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Enhanced Target Moderator Concepts for ISIS

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for

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1. Introduction

With ISIS now well on its way to become the world's leading and most powerful pulsed neutron source and in particular in view of the fact that it will probably for a long time be Europe's only pulsed neutron source. It seems quite natural that questions are being discussed now, on how access to ISIS for an international community could be organized and what potential exists for future enhancement of its capabilities. These questions are being dealt with at present by a project group established under the Memorandum of Understanding which has been signed by Great Britain, France and Italy. This paper we report on the state of the discussion in the Target Section of the project group. Two distinctly different cases are considered, namely whether or not Rutherford Appleton Laboratory will be operating with a nuclear site license in the future.

2. The present situation

At present there exists one extracted beam line with a neutron target station at its end. The design of the accelerator, however, would allow a second beam to be extracted approximately at right angles to the first one, i. e. in the direction where the old NIMROD Hall (Hall 1, or building R6) is located (fig. 1).

The present target station has 18 beam lines and will be able to accommodate an estimated total of 25 neutron scattering instruments. The beam lines are fed from four moderators of different characteristics and performance (fig. 2), located above and below the target, two ambient temperature water moderators (A, AP and D), a liquid methane moderator (CH_4) and a super-critical hydrogen moderator (H_2).

The target itself (fig. 3) consists essentially of a cylinder of depleted uranium, 34 kg in mass which is subdivided into 23 disks of three different thickness for cooling purposes. The disks are clad individually in zircaloy and mounted in a stainless steel support frame. The presurized D_2O-coolant is guided in a stainless steel manifold of quite elaborate design. At full proton current (≈ 180 μA), a total of about 230 kW of heat will be deposited in the target and its structural material, including the stainless steel pressure vessel in which the whole assembly is contained. Apart from a few components such as heat exchangers, which would have to be supplemented, the system could handle up to 1.5 MW, i. e. six times the present heat output. All pipework and the containment provided to avoid release of radioactivity from the target are designed and fabricated to meet the ASME standards required for a nuclear installation. The safety and control systems are similar to reactor practice.

3. Options for RAL operating without a nuclear site license

If RAL were to continue to operate without a nuclear site license, as is presently the case, the following potential for improving the neutron supply to the users can be seen:

3.1 Changes in the present target and moderator geometry

Research with respect to target-moderator optimization which has been carried out since important design parameters of the ISIS target had to be frozen has yielded

some clues on possible improvements that could be achieved from changes with respect to the present geometry.
There are two main points to be mentioned:

3.1.1 Improvement of geometric coupling into moderators by reducing the distance between target and moderator centre lines

Although great care was taken in designing the present target and its surroundings (fig. 4) to keep the target-moderator distance small, it may be possible to achieve even better geometric coupling by
(a) reducing the thickness of the stainless steel frame around the uranium,
(b) changing the shape of the pressure vessel in such a way that flat top and bottom sections can be avoided, which may allow a thinner wall thickness,
(c) scrutinizing the need for the 6 mm Boral layer between the target and especially for the cold moderator.

Taking all the possible gains from these measures together, an estimated improvement in neutron leakage from the moderators of the order of 10 % could be anticipated. It should be borne in mind, however, that moving the moderators closer to the target would make other changes necessary. This may include the centre section of the reflector and it requires an adjustment of the beam lines and instruments to the new moderator heights.

3.1.2 Change from cylindrical to "2-dimensional" target

Under the assumption, that the target would have a circular cross section, its optimum diameter was determined to be 9 cm (Atchison, 1981). Subsequent research done for a wheel-type high power target (Bauer et al, 1982) showed that, with a laterally extended target, important gains in target-to-moderator coupling can be achieved. Fig. 5 shows this effect for a set of uranium targets with an unreflected moderator. For comparison, the curve determined by Atchison (1981) for a reflected target with circular cross section is also shown. (This curve has been arbitrarily normalized to the one for a 10 cm wide target at 9 cm thickness.) The gain, that can be obtained by going from a 10 cm wide target to a 30 cm wide target is about 30 %. Since the topology of Atchison's curve for the reflected case seems to agree well with the measured data for the unreflected case (showing the superiority even of a 10 cm wide target of thickness t over a circular one with diameter t for t < 9 cm), it may be anticipated that this gain could also be obtained in a reflected target.

Together with some of the measures described under 3.1.1 it may be assumed, that this provides a potential to improve the performance of a depleted uranium target by up to 35 to 40 % relative to the present one.

3.2 Second target station

Making use of the possibility to add a second extraction beam line to the ISIS synchrotron, the construction and operation of a second target station can be envisaged. Unless the accelerator characteristics change, the most likely way to operate with two target stations would be a pulse-switching mode, directing e. g. 1 out of 5 pulses onto the second target. Without making use of fissile material (see below), this would result in a relatively low time average power (≈ 50 kW with a depleted uranium target; ≈ 20 kW with a W-target) at a pulse rate of 10 Hz. The design of the second target station could provide for better target-to-moderator coupling than in the present high power case by taking advantage of these features and by placing cryogenic moderators with as high a hydrogen density as possible, at the optimum positions. The low pulse repetition rate makes this source particularly suitable for cold neutrons which, in turn, are easily transported through curved guides for efficient background and fast neutron suppression. In view of this fact one might even consider the use of slab moderators which have a 2 times better coupling to the target than wing moderators. Taking all these effects together, it is not unlikely that the useful cold neutron flux from this low power target would more or less match the one from the present cold moderators, especially since at 10 Hz there is no risk of frame overlap and each of the pulses could be used by all instruments. In this way target 1 could be freed from the cold neutron instruments and about 10 to 12 new beam lines for cold neutrons would become available at target 2, with practically no loss in performance.

4. Options if RAL were to operate under a nuclear site license

In order to make possible more significant gains in neutron production than those discussed above, the possibility of using fissile material in the target has been examined both for the present and a new second target station.

The general problem in using fissile material, apart from the fact that a nuclear site license may have to be obtained, is that, with no special precautions taken, the pulses tend to be lengthened substantially. For a pulsed source it is therefore necessary to minimize thermal fission in the target by (a) preventing thermal neutrons from the moderator and reflector from diffusing back into the target and (b) allowing as little thermalization as possible within the target itself. Although it is essential to have very detailed calculations to assess the true source enhancement that can be obtained from any particular arrangement containing fissionable material, a crude estimate of the neutron production enhancement in the target can be attempted starting from the total energy dissipation in the target:

It is known, that in a non-fissile target, about 2/3 of the proton energy is dissipated inside the target and 1/3 is carried away by the particles leaving the target. The total neutron yield in a fissile target is taken as the sum of the yields from spallation and from subsequent fission processes. We set for the total energy dissipation per incident proton, E:

$$E = 2/3\ E_p + 190 \cdot (^f/_p) \qquad (1)$$

with $(^f/_p)$ giving the number of fissions per proton and 190 MeV being the energy release per fission process. Taking into account, that each fission process adds about 1.4 neutrons to the overall production, we have for the number of neutrons produced:

$$n_{tot} = n_s + n_f = n_s + (^f/_p) \cdot 1.4 \qquad (2)$$

For the reference case of 800 MeV protons on depleted uranium it has been shown (Atchison, 1981), that about 1460 MeV are released in the target per incident proton, destroying about 4.9 nuclei by fission processes and producing a total of 26 $^{n}/_{p}$. Inserting these numbers in (1) and (2), we obtain from (1)

$(^{f}/_{p}) = 4.8$ in good agreement with the above result

and from (2)

$$n_s = 19$$

Applying the same relations to a target of total power P_o (W) and assuming an incident current I (μA) we have

$$n_{tot} = 19 + (1.4/190)\,(P_o/I - 533) \qquad (3)$$

4.1 Use of enriched uranium on target 1

As mentioned before, the layout of the present target station is such, that no major amendments would be required from a technical point of view to operate it at a power level of about 1.5 MW. This amount of energy could be produced in a target of similar design to the present one but with the peak heat deposition of 770 W/cm^3 of the present target ocurring throughout the target. This would require a target consisting of 32 plates, each 7.7 mm thick (as are the front ones of the present target) and a heat flux across the plate faces of ≈ 300 W/cm^2. This heat flux is close to what is presently considered the safety limit, but some increase in the pressure of the cooling system could be envisaged.

Let then P_o be 1.5 MW and I = 180 μA. So we have from (3)

$$n_{tot} = 76.5\ ^{n}/_{p}.$$

giving a total enhancement in neutron production of a factor 3 over a depleted uranium target. It should be noted, however, that (a) this enhancement is not uniformly distributed over the length of the target due to the need for maintaining a flat power distribution and (b), more importantly, due to the spatial and spectral distribution of the neutrons produced from fission, target-to-moderator coupling as well as moderation efficiency of the moderator will be poorer than in the case of the depleted uranium target, especially since there is a need for decoupling the target to keep the pulses short. So, realistically, an enhancement for the thermal or cold neutron leakage of about 1.5 at the front moderators and 2.5 at the rear ones might be anticipated. These figures are also suggested from scoping calculations done within the present study work by D. Picton, University of Birmingham. These calculations indicate that the content in U-235 in such a target would have to vary between 0.2 % (centre of front plates) up to 60 % in different axial and radial zones.

4.2 Target 2 designed as a near-critical booster target

Assuming, as before, that ≈ 20 % of the proton beam (i. e. ≈ 36 μA) would be directed towards a second target station, a higher multiplication factor than above could be aimed for in a near-critical booster assembly.

4.2.1 Booster for short pulses using fast fission only

The reference model considered for initial scoping calculations in this case is shown in fig. 6. The booster consists of fuel plates, 30 cm wide and about 10 cm high which are stacked to a total depth of 35 cm and surrounded by a decoupling layer (≈ 10^{22} at.B_{10}/cm^2) to prevent thermal neutrons from the moderators from returning to the target. Slab water moderators were assumed on the two large faces of the target and the whole arrengement was surrounded by a reflector (Ni) except for the two moderators faces and the entrance face of the proton beam into the target. Although, initially, Na-cooling was assumed, it appears that, due to the small volume fraction of coolant in the target, also D_2O might be suitable.

The overall results of the calculations for Na-cooling are given in table 1, with the power in the target chosen to be 1.75 MW. The enrichment in the booster in U-235 was 65 % in an inner zone and 80 % in the outer zone resulting in an average of 75 %. For comparison, the same arrangement has also been run for the case of natural uranium.

It can be seen that, while the source enhancement is 17 between a target of natural uranium and the booster, the leakage from the moderator faces is only enhanced by a factor of 12. It must be assumed, however, that the coupling of a small wing moderator would suffer more from the extended source than that of the large slab moderator used here.

The volume of the target is about 10 l with a uranium fraction of 80 %, leading to an average power density of 220 W/cm³ which is relatively moderate. It should be noted, however, that it is assumed that the target will be operating at 10 Hz. thus depositing 175 KJ/pulse. This leads to a thermal cycling by about 10 K at each pulse. Work done by Krautwasser et al (1985) for the SNQ-project suggests that this should not be a problem from the point of view of thermal cycling growth, if U 10 % Mo is used. The concurrent effect of radiation damage can at present not be assessed.

The pulse shape to be obtained from this arrangement has also been investigated and is shown in fig. 7 together with the case for the reference target of natural uranium. Apart from the enhancement, both curves have equal characteristics and have a FWHM of about 100 µs. (Note, the thickness of the moderator is 7 cm, un-poisoned!) Also shown is the pulse for the case, where all delayed neutrons are included. From this it is obvious, that about 17 % of all neutrons produced will be spread out over the whole time between pulses. The delayed neutron background will therefore be about 0.2 ‰ of the pulse intensity.

Table 2 gives a comparison of some relevant data for D_2O cooling vs. Na-cooling. The pulse shapes for various energy groups are shown in fig. 8.

With its flux enhancement of about a factor 10, which might be expected in a real arrangement with wing moderators the booster target seems to be quite promising from a physics point of view, especially since reasonably short pulses would be obtained at a low repetition rate. It should not be overlooked, however, that the actual design and operation of such a target presents quite a challenge.

So far, in order to obtain a crude picture of the thermohydraulic situation, a reference target design has been looked at (Weisweiler, KFA) which is in principle similar to the present ISIS target (see fig. 9) and does not take into account any engineering or operational constraints. All 35 plates are of equal thickness (namely 7.7 mm including 2 x 0.25 mm cladding), and are seperated by 1.75 mm cooling channels. Temperature and coolant flow data for the cases shown in fig. 9a and b are compiled in table 3 for D_2O and Na-cooling.

As can be seen, D_2O-cooling (at 6 m/s flow velocity between the plates) in an arrangement according to fig. 9b results in very reasonable data although an optimization process might perhaps aim at reducing somewhat the flow rate, which is about five times higher than in the present target. It should be noted, however, that these data pertain to α-uranium. The metastable γ-phase, which might be required to reduce swelling due to thermal cycling, has poorer thermal conductivity.

While, as can be seen from table 2, the loss of coolant results in a negative void coefficient and therefore switching off the proton beam is an effective shutdown-mechanism in all situations. The heat production after shutdown is quite substantial - as in a 1.7 MW reactor (see fig. 10). Taking the decay heat as 3 % of the operating power over the first few minutes, with the dense packing of the material, little heat dissipation to the environment can be anticipated and a temperature rise of ≈ 3 K/s after a loss of coolant would result, making efficient emergency cooling mandatory.

A loss of the decoupling between the target and the moderators has to be avoided under all circumstances, since, as can be seen from table 2, this would result in k_{eff} exceeding 1 substantially. It is in particular these safety aspects, which require extensive further study, before the technical feasibility and cost of such a booster arrangement can be assessed. One possible conceptual design, which includes the decoupler (shrunk onto each target plate) in the pressure vessel to ensure adequate cooling as well as its rigid connection to the uranium in all cases is shown in fig. 11.

Since the burn up in the target is relatively low, the life-limiting factors will be radiation damage and target swelling. Efficient and independent means to monitor this effect will have to be provided. Unfortunately a low burn up at the end of life results in high operating costs.

4.2.2 Booster allowing thermal fission

Some of the problems associated with a booster designed for short pulses could be alleviated, if the multiplication was allowed to result from thermal fission in the target. The immediate consequence of this would be a significant lengthening of the pulse decay constant. Calculations by Scherer (KFA) have shown that, with a source multiplication of about 10, only about a factor of 3 would be gained in pulse height and the rest would be in the long tail of the pulse. In this case also the moderator design could be different from the present one on ISIS, namely as developed for the SNQ-project (see e. g. Bauer et al, 1985). With such non-decoupled moderators and grooved surfaces, the time average thermal neutron yield at the same source strength is increased by almost a factor of 20 over the present design. Without exceeding a power level of a few MW in the target, it might become possible to devise an intensity modulated source of the type proposed in the German SNQ-project but with a 10 times lower time average flux (i. e. of the order of 10^{14} cm^{-2} s^{-1}). With the elaborate experimental techniques that have been proposed to exploit such a time structure another factor of 10 to 20 can be obtained in effective gain over a cw-source of the same time average flux, this might be an interesting option.

5. Conclusions

Without either introducing a fissile target or increasing the current in the accelerator, the improvements possible relative to the present design values are moderate (≈ 15 %) as far as the pulsed thermal and cold neutron intensities are concerned. Adding a second target station would increase the number of instruments that could be accommodated, but would hardly allow a new quality of experiments.

Under the assumption, that RAL were to operate under a nuclear site license, the present target station could be upgraded to operate with a fissile target with relatively modest efforts, yielding an increase in neutron intensities between a factor 1.5 and 2.5 on the different moderators. If a second target station was to be built in this case, it would probably be wise to design for about 4 MW of total power. Depending on the outcome of future design study work, one of three options could then be realized:

(a) a fast booster for a pulsed source at a power level around 2 MW and at 10 Hz repetition rate,
(b) a thermal booster for an intensity modulated neutron source at 10 to 25 Hz repetition rate,
(c) a high power spallation target for either a pulsed or an intensity modulated source, if suitable amendments were made to the accelerator system. In this case, target 2 might take the bulk of the proton current, keeping target 1 around $2.5 \cdot 10^{13}$ ppp at 50 Hz.

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Proc. ICANS VIII; RAL-85-110

U-235 Enrichment

-inner: 65 % -outer: 80 % -average 75 %

Total Inventory

U-238: 38 kg U-235: 111 kg

Time for 1% Burn up: ≈ 600 days

Primary Proton Source	2.5 E14 p/s (≙40 μA)
Primary Spallation Source	5.7 E15 n/s
High Energy Power (> 14 MeV)	33 kW (≙820 MeV/p)

		natural U (0.7 %)	booster (75 %)
Low Energy Fission Power (< 14 MeV)	/kW	25	1 600
Low Energy Gamma Power	/kW	10	110
Total Power	/kW	≈ 70	≈ 1 750
Total Neutron Source	$/n \cdot s^{-1}$	8 E15	1.4 E17
Total Moderator Leakage J^+	$/n \cdot s^{-1}$	2.3 E15	2.9 E16

Enhancements	Booster: natural U
Power	25
Source	17
Output	12

Table 1 Some data for the booster target arrangement shown in fig. 6 (Na-cooled).
(Data by W. Scherer, KFA Jülich.)

	Na-cooled	D_2O-cooled
$K_{effective}$ (of assembly)	0.957	0.964
Source Multiplication		
(rel. to spallation yield)	23	28
Moderator Output per Source n		
- all energies	6.0	6.7
- < 0.5 eV	1.8	2.2
- < 0.01 eV	0.04	0.06
FWHM of Pulse (µs)		
- all energies	0.6	0.6
- < 0.5 eV	7.2	8.2
- < 0.01 eV	110	110
75 % of total n-emission (µs)		
- all energies	115	160
- < 0.5 eV	270	330
- < 0.01 eV	300	350
Loss-of-Coolant Reactivity (%)		
- in core	- 0.74	- 2.3
- in whole assembly	- 0.88	- 2.1
Loss-of-Decoupler Reaktivity (%)		
- total loss	+ 13	+ 12
- to reflector	+ 0.4	

Table 2 Comparison of Na and D_2O as coolant for the booster assembly of fig. 6.
(Data by W. Scherer, KFA Jülich.)

Target design (fig. 9)	a	b		present ISIS at full power
Coolant	Na	Na	D_2O	D_2O
Peak temperature in α-U (° C)	390	290	170	380
Coolant inlet (° C)	150	150	50	43
Coolant outlet (° C)	305	205	65	50
Pressure drop (bar)	1.8	0.9	1.05	1.36
Coolant flow rate (l/s)	11.3	34	34	7
Velocity in gaps (m/s)	6	6	6	5.5

Table 3 Thermal data for a reference booster design of α-uranium and at 2 MW total power (flat power distribution within the booster) with coolant flow channels arranged as shown in fig. 9 (a) and (b). For comparison the data for the present ISIS target at full power (270 kW) are also given.

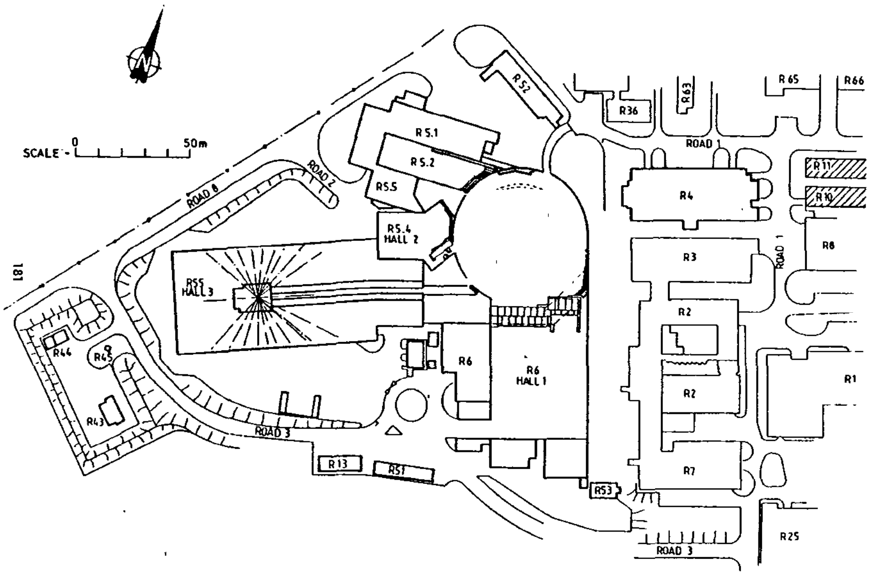

Fig. 1 The ISIS-site.

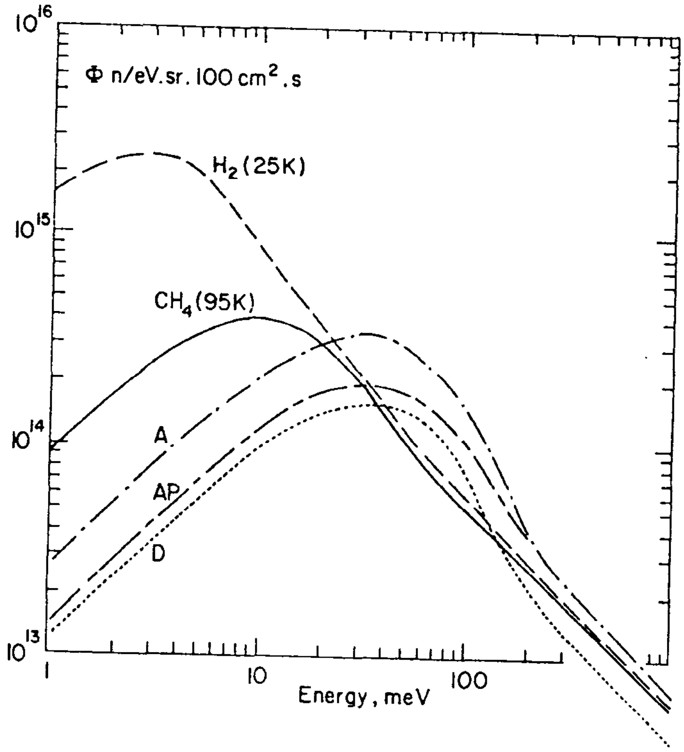

Fig. 2 The spectral distribution of neutrons from the six faces of the four ISIS-moderators CH_4 (two identical faces), D, A (ambient, one face poisoned, AP), and H_2.

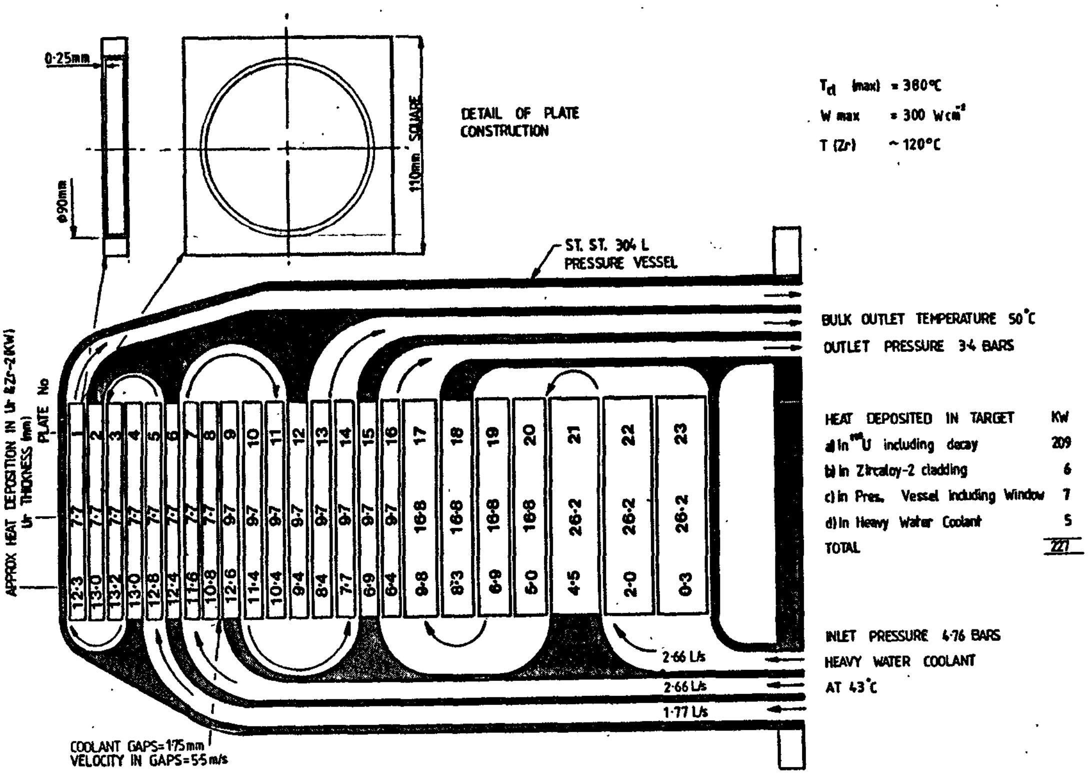

Fig. 3 Design schematic and target cooling parameters of the ISIS depleted uranium target (from Carne, 1982).

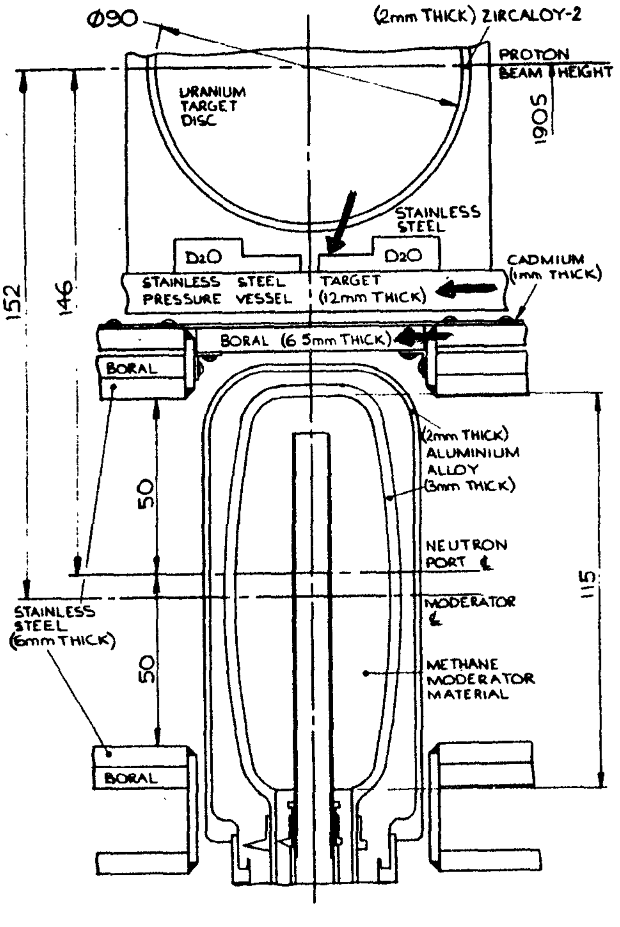

Fig. 4 CH_4 96 K-moderator location relative to the target. Areas where changes towards a reduction of the target-moderator distance might be possible are marked by arrows.

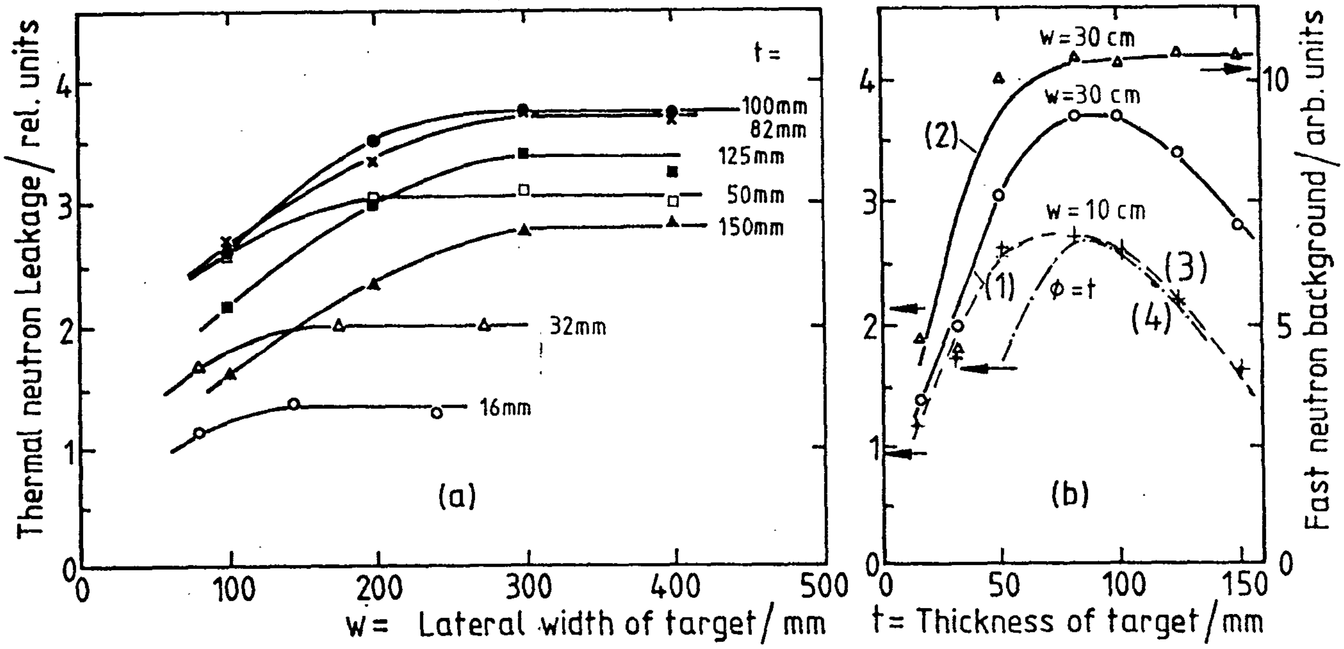

Fig. 5 Experimental results on thermal neutron leakage and fast neutron background from an unreflected polyethylene moderator as a function of the dimensions of a depleted uranium target (from: Bauer et al, 1982). Curve (4) in (b) is for a reflected arrangement with circular target cross section of diameter ϕ and has been arbitrarily normalized to curve (3) at t = 90 mm.

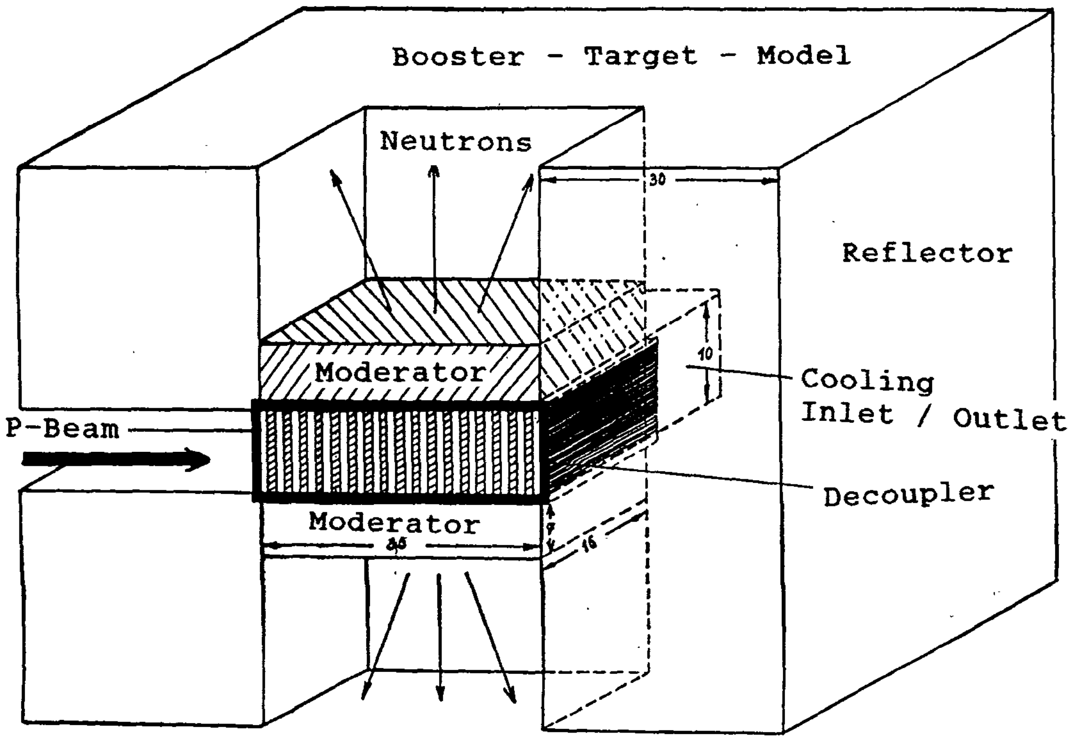

Fig. 6 Sketch of one half of the model used for the neutronic scoping calculations for the ISIS booster target.

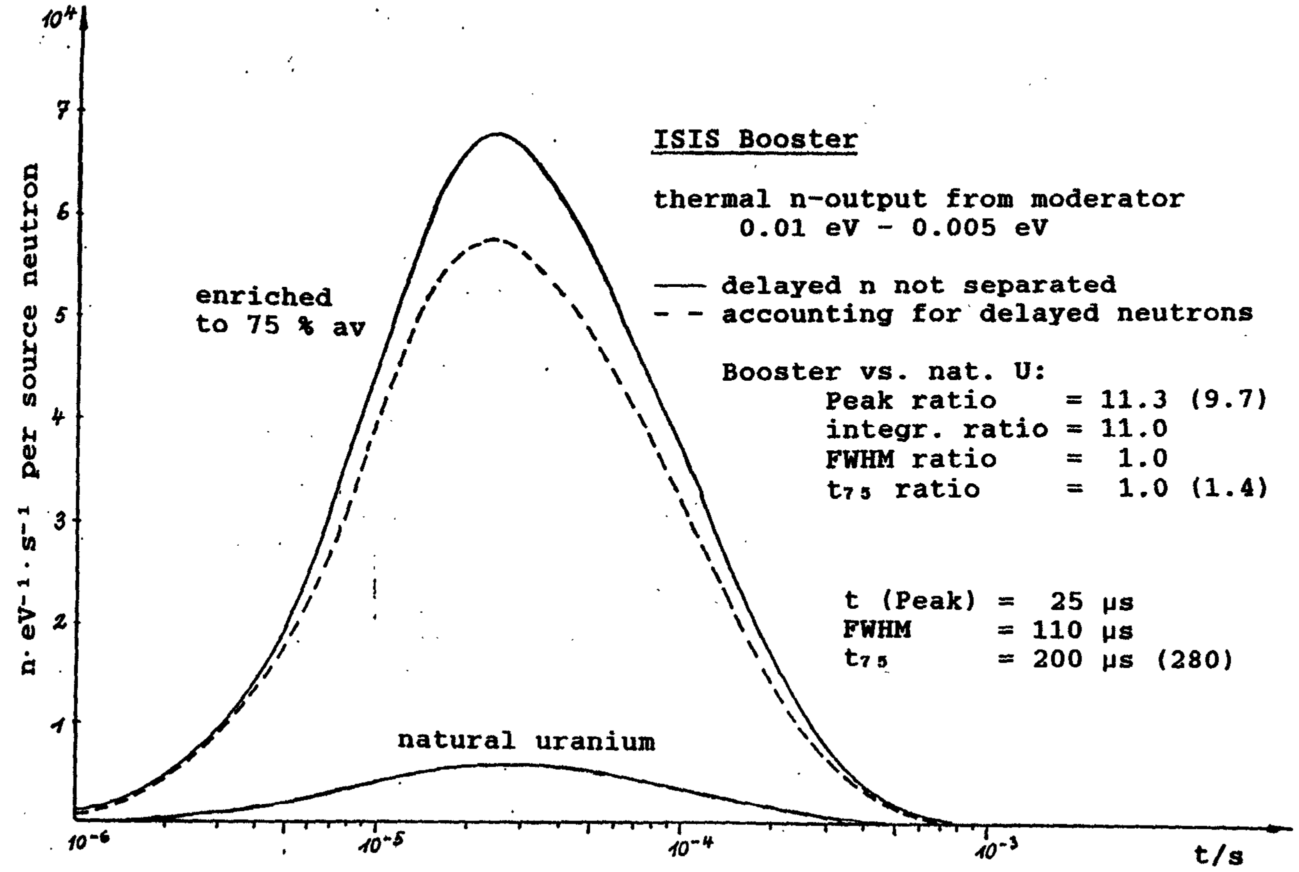

Fig. 7 Time dependence of the thermal neutron output from the arrangement shown in fig. 6 for a sodium cooled target of enriched and natural uranium.
The solid line includes all delayed neutron production in the peak.

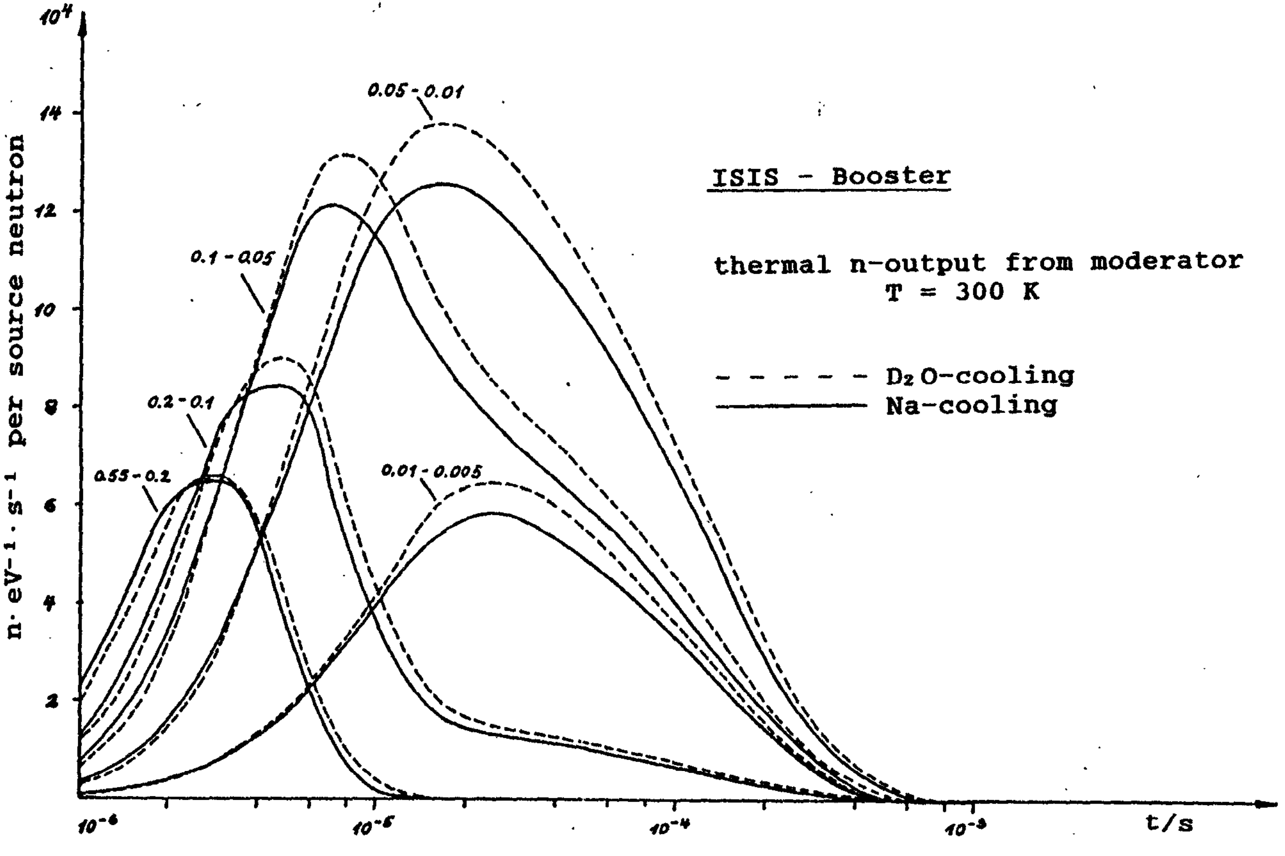

Fig. 8 Time dependence of the neutron output for various energy groups for an enriched uranium target cooled with Na (solid lines) and D$_2$O (dashed lines). The arrangement is as shown in fig. 6.

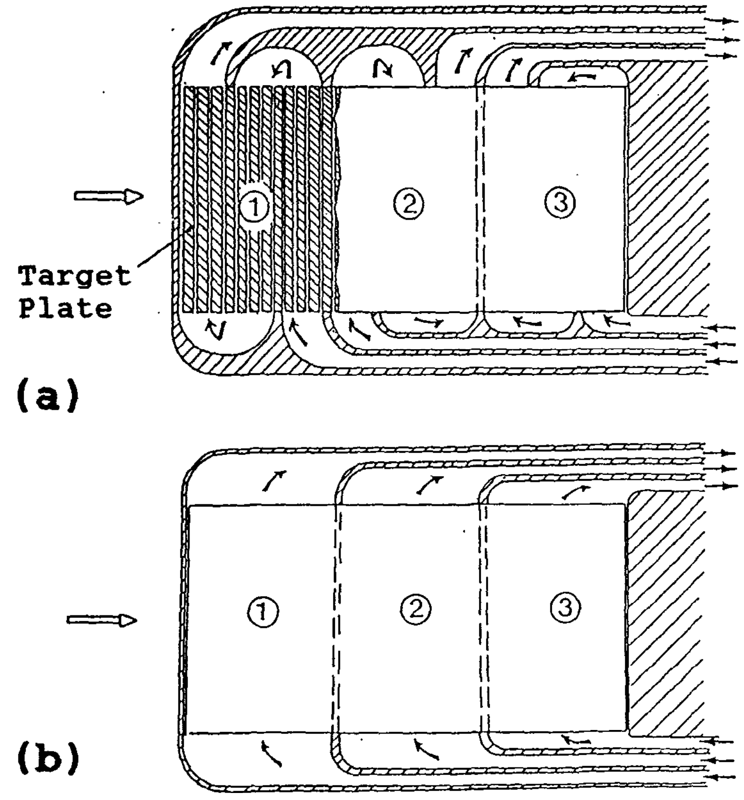

Fig. 9 Conceptual designs for the booster target used for the thermal studies. Plate thickness 7.7 mm with 2 x 0.25 mm Zr-2 cladding included, coolant gaps 1.75 mm in both cases.

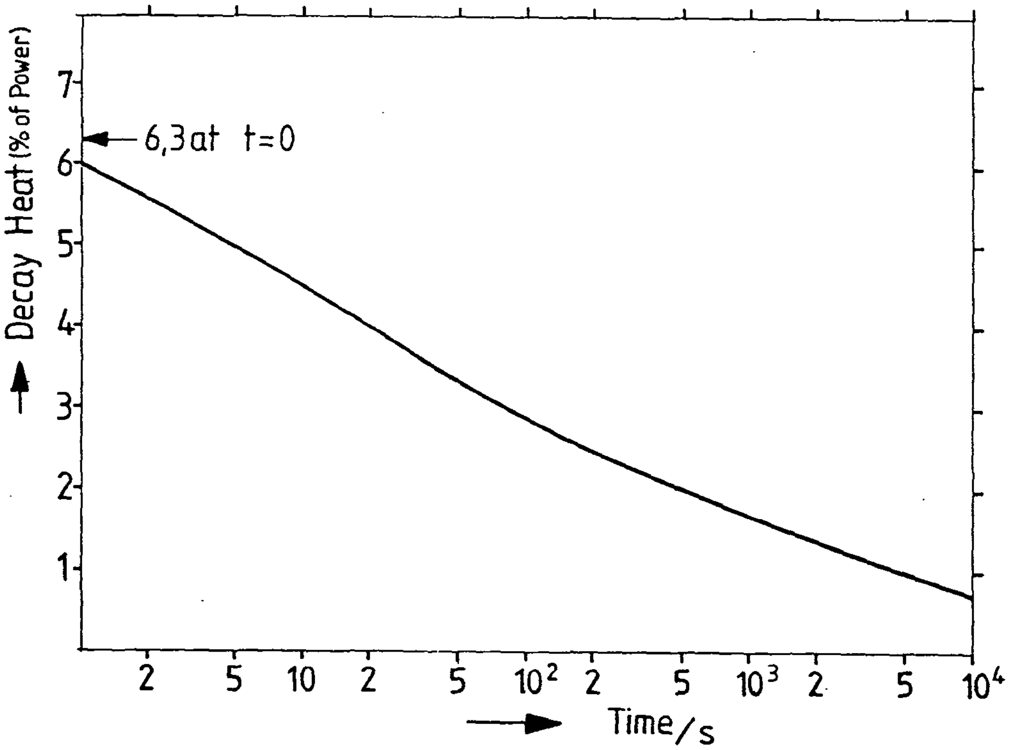

Fig. 10 Time dependence of the decay heat from the fission products of uranium given as a fraction of the operating power (after 30 days of operation).

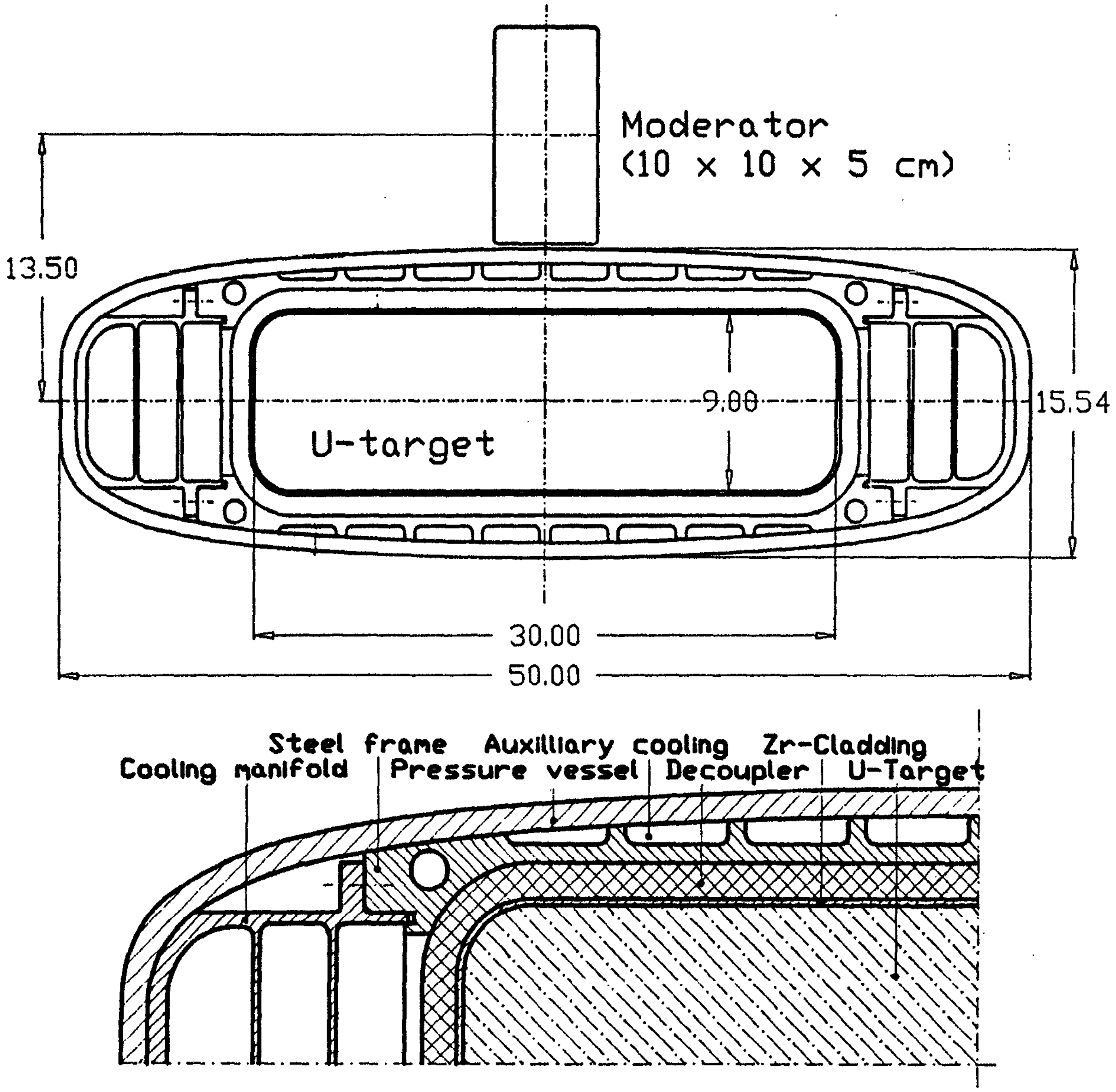

Fig. 11 Conceptual sketch showing a section through a booster target assembly with the decoupler shrunk on the target plates and included in the pressure vessel.