ICANS XIV
14th Meeting of the International Collaboration on
Advanced Neutron Sources
June 14-19, 1998
Starved Rock Lodge, Utica, IL

Engineering Design of the Lujan Center Target

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1. System Overview and Design Objectives

There are two primary engineering design objectives for the new Lujan Center Target System:

1. Provide increased thermal capacity of the tungsten target assembly to allow safe and reliable operation of the target at average proton beam currents up to 200 μA.
2. Increase system availability and access to critical components for replacement as required.

We believe that this engineering design provides a balanced approach that meets these objectives while maximizing overall system performance. The design provides for critical component access and replacement within a maximum three-week down period. Items defined as critical components include the proton beam diagnostic, the proton beam vacuum isolation window, the tungsten targets, and the neutron moderator assemblies.

2. Design Philosophy

The general philosophy of the design approach is one of modularization of critical components into easily accessible coaxial-nested inserts or modules. The objective is to reduce handling time and personnel radiation exposure for target replacement activities and to provide access at the component level for eventual disposal of used target modules. Target replacement will normally be accomplished during a standard maintenance period, however, if an unexpected component failure causes unplanned replacement, minimizing system downtime is critical. The target system must be designed to allow for safe and rapid handling, consistent with the goal of minimizing personnel radiation exposure. Eventual processing of spent target modules will involve separation of the modules into sections of like material and/or activation level (i.e. lead and beryllium reflectors, tungsten target etc.) This design incorporates key features that accommodate remote handling operations as required for this disassembly and disposal process.

3. Target Facility Configuration

The layout of the target system is largely unchanged from the basic configuration that has been in service since 1985. The tungsten target and moderator components are located in the center of a large evacuated vessel (target crypt vessel) that is surrounded by a large biological shield assembly. The biological shield is cylindrical in shape, with a diameter of about 10 meters, and is composed of layers of steel and concrete. The top of the biological shield is enclosed within a hot-cell type structure refered to as the target cell. An artist concept of a target change operation is shown in Figure 1. Note the relative position of the instrument flight paths, the target cell and the external bridge crane with its cover building as shown.

The proton beam leaves the Proton Storage Ring (PSR), inside a horizontal 4-inch diameter beam-tube, about 7.5 meters above the plane of the lower moderators. The beam is bent through a radius of roughly 4.3 meters and is injected vertically downward into the target crypt vessel where it strikes the tungsten targets. Inside the crypt vessel, surrounding the tungsten target region, is a group of steel plates and rings that provide immediate high-energy neutron shielding around the target-moderator section. Figure 2 is a cross-section view through the target crypt vessel and its contents. The elements of the target insert (targets, moderators and reflector components) are visible as well as the surrounding steel shielding.

During a target change or installation activity, water, instrumentation, and cryogenic connections to the target insert are made inside the target cell enclosure at the level of the large square closure plate on the top of the crypt vessel (Figure1). The target cell contains a small, 5-ton bridge crane (not shown in Figure 1) and a pair of remote manipulators. An access port through the roof of the target cell has been installed as part of the upgrade project to allow vertical access to the target module during installation and replacement operations. In the past, access to the target assembly has been through a large hinged shield door in the target cell wall. A large 30-ton bridge crane mounted above the target cell roof (external to the target cell) will provide lifting capability for the target insert and its shielding cask.

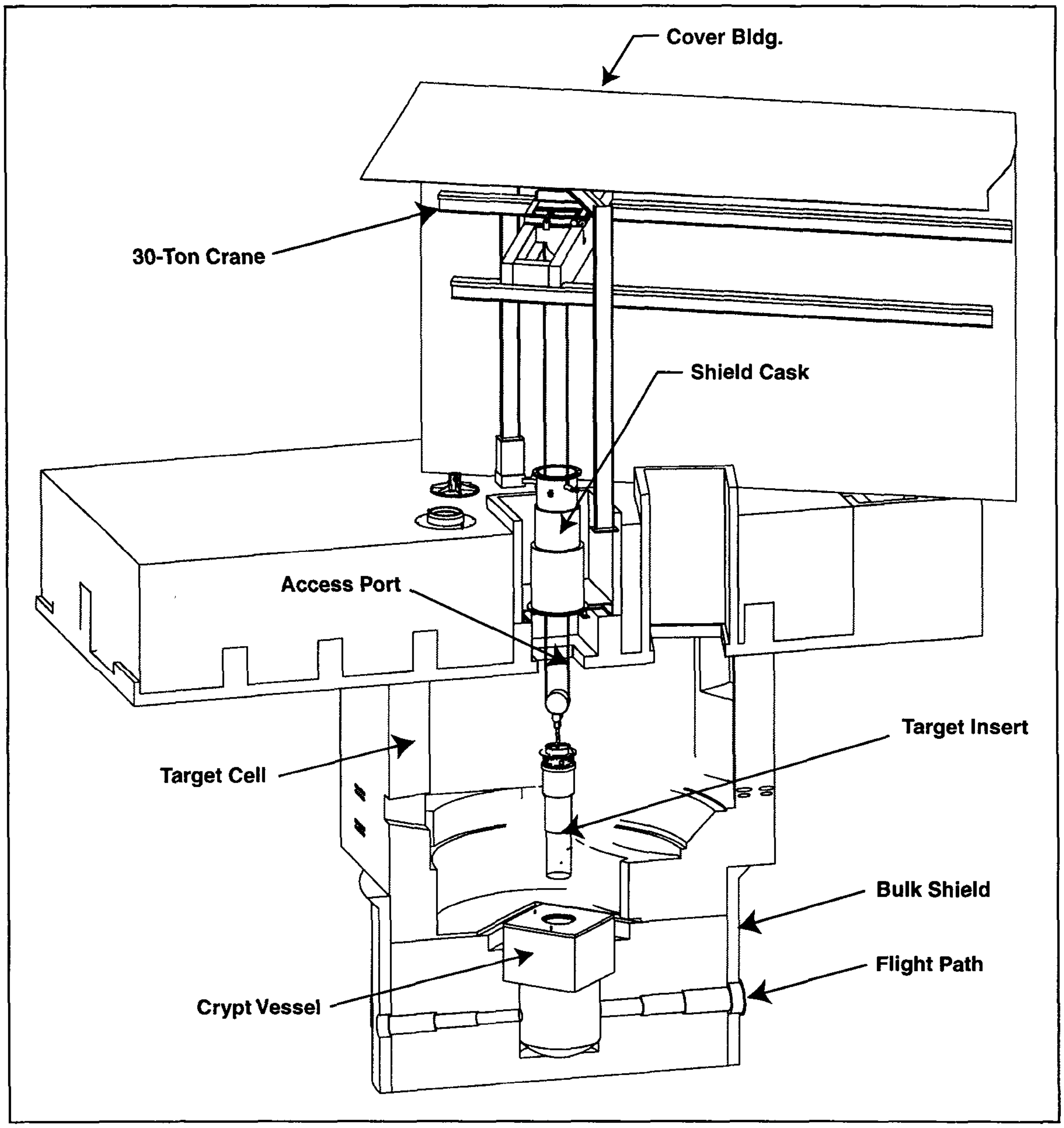


Figure 1. Target change operation

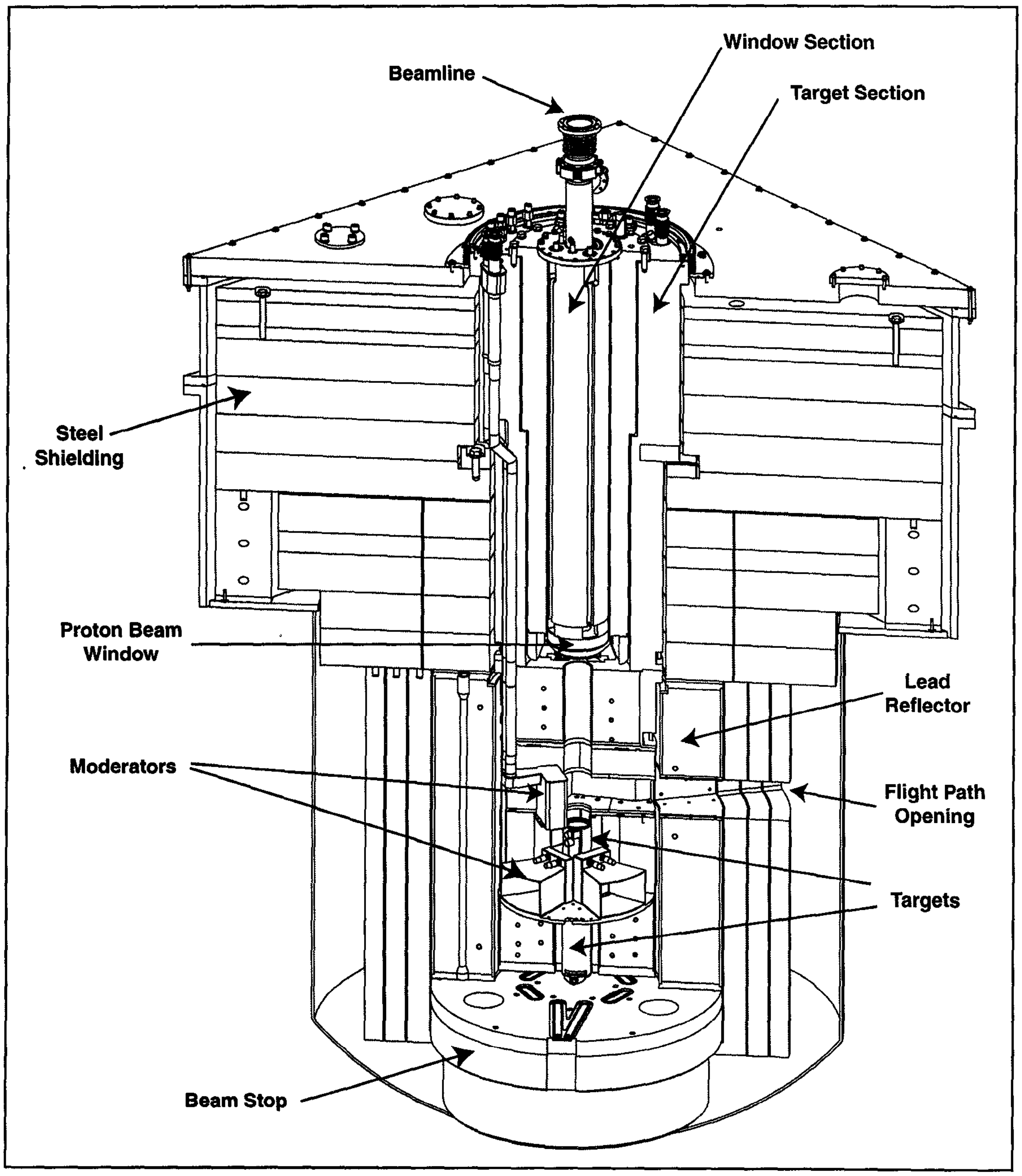
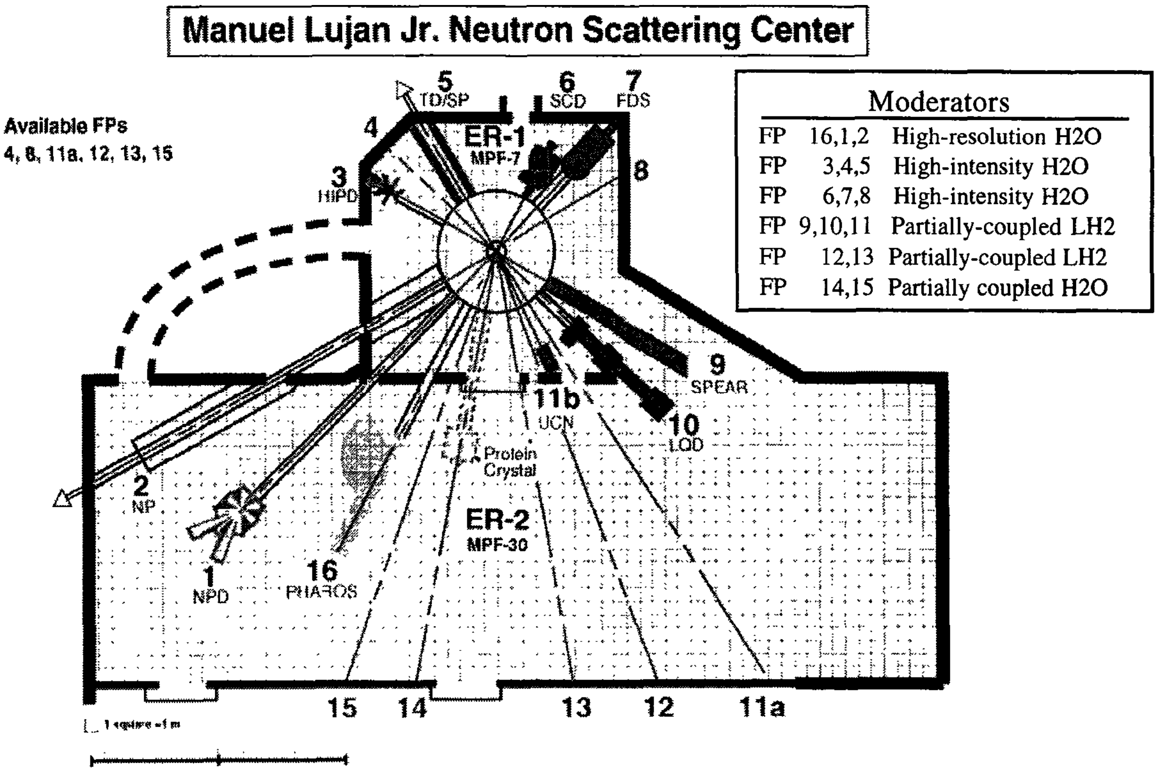


Figure 2. Section view of the target crypt region

The cover building incorporates air-handling equipment and provides atmosphere containment and weather protection during access to the target cell area.

A total of 16 radial ports extend horizontally from the target crypt vessel to the outer diameter of the biological shield, and neutron flight path tubes extend on outward to various neutron-science instruments in the experiment hall. The flight paths are arranged to allow viewing of the various moderators in the target assembly. Figure 3 shows the layout of the 16 flight paths in the experiment hall. Flight paths 12 through 15 were installed in 1991 but were not able to view a moderator until now. These new ports will be activiated as instruments are designed installed.



Moderators

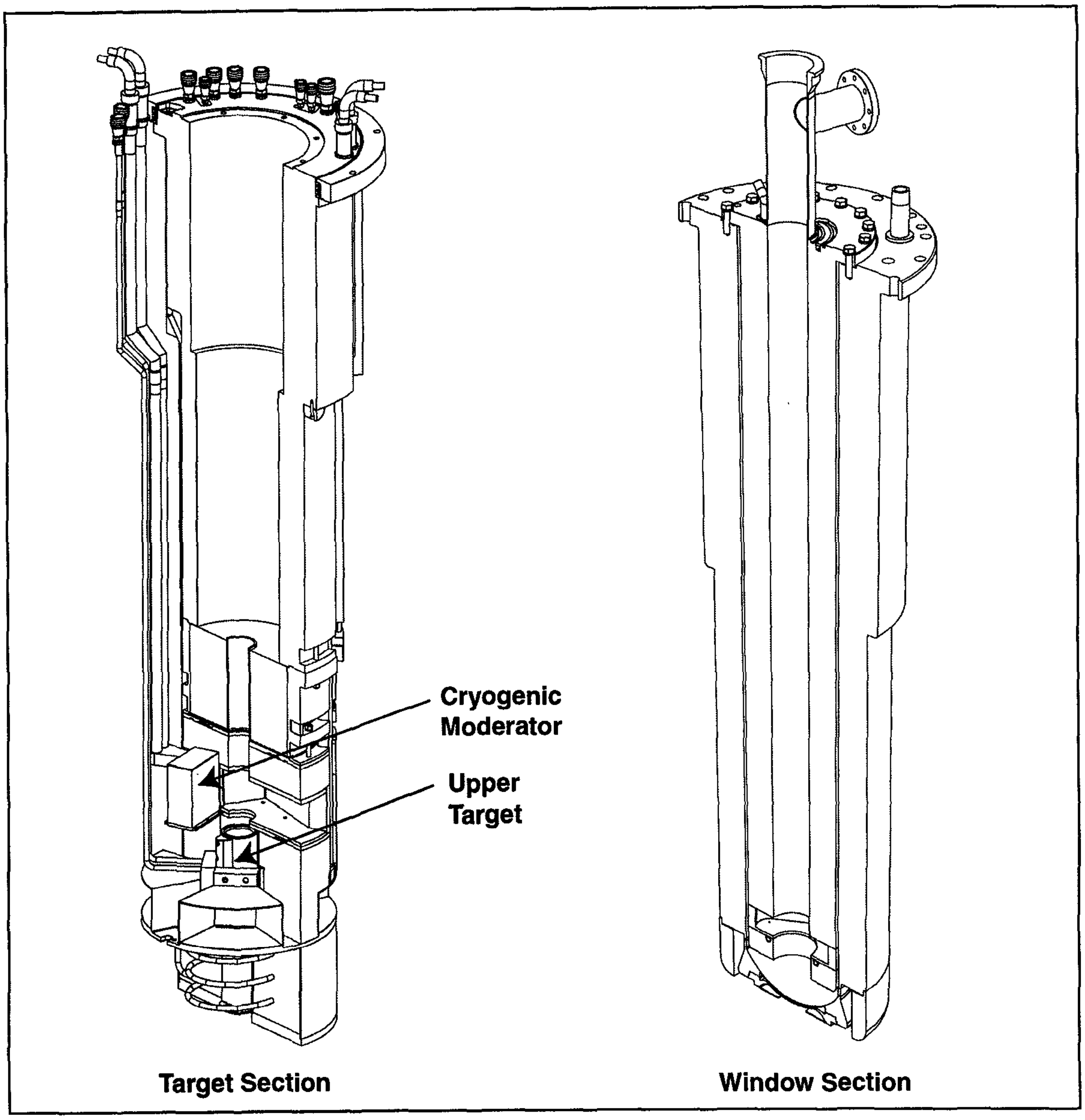
FP	16,1,2	High-resolution H2O
FP	3,4,5	High-intensity H2O
FP	6,7,8	High-intensity H2O
FP	9,10,11	Partially-coupled LH2
FP	12,13	Partially-coupled LH2
FP	14,15	Partially coupled H2O

Figure 3. Flight Path Layout in the Experiment Hall

4. Target Insert Configuration

The target insert assembly is comprised of three separately manufactured elements that are assembled in a coaxial nested configuration. Each element is supported and mechanically sealed to its outer neighbor. The inner element is the diagnostic element, the center element is the proton beam window, and the outer portion is the target-moderator-reflector. For simplicity and ease of handling the diagnostic element and the window element are always handled together and refered to as simply the window section. The target-moderator-reflector element is likewise simply called the target section. Figure 4 shows the target and window sections side-by-side, as they would appear before final assembly of the target insert unit. The window section nests inside the target section and can be removed from the crypt separately if required. Removal of the target section however, requires either prior or concurrent removal of the window section. The expectation is that both sections will normally be handled together as a unit (target insert) unless a failure occurs in the window section early in a service cycle. In such an event, the window section would be replaced separately, saving the expense of replacing the entire unit. The diagnostic element carries an electrical device (harp) that provides operational information about the shape and location of the proton beam as it enters the upper tungsten target. The harp requires a high vacuum environment for proper operation and reasonable lifetime so it resides in the high vacuum of the beam transport line. The window section separates the high vacuum environment of the proton beamline (10^{-6} torr), from the low vacuum environment (~1 torr) inside the target crypt vessel. The target section is composed of the upper and lower tungsten-targets, the 6 neutron moderators, the beryllium inner reflector, and two sections of lead reflector. The whole target insert assembly is supported by a steel plate attached to the main shielding blocks inside the crypt vessel. This support plate is installed and aligned to the instrument flight paths and proton beam delivery system during installation of the crypt steel. Precise and repeatable alignment of the moderators to the flight-paths and instruments is assured for all subsequent target insert units (see Figure 1).

Cooling lines and thermal diagnostics for each section of the assembly are routed through the top flange of that section in order that each be fully self-contained. A more detailed design description of each element follows in the next section.



Target Section

Window Section

Figure 4. Target Section & Window Section

5. Target Component Design Description

5.1. Proton Beam Design Parameters

Table 1 lists the proton beam characteristics for the design beam current of 200 μA. These parameters were used to generate neutron performance data and component energy deposition rates through the LAHET-MCNP code sets. The heating data were used in the finite element design code ABAQUS v5.6 to estimate component temperature and stress levels during operation.

Table 1. Proton Beam Parameters at 200 μA

Average Proton Beam Current	200 μA
Pulse Length	250 nsec
Average Pulse Rise/Fall Time	125 nsec
Pulse Repetition Rate	30 Hz
Average Particles per Pulse	4.16×10^{13}
Average Charge per Pulse	6.67 μC
Average Current During Pulse	26.7 A
Peak Current During Pulse	53.3 A
Beam Shape	Circular Gaussian
Beam Standard Deviation	1.5 cm, radius
Beam Size, FWHM	3.532 cm
Average Current Density at Beam Center	14.15 $\mu A/cm^2$
Peak Current Density at Beam Center	1.89 A/cm^2

It should be noted that the exact operational proton beam shape varies slightly during operation due to varying beam transport tune conditions. However, the chosen set of beam focus parameters bound the worst case heating conditions in the window and target components. The data are felt to represent a maximum possible focus intensity based on optics calculations for the transport line. This maximum intensity is not necessarily the exact tune that will be used. In practice, the beam diagnostic harp will provide real time measurement of beam focus and current density parameters to allow verification of proper settings (primarily beam steering) of the beam transport optics. This is especially important during the initial comissioning.

5.2. Window Section Assembly

The window section assembly consists of the proton beam diagnostic section and the proton beam window section. These two sections are bolted together at their top flanges using metal seals and are normally handled as a single assembly unit refered to as the window section (Figure 4). This bolted arrangement allows for independant construction and testing of the two sub-assemblies before final assembly of the combined unit. The combined unit weighs about 3400 pounds and is roughly 86 inches long.

5.2.1. Beam Diagnostic Section

The proton beam diagnostic section is the inner section of the window insert assembly. It is roughly 9.25 inches in diameter, 83.4 inches long, and weighs about 945 pounds including the harp and cables. The diagnostic section interfaces to the proton beamline at its top flange using a metal-seal Helicoflex-type quick disconnect flange. It interfaces to the window section through a bolted face-seal connection, also using a metal Helicoflex seal. The harp consists of several planes of individual electrically-isolated tungsten-carbide wires, attached to ceramic holder plates, and streached across the beam path. The mechanical aperature through the ceramic holder plates of the harp is about 2 inches larger than the inside diameter of the steel insert. The harp is thus shielded both from above, by the body of the insert, and from below by a tungsten shield ring that slides over the harp assembly (Figure 5). Both the body of the insert and the tungsten shield ring are actively cooled to prevent damage to the ceramic holder if the beam should be accidentally mis-steered during initial tuning.

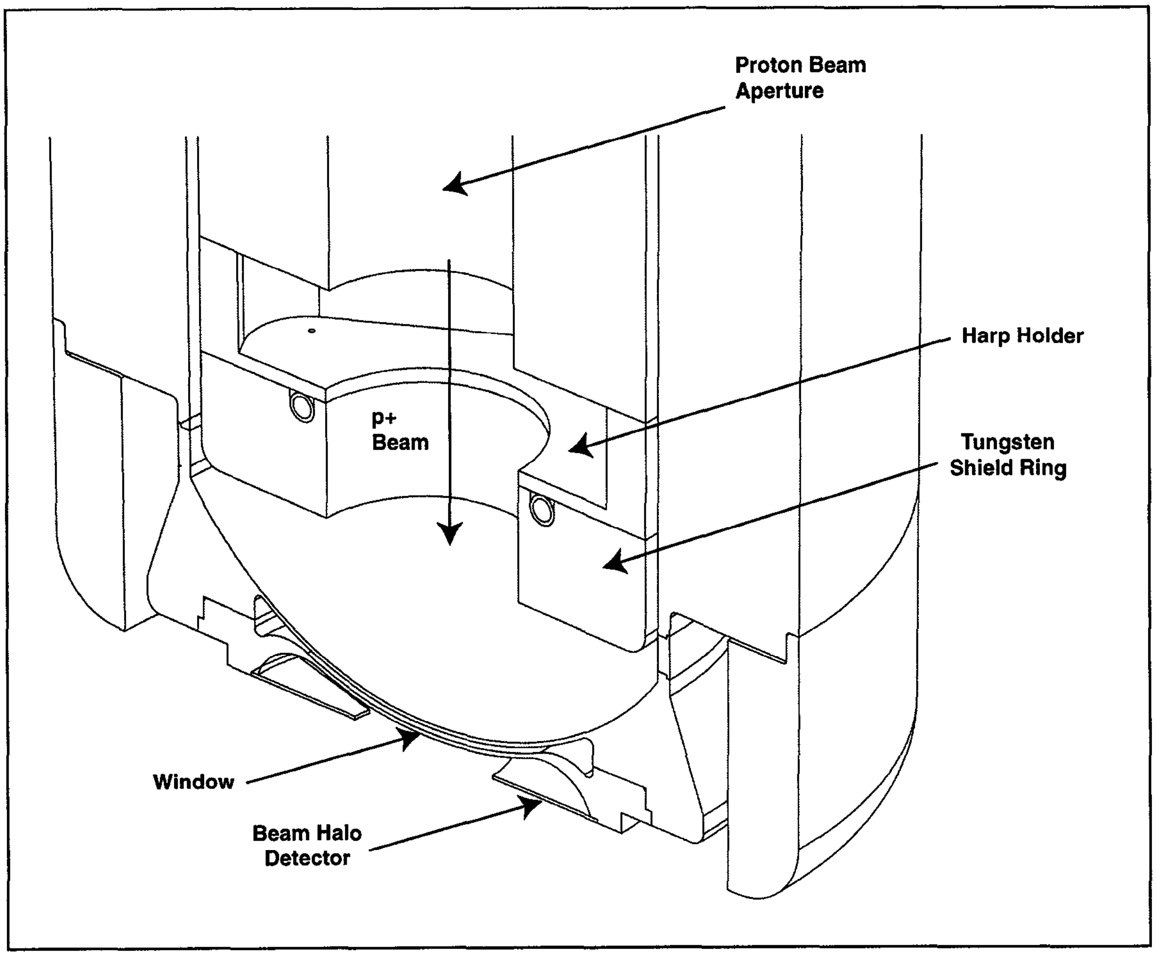


Figure 5. **Proton Beam Diagnostic Section Cutaway Diagram**

5.2.2. Proton Beam Window Section

The proton beam window section of the window insert (Figure 4) is roughly 17.5 inches in diameter, 66 inches long, and weighs about 2465 pounds. The window is a double-walled hemi-spherical Inconel 718 shell with water cooling between the two layers. The Inconel shells are each 2 mm thick with a 2 mm water-cooling space between. The design basis is a similar window used for vacuum isolation of the A6-beamstop at the LANSCE accelerator facility. Figure 5 is a close-up view of the lower section of the window insert showing the window, harp holder and other items as noted. We believe that the service interval for the window at 200 μA beam current is roughly 4 to 5 years based on performance of the LANSCE window at the same energy but at roughly 5 times higher current. The LANSCE accelerator window is normally replaced yearly. Thermocouples are mounted on the crypt side of the window to provide operational thermal data including a general indication of beam-spot position. The required coolant flow and calculated operational average thermal/stress conditions in the Inconel shell are listed in Table 2 below.

Table 2. Window Operational Parameters (200 μA Beam)

Maximum Beam-Center Heating Rate (based on 200 μA Beam, 1.5 cm σ)	350 W/cm^3
Coolant Type	Water (20 deg. C)
Minimum Allowed Coolant Pressure	60 psia
Maximum Allowed Coolant Pressure	200 psia
Minimum Allowed Coolant Flow Rate	10 gpm
Calculated Steady Operational Temperature, High Vacuum Side	105 C
Calculated Steady Operational Temperature, Water Side	58 C
Maximum Steady Operational Stress Level in Beam Area (von Mises Stress)	30 ksi (208 MPa)

5.3. Target Section Assembly

The target section is composed of many elements and subassemblies that are bolted together in a long, cylindrical unit (Figure 6). At the top of the assembly is a large steel cylinder that acts as neutron shielding for the target system. Attached to the bottom of the steel are the various components of the target, moderator and reflector system.

The target section is assembled from the bottom up, beginning with the lower target and lower moderators. The lower subassembly is then joined to the steel portion from below. To perform this operation, the upper steel portion is suspended vertically from a special assembly scaffold/work area, and the lower subassembly is raised to join from below. The cooling lines from the lower components slide up through holes bored in the top flange of the steel body and are seal-welded at the top surface. When the welding is complete, the window section is lowered into the target section and the entire assembly is leak tested using a specially designed test vessel. The whole target insert assembly is then fully tested to operational pressure, with the lower region in the test vessel under vacuum, before it is transported to the target cell for installation.

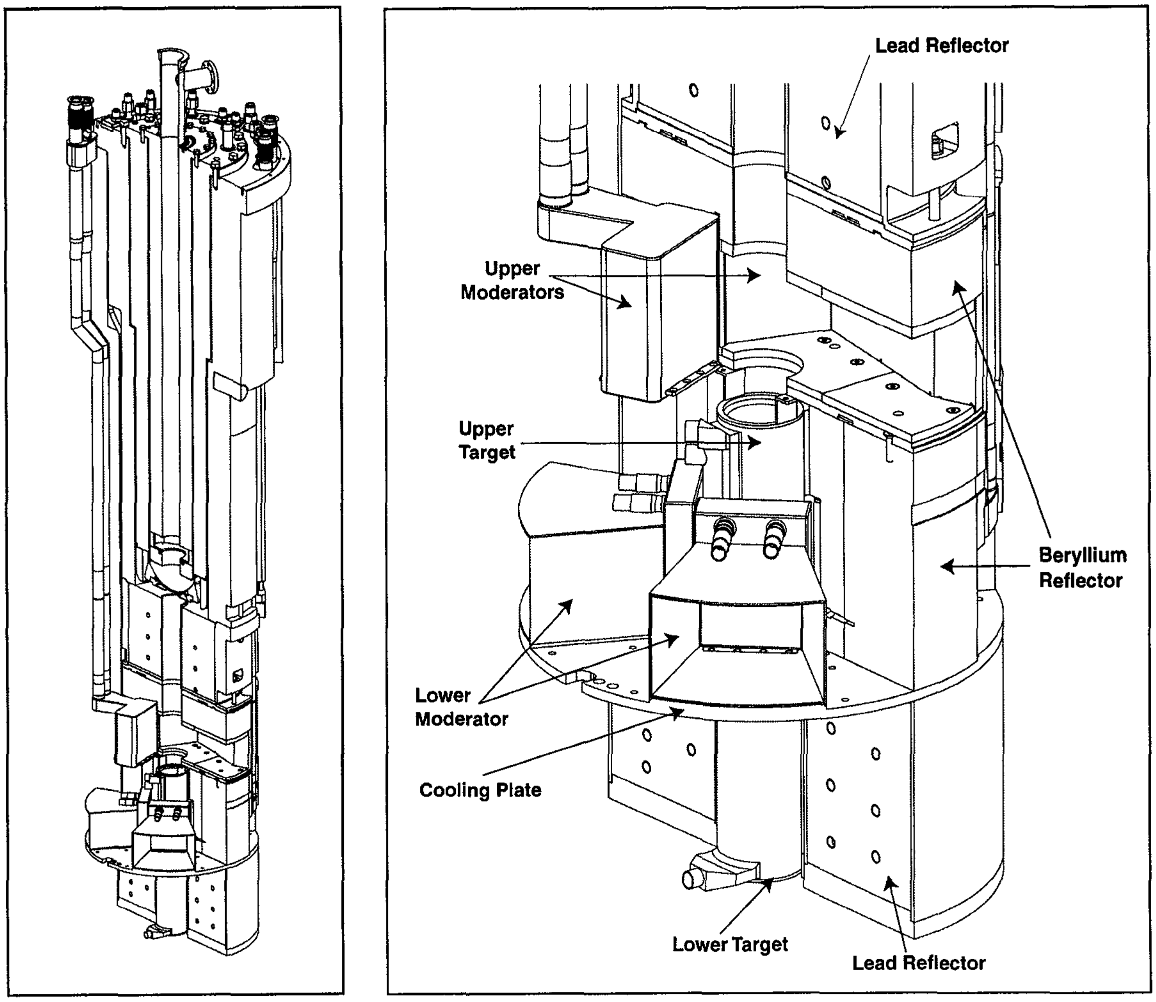


Figure 6. Target Section Cutaway Diagram

5.3.1. Tungsten Targets

The tungsten target consists of two separate sections with a flux trap region between. The top section is a plate-type design and consists of a cylindrical enclosure made of Inconel Alloy 718 containing 7 tungsten disks lying perpendicular to the proton beam. The disks vary in thickness from 8 to 19 mm, top to bottom. Light-water coolant flows between the disks, entering at the top between the container lid and disk 1, and exiting at the bottom of the assembly in a similar manner. Figure 7, shows a section diagram through the top target assembly. Plenna welded to the sides of the target vessel collect and redirect the water flow through each plate gap. The entrance plenum to the top gap has a special transition nozzle to allow a smooth flow transition from the round tube to the thin slot as the water enters the target container. The return pipe is a standard size stainless steel tube that welds directly to the side plenum.

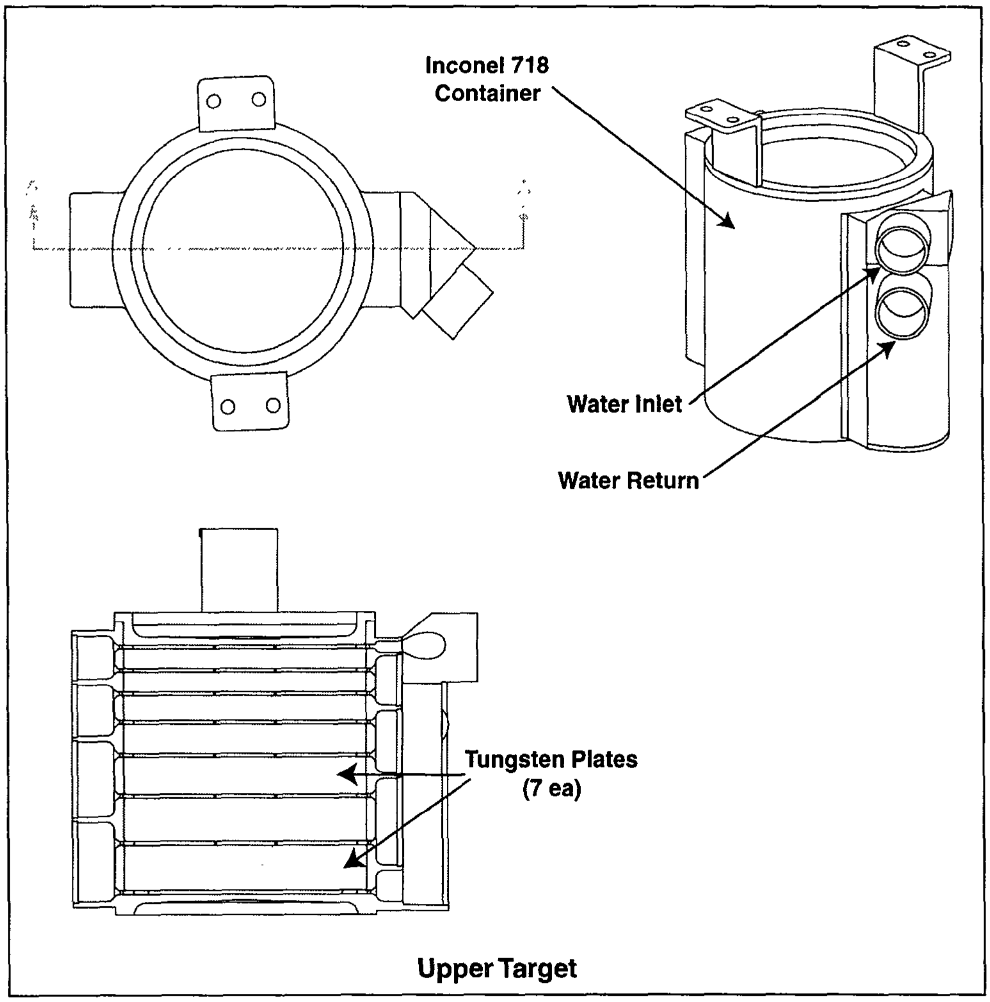


Figure 7. Top and Bottom Target Section Views

Table 3. Upper-Target General Operational Parameters

Target Configuration	Plate-type, light-water cooling
Thermal Load, Total Unit	64.2 kW
Coolant Type	H_2O
Inlet water pressure	1.38 Mpa (200.0 psi)
Total Coolant Mass Flow Rate	38 liter/min
Coolant Temperature Rise	24.3 C
Peak. Time-Averaged Power Density, Plate 1	596 W/cm^3
Peak. Time-Averaged Power Density, Plate 7	272 W/cm^3
Peak Tungsten-Surface Temperature (Plate 5)	134 C
Minimum Tungsten-Surface Sub-Cooling (Plate 6)	35 C

The lower target section (Figure 8) is a solid, bare, tungsten cylinder enclosed within an Inconel 718 cylindrical shell. The tungsten is edge-cooled with water that flows in an annular space between the tungsten and the cylindrical shell. This configuration is slightly more efficient in neutron production than the plate-style discussed because it has less water in the path of the proton beam. This arrangement is possible in the lower target because the peak volumetric heat loading in the bottom target is about 10 times lower than in the top target. The objective in using two different target styles is to more closely match maximum tungsten volume fraction with the heat load requirements at each location.

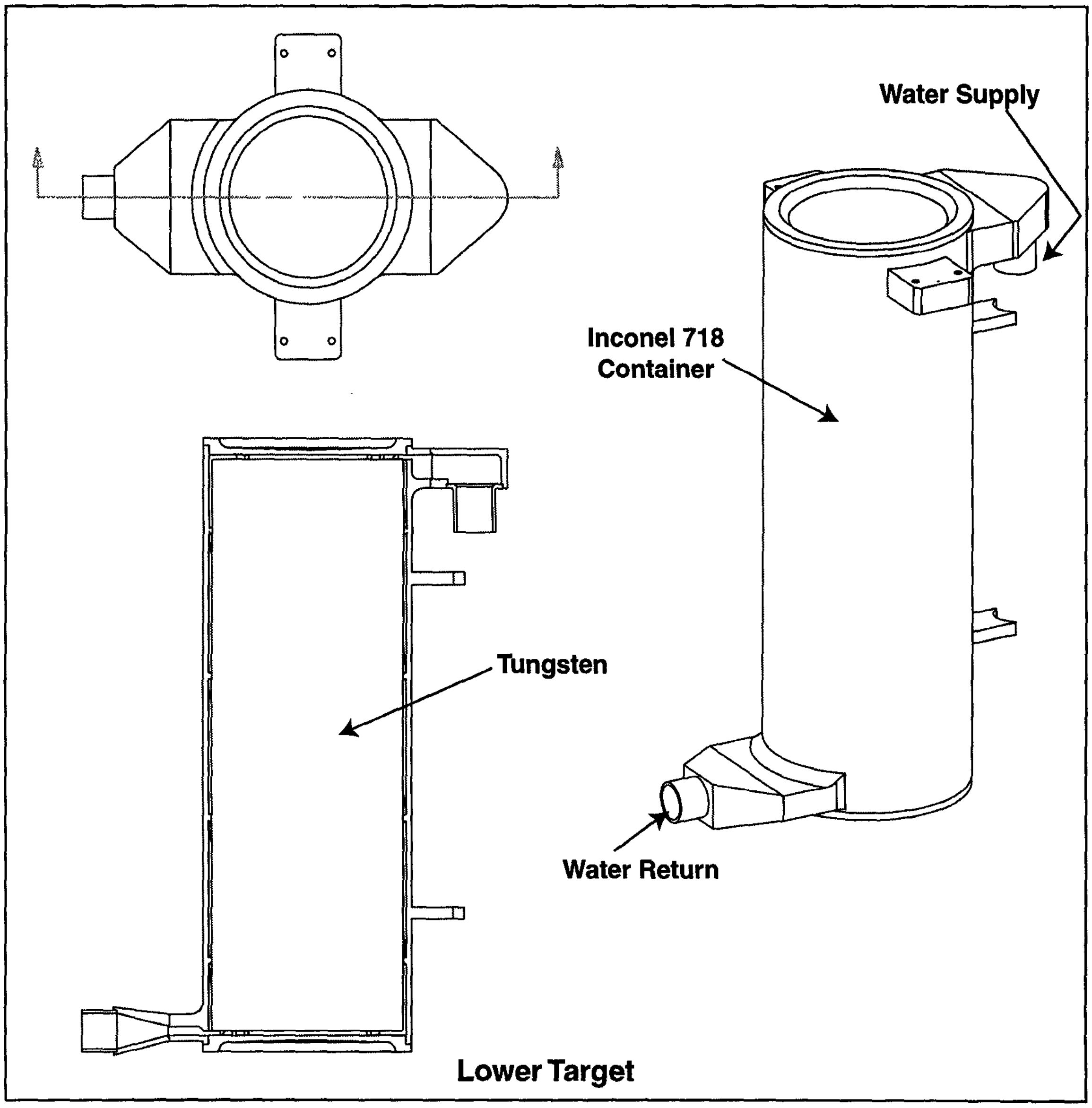


Figure 8. Lower Tungsten Target

Table 4. Lower Target General Operational Parameters

Target Configuration	Solid-type, light-water cooled
Tungsten Length	298.45 mm
Tungsten diameter	101.6 mm
Total Tungsten Heat Flux	25.9 kW
Peak Volumetric Heat Flux in the Tungsten	51.0 W/cm^3
Average Heat Flux in the Tungsten	10.8 W/cm^3
Water channel side (gap)	1.5 mm
Water channel top and bottom gap	2.5 mm
Pressure vessel wall thickness	3.0 mm
Inlet water pressure	1.38 Mpa (200.0 psi)
Design water flow rate	0.76 liter/sec (12 gpm)

5.3.2. Moderators

The suite of moderators is divided into a lower tier with four moderators and an upper tier with two moderators. The lower tier services 12 flight paths (1-11 and 16) and the upper tier, services 4 flight paths (12-15). There are three ambient-temperature water moderators in the lower tier and one in the upper tier. Each tier also has one cryogenic liquid-hydrogen moderator that operates at about 20 K. Characteristics of the 6 moderators are listed in Tables 5 and 6 below. Note that all of the lower tier moderators are viewed in transmission whereas the top tier moderators are viewed in back scattering. The upgrade target system has been designed so that no significant adjustments to the present instrument collamation or view-angle are required. The new moderators in the lower tier region are positioned as close as possible to the same locations as the previous moderators. In most cases, this is within 2 mm of the previous position.

Table 5. Moderator Specifications

Flight Path	Moderator Type	Flux-Trap Decoupler	Reflector Decoupler	Poison	Be Flight Path Liner	Lead Flight Path Liner
1,2,16	Water, High Resolution	0.002 inch Gd	0.032 inch Cd	0.002 inch Gd	0.032 inch Cd	0.032 inch Cd
3,4,5	Water, High Intensity	0.032 inch Cd	0.032 inch Cd	none	0.032 inch Cd	0.032 inch Cd
6,7,8	Water, High Intensity	0.032 inch Cd	0.032 inch Cd	none	0.032 inch Cd	0.032 inch Cd
9,10,11	Liquid Hydrogen	none	none	none	none	0.032 inch Cd
12,13	Liquid Hydrogen	none	none	none	none	0.032 inch Cd
14,15	Water, High Intensity	none	none	none	none	0.032 inch Cd

Table 6. Moderator dimensional information

Flight Path	Pre- moderator Thickness (mm)	Moderator Thickness (mm)	Operational Pressure (MPa)	Operational Temperature (K)	Temperature Uniformity Rqm't (+/- K)
1,2,16	21.2	16.1	0.41	293	1
3,4,5	N/A	25.0	0.41	293	1
6,7,8	N/A	25.0	0.41	293	1
9,10,11	N/A	50.0	1.38	20	1
12,13	N/A	40.0	1.38	20	1
14,15	N/A	50.0	0.41	293	1

Water Moderators

The water moderators consist of a one-piece machined body with electron beam welded top and bottom cover plates (see Figure 9).

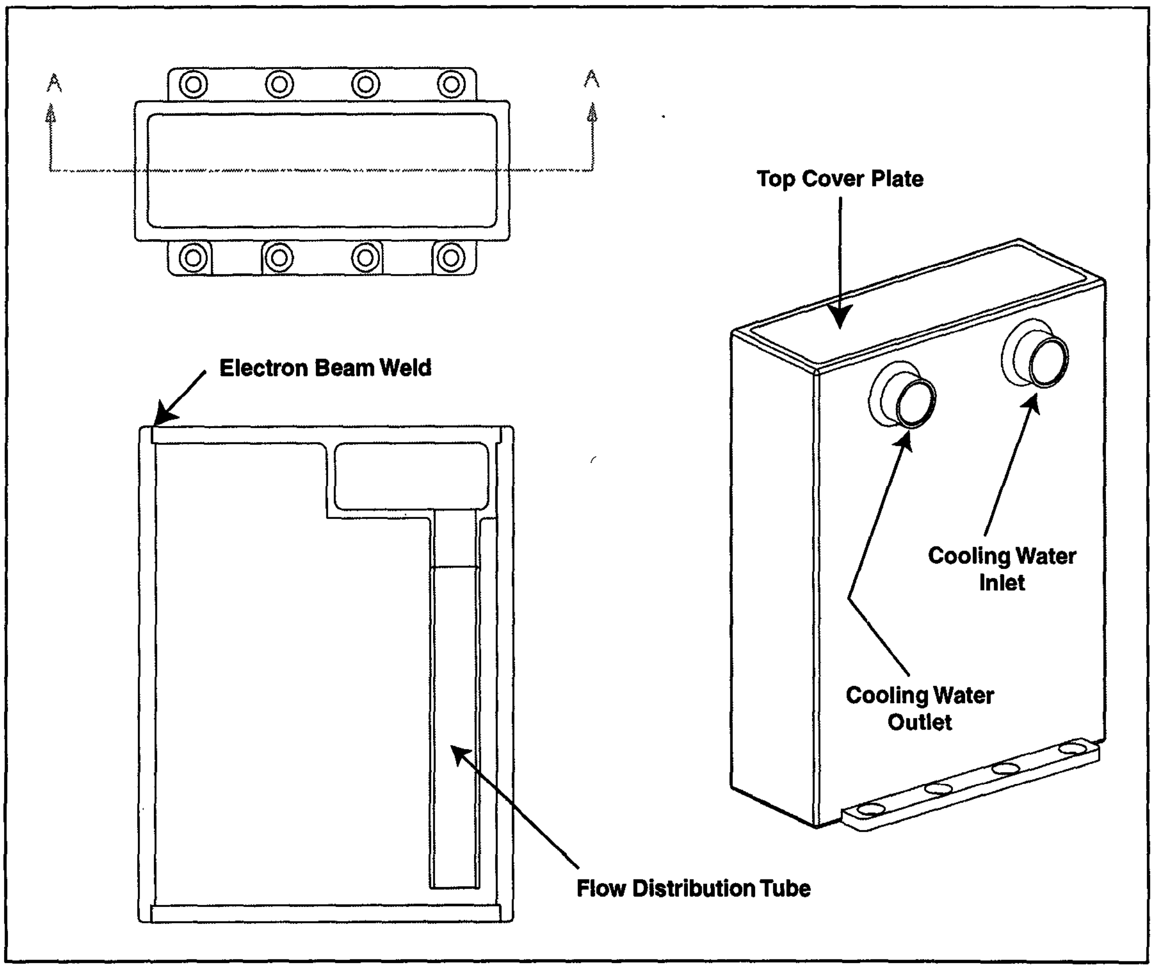


Figure 9. Water Moderator Design

Alloy 6061 aluminum was chosen for it's neutronic properties as well as corrosion resistance in water and it's strength. Electron beam welding the covers provides the best closure process to minimize the heat affected zone and overall distortion. The cooling lines are stainless steel 304 alloy and are joined to the aluminum vessels with a special Bi-Braze transition fitting that has been used successfully at LANSCE on the previous target systems. The fitting is TIG welded to the vessel and piping by hand at assembly. Welding procedures including heat-sinking instructions are provided by BI-Braze to prevent damage to the fitting during installation.

The liquid hydrogen moderators (Figure 10) consist of an internal pressure vessel and an external vacuum vessel. The pressure vessel operates at 20 K and the vacuum vessel at about 25 C. The gap between the pressure vessel and vacuum vessel provides the thermal insulation for the pressure vessel. The vacuum space is actively pumped and monitored for the hydrogen during operation. If hydrogen is detected in the space, the hydrogen safety system vents to prevent an explosive condition from existing in the moderator units or in the vacuum insulated transfer lines that supply liquid to the pressure vessel.

Heat transfer in this assembly is somewhat uncharacteristic of cryogenic systems; nuclear heating in the vessels and piping is significantly higher than either conduction or infrared radiation heating in the region of the moderator vessels near the target. As a result, the typical cryogenic superinsulation normally used in a 20 K unit is omitted in the vessel region, and used only in the upper section of the vacuum transfer line.

The moderators in both tiers are fastened to aluminum cooling plates that serve as an alignment and fixturing base as well as a primary heat sink for the vacuum jackets on the cryogenic moderators and a backup heat sink for the water modertors. The design allows for cooling of the containers without liquid inside, if required. The cooling plates also serve as heat sinks for the flight path liners in the decoupled lower tier as shown in Figure 11. The liners are 0.090 inch thick aluminum shells welded to the lower cooling plate and electroplated with cadmimum metal 0.04 inch thick. Cadmimum metal is also electroplated 0.040 inch thick on the surfaces of the water moderators in the lower tier to provide reflector and flux-trap decoupling. The high resolution moderator serving flight paths 1,2&16 has gadolinium 0.002 inch thick as a flux trap decoupler and also as an internal gadolinium poison divider plate. The gadolinium is plasma deposited on a 0.032 inch thick 1100 aluminum alloy plate that is electron beam welded to the wall of the vessel, this provides good mechanical positioning and good heat transfer to the cooled wall of the vessel.

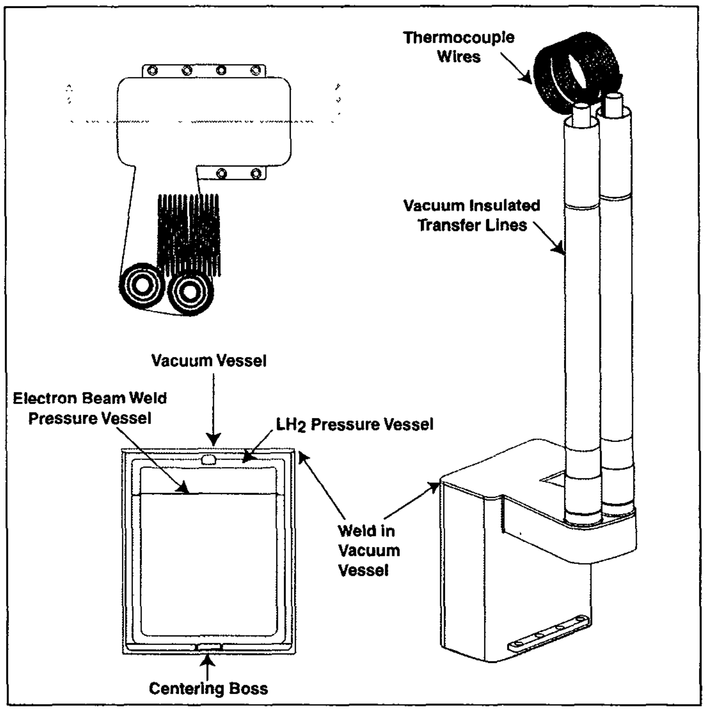


Figure 10. Cryogenic moderator section view

5.3.3. Beryllium Inner Reflector and Cooling Plates

The target and moderator vessels are surrounded by solid sections of beryllium metal that is assembled into a large cylindrical section. The beryllium reflector extends from near the target outside surface to a diameter of 60 cm. Cut-outs are provided for instrument view ports as well as cooling line routing from all the cooled components. The beryllium itself is cooled by mechanical attachment the cooling plates mentioned above. Heat energy is conducted through the bolted interface and into the aluminum plates. The amount of energy deposited in the beryllium reflector total is about 2.5 kw, requiring a coolant flow of about 2 to 3 gpm at 25 C in the cooling plates. The beryllium is assembled in three main sections with cooling plates to sandwich the assembly together (see Figure 11). The cooling plates serve to locate the beryllium and keep it cool as well as to position the moderators with respect to the reflector. The assembly was fabricated from beryllium shapes on hand at Los Alamos and the geometry was designed to utilize this material. The multiple sections of beryllium shown in the figure partially result from piecing together the available material as needed to produce the required geometry. An attempt was made to position most of the mechanical interfaces (bolted seams) in the unit parallel to the heat flow in the cooled assembly to allow most the effective heat removal by the cooling plates. Thermal analyses were done to insure that adequate cooling exists at 200 μA.

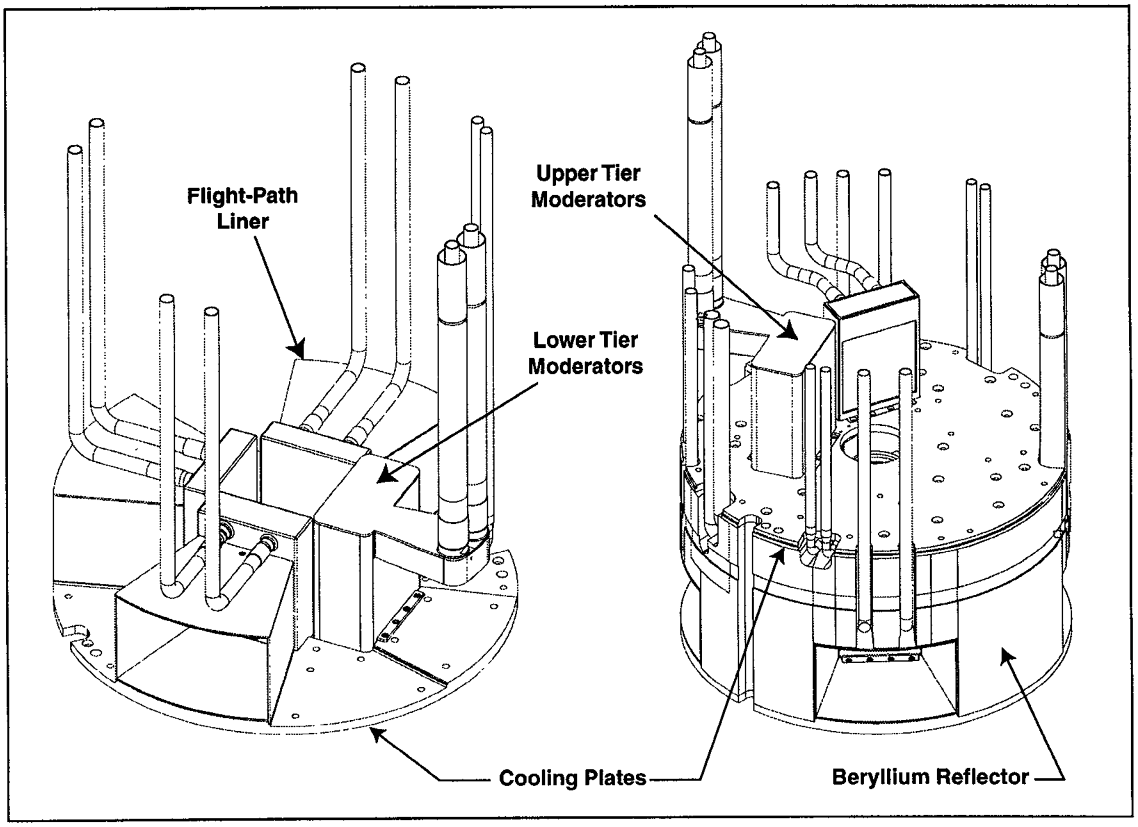


Figure 11. Aluminum Cooling Plate and beryllium inner reflector

6. Lead Outer Reflector

The outer reflector is composed of lead contained in a steel vessel that surrounds the beryllium section and extends out to a diameter of roughly 1.14 meters. The unit weighs about 17800 lb. and is supported from the main structural frame, see Figure 2. The lead is cast into a welded steel container that has an integral water cooling tube. The entire unit was produced as an assembly, complete with piping and lifting features.

It is sized to allow installation through the roof access port using the 30 ton overhead bridge crane. The total heat load is estimated at about 2 kW and it requires 2 to 3 gpm cooling water at 25 C.

7. Beamstop

The beamstop used for the upgraded target system is nearly identical to the present geometry except that a slight reduction in outer diameter will allow roof-port access. The Beamstop is composed of a water-cooled stainless steel top plate that is bolted a larger mild-steel lower section, see Figure 2. The cooled section will carry heat from the uncooled section across the bolted interface. The cooled plate is built from 304 stainless steel and the lower, larger, section is made from regular carbon steel to reduce cost of the assembly. The heat load in the combined volume is estimated at less than 1 kW, and it requires about 2 gpm of cooling water at 25 C.

8. Steel Shielding and Crypt Vacuum Vessel

The bulk shielding (see Figure 1) that resides in the crypt vessel surrounds the outer reflector and extends to the vacuum vessel wall, about 3 meters in diameter. The shielding is composed of flame-cut steel cylindrical rings and plates bolted together in some areas and stacked around the outside of the target-moderator-reflector assembly. The bulk shielding is not actively cooled and is not meant to require maintenance of any sort.

9. Present Status of the System

At the time this document was prepared, all of the crypt contents are installed except for the target insert, which is still in final assembly and testing. Final installation of the target insert is planned for early July 1998.