future development of the SINQ target, calculations were started and continue to be performed, using the LAHET-based code. Some special cases were modelled considering different target materials and the influences of structural materials.

As a first step, the rod bundle of the zircaloy target was described in detail to study its properties [6]. Next the consequences of modifications in the second target were studied [8], which will contain a number of test rods to examine radiation effects under the specific operating conditions of SINQ [9]. The present report describes preliminary results for alternative target concepts aiming at improving the neutronic performance and life time predictability of the SINQ target.

It is generally accepted that for a continuous neutron source as SINQ, lead will be the best target material from a neutronic point of view, because it gives good neutron yield and has low neutron absorption. However, the need to remove the heat from the target during operation will require either to introduce a cooling medium into the target material or to allow melting to move the lead in a circuit. The last option favours use of a low melting eutectic alloy (e.g. Pb-Bi) to operate at temperatures as low as possible. In terms of computer modelling, this target concept is relatively simple.

More complex models are needed if heterogeneous target designs are to be analysed that contain coolant and target material in relatively complicated arrangements. Besides neutronic performance the most important questions relate to power deposition in the target material and transmutation and gas production which can be the reason for life time limitations.

The most straight forward step in the development of the SINQ target is replacing the Zircaloy rods by lead filled tubes. In this case the choice of cladding (tube) material is of importance for neutronic reasons as well as for the safety of the target operation, especially in off-normal situations, where (partial) melting of the lead may occur.

Alternatively, it is conceivable to go for a composite target with an inner region of a highly temperature resistant (refractory) heavy metal and an outer ring and downstream part using lead. Both zones have to be cooled with heavy water. For practical reasons, all zones of this target will have a rod bundle structure, with corresponding materials filling of the cladding tubes.

2. Geometric model

In order to describe the SINQ facility regarding its use as efficient neutron source the outer zones like the moderator tank and shielding have to be accounted for in addition to the central target zone. This configuration is illustrated in Fig. 1 where the target region is represented only symbolically without any details.

The structure in the target region is shown in Fig. 2 for three different target versions as outlined above, version c consisting of different components with variable dimensions. This parameters will be investigated concerning their effect on performance The radius R and the height L of the refractory metal (tantalum) cylinder will be considered as parameters for the optimisation of the target performance. The lead zone around the tantalum will change in size accordingly, maintaining the outer dimensions to fit in the existing SINQ geometry.

For the current scoping study the targets were modelled to different degrees of detail: While the rod targets (Zircaloy and clad lead) were described as built up from individual rods and tubes as in the real design [6], no internal structure was assumed to exist in the liquid target models and the composite target was generated by varying the composition of individual zones in the target model as shown in Fig. 2c.

The beam profile used for all cases is as given in Ref. [6], a cylindrical beam with normalised Gaussian intensity distribution of standard deviation σ = 3.7 cm in both directions and truncated at a radius c*a, with c taken as 2. For the present purpose this approximates sufficiently well the distribution with σ_x = 3.3 cm and σ_y = 3.83 cm obtained from beam dynamics calculations. The beam energy is 570 MeV and all calculations are for 1 mA on target.

Since this study only aims at scoping calculations, no details of the materials distribution in the moderator tank were taken into account.

3. Thermal neutron field in the D_2O tank for the different target variants

3.1 Overview of results

In all calculations the zero level of the z-coordinate was taken as the centre of the moderator tank which coincides with the centre of the hemispherical bottom cap of the target container.

For the liquid metal target versions a completely filled 2 mm thick steel container with a radius of 9.6 cm was assumed and the safety hull was omitted. Clearly, this configuration can only give a first approximation to the target performance and more detail will have to be included as a design matures.

The isoflux contours obtained for the different target variants are shown in Fig 3.

Apart from the different maximum flux values obtained, the position of the flux maximum in the moderator tank (i.e. relative to the target) varies greatly. This is a consequence of the different average density on the one hand and of thermal neutron absorption in the target on the other. In the axial direction this effect could be compensated for by adjusting the target length if any of these variants were used. The difference being as much as 30 cm between Zircaloy and Mercury, this is an important piece of information. With the flux maximum being at the position of the beam tubes now, a Mercury target would have to be about 30 cm shorter in order to obtain the same situation again.

Although not immediately obvious from the contour plots, it is also observed that the radial position of the flux maximum varies markedly for the different target variants. This is due to the absence of moderation in the liquid metal targets on the one hand and to the flux depression near the target surface caused by absorbing materials on the other. In Fig. 4 the radial flux distributions found at the heights of the respective maxima are shown.

As expected, targets that contain only weakly absorbing materials produce a thermal neutron flux maximum near the target surface, while neutron absorption in the target results in a more or less pronounced flux depression near the target surface and in a flux peak at some distance from the target. Since the average position of the beam tube noses at SINQ is at a radius of about 25 cm with a width of 8 cm, it is the flux in this region which is important for the intercomparison. For the cold moderator the flux at the mean position of 40 cm and averaged over 20 cm is important These regions are marked in Fig 4. Some details and the results of parameter variations will be discussed in the following for the different target concepts.

3.2. Liquid metal targets

The most important technical problem with liquid metal targets is the operating temperature, because it immediately bears on the choice of the structural material, the concept of heat removal and on the precautions necessary for keeping the target molten at all times to avoid structural damage that might result from volume changes in the solid state and to ensure operational readiness after beam trips of any duration. Clearly a low operating temperature is most desirable. This is why the PbBi-eutectic mixture with a melting point of 125°C is most favoured. The only heavy metal with an even lower melting point (-39°C) is Mercury, which has a very high thermal neutron absorption cross section of 380 barns. In view of this high absorption it is surprising to see that even a Mercury target would give a significant flux improvement (70%) at the beam tube positions over the present Zircaloy target in SINQ. This is without any optimisation in terms of geometry, which might still be possible.

Clearly, with the high thermal neutron absorption in Mercury the thickness of the container wall should not play a role and has, therefore, not been investigated. This is different in the case of Lead-Bismuth. Fig 5 shows the results obtained for a variation of the thickness of the assumed steel container in the case of PbBi.

Due to the low intrinsic absorption in the PbBi, the absorption in the container wall has a marked influence on the source performance and great care will have to be taken in the optimisation procedure. It should be noted that, due to the power deposition in the container window, a thick wall will result in higher stress than a thin one, especially if cooling is to be accomplished via the liquid metal only. So far, no structural materials other than steel have been considered for PbBi, because too little is known about the behaviour of possible alternatives under the anticipated operating conditions. Also, in a more detailed study the internal structure of a liquid metal target will have to be accounted for in order to judge the real benefits in terms of neutronic performance. (Another benefit would, of course, be the absence of cooling water in the target volume, which is the source of most of the radioactivity in the cooling water plant room due to the production of ^{7}Be by spallation in the oxygen.)

3.3. Lead rod targets with different cladding materials

While the development of a liquid metal target still requires significant amounts of R&D work, the most straight forward way to improve SINQ's neutronic performance seems to be the use of lead rods instead of Zircaloy, as noted above. Since Lead, due to its corrosive and mechanical properties, cannot be used in water directly, some kind of cladding is required. In order to ensure sufficient mechanical stability of the rods, the temperature of the lead must either be kept below a value where creep becomes an issue, or the tubes must be rigid enough to be independent of the mechanical properties of Lead. This bears immediately on the choice of the cladding material and method. For reasons of simplicity of manufacturing it is assumed that Lead rods will be produced either by filling molten Lead into tubes or by inserting solid rods with a tight fit. One problem arising in this context is the high thermal expansion of lead, which might result in significant hoop stress in the tube walls upon heating. For this reason methods were investigated to establish good thermal contact between the lead filling and the tubes with the goal of being able to use Aluminium as tube material [10], [11]. Preliminary studies have shown, however, that the lead is likely to creep sufficiently rapidly even at moderate temperatures to expand into gaps that are left at the ends of the lead filling, so that no dangerous stress levels are reached in tubes of reasonable strength [12]. Of course, next to safety, the choice of the tube material is influenced by the neutron flux that can be expected in the moderator. Therefore different candidate materials were examined in a first run. Without accounting in detail for the fact that, from a mechanical point of view, the required wall thickness might depend on the material chosen, the wall thickness was assumed to be 0.75 mm in the cases of Aluminium and Zircaloy and 0.5 mm in the case of steel. The corresponding materials fractions were distributed homogeneously over the volumes of the rods but the heterogeneous distribution of rod material and coolant (D_2O) was simulated correctly. In all cases a target support structure (hexagonal casing) of Zircaloy was retained. The results of this study are shown in Fig. 6

According to these results, Zircaloy would be the best cladding material despite its higher neutron absorption cross section relative to Aluminium. This is attributed to the neutron production in the Zircaloy itself. The question whether Zircaloy can actually be used depends strongly on the effect of the hydrogen produced in the Lead and in the Zircaloy itself and mandates further investigation. Aluminium would be suitable if sufficient mechanical strength could be secured under all circumstances. However, since abnormal operating conditions (bypassing of Target E upstream of SINQ by part of the beam, see below) cannot be excluded, softening or even partial melting of the Lead inside the tubes should be an allowable situation. In this case, Aluminium is not considered a suitable structural material at least in the region of highest beam heating. The question, whether different tube materials can be used in different regions of the target needs yet to be investigated. For the time being, steel cladding is considered the safest choice, at least until sufficient data on the other options is available. This choice will yield a 60% increase of the neutron flux at the beam tubes over solid Zircaloy rods, although it will only yield 85% of the flux obtainable with Lead and Zircaloy cladding.

3.4. Composite Target

The phase space distribution of the proton beam on the SINQ target depends crucially on the interaction of the beam with the pion and muon production target "E" which the beam passes before being deflected onto SINQ. This is a rotating graphite target of 6 cm length and 6 mm width. The width is matched to the diameter of the proton beam at that position in order to optimise the output of surface muons. As a consequence of the interaction in this target the beam energy is lowered from 590 to 570 MeV and the phase space occupied by the beam is increased considerably, especially in transverse direction. Behind the target "E" the beam is scraped from its halo and reshaped for further low loss transport to SINQ [13]. If all beam hits the target "E", this results in the beam profile used for the present calculations. However, if part of the beam goes past target "E" unscattered, this results in an increase of the maximum current density on the SINQ target. The radial current density distribution on the SINQ window as a function of the fraction ε of the beam missing target "E" can be approximated by a sum of two Gaussian distributions:

$$i(r) = I_0 * [\varepsilon/(\pi\sigma_1^2)*\exp(-r/\sigma_1)^2 + \alpha(1-\varepsilon)/(\pi\sigma_2^2)*\exp(-r/\sigma_2)^2], \quad (1)$$

with I_0 being the current delivered by the accelerator and α the fraction of the collided beam that can be recollected and transported to SINQ ($\alpha \approx 0.57$) and σ_1 and σ_2 representing the standard deviations of the uncollided and the collided beam respectively. In our calculations we used 37mm for σ_2; σ_1 has been quoted as 13.4 mm [14], [15].

From equ. (1) it is obvious that the peak current density (at $r = 0$) more than doubles if 10% of the beam miss target E and goes up by more than a factor of 13 if all beam would go through uncollided. As can be seen from Fig. 7, however, all current density increase is inside a circle with a radius of 2.3 cm. Outside this area the current density decreases.

While it is likely that an Aluminium window will be able to cope with such an increase [15], the Lead in the target rods would certainly melt. This may not be a problem if the cladding material stays in tact, but if it is unacceptable, a target concept could be considered, where this central region is made up of a much more temperature resistant material, such as Tantalum or Tungsten, which show good neutron yield but are unsuitable for the full SINQ target because of their strong neutron absorption. As a first approach to such a concept the configuration shown in Fig. 2c with a Tantalum core was examined with respect to its neutronic and thermal characteristics under standard operating conditions, i.e. with the full beam passing through target "E". The thermal flux distributions for the reference core dimensions of 3 cm radius and 8 cm height have already been included in Figs. 3 and 4. It can be seen that, relative to a Zircaloy rod target the expected gain for this configuration is about a factor of 1.6, similar to a steel clad lead rod target.

In order to examine the effect of the size of the Tantalum core on the neutron flux in the moderator, its height and diameter were varied. The results obtained for the position at $z = 15$ cm and $r = 20$ cm are displayed in Fig. 8.

While there is obviously a marked dependence on the diameter, the effect of the length is moderate. (Note that the whole range of flux variation shown in Fig 8 is only about 12%!). From a neutronics point of view the optimum dimensions of the Tantalum core seem to be 5 cm in diameter and 6 to 8 cm in length. This diameter would be sufficient to avoid power surges in the Lead as a consequence of part of the beam missing target "E". The effect of the core length on the power density in the downstream Lead sector will be discussed in the next section.

4. Power deposition

Data on the power deposition in rod targets with Zircaloy and Lead as target material have already been given elsewhere [8]. Here we give some additional results on the composite target. Although the idea behind the composite target is to make power densities more manageable even in abnormal operating conditions, these questions will be examined in detail later. For the time being the change of the power density was investigated for the different dimensions of the inner tantalum cylinder and the corresponding outer lead zones only for the standard situation and in view of the effect on the downstream part of the target.

As for the Tantalum insert itself, its mean power density clearly changes as the diameter is varied because of the beam profile. The effect is less pronounced when the length of the insert is varied, probably because of build-up effects. The total effect for all cases considered (from volumes of 75 cm^3 to 400 cm^3) is in the region of about 20 % only.

The power deposition in the downstream Lead block is reduced by about 40% as the length of the Tantalum insert is varied from 4 to 14 cm.

The power deposited in the first Pb block also depends on the radius of the tantalum block, of course, because its inner radius changes accordingly. With the length of this lead zone is unchanged, the data given in Table 1 illustrate that there is a small reduction in the total power and in the sum of tantalum and the first lead block if the radius of the tantalum block is enlarged.

	radius of the Ta block [cm]		
	2	3	4
Ta	23.51	48.41	77.28
Pb 1	145.5	118.5	87.4
sum	169.01	166.91	164.68
Pb 2	148.3	146.3	144.6
total	317.31	313.21	309.28

Table 1: Distribution of the beam power (MeV/ proton) deposited in the different target zones and its shift when the diameter of the central Ta insert is varied

5. Conclusions

The present results clearly confirm that there is a potential for increasing the neutronic performance of SINQ significantly even with a solid target. The question, how closely the performance of a liquid metal target can be approached depends on the type and amount of structural material that must be employed in both cases. Table 2 gives an overview of relevant results.

	flux at 25 cm [cm^{-2} s^{-1} mA^{-1}]	relative to Zr	relative to Pb-Bi	flux at 40 cm [cm^{-2} s^{-1} mA^{-1}]	relative to Zr	relative to Pb-Bi
Zircaloy rods	3.25E+13	1.00	0.40	2.19E+13	1.00	0.38
Lead-Bismuth-eutecticum (2mm container)	8.15E+13	2.51	1.00	5.74E+13	2.62	1.00
Mercury	5.62E+13	1.73	0.69	4.07E+13	1.86	0.71
Lead rods without cladding	6.85E+13	2.11	0.84	4.47E+13	2.04	0.78
Lead rods with Zircaloy cladding (0.7 mm)	6.11E+13	1.88	0.75	4.02E+13	1.83	0.70
Lead rods with Aluminium cladding (0.7 mm)	5.84E+13	1.79	0.72	3.85E+13	1.75	0.67
Lead rods with Iron cladding (0.5 mm)	5.18E+13	1.59	0.64	3.49E+13	1.59	0.61
Lead rod target with Ta core	5.51E+13	1.69	0.68	3.52E+13	1.61	0.61

Table 2: Comparison of the expected thermal neutron flux levels for different target options for SINQ

If designing against large fractions of the beam missing the upstream target "E" becomes an issue, a composite target with a central insert of refractory metal may be a solution, provided that thermal hydraulics allow to cope with the high heat density. Possibly the flow of coolant must be influenced accordingly, since the fraction of beam power deposited in the insert would increase sharply as the beam narrows. In any case, the calculations show that, to a certain extent, absorbing material in the innermost region of the target can be tolerated without excessive penalties on the neutron flux in the moderator. This is corroborated by the observation that even a full size Mercury target would still perform approximately as well as a Lead rod target with steel cladding in terms of thermal neutron flux at the beam tube noses. More detailed calculations are, of course, required before a final decision is made.

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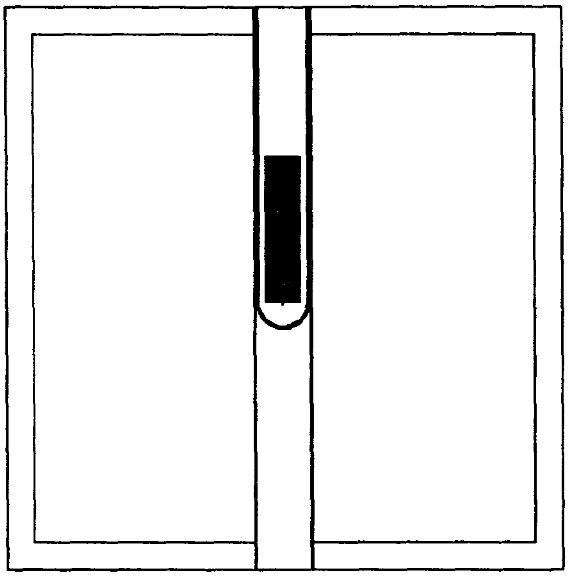
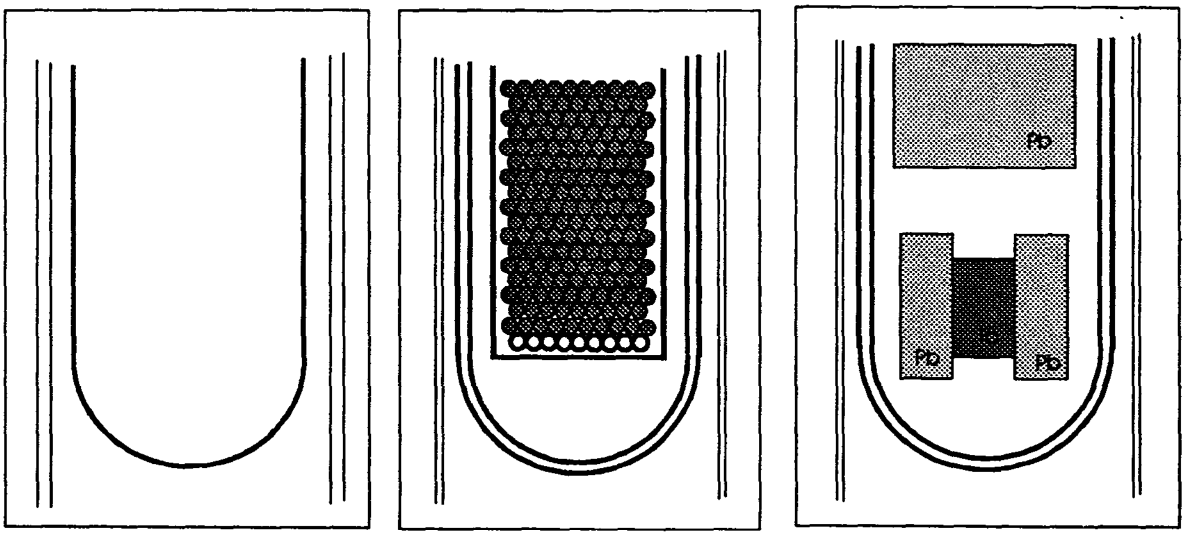


Fig. 1: Simplified model of the inner components of the spallation source SINQ without accounting for installations inside the moderator tank



a b c

Fig. 2: Models of the SINQ target versions considered: (a) liquid metal, (b) simple rod target, (c) composite target. Version (c) consists of different zones with varying dimensions and material compositions in the rod bundle structure.

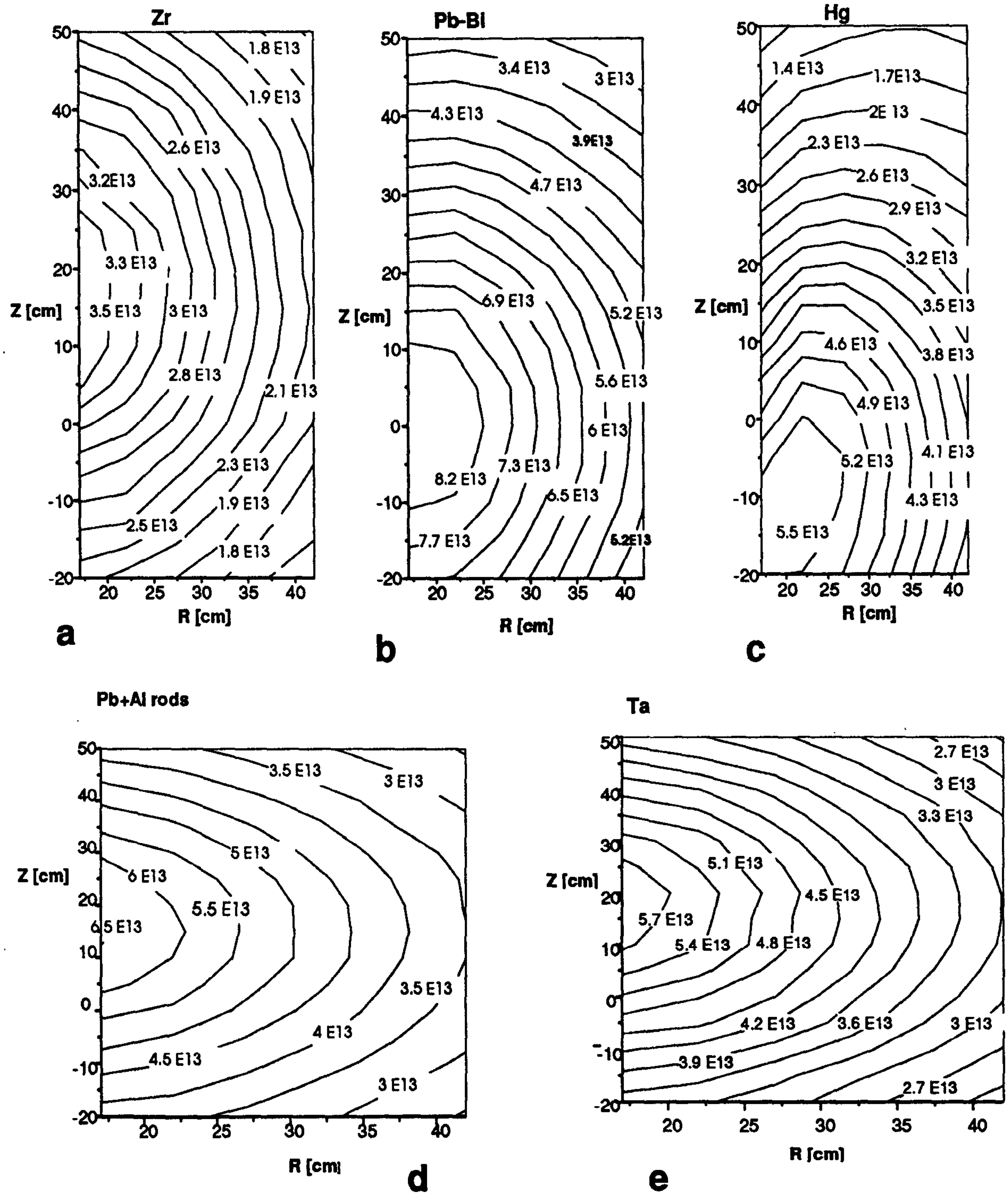


Fig. 3: Isoflux contours of thermal neutrons in the moderator for different target variants considered. (a) Zircaloy rod target; (b) PbBi-eutectic target; (c) Mercury target, (d) rod target with lead in aluminium tubes (e) composite target with 6 cm diameter and 8 cm high Tantalum block embedded in Lead and a gap width of 0 cm between the upper and lower part of the target

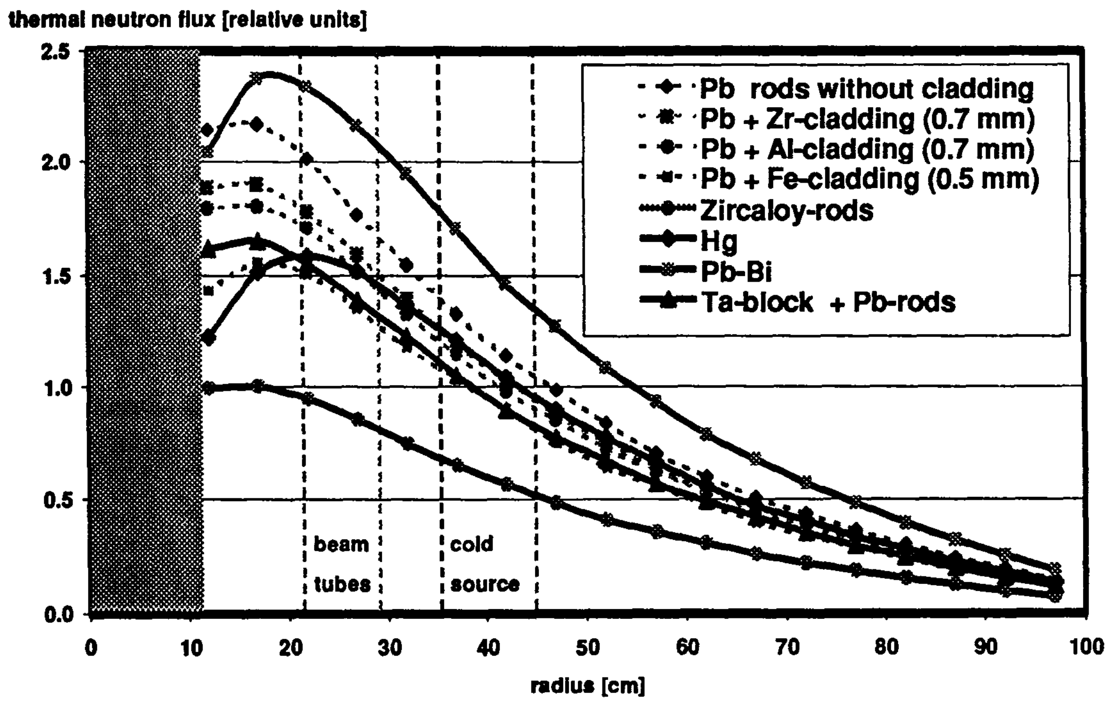


Fig. 4: Comparison of the radial distribution of the thermal neutron flux around the target region of the different target versions shown in Fig. 3 – viewed areas for thermal and cold neutrons are indicated

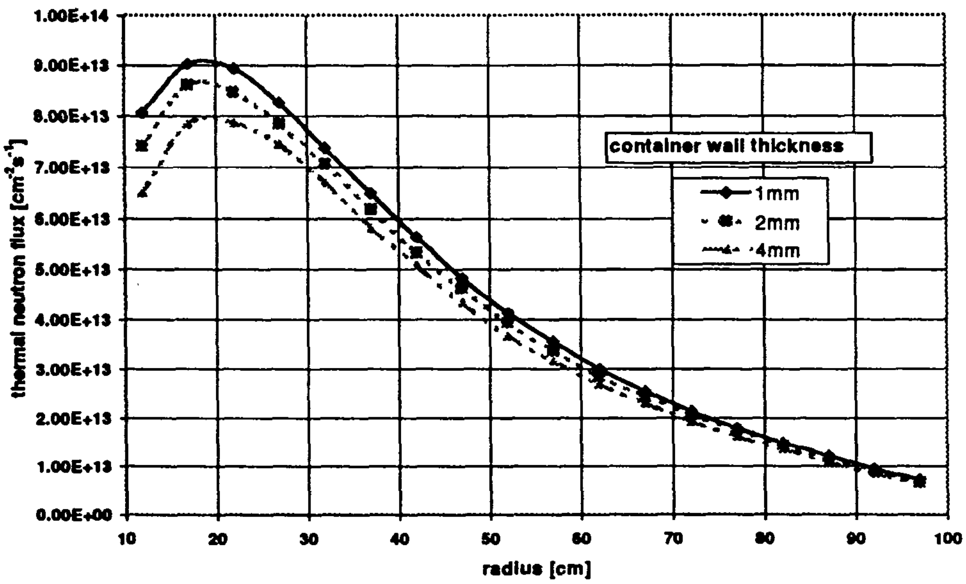


Fig. 5 Effect of the thickness of a steel container for the PbBi-target on the unperturbed thermal flux in the moderator of SINQ

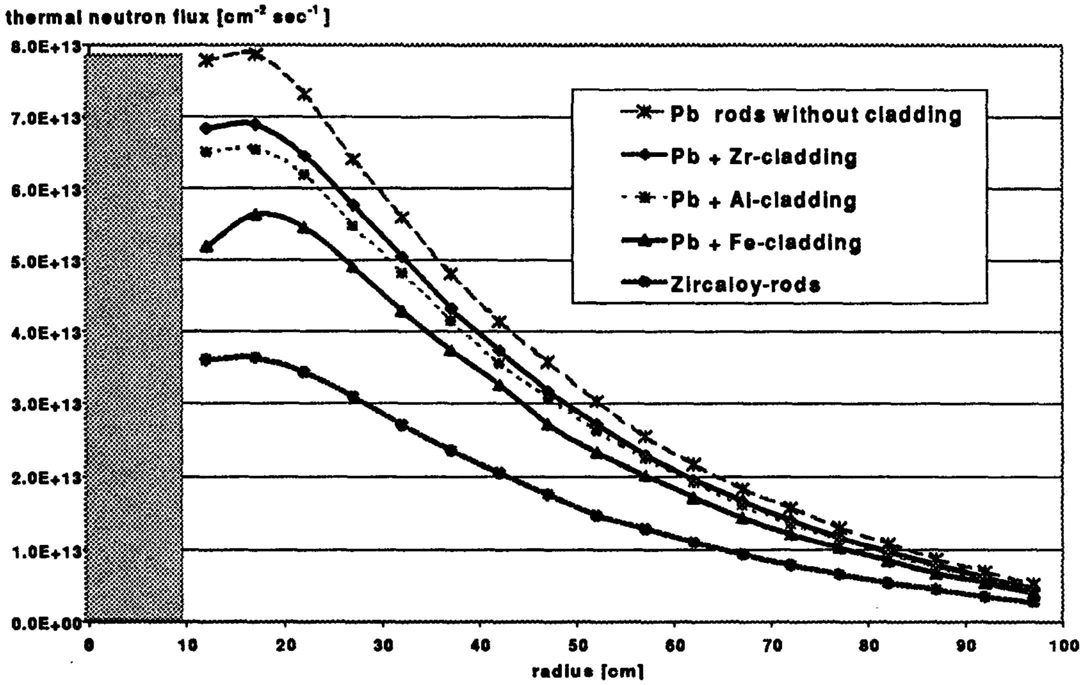


Fig. 6 Radial distributions of the calculated unperturbed thermal neutron flux in the SINQ moderator tank at the axial position of the flux maximum (z=15 cm) for Lead target rods with different tube materials. For comparison, the cases of Zircaloy rods and unclad Lead rods have also been included.

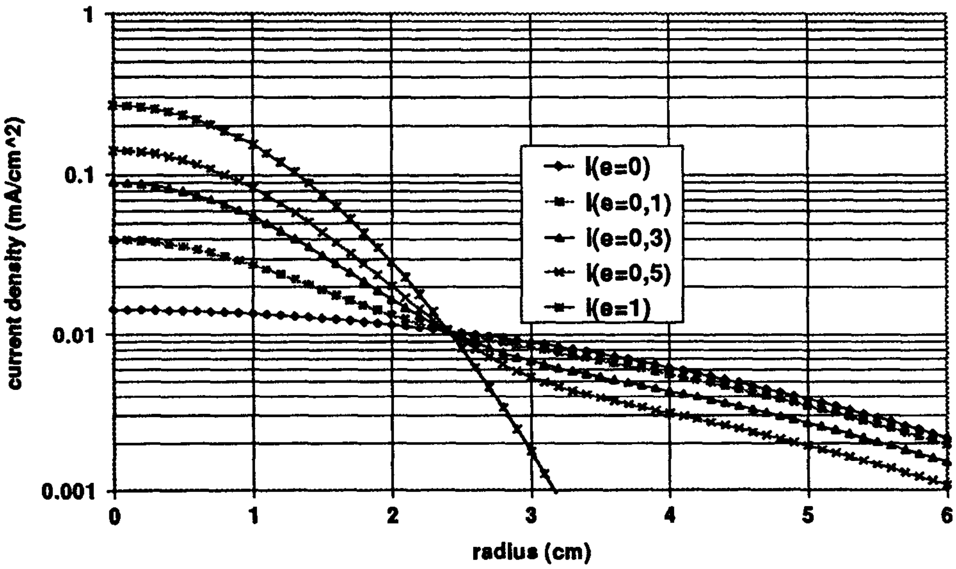


Fig. 7 Current density on the SINQ target window as a function of radius for different fractions e of the total beam current (1.5 mA) by passing target E

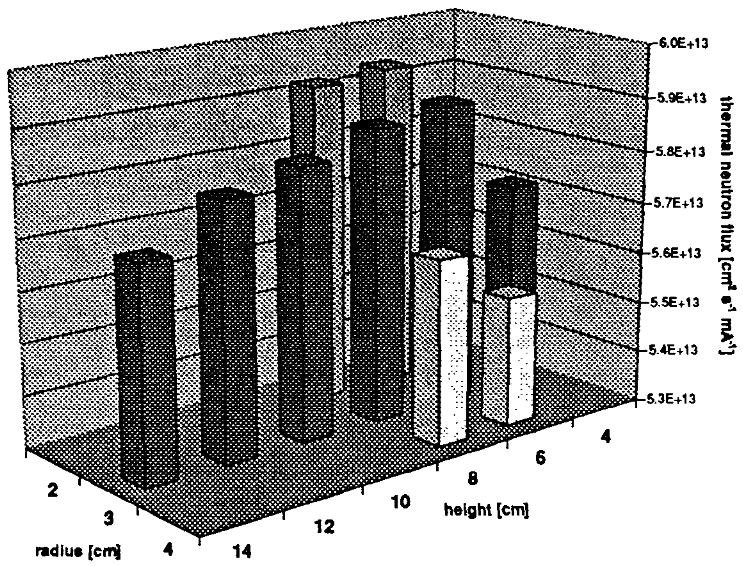


Fig. 8 Dependence of the thermal neutron flux at the position z = 15 cm, r = 20 cm on the dimensions of the Tantalum core of the composite target. The inner diameter of the Lead ring corresponded to the outer diameter of the tantalum core. The height of the lead ring was the same in all cases (14 cm).