MECHANICAL ENGINEERING PROBLEMS IN THE TFTR NEUTRAL BEAM SYSTEM†

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Summary

A conceptual design of a prototype beam line for the TFTR Neutral Beam System has been developed. The basic components have been defined, cost estimates prepared, and the necessary development programs identified. Four major mechanical engineering problems, potential solutions and the required development programs are discussed.

Design of the TFTR Neutral Beam System will require the solution of several mechanical engineering problems related to components which either presently do not exist or are designed to requirements which are less severe in neutral beam systems built to date. These problems result from the combination of increased beam power, multiple sources on each beam line, remote handling requirements and stringent design requirements on the allowable local pressures and leakage of cold gas into the torus.

These problems require the development of beam targets capable of handling up to 10 MW of beam power from a single ion source with peak power densities approaching 30 kW/cm^2. Pumping speeds approaching 3 x 10^6 ℓ/sec in each beam line coupled with severe space limitations will require the use of cryosorption or cryocondensing pumping. Minimizing cold gas leakage into the torus makes it necessary to use conductance limiting valves with opening and closing times of ~ 50 milliseconds. The radioactive environment requires that a hard seal or welded vacuum system capable of remote assembly and disassembly be developed.

Introduction

The experimental tokamak fusion test reactor which is being planned for construction at Princeton Plasma Physics Laboratory[1] will include a neutral beam injection system. Demonstration of a "reactor grade" plasma in the TFTR depends upon the successful operation of the neutral beam injection system to produce and inject energetic neutral particles into the plasma.

As a part of ERDA's DCTR development and technology effort, ORNL has been engaged in plasma heating development since 1970 when a program for development of neutral injection as a viable supplemental heating technique was initiated.[2] This program developed multiaperture closely coupled modules in 1971 which were incorporated into the ORMAK injection system in 1973 and in two additional higher power ORMAK systems in 1974.

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This successful development has produced technology which will serve as a basis for injection systems for future tokamaks. Use of these systems on the TFTR required that a conceptual design of the neutral beam injection system be completed as a part of the conceptual design of the TFTR. In an attempt to utilize the existing neutral beam injection expertise DCTR requested that ORNL and other beam developers participate in the conceptual design of neutral beam systems for the TFTR. The work discussed in this paper is the result of the cooperative effort of personnel from the ORNL Plasma Heating Department, the UCC-ND Engineering Division, and the Westinghouse - PPPL TFTR Design Team.

TFTR Beam Requirements

The TFTR neutral beam injection system must provide four beam lines capable of injecting 120-keV deuterium neutral particles in sufficient quantity to deliver in excess of 20 MW to the plasma. Higher energy beams (150-keV) are desirable in TFTR if they can be attained for small increases in costs and have been considered in the design. Location of the beam must provide a beam tangent to a plasma radius of either 220 or 270 cm for different operations of the TFTR device. Operating data for both the 120-keV and a 150-keV beam are given in Table 1.

Table 1. Operating Data

	120-keV	150-keV
Ion Current Per Source (Amperes)	55	44.0
D^+ Per Source	44	35.2
D_2^+ Per Source	11	8.8
D° at Rated Energy (As Amperes)	17.6	10.1
D° at Half Energy	14.5	10.3
Total D° to Torus (Calorimeter)	25.3	20.44
D^+ to Dump at Rated Energy	26.4	25.1
D^+ to Dump at Half Energy	7.5	7.3
Gas Loads Per Source (torr-liters)		
Un-ionized Gas	10.6	8.8
Gas to Neutralizer Cell	20.0	20.0
Gas to Beam Dump	6.5	6.5
Gas to Torus (Calorimeter)	6.2	4.1
Total Gas Per Source	43.3	39.4

Pressure in the Pumping Regions (torr)		
Source Region	2.5×10^{-4}	2.3×10^{-4}
Beam Dump Region	2.5×10^{-5}	2.5×10^{-5}
Calorimeter Region		
Beam on Calorimeter	3.1×10^{-5}	2.1×10^{-5}
Beam into Torus	5×10^{-6}	5×10^{-6}

Design Approach

ORNL's design approach for the TFTR neutral beam injection system was to design a universal beam system which could accommodate ion sources of either 120- or 150-keV and could be aimed at either the 220 or 270 cm radius. This required that the system be designed to accommodate the more stringent of the two design conditions.

A multidisciplinary design team composed of plasma physicists, neutron physicists, materials, chemical, electrical, electronic, and mechanical engineers was formed to provide inputs and design experience relative to the various system elements.

Design Description

The TFTR neutral beam injection system conceived for the initial TFTR concept did not fully address all aspects of the required beam system due to primary efforts being concentrated on the tokamak. Further effort in developing a conceptual design for a neutral beam injection system resulted in the system shown in Figs. 1 and 2.

Note that the physical size of the neutral beam line is not small compared to the TFTR tokamak. Four beam lines almost completely occupy one half of the operating space around the TFTR as indicated in Fig. 1.

The physical size of a neutral beam line relative to the plasma size is clearly illustrated in Fig. 2. A single beam line is approximately 6 meters tall by 5 meters long and 2 meters wide with a mass of approximately 48 Mg. The estimated weight of various components is given in Table 2. A beam line is composed of several components which must function collectively to produce deuterium ions, accelerate them and then neutralize them to produce the energetic neutral particles, and to handle the resulting large gas loads.

Table 2. Component Mass

	(Mg)
Calorimeter	1
Beam Dump	1
Vacuum Pump and Valve	1
Sources and Valves	2
Magnet	8
Gas Cells	1
Vacuum Enclosure	14
Cryopanels	6
Radiation Shielding	14

The arrangement of the beam line is such that deuterium ions are produced and accelerated in three ion sources located at the extreme end of the beam line. The ions then pass through a gas neutralizing cell where a fraction of them are neutralized. The unneutralized fraction is deflected away by a bending magnet which provides a transverse magnetic field. These charged particles are deposited on a water-cooled beam dump. A retractable calorimeter immediately downstream from the bending magnet provides a beam stop for tuning of ion sources and a beam energy measurement system. A conductance limiting fast valve provides a means of separating the beam system from the tokamak liner except during the injection pulse. An absolute vacuum valve provides the necessary seal to allow the beam system to be disconnected for maintenance. Cryosorption panels located on almost all available surface within the beam system vacuum enclosure provides the necessary high speed pumping to allow efficient beam operation.

Mechanical Engineering Problems

A host of mechanical engineering problems are encountered in the design of a neutral beam injection system. The final solution of some of these problems must await the results of development programs and testing of a TFTR neutral beam injection system prototype. Table 3 lists four of the major mechanical engineering problems and indicates a measure of their difficulty, a proposed solution and what is required to confirm that the solution is adequate.

Cryopumping

The high pumping speeds required to handle the large gas loads while maintaining the required low operating pressure (1×10^{-4} torr) dictates the use of either a cryopump or getter pumping system. Although early results from cryocondensing pumping experiments[3,4]

Table 3. Mechanical Engineering Problems

Problem	Technical Requirements	Proposed Solution	Confirmation
1. High Speed Vacuum Pumping System	Pumping Speeds Approaching 3×10^6 ℓ/s	Use of either cryosorption or cryocondensing pumping.	Awaits results of A. Cryopanel development B. Beam compatibility test C. Radiation shielding and heat generation determination
2. Beam Targets (Calorimeter and Beam Dumps)	Must be capable of dissipating beam particle flux with peak power densities approaching 30 kw/cm^2.	Use of swirl tube targets to avoid thermal stress and melting problems.	Requires development program to A. Establish feasibility B. Determine materials compatibility C. Quantify coolant requirements
3. Fast Valve	Must be capable of opening and closing in $\sim$ 50 milliseconds.	Use of traveling aperture to avoid inertial problems.	Requires detail design and confirmation at prototype test.
4. Remote Maintenance	Ability to remotely maintain the TFTR Neutral Beam Injection System.	Use of modular design with vulnerable components remotely replaced with beam line in situ or removal of entire beam line to maintenance area.	Design for remote maintenance with development of remote hard seal or welded flanges with confirmation at prototype test.

are promising, some question remains relative to the effects of neutron heating of the cryopanels. Results of the neutron shielding calculations[5] for the TFTR neutral beam system indicate a potential heat generation rate of 0.13 watts/cc in the cryopanel which could result in a local temperature rise in an aluminum panel of ∿4K during a 500 millisecond pulse assuming an initial temperature of [illegible] K. The corresponding temperature rise for a 4 to 5K initial panel temperature are significantly worse due to the reduced heat capacity. The major concern lies with the impact of localized heating on the ability of cryocondensing and cryosorption panels to retain pumped gases. Cryocondensing panels must operate at the lower temperatures and are therefore more sensitive to possible heat pulses resulting in release of condensed gases. Although this may not rule out the use of cryocondensing panels, it does favor a higher operating temperature.

The compatibility of cryosorption panels with neutral beam conditions has not been established. Concern for sieving under the high gas pressures and deposition of energetic particles on the panel remain unresolved issues and will require development efforts. Figure 3 shows a proposed cryosorption panel design.

Beam Targets

Targets for handling particle fluxes with peak power densities approaching 30 kw/cm^2 have not been successfully developed. Inertial targets[6] handling fluxes with peak power densities of 5-10 kw/cm^2 have repeatedly given problems in the ORMAK injection systems. Swirl tube targets[6] appear to have the potential for handling peak power densities of up to 5 kw/cm^2 with high repetition rate. Effective reduction of the peak power densities from 30 kw/cm^2 to 5 kw/cm^2 can be accomplished by inclining the target as indicated in Fig. 4. This has the potential to reduce the magnitude of the problem to a tolerable level.

Development work will be required to produce reliable beam targets which do not require excessive cooling water flows.

Fast Valve

Gas handling requirements are such that separation of the neutral beam system from the TFTR torus by a conductance limiting valve is necessary. The valve is required to open and close in 50 milliseconds in order to limit the total inleakage of cold gas into the torus to 1 torr/liter during a single pulse of four beam lines. This results in an inertia problem in valves designed to open and close from and to a stationary position.

Use of a traveling aperture shutter type v·lve shown in Fig. 5 provides the ability to use pr.og ammed acceleration of the thin membrance while achieving the desired opening and closing times. In effect, the valve is in motion throughout the opening and closing cycle and is open for the desired 500 milliseconds pulse duration while the apertures in the two sheets are aligned.

Remote Maintenance

Since the TFTR will be a D-T burning device, all systems in the direct communication with the torus will be subject to neutron activation. After a relatively few plasma shots, the radioactivity will require remote maintenance techniques to be applied.

The approach employed in the TFTR neutral beam system is to utilize modular components which can be replaced in situ or in the maintenance cell. With the neutral beam system attached to the TFTR, a source filament or a complete source will be removable without destroying the vacuum conditions.

A complete beam line will be remotely removable to the maintenance cell where other modules such as the fast valve, calorimeter, beam dump, bending magnet, cryopanel assembly and neutralizing cell assembly can be removed using remote techniques.

The most difficult remote operation required is expected to be the disassembly and reassembly of vacuum hard seal or welded joints. In either case, a development program appears necessary to assure success. Figure 6 shows one possible technique for utilizing a conventional impact wrench to makeup a remote hard seal joint.

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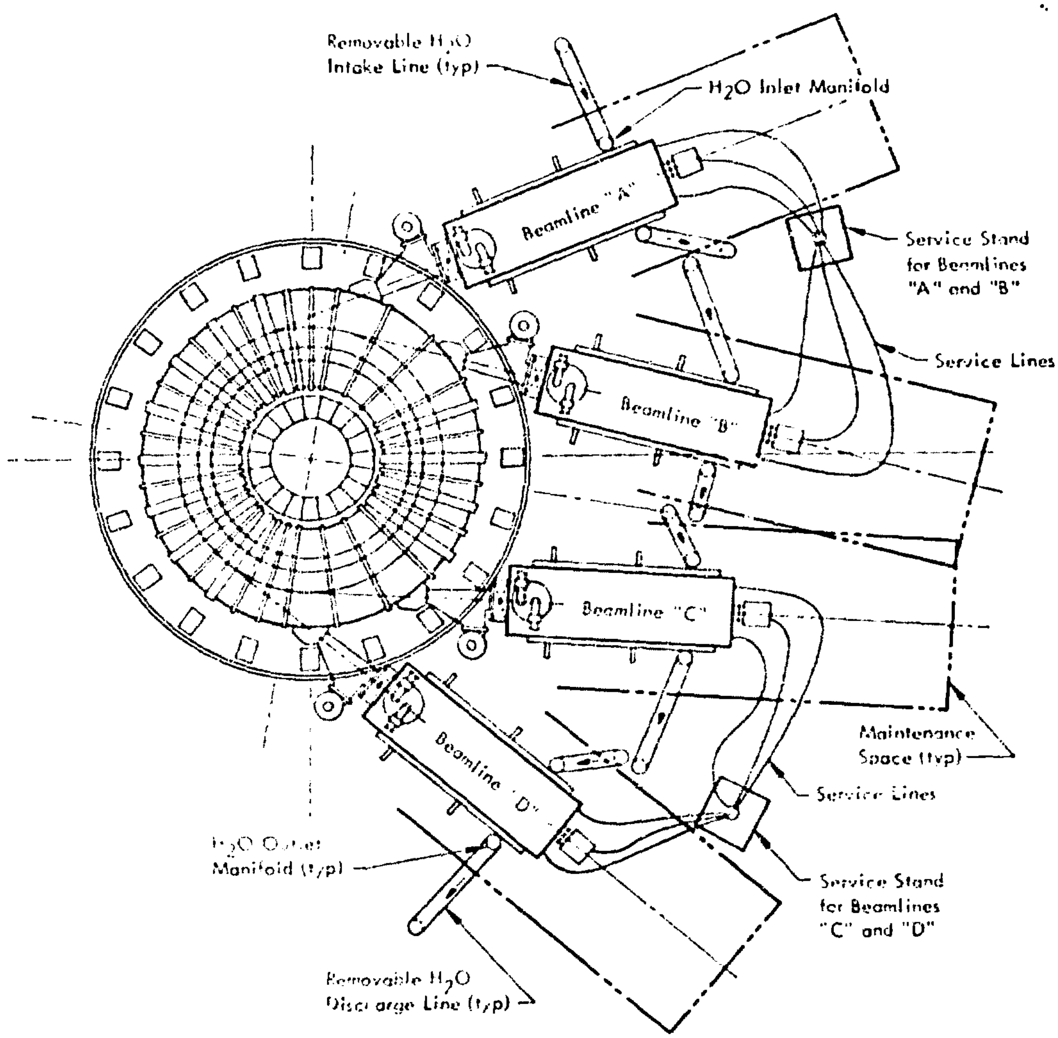

FIG. 2.1 PLAN OF FOUR BEAMLINES

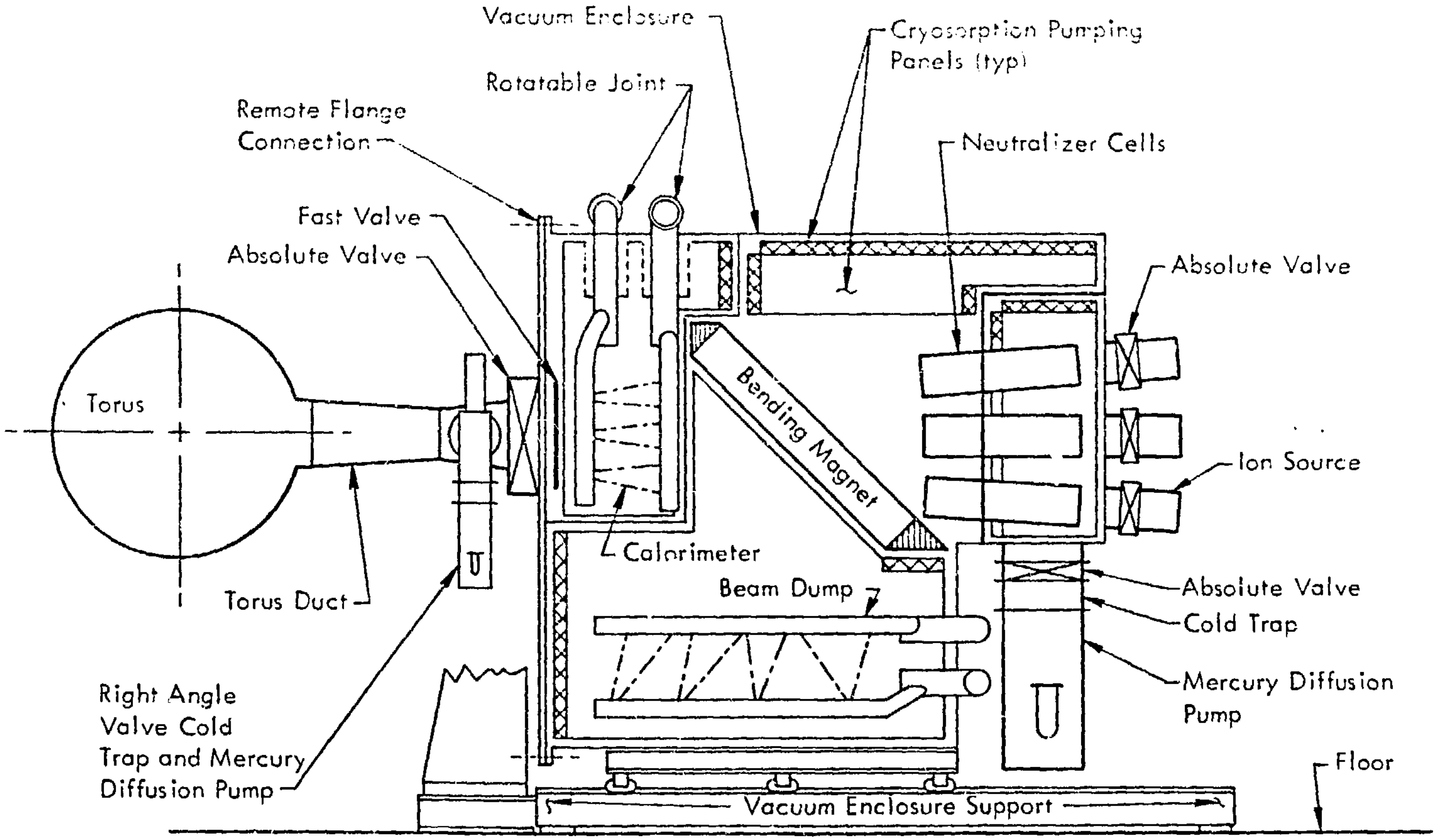

FIG. 2.2 ELEVATION OF TFTR BEAMLINE

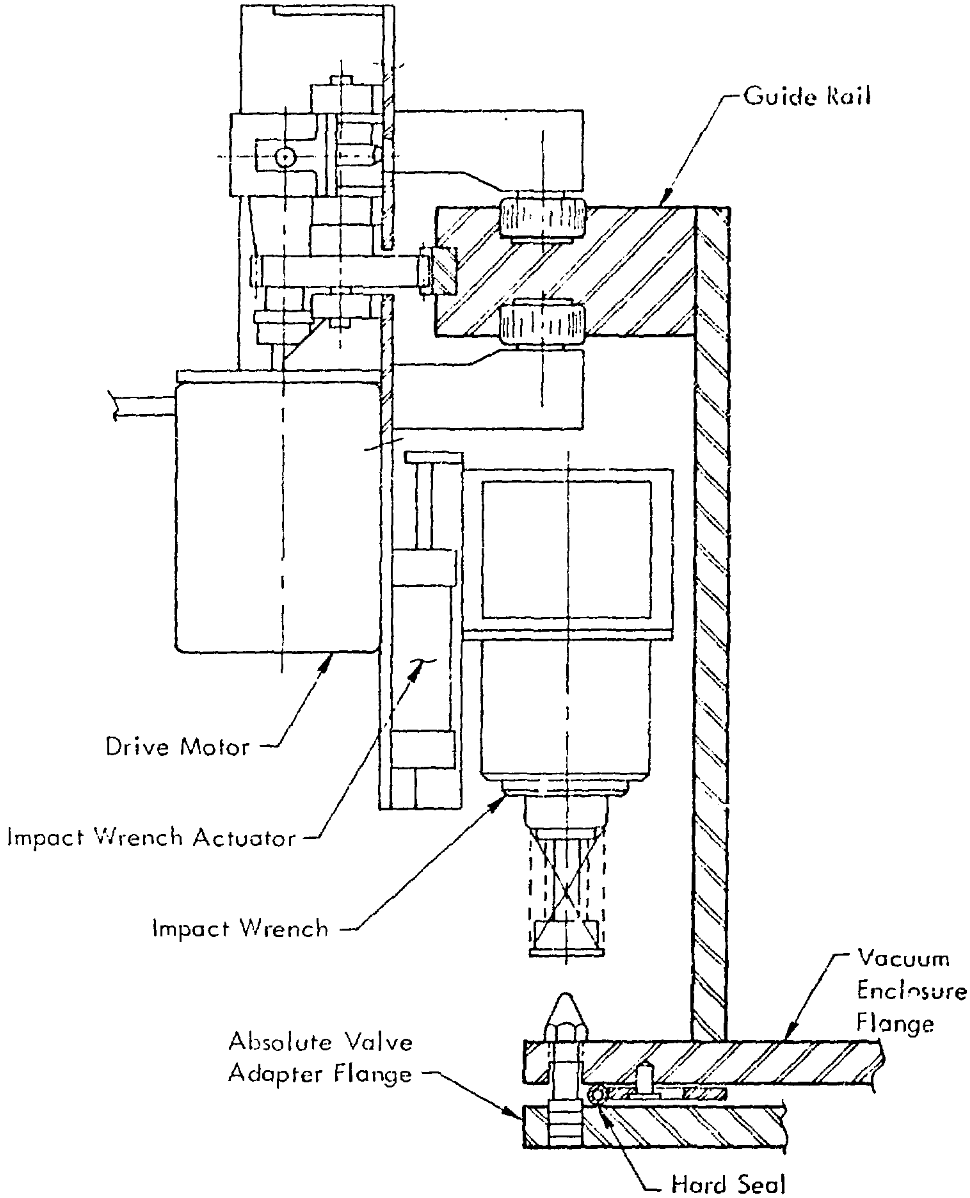

FIG. 2.9 REMOTE FLANGE AND TOOL

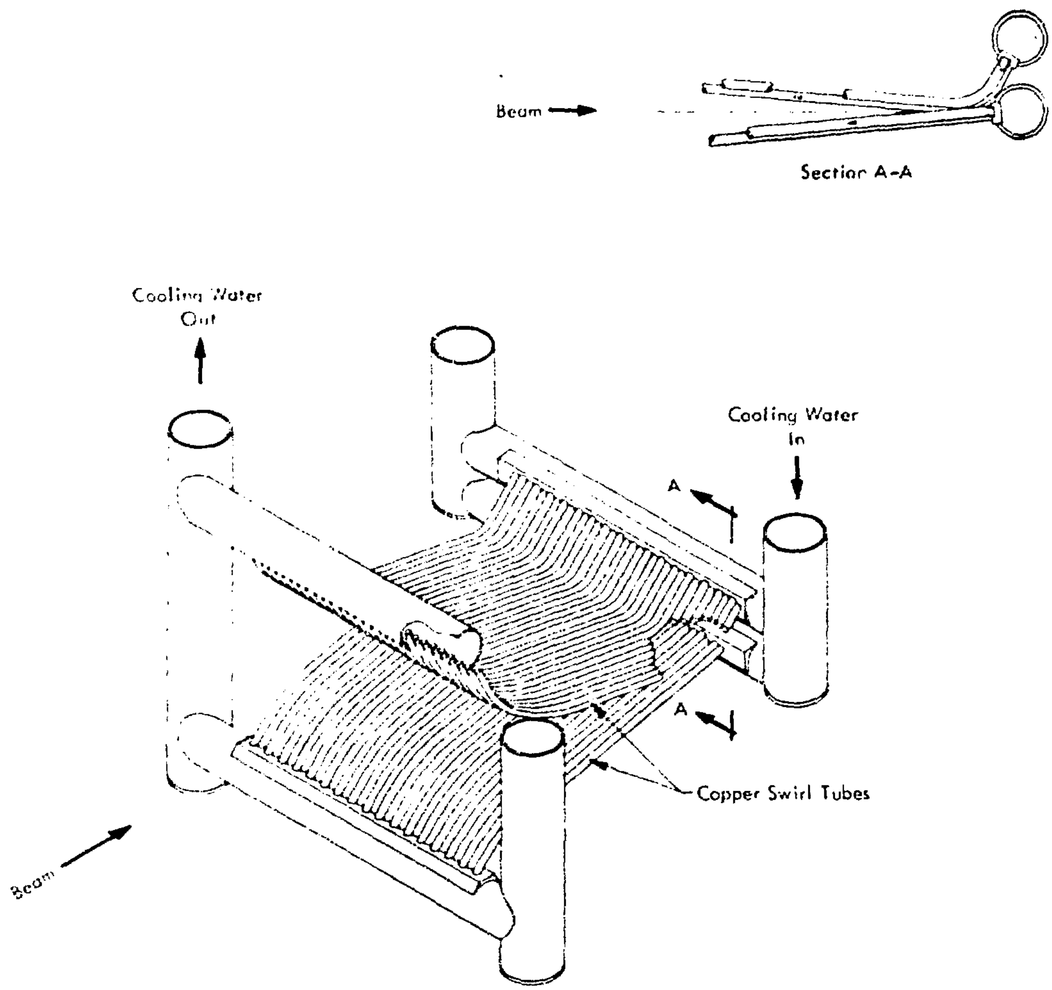

FIG. 2.10 TYPICAL TARGET SECTION OF CALORIMETER ASSEMBLY

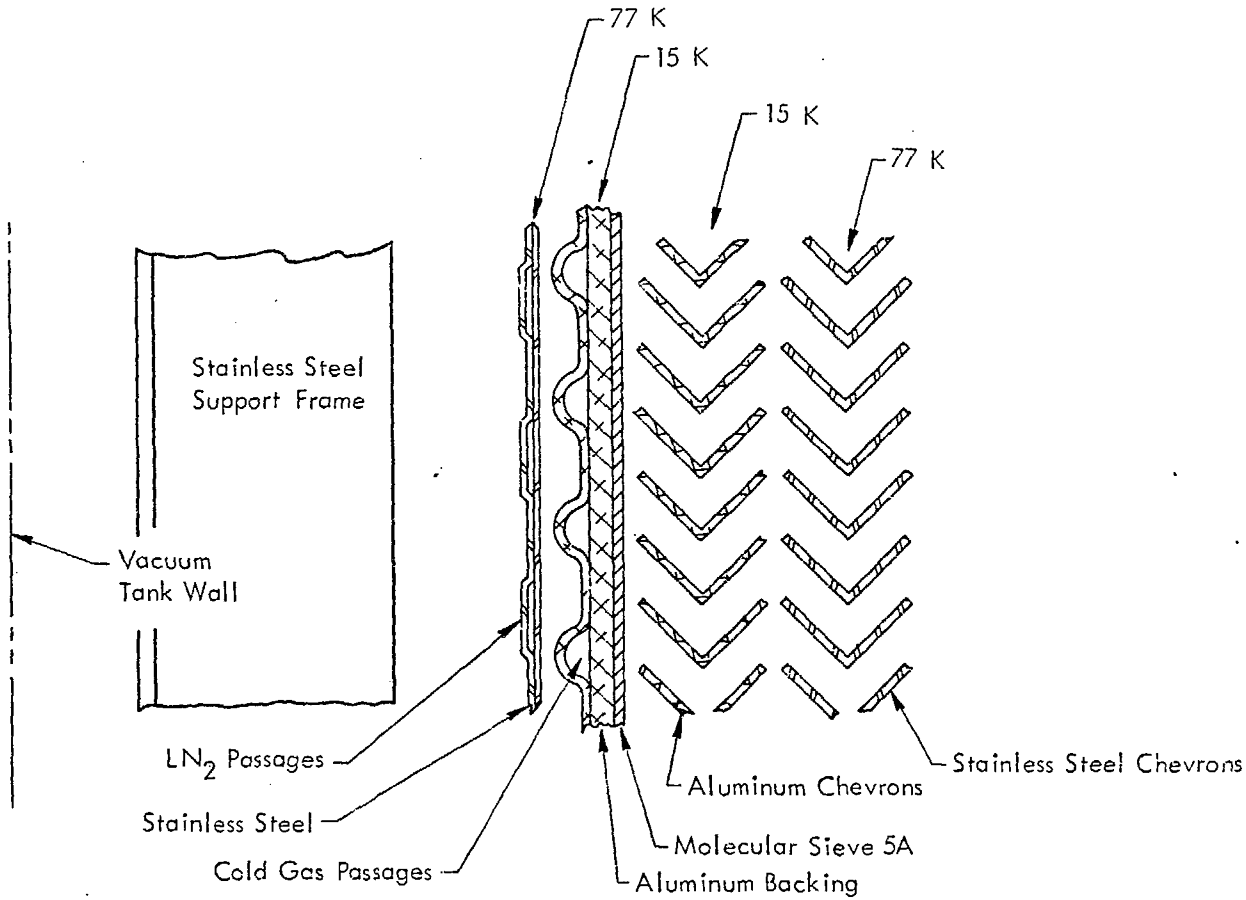

FIG. 2.8 TYPICAL SECTION THRU CRYOSORPTION PANELS