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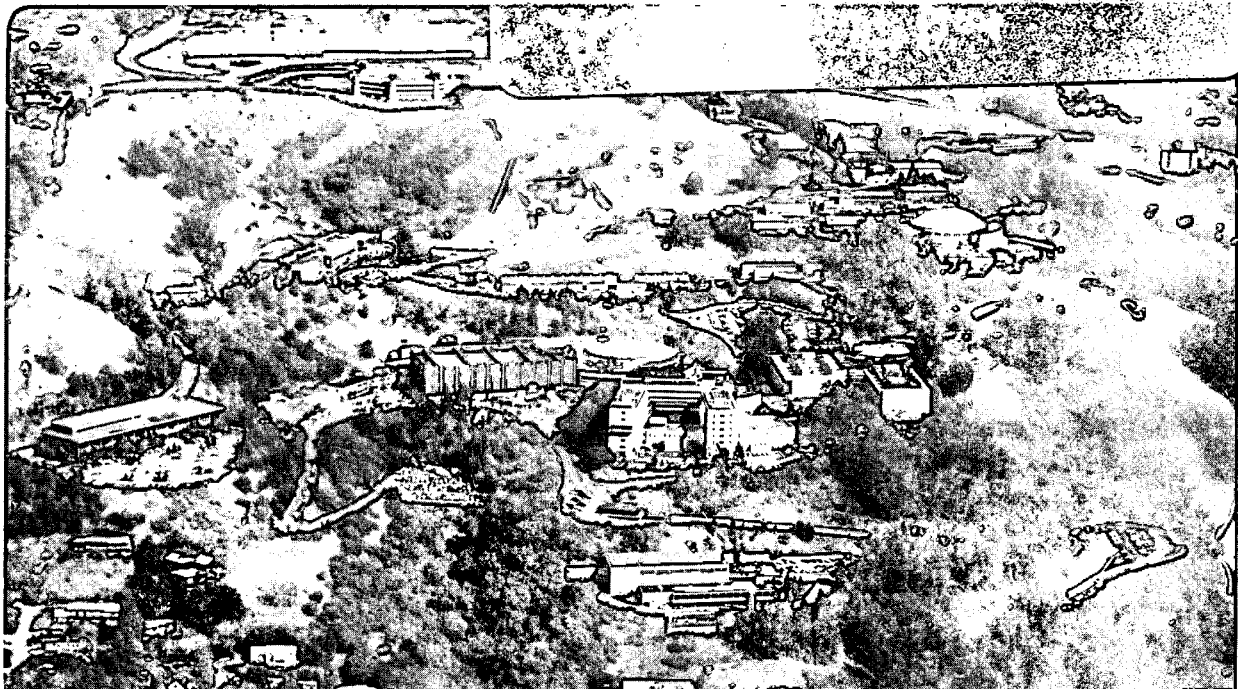
CONSTRUCTION AND TESTING OF THE MIRROR FUSION TEST FACILITY MAGNETS

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August 1986

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Abstract

This paper describes the construction and testing of the Mirror Fusion Test Facility superconducting magnet set. Construction of the first Yin Yang magnet was started in 1978. And although this particular magnet was later modified, the final construction of these magnets was not completed until 1985. When completed these 42 magnets weighed over 1200 tonnes and had a maximum stored energy of approximately 1200 MJ at full field. Together with power supplies, controls and liquid nitrogen radiation shields the cost of the fabrication of this system was over \$100M. General Dynamics/Convair Division was responsible for the system design and the fabrication of 20 of the magnets. This contract was the largest single procurement action at the Lawrence Livermore National Laboratory. During the PACE acceptance tests, the 26 major magnets were operated at full field for more than 24 hours while other MFTF subsystems were tested. From all of the data, the magnets operated to the performance specifications. For physics operation in the future, additional helium and nitrogen leak checking and repair will be necessary.

In this report we will discuss the operation and testing of the MFTF Magnet System, the world's largest superconducting magnet set built to date. The topics covered include a schedule of the major events, summary of the fabrication work, summary of the installation work, summary of testing and test results, and lessons learned.

Schedule of Major Events

From early conceptual design to the completion of the plant and capital equipment acceptance tests, the MFTF magnet system required a few months short of 12 years to complete. Starting in mid-1974, several magnet configurations were studied for the next upgrade in the Magnet Mirror Fusion Program at LLNL - the lead laboratory for the US Magnetic Mirror Fusion Program. Once the Yin Yang configuration was picked for a mirror ratio of two (on-axis mirror field to central field), conceptual studies and cost estimates were started for both superconducting and normal magnet designs. Because of power requirements and costs, the superconducting configuration was chosen. In addition to being a major size step forward in mirror fusion, this decision would allow advancement in the technology of superconductivity to a point approaching the requirements for a full size commercial fusion plant.

With the decision to proceed with the superconducting magnet approach, much research and development was necessary to ensure that an adequate superconductor with sufficient cryogenic stability could be mass produced. Because of this, an increase in the superconducting research activity at LLNL was started in 1975 to develop a high current, cryostatically stable conductor for the pool boiling MFTF Yin Yang magnet. Two designs were carried on for the better part of a year. These were the four-bar conductor (four conductors joined together with fins, one of 50% NbTi and 50% copper, the other three 100% copper), and the wrapped conductor (a 50% NbTi conductor wrapped with a

sheath of 100% copper. The wrapped conductor was chosen in 1976 because of ease and lower cost of fabrication in quantity, although both conductor designs performed well from stability and heat transfer standpoints. At full current both conductors had sufficient wetted surface area to recover from a stable normal zone at operating currents and fields. At this point research and development work was started on a highly reliable joint design for this conductor because each Yin Yang coil would have at least 54 joints. Several joining techniques were studied, including explosively bonding and cold welding. Additionally, the final joint was to be soldered in a copper holder for redundancy. By the completion of these designs, the MFTF magnet joint design was stronger than the parent conductor and required little additional space.

In 1977, the cold-welded joint was picked because of ease during winding and because it presented no safety problems that might be inherent in an explosively bonded joint. At this point, we started the specification and quality control requirements for both the superconducting core (again 50% NbTi and 50% copper) and the wrapping operation. For the initial procurement for the first Yin Yang magnet over 160,000 feet of conductor and wrapping was required. The official project start was October 1, 1977 (FY78), and shortly after that orders were placed for the superconducting core and the fabrication and operation of the stabilizer wrapping line.

In early 1978 a design contract was awarded to General Dynamics Convair Division for the design and assembly procedures for the large Yin Yang magnet. Prior to that time the coils had to be separated from the large structural case for ease of fabrication and to reduce the weight to be handled by the two-axis coil winding machine. General Dynamics was primarily involved with the structural design, but also helped with the conductor and coil thermodynamics for cool-down and warmup. Later, in this same year, the winding of the first Yin Yang C-shaped coil was started. Eventually, this original coil winder would wind four Yin Yang coils, then be moved to General Dynamics in San Diego to wind two C-shaped transition coils.

In 1979, 304LN steel plate was ordered for the fabrication of the structural case for the first Yin Yang. Shortly after award of the plate order, a contract was awarded to the Chicago Bridge and Iron Company for the fabrication of the magnet structural cases and the assembly of the first Yin Yang magnet. During this same year the first Yin Yang coil winding was completed and welded closed by Livermore personnel.

In 1980, based on the early tandem mirror experiment (TMX) results, the conceptual design for the Tandem Mirror Fusion Test Facility (MFTF-B), A-cell configuration was approved. This configuration used 22 large superconducting magnets that included two Yin Yang magnets on either end of the solenoid region, 14 5-meter central cell solenoid magnets at 1-tesla central field, two circularizing C-shaped magnets each inboard of a Yin Yang magnet pair, and two larger C-shaped A-cell magnets outboard of each Yin Yang magnet pair. Later this same year, the winding of the second Yin Yang magnet coil was completed and the installa-

tion of the coils in their structural cases and assembly of the first Yin Yang Magnet was started.

In 1981, the University of California's and LLNL's largest single contract was awarded to the General Dynamics Convair Division for the design and fabrication of the 14 solenoid magnets, two transition magnets (the aforementioned C-shaped circularizing magnets), and two A-cell magnets. This contract also included design work on the overall installation and system integration wherein all of the magnets would be tied together structurally. The assembly of the first Yin Yang magnet was also completed, its liquid nitrogen radiation shields were installed; and it was installed in the original MFTF vacuum vessel (which later became the east vessel for the MFTF-B configuration). After installation, the technology demonstration tests (a series of tests designed to prove the technology used in MFTF before undergoing the changes to MFTF-B) were started and the winding of the third Yin Yang coil was started.

With the continuation of the technology demonstration tests, in 1982, the first Yin Yang magnet was cooled down, filled with liquid helium, operated to full current, and warmed up. All major design parameters were achieved with this first magnet, and based on these achievements the design requirements for all of the remaining MFTF-B magnets were finalized. During this same year, the MFTF-B A-cell configuration was approved for change to the axicell configuration. While this change would improve the overall tandem mirror confinement physics, many of the magnets that had already been started for the A-cell configuration had to be changed. The C-shaped A-cell magnets were eliminated, four transition magnets (two on each end) replaced the two larger original transition magnets; two solenoid magnets were eliminated and the remaining 12 were moved closer together to provide a 1.6-tesla central field versus the original 1-tesla field; and in the space provided by shortening the central cell length were added six solenoidal axicell magnets (three on each end). Eventually, though not for another year, 16 small trim magnets were added to correct any magnetic errors induced during the installation and alignment of the 26 major magnets. In the final division of work General Dynamics would be responsible for the system design integration, magnet design and fabrication of 12 solenoid magnets, four transition magnets, and four NbTi axicell magnets, LLNL would fabricate the two Yin Yangs (four coils), the two high-field Nb₃Sn axicell magnets, the 16 trim magnets, fabrication and installation of the liquid-nitrogen and water cooled liners, magnet installation, and testing. With minor changes to the inside coil windings for the 5-meter solenoids, General Dynamics started winding this same year.

By the start of 1983, all four coils for the two Yin Yang magnets had been wound and the coil winding covers installed. Since this was the last requirement for winding large C-shaped magnets at LLNL, the large coil winder was dismantled and shipped to General Dynamics to wind the transition magnets in parallel instead of four in series. Later this year, with the original Yin Yang winder and a new two-axis winder at General Dynamics, the winding of the four transition magnets using the original MFTF-type superconductor was started.

In 1984 three new single axis winding lines were installed in Building 531 at LLNL. The first two of these would be used to wind the 16 trim magnets and the third would be used to wind the two high field Nb₃Sn coils. Winding was started on all three lines by the end of the year. Also during 1984 General Dynamics completed the winding of the 12 solenoid coils and shipped them to LLNL. With these deliveries and the completion of leak checking of the of the

vessel central cell modules, Chicago Bridge and Iron began the installation of the solenoid magnets in the vessel modules. Once the installation and alignment were completed, LLNL technicians began the installation of the liquid nitrogen radiation shields. By the end of the year, the two end vessels were completed and the installation of the east and west Yin Yang magnets was started.

All magnet systems were completed and installed for the PACE acceptance testing in 1985. Difficulties with the alignment of the major magnets and leak checking the nitrogen and helium circuits delayed the start of the PACE testing from July to October. The power supplies and control system including magnet protection were installed and tested. General Dynamics completed the winding and case closeouts of the four axicell magnets and the four transition magnets. LLNL completed the winding and closeout welding and leak checking of the 16 trim magnets and the two high field Nb₃Sn magnets. The trim magnets were installed four each on the transition magnets prior to their installation in the vacuum vessel. The high field Nb₃Sn axicell magnets were installed in the outer axicell magnets prior to their installation in the vessel. On some of the magnets (both Yin Yangs, all 12 solenoids, and four axicell magnets) we completed partial installation of the liquid nitrogen cooled radiation shields before installation in the vessel. However, because of the magnet alignment and fitting requirements of the nitrogen panels, over 60% of the panel installation was completed after the magnets were installed and aligned in the vacuum vessel. During the panel installation (after magnet installation), the large current leads were installed and leak checked. These required additional radiation shields to be installed and additional leak checking. The vessel pumpdown in early October marked the start of the PACE acceptance testing.

Because of nitrogen and helium leaks that had to be repaired and because of some difficulties with the large 8-kW helium system that required repair, the magnets could not be cooled below 15 K in 1985. However, with repairs completed, the magnets were cooled all the way and filled in early 1986. Then the group power testing of individual magnet groups to full field was completed. Finally, the magnets were operated to full field in the thermal barrier physics configuration and held there for approximately 24 hours while other subsystem tests were performed. These other tests included the operation of the neutral beam and electron cyclotron heating systems. Once this testing was completed, the magnets were warmed and the vessel was opened to atmosphere.

Summary of Fabrication Work

During the course of the fabrication of the MFTF-B magnets, we used eight different winding lines, four types of conductor, and over 100 people for winding the 42 coils at Livermore and General Dynamics. At times, some of these lines were operated around the clock (24 hours a day) seven days a week. Since this required more supervision and engineering follow up than we had personnel for, the third shift was generally used for cleanup and testing.

The design weights of the MFTF magnets and conductors is given in Table 1. The total design weight of all of the magnets was over 1100 tonnes, to which is added the support and alignment rods and liquid nitrogen radiation shields. More impressive than this figure is the fact that the combined weight of the superconductor used in the 42 magnets was almost 300 tonnes. Table 2 shows the operating currents and fields for the various superconductors used on the MFTF-B magnets. The most extraordinary conductor used in the magnets was the MFTF conductor for two-axis

Table 1. MFTF-B Magnet Parameters.

Coil	Number Required	Total Weight (lb)	Conductor Weight(lb)	Design Peak Field (tesla)	Where Wound
M1	2	336,000	60,000	4.0	LLNL
M2	2	336,000	60,000	4.6	LLNL
T1	2	52,800	11,700	5.5	GD/C
T2	2	99,200	26,400	5.3	GD/C
A1	2	58,500	29,000	7.7	GD/C
A20	2	62,000	29,000	7.5	GD/C
A2i	2	13,800	8,300	12.5	LLNL
S1-S5	10	23,400	10,100	3.2	GD/C
S6	2	24,000	10,100	3.2	GD/C
Tr(1-4)	8	3,000	900	2.9	LLNL
TR(5-8)	8	3,000	775	2.2	LLNL
TOTAL	42	2,246,600	583,400		

winding developed early during the conceptual design phase. Figure 1 shows the MFTF-TYPE of conductor with the copper wrapping sheath and the superconducting core shown separately. Other conductors employed in the MFTF magnets were the solenoid conductor, the trim magnet conductor, and the Nb₃Sn conductor. Both the solenoid conductor and the trim magnet conductor employed a copper/superconductor core soldered into a copper channel. These types of conductors had been used in many magnets prior to MFTF and therefore required little additional research. The Nb₃Sn conductor employed a copper/superconductor core soldered into a copper channel with a copper hat to totally surround the core with a copper case. Conductor similar to this had been used by Furukawa Electric (the manufacturer) prior to the work for MFTF and thus the only research work was to develop the conductor in the lengths necessary for the MFTF magnets.

The first winding line (of the eight mentioned above) was started early in 1978 for the first MFTF Yin Yang Magnet. Figures 2, 3, and 4 show the MFTF Yin Yang coil winding facility. Many of the techniques and mechanisms used for winding all of the MFTF coils were developed during the winding of the first Yin Yang coil on this line. At the start we developed techniques for installing the ground plane insulation and starting the first turn winding (Fig. 2). As the

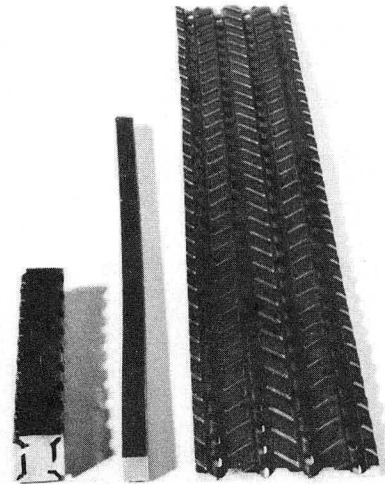


Figure 1. MFTF conductor showing separately the copper sheath and the superconduction core.

Table 2. MFTF-B Magnet Conductor Types.

Coil	Design Current (amperes)	Design Peak Field (tesla)	Conductor Type
M1	3837	4.0	MFTF-type
M2	4410	4.6	MFTF-type
T1	5266	5.5	MFTF-type
T2	6278	5.3	MFTF-type
A1	4238	7.7	MFTF-type
A20	4689	7.5	MFTF-type
A2i	1500	12.5	Nb ₃ Sn
S1-S5	2880	3.2	Solenoid
S6	2880	3.2	Solenoid
Tr(1-4)	900	2.9	Trim
Tr(5-8)	775	2.2	Trim

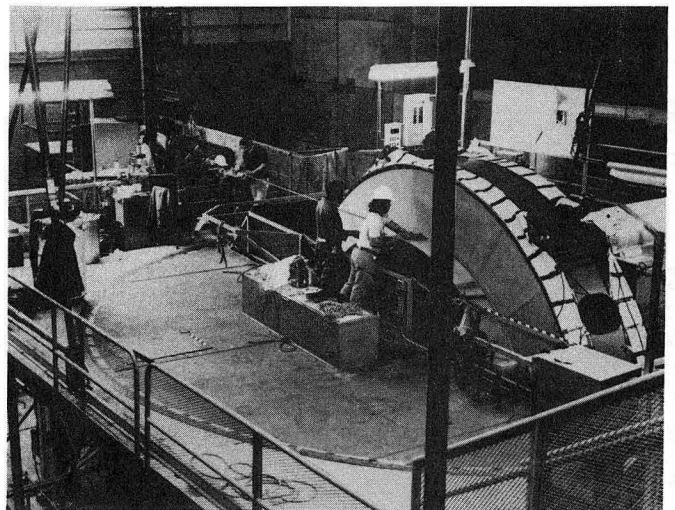


Figure 2. MFTF Yin Yang and transition coil winder, showing the start (first turn) of the first Yin Yang coil.

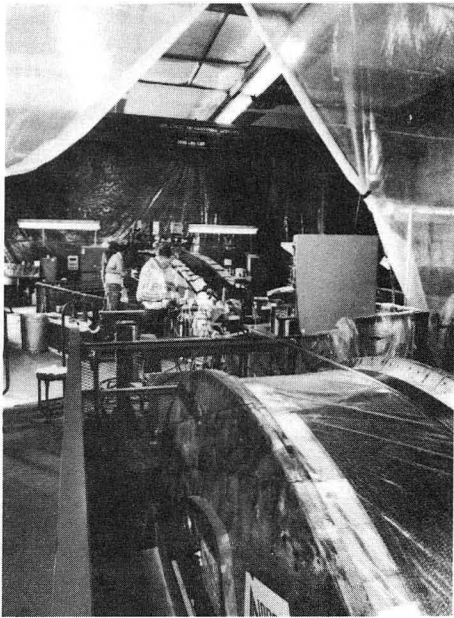


Figure 3. MFTF Yin Yang and transition coil winder. Pictured in the foreground is the conductor reel support system and in the background is the turn insulation installation system.

winding progressed, we developed several mechanisms for attaching the button-on-a-string turn insulation to the MFTF-type conductor (Fig. 3) and the air operated holding clamps (Fig. 4) to support the conductor as the winding operation progressed. Two of the four winding lines at General Dynamics were exactly the same as this and will not be shown. (Indeed, this winder was one of the two used by General Dynamics for the transition magnets.)

The next winding lines to be constructed were the two solenoid winding lines at General Dynamics. The setup of these two is depicted in Fig. 5. Here General Dynamics developed special "spider fixtures" to support the U-shaped coil form during the winding and the coil closeout welding operations. These two winding lines were later modified to handle the heavier axicell magnets (A1 and A20) when the magnetic configuration was changed from the A-cell to the axicell.

The final three winding lines to be put into operation were the two trim coil winding lines and the Nb₃Sn high field winding lines in Building 531 at LLNL. This new area also had sufficient room to do

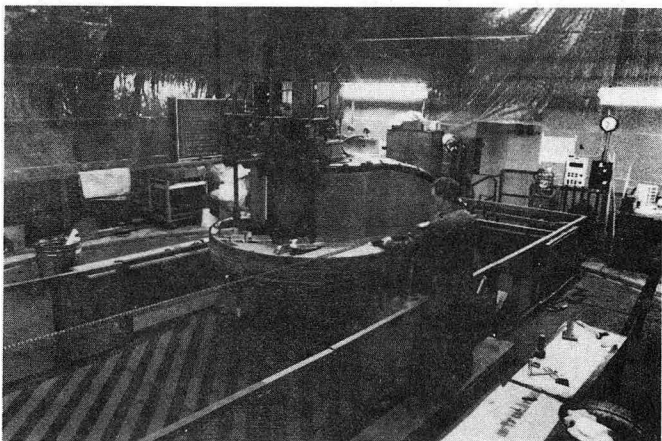


Figure 4. MFTF Yin Yang and transition coil winder and conductor support clamps.

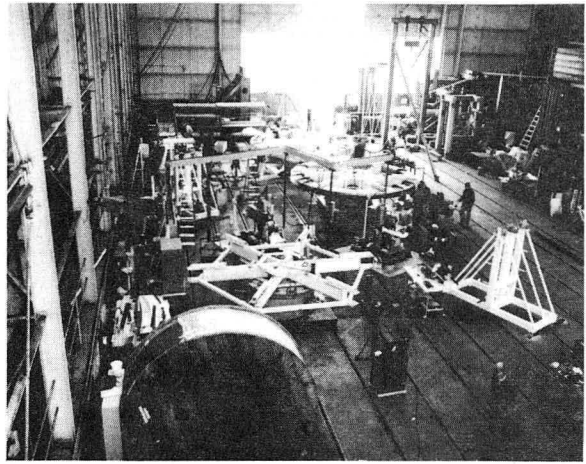


Figure 5. Setup of the two solenoid winding lines at General Dynamics. Shown are the special "spider fixtures" used to support the U-shaped coil form during winding and close-out welding.

the final coil closeouts and coil cover installation while other coils were being wound. This parallel activity allowed us to save at least 3 months from the schedule had this effort required more serial events. This was necessary since the trim magnets were added at a late date in the program. Figure 6 shows the two trim coil winding lines in operation and Figs. 7 and 8 show the Nb₃Sn high field Axicell winding line. Figure 7 shows the winding line during the installation of the conductor lead-in while Fig. 8 shows the winding line during the winding of the first coil.

After the winding operation was completed, the final coil closeout and case welding (or coil form welding) was done. Although slightly different for each of the magnets fabricated, there is sufficient similarity that only one type of coil will be discussed. The first step was to radially compress the conductor and surround it with the outer ground plane insulation. Once this was completed the segments of the coil case surrounding the outer ground plane were installed and welded together. Figure 9 shows the installation of the coil covers on the wound coil with the ground plane insulation installed, and Fig. 10 shows the final closeout welding. Both of these figures are for the Nb₃Sn high field axicell magnet, however the process is similar for all other coils wound.

Some of the MFTF Magnets required additional work prior to the installation into the vacuum vessel. The Nb₃Sn high field axicell magnet (A21) had to be matted

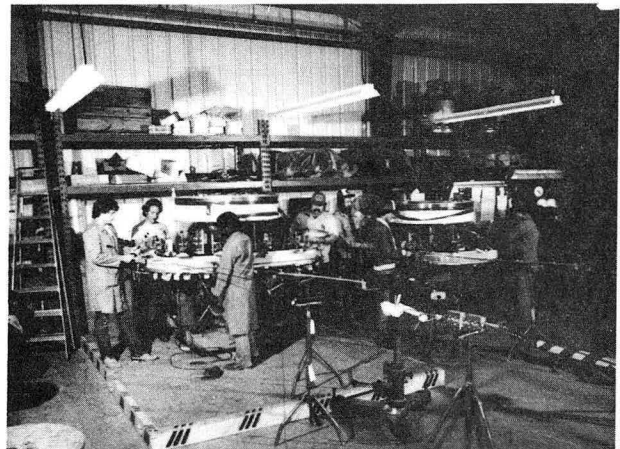


Figure 6. Two trim coil winding lines.

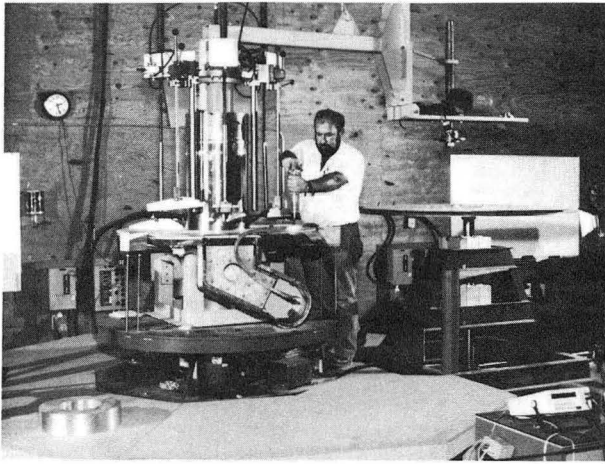


Figure 7. Nb_3Sn high field axicell winding line, showing the installation of the lead-in conductor.

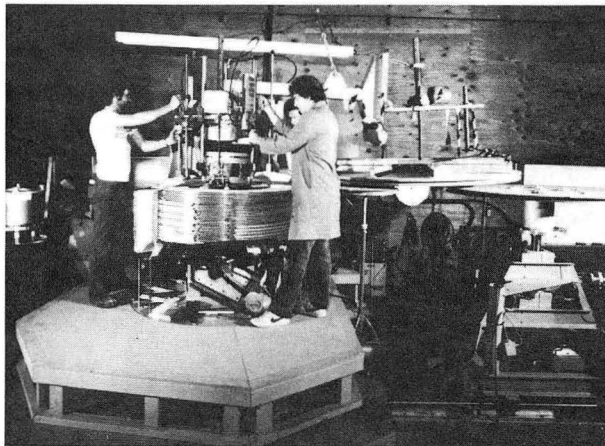


Figure 8. Nb_3Sn high field axicell winding line, showing the first coil winding.



Figure 9. Nb_3Sn high field axicell coil cover installation.

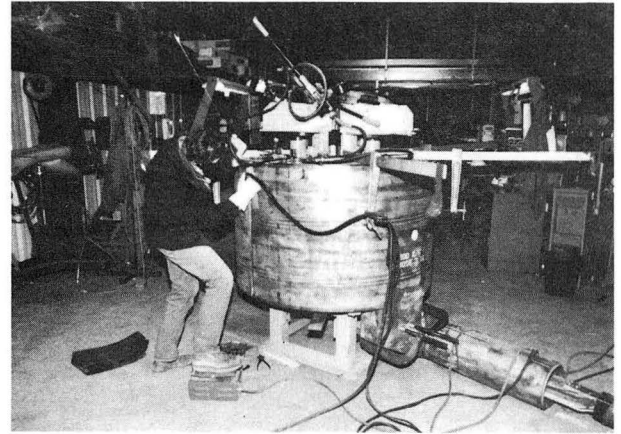


Figure 10. Nb_3Sn high field axicell magnet close-out welding.

and welded to the larger lower field NbTi axicell magnet (A20). The completed magnet set is shown in Fig. 11. The inside eight solenoid magnets had to be welded together in pairs prior to installation in the vessel (this will be shown in later photographs). Finally, the Yin Yang magnet assembly required the most work. First, each individual coil form had to be installed in its structural case. This installation work is shown in Fig. 12. Once installed in the case the coil form surrounding bladder was filled with high density polyurethane and allowed to cure. Once cured, the final case welding was completed, ultrasonically tested, and helium leak checked. When this was done, the two Yin Yang coils (M1 and M2) were joined to form the final Yin Yang magnet. This sequence of events is shown in Figs. 13-16. Figure 13 shows the process where one coil was moved under the other for the final alignment. At this stage each coil in its structural case weighed more than 150 tonnes. When the two coils were aligned relative to one another and verified by LLNL, Chicago Bridge and Iron installed the interconnecting pieces and welded the two coils together (Fig. 14). Once completed, the final Yin Yang magnet assembly weighed close to 400 tonnes. The final assembly was supported by non-magnetic sand (Fig. 15) so that it could be rolled to the proper position to assemble the transporter around it. Non-magnetic sand was used so that magnetic field measurements could be made by passing a small current through the conductor. These measurements would be used to align the magnet

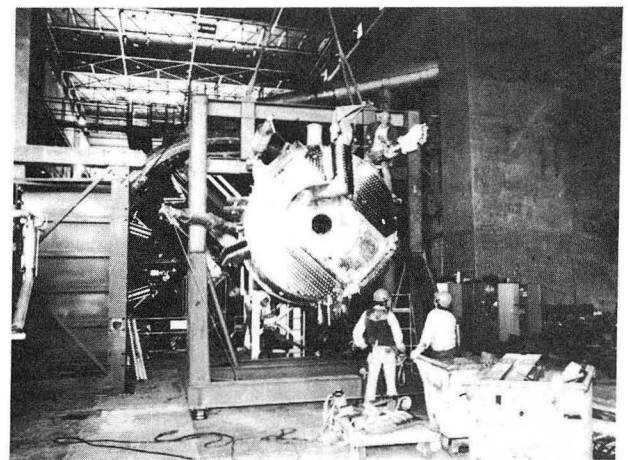


Figure 11. The high field Nb_3Sn axicell magnet (A2i) installed in the outer low field axicell magnet (A20).

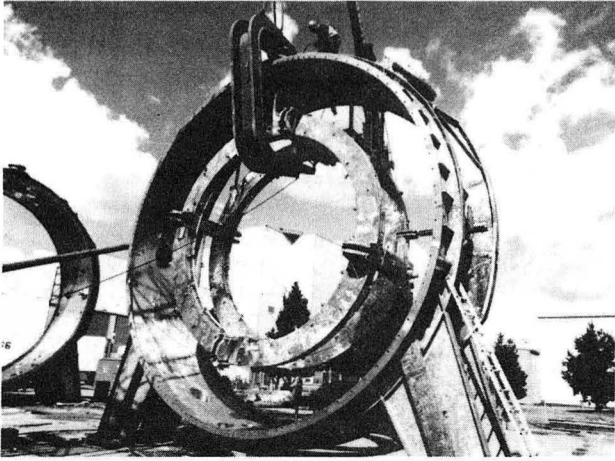


Figure 21. Two solenoid magnets being installed in a central vessel module.

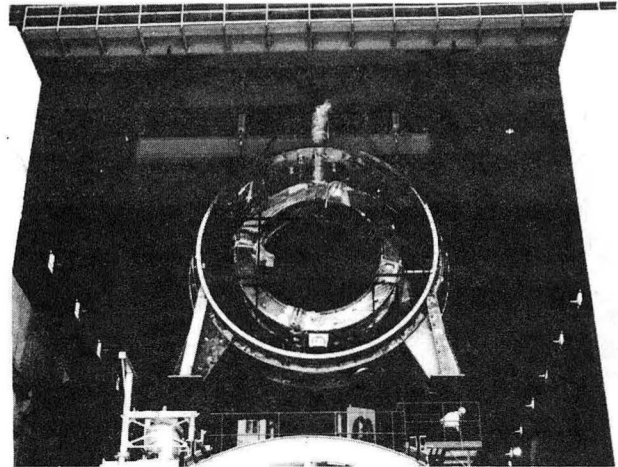


Figure 24. A single central vessel module (two solenoids) being lifted over the west vessel during installation.

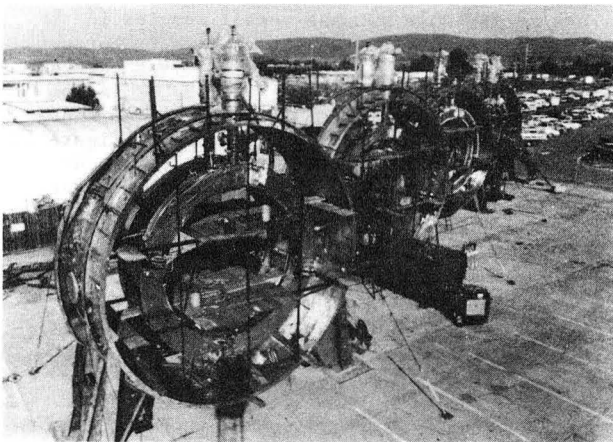


Figure 22. Four central vessel modules (eight five-meter solenoids) being prepared for transport to the MFTF vault.

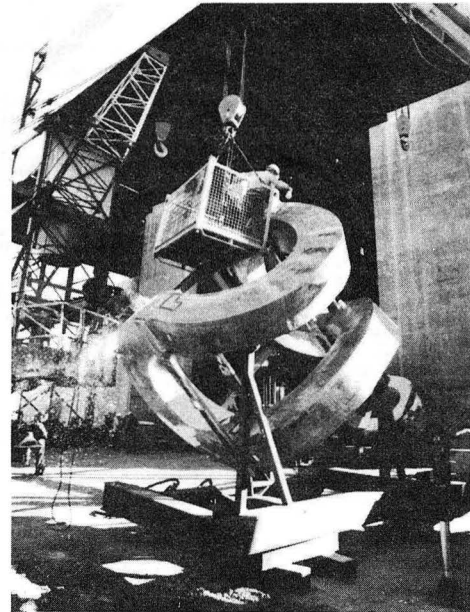


Figure 25. Transporter fixture for one of the transition magnets with magnet installed.

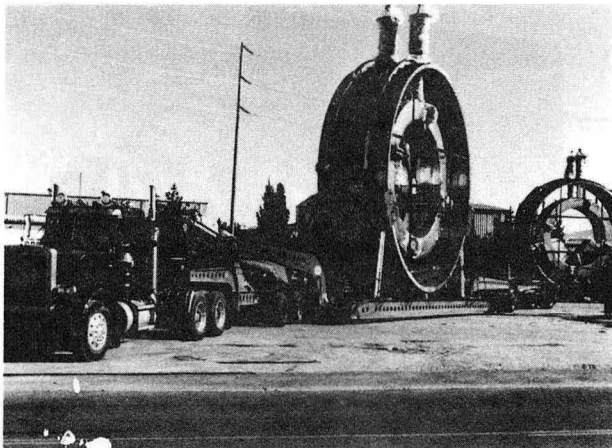


Figure 23. A single vessel module loaded on a truck/trailer for transport to the west end of the MFTF building.

these for one of the transition magnets. This transporter fixture was designed so that the trim magnets (four required for each transition magnet) could be installed while they were on the fixture. These fixtures also allowed enough flexibility that additional rigging could be installed for use in the alignment process. Figure 26 shows the installation of one of the 32 current lead stacks. When received from the vendor (Meyer Tool and Manufacturing, Inc.) each lead stack was inspected and leak checked prior to vessel installation. Because of the sharp bends in some of these leads, installation was careful and time consuming so that neither the lead nor the magnet panels would be damaged. Figure 27 is shot from inside the vessel in the solenoid region just prior to pumpdown. In the background can be seen the axicell magnets with the small bore Nb_3Sn high field axicell magnet in the center.

In addition to the main mechanical hardware described above, there was much time spent installing the electrical systems including all monitoring systems and local controls. Figures 28 through 32 show

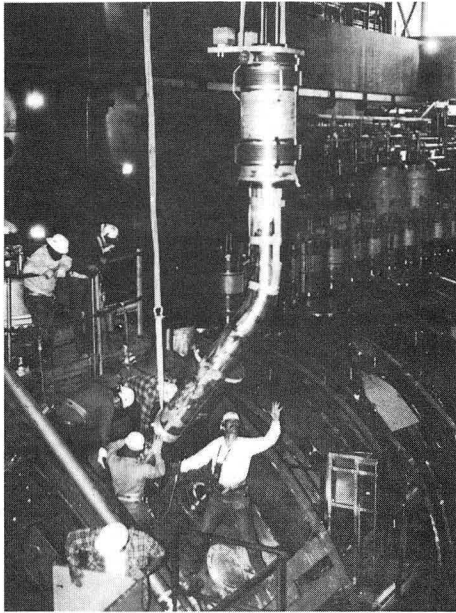


Figure 26. Installation of one of the 32 current lead stack assemblies.

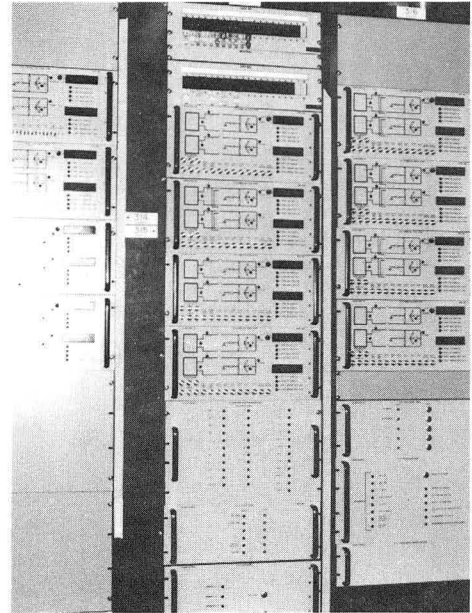


Figure 28. Installed electrical magnet instrumentation and control hardware.

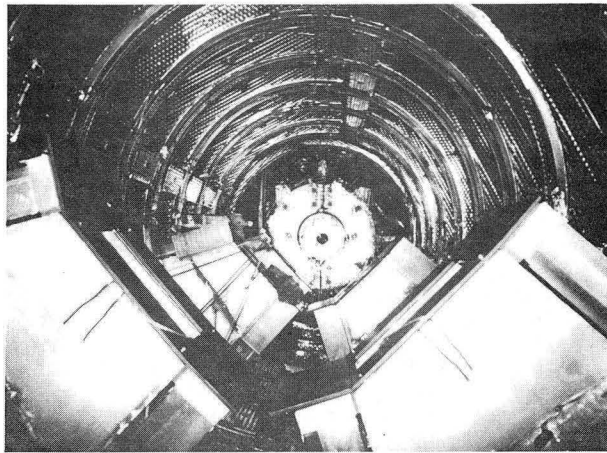


Figure 27. View from inside the solenoid magnet region just prior to pumpdown. Axicell magnets are visible in background.

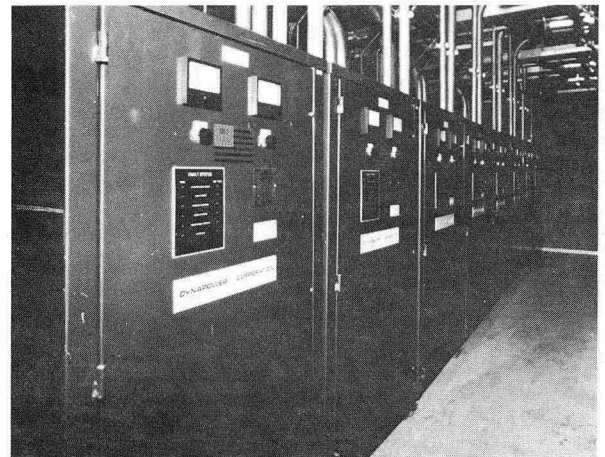


Figure 29. Installed power supplies for some of the magnets.

some of the installed electrical systems. Figure 28 depicts some of the control and instrumentation chassis installed on the third and second floor of the MFTF building. Figure 29 shows some of the installed magnet power supplies for charging the magnets. The requirement was for all coils to be charged to full field (therefore full current) in less than four hours. These power supplies were operated from the magnet controller such that the charging trajectory was faster at the lower current settings than at the higher current settings. The largest single installation job for the electrical system was the installation of the magnet power and instrumentation cabling. Figure 30 shows the cabling leading from the seven-foot-thick block wall to the magnets and Fig. 31 shows the attachments on the other side of the block wall to the magnet power supplies and controllers. Part of the magnet protection system required dump resistors for removing the energy in the magnets either rapidly (fast dump resistors dumped the entire current in a few minutes) or slowly (slow dump resistors dumped the entire current in about four hours). These dump resistors were installed under the vessel and a few are shown in Figure 32.

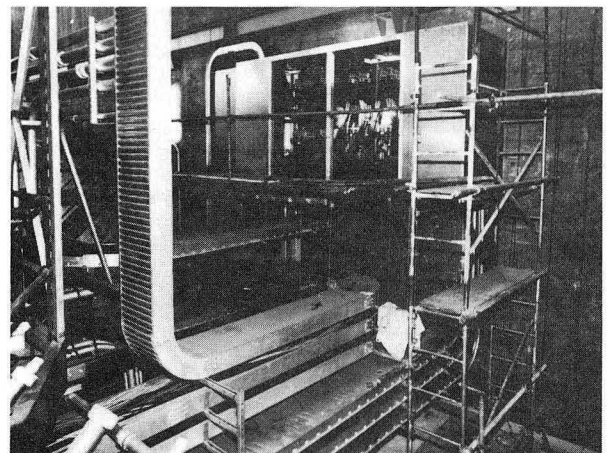


Figure 30. Magnet cabling in MFTF vault.

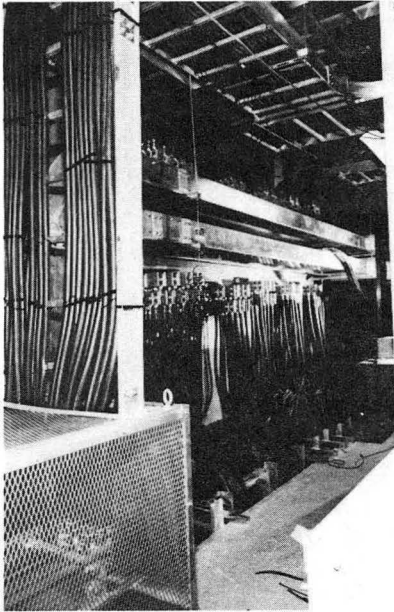


Figure 31. Magnet cabling inside power supply area.

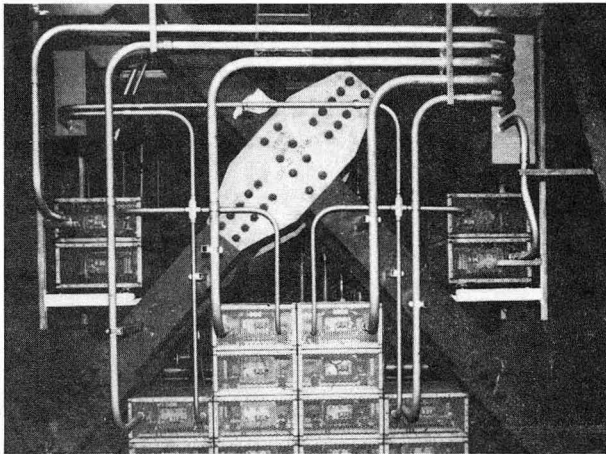


Figure 32. Magnet dump resistors.

Magnet misalignments, both translational and rotational, can be significant factors that contribute to plasma instabilities. An attempt was made to quantify the expected coil alignment errors considering such factors as mechanical location of the conductor pack, effects of magnet cooldown, vessel temperature changes and sag, magnet steady state loads, etc. When the effects of these expected coil misalignments from installation errors and calculational errors on the plasma stability were analyzed, it was discovered that the plasma would be adversely affected. The coil alignment requirements were beyond the state of the art alignment techniques and the calculation error estimate, so a set of trim magnets was added to the transition magnets, resulting in requirements that were more practicable (basically each coil had to be aligned to the magnetic centerline within 1.5 cm and 0.5 degrees).

The magnets were misaligned during installation according to the movements they would undergo based on calculations by both LLNL and General Dynamics. The misalignment was chosen so that the magnets would be in the correct position after being cooled to liquid helium temperature and energized. They were set in position using conventional surveying equipment

mounted external to the vessel with targets consisting of cross wires mounted on the separate magnets. The Yin Yang magnets were fitted with targets to which the magnetic axis was referred. The magnetic axis was found at room temperature by passing approximately 100 amperes through the magnet and locating the axis with a rotating coil apparatus. This technique was needed only for the Yin Yang magnets because the coil pack was wound in a coil case separate from the external structural case. All other magnets were aligned so that the conductor bundle, as determined from buttons welded onto the case at the time of winding, was displaced the required amount so that they would be in the correct location relative to the magnetic axis defined by the Yin Yangs when cooled down and energized.

During the PACE acceptance tests, a measurement of the degree of coil alignment was made using the magnetic field alignment (MFA) apparatus. A comparison of the expected coil position errors with the results of the MFA analysis can be made by using Tables 3 and 4. The data presented in Table 3 are the standard deviations of magnet alignment errors. Because of problems taking the MFA data Table 4 is not complete. However, the MFA data presented in Table 4 is in fair agreement with the expected values. The displacements of the west transition magnets in the y direction and both the east and west Yin Yang magnets in the x direction is somewhat greater than expected, but well within the 1.5 cm range that the trim magnets were designed to compensate for. The rotational errors for the A2 axicell magnets actually were not as great as listed in Table 4, because the cumulative errors for the solenoids and the A1 axicell magnets are taken together for the A2 value for computation ease. Even taking the total error into account the maximum capability of the trim magnets is more than three times greater than this error. In summary, although insufficient measurements were made during the PACE acceptance tests to obtain accurate determination of the coil alignment, the coils appear to be aligned in such a way that the trim magnets would have sufficient correcting capability. Any future operation of the entire MFTF-B magnet system for plasma physics operation would have to be preceded by a MFA run that yielded sufficient data to make an accurate assessment of the coil alignment and calculated the initial power settings for the trim magnets.

Summary of Test Results

Integrated Leak Rate Testing (Nitrogen and Helium Circuits)

The integrated leak rate testing for the internal circuits was done during the four vessel pumpdown periods from October 1, 1985 through December 1, 1985. The general procedure was to evacuate the vacuum vessel and measure the system sensitivity; then the circuit to be tested was charged with helium gas and the output, if any, of the mass spectrometer-type helium leak detector was recorded. The total circuit operational leak rate was calculated by multiplying the leak rate measured by the system sensitivity factor and then by a correction factor to account for the changes at operating temperatures and pressures. These correction factors (from tests) are 78.5 for the liquid nitrogen circuits, 172 for the liquid helium circuits, and 0.16 for the guard vacuum circuits.

Tables 5 and 6 give the results of these measurements prior to the system cooldown and operation. Where no response was indicated on the leak detector, this is so indicated in the tables; but the leak rate is calculated based on the lowest system sensitivity at that time. For plasma physics operation the desired total operating leak rates are 1.7×10^{-6} and

Table 3. Deviation of Expected Magnet Alignment Errors.

Magnet	X-dir. (cm)	Y-dir. (cm)	Z-dir. (cm)	R _x (deg.)	R _y (deg.)	R _z (deg.)
A1	0.39	0.39	0.654	0.15	0.15	0
A2	0.39	0.39	0.646	0.176	0.176	0
T1	0.454	0.454	0.649	0.172	0.172	0.168
T2	0.49	0.49	0.985	0.109	0.109	0.136
YY	0.456	0.456	0.813	0.064	0.064	0.104

Table 4. Alignment Errors from MFA Analysis.

Magnet	X-dir. (cm)	Y-dir. (cm)	Z-dir. (cm)	R _x (deg.)	R _y (deg.)	R _z (deg.)
EA2	-0.26	-0.09	not measured	+0.57 ^a	+0.56 ^a	not measured
WA2	-0.01	-0.23		+0.17 ^a	-0.64 ^a	
ET1	+0.21	-0.32		-0.03	+0.08	
WT1	-0.69	-0.85		-0.04	+0.05	
ET2	-0.41	-0.28		+0.08	-0.10	
WT2	-0.21	-0.86		+0.04	+0.01	
EYY	-0.69	-0.51		-0.008	-0.11	
WYY	+0.62	-0.12		+0.002	+0.01	

^aIncludes cumulative error of solenoid magnets and A1 magnets.

Table 5. Helium Circuits --
Measured Leak Rate (at Operating Conditions).

Magnet	Operating Leak Rate (TL s ⁻¹)
EYY and Guard Vacuum	<2.1×10 ⁻³ (No Leaks Detected)
ET and E Trims	>2.04
EA	<2.5×10 ⁻³ (No Leaks Detected)
ES5 and ES6	2.6×10 ⁻³
ES4 and ES3	<8.8×10 ⁻⁴ (No Leaks Detected)
ES1 and ES2	<8.8×10 ⁻⁴ (No Leaks Detected)
WS1 and WS2	<1.0×10 ⁻³ (No Leaks Detected)
WS3 and WS4	<5.2×10 ⁻⁴ (No Leaks Detected)
WS5 and WS6	8.6×10 ⁻²
WA	1.4×10 ⁻¹
WT and W Trims	3.0×10 ⁻³
WYY and Guard Vacuum	<2.4×10 ⁻² (No Leaks Detected)
Total	>2.3

Table 6. Nitrogen Circuits --
Measured Leak Rate (at Operating Conditions).

Magnet	Operating Leak Rate (TL s ⁻¹)
EYY	2.7×10 ⁻²
ET and E Trims	1.8×10 ⁻²
EA	<9.4×10 ⁻⁴ (No Detectable Leaks)
ES5 and ES6	1.6×10 ⁻²
ES3 and ES4	<4.0×10 ⁻⁴ (No Detectable Leaks)
ES1 and ES2	3.2×10 ⁻¹
WS1 and WS2	<1.5×10 ⁻³ (No Detectable Leaks)
WS3 and WS4	<1.5×10 ⁻³ (No Detectable Leaks)
WS5 and WS6	1.6×10 ⁻²
WA	<1.5×10 ⁻³ (No Detectable Leaks)
WT and W Trims	<9.4×10 ⁻⁴ (No Detectable Leaks)
WYY	4.0×10 ⁻²
Total	4.4×10 ⁻¹

1.0×10⁻⁵ torr-liters/sec (TL s⁻¹) for helium and nitrogen, respectively. Although about half of the circuits did not meet the system requirements, the remaining circuits would require better system sensitivity to determine if they would indeed meet these requirements. The overall system sensitivity was not part of the magnet PACE tests, but additional work with the leak detection system is planned for both magnet leak checking and vessel leak checking.

Magnet Cooldown and Warmup

The system requirements for both the magnets and the cryogenics system specify that the cryogenics systems be capable of cooling the magnet system down in

five days. An analysis performed by General Dynamics indicated this could be accomplished with flow rates they specified (Table 7). However some of the longer support rods would not have reached steady state conditions in that time, and the heat leak would be greater than when they did. Our actual experience, however, was that the cooldown time was considerably longer than the 120 hours specified. The solenoid magnets and the A2i high-field axicell magnets cooled down much faster than the other magnets, and, in fact, the helium flow to these magnets was shut off most of the time to keep the temperatures of these magnets close to that of the other magnets. Figure 33 presents the average case temperatures of the various

Table 7. Comparison of Required Versus Observed Helium Flow Rates.

Control Valve	Magnet	Required Flow (gps)	Flow at 100% (gps)	Maximum Flow (gps)
25-04	WM1	125.0 ^a	7.0	63.5
25-05	WM2	125.0 ^a	12.5	71.5
25-06A	W(T1 and trims)	18.0	19.0	47.5
25-06B	W(T2 and trims)	32.0	10.0	46.0
25-07A	WA2i	4.0	5.5	51.0
25-07B	W(A20 and A1)	45.0	6.0	51.0
25-08	W(S5 and S6)	14.0	10.0	58.0
25-09	W(S3 and S4)	13.0	18.0	55.5
25-10	W(S1 and S2)	17.0	20.0	23.0
25-11	E(S1 and S2)	13.0	10.0	45.0
25-12	E(S3 and S4)	13.0	13.0	56.0
25-13	E(S5 and S6)	14.0	6.0	46.0
25-14A	EA2i	4.0	8.0	50.0
25-14B	E(A20 and A1)	45.0	14.5	53.0
25-15A	E(T1 and trims)	18.0	10.0	46.0
25-15B	E(T2 and trims)	32.0	20.0	46.0

^aIncludes flow through the guard vacuum circuit

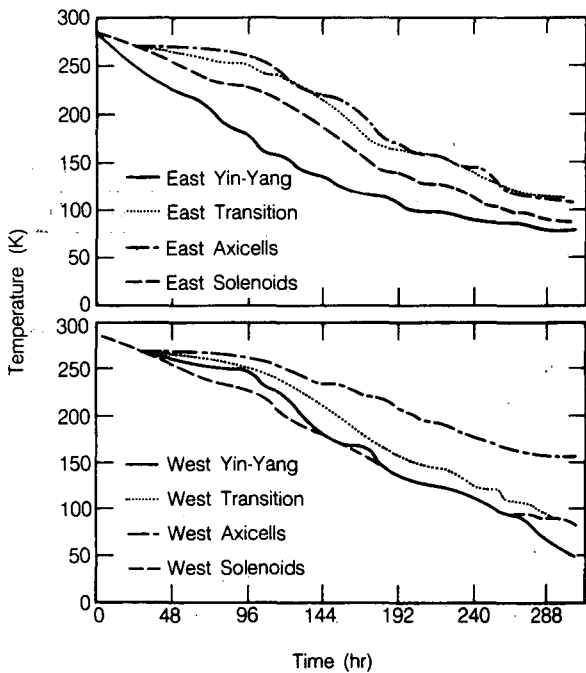


Figure 33. Magnet cooldown data.

main magnets as a function of time from the start of LN₂ flow to the cooldown heat exchangers. The values reported here are only for the first 300 hours. The outer axicell magnets were the slowest magnets to cool down; the west group was the slower of the two. The transition magnets cooled somewhat faster than the axicell magnets, and the T1 transition magnets and trims cooled somewhat faster than the T2 transition magnets and trims.

The east cryogenic system cooldown (supplying only the east Yin Yang magnet) was started on December 5, 1985, and testing of the east Yin Yang magnet commenced on January 20, 1986. The west-end cooldown (supplying all magnets other than the east Yin Yang

magnet) was started on December 7, 1985, and testing of the magnets serviced by this system commenced on February 5, 1986. A significant fraction of this period, amounting to at least 14 days, was spent repairing the west-end cryogenic system coldbox.

The magnet warmup was started on February 25, 1986, and continued through March 5, 1986. The warmup curves are given in Fig. 34 and reveal that approximately 170 hours were required to heat the magnets to room temperature after turning on the auxiliary heat exchangers. There are no specific warmup times defined in the systems requirements, however, from an operational standpoint this time is adequate.

In order to understand the excessive cooldown times, a series of room temperature measurements was made after March 5, 1986. These measurements were made to determine the mass flow rates that were available when the helium control valves were set to 100%

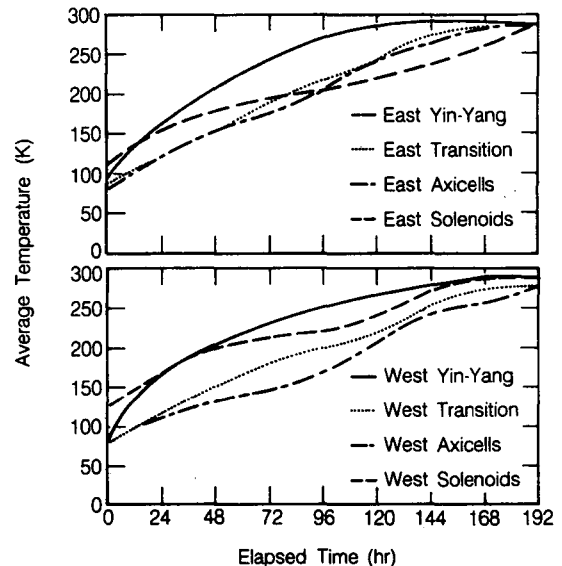


Figure 34. Magnet warmup data.

and the mass flow rates available when the mechanical control stops were removed allowing the maximum opening of the valves. These figures with the required mass flow rates are presented in Table 7. Examination of these data reveal some correlation to the cooldown data. The 100% flow rates for the inner axicell magnets and the solenoid magnets, with the exception of ES5 and ES6, were close to the required flow rates. During cooldown, these magnets cooled more rapidly than the others. The 100% flow rates for the outer axicell magnets were much less than the required flow rates and their cooldown required more time. Furthermore, the west outer axicell magnets had less flow than the east ones and cooled more slowly. Finally, the flow rates to the transition magnets were generally less than the required values, although not to the same extent as the axicell magnets, which resulted in an intermediate cooling rate. In summary, it appears that although the system's requirement of a 120-hour cooldown time was not met, a significant contributing factor was that the dewar control valves were not set and opened enough. This problem can be easily remedied by readjusting the mechanical stops on all control valves prior to the next cooldown.

Nitrogen and Helium Heat Loads

The system of liquid nitrogen cooled panels shields the liquid helium cooled surfaces from ambient thermal radiation. Because of the T^4 behavior of radiative heat transfer, it is imperative that the liquid nitrogen panels have a minimal increase in temperature above the nominal for the liquid nitrogen system. The MFTF-B instrumentation does not include an array of temperature sensors on the panel surfaces, so a measurement of heat load on the LN₂ panels is essential to demonstrate that the panels are operating properly. During the MFTF-B PACE acceptance tests the heat load on the liquid nitrogen system was determined from measurements of the mass flow rate, measurements of the pressure drop across a precision orifice in the return line, and conversion to mass flow using conventional formulas for orifice-type flow meters. Comparing the observed heat loads with calculated values based on an emissivity of 0.1 for both vessel wall and LN₂ panel and assuming a view factor of 1, there was very good agreement except for the axicell magnets, which had significantly lower than expected heat loads. These emissivity values are consistent with experimental results reported for large scale practical materials. The lower heat loads on the axicell magnets may have been due to a view factor less than 1.

The situation was different for the liquid helium heat loads. Table 8 presents a breakdown of the heat loads expected in the conditions of the PACE test versus the actual measurements. The column entitled "Expected Heat Loads" contains the expected heat loads from the LN₂ panels, assuming an emissivity of 0.1 rather than the more conservative 0.3 that was used in the initial engineering design. The column entitled "Residual Gas Conduction" takes into account the fact that when the heat load measurements were made on the magnets connected to the 8-kW cryogenics system, the vessel was at a helium partial pressure of approximately 1.0×10^{-4} torr. This would result in a conduction heat flux of approximately 1 W/m^2 from the LN₂ panels to the magnet surface. The residual gas conduction heat loads take into account all LN₂/LHe interfaces. The column entitled "Excess Heat Load" is the difference between the observed total and expected heat loads. The total excess is about 4500 W.

Examination of Table 8 reveals that the heat loads measured for WM1, WM2, and EYY agreed with the expected values. For all other magnets, however, the heat loads were higher than expected. This implies that some of the LN₂ panels that cover the magnet or

helium pipe surfaces were unwetted and functioned as a thermal radiation shield that would float at about 250 K. The radiative heat load on the magnet from these unwetted portions would contribute approximately 11.5 W/m^2 and the conductive heat load through the panel supports would be approximately 3.5 times greater than the design value. Based on the excess heat load for magnets other than the Yin Yang magnets, this was used to determine that between 5 and 10% of the LN₂ panels were unwetted.

Magnet Operation

A chronology of the series of tests that were performed is presented in Table 9. The general testing plan was to first energize individual coils to low currents and then discharge them through their slow-dump resistors. This allowed time to calibrate quench detectors, correct instrumentation wiring errors, make changes to the controller software, and adjust the gains in the various power supply controllers. After these low power tests were completed, we proceeded to charge the coil groups in steps to high currents. Table 10 presents a listing of the design current and the choke mode currents for each magnet (which is the mode for the installed wiring). After completing the group tests, we charged the entire magnet system in the full choke mode. Our initial intention was to do this in one step to 100% current and then fast discharge the entire magnet set. However, when we were at about 90% of full current, we experienced a spontaneous fast dump. The reason for this was traced to a problem in one of the solenoid trimming power supply controllers. When some of the magnets would approach this current setting, this trim controller would open full negative charge, which would indicate a very large induced voltage and the overall magnet controller would view this as a large rapidly increasing normal zone and dump the magnets. Once the trimming power supply board was changed, we had no further problems and the magnets were charged to 100% full choke mode and held there for one day while other tests were being performed.

During all chargings and dischargings the magnets behaved as predicted. There was no evidence of quenches, and the charging and discharging times agreed with the design values. Many other systems were operated simultaneously with one or more magnets, including the operation at full current of two neutral beam source modules and ECRH while in the 100% current choke mode. None of these other systems effected the magnet system operation. Except for the A1 axicell magnet and the inner solenoid magnets, all magnets were charged to their full design current. These two systems were not because the system was wired for choke mode operation. However, based on the performance of the similar A20 axicell magnets and the other solenoid magnets, it is safe to assume that these coils would have performed equally well. Additionally, during choke mode operation the magnet fields were measured by NMR probes, and the results agreed well with the design requirements. The only NMR probe that did not function was the important 12-tesla probe. Because of such a high field this probe could not be calibrated prior to the PACE acceptance tests and therefore we don't have any explanation for why there was no reading. Table 11 presents the measured field data with calculated field data based on current settings. Calculation 1 uses the power supply requested current settings and Calculation 2 uses the actual current settings in the magnets and a calculated deflection of the magnets. The experimental data agree well with the calculated values. One possible cause of slight error is the alignment of the NMR probes to the coil bundle which was only done at room temperature.

Table 8. Expected Versus Measured Helium Heat Loads.

Magnet	Expected Heat Load (W) ₁	Residual Gas Cond'n. (W) ₂	Total Expected (W) ₁₊₂	Observed Heat Load (W) ₃	Excess Heat Load (W) ₃₋₁₋₂
WM1	195.0	186.0	381.0	375 ± 5	-6.0
WM2	182.0	186.0	368.0	337 ± 10	-31.0
W(T and Trims)	178.0	139.0	317.0	1340 ± 50	+1023.0
WA	127.0	75.0	202.0	443 ± 120	+241.0
W(S5 and S6)	98.0	55.0	153.0	294 ± 45	+141.0
W(S3 and S4)	71.0	55.0	126.0	376 ± 25	+250.0
W(S1 and S2)	84.0	55.0	139.0	494 ± 25	+355.0
E(S1 and S2)	84.0	55.0	139.0	508 ± 20	+369.0
E(S3 and S4)	71.0	55.0	126.0	374 ± 55	+248.0
E(S5 and S6)	98.0	55.0	153.0	528 ± 20	+375.0
EA	127.0	75.0	202.0	490 ± 90	+288.0
E(T and Trims)	178.0	139.0	317.0	1470 ± 110	+1153.0
EYY	363.0	0.0	363.0	405 ± 70	+42.0

Magnet Case Strains and Strut Loads

The magnet strains and strut loads were calculated by General Dynamics during design for the Mars and Kelly modes of operation. In the PACE test and

for the first physics operational runs, the magnets were configured in the choke mode. Although there were some differences in the current settings in the three modes, they were small, so that we anticipated small differences in the the strain and load data.

Table 9. PACE Magnet Operation Test Chronology.

Date (1986)	Accomplishment
Jan. 20	Calibrate EM1 quench detector (EM2 to 500 A and slow dump)
Jan. 21	Calibrate EM2 quench detector (EM1 to 500 A and slow dump) EYY to 10% current and fast dump EYY to 25% current and fast dump EYY to 50% current and fast dump
Jan. 22	EYY to 75% current and fast dump EYY to 100% current and fast dump
Jan. 24	EYY to 100% current and slow dump (ECRH Testing)
Feb. 5	Calibrate WM1 quench detector (WM2 to 500 A and slow dump) Calibrate WM2 quench detector (WM1 to 500 A and slow dump) WYY to 50% current and fast dump WYY to 75% current and fast dump
Feb. 6	WYY to 100% current and fast dump
Feb. 8	Calibrate T1 quench detector (T2 to 500 A and slow dump)
Feb. 9	Calibrate T2 quench detector (T1 to 500 A and slow dump) All transition magnets to 50% current and fast dump All transition magnets to 75% current and fast dump
Feb. 10	All transition magnets to 100% current and fast dump
Feb. 11	Calibrate all axicell quench detectors A1 and A20 to 500 A, A2i to 200 A and fast dump
Feb. 12-15	Calibrate solenoid quench detectors (300 A and slow dump)
Feb. 16-17	Calibrate trim quench detectors (300 A and slow dump) E Trim 1-5 and W Trim 1-5 only
Feb. 17	Axicells to 50% choke mode current and fast dump
Feb. 18	Axicells to 100% choke mode current and fast dump Solenoids to 100% choke mode current and fast dump
Feb. 19	All magnets charging -- spontaneous fast dump at 90% choke mode current due to problems with one of the solenoid magnet trim power supply controls -- problem corrected.
Feb. 20	Full choke mode current in all magnets (start testing neutral beams and diagnostics)
Feb. 21	Magnets dumped

Table 10. Magnet Currents Used in the PACE Test for Choke Mode.

Magnet	Design Current (A)	Choke Mode Current (A)
M1	3837	3837
M2	4410	4410
T1	5266	5101
T2	6278	5875
A20	4648	4648
A2i	1504	1504
A1	4208	960
S5 and S6	2866	2866
S3 and S4	2778	1707
S1 and S2	2746	1707

For the strain gauge measurements, there were small discrepancies between the calculated data and the measured data. Again this is due primarily to a difference in the operating mode. The strains remain within the LLNL design requirements document design limits. However, additional calculations based on the choke mode operating scenario should be made prior to starting actual physics operations.

For the measured strut loads, the axial struts had measured loads about 10% higher than calculated by General Dynamics for the Kelly/Mars mode operating case. Again, although higher than anticipated, these were within the design limitations. The axial links between magnets had loads measured about one-half of the calculated values and the hide struts had kick loads (due to misalignments) of about 70% of the General Dynamics maximum design limits. The strains and loads were within the design limitations and presented no problems during magnet operation.

Table 11. Calculated and Measured Choke Mode Magnetic Fields.

Magnet	Calculation 1 Field (T)	Calculation 2 Field (T)	Measured Field (T)
WM2	3.0330	3.0058	2.8924
WYY (center)	1.0051	1.0447	1.0179
WM1	3.0339	2.9701	2.9423
WT2	0.9451	0.9069	0.9525
WT1	1.6087	1.5669	1.5727
WA2	11.9050	11.9560	Not Measured
WA1	2.3358	2.3467	2.3069
CC	1.0471	1.0508	1.0618
EA1	2.3306	2.3488	2.3033
EA2	11.8820	11.9220	Not Measured
ET1	1.6081	1.5689	1.5879
ET2	0.9217	0.8845	0.9299
EM1	3.0076	2.9204	2.9539
EYY (center)	1.0016	1.0271	1.0307
EM2	3.0391	2.9596	2.9631

Lessons Learned and Additional Work

The most important aspect of the MFTF magnet project is that with the successful completion and operation, superconductivity is now a mature technology at least as far as pool-boiling magnets are concerned. No longer do superconducting magnets have to remain only in the laboratory as a research science endeavor. Indeed, with the successful completion and operation of these 42 magnets, we have shown that superconducting magnets can be a tool for science and industry almost in the same way as normal conducting magnets. One of the reasons for this success is because industry is now willing and able to work with cryogenics, vacuum, and superconducting materials. Indeed, because of management interest in future work as well as commitment to the timely successful completion of MFTF, the superconducting industry is now ready for the next step, whatever that may be. Below are listed some of the major industrial subcontractors and their portion of the MFTF magnet system. Their efforts and management attention greatly helped with the MFTF success.

- General Dynamics -- Magnet Design, Fabrication
- Chicago Bridge and Iron -- Coil Cases, Installation
- Rigging International -- Installation
- Kobe Steel Limited (Japan) -- Support Rods
- Lear Siegler, Incorporated -- Support Rods
- Oxford Airco Superconductors -- Superconductor
- Intermagnetics General Corporation -- Superconductor
- Supercon, Incorporated -- Superconductor
- Furukawa Electric (Japan) -- Superconductor
- Meyer Tool and Manufacturing, Incorporated -- Vapor Cooled Current Leads
- Dynapower Corporation -- Power Supplies
- Hewlett Packard -- Control System
- Hydro Electric -- Electrical Installation.

There is more work to do before physics operations that is important to the future operations of MFTF as well as for the planning of additional superconducting magnet systems in the future. Some of the items listed below will apply to systems other than the magnet system and therefore are not limited to superconducting magnets.

- Helium Leak Checking. For large vacuum vessels and magnets, more system sensitivity is needed. This should be planned in the preliminary design phase and not just incorporated as an add-on during construction. Leak checking sensitivity has been a major concern for fusion machines for the better part of a decade and needs to be improved. Additionally, more time should be allowed in the project construction schedules for this testing and repair.
- Cryogenic Helium Flow Control Valves. The seating and calibration of these valves should have been done prior to the first cooldown of the magnets. It is imperative that this be accomplished prior to the next cooldown.
- Magnet Testing Schedule. Because of delays during cooldown and successful operation of the cryogenics systems, the length of time for the magnet group and choke mode testing was less than desired. The magnet tests and sequence of events were well planned in advance but were shortened because of other delays (at the start) and project dedication and shutdown (at the end). For future tests, this schedule should be adhered to.
- Liquid Helium Heat Loads. The higher than calculated helium heat loads will require the following work to make the system more efficient. First, LN₂ shrouding should be added to all solenoid magnet

helium pipes and should be checked for the east axicell magnet helium pipes. Secondly, the magnet supply dewar heat leaks and the LN₂ shield system unwetted areas needs to be checked and repaired.

- Additional Measurements. Prior to the next operation of MFTF, a calibration procedure needs to be developed for the 12-T NMR probes so that the high field axicell magnet field can be measured. Also,

additional stress analysis for the actual choke mode current settings should be performed to explain the stress and strain discrepancies measured.

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