ICANS IX

INTERNATIONAL COLLABORATION ON ADVANCED NEUTRON SOURCES

22-26 September 1986

THE LANSCE TARGET SYSTEM

G. J. Russell, H. Robinson, G. L. Legate, R. Woods, E. R. Whitaker,
A. Bridge, and K. J. Hughes

Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, New Mexico 87545 U.S.A.

and

R. D. Neef

Institüt für Reaktorentwicklung
KFA, D-5170
Jülich, West Germany

ABSTRACT

During the summer of 1985, we replaced the WNR T-shaped target/moderator scheme with the LANSCE split-target/flux-trap-moderator design. The intent of this 'LANSCE upgrade' was to increase (to 12) the number of neutron beam lines serviced simultaneously, and to enhance the target area shielding and target system to accept 200 μA of 800-MeV protons. The four LANSCE moderators consist of three (chilled) water moderators, and a liquid hydrogen (20 K) moderator. The LANSCE target is machinable tungsten.

INTRODUCTION

The Los Alamos Neutron Scattering Center (LANSCE)[1] consists of the Proton Storage Ring (PSR)[2], and the high-current target area of the 'old' Weapons Neutron Research (WNR) facility[3] (see Fig. 1). As can be seen in Fig. 1, the LANSCE target area has vertical proton insertion; the layout of the neutron flight paths is shown in Fig. 2. This particular combination of vertical proton insertion and four flight path clusters at 90 degrees to each other (three flight paths per cluster) provides peculiar challenges for target/moderator design. Our split-target/flux-trap-moderator concept (see Fig. 3) provides an innovative and excellent solution to these particular design constraints. The four flux-trap moderators shown in Fig. 3 exist; the two 'future' upper moderators (depicted in wing-geometry) will accommodate additional flight paths constructed specifically to service the new expanded experimental hall.[1] We will do further studies to determine if the upper moderators should be in wing- or slab-geometry.

The LANSCE target system has four unique features:

- There is **no crypt** per se (a void region) surrounding the target-moderator-reflector-shield (TMRS).

- The target is **not in one piece**, but is split into two unequal segments separated by a void.

- Moderators are **not** located adjacent to the target as in conventional wing-geometry design. In the LANSCE TMRS, moderators are located between the target elements next to a void region (flux-trap) between the target elements.

- A conventional all beryllium reflector is **not used**; instead, a composite beryllium/nickel reflector/shield is employed.

For ease of installation and to retain flexibility, we built the LANSCE TMRS in two distinct sections: a) an inner region housing the targets, moderators, and the start of the beryllium/nickel reflector/shield, and b) an outer nickel reflector/shield zone. We cool both regions with light water.

When a reflector is used to enhance neutron production, there is no reason to surround the reflector with a void region. This space is better utilized for shielding purposes. For the LANSCE upgrade, we removed everything from the 2-m-diam by 2-m-high WNR crypt[3], and reinstalled the LANSCE TMRS plus additional iron shielding in the forward, backward, and radial directions. By using a split-target with four moderators around the void region between the targets, we are able to neutronically service all 12 LANSCE flight paths simultaneously.

The layout of the LANSCE flux-trap moderators is further illustrated in Fig. 4. The poison defines an 'effective' volume for thermal or cold neutron production. The decoupler neutronically isolates a moderator from the reflector/shield. The liner eliminates neutron 'crosstalk' between the moderator surface viewed by a flight path and the reflector/shield. The energies at which poisons, decouplers, and liners are effective in tailoring neutron pulses depend on the material used. By employing various combinations of poison, decoupler, and liner materials, we customize the neutronics of each moderator to meet specific experimental requirements. By combining beryllium and nickel in a reflector/shield configuration, we enhance both our thermal neutron production and neutron shielding capabilities.[4]

We will now describe what we did during the LANSCE upgrade, review neutronic calculations done to support our liquid hydrogen moderator design, discuss our operating experiences with the liquid hydrogen moderator, and examine further improvements to LANSCE.

LANSCE UPGRADE

Shielding

Everything in the 'old' WNR crypt (including the borated water tank) was removed in preparation for the LANSCE upgrade. We enhanced the neutron shielding in the forward direction to the proton beam by installing a water cooled stainless steel shield designed to remove two kW of heat. Primary protons are completely stopped in the LANSCE TMRS, and do not contribute to this heat load. The stainless steel shield (shown in Fig. 5) was the first element installed in the LANSCE upgrade, and added about 50 cm of iron shielding. Besides this new shield component, the LANSCE lower tungsten target provides additional neutron shielding in the extreme frontal direction to the proton beam.

We also enhanced the neutron shielding in the backward direction to the proton beam. Progressing out from the TMRS center, this rearward shielding now consists of 30 cm of nickel (provided by the TMRS) and 150 cm of iron. We also have 10 cm of poleythylene above the iron layer to mitigate the 'iron window' effect. Cadmium (0.8 mm thick) is placed on the service cell side of the polyethylene to help reduce thermal neutron activation in the service cell. The service cell is the area above the TMRS that houses the 90-degree-bending-magnet assembly for the proton beam and various TMRS support and remote handling systems.

The shielding added in the radial direction (illustrated in Fig. 2 and shown in Fig. 6) consists of two parts: a) an iron layer 30 cm thick placed between the crypt wall and the LANSCE TMRS, and b) the TMRS itself. In the TMRS, the nickel layer not only serves as a neutron shield, but is also an integral part of the reflector system. The overall radial thickness of the nickel in the TMRS is 30 cm. The composite beryllium/nickel reflector/shield is neutronically better (in the 10-20% range) for thermal neutron production than an all beryllium reflector,[4] with the added benefit of the additional shielding provided by the nickel. The inner portion of the TMRS is shown in Fig. 7.

The shielding enhancements described above were designed to allow for LANSCE operation with 200 μA with 800-MeV protons.

Targets and Moderators

The LANSCE split target is shown disassembled in Fig. 8 and assembled in Fig. 9. The target consists of two solid pieces of tungsten surface-cooled with light water. The upper target is 10 cm in diameter and 7.25 cm long; the lower target is 10 cm in diameter and 27 cm long; the flux-trap region between them is 10 cm in diameter and 14 cm long. We designed the target to accept 100 μA of 800-MeV protons. The target is simple and relatively inexpensive to build. In Fig. 10, where we compare the LANSCE and ISIS[5] target designs, one can see how the basic neutron production advantage of depleted uranium (as in the ISIS target) compared with 'solid' tungsten, is significantly compromised in 'engineered' targets. This occurs primarily because the depleted uranium target must be severely segmented for cooling purposes, and each segment must be clad to contain fission products. Because of the necessity to deal aggressively with cladding and containment requirements, fission products, and potential radiation damage problems, a fissile target is much more costly to build and operate than a pure spallation target, such as tungsten or tantalum.

Light water (chilled to 10 C) was chosen for three of the four LANSCE flux-trap moderators, and liquid para-hydrogen at 20 K for the fourth moderator. The water moderators are kept chilled for better temperature stability. We chose liquid hydrogen for our initial cold moderator for the following reasons: a) the availability of local expertise in extensive use of liquid hydrogen, b) access to a refrigeration system capable of meeting our needs, c) consideration of a properly developed liquid hydrogen moderator as a true high-power, high-intensity cold neutron source, and d) recognition that other practical cold moderator candidates, i.e., liquid and solid methane, being developed at other laboratories (ISIS,[6] IPNS,[7] and KENS[8]) may suffer from radiation damage at high-power (>100 μA) operation.

The physical moderator sizes and our choices of poisons, decouplers, and liners are summarized in Table I. We designed two of our water moderators for high intensity and moderate resolution by placing a gadolinium poison layer at 2.5 cm from the output face, and using cadmium decouplers and liners. We designed the third water moderator for high resolution by placing gadolinium poison at 1.5 cm, using elemental boron-10 as the decoupler, and employing a boral liner. The boron compounds decouple (1/e) at an energy of about 3 eV. For our initial liquid hydrogen moderator design, we are mainly interested in intensity and not too concerned with neutron pulse widths. Accordingly, we did not poison, decoupled with gadolinium, and used cadmium liners. Disassembled and assembled light water moderators are shown in Figs. 11 and 12, respectively. The liquid hydrogen moderator is shown in Fig. 13. Exclusive of the void region between the targets, there is about 10 cm of beryllium between the moderators and the nickel reflector/shield.

Support Systems

In addition to modifying the shielding and neutron production schemes, we also upgraded the LANSCE support systems. These support systems include the ventilation, moderator cooling, and target/reflector cooling systems.

Ventilation

During the LANSCE upgrade, we did not modify the ventilation scheme. However, we did recognize two potential changes: a) modifications will be required if a depleted uranium target is installed, and b) instead of evacuating the LANSCE crypt, we may want to fill it with helium. We presently evacuate the crypt to about 20 microns, and have found the crypt vacuum to be an extremely useful diagnostic for monitoring the integrity of the target system inside the crypt. We continually watch crypt vacuum, and have it tied into the LANSCE 'run permit'.

Moderator Cooling Loop

We designed this system to provide (chilled) 5 ± 0.3 C demineralized (processed) water to the moderator canisters, and presently operate the loop at a nominal 10 C. Except for the aluminum moderator canisters, the system has all stainless steel components, and is shown schematically in Fig. 14. We designed the loop to remove 4 kW of heat. The system volume is 1000 liters.

We maintain the moderator water temperature with a water cooled freon-12 chiller system to cool the 880 liter process water storage tank. A centrifugal pump circulates the processed water through a closed loop to the moderator canisters. In a bypass polishing loop, we flow 15 ℓ/min through a set of demineralizer resin beds to maintain a resistivity of about 5 megohms in the main loop. Makeup water is automically added to the storage tank from the LANSCE demineralized water supply.

Target/Reflector Cooling Loop

We have a separate system for cooling targets, reflector, beam stop, and 'future' high-power liners. This cooling loop is shown schematically in Fig. 15. We used all stainless steel components in the crypt, service cell, and beam channel areas. Because of cost considerations, we used some brass and copper components in the service area; these brass and copper components will be removed in the near future. We designed the system with the capacity to cool a 'future' depleted uranium target bombarded by 200 μA of 800-MeV protons; we can remove 500 kW of heat at a flow rate of 22.7 ℓ/s at a pressure of 100 psig. For a depleted uranium target, we will need multiple flow channels through the target and provisions for removing decay heat (see Fig. 15).

We built the system on four separate skids, and interconnected them with piping. The pump, heat exchanger, expansion tank, demineralizer, and valving are on skids in the service area. A valve gallery skid containing valves, flow, and pressure monitoring components is located in the service cell.

We circulate the water with a single 60 HP centrifugal pump to the valve gallery where it divides to cool all components. We monitor the input and output temperature, flow, and pressure for each of the three target cooling subloops. The target cooling circuit also contains provisions for a 'future' emergency decay cooling section using a pump powered by a motor-generator set. If necessary, this latter pump is backed up with the provision for single pass flow of industrial water. We monitor the output side of reflector, beam stop, and liners for temperature, flow, and pressure. The volume of the cooling system is about 1000 liters.

The system has an air separator for removing entrained air through a HEPA filter. We make the heat exchange through a plate type heat exchanger cooled by facility tower water. Makeup water is added automatically from the LANSCE demineralized water supply. We strip off about 0.3 ℓ/s of water from the main flow, drop its pressure to 40 psig, and flow this bypass stream through a demineralizer tank containing a mixed resin bed and an oxygen scavenger resin. We continually monitor the resistivity and pH of the main cooling loop.

All flow circuits can be purged with dry helium to force the residual water into radioactive waste storage tanks. All skids have drip pans to catch and drain lost water into radioactive waste storage tanks. Water from the cooling system is routinely monitored for radioactivity by the Laboratory's Accelerator Health Protection Group.

TARGET/MODERATOR NEUTRONICS

The LANSCE neutron production scheme, consisting of a split-target with moderators located around the void space between targets, is **an unconventional spallation neutron source target system design.** We have had to convince both ourselves and our colleagues of the viability of this approach. Accordingly, we have done extensive Monte Carlo neutronic simulations of the LANSCE TMRS concept. We also have a comprehensive experimental effort to support our general understanding of spallation neutron source neutronics.[9-11] We combined both these endeavors to bolster the unique LANSCE TMRS design.

Split-Target Performance

We have gone through a comprehensive series of Monte Carlo neutronic calculations for the LANSCE TMRS. We were primarily looking for neutron intensity shortcomings, and any degradation in neutron pulse widths due to the void space between the targets. Compared to a conventional wing-geometry system (where moderators are placed close to targets for 'good' geometric and neutronic coupling), the LANSCE TMRS appears to suffer a 15-20% reduction in thermal neutron intensity. This is an acceptable compromise for serving the twelve LANSCE flight paths simultaneously. In contrast to the aft moderators in a multi-moderator, wing-geometry design (where the forward moderator intensity is about twice that of the rearward moderators), **all LANSCE flux-trap moderators are 'high intensity'.** We see no evidence of any degradation in **thermal neutron pulse widths** from the LANSCE flux-trap moderators.

Water Moderator Neutronics

As can be seen in Fig. 16, flux-trap moderator performance is strongly tied to the thickness and type of liner (and decoupler) used. As a 'rule of thumb', one wants to get as much neutron intensity from a moderator as possible with little or no attendant degradation of the neutron pulse width. This is obviously an over simplification because it is an energy dependent consideration; we are concentrating on 'thermal neutrons' in Fig. 16. Referencing 1 cm of sintered $^{10}B_4C$ as a neutronically 'thick liner', one can get at least a factor of 5 relative increase in neutron intensity (without a neutron pulse width penalty) if a 0.05 cm-thick $^{10}B_4C$ liner is employed (see Fig. 16). The same effect can be achieved using 0.0762 cm (30 mils) of Cd.

The importance of a reflector in the LANSCE TMRS concept is also illustrated in Fig. 16, where it can be seen that the reflector enhances the thermal neutron production by about a factor of 100 compared to the 'no reflector' case. This relative gain is obtained by referencing the intensity with a 1-cm-thick $^{10}B_4C$ liner (which essentially negates the effect of a reflector) to that of a liner of zero thickness (a coupled system). Such a large reflector gain does not occur for the T-shape, wing, and slab moderator configurations. For our two 'high-intensity' water moderators, we chose 0.0762 cm of Cd for both the decouplers and liners. For our 'high-resolution' water moderator we use elemental ^{10}B for the decoupler, and boral for the liner. The neutron decoupling energy for these two boron compounds is about 3 eV.

Overall moderator thickness determines epithermal neutron performance; we chose the thickness of our water moderators using the data given in Fig. 17. In this figure, we show 'figure-of-merit' (defined as neutron intensity divided by the square of the neutron pulse width) versus moderator thickness. Using the data in Fig. 17, we selected overall moderator thicknesses of 3.5 cm for two moderators, and 4.0 cm for the third. We would have made all three moderators 3.5 cm thick, but could not because of an early decision required on moderator field-of-view locations. This early determination was needed so that neutron collimation systems could be designed.

The poison material, thickness, and depth from the viewed surface determine the thermal neutron performance of a moderator. We chose gadolinium as our poison material; the thickness of the gadolinum poison ranges from 0.00381 to 0.00508 cm (1.5 to 2.0 mils). For the two high intensity moderators, we set the poison depth at 2.5 cm; for the high resolution moderator, the poison depth is at 1.5 cm.

As mentioned above, the effect of a reflector on enhancing moderator neutronics is **strongly dependent** upon the geometry of the target/ moderator/reflector system. For our flux-trap system, the reflector enhancement is about 100! For wing-geometry, the embellishment is more like a factor of 3-4.[9] For slab-targets and slab/moderators[12,13] or a hybrid system,[14] reflector augmentation of moderator neutron intensity is around a factor of 2. The reason is that **slab systems in general are intrinsically neutronically efficient**, and the addition of a reflector has a minimal (but significant) effect on moderator neutronic performance. The effects of a reflector and liner thickness on a hybrid moderator system are shown in Figs. 18-20.

Cold Hydrogen Neutronics

Monte Carlo techniques are generally used for doing the complex neutronic calculations required in spallation neutron source design. The complicated geometries of these sources are (more-or-less) adequately handled by Monte Carlo methods. However, it is not sufficient to just treat the geometry correctly; the physics of the problem (which is even more involved) must also be dealt with properly. The physics comes in via the neutron cross sections used. A particularly weak link at low energies is the availability and adequacy of scattering kernels to describe these cross sections.

This could be a particular problem for liquid hydrogen, where there may be serious deficiencies in pertinent data and adequate theoretical kernel formalisms. In particular, theoretical scattering kernels for liquid hydrogen should: a) model 'liquid' effects properly, and b) adequately account for the different cross sections of ortho- and para-hydrogen. We have not made any effort to find the most recent experimental data for liquid hydrogen cross sections or the latest theoretical kernel formalisms. Instead, we obtained from our Jülich colleagues[15] a **cold molecular-hydrogen gas** kernel formulated by Young and Koppel.[16] This kernel should be applicable to liquid hydrogen for input neutron energies above 7 meV. This latter qualification is not too comforting; however, the severity of the restriction depends on how important 'liquid' effects are below 7 meV in a particular application. We implemented this kernel at Los Alamos and used it in all neutronic calculations supporting our liquid hydrogen moderator design.

As mentioned above, Young and Koppel (in 1964) published a formalism for calculating neutron cross sections for **cold molecular-hydrogen gas.** Their calculated total cross sections for both para-hydrogen and ortho-hydrogen gas at 20.4 K agreed reasonably well with the limited experimental data available at that time. Their calculated results and comparison with experimental data are shown in Fig. 21. A pronounced rise in the para-hydrogen cross section can be seen at roughly 10 meV. In their paper, Young and Koppel also gave a simplified cross section formalism where vibrations were not considered. It was this latter formalism which we received from our Jülich collaborators (in coded form) and implemented on the Los Alamos computers. In Fig. 21, we also show the cross sections as calculated at Los Alamos using the kernel obtained from Jülich. The difference between the results obtained using the approximate formalism compared to the more complete treatment, as calculated by Young and Koppel, are evident. The effect of these differences on an applied calculation of spallation neutron source neutronics is difficult to quantify.

The 'normal' concentration of hydrogen at 300 K is 25% para-hydrogen and 75% ortho-hydrogen; at 20 K the concentration is 100% para-hydrogen. If neutronically wise and physically possible, we would like to take advantage of the larger ortho-hydrogen cross section in designing liquid hydrogen moderators. Because of the rapid changes in the para-hydrogen cross section in the region around 10 meV, we binned the data from our Monte Carlo calculations into the following energy ranges: a) $E \lesssim 10$ meV, b) 10 meV $\lesssim E \lesssim 100$ meV, and c) $E \lesssim 100$ meV. By binning the results in these energy ranges, one should get a feel for the relative importance of para- and ortho-hydrogen cross sections on hydrogen moderator neutronics.

In Fig. 22, we show calculated results of moderator neutron leakage versus moderator thickness for two different para-hydrogen concentrations. The computations were for a coupled moderator, that is, no decoupler/liner. For 100% para-hydrogen and 'cold' neutrons (defined here to be neutrons with energies below 10 meV), the neutron leakage reaches a 'plateau' at a moderator thickness of about 3 cm. The maximum neutron leakage for 'epicold' neutrons (defined here to be neutrons in the energy range 10 meV $\leq E \leq$ 100 meV) is between 1 and 2 cm. The situation is somewhat different for the 'normal' (25% para- and 75% ortho-) hydrogen concentration where there is no plateau effect for the cold neutrons. For normal hydrogen, cold neutron leakage has broad maximum around 4 cm, and epicold neutron leakage peaks just below 1 cm. Note that the **maximum neutron leakage intensity** from a pure para-hydrogen moderator exceeds that from a normal hydrogen moderator! One must remember, however, that all hydrogen moderator neutronic calculations reported here use Young and Koppels' approximate **cold molecular-hydrogen gas** kernel at 20 K.

We show the same type of data for a decoupled system in Fig. 23. The gadolinium decoupler/liner was 0.00381 cm thick (1.5 mils). Comparing the data in Figs. 22 and 23, we see that the shapes of the curves are different for the coupled and decoupled cases. This just emphasises the complexity of what is going on in the physical process of producing cold neutrons. For these calculations, moderator neutron leakage is strongly dependent on the energy distribution of the neutrons 'feeding' the moderator. The differences in absolute neutron intensities between coupled and decoupled moderators (Figs. 22 and 23) are indicative of the penalties paid when neutron pulses are shaped with decouplers and liners. Using the data in Fig. 23, together with the criteria of keeping energy deposition minimal, we set the LANSCE liquid hydrogen moderator thickness at 5 cm. The calculated energy deposition in a coupled cold hydrogen moderator as a function of moderator thickness is depicted in Fig. 24.

In Fig. 25, we show neutron leakage versus para-hydrogen content for a 5-cm-thick decoupled and coupled hydrogen moderator. The neutron leakage intensities do not vary dramatically, have different shapes depending on whether the moderator is decoupled or coupled, and, for the decoupled case, are essentially flat. For a coupled moderator, our data show cold neutron leakage increasing linearly with para-hydrogen concentration. This is in slight difference to the results given in Ref. 17, which, for a coupled system, show an intensity peak at a hydrogen concentration of 90% para and 10% ortho. However, the referenced data do not vary by more than 25%, and quote neutron leakage intensities in the 5-6 Å range compared to our integral results which are for neutron wavelengths greater than 3 Å. Deviations in the details of data reporting probably account for the minor disparances between the two calculational results.

In Figs. 26 and 27, we show calculated neutron leakage intensities and pulse widths for a 5-cm-thick moderator; this is the thickness of the LANSCE cold source. The intensity penalty for using decouplers and liners is evident. However, the degradation in neutron pulse widths below the cutoff energy of the decoupler/liner (about 0.2 eV for the Gd used here) can be severe. Depending on the application, neutron choppers can be used to better shape the neutron pulses from a coupled moderator. In Figs. 26 and 27, there is very little difference in the energy distribution and intensity of neutrons from a 100% para-hydrogen moderator compared to a 25% par- and 75% ortho-hydrogen one. This is independent of whether the moderator is decoupled or coupled. This should not be too surprising because we deliberately chose the thickness (5 cm) of the LANSCE cold hydrogen moderator to minimize the effects of differing para-hydrogen concentrations. To take advantage of any gain attributable to ortho-hydrogen, one must design a specialized moderator canister (for example, a re-entrant canister).

For the LANSCE hydrogen moderator thickness of 5 cm, we directly compare leakage neutron spectrum from a 100% para-hydrogen moderator to that from a

25% para- and 75% ortho-hydrogen one in Fig. 28. As can be seen, there is little quantitative difference predicted by the Young and Koppel **cold molecular-hydrogen gas** kernel. For 100% para-hydrogen, there are a few more neutrons in the 5-50 meV range. The presence of ortho-hydrogen produces a slightly 'cooler' spectrum. The enchancement of 'cold' neutron production from a cold source compared to an ambient temperature moderator is dramatic.

For a 100% para-hydrogen moderator 6 cm thick, the penalties for shaping neutron pulses with decouplers and liners are further illustrated in Fig. 29. Here we see that cold neutron production increases by a factor of about six when going from a decoupled to a coupled moderator. For a pulsed spallation neutron source, not all this gain is useful because a significant fraction of the neutrons are produced in the 'tails' of the neutron pulses. If one assumes that neutrons produced in the first 200 μs of a pulse are useful, the cold neutron intensity gain of a coupled compared to a decoupled moderator is about 2.3. To take advantage of this latter intensity increase, one would use a neutron chopper to produce neutron pulses from a coupled system. In Fig. 29, the relative importance decouplers and liners have on neutron leakage intensity can be seen. The impact on neutron pulse widths should be more pronounced for liner removal than decoupler removal. As shown in Fig. 29, the effects of decoupling and coupling on neutron leakage intensity are energy dependent, again demonstrating the complexity of the physical processes going on during moderation. As can be seen in Fig. 29, neutron leakage intensity is not too sensitive to the type of material used for decouplers and liners.

LIQUID HYDROGEN MODERATOR SYSTEM

We installed the LANSCE liquid hydrogen moderator system during the 1985 LANSCE upgrade, and reported on it at ICANS-VIII,[18] and more recently at the 1986 annual meeting of the American Institute of Chemical Engineers.[19] While the system has remained operational since ICANS-VIII, we have been limited to approximately 2500 hours of operation at proton beam currents up to 35 μA. This running time has primarily been influenced by: a) PSR commissioning, where high priority has been given to understanding PSR operation in lieu of production time, and b) delays in design, fabrication, and installation of the small angle scattering instrument which utilizes the cold moderator.

System Description

We flow liquid hydrogen to and from the moderator canister. The system consists of the following major components: a) a KOCH model 1430 liquid helium refrigerator, b) the helium-to-hydrogen heat exchanger, c) a resistance heater, d) the liquid hydrogen circulating pump, and e) the moderator canister. The layout of these components is shown in Fig. 30. The KOCH unit is powered by three reciprocal compressors and has a capacity of 500 Watts at 20 K.

Through cryogenic transfer lines, we circulate cold helium gas from the refrigerator to the helium-to-hydrogen heat exchanger. As the hydrogen loop cools down, we add hydrogen at a pressure of 15 atm. When full, the volume of liquid hydrogen in the hydrogen loop is about 6 liters. Using a centrifugal pump, we circulate liquid hydrogen to the moderator canister through cryogenic transfer lines. A schematic of the liquid hydrogen system is shown in Fig. 31.

In addition to nuclear heating during operation, we deliberately add heat to the hydrogen loop through the resistance heater. We do this to maintain a steady heat load for the refrigerator, and a moderator temperature variation of ± 1 K. The moderator, pump, and heat exchanger are in an evacuated space. We continually monitor the moderator temperature using a hydrogen vapor bulb thermometer and the heat exchanger temperature with silicon diodes. Pressure transducers are located throughout the system to monitor hydrogen pressure.

System safety is assured through multiple overpressure relief devices which vent the hydrogen into an exhaust stack when overpressure occurs. A solenoid 'dump' valve (controlled by relay logic with inputs from combustible gas detectors, vacuum gauges, and pump and refrigerator status) is also connected into the vent stack.

System Problems

The helium-to-hydrogen heat exchanger is presently located in the service cell, an area which may experience radiation levels as high as 50 Rem/h at 100 μA of proton current. At this current, we estimate 30 Rem/h at the location of the pressure transmitter for the vapor bulb thermometer. One potential problem associated with such relatively high radiation levels is premature failure of the signal conditioning electronics for the pressure transmitter. At the nominal proton currents of 20-25 μA run to date, we may have begun to experience temperature drifts attributable to the onset of radiation damage in the pressure transmitter electronics.

Several power failure problems have caused our safety rupture diaphragm to do its job and burst. We designed the vent valves to open on a power failure and leave the loop in a safe state after unscheduled power outages. The breaking of the rupture diaphragm occurred when the valve opened starting a flow of liquid hydrogen, and, when the power returned shortly thereafter, liquid hydrogen was trapped in warm lines. This trapped liquid hydrogen rapidly turned to gas causing an overpressure and breaking of the rupture disk. This failure mode has been eliminated by modifying the power supply electrical operation to carry us through 'short' power glitches.

On the positive side, the liquid hydrogen system has performed as expected with no active controls being required.

Short-Term Improvements

During the upcoming cycle break starting roughly mid-December and lasting through about mid-June of 1987, we will relocate the vapor bulb thermometer electronics from the service cell to the service area. This will essentially mitigate any radiation damage problems to this unit.

Our present startup and cool down procedures require personnel to be in the service area to do the needed tasks. This requirement, in turn, prohibits proton beam from being delivered to LANSCE. We will eliminate this unnecessary perturbation to the already precious LANSCE production time by extending the charge piping for the hydrogen loop to an area accessible when LANSCE is operating. This will reduce LANSCE downtime during the cool down period for the hydrogen moderator system.

Long-Term Modifications

Our long range plans include moving the helium-to-hydrogen heat exchanger unit from the service cell to the service area. The service area has a much lower radiation level, essentially eliminating any radiation damage concerns. Relocating the heat exchanger and helium refrigerator units outside the service area is an option we will also consider.

The present hydrogen moderator canister is a 'flat plate' design. With help from our colleagues at the Rutherford Appleton Laboratory, we intend to fabricate and have on hand a 'spherical sided' hydrogen moderator canister. This will improve the safety factor for materials failure at our present operating pressure of 15 atm. This improved canister design will also allow us to fabricate the canister with thinner walls.

Finally, we are investigating methods to maintain and monitor a liquid mixture of 25% para and 75% ortho hydrogen. As noted in the cold hydrogen neutronics section, we would have to neutronically optimize the target canister design to take full advantage of this capability.

FUTURE IMPROVEMENTS TO LANSCE

In addition to the specific betterments to the liquid hydrogen moderator system discussed above, we will continue to enhance the neutron production and understand the performance of LANSCE. The improvements will primarily be in the following areas (arranged roughly according to priority):

- optimization of the TMRS materials and geometry,
- maximization of moderator neutronic performance to experimental requirements,
- implementation of more cold moderators,
- application of a fissile depleted uranium target, and
- if technologically feasible and warranted, utilization of a fissile (^{235}U, ^{239}Pu, etc.) booster target.

For Los Alamos spallation target system designs, we have always emphasized optimal neutron production and efficient neutron utilization. This can easily be as important in useful neutron production for experiments as making more neutrons by using advanced targets such as depleted uranium. We are taking both approaches (optimal neutron usage and implementation of advanced targets and moderators) in our upgrades to the LANSCE target system. This involves: a) proper choice of target, moderator, reflector, poison, decoupler, liner, structural, and cooling materials, b) placing these materials in an optimal geometry, c) matching source neutronics to instrument requirements, and d) engineering the system to operate at high-power for a useful period of time. In addition, we need to better understand LANSCE shielding requirements, and improve the LANSCE target area remote handling capabilities. **We must also look to the next generation of LANSCE.**

If one considers materials like tungsten, tantalum, and 'lead' to be pure spallation targets, then depleted uranium is a spallation/fission target, and a booster target is a fission/spallation target. We 'sorted' the targets according to the importance fission plays in neutron production. This ordering automatically ranks the targets according to cost and complexity, with the booster target being the most expensive and difficult to implement. We put lead in quotes because at proton energies of 800-MeV and higher, even a lead target fissions slightly.

For a LANSCE target designed to handle 100 μA of 800-MeV protons, we have calculated the gain in useful neutron beam flux from an engineered depleted uranium target to be 1.4-1.5 that from an engineered tungsten target.[4] We consider this gain to be significant, but only one of the many issues which must be addressed to employ a fissile target. Other important considerations are safety, cost, complexity, and **the 'quality' of the neutron beams delivered to the users.** This latter consideration must include such effects as delayed neturons, delayed fissions (as they contribute to neutron pulse broadening), and additional gamma-ray contamination of the neutron beams. However, depending on funding support and user input, we are including a depleted uranium target in the plans for the future betterment of LANSCE, and have started considering some initial detailed issues necessary for implementing a LANSCE depleted uranium target system.

One such item is the induced radioactivity and afterheat production for such a target.[20] Detailed procedures to calculate the time behavior of radioactivity, thermal power, nuclide production, etc. from proton bombardment of a spallation target have been devleloped by Atchison[21] and Schaal.[22] At Los Alamos, we developed a similar capability by coupling our Monte Carlo code package[23] with the KFA/Jülich version of ORIHET and ORIGEN. We adapted the Jülich ORIGEN code to accept the expanded Los Alamos ORIGEN library. It is not possible for the ORIGEN code to calculate the time behavior of all nuclides produced by spallation reactions because the cross section libraries of the ORIGEN code are based on fission reactor applications. Also, calculational procedures do not account for nuclide burnup, and Atchison's ORIHET data libraries do not contain nuclides with mass numbers below 40. Shaal extended these libraries into the mass number range $A < 40$, but still the libraries are incomplete.

For LANSCE depleted uranium target, an irradiation time of two years is foreseen with two half-year operating periods. We did a calculation of induced radioactivity and afterheat for a split-target imbedded in the LANSCE TMRS. We assumed an irradiation time of one year without any shutdown; this assumption leads to pessimistic values of target radioactivity and afterheat. The results of the computation are shown in Figs. 32 and 33 and in Tables II and III. We used this type of data to determine the capacity of our target cooling system, and to size the emergency backup cooling loop. The data are also necessary for safety considerations.

To assure ourselves that our innovative flux-trap design is competitive with the more 'classical' wing-moderator approach, we calculationally compared thermal neutron production from flux-trap and wing-geometry moderators. We did the computations for two 'viewed' moderator surfaces; the geometries used are illustrated in Fig. 34. We further quantified the intercomparison by using IPNS, ISIS, and LANSCE 'as built' target designs and proton beam characteristics. The results of the calculations are shown in Figs. 35 and 36. We believe these intercomparisons between facilities to be the best **relative** comparisons that exist to date; and demonstrate our resolve to keep LANSCE at the forefront of the world's pulsed spallation neutron sources. The moderator, poison, decoupler, and liner materials, and poison depth from the moderator viewed surface were the same in all the computations. The reflector material was that used at each facility. We did not account for either reflector coolant nor (with the exception of the target itself) for any particulars associated with real engineered systems. **As can be seen in Fig. 36, LANSCE (when operating at design specifications) will be the most intense pulsed spallation source in the world.**

If we denote the existing LANSCE facility as **LANSCE-I**, then **LANSCE-II** designates a target area at the proposed Los Alamos Advanced Hadron Facility (AHF).[24] As presently envisioned, LANSCE-II would be a 'world class' cold neutron facility for materials science research; we are attempting to integrate LANSCE-II with a neutrino facility. Preliminary LANSCE-II proton beam characteristics are 500 μA of 1-2 GeV protons in 1 μs bursts at 12 Hz. The LANSCE-II target area concepts are just evolving as well as the proton beam properties. Our preliminary thinking should become firmer in about a year's time.

CONCLUSIONS

The LANSCE upgrade involved **major changes** to the 'old' WNR high-current target area. We are glad the enhancements of the target area shielding, and the installation of the unique split-target/flux-trap-moderator system (including upgrades to support systems) are behind us. The successful implementation of a liquid hydrogen moderator is particularly gratifying given the minimal resources we had to devote to the effort.

Initial indications are that the neutronic performance of the LANSCE TMRS is as expected. However, during the next few months, we will make detailed neutronic measurements of moderator performance, and compare the results with calculations of the 'as built' LANSCE TMRS. We need a definitive measurement of the neutron leakage spectrum from the LANSCE hydrogen moderator to compare with our calculations.

ACKNOWLEDGEMENTS

We acknowledge the efforts of Bob MacFarlane in implementing the cold hydrogen kernel on the Los Alamos computer system, and for useful discussions concerning the limitations of the kernel. We appreciate Dick Prael's help in integrating the cold hydrogen kernel into the Los Alamos Monte Carlo code package. We are indebted to Teri Cordova for her typing help. Special thanks to Francis Atchison for being so patient, and to the 'SINQ crew' for a successful ICANS conference, and for a very special day at the 'Rigi'.

This work was performed under the auspices of the U. S. Department of Energy, Office of Basic Energy Science.

REFERENCES

1. F. A. Morse, "LANSCE Overview," ICANS-IX, Proc. of the Ninth Meeting of the International Collaboration on Advanced Neutron Sources, Villigen, Switzerland, 22-26 September 1986 (this conference), LA-UR-86-3227, Los Alamos National Laboratory (1986).

2. G. P. Lawrence, R. A. Hardekopf, A. J. Jason, B. Blind, and T. Hardek, "Proton Storage Ring Commissioning at LANSCE," ICANS-IX, Proc. of the Ninth Meeting of the International Collaboration on Advanced Neutron Sources, Villigen, Switzerland, 22-26 September 1986 (this conference), LA-UR-86-3971, Los Alamos National Laboratory (1986).

3. G. J. Russell, P. W. Lisowski, S. D. Howe, N. S. P. King, and M. M. Meier, "Characteristics of the WNR - a Pulsed Spallation Neutron Source," Nucl. Data for Sci. and Tech., pp. 831-835, K. H. Bockhoff, Ed. (1983).

4. G. J. Russell, C. D. Bowman, E. R. Whitaker, H. Robinson, and M. M. Meier, "LANSCE High-Power (200 μA) Target-Moderator-Reflector-Shield," ICANS-VIII, Proc. of the Eighth Meeting of the International Collaboration on Advanced Neutron Sources, Oxford, England, 8-12 July 1985, RAL-85-110, pp. 272-293 (1985).

5. A. Carne, "Review of SNS Target Station," ICANS-IV, Proc. of the Fourth Meeting of the International Collaboration on Advanced Neutron Sources, Tskuba, Japan, 20-24 October 1980, KENS Report II, pp. 136-153 (1981).

6. A. D. Taylor, SNS Moderator Performance," ICANS-VIII, Proc. of the Eighth Meeting of the International Collaboration on Advanced Neutron Sources, Oxford, England, 8-12 July 1985, RAL-85-110, pp. 319-328 (1985).

7. J. M. Carpenter, A. W. Schulke, T. L. Scott, D. G. Wozniak, B. E. Benson, and B. D. Leyda, "The IPNS Grooved, Solid Methane Moderator," ICANS-VIII,

Proc. of the Eighth Meeting of the International Collaboration on Advanced Neutron Sources, Oxford, England, 8-12 July 1985, RAL-85-110, pp. 311-318 (1985).

8. Y. Ishikawa, M. Furusaka, S. Itoh, S. Ikeda, N. Watanabe, K. Inoue, and H. Iwasa, "Mock-up Experiments for KENS-I Cold Moderator," ICANS-VIII, Proc. of the Ninth Meeting of the International Collaboration on Advanced Neutron Sources, Oxford, England, 8-12 July 1985, RAL-85-110, pp. 329-343 (1985).

9. G. J. Russell, M. M. Meier, J. S. Gilmore, R. E. Prael, H. Robinson, and A. D. Taylor, "Measurements of Spallation Target/Moderator/Reflector Neutronics at the Weapons Neutron Research Facility," ICANS-IV, Proc. of the Fourth Meeting of the International Collaboration on Advanced Neutron Sources, Tsukuba, Japan, 20-24 October 1980, KENS Report II, pp. 210-241 (March 1981).

10. G. J. Russell, M. M. Meier, H. Robinson, and A. D. Taylor, "Preliminary Neutronics of a 'T'-Shape Premoderator/Moderator for the Weapons Neutron Research Facility," ICANS-V, Proc. of the Fifth Meeting of the International Collaboration on Advanced Neutron Sources, Jülich, West Germany, 22-26 June 1981, Jülich-Conf-45, ISSN-0344-5789, pp. 389-416 (October 1981).

11. G. J. Russell, "Applied Spallation Physics Research at Los Alamos," LA-UR-84-778, Los Alamos National Laboratory (1983).

12. G. J. Russell, P. A. Seeger, and R. G. Fluharty, "Parametric Studies of Target/Moderator Configurations for the Weapons Neutron Research (WNR) Facility," LA-6020, Los Alamos Scientific Laboratory (1977).

13. G. J. Russell, P. A. Seeger, and R. G. Fluharty, "Monte Carlo Studies of Target/Moderator Configurations for the Weapons Neutron Research Facility," Trans. Am. Nucl., Soc., 22, 715-716 (1975).

14. G. J. Russell, "Inital Target/Moderator Configuration for the Weapons Neutron Research Facility," Trans. Am. Nucl. Soc., 27, 861-862 (1977).

15. D. Filges, KFA Jülich (private communication).

16. J. A. Young and J. U. Koppel, "Slow Neutron Scattering by Molecular Hydrogen and Deuterium," Phys. Rev., 135, No. 3A, A603-A611 (1964).

17. R. D. Neef and H. Schaal, "Evaluation of Hydrogen Data for Cold Neutron Sources and Their Application to Source Design Studies, KFA Jülich (unpublished).

18. H. Robinson, G. J. Russell, E. D. Tucker, E. R. Whitaker, K. D. Williamson, Jr., and F. J. Edeskuty, "LANSCE Liquid Hydrogen Moderator System Hardware-Characteristics-Operation," ICANS-VIII, Proc. of the Eighth Meeting of the International Collaboration on Advanced Neutron Sources, Oxford, England, 8-12 July 1985, RAL-85-110, pp. 294-310 (1985).

19. H. Robinson, G. J. Russell, K. D. Williamson, Jr., and F. J. Edeskuty, "The Los Alamos Liquid Hydrogen Neutron-Moderator System," Proc. of Symp. on Cryogenic Properties, Processes and Applications 1985, AICHE 251, 82, 172-176 (1986).

20. R. D. Neef, "Calculation of Initial Induced Radioactivity and Afterheat Production for a LANSCE Depleted Uranium Target, "Los Alamos National Laboratory (1986) (unpublished).

21. F. Atchison, "A Theoretical Study of a Target Reflector and Moderator Assembly for SNS," RL-81-006, Rutherford and Appleton Laboratories (1981).

22. H. Schaal and G. Sterzenbach, SNQ 3 J../BH 27 11 84, KFA Jülich (1984).

23. R. E. Prael and H. Lichtenstein, "User Guide to the HETC Code System," Los Alamos National Laboratory (1986) (unpublished).

24. H. A. Thiessen, "An Advanced Hadron Facility: A Combined Kaon Factory and Cold-Neutron Source," Los Alamos National Laboratory (unpublished).

TABLE I

LANSCE MODERATOR CHARACTERISTICS

Moderator Type	Material	Width (CM)	Height (CM)	Thickness (CM)	Poison Depth (CM)	Poison Material	Decoupler	Liner
high-resolution	H_2O	13.0	13.0	3.5	1.5	Gd	^{10}B	Boral
high-intensity	H_2O	13.0	13.0	3.5	2.5	Gd	Cd	Cd
high-intensity	H_2O	13.0	13.0	4.0	2.5	Gd	Cd	Cd
cold	liquid H_2	13.0	13.0	5.0	---	none	Gd	Cd

TABLE II

GASEOUS ELEMENT PRODUCTION IN A LANSCE DEPLETED URANIUM TARGET

	Amount (g)			
	Spallation		Low-Energy Neutron Flux	
Element	t = 0	t = 10 yr	t = 0	t = 10 yr
He	1.04×10^{-2}	1.43×10^{-2}	1.21×10^{-5}	2.69×10^{-4}
Cl	3.78×10^{-8}	0.0	0.0	0.0
Ar	4.41×10^{-4}	3.85×10^{-4}	0.0	0.0
Br	7.60×10^{-2}	7.58×10^{-2}	1.27×10^{-2}	1.27×10^{-2}
Kr	3.75×10^{-1}	3.73×10^{-1}	2.47×10^{-1}	2.39×10^{-1}
I	3.85×0^{-1}	3.83×10^{-1}	1.88×10^{-1}	1.75×10^{-1}
Xe	1.00×10^{0}	1.01×10^{0}	3.11×10^{0}	3.11×10^{0}
Rn	3.35×10^{-5}	1.12×10^{-8}	2.34×10^{-15}	4.45×10^{-14}
Total	1.85	1.86	3.56	3.54

TABLE III

SPECIAL GASEOUS NUCLIDE PRODUCTION
IN A LANSCE DEPLETED URANIUM TARGET

Nuclide	Amount (g)			
	Spallation		Low-Energy Neutron Flux	
	t = 0	t = 10 yr	t = 0	t = 10 yr
^{85}Kr	2.52×10^{-2}	1.32×10^{-2}	1.60×10^{-2}	8.41×10^{-3}
^{85m}Kr	3.78×10^{-5}	0.0	6.02×10^{-5}	0.0
^{90}Sr	1.07×10^{-1}	8.36×10^{-2}	3.55×10^{-1}	2.77×10^{-1}
^{131}I	4.88×10^{-3}	0.0	1.52×10^{-2}	0.0
^{133}Xe	3.62×10^{-3}	0.0	2.01×10^{-2}	0.0
^{137}Cs	1.21×10^{-1}	9.62×10^{-1}	9.03×10^{-1}	7.17×10^{-1}

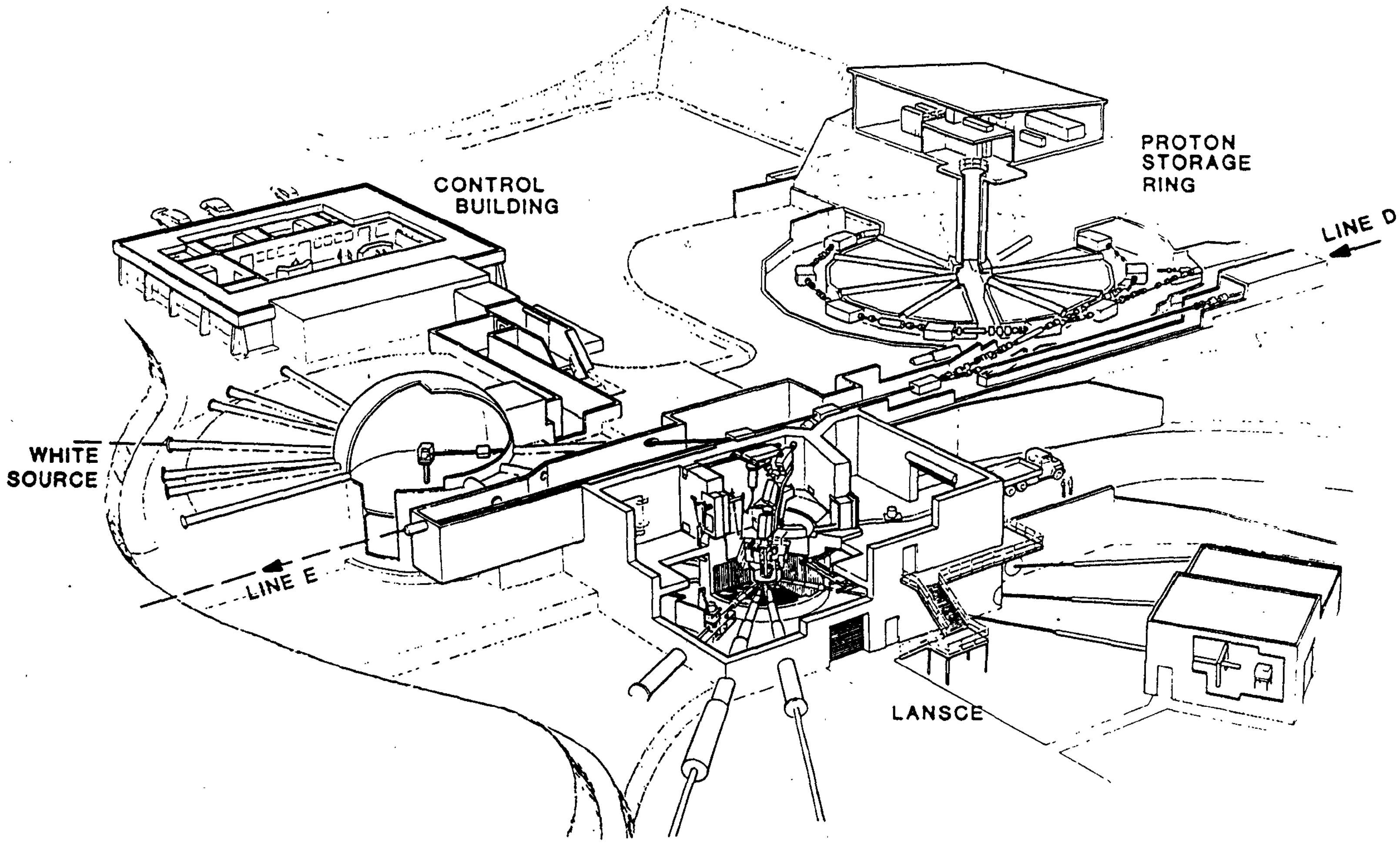


Fig. 1. General layout of the LANSCE/WNR complex. The new Neutron Scattering Experimental Hall, under construction in 1987, will surround the present LANSCE experimental hall (shown in the foreground) and will greatly enhance the LANSCE experimental area.

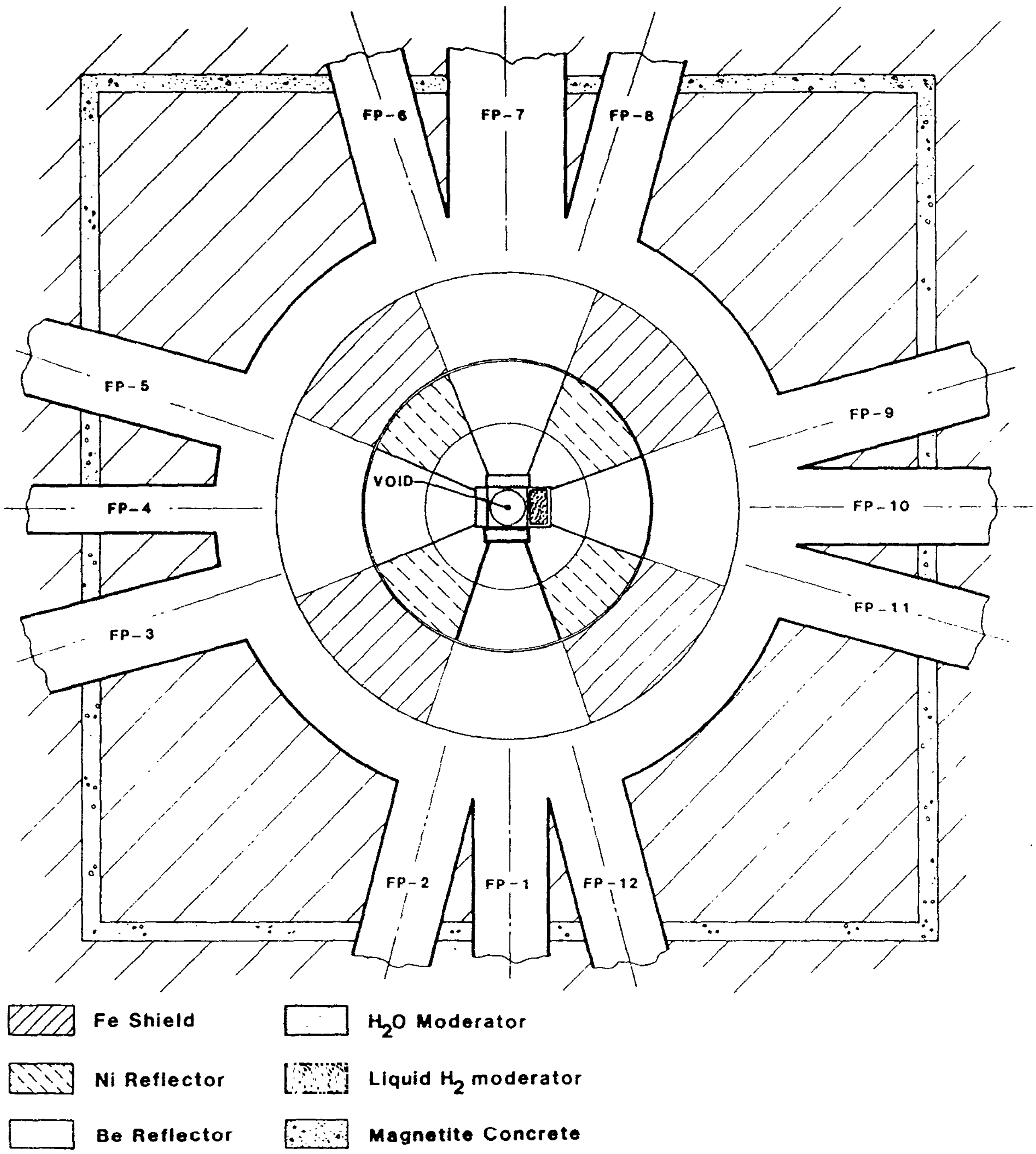


Fig. 2. Plan view of the LANSCE moderator and flight path arrangement.

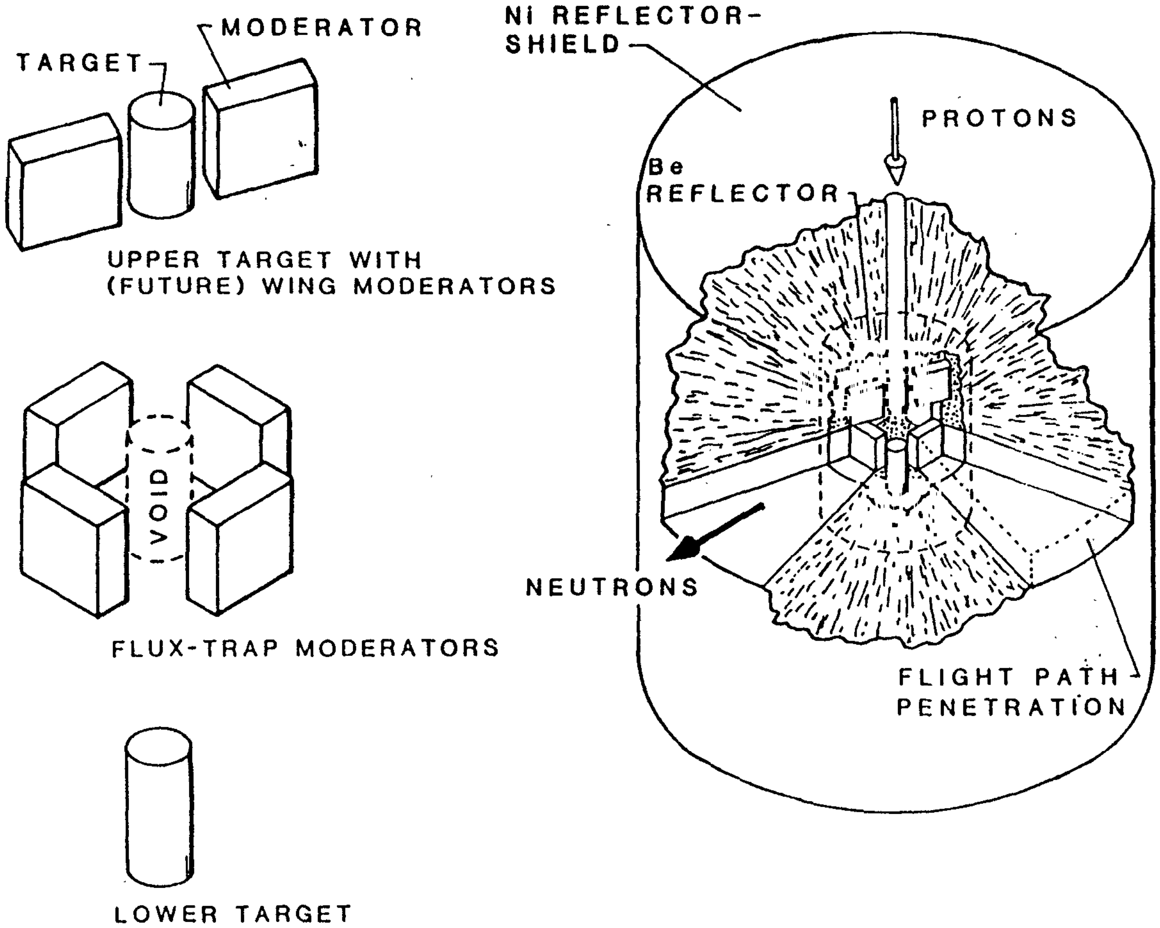


Fig. 3. Illustration of the LANSCE target system consisting of a split-target, an inner beryllium/nickel reflector region, and an outer nickel reflector/shield. Three water moderators and a liquid hydrogen moderator are in flux-trap geometry between the two tungsten targets. The system is one meter in diameter and one meter high.

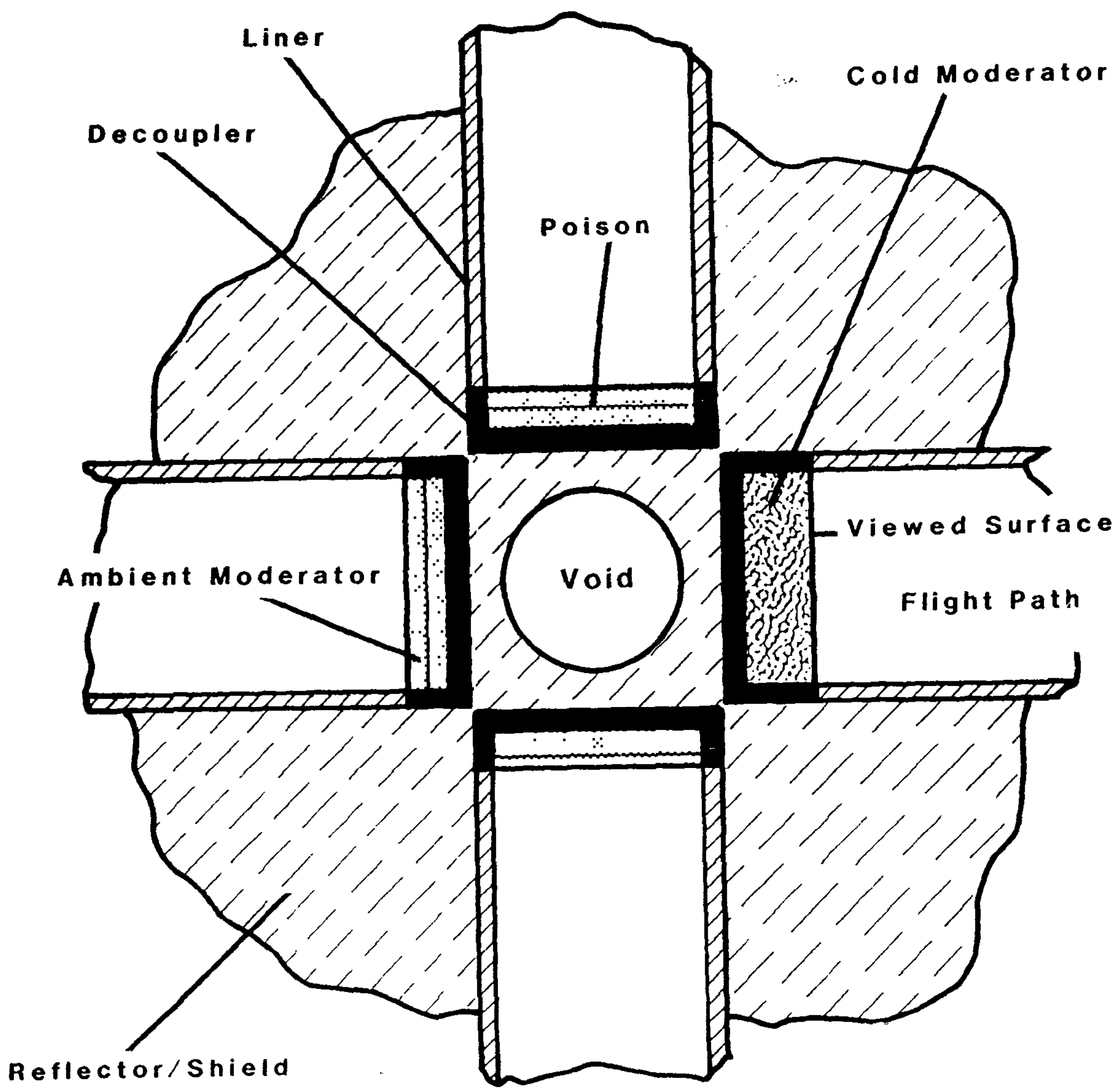


Fig. 4. Expanded plan view schematic of the LANSCE target/moderator arrangement. The liquid hydrogen moderator is depicted on the right side.

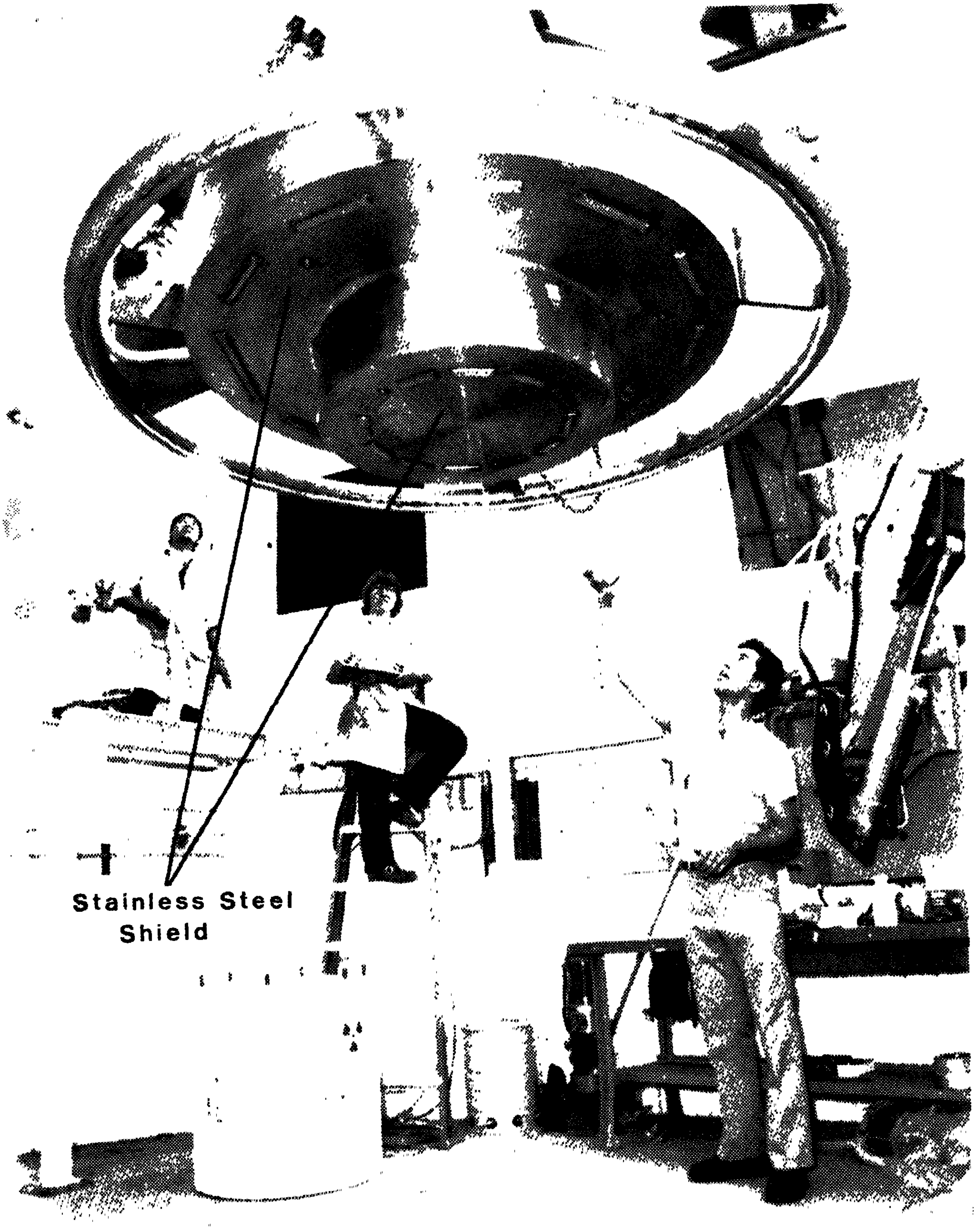


Fig. 5. Forward shield being lowered in place. The shield is shaped to fit the concave LANSCE target cavity and has a tubular support and centering ring.

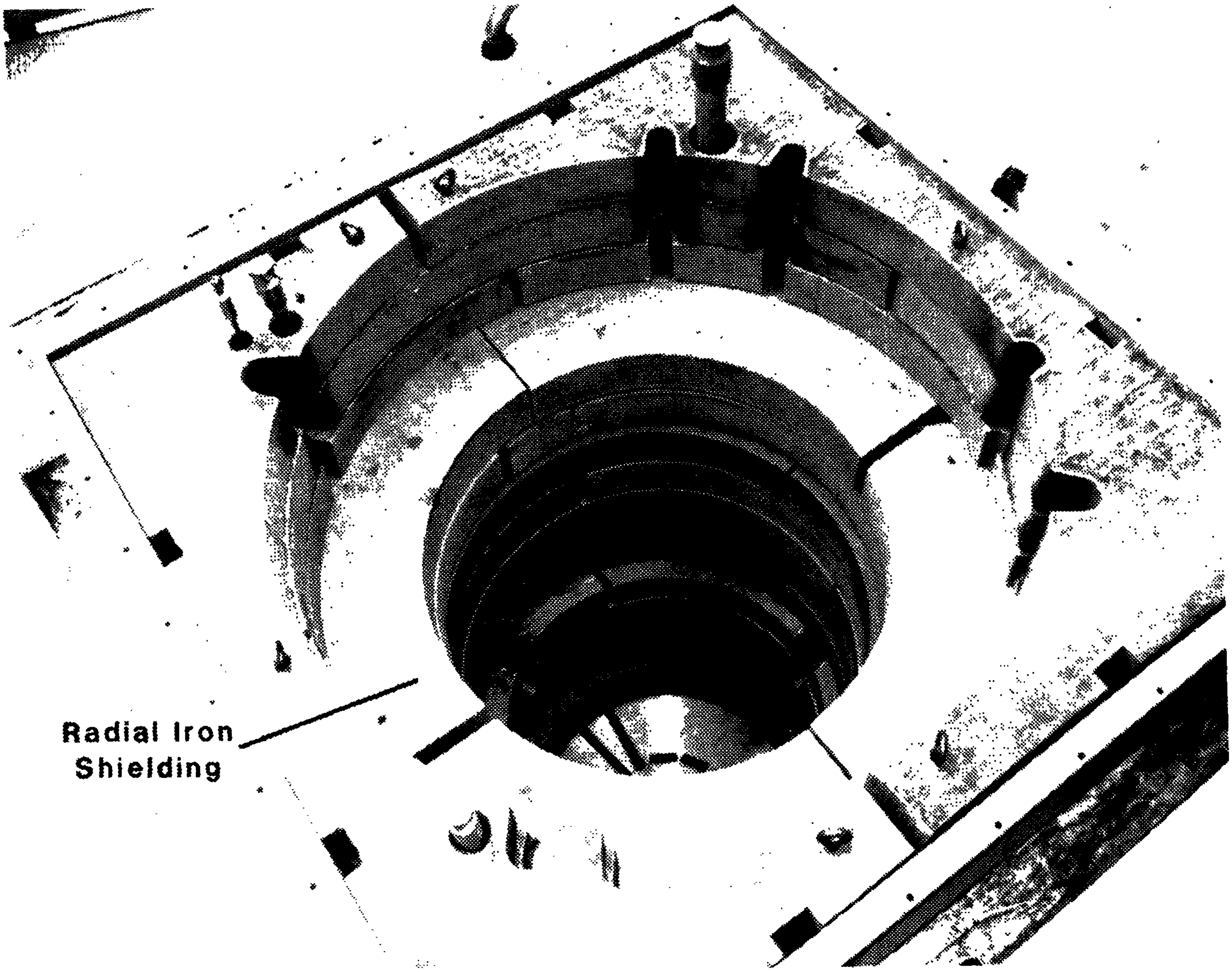


Fig. 6. Iron shielding as installed in the LANSCE target cavity. The forward stainless steel shield is visible at the bottom. Cooling and purge lines extend to the top of the shielding through offset holes in the shield elements.

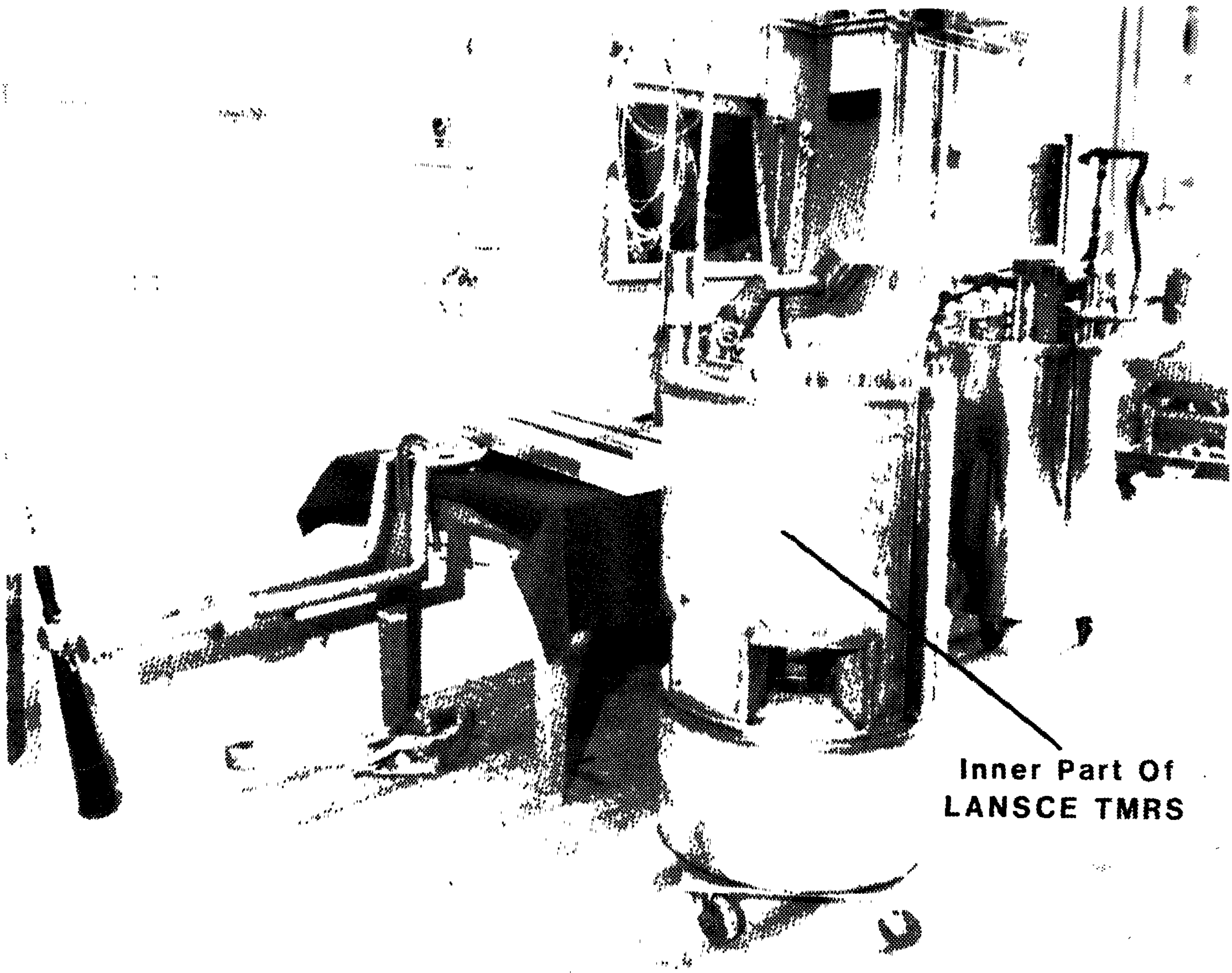


Fig. 7. Inner portion of the LANSCE TMRS showing neutron flight windows in the upper section.

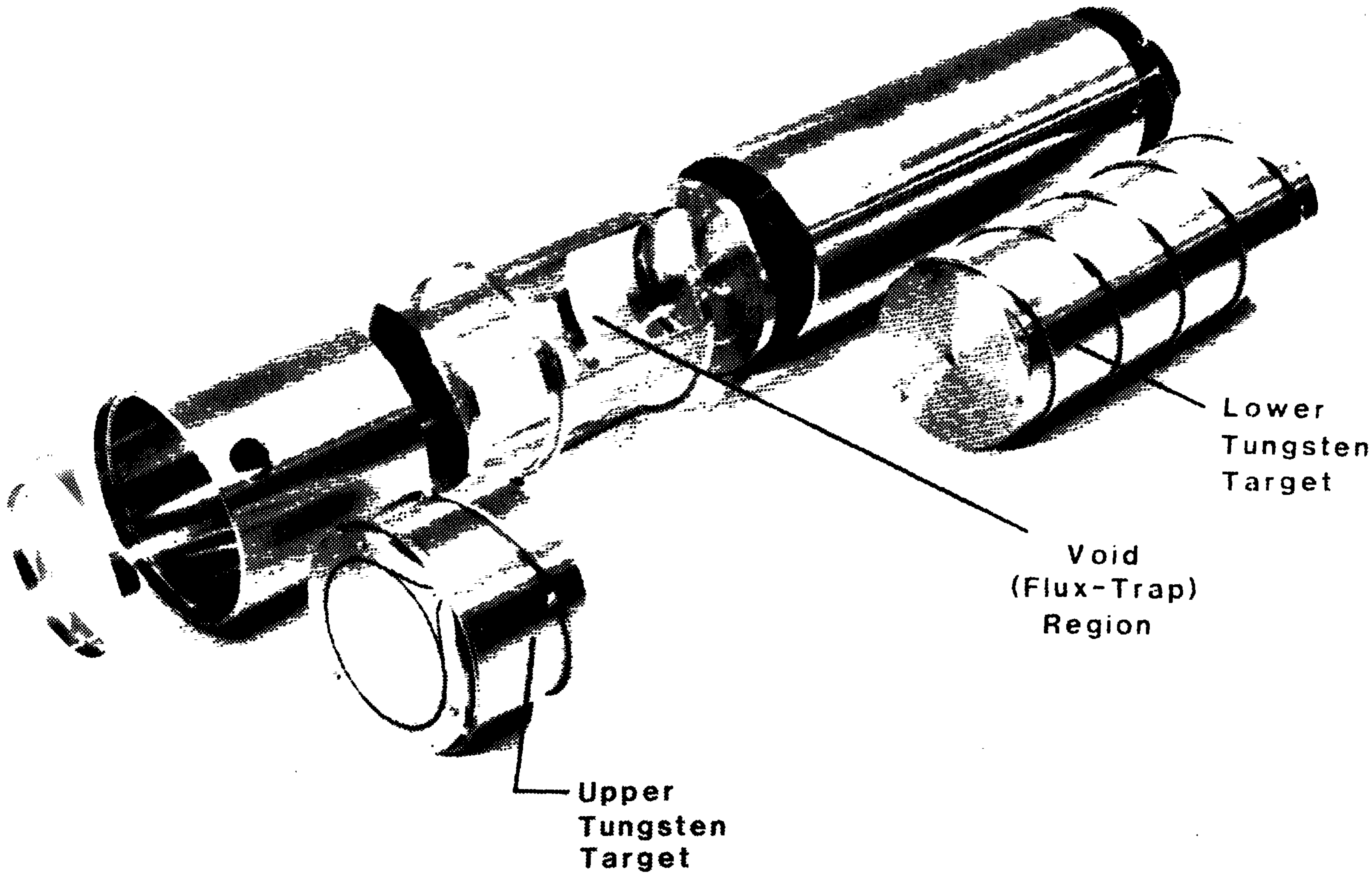


Fig. 8. Disassembled LANSCE target pressure vessel and targets, showing the spiral guides for target cooling.

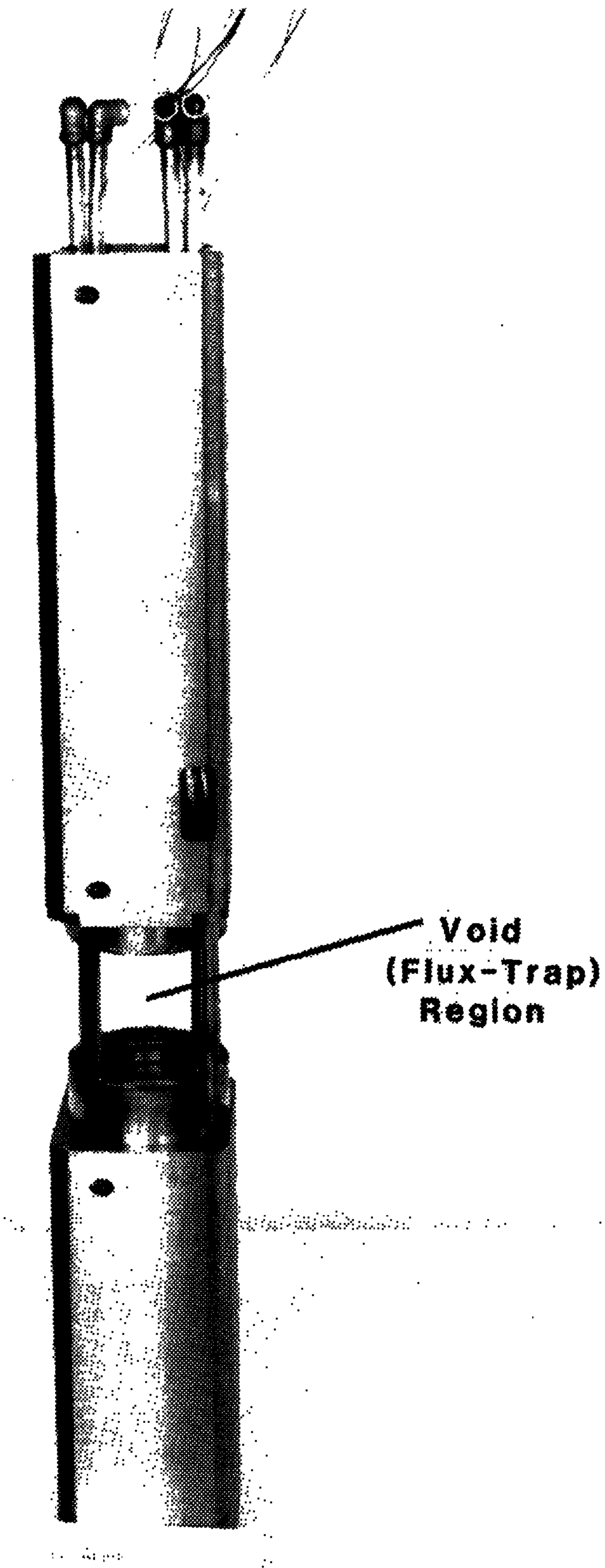


Fig. 9. Assembled LANSCE target with beryllium jackets installed.

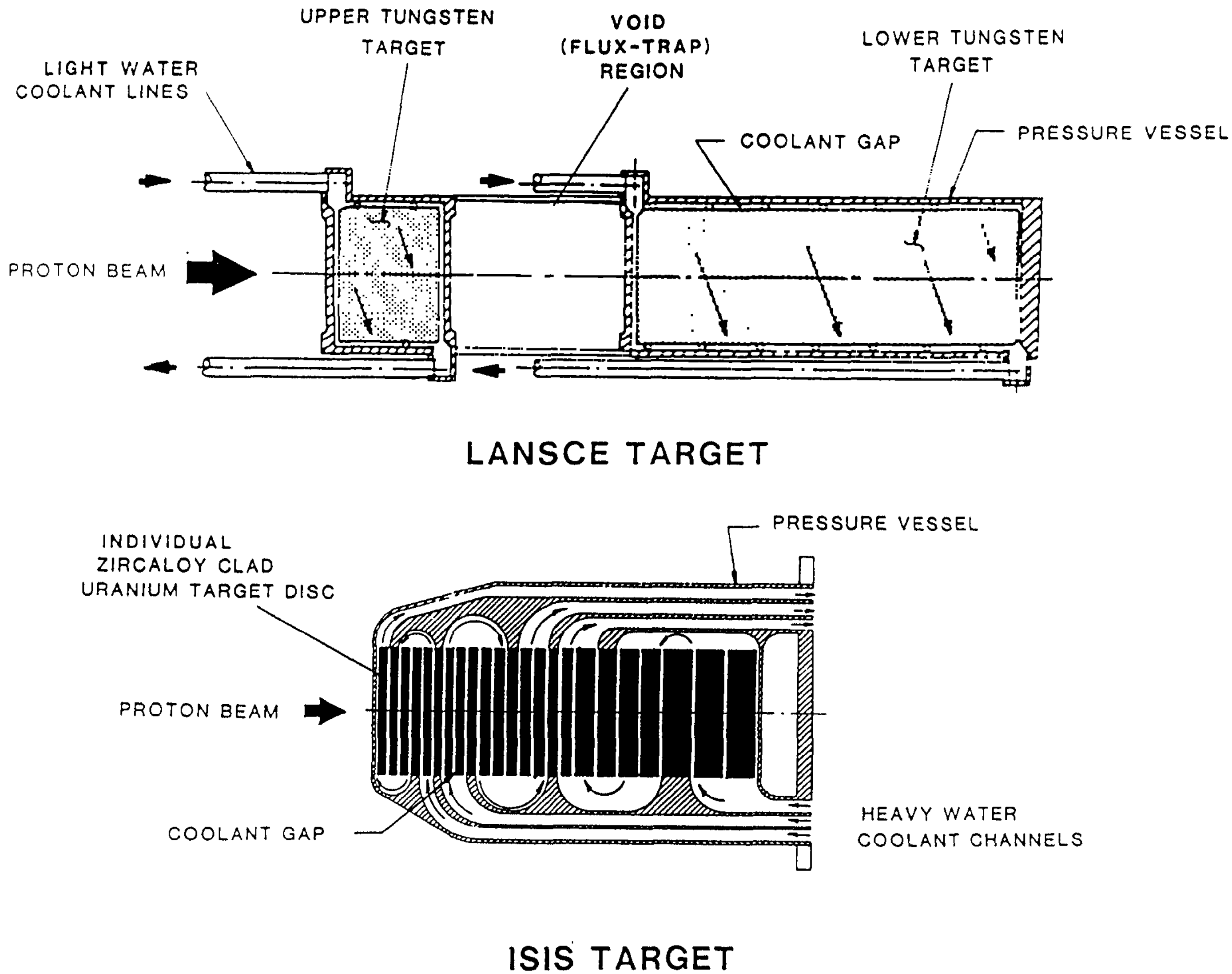


Fig. 10. Intercomparison of LANSCE and ISIS targets, overall target designs, and the different cooling approaches. Note the two solid LANSCE tungsten target elements compared to the multiply segmented ISIS depleted uranium target plates.

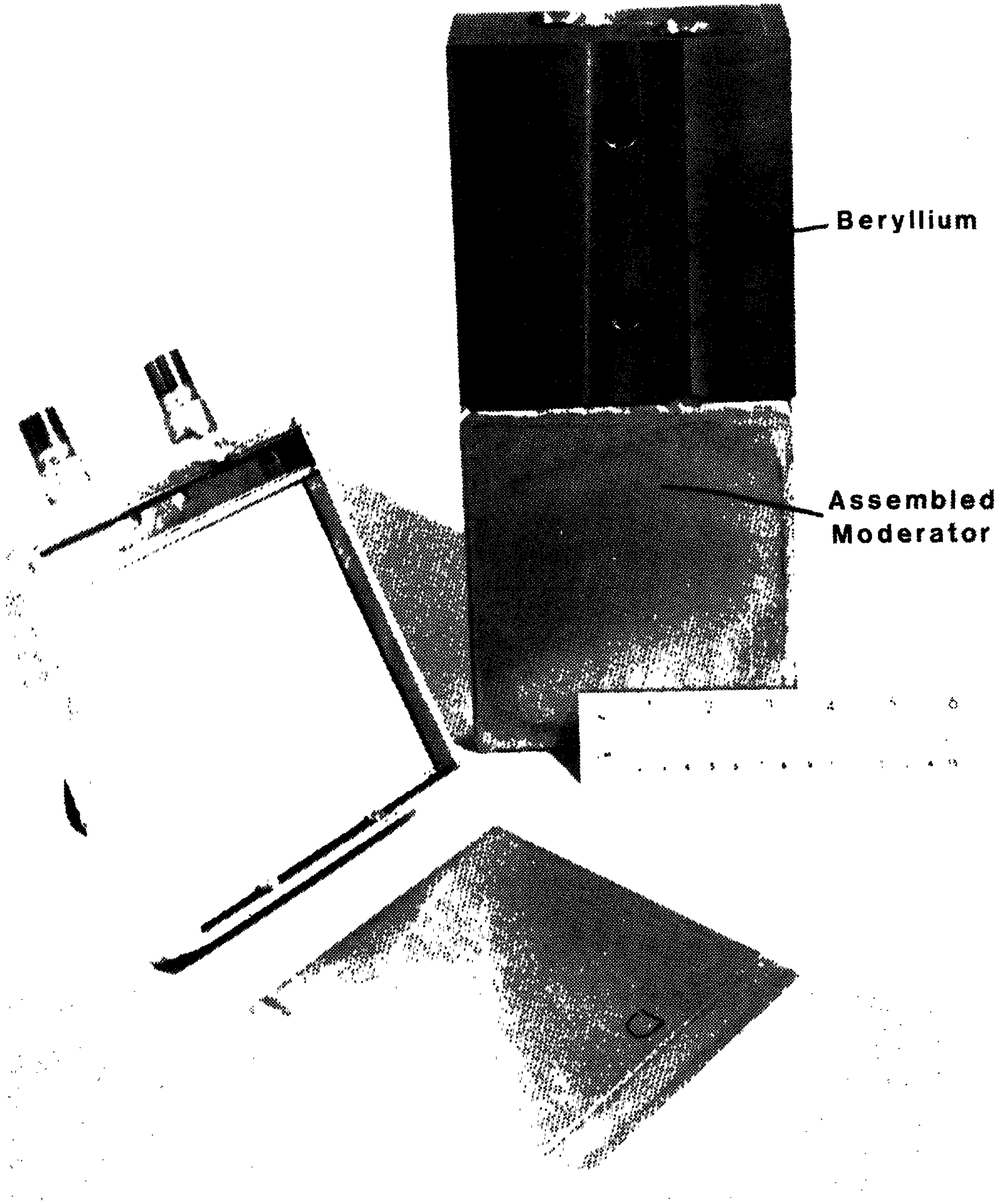


Fig. 11. Disassembled LANSCE light water moderator, showing the gadolinium poison insert behind the output face. An assembled moderator, with the beryllium reflector block, is shown in the background.

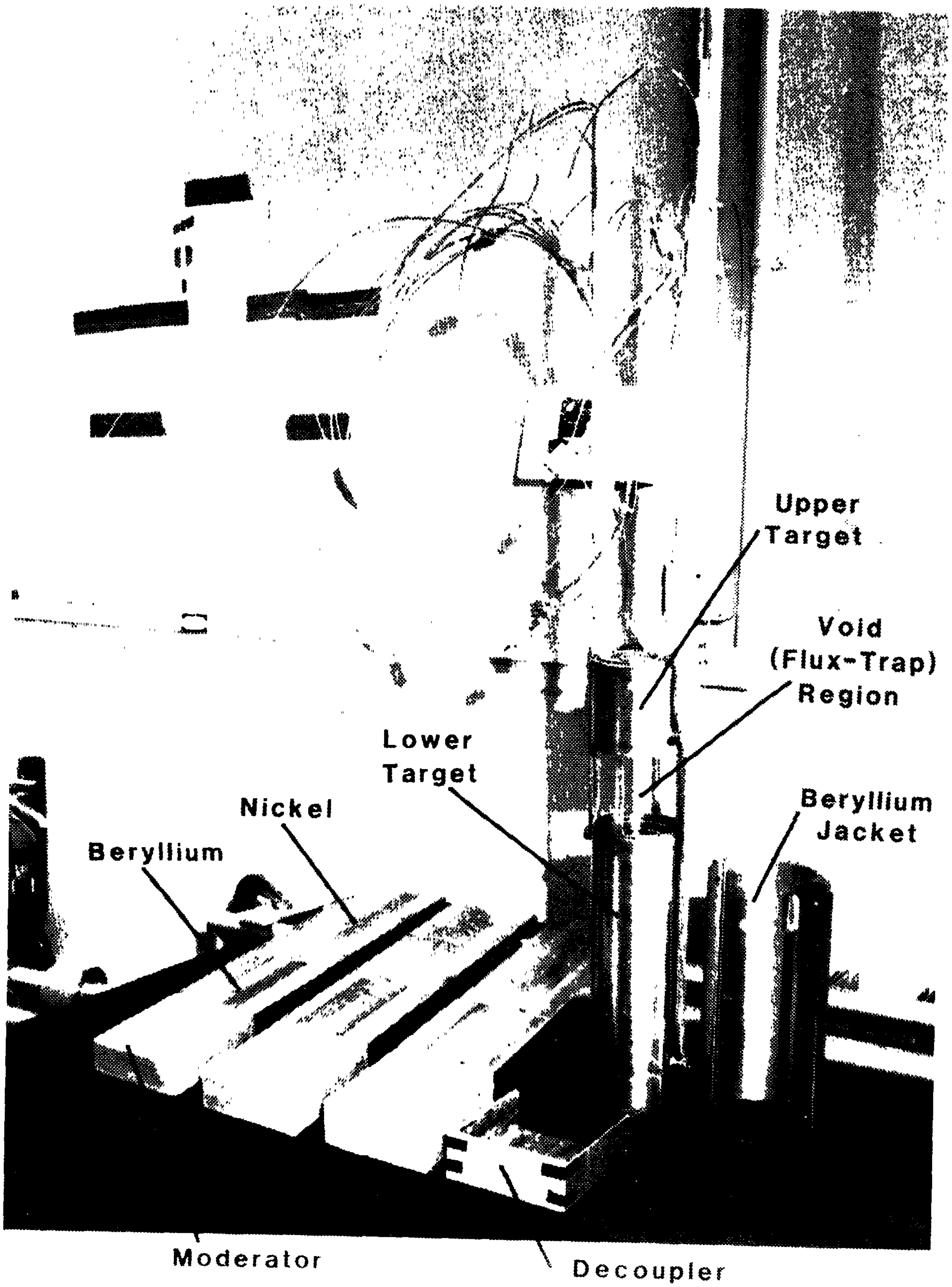


Fig. 12. Assembled LANSCE water moderators with beryllium reflector blocks, nickel reflector/shield blocks, a cadmium decoupler, and the assembled target (with beryllium jackets removed).

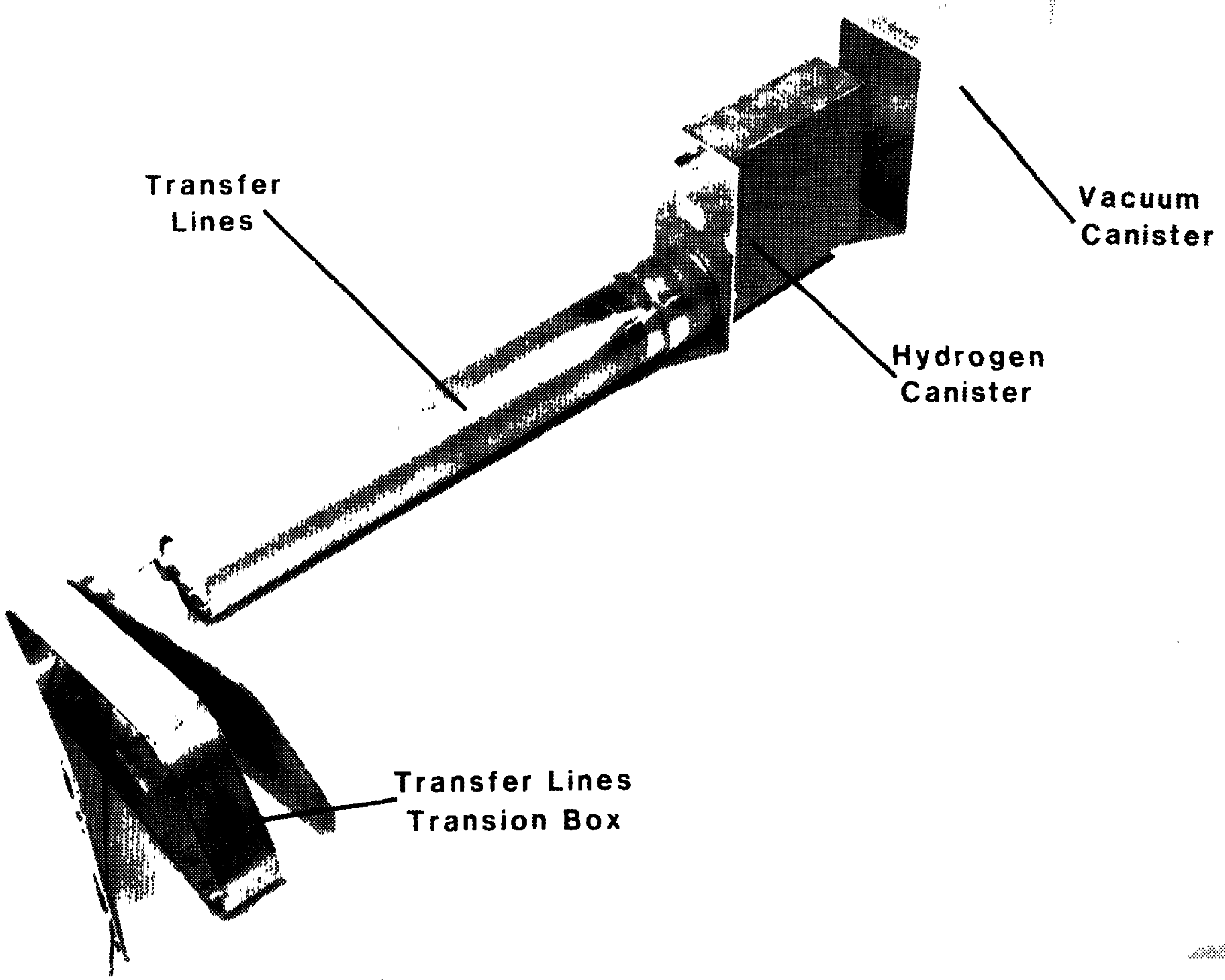


Fig. 13. LANSCE liquid hydrogen modeıator with vacuum jacket removed.

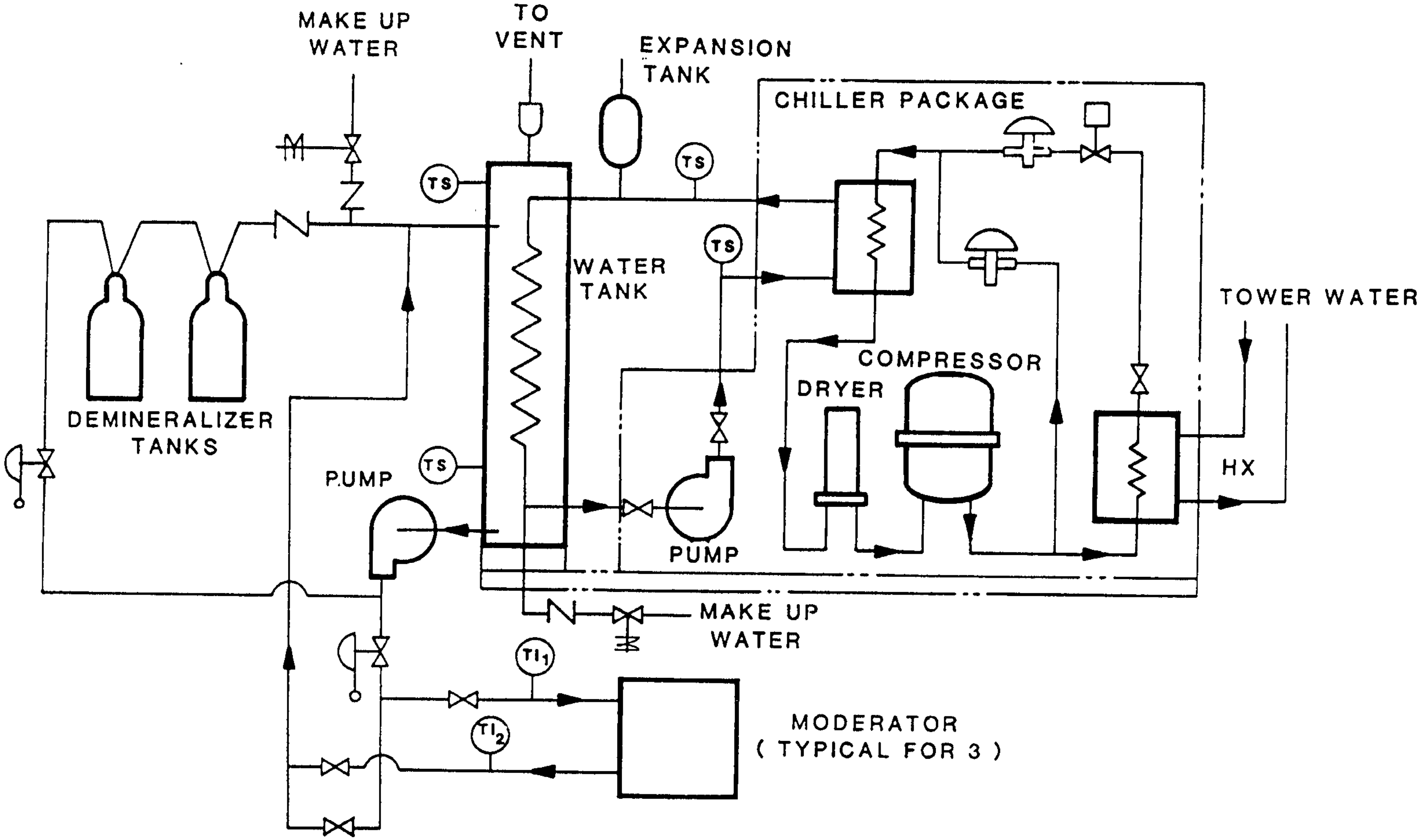


Fig. 14. Schematic of LANSCE (chilled) water moderator cooling system.

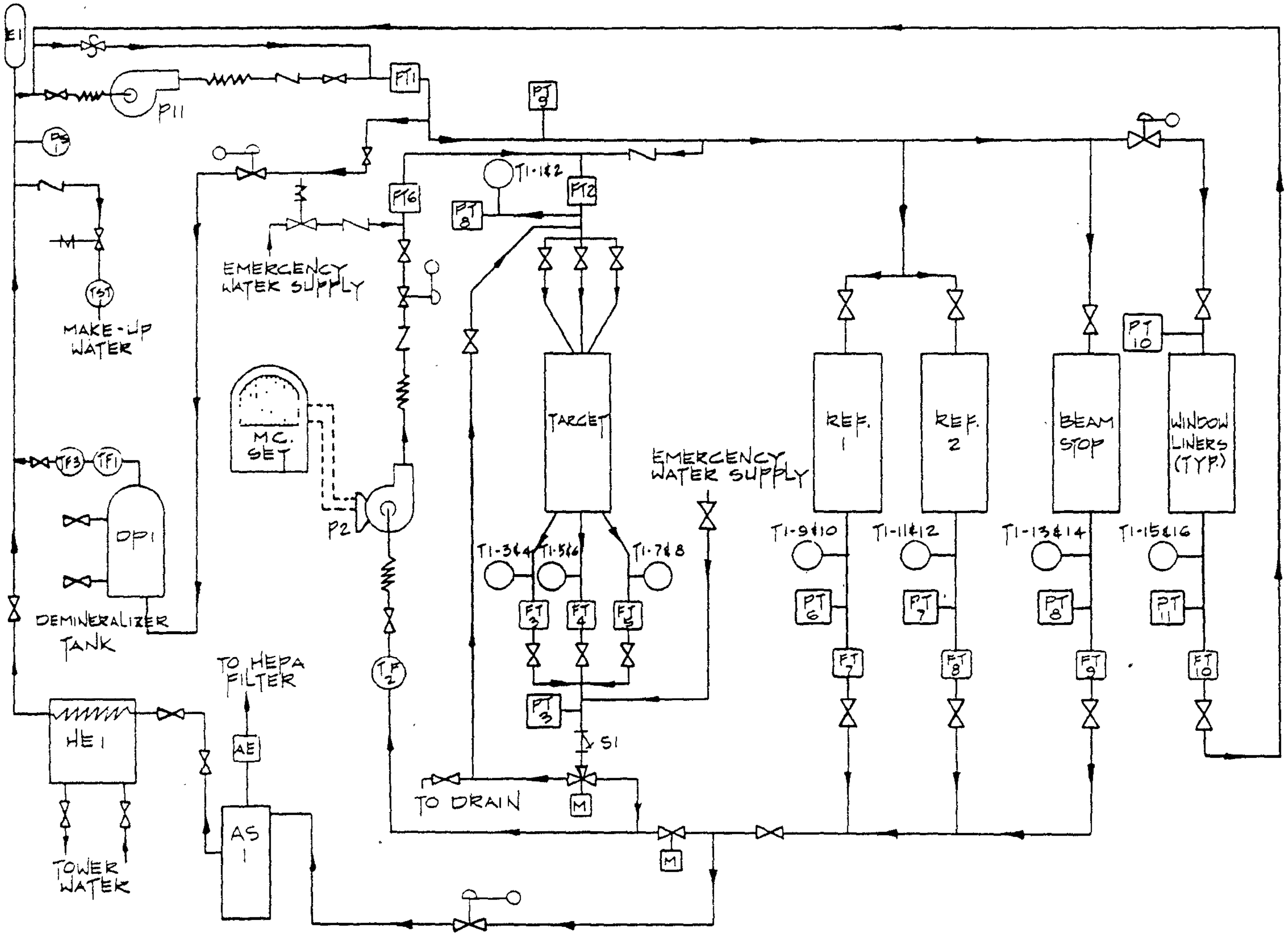


Fig. 15. Simplified schematic diagram of the LANSCE target/reflector cooling system.

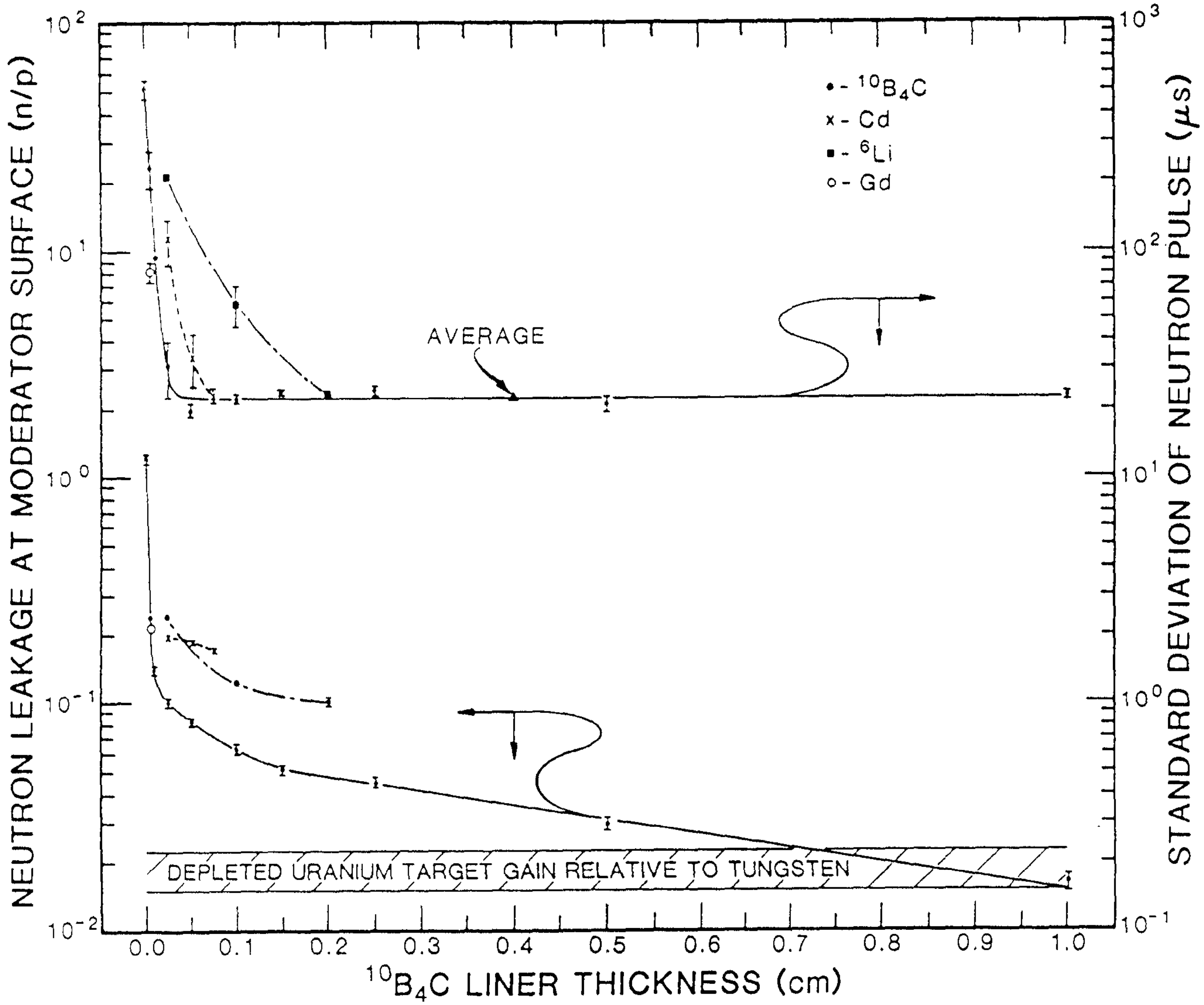


Fig. 16. Moderator performance as a function of liner thickness and type. The moderator used in the computations was a 2.5 by 13 by 13 cm water slab in flux-trap geometry. A beryllium reflector was used; the moderator was not poisoned.

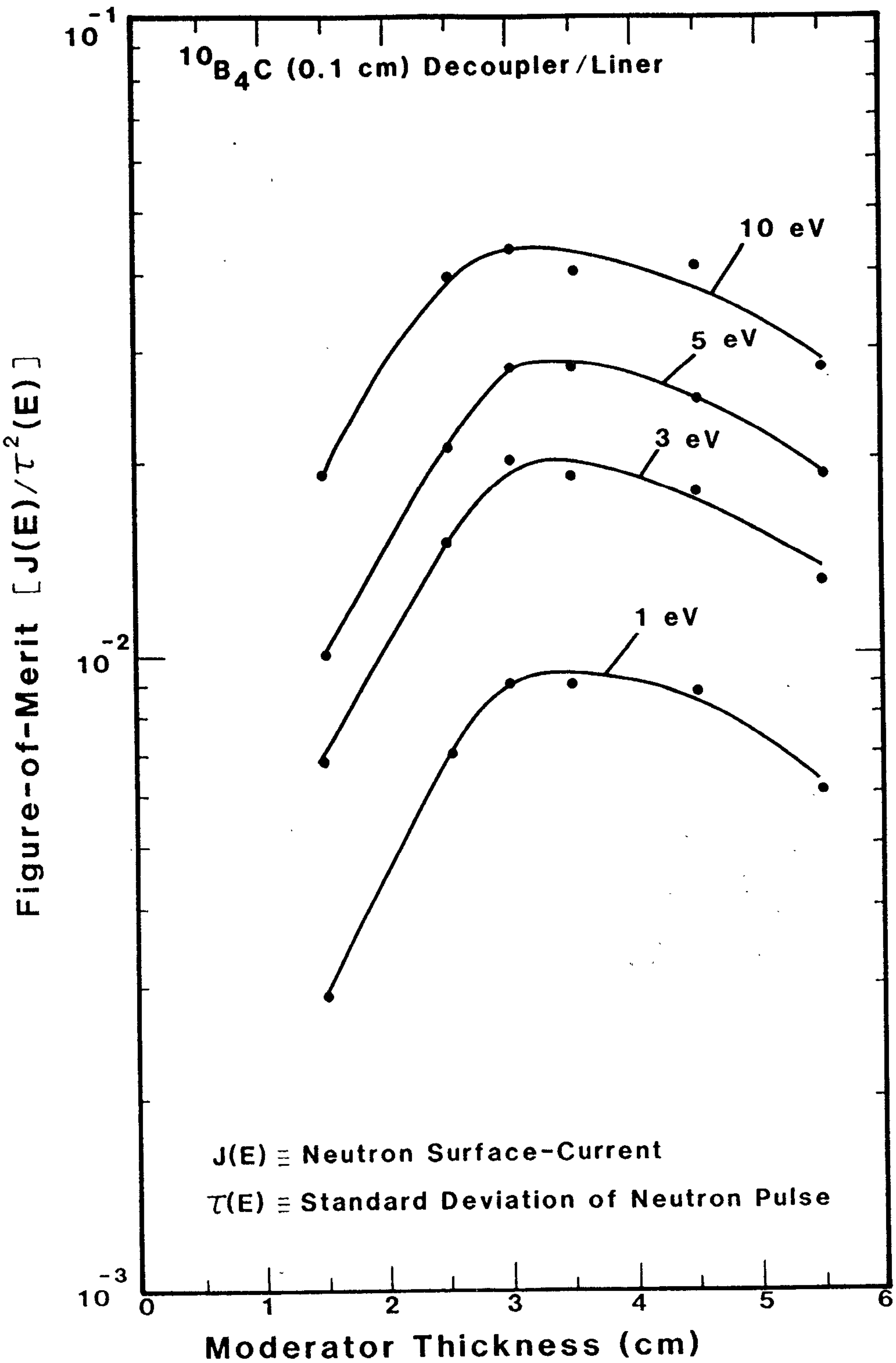
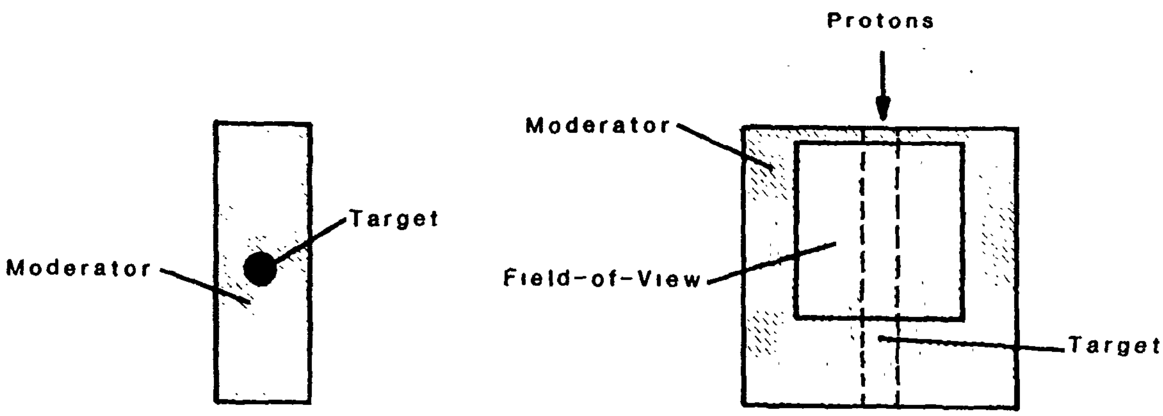
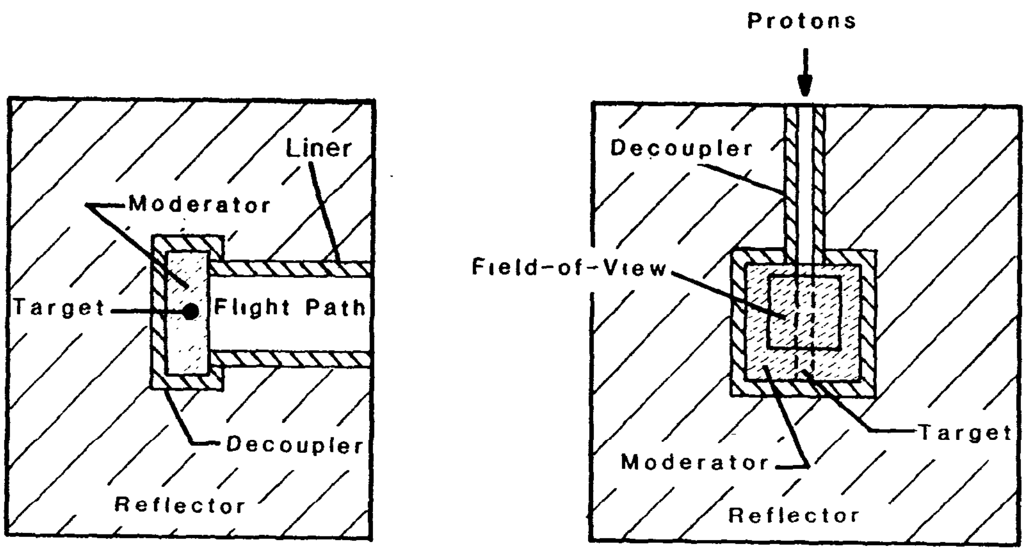


Fig. 17. Study to find the optimum thickness for epithermal neutron production from a water moderator in flux-trap geometry.



Bare Hybrid



Reflected Hybrid

Fig. 18. Geometries used for calculating reflector efficiencies in a 'slab-type' moderator configuration. The reflected hybrid is a very efficient neutron production scheme; it is only slightly bettered by a reflected slab-target/slab-moderator arrangement.

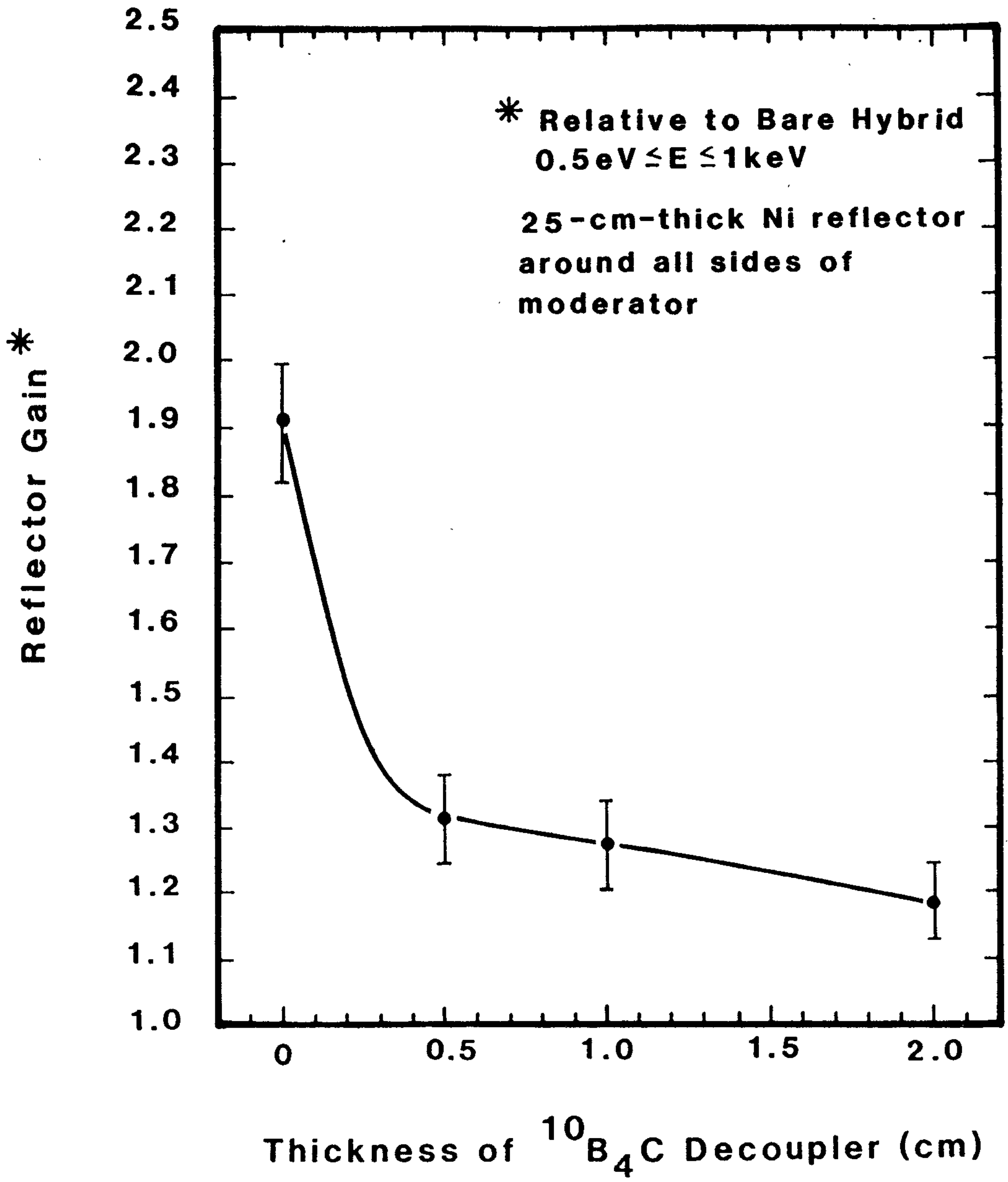


Fig. 19. Effect of decoupler thickness on reflector gain from a reflected hybrid moderator arrangement.

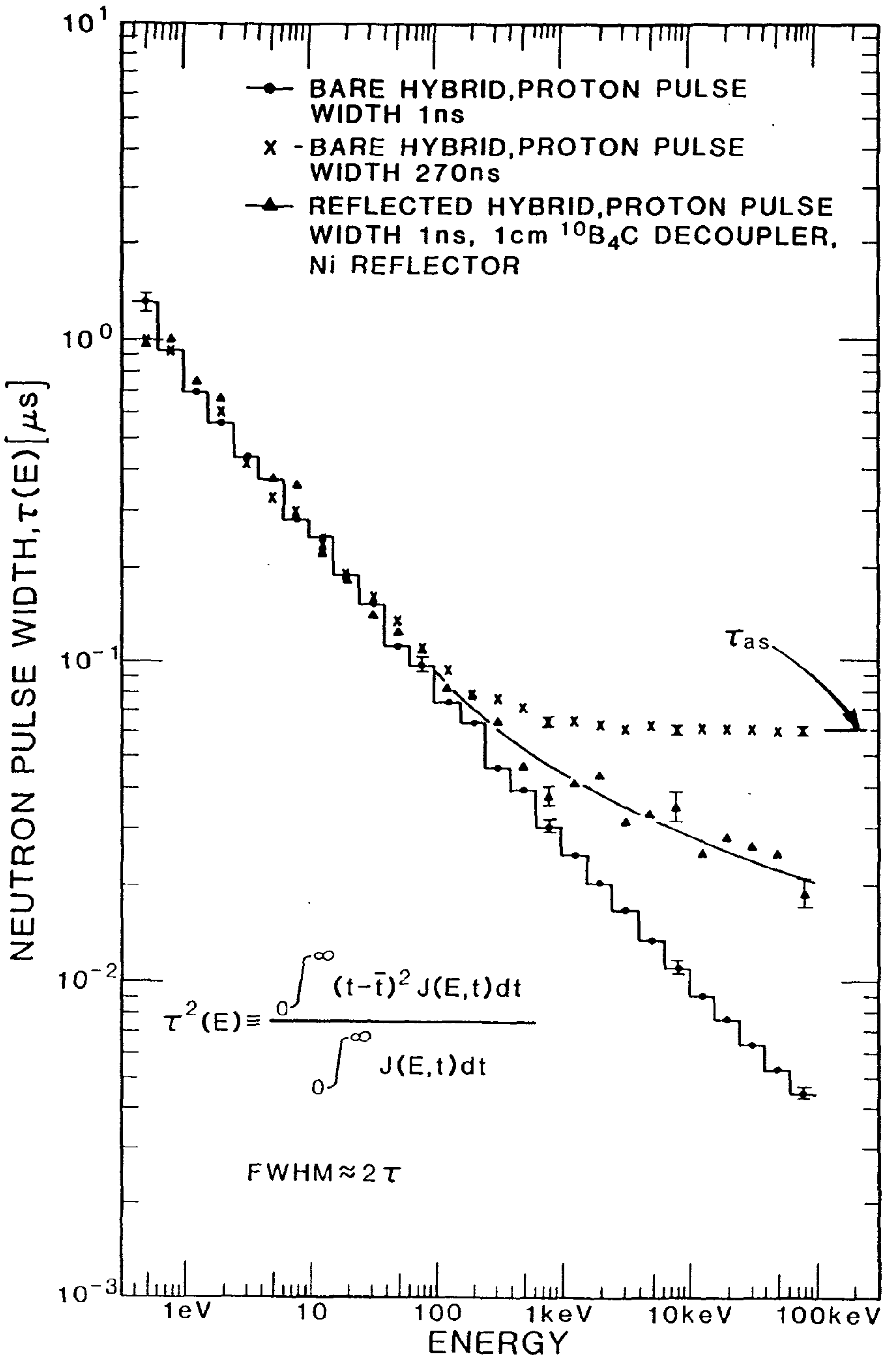


Fig. 20. Pulse width versus energy for various reflector/decoupler configurations.

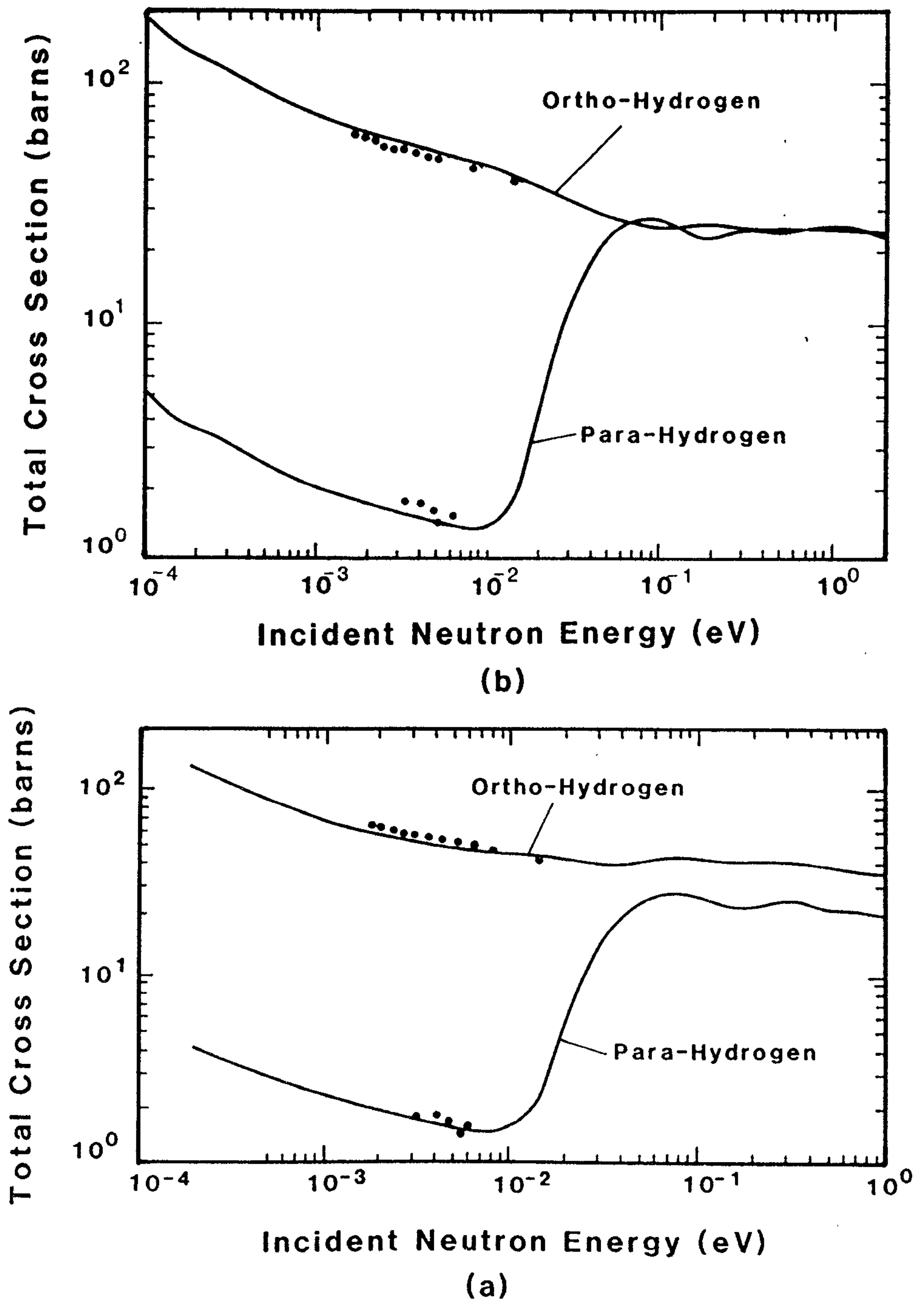


Fig. 21. a) neutron cross sections of para- and ortho-hydrogen as computed by Young and Koppel using their complete formalism, and b) cross sections calculated at Los Alamos using Young and Koppels' approximate formalism.

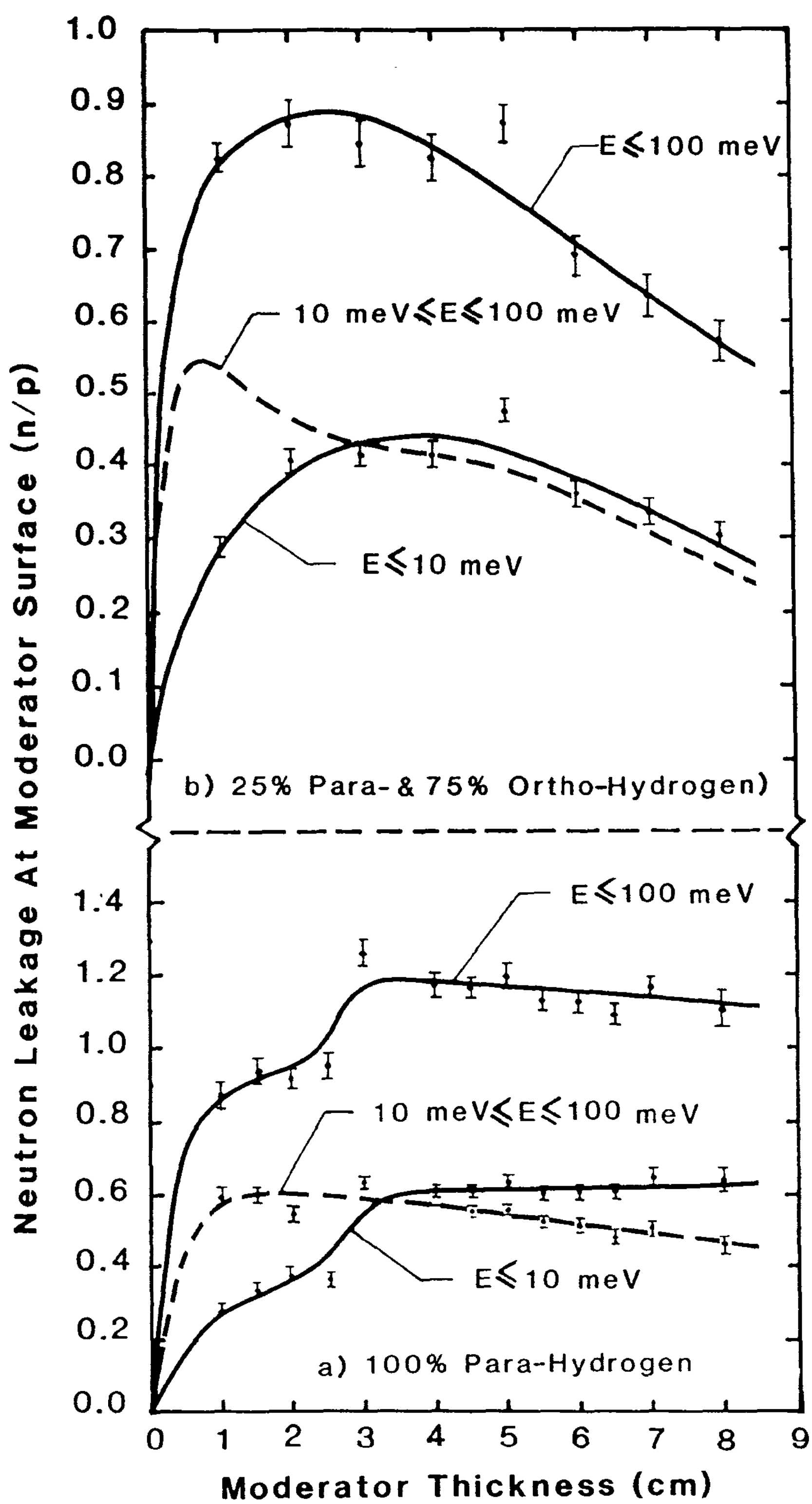


Fig. 22. Calculated cold moderator output versus moderator thickness for a coupled moderator in flux-trap geometry.

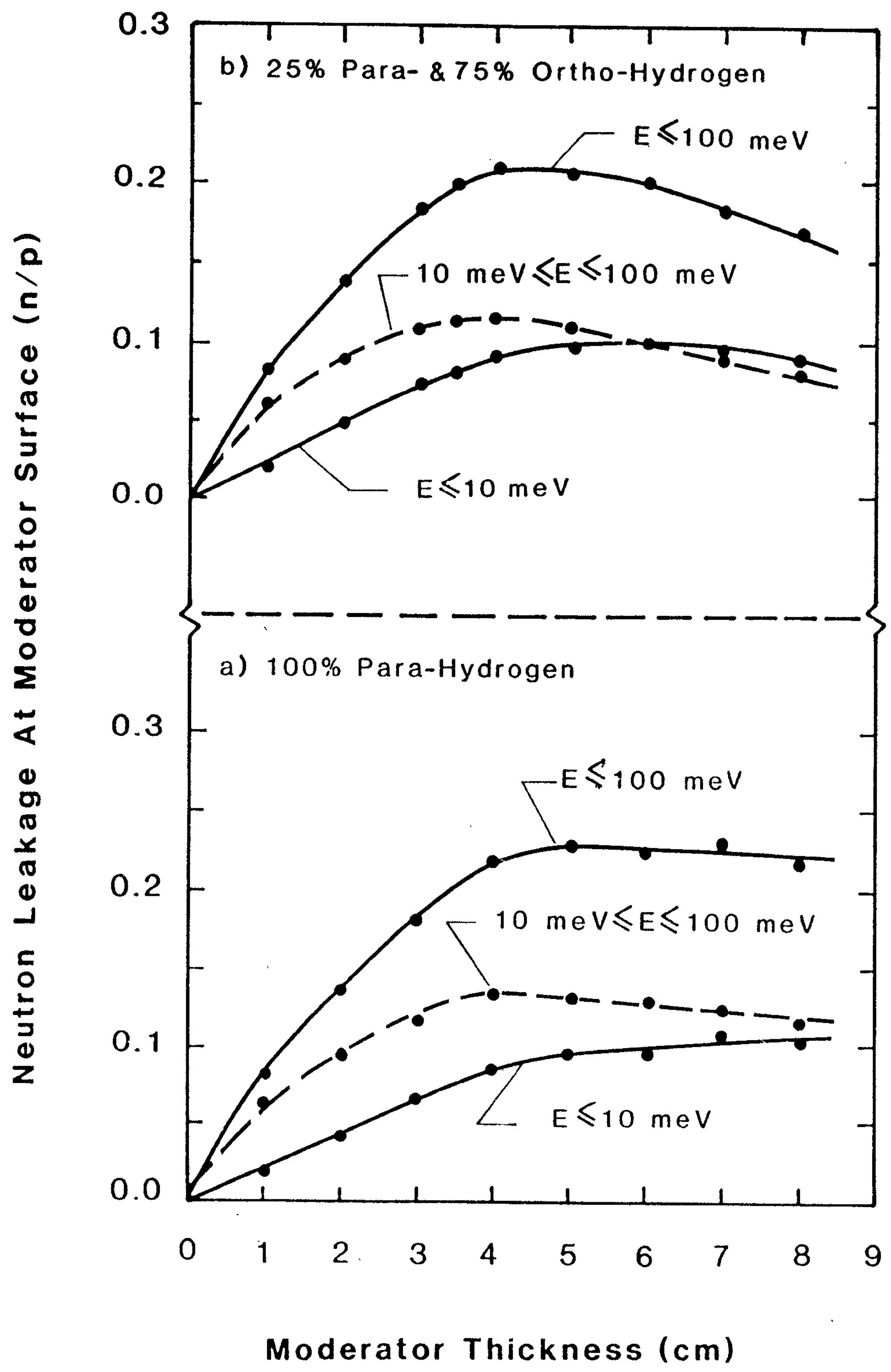


Fig. 23. Calculated cold moderator output versus moderator thickness for a moderator in flux-trap geometry decoupled from the reflector with gadolinium.

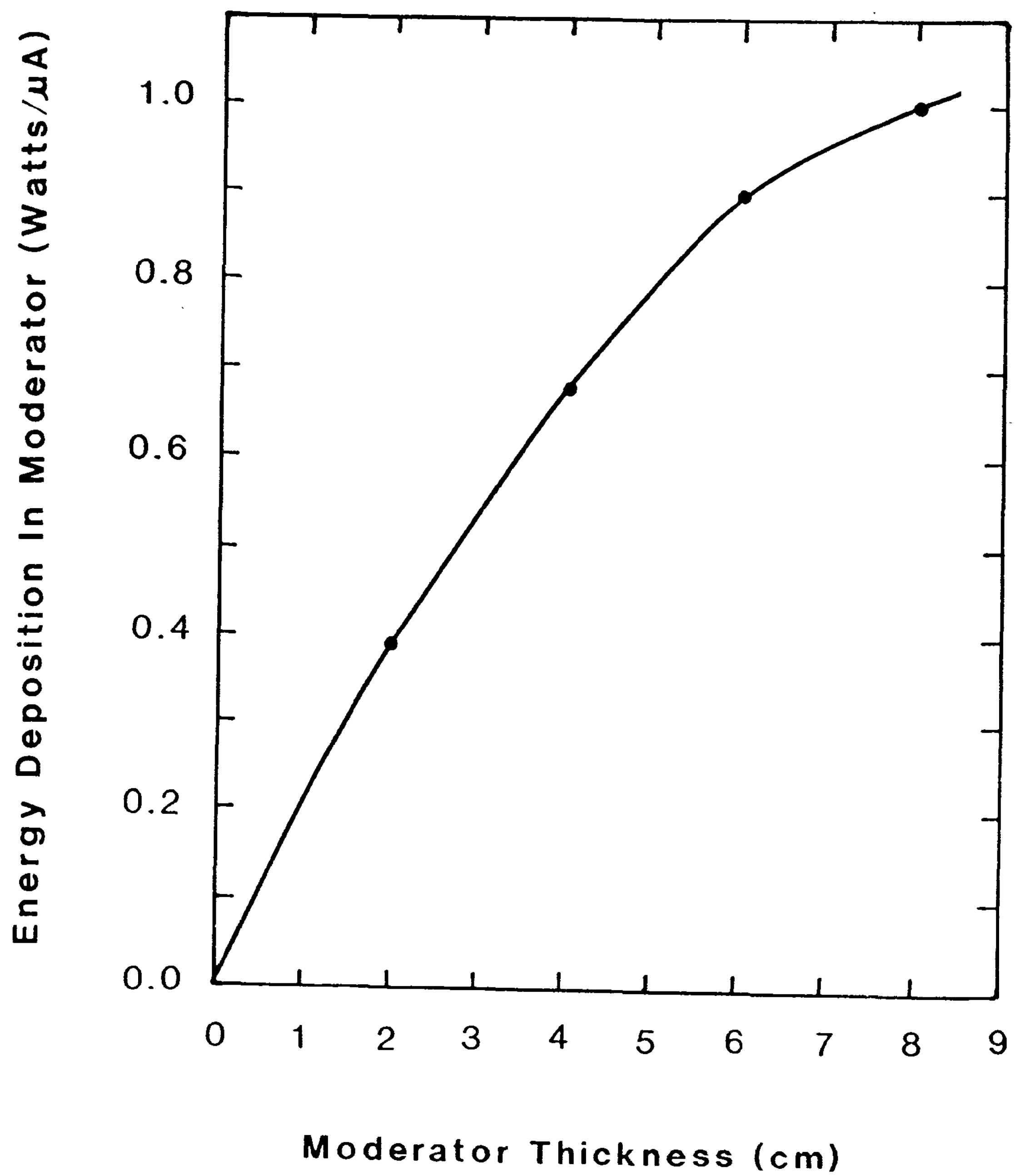


Fig. 24. Calculated energy deposition in a coupled cold hydrogen moderator in flux-trap geometry.

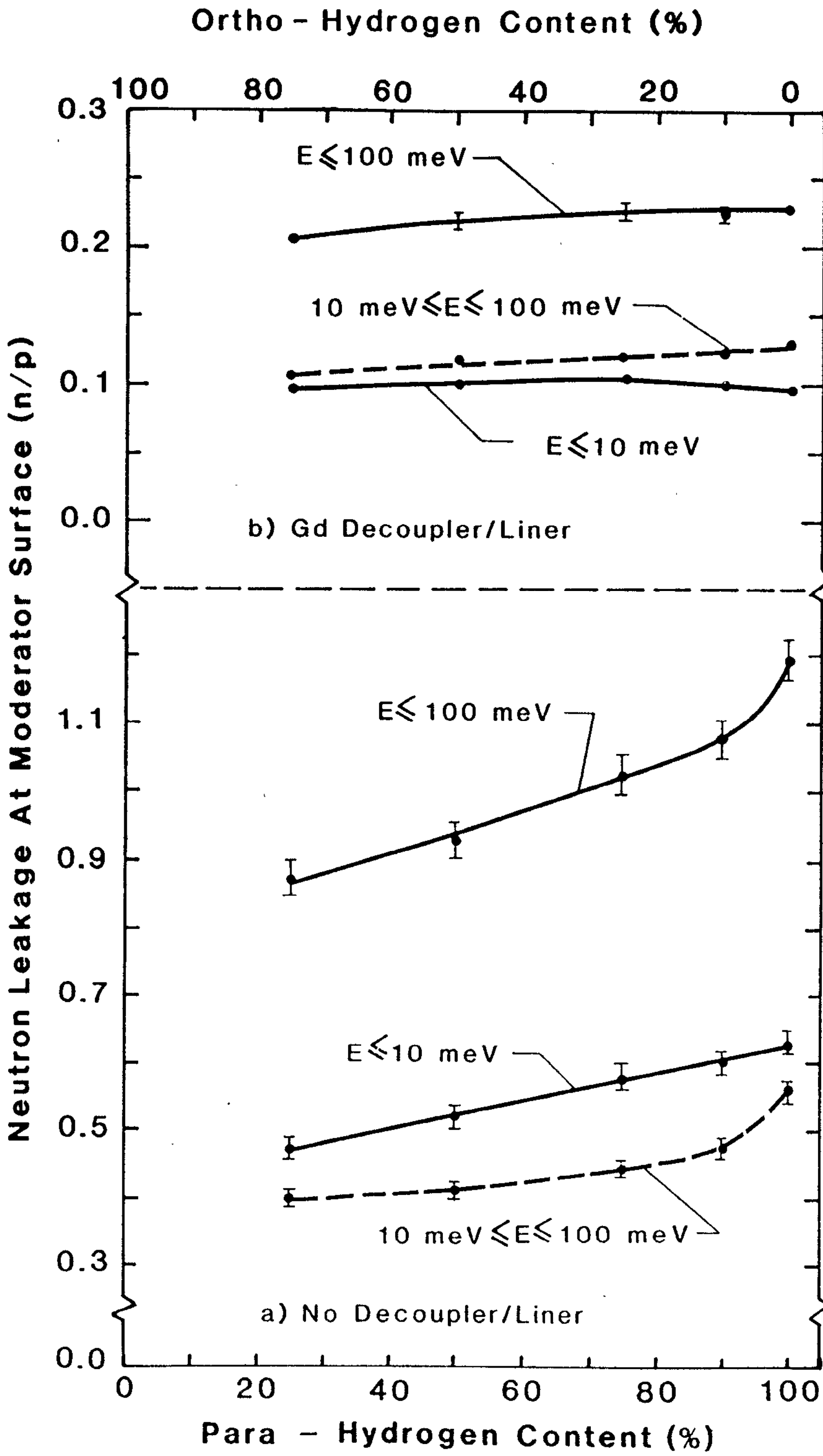


Fig. 25. Effect of para-hydrogen content on cold moderator output. The moderator was a 5 by 13 by 13 cm slab in flux-trap geometry.

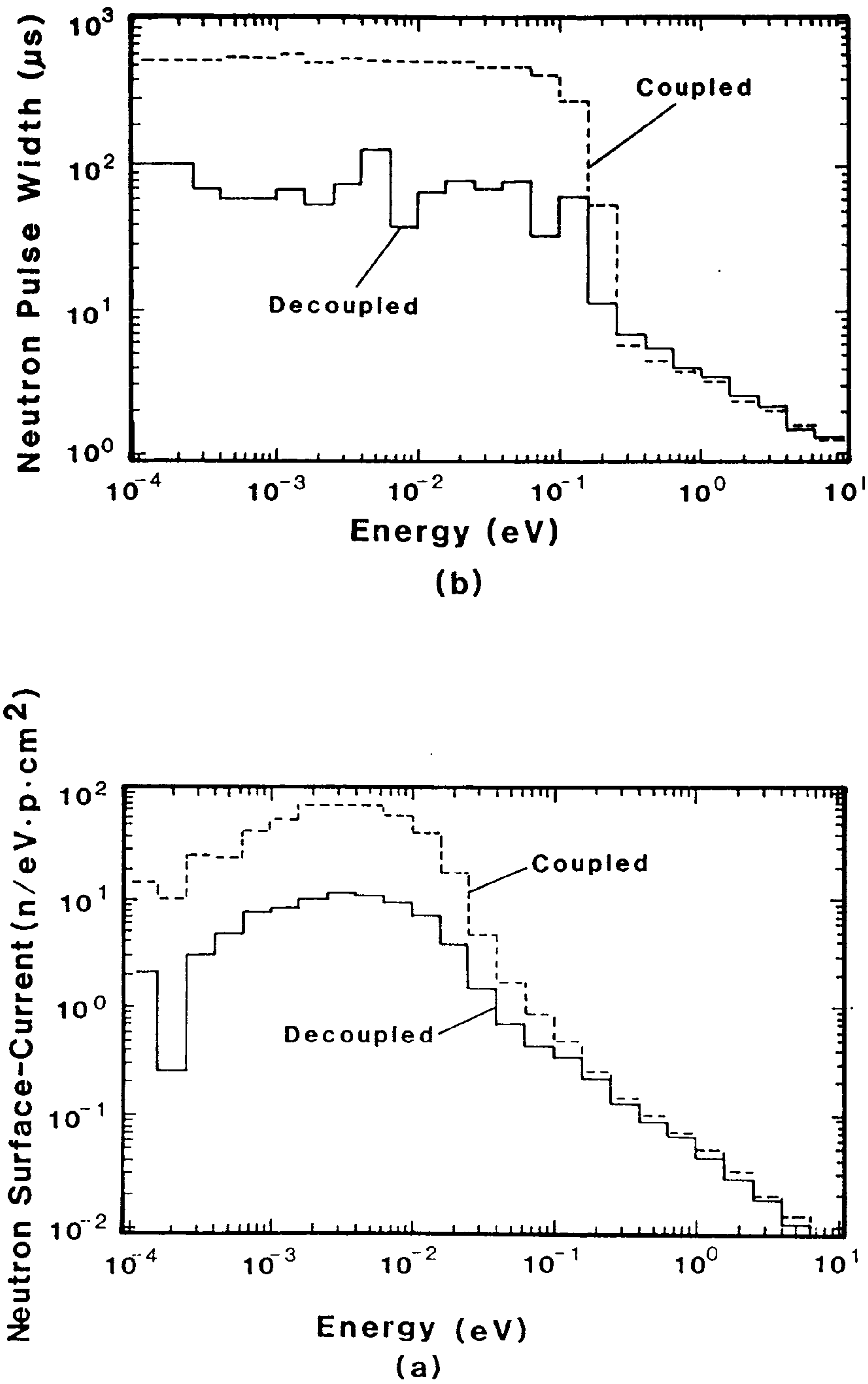


Fig. 26. Calculated neutron intensities and pulse widths for a 100% para-hydrogen cold source. The 5 by 13 by 13 cm slab moderator was in flux-trap geometry.

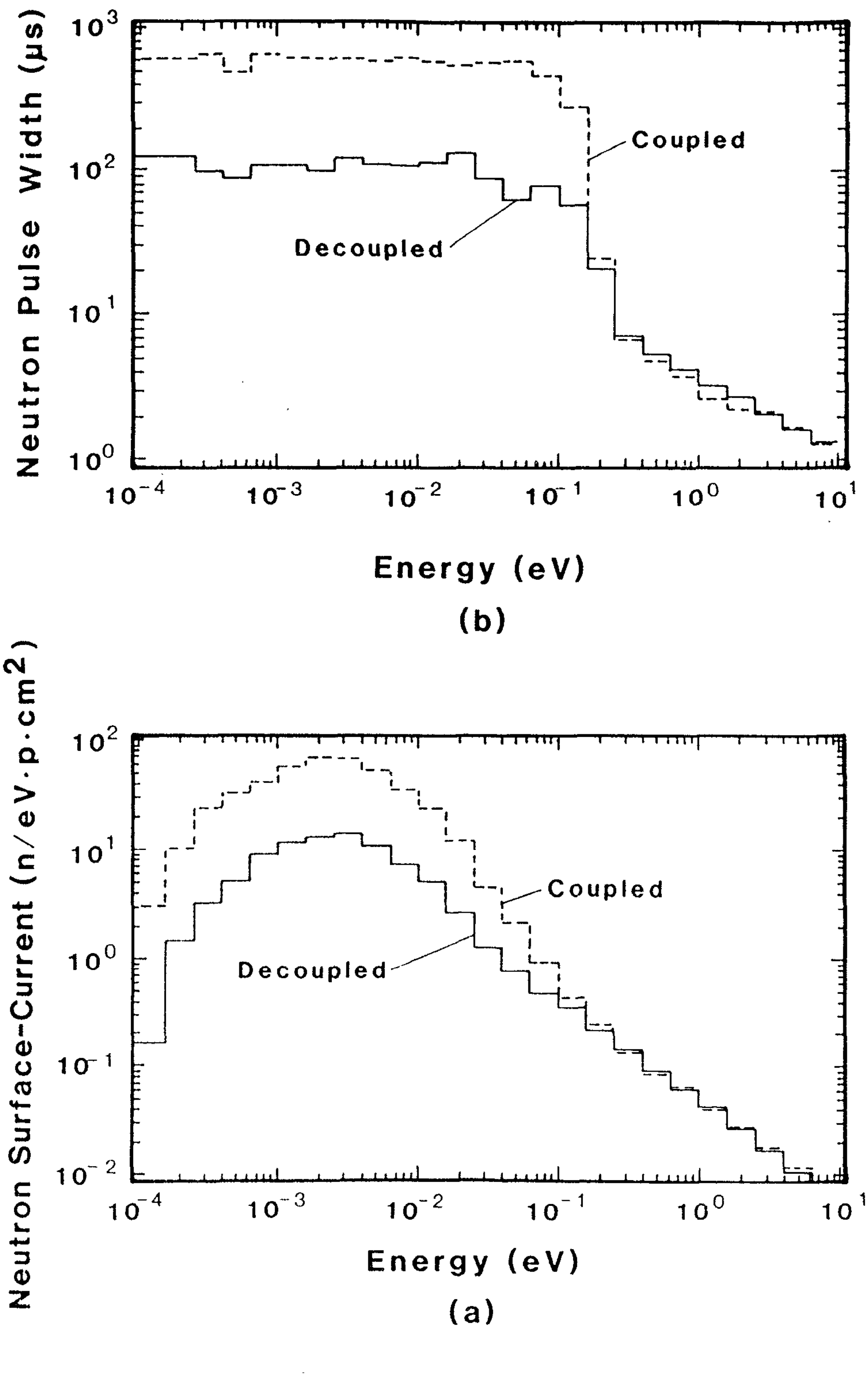


Fig. 27. Calculated neutron intensities and pulse widths for a 25% para- and 75% ortho-hydrogen cold source. The 5 by 13 by 13 cm slab moderator was in flux-trap geometry.

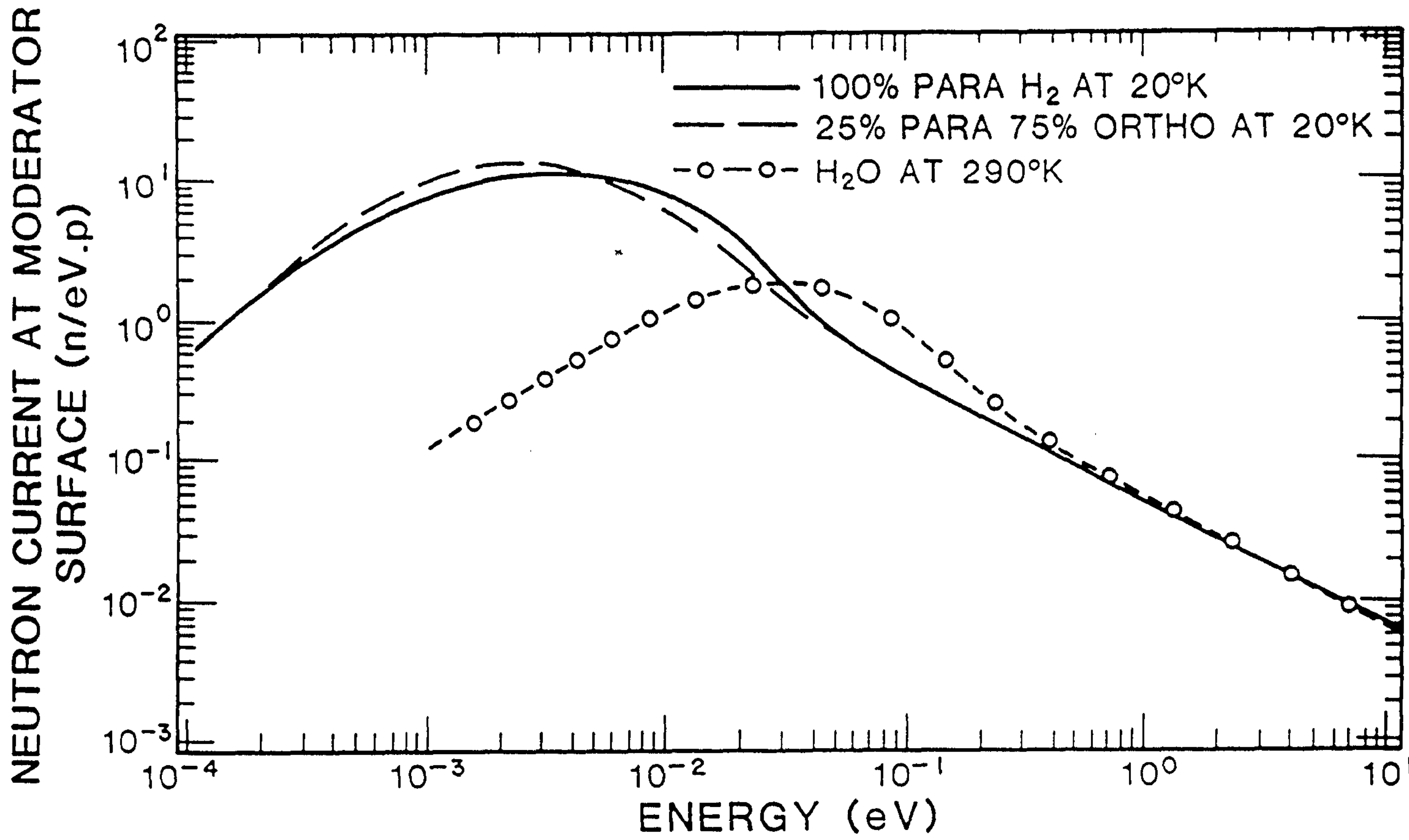


Fig. 28. Calculated LANSCE neutron energy spectrum from ambient and cold moderators.

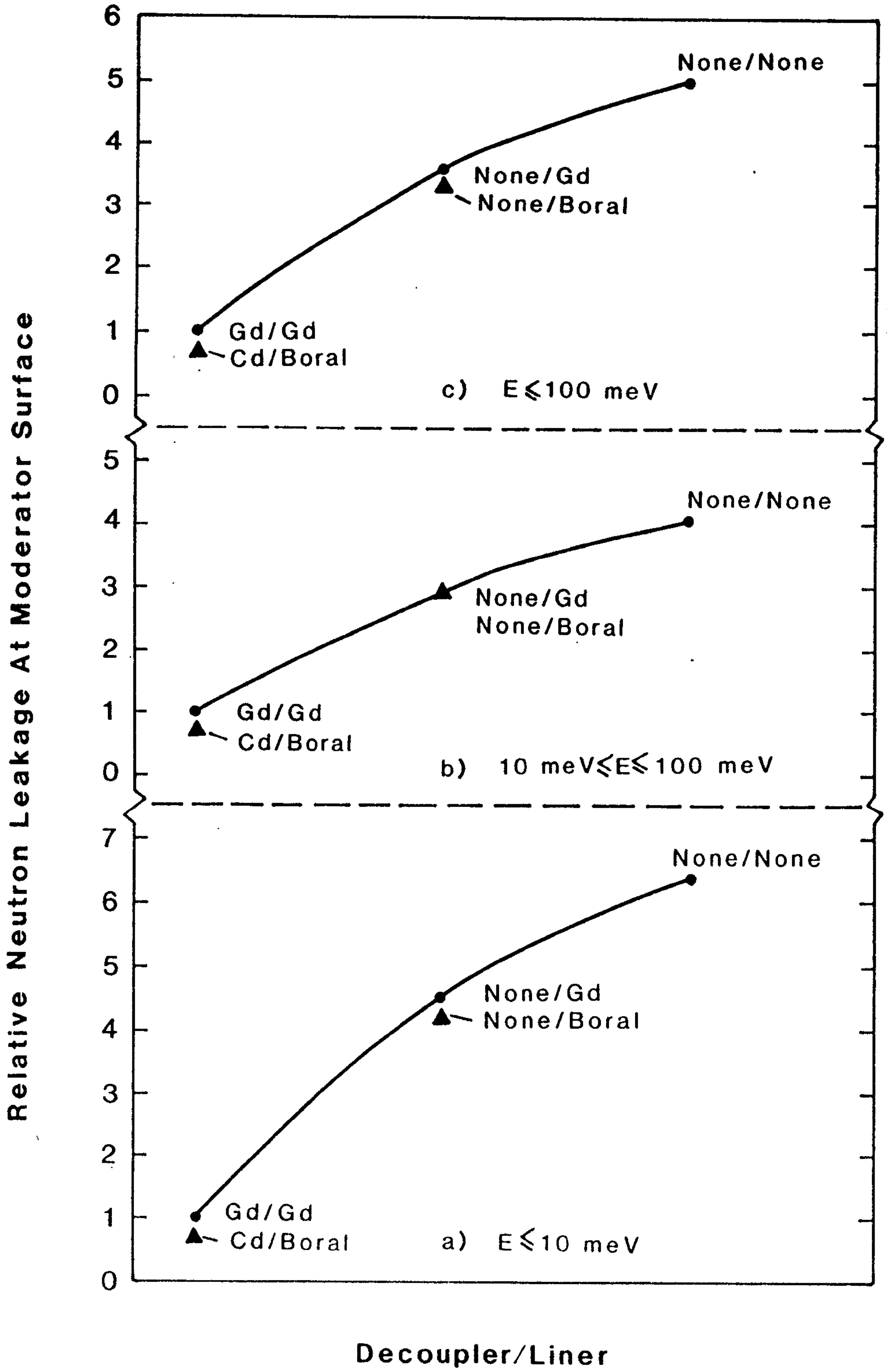


Fig. 29. Calculated neutron performance from a 100% para-hydrogen moderator for a variety of decoupler/liner combinations. The 6 by 13 by 13 cm moderator was in flux-trap geometry.

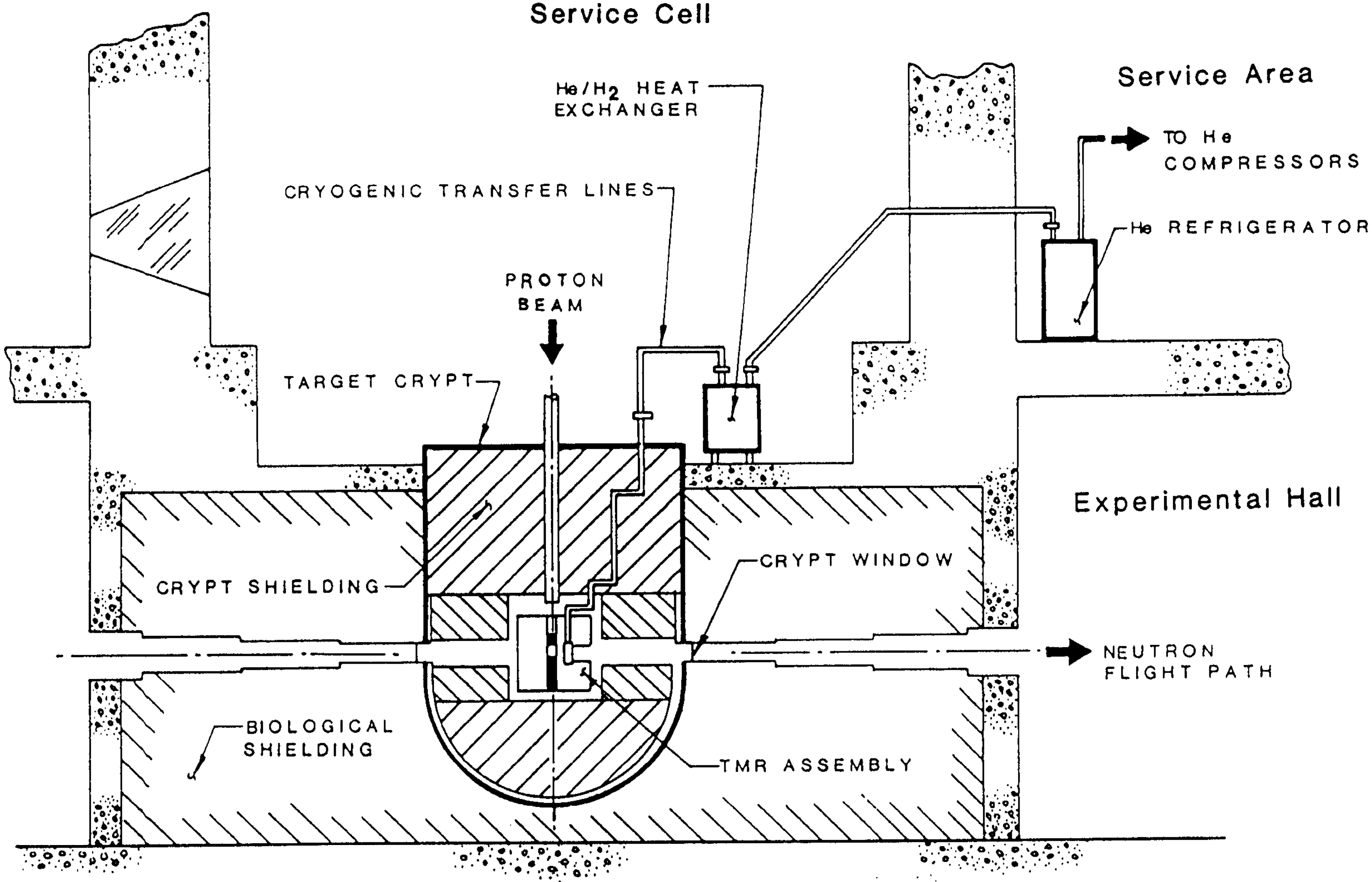


Fig. 30. Equipment layout for the LANSCE liquid hydrogen moderator system.

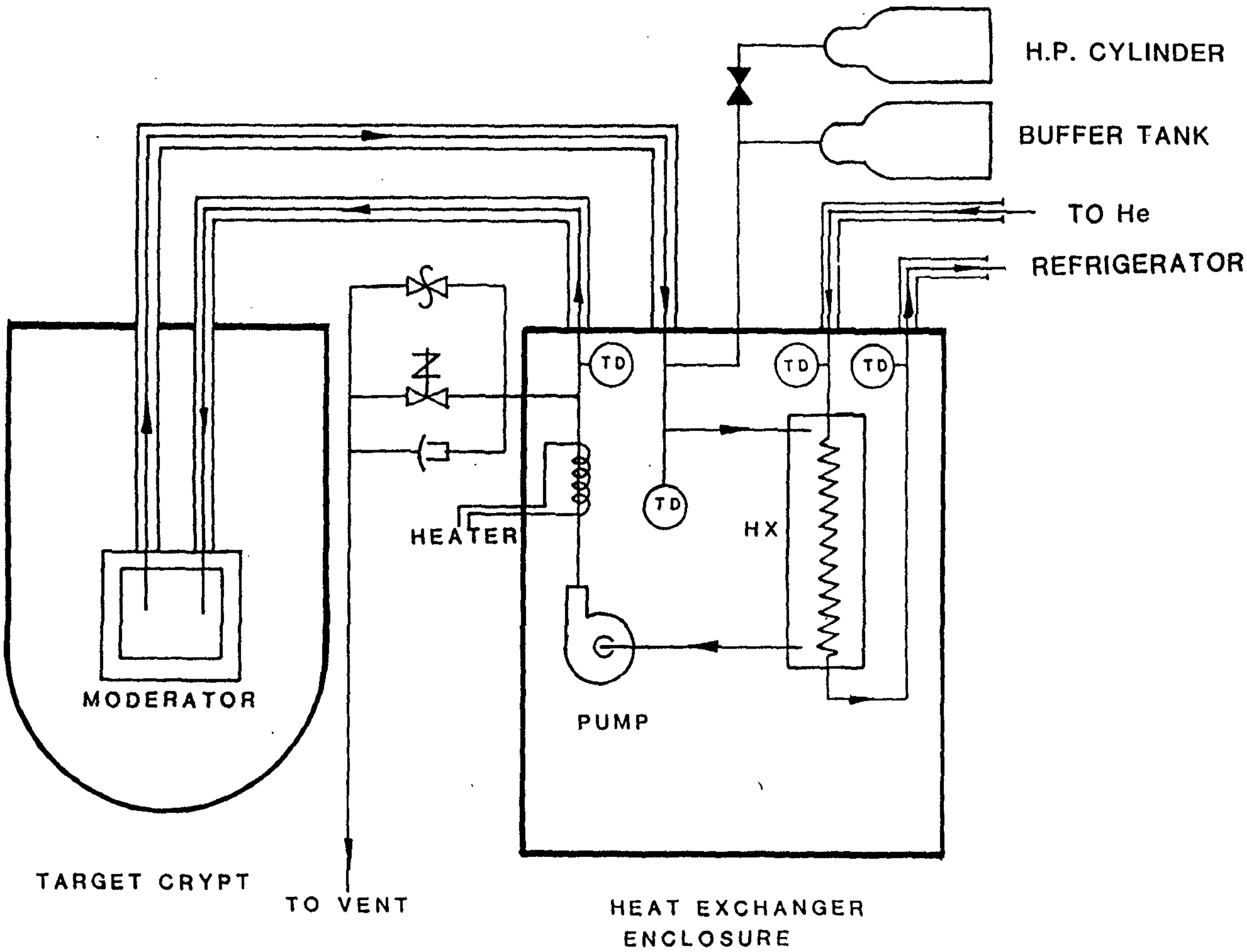


Fig. 31. Simplified schematic diagram for LANSCE liquid hydrogen moderator system.

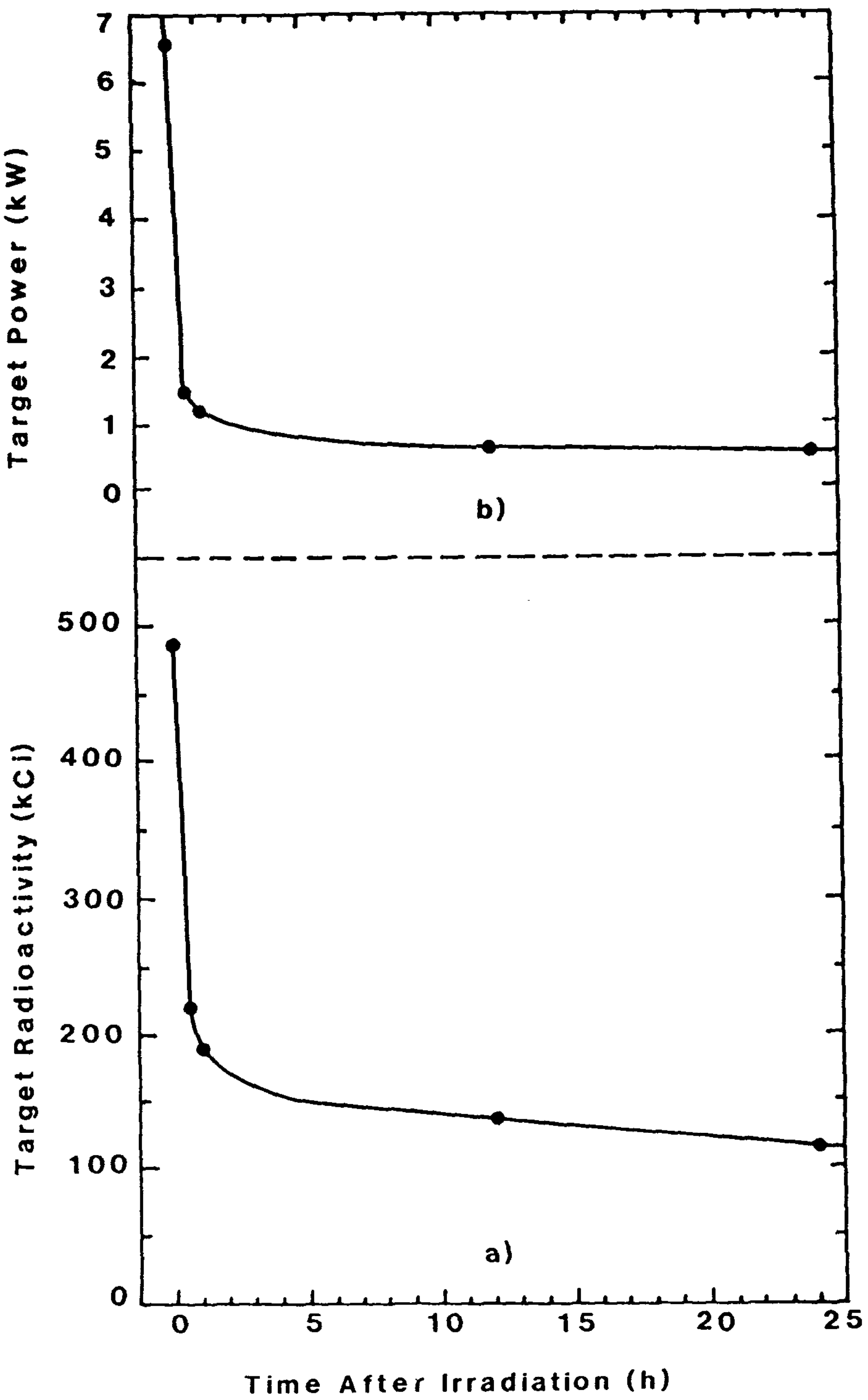


Fig. 32. Time dependent radioactivity and power of a LANSCE depleted uranium target. The target was assumed to be irradiated continuously for one year with 100 μA of 800-MeV protons.

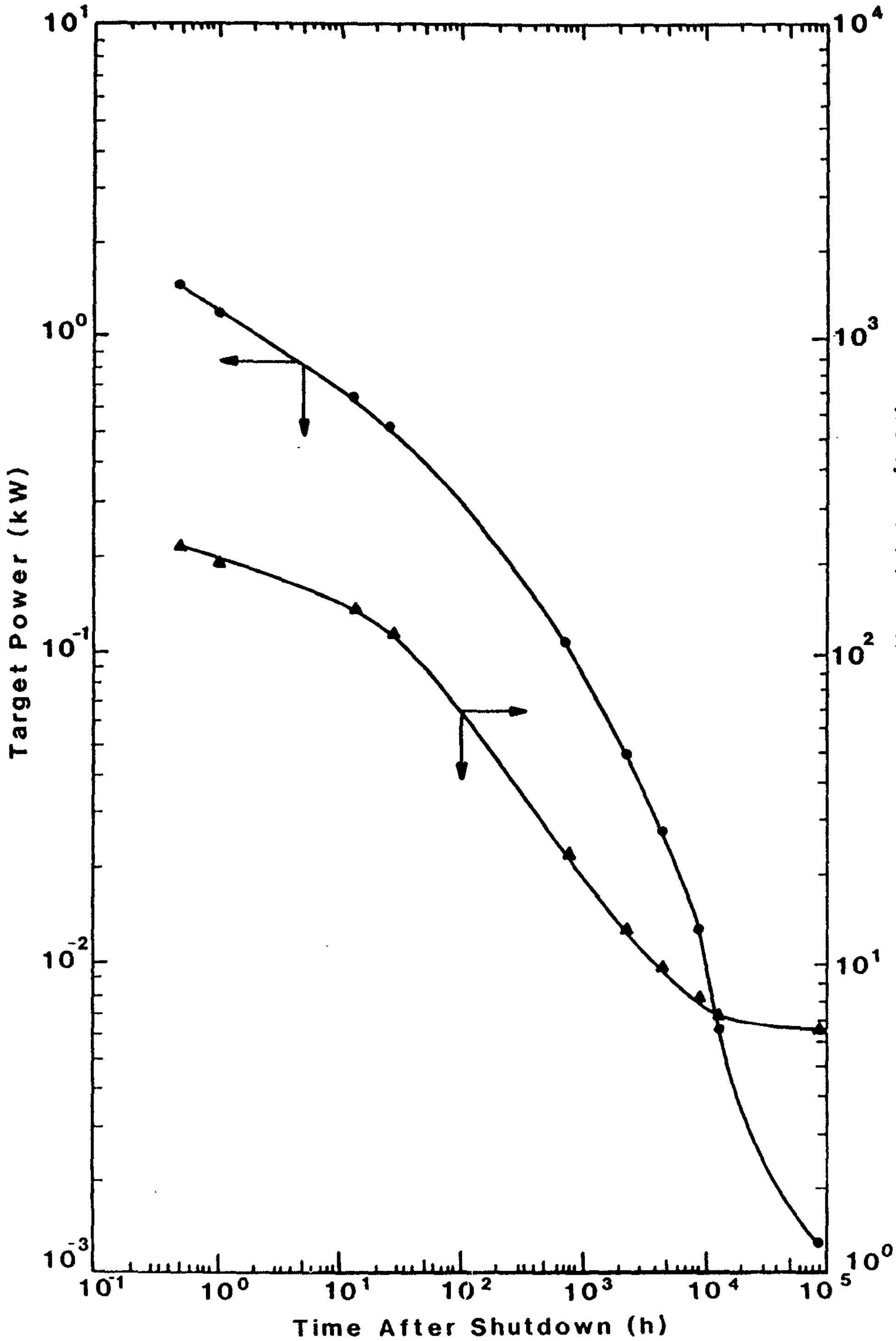


Fig. 33. Time dependent radioactivity and power of a LANSCE depleted uranium target. The target was assumed to be irradiated continuously for one year with 100 μA of 800-MeV protons.

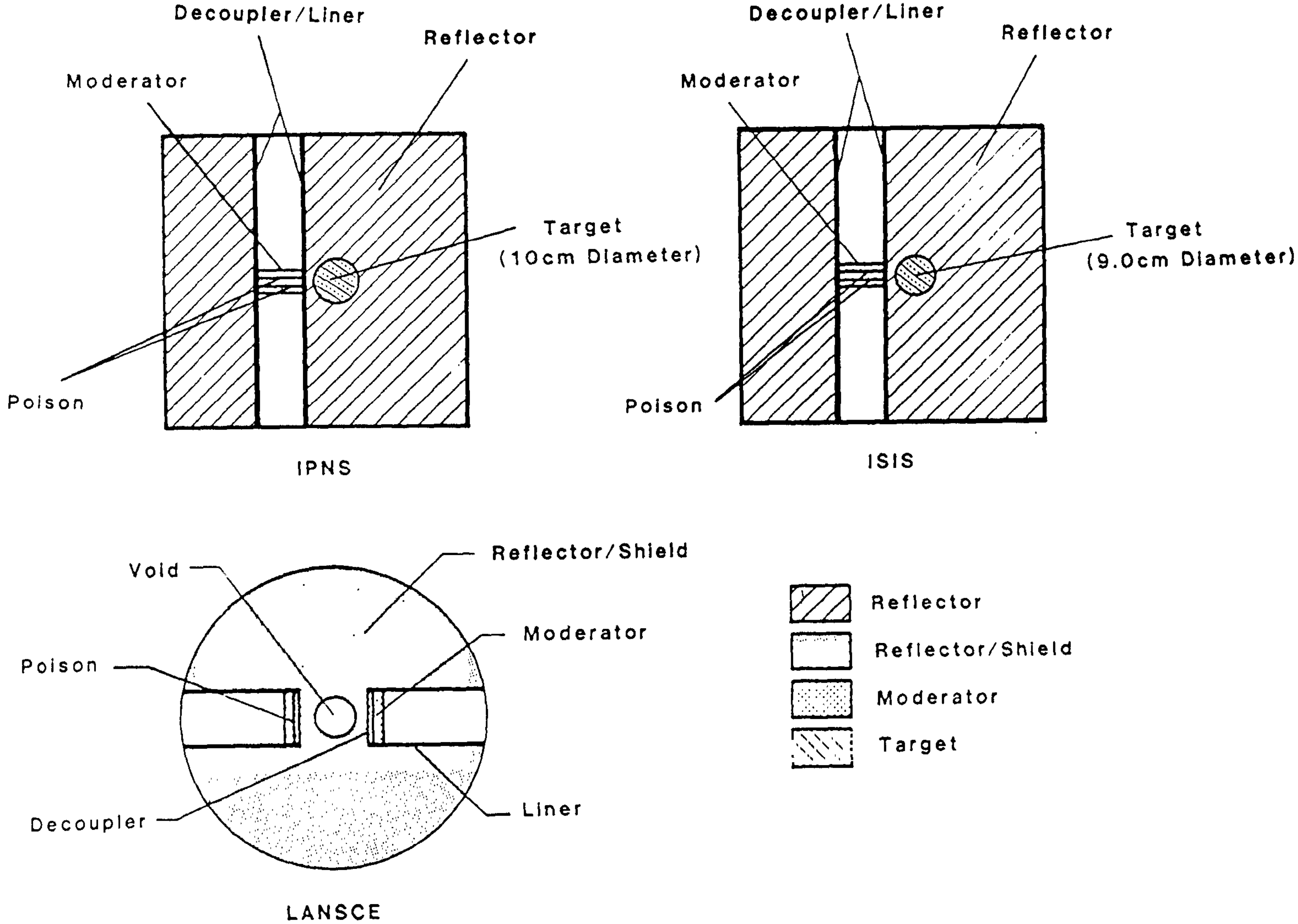


Fig. 34. Target/moderator/reflector geometries used to intercompare wing- and flux-trap moderator configurations.

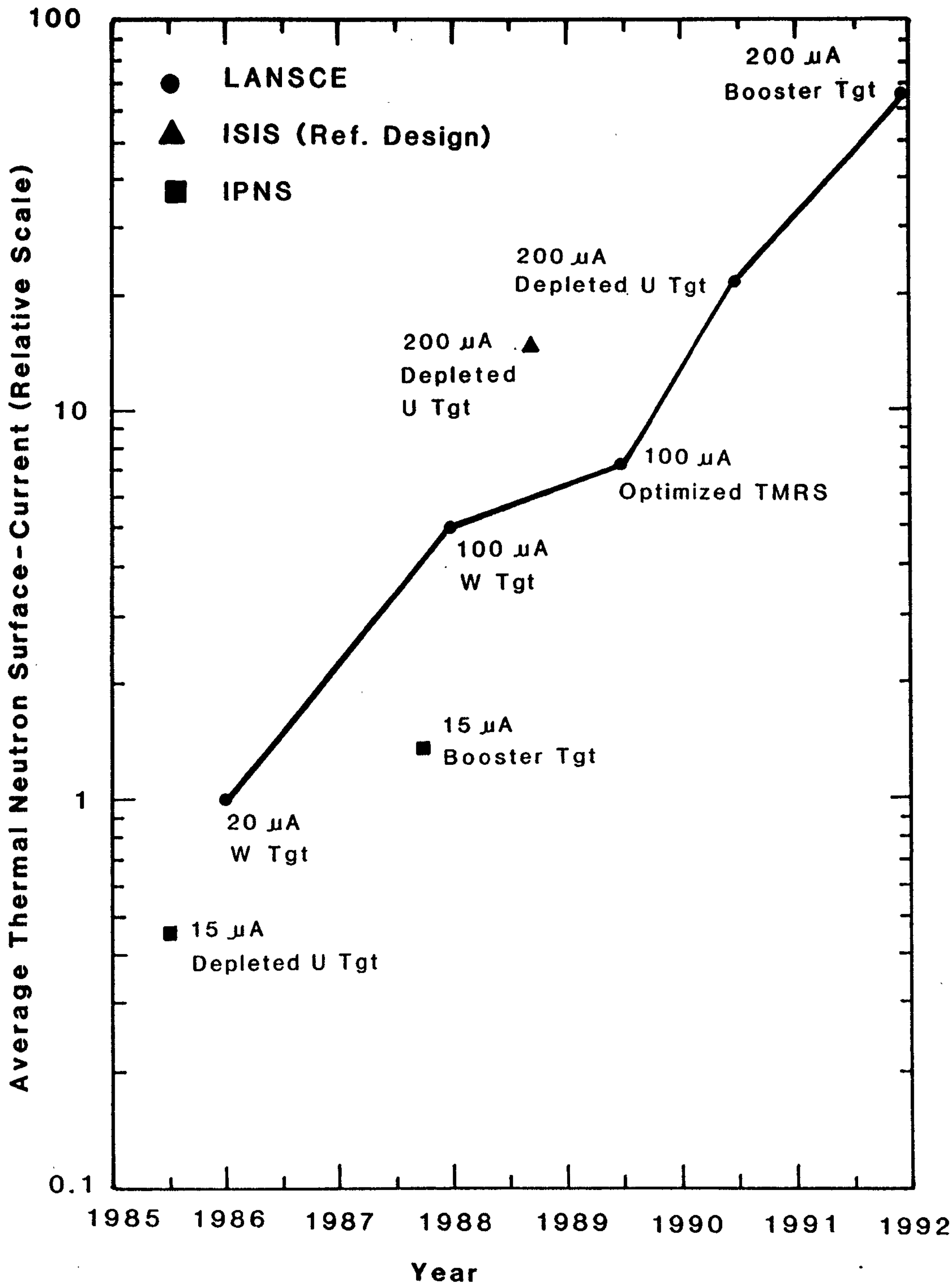


Fig. 35. **Relative** comparison of LANSCE performance (based on **average** neutron production) with other spallation neutron sources. Also indicated is one possible scenario for LANSCE development.

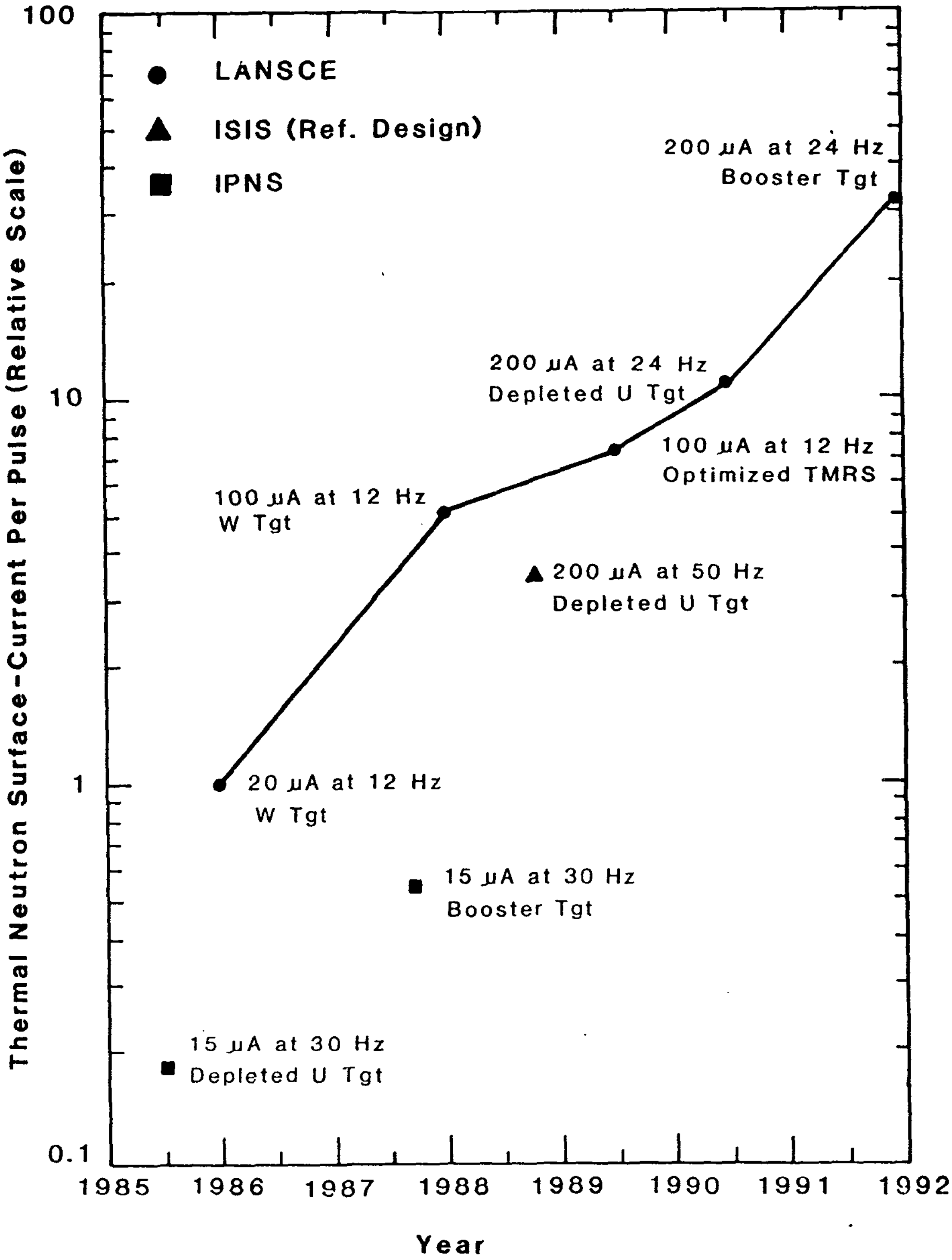


Fig. 36. **Relative** comparison of LANSCE performance (based on **peak** neutron production) with other spallation neutron sources. Also indicated is one possible scenario for LANSCE development.