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THE MFTF VACUUM VESSEL AND CRYOPUMPING SYSTEM*

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Summary

The Mirror Fusion Test Facility (MFTF) vacuum vessel and cryopumping system have attracted considerable interest within the fusion research community. Their extreme size, coupled with severe performance requirements and unique design features, justifies this interest. The planned expansion of the system to a tandem mirror configuration with thermal barriers further increases the engineering challenges of this complex facility.

Introduction

Originally, the MFTF was planned to be an advanced experimental mirror fusion device serving as a physics and engineering bridge between present experiments and an experimental reactor. This single-cell mirror facility was proposed by LLNL in March 1976 to explore scaling laws and to advance the technology of mirror fusion devices. The major technology objectives to be demonstrated include:

- Construction and operation of a large Nb-Ti superconducting magnet system.
- Construction and operation of reliable, long-pulsed, high-current, high-voltage neutral beams.
- Maintenance of high-vacuum conditions in the presence of equilibrium plasma-wall interactions.
- Handling without deleterious effects on the plasma or materials of construction, the intense particle and plasma energy deposition on surfaces in the vacuum vessel.

These objectives place considerable demands on both the vacuum vessel and cryopumping system.

Construction of the MFTF vessel, cryopanels, cryogenic supply, and external vacuum system was initiated in September 1978. Construction is being conducted by the CVI Corporation and Pittsburgh Des Moines Steel Company (PDM) under contract to LLNL. An initial set of Technology Demonstration Tests of the facility are planned for September 1981.

The MFTF Vacuum Vessel

The major design-determining requirements on the MFTF vacuum vessel were that it:

- Accommodate the inherently complex geometric demands of mirror devices
- Provide structural support for the massive superconducting magnet
- Provide support and precise mounting locations for neutral beam injectors and plasma streaming guns
- Provide access to the plasma for extensive diagnostics equipment
- Serve as the vacuum boundary, with low leak and outgassing rates
- Accommodate seismic, thermal and magnet-energization stresses

The vessel is superficially a horizontal cylinder, 10.5 meters in diameter by 18 meters long. It is constructed entirely of 304 stainless steel. Its weight is approximately 750,000 lbs. A somewhat dated model of the vessel is shown in Figure 1.

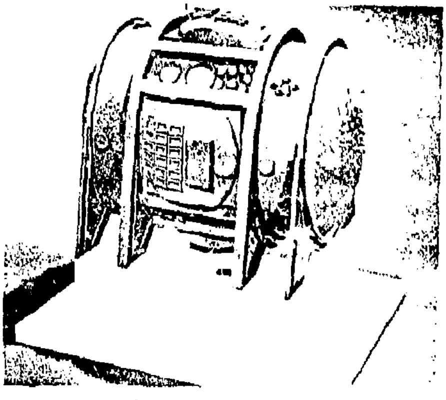

Figure 1 - Model of Vessel

The dominant structural elements are the longitudinal braces and the circumferential ring stiffeners. These attach to the vessel

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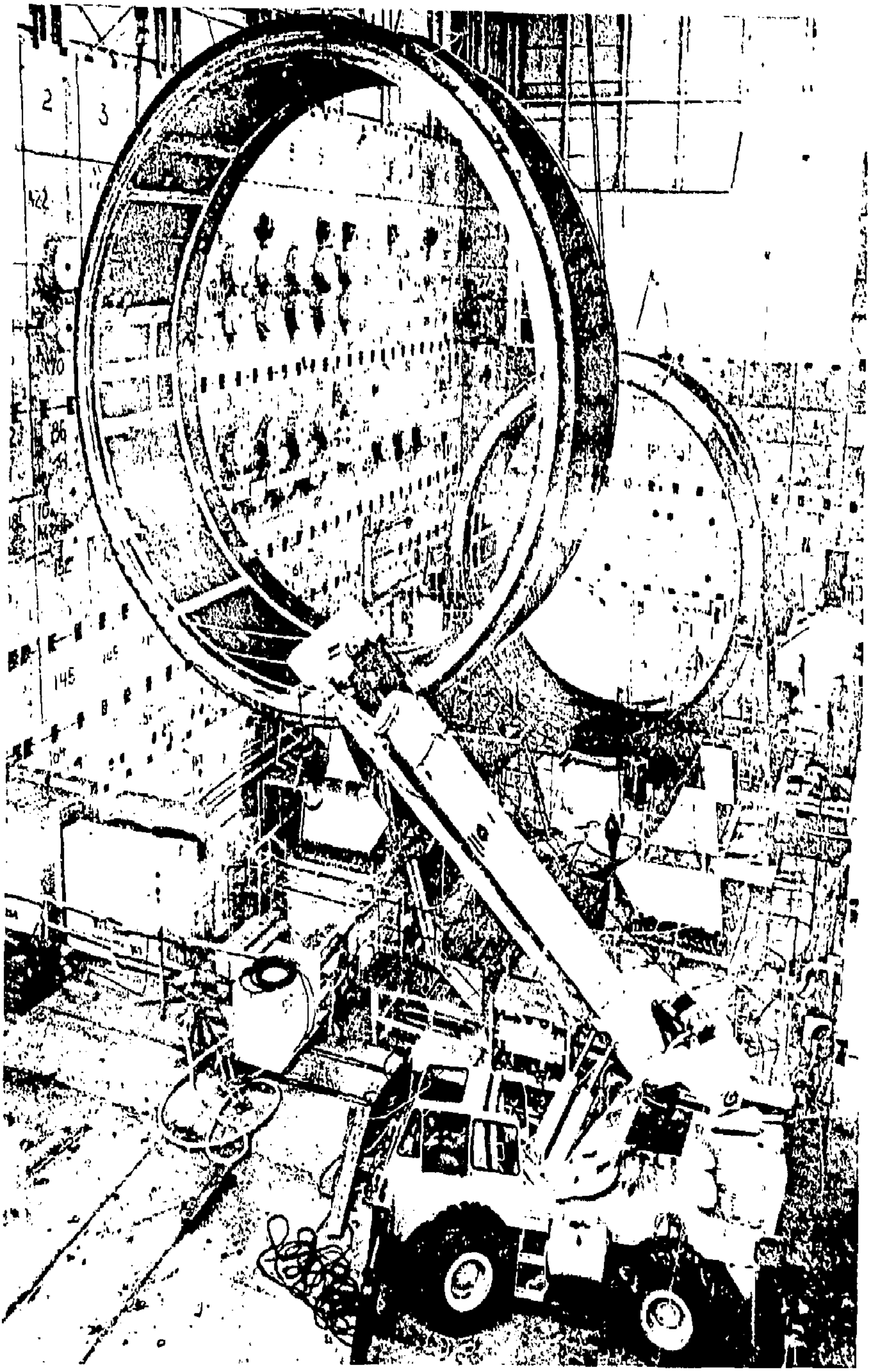

Figure 2 - Installation of Cylindrical Shell

footings, providing the primary load paths to the foundations.

The end cylindrical shells of the vessel, each about 4 meters in length, are made of plate varying in thickness up to 1-1/4". These sections, field assembled at LLNL with ring stiffeners attached, weigh nearly 60 tons each (see Fig. 2). An access door is installed in each section.

If Yin-Yang magnets were simple coil bundles, the geometric constraints would not be nearly so severe. Because of the large magnetic forces, extensive structure in the magnet is required for restraint.[1] Consequently, access to the plasma region for neutral beams, plasma diagnostics and other equipment is restricted.

Four neutral beam domes, each with 16 ports for injector mounting, are installed on the vessel. These ports are facets on spherically curved surfaces, formed from 2" thick plate and internally stiffened to prevent unacceptable deflections and consequent mis-aiming. Their location is controlled to within 1/8" of true. The neutral beam domes also include rectangular doors, 4 ft by 7 ft, for access to the neutral beam dumps.

Between the neutral beam domes, 80" diameter ports provide the major diagnostics access to the plasma. These are installed in 2" thick plate which has additional stiffening to prevent warpage of the seal surfaces.

The end closures are spherically curved shells (9 meter radius), with external stiffeners (see Fig. 3). They are O-ring sealed to the vessel using a PDM-patented design. Penetrations (50 each end) normal to the spherical surface are to be installed for plasma streaming guns and diagnostics equipment.

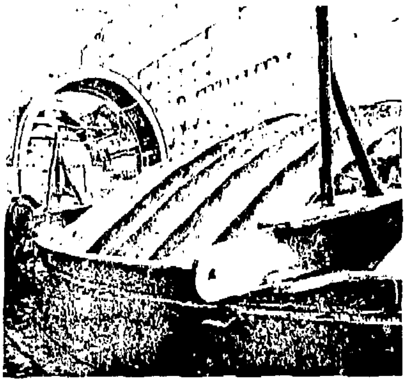

Figure 3 - End Closure with Vessel in Background

Numerous other ports, from 2" diameter up to 48", are provided on the vessel. Some of these, particularly for plasma diagnostics and getters, are installed at compound angles to permit access to the plasma region. Other ports are provided for the external vacuum system, cryogenic supply and return, ventilation during maintenance, and magnet electrical leads.

The dead weight of the magnet, approximately 750,000 lbs, and an additional 800,000 lb seismic load is supported by two forged hanger brackets which are welded directly to the ring stiffeners. These hangers penetrate the shell; prior to installation they were pull tested and examined by ultrasonic techniques. Five other brackets for stabilization of the magnet under seismic loads are installed.

Supports are also installed inside the vessel for the magnet transporter and for the system cryopanels, as well as rigging eyes for use during LLNL equipment installation.

The entire interior surface of the vessel has been polished to a simulated No. 4 finish to permit minimal outgassing. The total helium leak rate is not to exceed 10^{-6} torr-l/sec.

At the present time, vessel fabrication has been completed, and it is undergoing acceptance testing. Most dimensional checks have been performed; generally the required tolerances have been achieved. Leak testing is in progress, to be followed by tests for residual contaminants and rate of rise.

The MFTF Cryopumping System

The cryopumping system maintains a background gas pressure around the central plasma of approximately 3×10^{-6} torr during experimental shots while up to 2,220 torr-l/sec of D_2 is being injected, partly from neutral beam sources at the machine center, and partly from gas boxes in the plasma fans. The system is divided into three zones--east, central and west. The central zone, approximately 220 m^2 of pumping area, serves primarily to pump gas from up to 24 sustaining (1/2s) neutral beam sources, including ion and neutral beam dumps and excess neutralizer cold gas flow. It is also essential that the cold gas which streams from the neutral beam injectors and hits the plasma be limited, and that reionization losses in the beams be acceptable. LLNL performed extensive Monte Carlo analyses of this region to optimize the location and size of baffles and apertures.

In each of the two remaining (end) zones, about 440 m^2 of cryopanels are arrayed so as to result in local capture coefficients approaching 70% (see Fig. 4). The panels in each array are up to 30 ft long; the entire array (both sides) weighs approximately 60,000 lbs.

The elements of the arrays are individual

END ZONE CRYOPANEL ARRAY

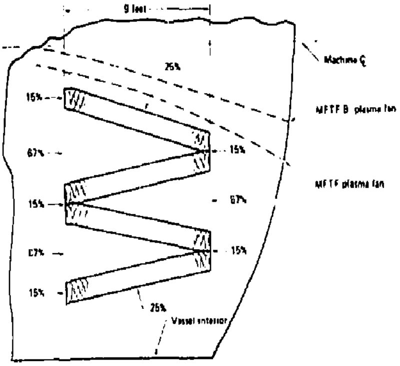

Figure 4 - End Zone Cryopanel Array

panels which pump from both sides. The nitrogen-cooled surfaces are a series of nested Z-shaped aluminum extrusions; the helium panels are also extruded aluminum and fill the space between successive nitrogen panels, which shield them from ambient radiation (see Fig. 5). The anticipated heat load is 1200 watts at 4.5 K (60 kW at 80 K), or roughly 1.1. watt/m^2. The helium circuits are flooded with liquid helium in multiple natural convective loops. The nitrogen circuits are fed with subcooled LN$_2$ (80 K at 80 psia). The total nitrogen plumbing length is nearly 5 km. Further details of the design are given in Ref. 2.

CRYOPANEL CONSTRUCTION

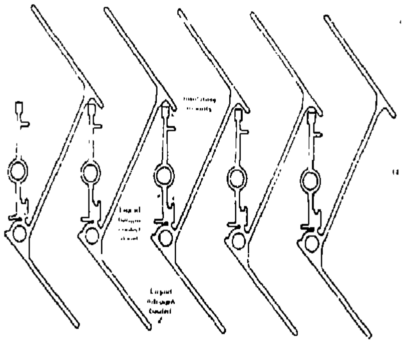

Figure 5 - Cryopanel Construction

The Upgrade to MFTF-B

LLNL is rescoping and upgrading MFTF. This upgrade, called MFTF-B, will convert the facility to a large tandem mirror configuration, which is now the main approach to a mirror fusion reactor. The plan is to proceed directly to the tandem configuration without first operating MFTF in the single-cell mode.

Essentially all components of MFTF will be utilized in converting to a tandem configuration. A tandem mirror consists of a long solenoid with "end plugs" consisting of single-cell mirrors at each end that create electric potentials that confine ions in the solenoid. In MFTF-B, the yin-yang magnet and vacuum vessel for MFTF will serve as one end plug, and a duplicate will be constructed to serve as the other end plug. In addition, it will be necessary to construct the solenoidal section, planned to be about 30 m long, and additional Cee-coils. Further information on the MFTF-B upgrade is presented in Reference 3.

Impact on MFTF Vessel

The MFTF vessel must be substantially modified for use as the east end plug vessel in MFTF-B. The basic reason is that the magnet system supported from the vessel doubles in weight.

• Yin-Yang	750,000 lbs
• Transition and 1 solenoid	250,000
• A cell magnet	500,000
	1,500,000 lbs

The existing magnet supports are not properly located to support the Yin-Yang/transition/solenoid combination. They must be moved and increased load capability provided. An additional six supports for the A cell magnet must be provided. The attractive forces of the magnets must also be reacted; these forces were not present in MFTF.

Consequently considerable modification of the ring and longitudinal stiffeners is expected. To provide added support for installation of the magnet assemblies, the transporter rail mounts must be modified and additional supports provided.

The A cell magnet occupies the space previously taken by the end zone cryopanels. To accommodate these, the vessel must be extended approximately 12 feet to the east, and supplemental legs and foundations provided. The present east head will be used; ports for plasma streaming guns and diagnostics (not installed on MFTF in anticipation of the upgrade) will be installed.

To provide access for getters into the high charge-exchange flux region between the Yin-Yang and the A-cell, one of the 80" diagnostics ports must be modified. A profusion of additional diagnostics ports is planned.

MFTF-B Cryopumping System

MFTF-B will operate in three basic modes:

- Standard tandem. Neutral beams are injected only in the end plugs.
- Two-component. Neutral beams are injected in both the center cell and end plugs.
- Thermal barrier. The function of the thermal barrier is to reduce end-plug technology requirements and to reduce the power input needed to maintain the potential "well" by which the end plugs confine ions in the solenoid.

The cryopumping requirements are the most severe in the thermal barrier mode. Recent studies of the physical phenomena have resulted in detailed requirements for this mode, which are summarized in Table 1. The cryopanel system is essentially the MFTF system, with an additional set of central zone panels for the west end.

Extensive analyses of this cryopumping system have been performed. The major analytical tools are a three-dimensional Monte Carlo model of MFTF-B, and a lumped parameter gas balance code.

The Monte Carlo code, written by Dr. David Margolies of LLNL, incorporates the significant features of the MFTF-B geometry. Sources of gas may be placed at any point; particles are followed until capture or escape. Dynamic calculations may be performed; at any instant a snapshot may be taken and the number of

Table 1

Requirements for Thermal Barrier Mode

Note: all sources are turned on at t = 0.

	REGION							
	Central Cell		Each Yin Yang		Each A-cell		Each End	
	t <.5s	t ≥.5s	t <.5s	t ≥.5s	t <.5s	t ≥.5s	t <.5s	t ≥.5s
SOURCES								
Streaming guns							30	
Startup (20 kV)			10					
1/2 s 80 kV	8		4		1			
30 s 80 kV		1		1		1		1
30 s 2 kV						1		
cold gas feed (A_a)	1000	100						
BEAM TO PLASMA (A_a)								
Startup			500					
1/2s 80 kV	300		200		50			
30 s 80 kV		16		11	(at 80 kV)	6		18
30 s 2 kV						6		
UNCONTROLLED COLD GAS FLOW(A_a)	50	10						
COLD GAS DENSITY								
10^{10} cm^{-3}				5		3.3		5

particles counted in an arbitrary test volume. Particles reflect off 300 K or 80 K surfaces diffusely; thermal accommodation coefficients may be varied so that a particle's true velocity is correctly modeled.

Particles are lost both to the cryopanels and to the surface of the plasma (in fact, in the A-cell region, where the cold gas density limit is the most restrictive, the plasma is by far the predominant pump). The cryopanels are currently modeled by an effective capture coefficient for each face; the detailed Z configuration may be included in the future. The plasma itself, by charge-exchange reactions, is a source of energetic particles; those which are not buried in machine surfaces become cold gas and can be modeled.

The code typically requires about 5 minutes CPU time on the CRAY-I computer at LLNL. To date, it has been used for initial studies of central cell beamlines and for detailed analyses of neutral beam injectors in the Yin-Yang region, including both time-dependent cold gas flow to the plasma and the line density of cold gas, to allow prediction of reionization losses.

Because energetic particles can desorb large quantities of cryotrapped gases on liquid nitrogen temperature surfaces, all cryogenic temperature surfaces in MFTF-B must be prevented from viewing sources of these energetic particles. High charge-exchange flux regions of the plasma are one such source; another is the end dome of the machine. The code is presently being used to optimize the required baffling betwen the cryopanels and the end dome, and the location of the end zone cryopanels.

The lumped parameter code, written by Monya Lane at LLNL, divides the machine into its major regions with appropriate gas sources, effective pumping areas (both plasma and cryopanels), and connecting conductances. The values used for these are derived from the Monte Carlo analyses performed. The code then performs a gas balance on the entire machine, providing both the actual particle densities in each region and the sensitivity of those densities to the input assumptions.

The results to date are encouraging. There appears to be little question that the density requirement in the A-cell region can be met. This density does not depend with great sensitivity on the values of the input variables presently used. Cold gas influx to the Yin-Yang plasma during the critical first 20 ms is small; however, the flying particles must eventually come to roost and it may prove desirable to sequentially shut off the 1/2 s sources (thus preventing excessive cold gas at $t \gtrsim 1/2$ s, when far fewer beams are on). Reionization losses for the Yin-Yang beams are low enough to give comfortable margins on the required energetic neutral currents to the plasma.

During the course of the vacuum environment studies, it became apparent that microwave heating of the plasma and synchrotron radiation losses during thermal barrier mode operation could cause substantial pulsed heat loads on the liquid helium cryopanels. These, together with neutron and energetic X-ray sources, may deposit kilowatts of power into the panels, possibly leading to flow instabilities, increase of tip temperatures and decreased pumping speeds. It will be necessary to perform detailed analyses to evaluate these effects; the present plan is to install sufficient microwave-absorbing surfaces in the machine to limit these pulsed heat loads to acceptable values.

Conclusion

Substantial challenges have been met by the designers of the major system elements of MFTF. The construction of such a large high vacuum vessel, with extremely close tolerances and able to support large structural loads, together with the design of a highly efficient cryopumping system in the restricted space available, are representative. The upgrade of the facility to a tandem mirror configuration with thermal barriers will present further challenges.

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3. V. N. Karpenko, "Mirror Fusion Test Facility-B", these proceedings

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