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The Neutronic Performance of Solid-Target Alternatives for SINQ

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ABSTRACT

The results from calculations of the neutronic performance of three possible 'solid' targets and that of the current version of the liquid Pb-Bi target are presented. Two are 'conventional' transverse cooled plate structures, one using tantalum, the other tungsten. The third is a Pb-shot based pebble-bed design. Some general results on the effect of neutron absorption on the performance of the Pebble-bed target are given.

1 Introduction

Neutronically, a liquid Pb target will always be the best possible target system for SINQ or any high-power continuous neutron source (solutions involving fissile materials discounted). The advantages are well known and are, briefly: (i) a high material density in the neutron production region, (ii) a low thermal neutron absorption cross-section, (iii) the target material can be flowed to act as its own primary coolant and has a high heat-transfer capability, (iii) radiation damage to the main bulk of the target material (at least) is not a major concern.

The realisation of such a target system has to balance neutronic requirements with practical considerations (material compatibility, safety, reliability etc.). The present design has a neutronic performance below our original hopes and still raises some doubts concerning reliability. The primary purpose of the study was to provide numbers which would allow the investment in this target system to be related to thermal neutron flux gain. The neutronic performance of the current design for the Pb-Bi target (including pertinent engineering details) and three alternative targets has been calculated. Two of the alternatives are based on transverse cooled plates of tungsten and tantalum respectively and the third is a Pebble-bed of Pb-shot [1]. The comparison of these systems is not strictly 'fair' as the alternative targets are only preliminary concepts and biased heavily to neutronic requirements, but some preliminary estimates for principal dimension (e.g. plate thicknesses to allow operation at 1.5 mA, dimensions that match those for the moderator etc.) are included.

To obtain the highest thermal neutron intensity (i) the neutron production should be concentrated in as small a volume as tolerable (which means also that the heat density will be high - about 40 MeV is deposited in the target per fast neutron produced), (ii) interactions with lighter-mass 'materials of construction' which encroach into the 'target region' should be avoided and (iii) as many of the fast neutrons as possible should be brought to thermal energies in accessible regions of the moderator.

All the neutrons will be lost eventually, at best through the outer wall of the moderator, as in this way the long random-walk involved leads to the highest concentration of neutrons in the moderator and hence neutrons available to the users. The major cause of flux reduction is neutron loss in the target region, either in the slowing-down process or as thermals by absorption: such neutrons will make only short random-walks and hence little or no contribution to the useful neutron intensity. Neutron loss in the region of the target cannot be totaly eliminated (e.g. those emitted back into the proton beam direction) but absorption loss can be kept to the minimum by the careful choice of materials.

A brief description [2] of the models of the individual systems together with calculation results, will be given in the next section. A performance comparison and some comments will be given in section 3. Section 4 will present the results of a more general examination of the effect of target neutron absorption.

Numbers in square brackets refer to entries in the section "Reference and notes": some details usefull but not strictly relevant to the main theme of the paper have been moved to this section together with references.

2 Performance of the various target systems

The calculations [3] have been made changing the target system within a fixed model of the SINQ moderator tank system as sketched in Fig. 1. The proton beam energy was 570 MeV and the beam current density distribution picked from that calculated for the present design for the SINQ proton channel [4]: the beam current density was approximately 17 μA/cm^2 at the peak (for 1 mA on target) and corresponded roughly to a radially symmetric Gaussian. The beam diverges from a focus below the beam window with an angle of approximately 30 mrad. The results are presented as (i) a two-part table with the distribution of energy in the inner parts of the system and the neutronic performance and (ii) a map of the undisturbed thermal neutron flux [5].

(a) Pb-Bi Eutectic Target: the design is fully described in (for example) [6] and the results give a reference standard for the flux comparison. The energy distribution and neutronic details are shown in Table I and the thermal-neutron flux distribution in Fig. 2.

(b) Plate Targets: the same conservative (author's claim) first estimates for the plate dimensions and coolant channel widths, to allow operation at proton currents up to 1.5 mA, have been used for both tungsten and tantalum. The systems are summarised in Fig. 3. D_2O is used as the cooling fluid and aluminium as the material of construction. The plate stack length was about 21 cm and the neutronically-sensitive region above the target and within the limits of the moderator filled with D_2O. The tantalum target was modelled with

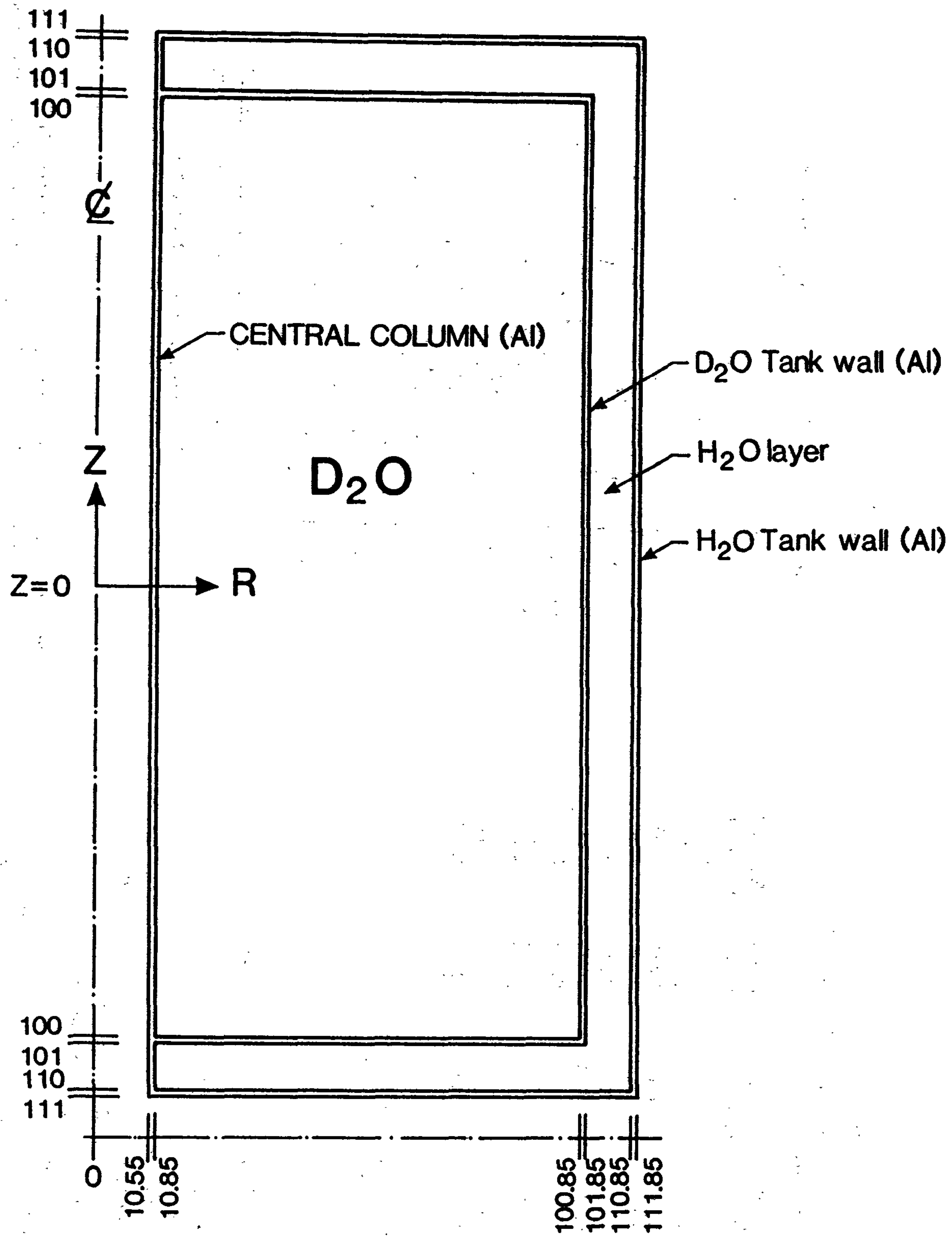

Figure 1: A sketch of the moderator tank assembly used in the calculations. The system is radially symmetric about the centre line of the central column. Dimensions are in centimetres and all walls shown are of 'pure' aluminium. Each of the target systems is mounted in the central column.

TABLE-I

(a) Energy Distribution in the Inner Regions of SINQ with the Pb-Bi Target.

Component	dE/dX(1) MeV/Proton	Gamma(2) MeV/proton	Absrptns /Proton	Energy(3) MeV/Proton
Target Material	382.06	11.25	0.235	1.59
Guide-Tube	16.07	0.64	1.053	8.01
Container Wall	2.10	0.15	1.324	10.06
Cooling Jacket	0.40	0.02	0.436	1.74
Window Complex	9.19	0.75	0.170	0.40
Central Column	0.69	0.03	0.253	2.73
D_2O	46.87	1.96	0.839	5.24
H_2O Layer	1.08	0.09	5.144	11.66
D_2O Tank Wall	0.24	0.03	0.656	7.09
H_2O Tank Wall	0.09	0.01	0.000	0.00
TOTALS	458.79	14.93	10.110	48.52

Notes:

(1) Ionization loss + Nuclear Recoil + Charged particles to rest.

(2) Prompt Nuclear Gammas + Pi zero decay.

(3) Absorption Gamma rays.

(b) Neutron Production and Loss Information

Neutrons per Interaction in Target	6.33
Interactions per Proton in Target	1.37
Neutrons per Proton in Target	8.70
Average Neutron Energy	3.42 MeV
Neutrons per Proton produced outside Target	1.30
Neutrons produced by Fast Neutrons (/proton)	0.455
Fast & Epithermal escapes	0.078
Thermal Neutron Escapes	0.213
Energy taken by H.E neutron escapes	15.93 MeV

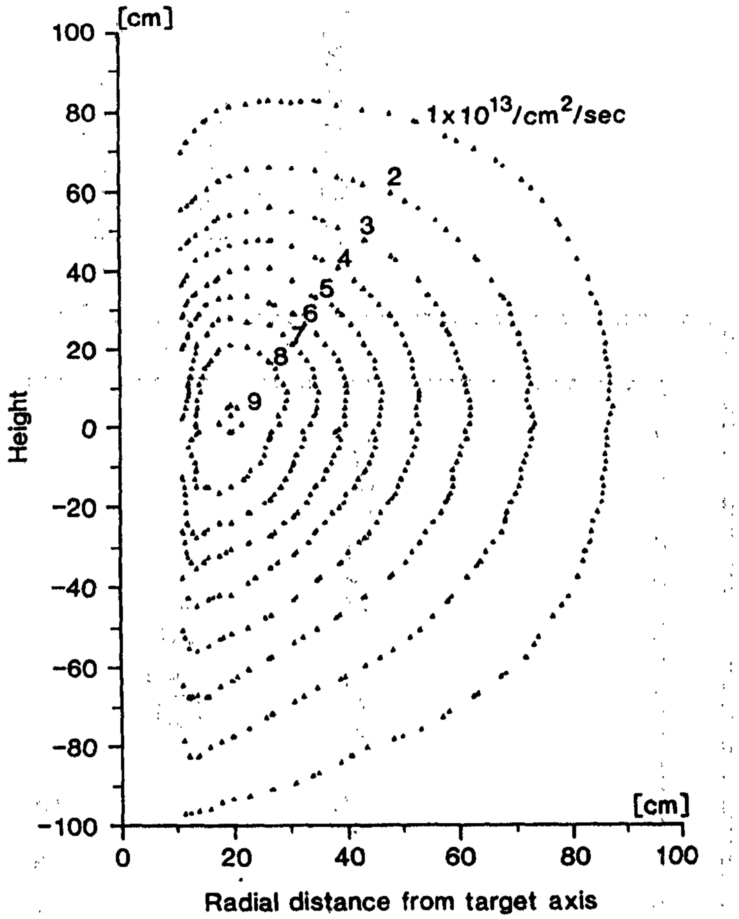

Figure 2: Contours of equal undisturbed thermal neutron flux in the heavy water for the Pb-Bi eutectic target at 1 mA proton current (see note 5 (ii)).

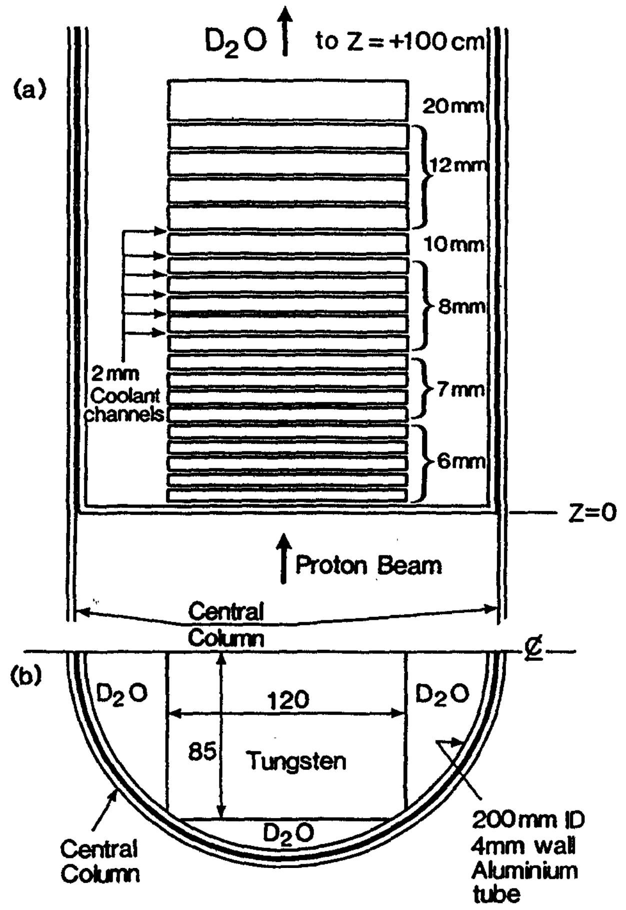

Figure 3: A sketch of the plate target systems.
(a) Vertical section: the heavy water above the plate stack extends to Z = + 100 cm.
(b) Cross-section of a tungsten plate: The 12 x 17 cm^2 plates are fitted into a 20 cm I.D. 4 mm wall aluminium tube to represent the manifold.
The tantalum plates (not shown) are 18 cm in diameter but also include an internal heavy water manifold (see reference 2 for more details).

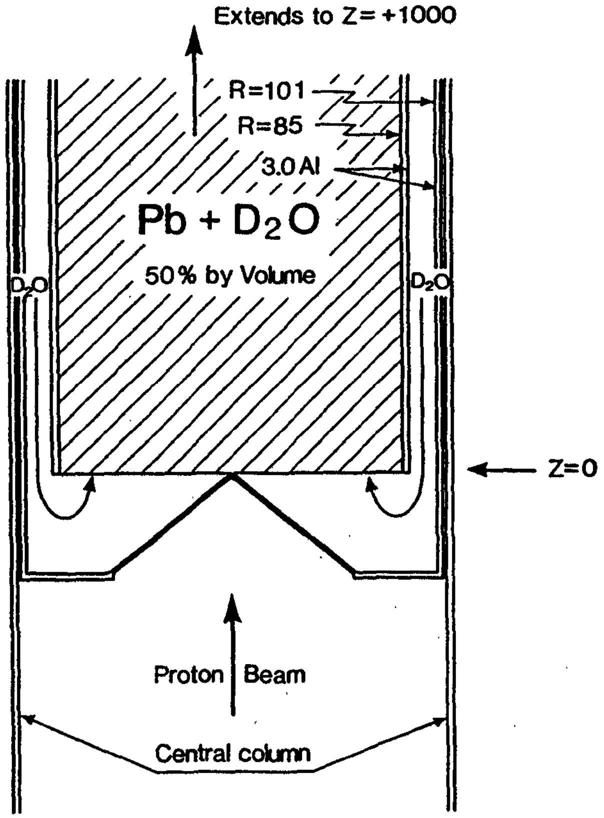

Figure 6: A sketch of a vertical section through the Pb-shot pebble bed target used in the calculation. Dimensions are in millimetres and the target extends upwards to Z = +1000 mm.

TABLE-II

(a) Energy Distribution in Inner Regions of SINQ with a Tungsten Target

Component	dE/dX(1) MeV/Proton	Gamma(2) MeV/proton	Absrptns /Proton	Energy(3) MeV/Proton
Target Material	379.037	12.018	4.961(4)	29.02
Heavy-water Gaps	14.684	1.342	0.000	0.00
Heavy Water Dump	10.294	0.359	0.004	0.03
Vessel Wall Complex	4.411	0.185	0.461	4.97
Window	2.144	0.187	0.007	0.08
Central Column	1.086	0.049	0.241	2.55
D_2O	35.144	1.754	0.525	3.28
H_2O Layer	1.324	0.078	3.234	7.21
D_2O Tank Wall	0.328	0.036	0.411	4.44
H_2O Tank Wall	0.065	0.009	0.000	0.00
TOTALS	448.517	16.017	9.844	51.58

Notes:

(1) Ionization loss + Nuclear Recoil + Charged particles to rest.
(2) Prompt Nuclear Gammas + Pi zero decay.
(3) Absorption Gamma rays.
(4) 58% of this loss during slowing-down.

(b) Neutron Production and Loss Information

Neutrons per Interaction in Target	5.64
Interactions per Proton in Target	1.50
Neutrons per Proton in Target	8.483
Average Neutron Energy	3.47 MeV
Neutrons per Proton produced outside Target	1.102
Neutrons produced by Fast Neutrons (/proton)	0.453
Fast & Epithermal escapes	0.055
Thermal Neutron Escapes	0.131
Energy taken by H.E neutron escapes	21.40 MeV

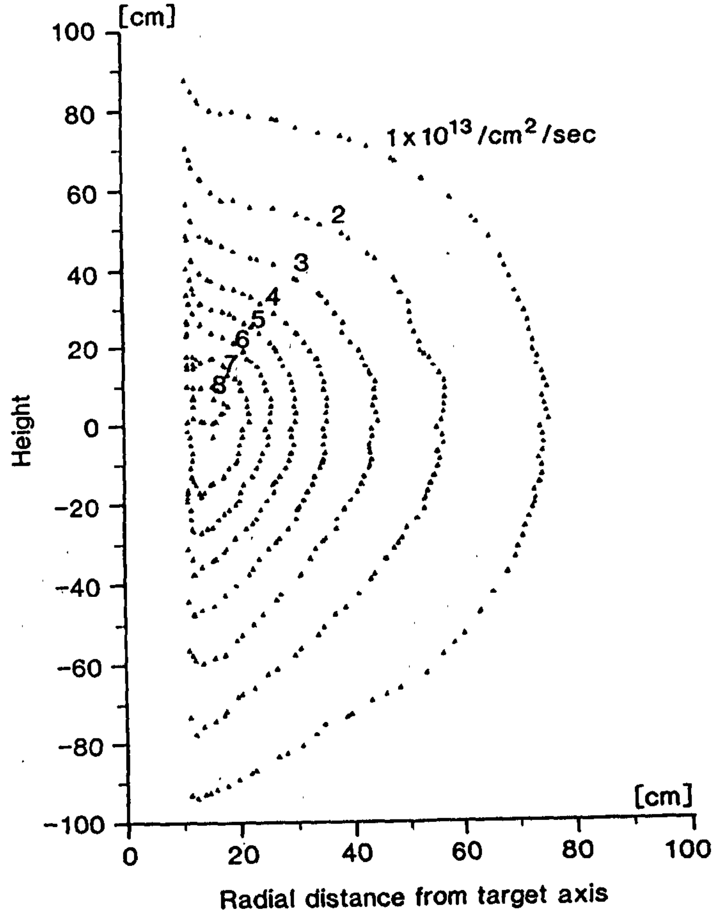

Figure 4: Contours of equal undisturbed thermal neutron flux in the heavy water for a Tungsten-plate target at 1 mA proton current (see note 5 (ii)).

a more elaborate "minimum-coolant-volume" manifold [2]. The tungsten results are shown in Table-II and Fig. 4 and those for tantalum in Table-III and Fig. 5. The quite high loss in the slowing-down process (down to 1.46 eV) should be noted.

(c) Pebble-bed Target: this target design was proposed by G. Heidenreich and is described in [1]. The geometry of the target used for the calculations is shown in Fig. 6. The values for the principal parameters assumed in the calculation were: (i) 50% volume fraction of Pb - represented by a homogeneous mixture, (ii) D_2O as cooling medium and (iii) aluminium for the beam window and target container. The energy partition, neutron production information and flux map are in Tables IV and Fig. 7.

3 Summary of Results and Comments

The neutronic information for the four systems is collected in Table-V. The relative performance is obtained from the maximum undisturbed thermal flux at a radius of 25 cm in the moderator (a typical beam-tube radial position). The importance of minimising the neutron loss in the target region is clearly evident: the lower losses in the 'Target Auxiliaries' of the Pb-shot pebble-bed target outweigh the better primary neutron production of the Pb-Bi to give a higher thermal neutron flux. Neutrons that manage to reach the outer limits of the moderator (i.e. absorbed by the H_2O or tank walls) are the ones that make the major contribution to the useful neutron flux: the '25 cm' fluxes in Table-V correlate quite well with neutron loss at the periphery of the moderator tank ($1.53 \pm .09 \cdot 10^{13}$ n°/cm^2/sec/mA for each neutron/proton lost at the periphery). Some comments specific to the individual target systems will now be given.

(a) Pb-Bi Target.

The neutronic performance of this target is about a factor of two lower than a theoretical 'best'. The principal causes are:-

20cm diameter target cf. 15cm	...20%
Interactions in guide-tube and other light nuclei	...10%
Absorption in auxiliary material within the target	...30%

0.8 X 0.9 X 0.7 = about 0.5

The first loss stems from thermo-hydraulic considerations and could be considered a consequence of being over-optimistic in defining the theoretical 'best'. The majority of the loss results indirectly from the inclusion of bismuth: it has the primary purpose of reducing the melting point and hence operating temperatures, but because of corrossion problems severely restricts the choice of materials of construction (presently a nickel-less steel). It also has considerable influence on safety system requirements (polonium). The losses also illustrate another concern in target design - the compounding of "small" loss factors to give a rather large effect overall. Work is in progress to find an alternative structural material.

(b) Plate Targets.

The high absorption cross-sections of tungsten and tantalum will always make these target materials better to avoid. Tungsten and tantalum are the highest mass materials which also have a high melting temperature and hence a good safety margin against melting when in

TABLE-III

(a) Energy Distribution in the Inner regions of SINQ with a Tantalum Target

Component	dE/dX$^{(1)}$ MeV/Proton	Gamma$^{(2)}$ MeV/proton	Absrptns /Proton	Energy$^{(3)}$ MeV/Proton
Target Material	387.722	11.706	6.086$^{(4)}$	9.13
D2O gaps and spacers	15.447	0.462	0.266	0.40
Container Wall	0.699	0.055	0.067	0.72
Window Complex	9.227	0.608	0.174	0.26
D2O Dump above Target	2.919	0.121	0.003	0.02
Central Column	0.884	0.055	0.175	1.89
D_2O	33.254	1.731	0.434	2.71
H_2O Layer	1.082	0.089	2.756	6.15
D_2O Tank Wall	0.189	0.034	0.349	3.77
H_2O Tank Wall	0.088	0.013	0.000	0.00
TOTALS	451.511	14.874	10.310	25.05

Notes:

(1) Ionization loss + Nuclear Recoil + Charged particles to rest.
(2) Prompt Nuclear Gammas + Pi zero decay.
(3) Absorption Gamma rays.
(4) About 70% of the absorptions are during slowing down.

(b) Neutron Production and Loss Information.

Neutrons per Interaction in Target	5.80
Interactions per Proton in Target	1.51
Neutrons per Proton in Target	8.76
Average Neutron Energy	3.45 MeV
Neutrons per Proton produced outside Target	1.14
Neutrons produced by Fast Neutrons (/proton)	0.56
Fast & Epithermal escapes	0.053
Thermal Neutron Escapes	0.110
Energy taken by H.E neutron escapes	16.02 MeV

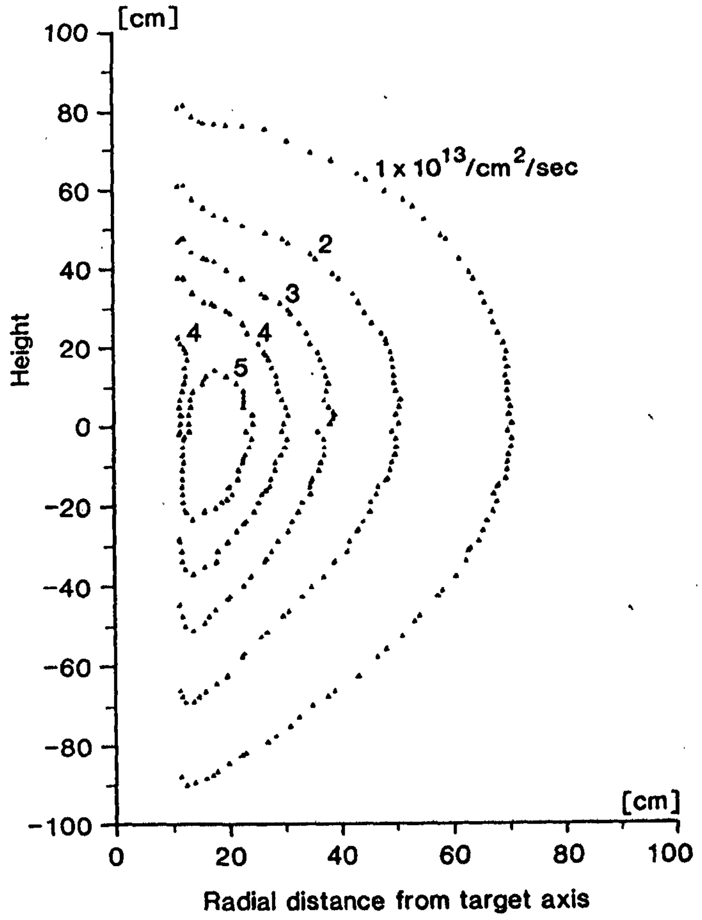

Figure 5: Contours of equal undisturbed thermal neutron flux in the heavy water for a Tantalum-plate target at 1 mA proton current (see note 5 (ii)).

TABLE-IV

(a) Energy Distribution in Inner Regions of SINQ with a Pb Pebble-bed Target

Component	dE/dX(1) MeV/Proton	Gamma(2) MeV/proton	Absrptns /Proton	Energy(3) MeV/Proton
Target Material	397.69	12.026	0.620	4.59
First Wall	2.113	0.082	0.187	2.02
Heavy-Water Downflow	4.990	0.124	0.007	0.04
Second Wall	1.523	0.076	0.255	2.75
Central Column	1.485	0.063	0.415	4.48
D_2O	49.410	2.111	0.915	5.71
H_2O Layer	1.491	0.126	5.646	12.59
D_2O Tank Wall	0.353	0.042	0.712	7.69
H_2O Tank Wall	0.078	0.012	0.000	0.00
TOTALS	459.133	14.662	8.757	39.87

Notes:

(1) Ionization loss + Nuclear Recoil + Charged particles to rest.
(2) Prompt Nuclear Gammas + Pi zero decay.
(3) Absorption Gamma rays.

(b) Neutron Production and Loss Information

Neutrons per Interaction in Target	5.682
Interactions per Proton in Target	1.298
Neutrons per Proton in Target	7.375
Average Neutron Energy	3.42 MeV
Neutrons per Proton produced outside Target	1.321
Neutrons produced by Fast Neutrons (/proton)	0.336
Fast & Epithermal escapes	0.063
Thermal Neutron Escapes	0.175
Energy taken by H.E neutron escapes	23.03 MeV

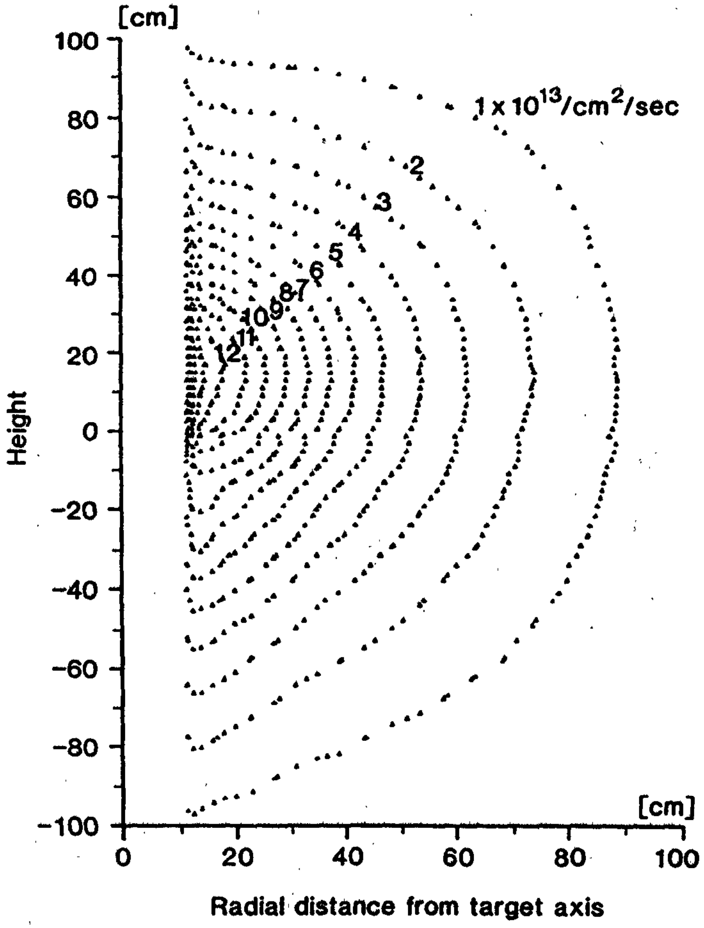

Figure 7: Contours of equal undisturbed thermal neutron flux in the heavy water for the Pb-shot pebble-bed target at 1 mA proton current (see note 5 (ii)). The Pb filling factor is 50% by volume. The low absorption in the target together with the significant quantity of moderator (D_2O) inside the target itself means that the flux maximum is close to or within the 'target'.

TABLE-V

Neutronic data for the four target systems calculated.

Target System	Pb-Bi	W	Ta	Pb Shot
Neutron Production				
(i) Target Complex	8.700	8.483	8.760	7.375
(ii) Moderator Complex	1.300	1.102	1.140	1.321
(iii) Fast Neutrons	0.455	0.453	0.560	0.336
TOTAL PRODUCTION	10.455	10.038	10.46	9.032
Neutron Loss				
(i) Fast/Epith. Escapes	0.078	0.055	0.053	0.063
(ii) Thermal Escapes	0.213	0.131	0.110	0.175
(iii) Absorption in:				
(a) Target Material	0.235	4.961	6.086	0.620
(b) Target Auxiliaries	2.983	0.472	0.510	0.449
(c) Heavy Water + CC	1.092	0.766	0.609	1.330
(d) Light Water + TWs	5.800	3.645	3.105	6.358
TOTAL LOSS	10.401	10.030	10.473	8.995
Approx. Flux Maximum	$9 \cdot 10^{13}$	$8 \cdot 10^{13}$	$5.5 \cdot 10^{13}$	$1.2 \cdot 10^{14}$
Radius of flux Max (cm)	20	15	17.5	small
Max. Flux at 25cm radius	$8.5 \cdot 10^{13}$	$6 \cdot 10^{13}$	$4.5 \cdot 10^{13}$	$1 \cdot 10^{14}$
ditto as %	100	70	53	117

operation. Tantalum is neutronically significantly worse than tungsten: its capture cross-sections are significantly higher. On the other hand, tantalum would seem to be a fairly normal metal, possibly more radiation resistant than a sintered material and has been used for (lower power) targets. With about 50% of the neutron flux of the Pb-Bi target system (or 3.8 times lower than the 'best'), it should not be considered as a contender for SINQ: that is, the plate target is only a possible alternative if it can be built using tungsten.

For tungsten, the selected plate dimensions lead to a system which gives about 70% of the flux obtained with the current Pb-Bi design (or 2.8 times lower than for a Pb-Bi target without the present loss factors): some of this might be recovered by optimisation, particularly the minimisation of coolant in the neutron production region and/or by changing to a high-mass coolant (e.g. liquid metal) to attempt reduction of the loss (about 30% of the fast neutrons produced) in the slowing-down process. Some reduction of the transverse dimensions of the plates should also bring improvement.

A major consideration could be radiation damage. The tungsten would be in the form of one of sintered agglomerates and assessment of how this would stand up to radiation damage together with the probable failure modes would need to be considered at an early stage of a design study. The major problems could be (i) swelling or other mechanical distortions constricting or interrupting the coolant flow and (ii) how to handle the activation, should failure modes involve significant fractions of the plate material entering the cooling system.

(c) Pebble-bed Target.

The calculations show this design of target to give a higher flux in the accessible regions of the moderator than the present Pb-Bi one (but 1.7 times worse than the 'best'). The actual final performance will probably be about the same, in terms of useful neutron intensity for the user, when the effect of the flux gradient is included (for a volume fraction of 50%). The shot filling density for a practical target should be about 57% (random packing), giving a slightly better performance than these calculations indicate.

This concept is being considered further to see if a practical design maintaining the neutronic performance can be realised [1].

4 The Effect of Absorption on Thermal Fluxes with a Pb-shot Target

4.1 Introduction

Calculations have been made to quantify the flux loss with the Pb-shot for small increase of the effective neutron absorption [7]. The effect of similar increases of the absorption in target 'auxiliaries' can be deduced from these results.

Two cases have been examined (i) an uniform increase of absorption cross-section throughout the whole Pb of the target (to simulate contamination) and (ii) a non-uniform distribution of absorber in the 'neutron-production' region to simulate the effect of burn-up poisoning.

This second case turns out to give a rather small effect but is of interest as it provides a natural 'background' level for assessment of the significance of absorption increase. Whilst any increase is to be discouraged, that at the 10 or so percent level of such a "natural" background is not really significant (but the magnitude has to be known).

4.2 Burn-up Poisoning

A first look at this problem was made for the Pb-Bi target [8]. The spallation/fission products of Pb include most of the well known high thermal-neutron absorption cross-section nuclides (see Table-I in reference 8). The production rate for these is about 48 g/mA·year (0.7 nuclei/proton) and corresponds to an average effective cross-section increase of about 190 mb/mA·year but because of the high cross-sections, burn-up limits the increase to an equilibrium at about 90 mb.

We may define an effective average absorption cross-section ($\tilde{\sigma}$) by:-

$$\tilde{\sigma} = \frac{208}{V \times 11.3} \sum_l N_l \sigma_l$$

where N_l is the number of gramme-atoms and σ_l the capture cross-section for nuclide l, V is the volume of the interaction region. The nuclide production rates come from the Bateman equation:-

$$\dot{N}_i = -\lambda_i N_i - \sigma_i \phi(\bar{t}) N_i + \sum_j f_{ij} \lambda_j N_j + \sum_k g_{ik} \sigma_k \phi(\bar{t}) N_k$$

where N_i is the amount of nuclide i (g.atoms) and where λ_i is the decay constant for the nuclide i, σ_i the capture cross-section, f_{ij}, λ_j & N_j give the *decay* feed from N_j and g_{ik}, σ_k & N_k the *capture* feed from N_k.

The thermal flux, $\phi(\bar{t})$, is a function of both time and position within the target making the equations non-linear. As the first step in the solution of the equation, equilibrium flux distributions [9] for fixed average absorption cross-section increases (50, 180, 360 and 540 mb) have been calculated, using a spatial distribution of absorbing nuclides based on that for energy deposition in the target. The average thermal-neutron flux in the production region of the target varies between $1.35 \cdot 10^{14}$ n°/cm²/sec/mA with pure Pb and $1.08 \cdot 10^{14}$ n°/cm²/sec/mA at +540 mb: this slow variation means that solutions of the Bateman equation with step-wise variation of thermal neutron flux should give adequately accurate answers. The calculated build-up of average absorption cross-sections for three fixed neutron fluxes are shown in Table-VI. Using the flux-to-peripheral-loss correlation of section 3 and the peripheral losses from the flux calculation (6.303 ± 0.032, 6.165 ± 0.033, 6.022 ± 034 and 5.914 ± 0.036 respectively for the four average absorption cross-section increases), interpolation indicates a reduction of the undisturbed thermal-neutron flux in the region of the beam-tubes of about 1.5% after 2 mA·years operation, rising to approximately 2.5% after 10 mA·years. The effect is rather small.

4.3 Uniform Increase of Absorption

The undisturbed thermal-flux in the moderator has been calculated for five cases in which the effective absorption cross-section of the Pb (170 mb) has been (arbitrarily) increased by 10, 100, 200, 300 and 400 mb [9]. The loss at 3 different heights in the moderator tank at a radius of about 25 cm as a function of cross-section increase is shown in Fig. 8. The general

Table-VI

Calculated average absorption cross-section contribution (mb) from spallation products as a function of operation time and for three different thermal fluxes.

Flux	Operation Time (mA.years)					
units of 10^{14}	0.027	0.27	1	2	5	10
0.0	5.1	51	187	376	943	1890
1.35	3.5	18	31	43	65	80
1.13	3.7	19	34	47	71	89

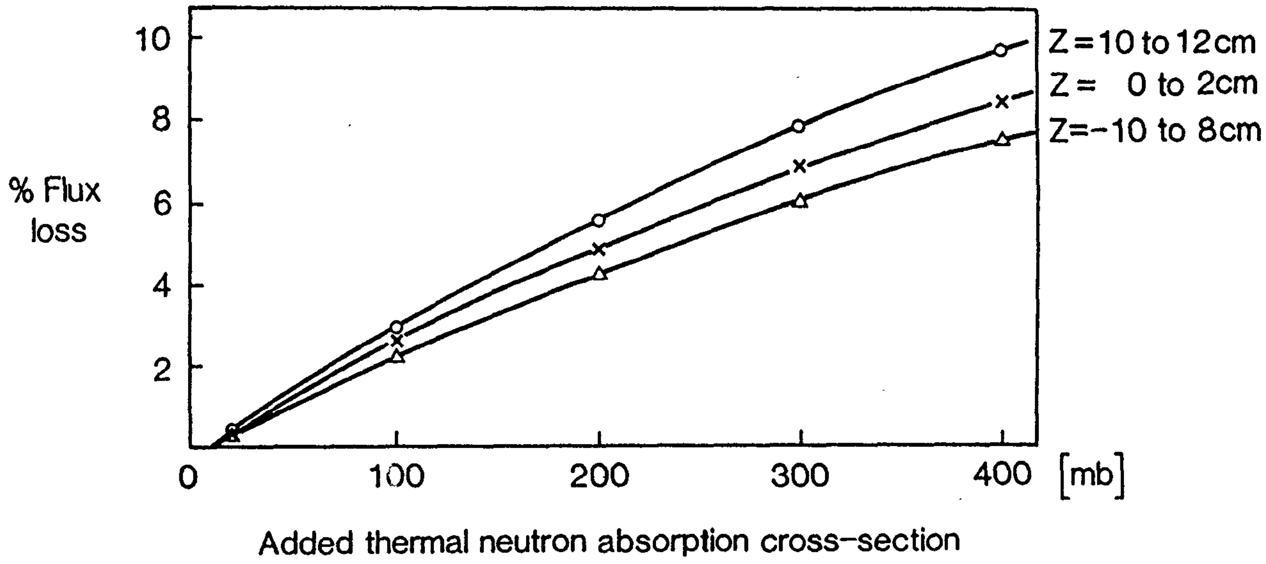

Figure 8: The percentage flux-loss at three different heights relative to the target beam-window and a radius of 25 cm as a function of added absorption cross-section.

trend is for the loss to be less as the distance from the target increases: at typical distances to the beam-tube tips (circa 25 cm) an extra 170 mb (a doubling of the absorption cross-section) gives a 4 to 5 % undisturbed flux reduction.

The results indicate that (for example) an 1% admixture of Sb (σ_{cap} = 5.4 b) would give at least a 1% loss (*there will be additional loss due to the fairly large (175 b) resonance integral which has NOT been considered*).

4.4 General Considerations

The neutron loss accounts are summarised in Fig. 9, where the loss in the various components of the system has been plotted as a function of additional absorption cross-section. The curves show the rather obvious effect that neutrons absorbed in the target (or anywhere in the inner part of the system) are lost to the number which reach the outer limits of the moderator:

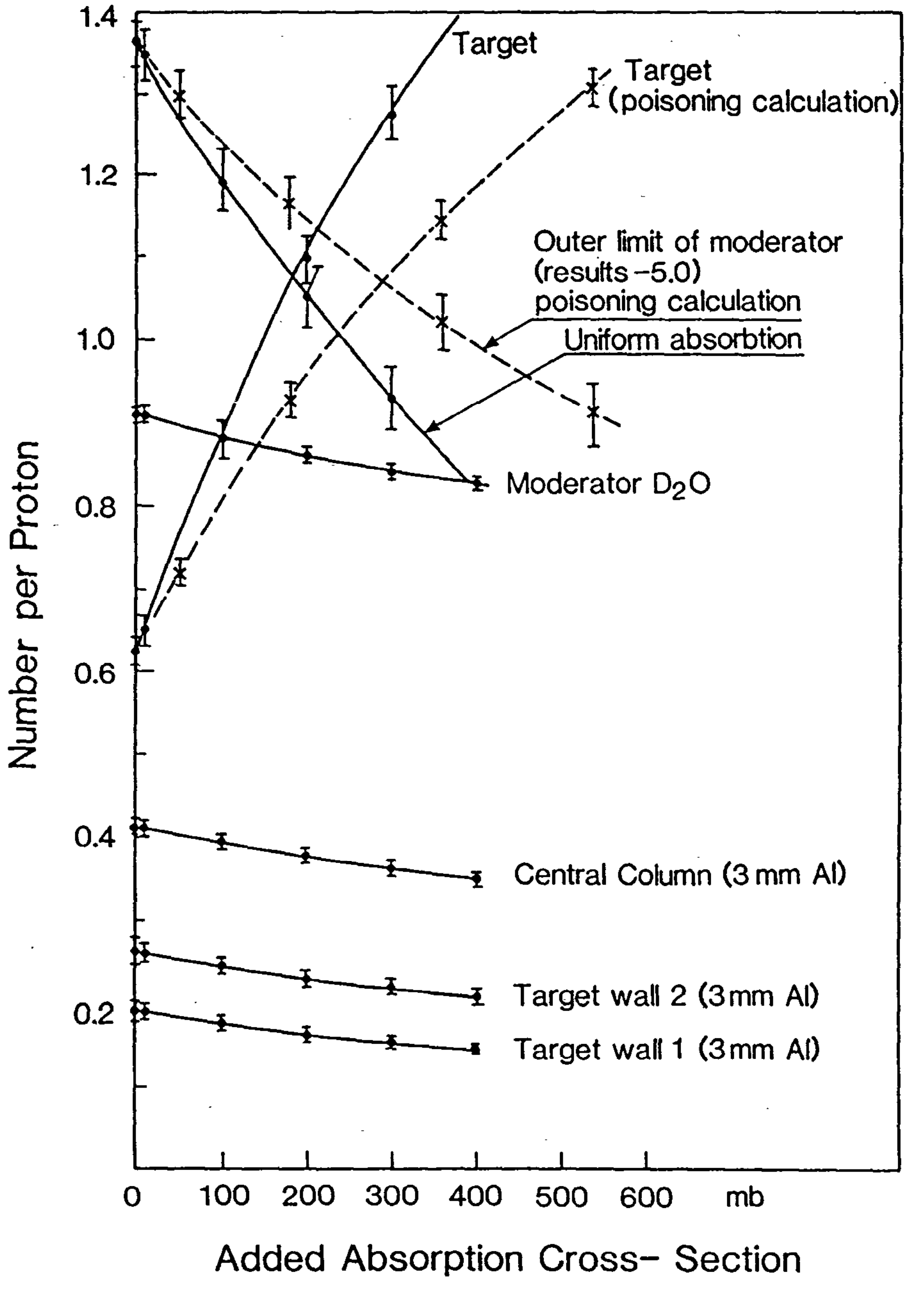

Figure 9: Thermal neutron absorption by the various components of the target-moderator system as a function of the added absorption cross-section in the target. Values shown with dots are for results with a uniform-density absorption increase and with crosses from the burn-up poisoning estimate (values for target material and periphery losses only included). Lines are drawn only as eye-guides and error bars indicate the statistical error in the estimates only.

this leads to an almost pro-rata reduction of the thermal neutron flux; the slight reduction of the loss in the other components comes from (and is a measure of) the average reduction of neutron flux in their vicinity due to these lost neutrons.

The neutron absorptions (β/proton) at the periphery of the moderator tank fit (with a correlation of 0.999_7) the relation:-

$$\beta = \frac{6.886}{1 + 0.1225 \times \sigma_{cap}}$$

where σ_{cap} is the *added* cross-section in barns and the relation simply expresses that the flux reduction is the ratio of the number of neutrons reaching the moderator tank wall with and without the extra absorption (absorption loss is proportional to flux) and system escapes (fast and thermal) are mainly geometry dependent and hence constant.

The target and periphery neutron-loss results from the burn-up poisoning calculation have been included into Fig. 9 and show (on a pro-rata average absorption increase basis) a significantly smaller effect. In some respects, one could say that the average cross-section as defined is not a correct measure of its significance. The +540 mb average corresponds to about 2.8 b in the innermost region of the target and the calculations show that for the Pb-D_2O mixture, this region is quite well decoupled from the moderator.

Two practical consequences from all this are:-

- Special treatment of the Pb in the inner (high heating, activation etc) regions which leads to a somewhat high effective absorption cross-sections can be tolerated (Note: *if such treatment also involves significant increase of the resonance integral, it would probably not be tolerable!*)
- The major importance of maintaining low absorption cross-sections for components at the outer limit of the target (particularly the container walls). Being adjacent to the moderator, these must necessarily "see" high thermal fluxes. Only 6 to 7 n°/proton are available to produce the thermal flux. With the 'pure' aluminium used in the calculations, 0.44 n°/proton are lost: a doubling of the absorption (i.e. another 0.44 lost neutrons) will mean a loss of the order of 7 %.

5 References and Comments

1. See contribution to these Proceedings : F. Atchison & G. Heidenreich, "A Solid Target for SINQ based on a Pb-shot Pebble-bed".
2. This report is a condensed version of two internal SINQ reports by the author: SINQ/816/AF38 001 and SINQ/816/AF38-003.
3. The calculations have been 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.
   Thermal neutron transport uses the perfect-gas scattering function and fluxes have been calculated from both track-length and collision density estimators and a stopping

criterion of less than about 5% statistical fluctuation in the 'higher' flux regions. The two separate flux estimates are in reasonable agreement.

4. U. Rohrer (SINQ Internal Communication).

5. (i) The calculations use undisturbed fluxes (the beam-tube structure in the moderator tank has not been included). Neutron flux is used in this report as a measure of performance (nothing more) and on the basis that the most "useful neutrons" will be diverted to the user when a beam-tube is inserted into a region with the highest flux (calculated or measured) without the beam-tube. Thermal neutron flux is a potential function and obtains its units (/unit area/unit time) from the multiplication of the probability (per unit volume) of finding neutrons at a given position by their velocity: that is, the flux is a measure of the neutron motion maintaining the density distribution and not physical transport. Physical transport of neutrons leads to a flux gradient, so the actual intensity at the monochromator remains a somewhat open question.

   (ii) The flux maps have been prepared using double logarithmic interpolation in both the R and Z directions of the data from the path-length estimator. No data smoothing has been made: the clear separation of the contours is additional evidence that the solution has converged. The localised irregularities on the contours come from the the irregular volume mesh used and the residual statisical fluctuations and are not considered to be physically significant.

6. See contribution to these Proceedings : M. Dubs and J Ulrich, "Design Considerations of the Target Window".

7. Commercially available Pb shot would be used which will have a higher effective thermal absorption cross-section. An assay of a sample indicates an absorption increase of less than 60 mb. Using the results of this study, this would correspond to a flux loss of the order of 1 or 2% and not significant.

8. F. Atchison, Proceedings of ICANS-VIII, Rutherford Laboratory Report RAL-85-110 (1985).

9. All the results in this section have been obtained in a single run of the neutronics codes using a parallel tracking technique.

Q(N.Watanabe): What coolant are you thinking for target other than Pb-Bi?
What shape and size of block or disk are you thinking for W-target?

A(G.S.Bauer): The coolant is D_2O in all cases to minimize absorption but also moderation in the target volume. The size of the target disks in the case of W and Ta has not been optimized yet; Only the thickness of the plates has been chosen such that the surface heat flux does not lead to subcooled boiling. This leads to about 20% by volume of D_2O-content in the target.