

THE TRIUMF THERMAL NEUTRON FACILITY

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Abstract

The beam stop for the 500 MeV, 100 μ A beam from the TRIUMF cyclotron has been optimized to provide a variety of facilities for fundamental and applied research. These include: facilities for irradiating specimens with high-energy protons for research and for isotope production; facilities for irradiating specimens with neutrons of all energies from thermal to 500 MeV; and collimated neutron beams from the assembly core, primarily of thermal energies but also of epithermal and higher energies. The combination of these facilities in one unit has resulted in a compact design with substantial savings in shielding and space. The unit consists of a molten lead stopping target surrounded by an H₂O/D₂O moderator, an H₂O reflector and iron and concrete shielding. Most of the beam power (50 kW) is transferred by natural convection in the molten lead to the target wall. From there it is transferred by nucleate boiling to the surrounding H₂O moderator. Subsequently the heat is transferred by natural convection to a heat exchanger coil in the upper half of the moderator tank. The facility was commissioned early in 1978. This paper discusses design details, operational experience and measured neutron fluxes and activation levels.

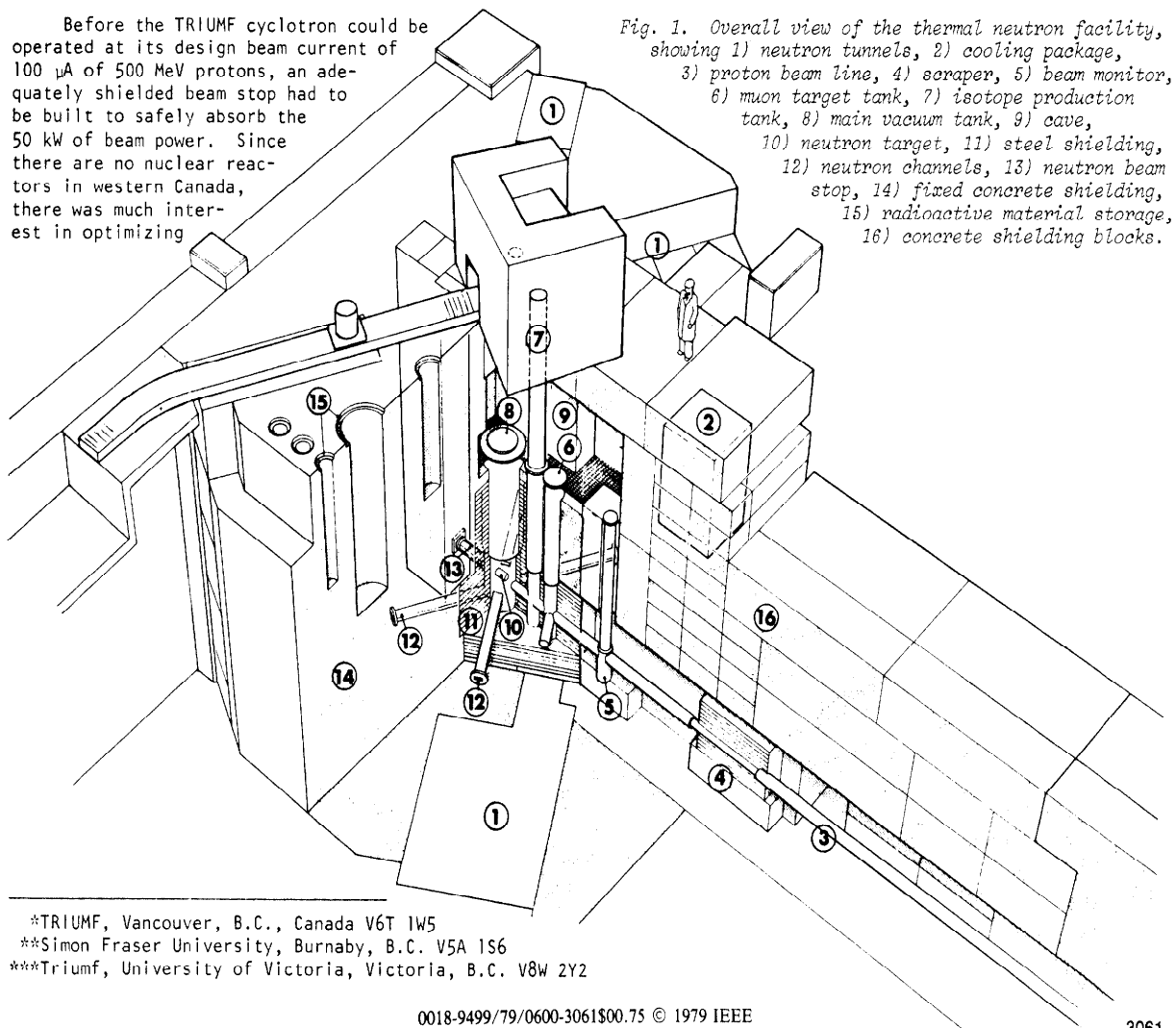
Introduction

Before the TRIUMF cyclotron could be operated at its design beam current of 100 μ A of 500 MeV protons, an adequately shielded beam stop had to be built to safely absorb the 50 kW of beam power. Since there are no nuclear reactors in western Canada, there was much interest in optimizing

the neutron flux and at the same time providing for collimated neutron beams. Further, it seemed cost effective to utilize to the fullest extent the large quantities of shielding required and allow space for isotope production targets and possibly a meson target.¹ This resulted in a very compact target assembly at a moderate cost (~\$850,000). The thermal neutron facility (TNF) was designed during 1976. Construction took place in 1977 and the facility was commissioned early in 1978. Ancillary facilities, such as for neutron activation analysis, isotope production and neutron diffraction spectroscopy, are being installed during 1979.

Facility Layout

Figure 1 shows a cut-away view of the facility, which is located at the end of the main proton beam line. The section ahead of the TNF has narrowed, steel-shielded sections called scrapers. These catch most of the beam loss in the line which can be as high as 30% due to scattering in the meson target farther upstream. The scrapers pose a relatively mild radiation problem, as they can be removed by crane in one piece with the narrowed beam pipe section and thus are largely self shielding.



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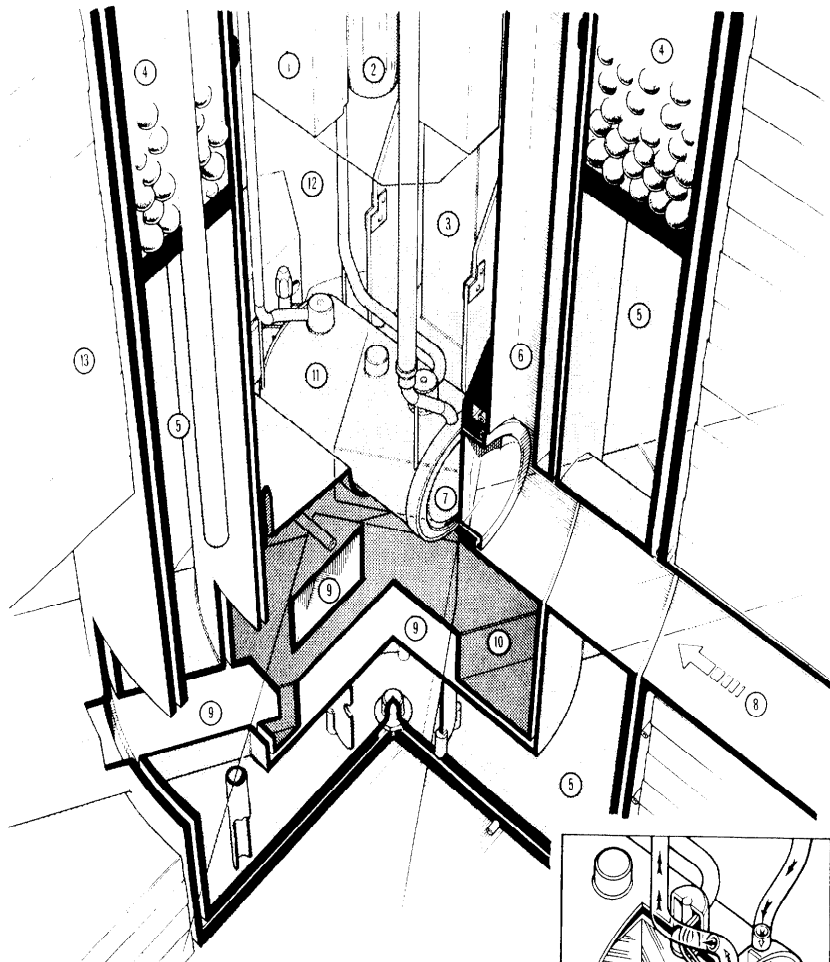


Fig. 2. Inside view of the thermal neutron target, moderator and reflector. 1) Shadow shield, 2) plug, 3) D_2O moderator access, 4) iron-concrete shield, 5) reflector H_2O , 6) proton beam access, 7) water window, 8) protons, 9) neutron channels, 10) moderator D_2O , 11) target, 12) moderator H_2O , 13) steel shield, 14) water window and target front cooling.

There is a beam-monitoring station just ahead of helium-cooled beam window that separates the beam line from the TNF vacuum tank. This vacuum tank consists of the main vertical tank which contains the neutron target, two smaller tanks to contain isotope production targets and possibly a muon target, connecting proton beam pipes and four neutron channels. The entire vacuum tank is enclosed by mill-rejected steel plate, encapsulated in concrete, and surrounded by poured-in-place concrete blocks and movable concrete blocks. The encapsulated steel plate and poured-in-place concrete blocks can be dismantled by crane in pieces not exceeding 100 tons, to avoid the use of pneumatic hammers when the facility ultimately may have to be dismantled.

Above the vacuum tank is a shielded cave that provides access to the tank's top flanges and the cooling system. The cave is locked up during operation of the facility but is accessible 30 min after the beam is shut down. Above the shielding over the cave is a single-purpose hot cell in which radioisotope targets are transferred from the irradiation tank into a lead container, for transportation to the radiochemistry laboratory.

Vertical holes in the poured-in-place shielding are provided for storage of radioactive components. Concrete blocks can be removed as necessary to gain access to the neutron channels. The hot cell and shielding over the cave can be removed if major components, such as neutron target, moderator and reflector tanks or the isotope production thimble, have to be removed.

Target Geometry

Figure 2 is a cut-away view of the lower section of the neutron target tank. The target consists of a stainless steel can, 150 mm diam \times 250 mm long, filled with lead, in which the beam is stopped. Lead was chosen after consideration of natural uranium, tungsten, lead-bismuth and copper. Natural uranium² is unattractive because of its six times higher heat production. Lead-bismuth would result in lower target temperatures but is undesirable because of the ^{210}Po hazard. Tungsten would be more difficult to cool and the resulting construction of the water-cooled thin plates would produce a 2.5 times lower neutron flux and expose too much water to the proton beam. Copper would perhaps be easier to cool but its lower neutron yield makes it unattractive.¹

The target is submerged in the H_2O moderator, which also acts as the coolant. Below the centre of the target is a compartment filled with D_2O . The moderator tank is surrounded by the reflector tank, also filled with H_2O . The upper part of the reflector tank is filled with a steel/concrete mixture as shielding. Directly above the target, shielding is provided by a steel shadow shield and the moderator water. Both the moderator and reflector tanks are located inside the vacuum tank and are serviceable through the top flanges in the TNF cave. The vacuum in the tank is kept at 0.01 Torr. A 3 mm thick aluminum beam window separates the moderator water from the vacuum.

Irradiation Facilities

Figure 3 shows the various targets as positioned within the steel shielding. Irradiation facilities are listed as follows:

Protons:

- A gas target and/or muon target in the first tank (#2)
- Six to twelve isotope production targets in the second tank (#4)
- Unspecified target in moderator tank (#8)

Neutrons:

- Thermal flux in moderator tank, for rabbits and thimbles (#9)
- Fast flux in reflector tank for unspecified use (#10)
- Fast flux in steel shield for unspecified use (#11)

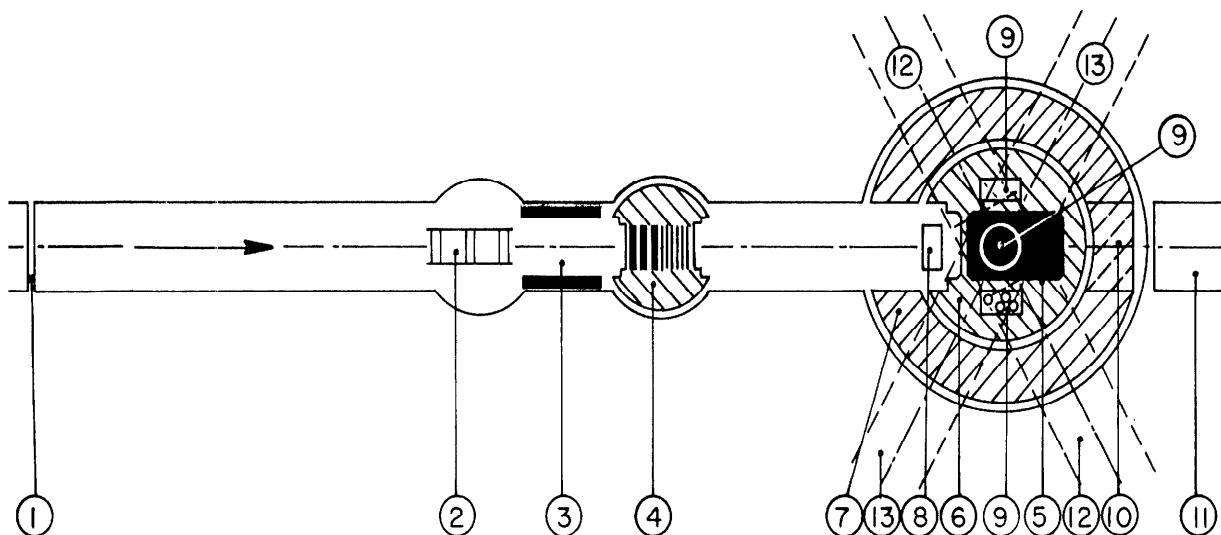


Fig. 3. Horizontal cross-section. 1) Beam window, 2) gas target, 3) collimator, 4) isotope production, 5) neutron target, 6) moderator, 7) reflector, 8) access to proton beam, 9) access to thermal neutron flux, 10, 11) access to fast neutron flux, 12) neutron beams, 13) neutron channel below target.

All these are accessible from above, in the TNF cave, except the fast flux in the steel shield for which a substantial number of concrete blocks would have to be removed.

In addition there are neutron beams, accessible from the experimental floor:

- Two channels, looking at the moderator directly under the neutron target (#12). One of these will be used for neutron diffraction spectroscopy.
- Two channels, forming one continuous channel 30 cm below target centre (#13). This channel can be used to install a reflector block, tailored to the requirements of a given experiment and/or a fast rabbit system.

For access to the neutron channels the concrete blocks in the neutron tunnels can be removed.

Beam and Flux Properties

The neutron target is designed for 300-500 MeV protons with a beam current of 100 μ A. The beam spot is approx 20 mm \times 40 mm. The gas target will degrade this beam by only a few MeV. The isotope production target may degrade it approximately 100 MeV. The neutron beam and flux properties given below are for an incident proton beam of 100 μ A and 500 MeV.

The thermal flux at the source point of the neutron beam channels in the D₂O moderator directly below the lead target (#12, Figs. 1 and 3) was measured to be 3×10^{12} cm⁻² s⁻¹. The lower neutron beam channel is a 'through channel' at the bottom of the D₂O moderator tank adjacent to the bottom of the H₂O reflector. It is intended to take a source block that can tailor the neutron beam to specific requirements such as cold or hot neutrons or a thin scatterer to suppress fast neutron contamination. The measured flux at the centre of the lower beam channel is approx 1×10^{12} cm⁻² s⁻¹.

The thermal and epithermal neutron fluxes were mapped at various points in the lower moderator compartment by activation of bare and cadmium-covered gold foils. The results for thermal neutrons with the moderator compartment filled with D₂O—the normal operating mode—are shown in Fig. 4. The flux values are shown in a lateral cross-section through the centre of the target and the $\sim 5 \times 13$ cm access channel to the

moderator compartment. Measurements were also made with the moderator compartment filled with H₂O. Separate measurements were made with cadmium-covered foils to obtain the epithermal component of the gold activation. All results were normalized for beam intensity by measuring the ²⁴Na activity induced in a thin aluminum foil mounted in front of the lead proton-stopping target.

The results for the D₂O moderator case were almost a factor two lower than those estimated previously^{1,3} with the two-dimensional multigroup neutron diffusion code EXTERMINATOR. Approximately half of the discrepancy is attributable to the use of stainless steel as the lead target can material whereas the estimates were based on using zirconium. The H₂O moderator flux measurements were generally much closer to the estimates, being about 15% lower at the points closest to the lead target but higher than the estimate by 30-50% at points as far out as the moderator compartment access channel. The difference between the calculated and measured flux distribution for both H₂O and D₂O moderators are consistent with the possibility that the evaporation neutron spectrum from the lead is significantly harder than the fission spectrum assumed in the optimization calculations.

The solid points in Fig. 4 represent the average of two foil measurements taken ~ 5 cm on each side of the symmetry plane of the assembly. The hollow points in the vicinity of the horizontal neutron beam tubes represent only one point immediately adjacent to this beam tube. The flux distribution in this region is substantially distorted by the presence of these tubes.

The epithermal neutron flux expressed as a neutron density ratio varies from ~ 0.012 to 0.034 for the H₂O moderator case; for D₂O it varies from 0.012 to 0.076 because of the poorer moderating properties of D₂O and the high leakage from the rather small moderator assembly.

Heat Transfer

When exposed to 100 μ A of 500 MeV protons the TNF has to dissipate 50 kW of beam power. Of this 75% is deposited in the lead target by proton ionization and nuclear recoil. The remainder ends up in the moderator, reflector and shielding via cascade and evaporation neutrons and capture γ -radiation.

Radiation

The only serious radiation problem proved to be the production of ^{194}Hg in the lead target. The target can has an expansion space at the top which is permanently evacuated by a small vacuum pump. This way gases evolving from the lead, primarily hydrogen resulting from the stopped protons at a rate of 1 cm^3 per day, cannot build up pressure as they would in a sealed can. Also, monitoring the vacuum is a very sensitive way to detect the slightest crack in the can, as an early warning of failure.

The radiogases produced in the target consist of noble gases, mercury and tritium. Most are produced at a rate below the maximum allowed release rate, or could be released after a decay period of less than a day. The exception is ^{194}Hg which decays into ^{194}Au with a half-life of 1.3 yr and is produced at the rate of $400\ \mu\text{Ci}/\mu\text{Ah}$.

The problem was solved by installing a gas-holding system in the vacuum line from the target. It consists of a mercury trap at -100°C which can be valved off and is located in its own shielded cave. There are also two shielded noble gas-holding tanks in which the noble gases can be stored until they can be disposed of below the maximum permissible release rate. Initial experience with the system has shown good separation between the mercury and noble gases.

When the facility is in full operation, the radiation level inside the TNF cave is of the order of 3 rem h^{-1} . Outside the shielding the highest radiation level was measured to be 10 mrem h^{-1} , directly above the 1.5 m concrete roof shield over the cave. These radiation fields are a factor 3-5 lower than estimated.

Activation of the cooling water is no problem during operation, as the whole irradiated water system is located within the cave. The ^{15}O , ^{13}N , ^{16}N and ^{11}C have short half-lives, while ^7Be is collected in a lead-shielded de-ionizer. Tritium is released by changing water at regular intervals before the tritium level reaches an objectionable concentration.

The neutron target was removed for inspection after the commissioning tests at $100\ \mu\text{A}$, 500 MeV , and a total exposure to $2500\ \mu\text{Ah}$ over a one-month period. After a 4-day decay period its activity was measured as 3 rem/h at a distance of 1 m. This is estimated to increase by roughly a factor of ten after prolonged use at full beam intensity.

References

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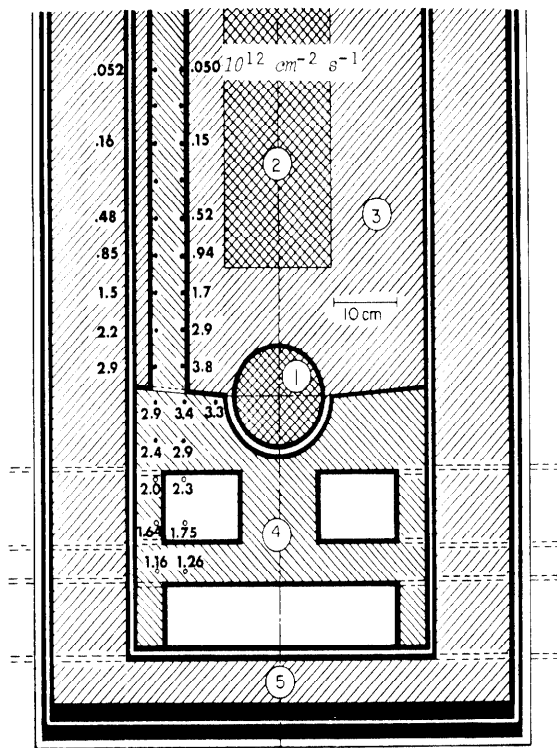


Fig. 4. Thermal neutron flux distribution: 1) lead target, 2) steel shadow shield, 3) H_2O moderator, 4) D_2O moderator, 5) H_2O reflector.

Under these conditions most of the lead in the target is molten, reaching close to 500°C at the centre, top and front of the target, while lower down some of the lead stays solid. Heat transfer from the lead core is as follows:

- 1) Natural convection in the molten lead
- 2) Conduction through the 3 mm thick target wall
- 3) Nucleate boiling to the surrounding moderator water
- 4) Natural convection in the moderator to a heat exchanger coil in the upper half of the moderator tank

The thickness of the target container was chosen such as to limit the heat flux at the outside to 125 W/cm^2 . This is a safe limit for heat transfer by nucleate boiling and prevents steam formation at the surface, which would result in cooling breakdown and overheating. The temperatures in the water are moderate and reach a maximum of 40°C in the vicinity of the target.

The beam window separating the tank vacuum from the moderator water is spaced 5 mm from the target front wall. Heat dissipation in the window is $\sim 300\text{ W}$ and in the target front wall $\sim 700\text{ W}$. Both are cooled effectively by circulating moderator water through the gap between them.

The vacuum tank and steel shielding are also water cooled. There is ample redundancy in the number of cooling tubes and cooling capacity to allow for future upgrading of the facility, as these parts cannot be interchanged.