GDC REPORT NUMBER LLNL-GDC-84-004¹

MIRROR FUSION TEST FACILITY-B (MFTF-B)

AXICELL CONFIGURATION

NbTi Magnet System	UCRL--15700-Vol.1
Design and Analysis Summary	DE85 017283

May, 1985

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Prepared under
Contract 9590309

Prepared for
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INTRODUCTION

General Dynamics Convair Division (GDC), with the support of the Lawrence Livermore National Laboratory (LLNL), has produced designs and confirmatory analysis for the MFTF-B (Axicell configuration) Axicell magnets, transition coils, and solenoid magnets as well as design modifications required for the existing yin-yang magnet design. Design responsibilities of GDC contract 9590309 with LLNL included the design of: magnet windings and structures; magnet supports out to the vacuum vessel; current leads out to the warm buses; instrumentation for all of the magnets, supports, and leads; and the LN and water-cooled thermal radiation shields for all coils and their supports.

This report summarizes the designs and analyses produced by GDC for the four Axicell magnets (A1 and A20, east and west), the four Transition magnets (T1 and T2, east and west), and the twelve Solenoid magnets (S1 through S6, east and west). The design and analysis of the two AWI Nb_3Sn insert coils is summarized in GDC report number MFTF-7200-R-911-RWB dated March, 1984.

Over four million drawings and specifications, in addition to detailed stress analysis, thermal analysis, electrical, instrumentation, and verification test reports were produced as part of the MFTF-B design effort. Significant aspects of the designs, as well as key analysis results, are summarized in this report. In addition, drawing trees and lists of detailed analysis and test reports included in this report define the locations of the detailed design and analysis data.

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MFTF-B AXICELL CONFIGURATION AND DESIGN REQUIREMENTS

2.1 Configuration

The magnet system for the Mirror Fusion Test Facility (MFTF-B) contains forty-two superconducting magnets. Twenty-six of these magnets produce the primary magnetic fields required for plasma confinement. An additional sixteen smaller trim coils are used to adjust field discrepancies caused by coil misalignments. General Dynamics' MFTF-B responsibilities relate to the twenty-six primary magnets illustrated in Figure 2-1. LLNL had the responsibility for the design and fabrication of the sixteen trim coils which have been deleted from Figure 2-1 for clarity.

The twenty-six primary coils are identified as follows:

<u>Coils</u>	<u>Designation</u>
12 Solenoid Coils (SM)	S1 through S6 (east and west)
4 Transition Coils	T1 and T2 (east and west)
4 Axicell Coils (NbTi)	A1 and A2 (east and west)
2 Axicell Insert Coils (Nb_3Sn)	A2I Inner (east and west)
2 Yin-Yang Coil Pairs	M1 and M2 (east and west)

Figure 2-1. MFTF-B Primary Magnet System.

The coils are numbered consecutively from the center of the machine to the outside. For example, the S1 solenoids (east and west) are nearest the machine centerline and the S6 solenoids are the coils nearest the ends of the machine. Also, the A1, T1, and M1 coils are nearer to the center of the machine, respectively, than the A2, T2, and M2 coils.

LLNL developed coil geometries for the MFTF-B Axicell Configuration that met the physics requirements for plasma containment and met conductor current density and peak field requirements, and magnet cross-section space requirements identified by GDC. This development was an iterative process that involved many changes, spanned many months, and continued into the preliminary design phase. The geometry that resulted from this iterative process is tabulated in Table 2-1 and shown graphically in Figure 2-2, which is part off the current MFTF-B magnet design Requirements document.

Table 2-1. MFTF-B Magnet Geometry

Coil (E&W)	Major Radius			Minor Radius		Coil Cross-Section MxM	Average Turn Length (M)
	Radius (M)	Angle (Deg)	CL Radius (M)	Radius (M)	Angle (Deg)		
M2	2.50	150.0	20.15	.75	180	.8235x.3277	17.80
M1	2.50	150.0	19.85	.75	180	.8235x.3277	17.80
T2	1.20	217.5	15.23	1.375	180	.3371x.3400	17.75
T1	.875	200.0	11.86	.700	180	.4215x.2038	10.51
A20	.928		10.00	.700	180	.9380x.4073	5.83
A21	.3883		10.10			.6572x.3523	2.44
A1	.928		7.88			.9380x.4073	5.83
S6	2.50		6.875			.163x.336	15.71
S5	2.50		5.625			.163x.336	15.71
S4	2.50		4.375			.163x.336	15.71
S3	2.50		3.125			.163x.336	15.71
S2	2.50		1.875			.163x.336	15.71
S1	2.50		.625			.163x.336	15.71

The individual M1 and M2 coils in Table 2-1 are the same geometry as the coils used in the MFTF-A yin-yang magnet. They are both "C"-shaped coils with two major radius segments and two minor radius segments. The plane of the major radius arcs (as in all of the "C" coils) is parallel to either the X-Z or Y-Z system planes. The only difference between the combined M1/M2 geometry in the MFTF-B axicell configuration and in previous (MFTF-A and MFTF-B A-Cell) designs is in the distance between coils. In the axicell configuration, the M1 and M2 coils were moved farther apart than they were in the previous designs.

The T1 and T2 transition coils are also "C" coils whose purpose is to transform the plasma shape, in a controlled manner, from the circular shape coming out of the axicell coils into the elliptical shape that enters the M1/M2 yin-yang magnets. The T1 and T2 coils are different from the M1 and M2 coils in that their major radius arc's span more than 180°. This produced a number of difficult helium ventilation problems that were solved during the magnet design.

The A1 and A2 axicell coils are solenoid coils whose function is to produce high on-axis magnetic fields that form one of the barriers in the plasma containment system. The A1 and A20 (outer) coils are identical except for their external support structures. They both produce, by themselves, on-axis fields of approximately 6 tesla. The A2 axicell coil, however, has a high-field insert coil designated A2I (insert) that fits inside of the A20 coil and raises this on-axis field to 12 tesla.

The twelve 5M central-cell solenoid coils provide most of the plasma containment volume in the MFTF-B system. These coils are all identical except for their external support structures and, in the case of the S6 coils, their case structures.

Figure 2-2. MFTF-B System Geometry (Ref. LLNL Drawing 82-107675-0D).

2.2 Operating Modes

LLNL defined the magnet operating parameters required to provide the plasma confinement field necessary for the proposed MFTF-B operating modes. The magnet system is required to produce the two on-axis field distributions, identified as the "MARS" and "Kelley" operating modes, shown in Figure 2-3. The primary difference between these two modes is in the field in the center cell region. This affects the operating currents in the 5M solenoid and A1 axicell coils. The magnet operating currents and peak fields for these two modes are given in Section 9 of this report.

In addition to the baseline field profiles shown in Figure 2-3, the magnet system must be capable of producing any other field profile within the envelope defined by the $B_c = 1.6T$ case that can be produced with the design power supplies. These may include:

- a) Acceptance test modes (various magnets on or off as limited by their power supply groupings).
- b) Experimental modes with varying current between adjacent solenoids as possible with the design power supply system.

One other additional operating mode was evaluated during the preliminary design phase. This mode, the inside barrier or TARA mode, requires relocation of the magnets. Although the magnets are capable of producing the required magnetic fields for the TARA mode, the structural design for this mode was not part of GDC's MFTF-B responsibilities. Further analysis and design would be required, therefore, to adapt the coils to the TARA mode.

Figure 2-3. MFTF-B On-Axis Field Requirements.

2.3 Design Requirements

The detailed MFTF-B design requirements are defined in the "MFTF Design Requirements Document," August 7, 1982, revised February 15, 1984, produced by the Lawrence Livermore National Laboratory. In addition to the geometric requirements listed in this section, and the operating current requirements listed in Section 9.0, the design requirements document specifies many performance requirements for the MFTF-B magnets. Several significant requirements are specified in Table 2-2.

Table 2-2. MFTF-B Magnet Design Requirements

Table 2-2(a) Conductor Requirements

1) Stability Margins -

Coil	Critical Current $\Delta I_c / I_{op} (\%)$	Critical Field $\Delta B_c / B_{op} (\%)$	Cryostable Current $\Delta I_s / I_{op} (\%)$
T1	10	10	10
T2	10	10	10
S1-S6	10	10	10
A20	15	10	15
A2I	100	7.5	15
A1	15	10	15

2) Stability margins adequate to accommodate current peaking for normal steady-state and dump conditions.

3) Charging Time <4 Hours.

4) Design voltage (coil-to-ground) = 1000V.

5) Maximum voltage across coil leads = 1000V.

6) Maximum quench temperature = 200K (2-D temperature calculation).

7) Design life = 550 magnetic cycles over 10 years.

Table 2-2(b) Magnet Heat Load Limitations

Coil Group	Thermal Load Limit (W)	Averaged 10% Duty-Cycle Time Neutronic Heating (determined by LLNL)	Instantaneous Neutron Heating	
			Total	Within Winding
T1 (2)	140	7.4	74	31
T2 (2)	200	4.5	45	24
A1 (2)	180	343	3430	2300
A2I (2)	40	98	984	616
A20 (2)	200	149	1486	800
S1-S6 (12)	650	225	2251	1442
Total for Entire System	1410	827	8270	5213

Table 2-2(c) Design Stress Requirements

ITEM	NORMAL OPERATION (HIGH PROBABILITY)	ABNORMAL OPERATION (LOW PROBABILITY)
Membrane Stresses, σ_m	2/3 Yield	100% Yield
Bending Stresses, σ_b	90% Yield	
Membrane + Bending	$\sigma_m + 0.741 \sigma_b$ $\leq 2/3$ Yield	$\sigma_m + \sigma_b \leq$ Yield
Ult. Stress, Magnets	1/2 Tensile Ultimate	60% Ultimate
Ult. Stress, Supports	33% Tensile Ultimate	60% Ultimate
Seismic Stress	120% of Above Allowables	100% of Above Allowables
Stress Cycles	At Least 4 x Operating Cycles	

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MAGNETIC FIELDS/FORCES AND INDUCTANCES

The superconducting magnets in the Mirror Fusion Test Facility have been configured to produce the required on-axis magnetic field distributions previously shown in Figure 2-3. The coil internal and external field distributions, the magnetic forces, and the coil inductances were calculated by LLNL using the EFFI (Electromagnetic Field Forces and Inductances) computer program. The following sections of the report summarize the EFFI modeling philosophy and some of the field force and inductance data for the MFTF-B Axicell Configuration magnet system.

3.1 EFFI Modeling

LLNL developed coil geometries for the MFTF-B Axicell Configuration that met the physics requirements for plasma containment and met conductor current density and peak field requirements, and magnet cross-section space requirements identified by GDC. This development was an iterative process that involved many EFFI model changes, spanned many months, and continued into the preliminary design phase. All of the magnetic fields and inductance data used in the magnet designs are based on the final L140-series EFFI models. The magnetic force data was obtained from both the L140 models and from earlier, slightly different, L70-series EFFI models. Some evaluations and magnet support analyses were based on data from the L70 models ratioed to agree with L140 magnet currents. All final case stress analyses were based on the L140 EFFI models.

The L140 (final) EFFI model geometry is the same as the coil geometry specified in Figure 2-2. The earlier L70 EFFI model used for some analyses has some differences in T2 transition coil geometry and small differences in coil pack sizes for T1, A2, and A1. The changes between the L70 and L140 series model geometry were necessitated by refinements to space constraints and conductor analyses that occurred during the

preliminary design and do not significantly affect those L70 model-based loads used for evaluation and support design. The model geometry differences are summarized in Table 3-1.

Table 3-1. Differences Between L70 and L140 EFFI Models

Coil	Parameter	Units	L70	L140
T2	Z _{CL} (Major Radius)	M	15.20	15.23
	R (Minor Radius)	M	1.35	1.375
T1	Coil Cross Section	M	.4495/.2038	.4215/.2038
A20 & A1	Coil Cross Section	M	1.0056/.4073	.4215/.2038
	Radius (Mean)	M	.950	.928
A2I	Coil Cross Section	M	.6136/.396	6572/.3523
	Radius (Mean)	M	.4276	.3883

The EFFI program represents a coil as a series of connected straight or curved current density elements. For MTF-B, two basic types of EFFI models were used to generate data. One model, described as a single-filament model, represented each coil with several parallel current density elements. The numbers and sizes of these current density elements in each of the coil cross sections were selected to coincide with the geometry of the NASTRAN finite-element structural models of the coils. This facilitated the transfer of force data from the EFFI analysis to the NASTRAN structural analysis. EFFI single-filament models were used to generate all field and inductance data and some of the force data. The magnetic field and inductance data was based on L140 model geometry and is summarized in Section 3.2. The single-filament force data generated for the MTF-B Axicell Configuration was based on L70 model geometry and L140 magnet currents and is discussed in Section 3.3. This data was used to select critical design conditions and to calculate magnet support system loads.

EFFI multi-filament models were used to generate detailed forces for those critical conditions that had been selected based on the single filament force data. This data was then used in the analysis of the coil cases. All multi-filament EFFI data is based on L140 model geometry.

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3.2 Magnetic Fields and Inductances

LLNL calculated on-axis, internal, and far field magnetic fields for use in the MFTF-B Axicell configuration design. All of these magnetic fields were based on the L140 EFFI geometry. The on-axis fields were previously shown for the MARS and Kelley operating modes in Figure 2-1. Internal magnetic field distributions were calculated at several locations in each MFTF-B coil. These distributions were used to determine the peak fields on the magnet conductors and to calculate internal pressure distributions in the coil packs. Selected field distributions are shown in Section 9.3 (conductor critical current margins) of this report. Far field magnetic field distributions were calculated by LLNL to assess the effects on surrounding equipment. This data was used by GDC to determine magnetic forces on the magnet current leads as they were routed to the vacuum vessel. The magnetic fields used by GDC in the lead analysis are documented in those analyses.

LLNL calculated the inductance between each magnet pair in the MFTF-B system. This data was used in the determination of coil-stored energies, discharge time constants used in conductor temperature rise calculations, and in the electrical circuit analyses of the transient current behavior of the magnets during a quench or fast dump. The self and mutual magnet inductances are tabulated in Table 3-2. The self- and mutual-stored energy contributions for each magnet are listed in Table 3-3 for the worst-case Kelley operating mode. The temperature rise calculations are summarized in Section 9.5 and the transient current analysis is summarized in Section 12.0.

Table 3-2. MFTF-B Magnet Inductances.

INDUCTANCE MATRIX 3/2/83 - L-142 MODE													
PAIRS	COIL	RZ	R1	T2	T1	A20	A21	A1	S6	S5	S4	S3	S1
1392	R2	11.11											
1392	R1	0.529	11.11										
600	T2	0.0303	0.0259	2.709									
430	T1	2.54×10^{-3}	6.16×10^{-3}	0.0494	0.7691								
2001	A20	8.41×10^{-3}	0.0175	0.0241	0.136	6.018							
3078	A21	2.34×10^{-3}	4.91×10^{-3}	1.11×10^{-3}	0.0641	1.93	3.77						
2001	A1	4.96×10^{-3}	8.86×10^{-3}	7.38×10^{-3}	0.0167	0.394	0.1270	6.018					
500	S6	8.23×10^{-3}	0.0139	5.37×10^{-3}	0.0133	0.0185	0.0529	0.649	3.607				
600	S5	6.45×10^{-3}	0.0104	6.76×10^{-3}	7.53×10^{-3}	0.0938	0.0264	0.330	0.9972	3.607			
600	S4	5.74×10^{-3}	8.00×10^{-3}	4.39×10^{-3}	4.64×10^{-3}	0.0521	0.0145	0.157	0.4442	0.9972	3.607		
600	S3	4.18×10^{-3}	6.28×10^{-3}	1.20×10^{-3}	1.02×10^{-3}	0.0311	8.72×10^{-3}	0.0816	0.228	0.4442	0.9972	3.607	
600	S2	2.62×10^{-3}	5.01×10^{-3}	2.40×10^{-3}	2.08×10^{-3}	0.0199	5.58×10^{-3}	0.0482	0.128	0.228	0.4442	0.9972	3.607
600	S1	2.85×10^{-3}	4.07×10^{-3}	1.85×10^{-3}	1.49×10^{-3}	0.0136	3.77×10^{-3}	0.0280	0.0770	0.128	0.228	0.442	0.9972 3.607

(Inductance in Henries)

Table 3-3. MFTF-B Magnet Stored Energies (10^6 Joules)

STORED ENERGY (MJ) "HELLEY" MODE													
PAIRS	COIL	RZ	R1	T2	T1	A20	A21	A1	S6	S5	S4	S3	S1
4409	R2	108.0	4.44	0.417	0.0292	0.0857	7.16×10^{-3}	7.01×10^{-3}	0.0520	0.0408	0.0315	0.0256	0.0207
3004	R1	4.44	80.4	3.08	0.0612	0.154	0.0141	0.0105	0.0158	0.0561	0.0423	0.0337	0.0282
6248	T2	0.417	3.08	52.8	0.806	0.348	0.0334	0.0150	0.0634	0.0560	0.0281	0.0278	0.0206
5222	T1	0.0292	0.0612	0.806	10.5	2.17	0.260	0.0283	0.0995	0.0563	0.0337	0.0219	0.0149
4620	A20	0.0857	0.1540	0.348	2.12	84.2	6.71	0.591	1.22	0.621	0.334	0.200	0.126
1504	A21	7.16×10^{-3}	0.0141	0.0150	0.260	6.71	4.25	0.0620	0.116	0.0561	0.0303	0.0182	0.0115
649	A1	7.01×10^{-3}	0.0109	0.0150	0.0283	0.591	0.0620	1.27	0.622	0.307	0.142	0.0736	0.0412
2866	S6	0.0520	0.0738	0.0634	0.0995	1.22	0.116	0.622	14.8	4.10	1.77	0.908	0.504
2866	S5	0.0408	0.0567	0.0590	0.0563	0.671	5.68×10^{-2}	0.307	4.10	14.8	3.97	1.77	0.897
2778	S4	0.0315	0.0423	0.0361	0.0337	0.334	0.0303	0.142	1.77	3.97	13.9	3.85	1.69
2778	S3	0.0256	0.0332	0.0278	0.0219	0.200	1.82×10^{-2}	0.0736	0.908	1.77	3.85	13.9	3.24
2748	S2	0.0207	0.0262	0.0206	0.0149	0.126	0.0115	0.0412	0.504	0.897	1.69	1.80	13.6
2748	S1	0.0173	0.0213	0.0159	0.0107	0.0843	0.00779	0.0250	0.393	0.504	0.870	1.69	3.76
Total E		113	88.4	57.7	14.0	76.8	11.6	3.20	24.7	27.5	27.5	27.3	28.0

3.3 Magnetic Forces

Electromagnetic loads constitute the primary source of structural loads on the MFTF-B magnet system. They are virtually the only source of stresses in the magnet conductor and cases and they contribute a significant amount to the magnet support system design loads. The definition of the critical design magnetic loading conditions and the calculation of the magnetic loads for those conditions was a complex task. A large number of potential loading conditions are possible in the MFTF-B magnet system because of the large number of coils and their many possible steady-state and transient operating modes. It was necessary to evaluate the magnet loads caused by many of these possible conditions in order to select the critical design conditions.

Because of the time and cost involved in generating detailed EFFI loads for each potential condition (and because it was not possible to identify all potentially critical conditions early in the program), we developed a systematic, automated way of generating and evaluating magnet loads using single-coil and coil-pair "unit-current" loads. This method is documented, in detail, in Volume III of the MFTF-B Final Stress Report (GDC-LLNL-84-002). In summary, however, we accomplished the following tasks:

- 1) LLNL used the EFFI single-filament models described in Section 3.1 to generate magnetic force data for each coil standing alone and interacting forces between each coil pair using "unit" current densities.
- 2) GDC determined the possible steady-state and transient magnet operating modes consistent with the magnet power supply and protection circuitry defined by LLNL and consistent with the magnet functional operating requirement. We considered both normal- and fault-type conditions including the following:

- Any steady-state condition with coil groups on common power supplies on or off.
- Any fast-dump condition with any combination of coil groups on or off.
- Any quench condition where the protection system operates as planned.

A fault condition was considered to be any quench condition where the circuit breakers did not open.

- 3) GDC determined magnet currents for the potential steady-state operating modes. GDC and LLNL both conducted electrical analyses to determine the magnet currents for transient conditions. It was determined that there was no current peaking for "normal" transient conditions and that the peaking for fault conditions was less than the 15 percent preliminary number used in the loads and stress analysis.
- 4) GDC then ratioed and combined the "unit" current density loads from the single-filament EFFI model for each loading condition to be analyzed. The L70 EFFI unit data was used along with the L140 magnet currents to generate this data. GDC developed a special purpose computer program called ELPP (Electromagnetic Loads Processing Program) to combine and plot these loads. This program is also documented in Volume III of the Final Stress Report. This data was then evaluated to determine potential critical conditions.

After evaluating the single-filament, combined loads created by the ELPP program, GDC selected several potential critical conditions for detailed stress analysis. GDC then used the ELPP program to ratio and combine data from the L140 multi-filament EFFI models to create detailed loads for input into the NASTRAN finite-element structural analyses. Because of the correspondence between the EFFI and NASTRAN model geometry mentioned in Section 3-1, the ELPP program can create a NASTRAN loads input file that requires no additional work by the analysts.

The detailed magnetic loads used in the structural analyses are not presented in this summary report. Computer listings of the F.E. analysis loads and model data are available in the Final Stress Report. Useful examples of the MFTF-B loads, however, are shown in the tables and figures in this section and are discussed briefly in the following paragraphs.

The steady-state normal operating loading conditions were critical for the design of the transition coil magnet case structures. Figure 3-1 illustrates the distributed loads on the T1 and T2 coils for their critical conditions. Figure 3-2 illustrates the radial and axial loads on the axicell coils for normal operating conditions. Although these loads are critical for the axicell magnet conductor, the case structure for the axicell coils is designed by normal (with some coils off) and fault conditions that cause high (2.5-3.0 million pounds) side (axial) loads on the magnet cases. Figure 3-3 illustrates the axial loads on each coil in the magnet system for the normal operating MARS and Kelley modes. The highest axial loads on the magnets, however, occur for steady-state or transient conditions where some coils are on or off.

Electromagnetic loads are also critical to the design of the magnet support system. The axial support struts and links are designed by conditions that create the maximum axial forces on individual magnets or groups of magnets. The critical conditions were determined by evaluating coil pair axial load interaction data in a manner similar to that employed for determining critical magnet case loads. Tables 3-4 and 3-5 list the loads between each coil pair for the Kelley and MARS modes operating currents that were used to determine the maximum normal (non-fault) condition axial loads. Nonaxial electromagnetic loads between coils caused by coil misalignments were also calculated for use in the design of the magnet hanger support system. These loads are documented in the Final Stress Report.

Table 3-4. Axial (Z) Force Interaction Between Coils
(10³ lb., Kelley Mode)

	M2	M1	T2	T1	A20	A21	A1	S6	S5	S4	S3	S2	S1	S1	S2	S3	S4	S5	S6	A1	A21	A20	T1	T2	M1	M2
M2	0-1051	-81																								
M1	1051	0-1244																								
T2	04 1244	0	0-627	-111	-11	-2	-9	-9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T1	5	0	427	0-1491	-255	-10	-33	-7	-7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A20	0	25	113	1491	0	0	-324	-197	-197	-72	-39	-19	-19	0	0	0	0	0	0	0	0	0	0	0	0	0
A21	0	3	11	255	0	0	-39	-39	-16	-5	-5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A1	0	1	2	10	324	39	0	-141	-99	-42	-10	-9	-4	-2	-1	0	0	0	0	0	0	0	0	0	0	0
S6	6	5	9	23	335	39	141	0-1356	-444	-197	-95	-50	-25	-16	-8	-3	0	0	0	0	0	0	0	0	0	0
S5	6	5	0	7	152	16	99	1356	0-1314	-444	-195	-93	-50	-25	-17	-3	-8	0	0	0	0	0	0	0	0	0
S4	0	5	0	7	71	5	42	444	314	0-1274	-444	-189	-90	-49	-24	-14	-8	-4	0	0	0	0	0	0	0	0
S3	0	5	0	0	39	5	18	197	444	1274	0-1259	-444	-189	-90	17	-21	-17	-4	0	0	0	0	0	0	0	0
S2	0	0	0	0	10	0	0	93	195	444	1259	0-1240	-439	-187	-90	-49	-25	-16	-3	0	0	0	0	0	0	0
S1	0	0	0	0	13	0	4	50	93	189	444	1240	0-1240	-439	-189	-90	-50	-25	-16	-2	0	0	0	0	0	0

Table 3-5. Axial (Z) Force Interaction Between Coils
(10³ lb., MARS Mode)

	M2	M1	T2	T1	A20	A21	A1	S6	S5	S4	S3	S2	S1	S1	S2	S3	S4	S5	S6	A1	A21	A20	T1	T2	M1	M2
M2	0-1051	-64																								
M1	1051	0-1235																								
T2	04 1235	0	0-573	-110	-11	-14	-5	-5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T1	5	0	423	0-1444	-251	-20	-14	-4	-4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A20	0	25	116	1444	0	0	-2056	-214	-95	-43	-23	-11	-7	0	0	0	0	0	0	0	0	0	0	0	0	0
A21	0	3	11	251	0	0	-251	-23	-10	-3	-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A1	0	7	14	10	2056	251	0	-559	-392	-167	-72	-36	-18	-10	-7	-3	0	0	0	0	0	0	0	0	0	0
S6	3	3	3	14	314	23	559	0	-213	-173	-70	-35	-18	-10	-7	-3	-1	0	0	0	0	0	0	0	0	0
S5	3	3	5	4	85	10	392	513	0	-402	-193	-75	-35	-18	-10	-6	-1	-3	0	0	0	0	0	0	0	0
S4	0	3	0	4	41	3	147	173	402	0	-473	-145	-70	-33	-18	0	0	3	-3	0	0	0	0	0	0	0
S3	0	3	0	0	21	3	72	74	173	473	0	-467	-145	-70	-33	-18	-4	0	-3	0	0	0	0	0	0	0
S2	0	0	0	0	11	0	16	35	73	145	467	0	-463	-145	-70	-33	-18	-4	-6	-3	0	0	0	0	0	0
S1	0	0	0	0	7	0	18	19	35	70	145	463	0	-463	-145	-70	-33	-18	-4	-10	0	0	0	0	0	0

(a) T1 Coil

(b) T2 Coil

Figure 3-1. Transition Coil Electromagnetic Loads.

Figure 3-2. Axice11 Coil Electromagnetic Loads.

Figure 3-3. MFTF-B Normal Operating Axial Magnetic Loads.

4.0

TRANSITION T2 AND T1 COIL DESIGNS

4.1 Introduction and Drawing Tree

The MFTF-B axicell magnet configuration required two unique transition coil designs, T2 and T1, at the location where the previous transition coil for the A-cell configuration had been. The T2 and T1 coils are "C"-shaped coils similar to the previous yin-yang, A-cell, and transition coils, except that the major radius half-angle is in excess of 90 degrees. There are also more stringent space constraints required, and the scheduling limitations required maximum utilization of existing materials. A later impact was the determination that trim coils would be required in the magnet system which resulted in even greater space constraints being imposed.

The large major radius wrap angles for the T2 and T1 coils (108.75 and 110 degrees, respectively) required two additional or auxiliary vents, a more complex inlet lead configuration and different treatment of layer-to-layer and ground layer insulations, than the previous transition coil.

One high point in each coil required venting out the bottom of the conductor pack through the case coil form, posing a potential shorting problem. The design solution is shown in Figure 4-1 and involved the removal of two turns of conductor in the first layer, one turn in the second layer, counterboring of the coil form structure and the location of the vent such to allow a 15-degree upward angle of helium flow from the top of the highest conductor.

The stringent space restrictions and necessity of trim coils removed any possibility of using external superstructures to limit major and minor lobe spreading of the coils. This was achieved by the use of thicker (4-inch) case structures. The case structures were then trimmed where

required to provide a maximum clearance between adjacent coils while still maintaining acceptable local stress levels. Significant trim on both the T2 and T1 coils were also required for passage of the systems P2B2 beam. Figure 4-2 shows the relative location of coils and trim features.

All previous transition coils have had the primary vent and lead stacks located at the high point in the minor radius; whereas the T2 and T1 coil's stack is located on the major radius centerline which is the high point on the coil. The chosen concept of winding transition coils requires that the inlet lead exit the Kapton-covered conductor pack and contain its own convective helium flow by transversing the outside of the conductor pack with a minimum upward 15-degree flow angle. Flow passages are provided in the lead and helium containment and insulative properties are provided by Kapton-wrapping the leads when outside the conductor pack. For the T2 and T1 coils, the path is both long and complex in its geometry. These leads presented installation problems during fabrication, but were resolved within the design requirements imposed.

Again, the large wrap angle produces different helium flow requirements than for previous transition coils. A thicker ground layer perforated insulation was required, similar to that required for solenoids, with cross-flow and up-flow slots installed at a minimum angle of 20 degrees. This resulted in smaller sized panels and selective orientation of panels in the ground-layer, layer-to-layer, and plenum insulation.

In the T2 coil, a 4-inch case thickness was insufficient in limiting minor radius lobe spreading and four 2x10-inch tie plates were required across the extremities of the major radius.

The T1 and T2 transition coil designs relied heavily on concepts developed during the design and fabrication of the yin-yang coils and the design and winding of the A-Cell coil. Maximum utilization of conductor, insulation, and 304LN stainless-steel plate ordered during the A-Cell configuration was required in order to meet both economic considerations and critical schedules. Requirements on orientation of the T2 and T1

coils in the magnet system and constraints on inlet lead exiting geometry require differing winding directions be used. Winding of the T1 coil is initiated with a clockwise wind, whereas the T2 coil uses a counter-clockwise wind.

The drawing trees for the T2 and T1 coils are shown in Figures 4-3 and 4-4, respectively. The coil winding procedures for the T2 and T1 coils are 71EQ045 and 71EQ046 respectively. These specifications establish the procedures, materials, and associated documents required to wind and close out the transition coils.

Figure 4-1. Auxiliary Vent Exiting Bottom of Conductor Pack

Figure 4-2. Clearance Between Coils - M1/T2/T1/A2

Figure 4-3. Transition T2 Coil Drawing Tree.

Figure 4-4. Transition T1 Coil Drawing Tree.

4.2 Insulation and Coil Winding Design

The T2 coil, Figure 4-5, is significantly larger than the T1 coil, having a major radius of 1.2 meters with a half-angle of 108.75 degrees and a 1.375-meter minor radius. The conductor pack has 24 layers of 25 turns except again for layers one and two which have 23 and 24 turns respectively. This results in a coil with 597 turns. As with the T1 coil, the first two layers are Grade I conductor and the rest Grade II conductor.

The T1 coil, Figure 4-6, has a major radius of .875 meters with a half-angle of 100 degrees and a .7 meter minor radius. The conductor pack has 30 layers and 15 turns except for layers one and two which have 13 and 14 turns respectively. This results in a coil with 447 turns. The first two layers are Grade I conductor with the remainder being Grade II.

Both T2 and T1 coils have a common geometry characteristic that has influenced the conductor pack design. Both have a major radius half-angle in excess of 90 degrees which produces two local maximums in addition to the absolute maximum at the top of the coil. These local maximums result in the need for two auxiliary vents to prevent gas entrapment areas. One of these is required to exit at the bottom of the conductor pack which presented a potential shorting problem. The solution selected was to remove the last two turns of the first layer and the last turn of the second layer, relocating the vent in from the sidewall, and counterboring the case 1.5 inches at the vent (Figure 4-1). This produced a minimum distance-to-ground of 2 inches without any additional insulation, and a minimum up-angle of 15° from the conductor pack to the auxiliary vent.

4.2.1 Ground Layer Insulation

A filled epoxy compound is used to true-up the coil form on both the inner wall and flange. Six layers of .005-inch thick Kapton strips are glued onto the epoxy surface. These strips provide a minimum shorting path of 3 inches, even if there is a hole in one

of the layers. On top of the Kapton, single sheets of .063 thick solid G-10CR are placed. The next layer consists of perforated G-10CR sheets. One .063-inch sheet is used on the inner wall, while four sheets are used on the flange. These four sheets have their perforation pattern at $\pm 20^\circ$ which forms a plenum-like condition to ensure steady-state flow at the auxiliary vent.

4.2.2 Conductor Pack

The conductor pack is wound onto the ground layer insulation. A typical conductor-pack cross section, taken at the coil's major radius, and major components of the conductor pack are shown in Figure 4-7. The conductor used consists of a small monolithic NbTi/Cu superconductor in a vented stabilizing jacket constructed of copper. The winding technique for these coils results in a layer wind in major radius areas and a pancake wind in the minor radius areas. Splices occur at the bottom centerline of all layers in the coil except the first and last, all at the coils bottom centerline. The splices are at the first inside conductor turn on even layers and last outer conductor turn on odd layers.

The turn/turn insulation, also termed "button-on-a-string," consists of .048/.042-inch thick G-10CR fiberglass laminate octagonal-shaped bittons, .437-inch across the flats, adhesively bonded to dacron tape on .725-inch centers. This insulation serves as the standoff insulator between adjacent turns of conductor, allows for controlled helium flow throughout the pack, and provides the electromagnetic load transmissions.

The layer/layer insulation is .066/.060-inch thick perforated G-10CR fiberglass laminate. This insulation serves as the stand-off insulator between conductor layers and provides for controlled helium flow throughout the coil pack. The perforations are orientated so that the angle between them and the conductor is approximately 48° . Two types of layer/layer insulation are used; one has

a bearing area of 48 percent, the other 57 percent. The T2 coil uses the 48 percent bearing area insulation. The T1 coil has large forces in the upper half of the conductor pack which could cause coining of the conductor if the 48 percent bearing area insulation was used. Therefore, 57 percent bearing area insulation is used in this part of the T1 coil conductor pack.

Each completed layer of wound conductor is closed out by side glue blocks which serve to locate and hold the geometry of finished layers. The glue blocks are bonded to the lower adjacent layer/layer insulation. The radial glue blocks located at the minor radius ends serve to develop a controlled geometry from that resulting from reversed spiral winding and variations of the inner and outer splices and ramps. The glue blocks also provide a means of truing the coil pack geometry to a specified size and surface finish by a final machining operation. This is an important consideration since Kapton wrap is applied to this surface. The blocks are made slightly undersize relative to the conductor in the thickness direction to isolate any relative motion or tolerance influences to the conductor.

A 2.5-inch thick plenum chamber is located above the conductor pack and provides for controlled flow of helium and quick dispersal of gas bubble formation out through the vent. The plenum material consists of both solid and perforated fiberglass laminate, with the solid laminate construction occupying the section ± 37.5 degrees and ± 45 degrees about the major radius centerline for the T1 and T2 coils respectively.

The perforated plenum material has the same slotted perforation pattern as that of the layer/layer insulation except its slot orientation is ± 20 degrees about the coil's length direction. The perforated portion of the plenum is built up from four .066/.063-inch sheets with slots indexed and then bonded together on the coil to obtain correct curvature. The slot orientation is then alternated until the full buildup is obtained. In the major

radius portion of the coil, the full 2.5 inches of plenum are contained within the Kapton wrapping, whereas at the minor radius ends, only the first 1.0 inch of the plenum is Kapton wrapped. This allows for a .5-inch clamp plate installation and an upper 1.0 inch of plenum material for the inlet lead passage.

The high forces in the upper half of the conductor pack for the T1 coil requires the 57 percent bearing area pattern be used for the lower two layers of the plenum material. The upper eight layers of the plenum use the 48 percent bearing area pattern.

4.2.3 Conductor Ramps

The ramping of the conductor from one layer to the next is all accomplished in the upper minor radius end, Figure 4-8. The ramping from an odd layer to an even layer above it is done on the inside of the conductor pack. The ramping from an even layer to the odd layer above it is done at the outside of the conductor pack. In this way, the ramps alternate between the inside and outside of the conductor pack as the coil is wound.

The parts that make up the ramp details are all machined from G-10CR. They are designed to allow the conductor to make a smooth transition from one layer to the next and to provide good liquid helium ventilation in that area Figure 4-9.

4.2.4 Conductor Splices

The conductor splice fittings have an overall 22-inch length and are symmetrical about their centerline. Geometry of the fitting is established from the radius of the adjacent surface, practical minimum thickness of the tang ends (.065), and a width of 1.00 inch at a location 6 inches in from the ends. The first 3 inches of the fitting from each end accommodate the full conductor, the next 3 inches a conductor with the lower jacket surface removed, and the remaining 5 inches only the superconducting portion. The

conductor ends to be spliced are trimmed, leaving an excess of superconductor. The two ends of superconductor are then cold welded, shortening the superconductor until a good fit is made with the splice. The conductor is then soldered into the splice fitting which is machined from 1/8-hard copper with annealed tangs.

All splices occur at the centerline of the lower minor radius end of the coil, Figures 4-10 and 4-11, inner splices on even layers and outer splices at odd layers. The first layer of conductor splices into an inlet fitting and the last layer of conductor into an outlet fitting. The first two layers of the T2 coil use Grade I conductor whose available lengths were insufficient to complete a total layer, therefore, two additional splices were required. This results in the need for a total of 28 and 24 splice fittings for the T2 and T1 coils respectively.

On both minor radius ends there is a component designed to keep the conductor pack from springing up during final closeout. It consists of a 1/2-inch thick G-10CR clamp plate which sits on top of one inch of plenum material. To hold the plate down on the inside radius, shims are installed between the plate and the clamp bar. On the outside radius, 15 threaded clamp rods extend from one plate, along the edge of the conductor pack to the coil form.

4.2.5 Inlet and Outlet Leads

The inlet lead, Figure 4-12, connects the lead bus in the stack with the last turn of the first layer. It attaches to the conductor using the basic splice design. To get from the bottom to the top of the conductor pack, the lead exits the pack and is routed up through the clamp-down blocks. The inlet lead is wrapped with Kapton strips in this area to electrically isolate it from the case. This area has no liquid helium flow and so channels to carry liquid helium are cut in the lead. In order to

prevent entrapment areas in these channels, the inlet lead is designed to have a minimum up-angle of 15°. The inlet lead is secured to the clamp-down blocks through the use of a G-10CR wedge. A minimum cross-section of 1.5 square inches is used throughout the inlet lead.

The outlet lead, Figure 4-12, connects the lead bus in the stack with the last turn of the last layer. Again, the basic splice design is used for attaching the lead to the conductor. Tension is maintained on the conductor through the use of a .75-inch thick G-10CR block which butts up against the outlet lead. This block is bolted to a .25-inch thick 304L plate which is welded to the coil form. A minimum cross-section of 1.5 square inches is used throughout the copper outlet lead.

Upon exiting the conductor pack, each lead is bolted to a G-10CR plate. The two plates are then bolted together with three sheets of Kapton film between them. In this way, a minimum shorting path of three inches is maintained between the two leads.

4.2.6 Conductor Pack Closeout

After the pack is completed, the Kapton strips, which were part of the ground layer, are brought up around the pack to electrically isolate the conductor pack from the case. Sheets of solid G-10CR are placed over the Kapton strips to further protect the conductor pack. Filled epoxy is used between the G-10CR sheets and the case closures to ensure a tight fit.

COMPONENT	WT-LBS
CONDUCTOR PACK	26,390
COIL FORM	33,890
CASE CLOSURE	33,930
TIE PLATES	3,520
PLENUM	960
FILL & INSULATION	2,930
SUPPORT LUGS	1,000
	102,720
LINERS - DRY	2,670
SUPPORTS	2,920
STACK	1,550
	110,860

DOES NOT INCLUDE DIAGNOSTIC AND INSTRUMENTATION PACKAGES, UPPER TOLERANCE ON PLATE MATERIAL, OR TRIM COILS.

Figure 4-5. T2 Transition Coil Assembly

COMPONENT	WT-LBS
CONDUCTOR PACK	11,700
COIL FORM	18,260
CASE CLOSURES	18,680
PLENUM INSULATION	400
FILL & INSULATION	1,700
SUPPORT LUGS	2,030
	52,820
LINERS - DRY	1,410
SUPPORTS	2,420
STACK	2,200
	58,870

DOES NOT INCLUDE DIAGNOSTIC AND INSTRUMENTATION PACKAGES OR UPPER TOLERANCE ON PLATE MATERIAL.

Figure 4-6. T1 Transition Coil Assembly

Conductor Pack Cross Section

TURN/TURN INSULATION

PERFORATED INSULATION

Figure 4-7. Conductor Pack Cross Section and Details--Major Radius

Figure 4-8. Ramp End--Upper Minor Radius--Cross Section.

Figure 4-9. Ramp End--Upper Minor Radius--Plan View.

Figure 4-10. Splice End--Lower Minor Radius--Cross Section.

Figure 4-11. Splice End--Lower Minor Radius--Plan View.

Figure 4-12. Inlet and Outlet Conductor Leads.

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4.3 Structural Design

The T2 and T1 transition coil's structures consist of a coil form, twelve outer case subassemblies, four tension straps or superstructure for the T2 coils only, helium inlet and vent stack fittings, and clevis fittings for the hanger and side load struts and axial links.

The coil forms, Figure 4-13, are an all-welded, one-piece component on which the conductor pack is wound. Its inner peripheral wall and flange form a continuous "L"-shaped section. Both the wall and flange are fabricated from 4-inch thick 304LN stainless-steel plate welded together using E316L weld wire. The coil form's inside dimensions are dictated by the conductor pack sizing, with allowance for true-up, ground and plenum insulation, closeout requirements, and plate thickness tolerance. Both minor radius flange ends of the coil have fifteen 1/2-inch diameter tapped holes to accommodate studs. These studs, together with G-10CR fiberglass plates provided clamped-down provision of the minor radius coil winding pack at closeout.

The case structure consists of the coil form and twelve outer case subassemblies, Figure 4-14. The size of the "L"-shaped subassemblies, fabricated from 4-inch thick 304LN stainless steel plate, are determined by their weight and inside surface areas. During closeout, a controlled space between the completed coil pack and the case subassemblies is filled with epoxy compound. This requires a minimum of two case subassembly fit-ups before the closeout welds are made. Internal surface area is a factor due to its influence on epoxy compound set-up times. All closure welds require back-up bar provisions. This, together with critical area considerations, such as the vent stacks, inlet and auxiliary vents, required a preplanned installation sequence for the case subassemblies. The case structure is the primary structural component for the T2 and T1 coils. However, for the T2 coil case structure, additional stiffening of the major radius was required to prevent minor radius lobe spreading. This was done by the addition of four tie plates, 2 x 10 inches, connected across the inner and outer surfaces of the coil

close to its major radius centerline. The edges of the tie plates are located 2 inches from the coil's major radius centerline in the direction of the minor radius lobes. This location provided a 2.98-inch clearance between the tie plates and the M1 coil, and good structural efficiency. The tie plates were not directly welded to the case due to the adverse load pick-up and difficult weld techniques. The tie plates are welded to eight 2 x 3.75-inch high plates running the full depth of the case structure. These plates are then welded to the case, giving a 1.75-inch offset of the tie plates from the case surface.

Interference with adjacent coils, "stay-out" zone limits, and the addition of trim coils did much to influence the resulting structural design of the transition T2 and T1 coils. The addition of trim coils forced a design approach that eliminated any exterior superstructure that had previously been advocated to prevent minor and major lobe spreading. Both coil cases were chosen to be fabricated from available 4-inch thick material to keep lobe spreading to within acceptable limits. This proved acceptable for the T1 coil, but required the addition of four tie plates across the major radius of the T2 coil to limit the minor lobe spreading. The use of a 4-inch thick case over the previously advocated 1.75-inch thick case, created increased problems of interference with adjacent coils and violation of "stay-out" zones. After reiterative analysis a maximum trim was established in all critical areas. The resulting minimum wall thickness in the more critical areas was determined as being 2 inches, minimum. The nominal clearance between coils is given in Figure 4-2. Of these, the most critical clearance is the 2.71 inches between the T2 and T1 coils. This is due to the need to bring together the axial load groupings of the M2/M1/T2 coils and the T1/A2/A1/S6 coils during the room-temperature coil alignment procedure. This clearance will close down to approximately .75 inch during the alignment procedure. Great care was taken during the design and fabrication phases of the work to ensure the maximizing of this clearance.

The T2 and T1 coils each have a vent stack, LHe inlet, and two auxiliary vents. The vent stacks interface with the stack designs described in Section 8.0. The LHe inlet and two auxiliary vents interface with LLNL's

system piping. The cutouts in the T2 and T1 coil case structures, to accommodate the auxiliary vent fitting (1.0-inch pipe, Schedule 40) and the inlet fittings (3.0- and 2.0-inch pipe, Schedule 40, respectively), directly related to the internal diameter of the pipe. However, in the case of the vent stacks, the holes required (12-inch, Schedule 100, and 10-inch, Schedule 40, pipe for the T2 and T1 coils, respectively) were impractical. Cutouts in the cases, 8-inch diameter for the T2 coil and two 6-inch diameter half-circles spread 2 inches for the T1 coil, satisfied lead exiting requirements with insulation backup. Peak stresses in the area of these cutouts were kept to acceptable levels.

The T2 and T1 coils each have two hangers and one side-load strut and are connected to adjacent coils, M1 and A20, respectively, by four axial supports. The support systems for these coils are described in detail under Section 7.0.

T2 COIL
71E3305
WEIGHT=33,889 LBS.

T1 COIL
71E3215
WEIGHT=18,264 LBS.

Figure 4-13. Coil Forms - T2 and T1 Coils.

T2 COIL
71E3304
WEIGHT=33,928 LBS.

T1 COIL
71E3216
WEIGHT=18,679 LBS.

Figure 4-14. Case Subassemblies - T2 and T1 Coils.

AXICELL COIL DESIGN

5.1 Introduction and Drawing Tree

The MFTF-B axicell magnet configuration has three axicell coils at both the west and east ends of the facility. These axicell coils are designated WA20, WA2I, WA1, EA1, EA2I, and EA20. The axicell coils are the heart of the magnet configuration and experience the highest fields and currents. The A2I axicell insert coil is mounted in the bore of the A20 axicell barrier coil on a common magnet center. The A2I axicell coil uses an Nb_3Sn superconductor and was covered in detail under "High Field Nb_3Sn Axicell Insert Coil for the Mirror Fusion Test Facility-B (MFTF-B) Axicell Configuration," GDC Report No. MFTF-7200-911-RWB dated March, 1984. The A2I coil in combination with the A20 coil produces an on-axis field of 12 tesla. The peak fields in the A1 and A20 coils reach 7.7 tesla in the TARA operating mode.

The design of the axicell A2 and A1 coils posed a challenging problem due to the critical space constraints imposed by adjacent coils and diagnostic "stay-within" zones and the need to use existing conductor. The critical space constraints resulted in the need for an all-machined 304LN stainless steel bobbin and the loss of twelve conductor turns. Both the inner ring and sidewalls of the bobbin required extensive sculpturing to satisfy the structural requirements within the limited space. Further details on this are given in the appropriate sections of this report. The axicell coil design combines features of the solenoid and transition coil designs. The conductor, used in the transition coils, is a monolithic $NbTi/Cu$ superconductor contained in a ventilated copper jacket (Figure 4-7). The axicell coils are a solenoid-type coil and it was decided to make a layer-wound coil in a bobbin similar to that used in the solenoid coil winding. Two major differences were the use of a pancake-wound inlet lead and the ability to accommodate a conductor

splice in any layer or turn of the conductor pack within certain restrictions. The use of a pancake-wound inlet lead provided a more compact conductor pack without the need to recess the lead in the coil bobbin's sidewall. Incorporating a splice within any layer or turn was a requirement brought about by the need to use the available conductor lengths from the previous MFTF-B A-Cell magnet configuration. The A20 and A1 axicell coils all have identical conductor packs with 29 layers of 68 turns of conductor. However, a requirement of the bobbin inner ring for internal case reinforcement, at the opposite end to the inlet lead, resulted in the loss of six turns on the first two layers. This did not have a significant effect on the coil performance.

The support locations for the coils are 307.09 for the A1 coil and 397.64 for the A2 coil. These stations were originally the coil's magnetic center stations. In May of 1983, the "Design Requirements Document" (DRD) was updated which included the relocation of the magnetic center of the west and east A1 coils from 7.80M to 7.88M (307.09 to 310.24). The support locations, however, were not changed.

The drawing trees for the A20 and A1 axicell coils are shown in Figure 5-1.

The coil-winding procedure for the A20 and A1 axicell coils is 71E0047. This specification establishes the procedures, materials, and associated documents required to wind and closeout the coils.

Figure 5-1. A2 and A1 Coil Drawing Tree.

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5.2 Insulation and Coil Winding Design

The axicell coils, A1 and A20, are solenoid-type magnets and are identical except for their helium inlets. Features of the MFTF solenoid, A-Cell, and transition coils are incorporated into the axicell design.

A cross section through one of the axicell coils is shown in Figure 5-2. The section is taken at the top of the coil, showing the typical arrangement of all components within the coil. Some of the prominent features are the isolated pancake wind, reinforced case corner with filler insulation, entering and exiting leads, and the recessed G-10CR anchoring blocks fastened to the leads. These components are all presented in detail in the following pages.

5.2.1 Conductor Pack

Conductor previously manufactured for use in the A-Cell magnet is used to wind the axicell coils. To maximize the use of the available conductor, and to minimize the number of splices required, the conductor pack is layer-wound. The conductor pack has a mean radius of 0.928 meters (36.54 inches) and consists of a single pancake wind and a layer-wound pack. The single pancake is 29 turns and acts as the entering lead. The layer-wound pack is 29 layers of 68 turns each. Twelve turns are left out in the first two layers (six turns each in layers one and two) to allow space for the reinforced case corner. In addition, a splice within a layer incurs a loss of approximately one-half of a turn. The conductor pack is a graded layer wind. The first (inner) 13 turns are Grade I and the remaining (outer) layers are Grade II. The pancake wind entering lead is also wound with Grade I. Component details of the conductor pack are shown in Figure 5-3.

5.2.2 Layer and Turn Insulation

All of the conductor pack insulation allows for controlled helium flow throughout the pack and electromagnetic load transmission. The layer-to-layer insulation is .063-inch thick, G-10CR fiber-glass laminate with slotted perforations having a 48-degree orientation to the coil centerline. The turn/turn insulation, termed "button-on-a-string," consists of .045-inch thick, G-10CR laminate octagonal-shaped buttons, .437 across-the-flats, attached to dacron tape. The buttons are spaced on .600-inch centers. The insulation between turns of the single pancake wind is .063-inch thick G-10CR, "fishbone" insulation. It is similar to the button-on-a-string insulation except that the strip connecting the buttons is G-10CR instead of dacron tape. This makes the "fishbone" insulation easy to install by hand.

5.2.3 Ground Layer Insulation

Figure 5-4 shows the insulation that isolates the conductor pack from the coil bobbin. Also shown is the insulation that separates the pancake wind from the layer-wound conductor pack.

The critical electrical insulation is the six layers of 0.005-inch thick Kapton film. The Kapton is layered in strips with the seams staggered. In addition, there are two sheets of 0.005-inch thick kapton film wrapped around the inner ring. Seams are located so that a 3.0-inch minimum short path is maintained even if one layer is punctured. The Kapton is always sandwiched between solid layers of insulation to protect it from piercing or tearing.

The coil bobbin sidewalls are coated with epoxy true-up compound, which creates a smooth, true winding surface. No true-up is necessary on the inner ring since it is machined to the required tolerances. There are three layers of solid G-10CR sheet against the inner ring to allow the Kapton to stand away from the steel structure. The Kapton layers are added on top of the trued-up

sidewalls and G-10CR layers on the inner ring. The next layer of G-10CR insulation contacts the conductor windings and is "open" for helium circulation. Against the pancake wind is a .213-inch thick G-10CR sheet with machined channels. The channels are oriented so that helium bubbles are channeled towards the outer ring. At the inner ring is a layer of .375-inch thick grid-type insulation. Also, a single sheet of .063-inch thick perforated G-10CR insulation (layer/layer insulation) is placed on top of the grid insulation to prevent the button-on-a-string from falling into the channels. On the side wall opposite the pancake lead, G-10CR post insulation against a solid G-10CR sheet is used.

There is also a series of insulation layers between the pancake wind and the conductor pack. The purpose of this insulation is to separate the two electrically, while also ensuring each adequate helium circulation. The insulation surrounds six layers of Kapton tape and is the same as that used on the sidewalls.

5.2.4 Conductor Splice

The conductor splice is designed to fit easily into the layer-wound pack, Figure 5-5. It occupies two conductor widths in the turn direction, and one conductor width in the layer direction.

The splice fitting is machined from 1/8-hard copper and the tangs are fully annealed. It has an overall 22-inch length and is symmetrical about its centerline. The first 3 inches of the fitting from each end accommodate the full conductor, the next 3 inches a conductor with the lower jacket surface removed, and the remaining 5 inches only the superconducting portion. The conductor ends to be spliced are trimmed with a tool leaving an excess of superconductor. The two ends of superconductor are then cold-welded, shortening the superconductor until a good fit is made with the splice. The conductor is then soldered into the splice fitting.

5.2.5 Typical Winding Layer

A flat pattern of a typical layer wind is shown in Figure 5-6, with the arrows indicating the winding direction. The layer begins with a ramp-up from the layer immediately below (except for layer one which begins with a conductor joggle from the pancake wind entering lead). The first turn is wound against the post insulation on the sidewall. After the first turn is wound and it reaches its starting point, a G-10CR ramp causes the conductor to joggle over and begin the second turn. Turns are then added by winding against the previous turns.

Since the barrier coils use existing lengths of conductor, splices are necessary in the middle of the layers. In order to minimize the number of turns lost due to the existence of the splices, they are positioned immediately before the joggle area. By positioning the G-10CR ramps around the splice as shown, the winding pattern is not affected and a conductor length of approximately one-half turn is lost. The presence of the splice shifts the joggle area backwards (against the winding direction) for the remaining turns of the layer.

As the final turn (68th) is wound, shims are placed between the post insulation and ground layer to maintain tightness in the layer. The conductor is joggled over at the end of the last turn (the shims are placed between the 67th and 68th turns) to begin the ramp-up to the next layer. The first turn of the next layer can then begin without the necessity for shims between the post insulation and the ground layer.

5.2.6 Current Leads

The current lead system is the same for both the entering and exiting ends of the conductor pack. The lead components carry the superconductor from the conductor pack to the outside of the coil to mate with the stack assembly. All of the components are installed at the top of the coil as shown in Figure 5-7.

After the conductor pack is wound, the entering and exiting conductor turn has its copper jacket removed and is soldered into the conductor tension clamp. The tension clamp holds the winding tension of the conductor pack and transitions the superconductor into the entering/exiting lead. The tension clamp is similar in design to the conductor splice, with tapered tangs that pick up the jacketed conductor leaving the pack.

The entering/exiting lead is brazed and bolted to the tension clamp to provide a strong, conductive joint. The lead routes the superconductor from the sidewall, over the top of the conductor pack, and up and out of the coil at the stack opening. Because the stack opening is not centered on the coil case, the entering and exiting leads differ in total length. They are identical in every other respect.

The entire assembly of conductor tension clamp and entering/exiting lead (with conductor soldered in) is bolted to the G-10CR anchor block, which is recessed into the coil bobbin sidewall. To prevent shorting, the anchor block is surrounded by Kapton and a 3.00-inch minimum short path is maintained between the bolts attaching the current lead assembly to the anchor block and the bolts securing the anchor block to the coil bobbin.

Due to electromagnetic loads in the axial direction, the conductor has a tendency to pull away from the sidewall. To ensure that the conductor does not break the solder bond in the tension clamp, G-10CR braces are used. The conductor braces are secured to the sidewall by bolting into the anchor block.

5.2.7 Plenum

Figure 5-8 is a section taken at the top of the coil showing the insulation outside of the conductor pack. The majority of the insulation is plenum, which is "open" for helium circulation. The remainder is solid, closeout insulation.

The plenum insulation is made up of multiple layers of .063-inch thick G-10CR sheet with slotted perforations (same as the layer insulation). The plenum is installed in plies of four sheets bonded together. There are nine plies (2.25 inches) around the conductor pack at the top of the coil and ten plies (2.50 inches) around the rest of the coil. Only nine plies are used at the top of the coil to provide space for the plenum channel insulation and plenum wire run insulation. The plenum channel insulation covers the top 120 degrees of the coil and is used to direct the helium bubbles to the vent area at the top of the coil. The plenum wire run insulation also covers the top portion of the coil, but is outside of the "open" plenum. It is used to protect the voltage tap wires as they are routed to the stack opening.

The plenum insulation is trimmed in certain areas to allow space for the entering and exiting leads. Where the entering and exiting leads cross over the top of the conductor pack, an open area is left in the plenum insulation. This open tunnel provides helium circulation around the leads.

Outside of the plenum insulation are layers of closeout insulation, consisting of formed fiberglass pieces and solid G-10CR layers. These layers protect the Kapton, and the rest of the conductor pack, from the heat of closeout welding and the welding of support clevises.

Figure 5-2. Typical Coil Cross Section (Top of Coil).

Figure 5-3. Conductor Pack and Details

Figure 5-4. Ground Layer Insulation.

Figure 5-5. Conductor Splice (71E3406).

Figure 5-6. Typical Layer Wind (Flat Pattern)

Figure 5-7. Current Leads.

Figure 5-8. Plenum Insulation.

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5.3 Structural Design

The barrier coil case structure encloses the conductor winding pack in a liquid helium environment, reacts the electromagnetic conductor forces, and transfers loads from the winding pack to the axial links and support struts. The case is an all-welded structure made of annealed CRES 304LN plate and E316L weld wire. It consists of a U-shaped bobbin, on which the conductor is wound, and an outer ring which serves to close out the coil case, Figure 5-9.

The coil bobbin has a U-shaped section which is advantageous because it provides two surfaces between which the conductor windings can be tightly packed. The bobbin is made from 3.00-inch sidewalls that are welded to a 3.00-inch inner ring. The inner ring is then machined to 1.50 inches with .50-inch reinforcements at the corners. This allows space for the A21 coil to be installed inside the inner ring, and reduces the conductor pack by only twelve turns.

Because of the thickness of the bobbin sidewalls, areas are machined to provide a more compact coil. There is a machined pocket on the inboard surface of each sidewall to anchor the current leads. Each pocket is located at the top of the coil and is .59 inches deep. There is also a machined zone on the outboard surface of the sidewall facing the T1 coil. This .50-inch deep area allows for greater clearance between the two magnets. The T1 machined clearance zone is not in the same area as the inboard current lead pocket.

The outer ring consists of three sections that are 3.00 inches thick. Each section has weld back-up bars that provide temperature control and prevent damage during closeout welding. There is a 10-inch vent hole at the top of the coil and a 4.00-inch inlet hole at the bottom. Vent and inlet fittings are welded to the outer ring prior to coil closeout.

Both the A1 and A20 coils have 304LN support clevises welded to their case structures, Figure 5-10. The A1 coil has seven clevises, which are used for the hangers, side strut, and A1-A2 axial supports. The A20 coil

has nine clevises, which are used for the hangers, side strut, A1-A2 axials, A2-T1 axials, and A1-S6 axials. A single axial clevis supports the A1-A2, A1-T1, and A2-S6 axial links.

In addition to the clevises, there are also vent and inlet fittings welded to the case (these fittings are welded to the outer ring before closeout). Both the A1 and A20 coils have identical 10-inch vent fittings at the top. The A1 coil has a 4-inch inlet fitting at the bottom. The A20 coil has a reducing inlet fitting at the bottom, transitioning from 4 inches at the coil to 3 inches where it joins with the inlet pipe.

Figure 5-9. Bobbin and Case Structures.

Figure 5-10. Completed Coil Assemblies.

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6.0

SOLENOID COIL DESIGN

6.1 Introduction and Drawing Tree

The MFTF-B axicell configuration has twelve solenoid coils, shown in Figure 6-1, compared to the previous A-cell configuration which had 14 solenoid coils. This configuration has a closer solenoid coil spacing (1.25m vs. 2.0m) and higher central fields (1.6T vs. 1.0T). All twelve solenoid coils have 5m (196.8-inch) diameter layer-wound conductor packs with 24 layers of 25 turns of conductor. The conductor used has a small NbTi/copper monolith soldered into a copper stabilizer. Two grades of conductor are used, Grade I for the first 8 layers and Grade II for the remaining 16 layers. For further details on the conductor design and performance, see Section 9.0 of this report. The coil bobbin, outer ring segments, support clevises, and intercoil box beams are all fabricated from 304LN stainless steel and are welded together using E316L weld wire.

The cross-section of the total conductor pack for the S1 through S5 solenoids is shown in Figure 6-2. The S6 solenoid has an identical conductor pack, but the case is 1.5 inches thick versus 1.0-inch thick for the other solenoid coils.

Prior to winding, the inner surfaces of the "U"-shaped coil bobbin are trued-up using an epoxy compound. Only the sideplates were found to require true-up. The epoxy compound provides flat surfaces and parallel sidewalls to within a specified dimensional control. The solenoid coil winding procedure, 71E0021, establishes the procedures, materials, and associated documents required to wind and close out the solenoid coils.

The solenoid support system design is summarized in Section 7.0, while the current lead and stack design is summarized in Section 8.0 of this report. The magnet stress and thermodynamic analyses are contained in Sections 10.0 and 11.0 respectively.

A complete drawing breakdown for the solenoid coils is shown in Figure 6.3.

Figure 6-1. Solenoid Coils

Figure 6-2. Solenoid Coil Conductor Pack
Cross Section

Figure 6-3. Solenoid Coil Drawing Tree

6.2 Insulation and Coil Winding Design

All twelve solenoid coils have identical conductor packs, each being layer-wound with 24 layers of 25 turns each. A perspective view of the coil winding and insulation is shown in Figure 6-4. The coils are wound with a two-layer cycle across and back, spliced and repeated twelve times. Each turn of the layer winding has the conductor running parallel with the coils sidewall, with the exception of a joggle area of one conductor width. This is repeated until it reaches the opposite sidewall where it ramps up to the next layer and the winding continues. The conductor is spliced after completing each two-layer cycle, resulting in 12 splices per coil.

All winding is done with the conductor on edge. The conductor, shown in Figure 6-5, consists of a small (.072 x .121-inch) monolithic NbTi/Cu superconductor soldered into a grooved copper stabilizer (.197 x .492-inch). Based on changes in the critical current testing criteria, combined with the as-built performance of the conductor, two grades of solenoid conductor were determined to be required. Grade I is used for the first 8 layers and Grade II for the remaining 17 layers. Complete information on the solenoid conductor is given in Section 9.0 of this report.

6.2.1 Ground Insulation -- The solenoid ground insulation consists of multiple layers of .005-inch thick Kapton (polyimide) film and G-10CR epoxy glass laminate.

The Kapton film alone is relied upon to prevent shorting between the conductor pack and case. Six layers of Kapton in the form of sculptured strips with a width of three inches are used. The need for strips is due to the fact that Kapton is not formable, and all areas of the coil have, effectively, double curvatures. The larger the radius, the greater the width of Kapton that can be used. A width of three inches was found to best satisfy the solenoid coils. Sculpturing was required to provide good gap control between strips under changing radius conditions, i.e.,

vertical walls of bobbin. The .06/.13-inch gap between the strips was maintained in order that adjacent strips would not cut or damage one another while wrapping, or reduce the shorting path. Each layer overlaps the previous layer by one-half of its width throughout the six layers. This gives a conservative 3-inch to-ground arcing distance with consideration that one layer is assumed perforated at the most critical location. The one-piece strip surrounds the total conductor pack and plenum and, on closeout, has an overlap of a little less than the width of the conductor pack.

The inner-ring G-10CR fiberglass ground-layer insulation consists of a single, solid .062-inch thick laminate, a machined .375-inch thick channeled insulation, and a perforated .059-inch laminate. The joints in these three layers are staggered to reduce the potential for local bulging at the joints. The six layers of Kapton film are sandwiched between the solid laminate, which is against the stainless steel bobbin surface, and the machined, channeled insulation. The solid laminate, together with a trim of the epoxy true-up material, serves to provide a recess at the bobbin corners, when made undersize in width. This recess allows the Kapton film to lay flat against the vertical sidewalls of the bobbin. This solid laminate also serves to bridge any minor variations in the coils geometry. The channeled insulation, Figure 6-6, has grooves in the transverse direction .60 inches wide by .315 inches deep on .90-inch centers and slots of the same depth .06 inches wide on .75-inch centers in the longitudinal direction. This channeled insulation maintains a large volume of helium at the inner wall which is required to keep the conductor cryostable in this high field area. The thin .060-inch thick lower surface of the channeled insulation allows it to conform to the coil's curved surface. The perforated laminate on top of the channeled insulation is conductor layer insulation and serves to prevent drop through of the turn-to-turn button insulation. Further details on this insulation are given in a following section.

The sidewall G-10CR fiberglass ground layer insulation consists of two .062-inch thick laminates sandwiching the six layers of Kapton film and applied to the trued-up epoxy surface. Again, the joints in the laminates are staggered.

6.2.2 Turn and Layer Insulation

The turn and layer insulation serves as standoff insulation between adjacent turns or layers of conductor while balancing helium flow requirements with electromagnetic load transmission.

The turn insulation is similar to that used on the original yin-yang coils, and the current transition and axicell coils. This insulation is also called "button-on-a-string" insulation, because it is made up of hexagonal-shaped G-10CR fiberglass buttons adhesively bonded to a dacron tape. These buttons are .437 inch across the flats, .059 inch thick, and have a centrally located .050-inch slot to accept the connecting tape. The buttons are punched from fiberglass laminate and bonded to the tape on 1.03-inch centers with Loctite 414 adhesive in a totally automated process.

The layer insulation is a perforated .059-inch thick G-10CR epoxy glass-fabric laminate. The perforations are punched slots forming a modified chevron pattern. This pattern directs the energy-laden helium from the sidewalls to the center of the conductor pack and insures a supply of cold helium at the side plates which experience high neutron heating. The slots are narrow to prevent any likelihood of the turn-to-turn buttons breaking off and dropping through the slots.

Figure 6-4. Solenoid Coil Winding and Insulation

Figure 6-5. Solenoid Conductor Design

Figure 6-6. Ground Channeled Insulation

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6.2.3 Vented Post and Shim Insulation

Vented post insulation is installed at the sidewalls before and after the first and last conductor turn of a layer is wound and provides good helium flow and volume at the sidewall. The shim insulation has variable thicknesses and is used to keep each layer of conductor tight laterally, preventing any adverse conductor motion.

The post insulation is machined from a .25-inch thick G-10CR laminate and, in concept, resembles the "button-on-a-string" insulation. The posts, which replace the buttons, are slightly less than the conductor in height, are .25 inch thick, and .30 inch wide with the posts on 1.0-inch centers. A centrally located backface machined-on strip .15-inch wide by .10-inch thick replaces the tape.

6.2.4 Plenum Insulation

The plenum is a perforated insulation which is installed between the outer winding layer of the conductor pack and the inside surface of the outer case ring. This insulation provides radial support to the conductor winding when the coil is energized, controls the flow of helium around the coil, and controls the bubble dispersion at the coils' inlet and outlet. This perforated insulation is identical to that used on the transition and axicell coils. It consists of staggered slots punched out of .062-inch thick G-10CR laminate which a 48-degree orientation to flow. Four sheets are bonded together and formed to match the radius of the coil, and are followed by another four sheets in a flip-flopped angle orientation. This pattern is repeated throughout the 2.5-inch thick plenum.

6.2.5 Conductor Splices

The solenoid coil conductor splice, Figure 6-7, uses an overlapped superconductor soldered into a copper splice bar (71E0817-2) whose ends are cold welded to the conductor stabilizer. The splice bar is 25 inches long with the same cross section at each end as the conductor stabilizer. The 12.76-inch central portion has an increased width, from .197 inch to .379 inch, which allows for the superconductor joggle and overlap (6.2 inches) and another 3.0 inches at each end for transitioning of splice loading. The increased cross section maintains a low stress level at the splice and improves thermal performance.

First, both splice ends of the superconductor are peeled back out of the stabilizer to a sufficient length to provide the required overlap and clear the cold weld dies. The stabilizer is then carefully cut square and is cold welded to both ends of the splice bar and the flash is removed. The superconductor is then reinstalled into the slotted stabilizer and the splice bar, together with the required joggle and overlap, is soldered in place (71E0817-1). Detailed procedures for splices and cold welds are given in Specification 71E0021, Section 5-12.

6.2.6 Entering Lead

The entering lead for the solenoid coils, shown in Figure 6-8, consists of two large cross-section stabilizer components with a mechanical-lock splice fitting for joining the basic solenoid conductor to the primary entering lead component. The lead enters just above the coil stack, transverses a length of plenum insulation, and then down into a recess machined in the case sidewall to the first layer of winding. When surrounded by well-ventilated insulation, the large copper cross section of the stabilizer satisfies the cryostability requirements. The mechanical-lock

feature was found necessary after tests showed soldered joint methods could not take the above-yield loading. The NbTi superconductor is continuous through all elements of the entering lead.

The primary entering lead component is a contour-machined copper plate, .25 x 3.0 inches, with grooves in the upper end for the superconductor, and in the lower end for the mechanical-lock splice fitting. The splice fitting has a cross section identical to the conductor stabilizer, except at the lock feature where it increases in width. After soldering, the splice fitting is riveted to the primary lead component at the locking area. The lead section which is against the sidewall is riveted to a G-10CR machined insulation with helium flow channels and bearing pads to satisfy the thermostructural requirements. The machined insulation is, in turn, bolted to the case sidewall. To prevent shorting between the lead and case, insulation is provided by layers of Kapton film and stand-off distances between the bolts and the lead. This concept electrically isolates the inlet lead and structurally anchors it to react the winding and operational loads.

The primary lead component is soldered and bolted to another machined copper stabilizer component at the stack which serves for bolted attachment of the stack leads. In the area of the plenum, these two components function like a leaf-spring that allows the lead to deflect. This accounts for the thermal contraction during cooldown of the coil, stack lead, and the vapor-cooled lead. A space is provided in the plenum buildup to allow for this motion.

All of the copper is type C10100, temper H01. The solder is eutectic Sn63Pb37. Further details on the procedures for installing the inlet lead and the quality assurance requirements, together with associated documents, are found in Section 5.7 of Specification 71E0021.

6.2.7 Exiting Lead

The exiting lead, shown in Figure 6-9, connects the 1st turn of the last layer of the conductor pack to a large copper stabilizer fitting which transverses a portion of the plenum length. It then exits the stack using a second fitting. The superconductor is continuous from the basic conductor through both fittings. The lead is insulated from shorting by Kapton film together with ventilated G-10CR insulation providing the thermostructural requirements. The length of the exit lead is determined largely by its ability to provide a leaf spring effect, similar to that described for the inlet lead. Additionally, it is required to provide sufficient length for reacting its tension load to the case wall. The exiting lead is installed under winding tension by bolting it to the G-10CR block which, in turn, is attached to a stainless steel plate welded to opposite case sidewalls. Additional details on procedures for installing the exiting lead quality assurance requirements, together with associated documents, can be found in Section 6.9 of Specification 71E0021.

Figure 6-7. Solenoid Conductor Splice Design

Figure 6-8. Solenoid Entering Lead

Figure 6-9. Solenoid Exiting Lead

6.3 Structural Design

There are twelve solenoid coils, S6-S1 west and S1-S6 east, spaced 1.25 meters apart in the vacuum vessel. The inner eight coils are fabricated in paired modules (WS4/WS3, WS2/WS1, ES1/ES2, ES3/ES4) by each having four intercoil box beams with integral clevis fittings, see Figure 6-10. The WS5 and ES5 are single coils, each having four partial box beam structures. All box beam structures are offset by 15 degrees about the vertical and horizontal centerlines, counterclockwise when viewed from the west. The inner ten solenoids form an axial load grouping when connected with axial links. The resultant axial electromagnetic forces from this grouping are reacted by four drag struts attached between the WS2/WS1 intercoil box beams and the vacuum vessel wall. All four of the inner solenoid modules have two hanger struts and a side load strut on the east coil. The hanger struts are located at 85.24 inches on each side of the coil vertical centerline, while the side load strut is located on the coil horizontal centerline going south. The single S5 solenoid coils have the same support arrangement. The inner ten coils, WS5-ES5, have a 1.0-inch hick 304LN stainless steel case reinforced with stiffeners locally in the area where the coils inlet lead is recessed 3/8's of an inch into the case sidewall. The 1.0-inch thick material had been ordered for the previous MFTF-B A-Cell configuration which had lower solenoid loadings. The higher solenoid loading for the AxiCell configuration was shown to require this reinforcement. The WS6 and ES6 solenoid coils have a 1.5-inch thick case structure without any reinforcement. The S6 solenoid coils join with axicell coils A1 and A2, the inner A2 tin coil, and the T1 transition coil to form an axial load group. The solenoid coils inlet lead and associated sidewall's machined recesses are located on the east side of the coil in all cases.

6.3.1 Case Structure. The solenoid cases are made from 304 LN stainless steel plate and are an all-welded structure using E316L weld wire. The structure is dimensionally controlled by the inner cavity requirements which originate from the 5-meter radius conductor pack. All solenoids have identical conductor packs and hence inner space requirements. The "U"-shaped bobbin on which the

conductor pack is wound has a 182.25-inch outside diameter on its inner ring and a 16.24-inch inside sidewall height, with a 7.75-inch width between the sidewalls, Figure 6-11. The inner ten solenoids, WS5 to ES5, have a 1.0-inch thick case while the outer two solenoids, WS6 and ES6, have a 1.5-inch thick case. The inner ring is fabricated by forming it in two parts and then welding it together using a balanced double "V" groove weld preparation to control distortion. The sidewalls are each fabricated in six parts which are then welded together. The sidewalls are then, in turn, welded to the inner ring using a double-bevel weld groove preparation. Control of weld distortion was critical due to coil winding requirements. Only the vertical sidewalls required true-up before winding. A reinforced epoxy compound was used to provide the required degree of sidewall flatness and accurate dimensional control between sidewalls.

The outer ring of the case is fabricated in three parts with transverse weld preps and with the circumferential and transverse weld backup bars installed. The outer ring structure closes out the case after completion of winding and the plenum and coil leads have been installed. The sidewalls were given weld preps prior to winding. The top outer ring section is installed over the protruding coil leads through a hole. The hole in the ring section is at the coil's top vertical centerline and its shape is that of two 6-inch diameter half circles spread two inches apart in the circumferential direction. This hole shape best suited clearance and acceptable shorting distances of the leads exiting the case while minimizing stress concentrations in the ring. The hole is for the stack current leads to exit and helium venting. A 2-inch diameter hole is located in the lower outer ring structure at the coil's bottom centerline for a helium inlet fitting. Allowance for fit of the weld backup bars in the coil's plenum was made during coil winding. After the coil closeout is complete the helium inlet fitting, vent stack fitting, and case reinforcement are welded to the case structure.

The inlet fitting is a 2-inch diameter and 3-inch high, all-machined pipe fitting with integral weld backup rings, and reinforced with a .5-inch thick wall at the case to take care of any high stresses and reduce vulnerability to damage. The vent stack fitting is also an all-machined fitting with an 8-inch diameter expanding to a 10-inch diameter pipe fitting, schedule 40, over a 7-inch height. To provide local reinforcement to the large hole in the outer ring structure, the fitting has a wall thickness of .75 inches where it attaches to the wall. Both fittings are fabricated from the 304L stainless-steel material.

Coil case reinforcement (Figure 6-10) was required in the area where the coil's inlet lead is recessed .375 inches into the case's east sidewall plate. Twenty-two stiffeners were required, running radially the full depth of the case, having a cross section 1.0 inch wide and 1.5 inch deep and 5.0-inch spacing between centers.

Figure 6-10. Typical Solenoid Module.

Figure 6-11. Solenoid Coil Winding Bobbin.

SUPPORT SYSTEM DESIGN

7.1 Introduction and Drawing Tree

The MFTF-B axicell configuration support system consists of five axial load groups as shown in Figure 7.1. The inner ten solenoid coils form one axial load group, WS5 to ES5. The WT1 transition coil forms an axial-load grouping with axicell coils WA2 and WA1 and the WS6 solenoid coil, as does ES6 with the EA1, EA2, and ET1 coils. The outer axial load groups are the WM2/WM1 mirror coils with the WT2 transition coil, while at the east end, ET2 couples with EM1/EM2. Although not shown in the support configuration, the transition coils T2 and T1, each support four LLNL-designed and fabricated trim coils, while the A2 axicell coils internally house a GDC-designed and LLNL-fabricated Nb₃Sn insert coil. All coils and associated features, such as supports and current lead assemblies support their own LN₂ and H₂O radiation shields or liners. Each axial load group has one set of drag supports consisting of four equally spaced radial struts for the three inner groups and two radial struts for the outer groups.

The determination of this axial load grouping was arrived at through an iterative process of minimizing forces at the vacuum vessel, providing where possible a statically determinate support arrangement, minimizing of coil misalignment influences on cooldown to 4K, and satisfying the stay-in zone requirements. Axial load coupling of individual coils from electromagnetic forces were based upon minimizing axial loading to the vacuum vessel wall. Employing only one set of drag struts for each axial load group reduces redundancy. Each fixed coil arrangement has two vertical hangers and a single side load strut. Employing pin-jointed struts and axial links between coils also limits redundancies in the

system. Side-load struts, with the exception of the ET2/EM1/EM2 group, are located south of the system to minimize redundancies and misalignment influences during cooldown to 4K. All struts and axial links between the west and east M2/M1 to T2 coils are flip-flop versions of each other. The east group is the only group having horizontal struts going to the north side of the vacuum vessel.

General designing criteria established for all struts included that they have a $\pm$ 3-inch adjustment capability, incorporate a spherical ball-bearing at both ends with a 3-degree free-rotational capability, and have common sizing characteristics determined around the pin diameters. Also, all struts located between the coils and the vacuum vessel have liquid nitrogen thermal intercept device located approximately 40 percent of the strut length from the cold end and house an internal through-radiation restriction device. These last requirements are to limit heat leaks into the coils to acceptable values.

Factors influencing the overall support system design were the temporary support and stabilizer needs during magnet installation together with associated transporter design requirements. These influences are described in the appropriate axial load group sections. All support struts and links have their own individual designations; either MHXXXX, GDXXXX, or THXXXX. The MH designation is only for those struts connecting the coils to the vacuum vessel wall. The GD designation is for internal links and struts. The TH designation is for temporary hangers that are removed prior to system operation. The numbers in the designations were for a previous support arrangement which, when updated, lost a little of the numerical logic. In general, the numbering is initiated at the east end of the magnet system, with MH 4XXX for M2/M1/T2, and MH 6XXXX for the west end T2/M1/M2, and MH 5XXX for all coils in between in a somewhat random numerical sequence.

The drawing tree in Figure 7.2 gives the breakdown of all elements of the support system, from the axial load groupings to the individual coil clevises, and details of each support strut and axial link in the system. This includes the liquid-nitrogen intercepts on each of the support struts attaching to the vacuum vessel, together with through-radiation devices. All details will be described in later sections of this report. The clevis attachments at the vacuum vessel were not a part of the design task, but were coordinated through LLNL on a pin-location basis to provide for correct strut lengths.

Figure 7-1. MFTF-B Magnet Support System

Figure 7-2. Support System Drawing Tree

7.2 Axial Load Groupings

Further details on the five axial-load groupings are given in the following sections:

7.2.1 Solenoid Coils - Axial Load Grouping

The axial load grouping of the inner ten solenoid coils is shown in Figure 7-3. The inner eight solenoid coils are paired into fixed modules: WS4/WS3, WS2/WS1, ES1/ES2, and ES3/ES4, using four radial equally spaced all-welded box-beam structures. The WS5 and ES5 solenoid coils have partial box-beam structures. The box-beam structures have integral clevis fittings that allow the solenoid coil modules to be connected together through the use of axial links into a complete axial load grouping. Each fixed solenoid module and the WS5 and ES5 solenoid coils have two hanger struts and one side-load strut. These struts are located on the east coil of each fixed module and on the individual WS5 and ES5 solenoids. There is one set of four equally spaced drag struts for this axial load group which attach to the WS2/WS1 integral box beam and the vacuum vessel at an angle of 25 degrees in an easterly direction.

The WS2/WS1 solenoid module, Figure 7-4, is typical of all solenoid modules with the exception of the four drag struts. All have two hanger struts, a side-load strut, and four intercoil box beams. The location of these struts and box beams satisfied the stayout zone requirements without imposing any thermostructural penalties on the solenoid coil cases. In all cases, the hangers and side load struts are located on the east solenoid coil of the module. The hangers are located 85.24 inches each side of the coil's vertical centerline and the side-load strut on the coil's horizontal centerline going south. The four intercoil box beams are located about the solenoid case at angular locations of 15 degrees from the vertical and horizontal centerlines in a counter-clockwise direction.

Typical intercoil box-beam structure for the WS4/WS3, ES1/ES2, and ES3/ES4 solenoid modules is shown in Figure 7-5 and the WS2/WS1 intercoil box-beam structure, modified to react the axial load of the grouping to the vacuum wall, in Figure 7-6.

Typical intercoil box beams are all-welded structures fabricated from 304 LN stainless-steel plate. The structure consists of upper and lower 1.0-inch thick plates passing above and below the solenoid case which interface with, and are welded to, clevis fittings and the solenoid case. The structure is closed out into a box configuration by two 1.0-inch thick side plates welded to the upper and lower plates and the inner faces of the two solenoid coil cases. The clevis fittings are fabricated from 2.5-inch plate with machined cutouts and are sculptored to provide an efficient load transfer to the solenoid upper and lower case flanges and intercoil box-beam structure. The configuration of individual parts is strongly influenced by a requirement for a simple assembly technique and welding accessibility. The dimensions of the coil-to-coil conductor pack centers are oversized such that at a 4K cooldown condition they meet the on-station requirement of 1.25 meters apart. The outer plate of the box beam has a plate welded to it which serves to attach temporary hangers when it is installed in the vacuum-vessel module.

The intercoil box beams for the WS2-WS1 solenoid module are similar in concept to the above except that the outer plate is required to be 2 inches thick, clevis fittings are incorporated for the drag struts and temporary hangers, and copper plates are required on the two sides walls for thermal augmentation during cooldown. The requirements on the copper plates are to provide the required conduction characteristics including a 9-square-inch cross-sectional area split between the two sides, a width of 9 inches, and terminate at no less than one inch from each of the

two solenoid coil sidewalls. The plates are bolted to the box beam sidewalls on a minimum of 4-inch centers to maximize surface contact. The inner surface of the plates are grooved along the full length of plate at the bolt pattern centerlines to improve outgassing capability.

All solenoids and solenoid modules are required to be installed in individual vacuum vessel modules. Since a single solenoid module is not self-supporting, additional temporary supports are required until the vacuum vessel modules are mated. LLNL decided upon the temporary support concept for the WS4/WS3, ES1/ES2, and ES3/ES4 solenoid modules which is shown in Figure 7-7. A temporary hanger strut and three temporary drag struts are used. The hanger strut is located on the west solenoid coil of the module close to the vertical centerline. The temporary drag struts attach to three of the intercoil box beams, close to the west solenoid coil and to the vacuum vessel at the east solenoid coil station. This support configuration provides good temporary support for the module while also allowing good adjustment capability of the solenoid module within the vacuum vessel module to meet the strict alignment requirements. The WS2/WS1 solenoid module temporary support configuration, Figure 7-8, is very similar to the above except the group's axial drag clevises were made to incorporate provisions for the temporary drag struts. The S5 and S6 solenoid coils are not within the same axial load group, however, they are required to be installed in the same vacuum vessel module. Since both of these solenoid coils have permanent hangers and side support struts, there is no requirement for temporary hangers. The S5 and S6 solenoids are made into a temporary module by four temporary axial struts and are stabilized within the module by four temporary drag supports located at the same locations as the previous solenoid modules.

7.2.2 T1/A2/A1/S6 Coils Axial Load Group

The west axial load grouping of the T1, A2, A1, and S6 coils is shown in Figure 7-9. The axial or "z" station locations for hangers struts of these coils are 465.07, 397.64, 307.09, and 270.66 respectively. These are the stations for the steady-state or 4°K temperature condition. When installed, the coils are individually adjusted to a predetermined alignment position such that, at the 4°K condition, all coils have a common center and are at their specified stations. The adjustment of the coil position is accomplished in part by turnbuckles on the struts. Also, the axial adjustment is made by drilling and installing the bearing at the free end of the axial links in the room-temperature coil-alignment position.

The A2 coil consists of an outer (A20) axicell coil and an (A21) insert coil mounted within the bore of the outer coil at the common magnetic center. The T1, A2, and A1 coils are connected by four axial links between each of the coils. The S6 solenoid coil is in turn connected to the A2 coil by four diagonal struts. The group's total electromagnetic loading is reacted to the vacuum vessel wall by four struts between the wall and the S6 solenoid coil. The clevis fittings on the S6 coil case are common to both sets of strut configurations. This is also true of the clevis fittings on the A2 coil which are common to both of the struts to the S6 coil and to the A2 coil. The radial location of the clevis fittings on each coil is common to that established for the solenoid coils except for two locations between the T1 and A2 coils. The T1 coil's geometry in its rotated position required its fittings to be symmetrical about the centerline. The two radial locations off the horizontal centerline interfaced well between the A2 and T1 coils. The other two clevis fittings were then located symmetrically about the coil's centerline (View B-B of Figure 7-9). Each coil has its own two hangers and one side-load strut.

The west T1 coil has two hanger struts (View B-B of Figure 7-9). The primary hanger is located close to the coil's center of gravity. The intent is for this strut to support most of the coil's weight and vertical loadings. The strut's offset from the centerline allows for a more efficient load transfer into the coil's case structure. The secondary hanger strut provides stabilization against torsion. Its location provides the greatest distance from the primary hanger, and at the same time provides for efficient load transfer into the case structure. The side-load strut was offset from the horizontal centerline to provide increased clearance of the vertical strut clevis and a better interface with the coil case structure.

The west A2 and A1 axicell coils' hanger and side-load struts have identical geometry in the "x" and "y" plane but are located at differing dimensions along the case structure. The reason for this is that the decision on the support station locations for these coils was made well in advance of the coil design and its associated magnetic center. The two hangers are symmetrically located about the center of the coil. To satisfy the "stay-within zone" requirements, the struts are angled out towards the vacuum vessel. The clevis fittings for the hangers at the T1 coil case structure are long, incorporate a special outside pin reinforcement extension fitting, and are gusseted. The features of clevis length and the outside pin reinforcement extension fitting are to satisfy the design requirements of the T1 coil transporter. The gusset plate provided the extra stability for the increased length of the clevis.

The S6 solenoid coil hanger and side-load support system is identical to that of the other solenoids described earlier.

The east S6/A1/A2/T1 axial load grouping support system is very similar to that of the west group. The coils have the same axial or "z" stations at the east end of the facility, are all rotated 180 degrees about the vertical or "x" axis, and have side-load struts going to the south vacuum vessel wall.

7.2.3 M2/M1/T2 Coils Axial Load Group

The west axial load grouping of the M2/M1 and T2 coils is shown in Figure 7-10. The axial or "z" station locations are 787.40 for the combined M2/M1 coil and 599.61 for the T2 coil and associate with the steady state or 4°K condition. The M2/M1 coils are prealigned at installation such that at 4°K and under load they have precise axial alignment on the specified axial station. The T2 transition coil is connected to the M2/M1 coil by four axial links located symmetrically about the T2 coils' centerlines. The major radii of the M1 and the T2 coils are parallel with a large overlap. The inner surface of the T2 coil case was machined undersize by .5 inches in the area of the overlap to provide a 1.97-inch nominal space between the coils. This space is required to account for adverse tolerance buildup and relative coil motions.

The fixed M2/M1 coil module has three hanger struts and one side-load strut. The clevises for the one of the hanger struts (MH 6002) and the side-load strut (MH 6007) attach to the M2 coil case at station 936.90. The hanger is located on the coil's vertical centerline and the side-load strut on its horizontal centerline going to the south wall of the vacuum vessel. The other two hanger struts interface with clevises on the M1 coil case at station 637.90 and are located symmetrically (95.0 inches) on each side of the coil's vertical centerline. The combined electromagnetic axial load for the three coils is transferred to the vacuum vessel walls by two drag struts located symmetrically about the M2/M1 coils. When viewed from the west, the struts are

located 40 degrees radially about the vertical centerline. The drag angle between the intercoil structure and the vacuum vessel wall is approximately 15 degrees.

The T2 coil has two hanger struts and one side-load strut located at station 637.90 which is the same station as the M2/M1 coils' inner hanger struts. The primary hanger strut (MH 6101) is located on the coils' vertical centerline and reacts the coils' dead weight and any kick loading. The stabilizer strut (MH 6102) reacts any tendency by the coil to rotate. It is angled to the vertical to satisfy "stay-within zone" requirements.

The east T2/M1/M2 coil axial load grouping is identical to the west end except that the coils are all rotated 180 degrees about their vertical axes. This locates the coils' side-load struts going north to the vacuum vessel wall. These are the only side-load struts that go to the north vacuum vessel wall.

VIEW LOOKING NORTH

Figure 7-3. WS5 to ES5 Axial Load Group

VIEW LOOKING WEST

Figure 7-4. WS2/WS1 Solenoid Support Module

Figure 7-5. Typical Intercoil Box Beam Structure

Figure 7-6. WS2/WS1 Intercoil Box Beam Structure

Figure 7-7. Temporary Stabilizer Support System - WS3/WS4, ES1/ES2, and ES3/ES4 Modules

Figure 7-8. Temporary Stabilizer Support System - WS1/WS2 Module

VIEW A-A

VIEW B-B

Figure 7-9. West T1/A2/A1/S6 Axial Load Group

Figure 7-10. WM2/WM1 to WT2 Axial Load Group.

7.3 Struts and Axial Links Members

There are eighty support struts and forty-four intercoil links in the MFTF-B magnet support system, without counting those required for the trim coils which are not covered by this report. These support members are designed by loads generated by dead weight, seismic accelerations, thermal contractions, and coil magnetic interactions. This loading can occur in air (weight and seismic) or in a vacuum (weight, seismic, thermal, and magnetic) and at temperatures ranging from room temperature (approximately 300° Kelvin) to liquid helium temperature (4° Kelvin). All primary hanger struts are proof tested.

7.3.1 Struts

The struts, Figure 7-11, consist of a 304LN stainless-steel turnbuckle tube, two forged A286 precipitation-hardened iron-base rod end fittings, and two bearing balls and pins of the same material. All struts going from the coils to the vacuum-vessel walls have an LN₂ thermal intercept located at approximately 40 percent of the strut length from the cold end. All struts have a through-radiation restriction device installed within the tube section of the strut. The struts have a ± 3 -inch adjustment capability.

7.3.1.1 Turnbuckle Tubes

The turnbuckle tubes, Figure 7-12, are made from gun-bored 304LN forged bar stock. The material specification for plate material, MEL 78-001408, was used because it has the same required material property values. The tube ends are internally threaded, right handed for the end at the vacuum chamber and left handed for the end at the coil. The thread form is UNJ-3B per MIL-S-5-8879, and either 4 or 8 threads per inch depending on the diameter involved. The threaded lengths are 1.5 times the diameter

plus 3 inches. This allows for the required adjustment capability of ± 3 inches for the strut. To prevent using too much adjustment, a .25-inch diameter through-hole is located at the 1.5-times-diameter location so that inspection can be made for the presence of the rod end. Two .5-inch diameter through-holes are made at approximately the center of the tube to provide turning capability of the turnbuckle tube. Four .125-inch diameter diagonal holes are placed symmetrically at each end of the tube to provide for lockwiring of the tube to the rod end fittings.

7.3.1.2 Rod End Fittings, Bearings, and Pins

The rod end fittings, Figure 7-13, are all made from A286 precipitation-hardened iron base alloy forgings to specification MEL 83-001677. This bearing concept is known as "Messerschmidt" or "slot-loaded." For the large bearing sizes it is both a practical and economical approach. The rod end fitting becomes the bearing housing and the ball can be simply removed or installed. The ball is silver-plated to provide lubrication. The ball width is larger than the rod end in order to provide a required rotational or alignment capability of ± 3 degrees when installed in the associated clevis fittings. A .187-inch diameter hole is located in the flat lug portion of the rod end fitting for wire locking to the turnbuckle tube. When installed, the pins extend past the outside surfaces clevises by a minimum of 1.0 inch which allows for .166-inch diameter holes to be drilled .5 inches from the pin ends for incorporation of the cotter pins (MS 246665).

7.3.1.3 LN₂ Thermal Intercept

LN₂ thermal intercepts are installed on all struts (72 of the 80 total struts) attaching to the vacuum vessel wall. The original design, Figure 7-14, for the LN₂ thermal intercepts was revised after LLNL took over the procurement of the support system. The drawing breakdown on the strut assemblies does not cover the new design. The LLNL drawing is AAA 04-109267-0A. Requirements of proof pressure and helium leak testing, materials, and maximum allowable spring constant of the bellows remained the same. The height and number of convolutions for a lifespan of 2000 cycles was to be determined by the vendor. Each cycle consists of a cooldown from 80°F to -315°F concurrent with a .00285 in/in axial expansion while pressurized. The intercept is then warmed to 80°F concurrent with a .00285 in/in axial compression. The allowable maximum spring constant for each bellows was specified. Prior to leak testing, each assembly was proof pressure tested at 218 psig. Helium leak testing was carried out in accordance with ASTM E 489.73, Method "A." Leakage was to be no greater than 1×10^{-9} torr-liter/second.

7.3.1.4 Through-Radiation Restriction Device

The through-radiation restriction device, Figure 7-15, is installed inside the turnbuckle tube and serves to reduce radiant heat transfer from the warm vacuum vessel end to the cold coil end. It consists of a series of coated aluminum discs located on a fiberglass rod. The discs are located and supported by external retaining rings fitting into grooves on the fiberglass rod. The coating on the discs is a chemical film of low emissivity which also serves to prevent galvanic corrosion between the disc and the steel tube.

7.3.2 Axial Link Members

The axial link members, Figure 7-16, consist of a 304LN stainless-steel plate and two spherical bearings with housings and pins fabricated from the A286 precipitation-hardened iron-based alloy forgings. The bearings are the "slot-loaded" variety as described for the struts. Due to the low bearing allowable for the 304LN stainless-steel plate, the recess for the ball is not machined into the plate. A separate housing, similar to conventional spherical bearings, was fabricated. The links are required to have adjustment capability for alignment during coil installation. Only one bearing is installed in the link prior to final alignment of the coils. The undrilled link ends are then marked and the bearings installed.

Figure 7-11. Strut Support Assembly - 71E3652.

Figure 7-12. Strut Turnbuckle Tubes.

Figure 7-13. Strut Rod End Fittings, Bearings, and Pins.

Figure 7-14. LN₂ Thermal Intercept.

Figure 7-15. Struts Internal Radiation Shield - 71E3651.

Figure 7-16. Axial Link Member.

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8.0

CURRENT LEAD/STACK DESIGN

8.1 Introduction

This section of the report covers the design of the stack assemblies for solenoid coils S1 through S6, transition coils T1 and T2, axicell coils A1/A20, and the axicell insert coil A2I. The described design features and drawings in association with these stack assemblies are those at the time of the procurement transfer to LLNL. Modifications made after procurement transfer are not covered by this report or associated drawings. The drawing tree for each of the coils is given in the subsection associated with that coil. The stress and thermal analysis for the stack assemblies are given in Sections 10.0 and 11.0 respectively.

A typical stack installation in the vacuum vessel, represented by the twelve solenoid coils, is shown in Figure 8-1 together with its major elements. The design of the stack assembly consists of two major sub-assemblies, the current lead assembly and the stack subassembly. All stack assemblies employ the same basic design concept varying only in overall geometry considerations, size of bus leads, number of vapor-cooled lead copper tubes, size and material of superconductor, and relative location of liquid helium return and bypass ports. Major design differences between the A1/A20, A2I, T1, and T2 stack assemblies and the S1-S6 solenoid stacks are given in Table 8-1.

The full description of a typical stack assembly and its components are given under Section 8-2, Solenoid Stack Assemblies. Other coil stack assemblies in following sections will relate primarily to the differences. Overall system considerations relating to the stack assemblies are direction of warm bus leads, Figure 8-2, for all coil stacks. All solenoid stacks (S1-S6, east and west) warm bus leads point south. The transition coils' stacks (T1 and T2, east and west) all point to the "Z" center line. All axicell coil stacks (A1/A20 - A2I, east and west) warm

bus leads also point south. The original solenoid stack enclosure had interference problems with a helium dewar, Figure 8-3. The new design then became typical for all coils. The warm bus bars within the stack enclosure were determined as needing heaters. The purpose, requirements, and operating parameters of this heater are given in Figure 8-4. Arcing between the leads and the vessel is an important consideration. The minimum arcing distances occur between the vapor-cooled lead lower block and the helium pipe, as shown in Figure 8-5. A special seal system was required where the vapor-cooled leads exited the stack at the lower plate of the enclosure. The design is shown in Figure 8-6 and involves a serrated flange bolted to the plate. The flange incorporates two Keil-F covered radial spring-loaded seals against the exiting vapor-cooled lead. The top seal contends with vacuum pump down and leak testing. The lower seal prevents gaseous helium leakage during system operations.

Table 8-1. Major Design Differences in A1/A20, A21, T1, and T2 Stacks Compared to Solenoid Stacks.

Design Difference	Solenoid Stacks S1 - S6	A1/A20	A21	T1	T2
Geometry	Vertical Stack	Vertical Stack	Vertical w/23.0" Offset	Stack, 45° Slope to Horizontal	Stack, 51° Slope to Horizontal
Outside Diameter of VCL Outer Tube - Inches	2.25	3.25	2.25	3.25	3.25
Number of .25 O.D. VCL Copper Tubes	26	42	14	48	57
Size of Copper Bus Leads - in.	3.50x.75	4.00x1.375	3.50x.75	4.00x.47	4.00x.75
					4.00x1.375
Size and Material of Superconductor	2.00x.067 Nb ₃ Sn	.436x.214 Nb ₃ Sn	.256x.256 NbTi	.436x.214 Nb ₃ Sn	.256x.256 NbTi
			.272x.083 Nb ₃ Sn		.436x.214 Nb ₃ Sn
Orientation of Warm Bus Leads	Standard	Standard	Standard	Rotated 90°	Rotated 90°
Enclosure and 2" G-10CR Feed-Thru Plate	Standard	Standard Enclosure and Feed Thru Plate	Standard	Special Enclosure and Feed Thru Plate	Special Enclosure and Feed Thru Plate

Figure 8-1. Typical Stack Installation - Solenoid S1-S6.

Typical Top View
of Stack

Figure 8-2. Direction of Warm Bus Leads

Figure 8-3. Common Enclosure - Solenoid Stack Flange Having Interference with Helium Dewar.

FOR 4000 TO 6000 AMP LEADS

REQUIREMENTS:

1. OUTLET HELIUM TEMP. OF $300K \pm 10K$ FOR .11 G/S-KA-LEAD PAIR AND WITHOUT CURRENT.
2. THERMOSTATIC CONTROL OR FEEDBACK TEMPERATURE TO COMPUTER.
3. MAKE UP ALL HEAT LOSSES.

OPERATING PARAMETERS

1. HELIUM TEMPERATURE • $300.0K$
TOP-OF-LEAD TEMPERATURE • $325.0K$
BUS TEMP. AT HEATER • $362.2K$
MAX. HEATER ELEMENT TEMP. • $399K$
2. MAX. HEAT OUTPUT DEMAND • 936 WATTS/LEAD
3. HEATER DESIGN CAPACITY • 1500 WATTS/LEAD

FOR 1500 TO 3000 AMP LEADS

REQUIREMENTS:

1. OUTLET HELIUM TEMP. OF $300K \pm 10K$ FOR .11 G/S-KA-LEAD PAIR AND WITHOUT CURRENT.
2. THERMOSTATIC CONTROL OR FEEDBACK TEMPERATURE TO COMPUTER.
3. MAKE UP ALL HEAT LOSSES.

OPERATING PARAMETERS

1. HELIUM TEMPERATURE • $300.0K$
TOP-OF-LEAD TEMPERATURE • $321.2K$
BUS TEMP. AT HEATER • $338.0K$
HEATER ELEMENT TEMP. • $362.7K$
2. MAX. HEAT OUTPUT DEMAND • 652.0 WATTS/LEAD
3. HEATER DESIGN CAPACITY • $1500 \text{ WATTS/LEAD}^*$

* For commonality with heaters on larger VCLs.

Figure 8-4. Warm Bus Lead Heater.

Figure 8-5. Nominal Stand-Off Arcing Distance at Inner Pipe.

Figure 8-6. Vapor-Cooled Lead Seals.

8.2 Solenoid Coil S1-S6 Stack Assemblies

The solenoid stack assembly, Figure 8-7, consists of two major subassemblies: the current lead subassembly and the stack subassembly. The preparation of forty-four drawings was required to complete the design, many of which consist of multiple sheets. The drawing tree, Figure 8-8, shows the drawings and their assembly into the top drawing which is the solenoid stack installation.

The stack assembly will experience excursions due to thermal expansion and contraction, gravity loads, and seismic excitation. These excursions from ambient to operating temperatures are lateral (δ_y) .472 inches and axial (δ_z) .665 inches. The vertical (δ_x) movement is .037 inches. This motion will be absorbed by the "leaf spring" design of the entering and exiting lead buses within the coil.

The primary concern here is the combined axial and lateral motion. The design approach for achieving this motion is for the stack outer can to accommodate this motion, independent of the current lead subassembly. A double bellows in the stack outer can is optimized for the desired stiffness. Excess motion capability is provided. The current lead subassembly is rigid, as it contains no bellows. Under vacuum load the stack outer vessel tends to move toward the magnet, but the supported coil and current lead subassembly react the load and limit axial movement.

The entire stack assembly is prefabricated down to the coil and is installed through the vacuum vessel port. A split sleeve design provides access for making the necessary electrical connection of the leads. The split sleeve is then welded to close out the lead stack.

8.2.1 Current Lead Subassembly

The primary elements of the current lead subassembly, Figure 8-3, are the lead bus bars, the current lead duct, G-10CR divider planks, support guides, clamp brackets, two concentric reducers, a helium return line, and a helium bypass line.

The current lead bus bars are capable of uncooled operation for ten minutes. The 1-inch-diameter helium bypass line, Schedule 5, is located considerably below the optimum location because of a structural constraint. The optimum location of this line would require passing through the web of a vacuum vessel stiffening ring. This line is located inside the vacuum vessel to avoid an interface problem. As a result, the bus bar was resized from 3.1 x 0.5 inches to 3.5 x .75 inches. A niobium tin superconducting insert is soldered into the lead buses.

The current lead duct is 10-inch diameter pipe, Schedule 40. Preserving the required spark gap of 1.55 inches presents no difficulties in this section of pipe. At the junction of the current lead assembly and the coil there is a 10-inch x 8-inch diameter concentric reducer. Polyurethane boots are employed to obtain the required spark gap. Concentric reducers are employed where diametral growth in the current lead subassembly is required. These reducers provide a continuous load path from the current lead duct into the solenoid coil case.

To complete the weldment, the 4-inch diameter helium return pipe and the 1-inch diameter helium bypass pipe are welded to the 10-inch diameter duct.

The support guides run the length of the 10-inch diameter current-lead duct and are welded to the pipe at its ends. Even though the support guides are not welded continuously over their lengths, they still react the spreading forces that the G-10CR divider planks exert. Also, by using only two long support guides, problems of aligning several short support guides are avoided. Circumferential welds of the pipe are also minimized.

G-10CR divider planks provide support for the lead busbars, and with the application of Kapton film, provide electrical isolation between the entering and exiting leads. G-10CR clamp brackets at

6-inch spacings secure the current leads to the divider planks. Clearance is provided between the brackets and the leads to prevent binding.

The G-10CR divider planks, leads, and brackets are assembled separately. They are then inserted into the current lead pipe weldment, the divider planks sliding into the support guides to complete the assembly.

A 5-inch long split sleeve is utilized at the bottom to complete the installation sequence.

8.2.2 Solenoid Stack Subassembly

The solenoid stack subassembly consists of two concentric pressure vessels, Figure 8-10. The outer vessel is part of the vacuum vessel system. The inner vessel is a helium vessel, and it contains the vapor-cooled leads.

The outer vessel is a 22-inch Schedule 20 pipe with a double-bellows arrangement optimized for lateral stiffness and is responsible for thermal, gravity, and seismic excursions. Steel flanges are welded to each end. The lower flange contains an O-ring seal and interfaces with the vacuum vessel port flange. The top flange bolts to a 2-inch thick G-10CR feed-thru plate. Within the vacuum space is a thermal barrier consisting of a G-10CR framework which support six layers of .004-inch 302 stainless steel foil which are cylindrically located within the framework.

The inner vessel is a 12-inch diameter helium enclosure. The helium enclosure is flanged at the top and connects to the current lead duct assembly at the lower end. An LN_2 thermal intercept introduces 77K temperatures at a location optimized at 60 percent of the length of the vapor-cooled leads from their warm ends. The intercept consists of two wraps of 3/8-inch diameter CRES tubing brazed to the helium enclosure.

Two vapor-cooled leads are contained within the helium enclosure. They connect to the current leads and extend through the feed-thru plate. As they emerge they are supported from the plate by a serrated flange with two Kel-F covered radial spring-loaded seals. The top seal is designed for initial system vacuum pump-down and leak testing and the bottom seal is for gaseous helium during system operations. Electrical isolation of the two leads is provided by two .062 fiberglass epoxy sheets installed between the leads.

Instrumentation wires from the magnet are encased in both polyurethane zipper tubes and G-10CR tubes and are routed adjacent to the vapor-cooled leads. The instrumentation wiring is electrically isolated from the vapor-cooled leads throughout the stack and also from the lead buses in the current lead duct. They emerge through the top plate, through two (ten 18-gauge wires) Conax feed-throughs with Kel-F sealant and insulating sleeves. The instrumentation wires then exit the plexiglass enclosure through a silicone grommet.

The design has a bulk filler material in the helium vessel to stratify the temperature gradient and stagnate the helium. This bulk filler material is an open cell polyimide foam with a density of .50 lb/ft³.

The interface with LLNL and the stack installation are the warm bus leads. These leads are six inches wide and 1.5 inches thick and are oriented to the south.

8.2.2.1 Vapor-Cooled Leads

The design of the vapor-cooled leads, Figure 8-11, is similar to the design employed on the yin-yang magnets. The vapor-cooled lead design for all coils is similar;

the only difference being the number of tubes and the diameter of the outer vapor-cooled lead pipe.

Components of the vapor-cooled lead are the tubes, bottom block, outer pipe, top block, and the cap.

The design requirements are:

- 1) Boil-off helium vapor exit temperature should be 300K.
- 2) Maximum helium vapor coolant flow rate should not exceed 0.14 G/sec/kA/lead pair.
- 3) Leads must be capable of uncooled operation for ten minutes without exceeding the superconducting critical temperature (16.4K) of the bus bar and without excessive temperature rise in the tubes (400K).

The overall length of the vapor-cooled leads is 70.31 inches. Copper tubes .25-inch O.D. with a .025-inch wall thickness are thermally stabilized by a .3125-inch O.D. x .020-inch wall stainless steel tube over each copper tube.

The number of tubes is determined by a design current of 110 amps/tube. The number of tubes required for each of the vapor-cooled leads is as follows:

Solenoid	26 tubes
Transition T1	48 tubes
Transition T2	57 tubes
Axicell A1/A20	42 tubes
Axicell A21	14 tubes

Optimum performance of the vapor-cooled lead favors copper tubes with a low residual resistivity ratio (RRR) in the 30-50 range after the brazing operations.

After the brazing operation, the outer tube of the vapor-cooled lead is machined to ensure a good seal between the vapor-cooled lead and the radial spring loaded seals which are seated on top of the 2-inch thick G-10CR plate.

8.2.3 Stack Installation and Final Closeout

In the preferred manufacturing assembly sequence, the entire stack assembly is prefabricated, requiring only one closeout joint. This is achieved in the solenoid coils by using a 10-inch split sleeve.

The entire stack assembly is lowered into place. The current lead pipe is guided into the vacuum vessel port and aligned with the current lead pick-up blocks protruding from the top of the coil. Concurrently, the vacuum vessel flange and the stack flange are properly seated. The copper pick-up blocks are pre-drilled. The lead buses are aligned and marked for match drilling, Figure 8-12.

The stack assembly is then removed from the vacuum vessel and the holes are drilled using the same template employed to make the hole pattern in the lead pick-up blocks.

The current leads mating surfaces are then tinned using 60Sn/40Pb solder per MIL-S-6872, Type II (torch 380°F - 400°F) in the horizontal position on a bench. The lead pick-up block mating surfaces are similarly tinned in the vertical position.

The stack assembly is then lowered into place once again. The current leads and coil pick-up blocks are then reheated to 380°F. Care is taken not to burn or destroy the insulation properties of the Kapton film or G-10CR plate. While the solder is soft, the bolts are installed and torqued to the specified values. When the copper joint returns to room temperature the bolts are retorqued to the specified values.

The final closeout welds are then made to the split sleeve. Two circumferential and two longitudinal closeout welds are made. Backup bars are trimmed on assembly to fit snugly and prevent any weld splatter from contaminating the lead pipe or winding.

The final assembly step is torquing the bolts on the vacuum vessel mating flange.

Figure 8-7. Stack Assembly.

Figure 8-8. Solenoid Stack Drawing Tree.

Figure 8-9. Current-Lead Subassembly.

Figure 8-10. Typical Inner Components of Stack Subassembly.

Figure 8-11. Vapor-Cooled Lead.

Figure 8-12. Stack Assembly Final Closeout Joint

8.3 Transition T1 Coil Stack Design

Forty-two drawings are necessary to complete the transition coil stack design, Figure 8-13. Many of these consist of multiple sheets. The drawing tree, Figure 8-14, illustrates the drawings and their assembly into the transition stack installation.

8.3.1 Current Leads Subassembly

The current leads subassembly consists of the current leads and helium ducts between the magnet and the stack. The geometry requirements for the current leads are dictated by the LLNL-defined stay-in zones. The transition coil current lead subassembly sequence is similar to that of the solenoids.

8.3.2 Transition Coil T1 Stack Subassembly

The stack subassembly for the transition coil stack is conceptually identical to the other coil stack assemblies. The stack centerline is 45° from the horizontal.

Lateral excursions due to thermal expansion and contraction, gravity loads, and seismic excitation are accommodated by a double bellows arrangement in the stack vacuum enclosure (Figure 8-15). The vacuum enclosure, or outer can, is sized to provide adequate radial clearance between the foil radiation shield and the outer can in the deflected position. The helium vessel, or inner can, is a 12-inch diameter pipe.

The warm bus leads that interface with LLNL hardware are oriented towards the magnet system centerline ($Z = 0.0$).

Figure 8-13. Transition T1 Coil Stack Assembly.

Figure 8-14. Transition T1 Coil Drawing Tree.

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8.4 Transition T2 Coil Stack Design

Fifty-four drawings are necessary to complete the transition coil stack design, Figure 8-15. Many of these consist of multiple sheets. The drawing tree, Figure 8-16, illustrates the drawings and their assembly into the transition coils' stack installation.

8.4.1 Current Leads Subassembly

The current leads subassembly consists of the current leads and helium ducts (12-inch Schedule 100) between the magnet and the stack. The geometry requirements for the current leads are dictated by the LLNL-defined stay-in zones.

The geometric restrictions on the lead design resulted in a complex current lead configuration that includes two elbows; the upper elbow is 38° and the lower elbow is 32° .

The T2 transition coil current lead subassembly manufacturing sequence is similar to that of the solenoids. The only difference is that the final closeout joint is made in the tee and the split sleeve. The tee is 12 inches in diameter and provides adequate clearance for making the final current lead electrical connections from the top. The final closeout procedure is welding the cover plates over the LHe return and LHe bypass ports.

8.4.2 Transition Coil Stack Subassembly

The stack subassembly for the transition coil stack is conceptually identical to the other coil stack assemblies. The stack centerline is 51 degrees from horizontal.

Lateral excursions due to thermal expansion and contraction, gravity loads, and seismic excitation are accommodated by a double bellows arrangement in the stack vacuum enclosure. The vacuum

enclosure, or outer can, is sized to provide adequate radial clearance between the foil radiation shield and the outer can in the deflected position. The helium vessel, or inner can, is a 22-inch diameter pipe.

The warm bus leads that interface with LLNL hardware are oriented towards the magnet system centerline ($Z = 0.0$).

Figure 8-15. Transition T2 Coil Stack Assembly.

Figure 8-16. Transition T2 Coil Drawing Tree.

8.5 Axicell A1/A20 Coil Stack Design

The design package for the axicell A1/A20 stack, Figure 8-17, is comprised of forty two drawings. The drawing tree, Figure 8-18, illustrates the drawings and their assembly into the axicell stack installation.

8.5.1 Current Leads Assembly

The geometric requirements for the routing of the current leads between the stack and the magnet are determined by the LLNL stay-in zones. The manufacturing sequence for the axicell lead subassembly is similar to that of the solenoid stack assembly.

8.5.2 Stack Subassembly

The stack subassembly for the axicell coil stack is conceptually identical to the solenoid coil stack assembly.

Lateral excursions due to thermal expansion and contraction, gravity loads, and seismic excitation are accommodated by the stack vacuum enclosure. These excursions are small compared to the transition coil excursions, but in the interest of commonality, the same size vacuum vessel enclosure, 22-inch diameter pipe is employed. The helium vessel is a 10-inch diameter pipe.

The warm bus leads that interface with LLNL hardware are oriented towards the south.

Figure 8-17. Axice11 A1/A20 Coil Stack Assembly.

Figure 8-16. Axicell A1/A20 Coil Stack Drawing Tree.

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8.6 Axicell A2I Coil Stack Design

Forty-eight drawings comprise the design package for the axicell A2I coil stack shown in Figure 8-19. The drawing tree, Figure 8-22, illustrates the drawings and their assembly into the axicell stack installation.

8.6.1 Current Leads Assembly

The geometric requirements for the routing of the current leads between the stack and the magnet are determined by the LLNL stay-in zones. The complex geometry complicates the design of the lead details. For example, the current lead buses have two 45° elbows and a 23-inch offset.

The manufacturing sequence for the axicell A2I lead subassembly is similar to that of the solenoid stack assembly. The only difference is that the final closeout joint is made in the 20-inch long split pipe and the short split sleeve. The final closeout procedure is welding cover plates on the access ports.

8.6.2 Stack Subassembly

The stack subassembly for the axicell coil stack is conceptually identical to the solenoid coil stack assembly.

Lateral excursions due to thermal expansion and contraction, gravity loads, and seismic excitation are accommodated by the stack vacuum enclosure. These excursions are small compared to the solenoid coil excursions, but in the interest of commonality, has the same 22-inch diameter pipe vacuum vessel enclosure. The helium vessel is a 10-inch diameter pipe.

The warm bus leads that interface with LLNL hardware are oriented towards the south.

Figure 8-19. Axicell A2I Coil Stack Assembly.

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9.0

CONDUCTOR DESIGN AND ANALYSIS SUMMARY

9.1 Design Requirements

The basic MFTF-B coil geometries and overall magnet current requirements are defined by LLNL so as to produce the required on-axis field distributions illustrated in Figure 2-1. The selections of detailed conductor designs and the operating parameters are the responsibility of General Dynamics. Table 9-1 summarizes the operating parameters for all of the MFTF-B NbTi magnets for the proposed MARS and Kelley operating modes. The total current requirements, conductor peak fields, and approximate overall current density in Table 9-1 were defined by LLNL and are based on parameters used in the EFFI analyses that determined the overall magnetic fields and forces. The number of turns in each of the magnets listed in Table 9-1 and the resulting currents and current densities are based on the final magnet designs and account for the actual coil geometry and actual number of turns in the coils (note that some turns are lost due to conductor splices or infringement of structure into the nominal coil pack envelope).

In addition to the overall current requirements, the MFTF-B magnets are also designed to the following system requirements:

a) Conductor Stability Margins

Conductor stability margins established for the MFTF-B magnets are adequate to accommodate the current peaking expected for normal fast dump conditions and most fault conditions (as shown in Section 12.0). The required margins also account for the normal uncertainties in magnetic field calculations and for geometric tolerances inherent in coil fabrication. The required stability margins are shown in Table 9-2.

b) Charging Time <4 Hours

The coils are required to have the capability of being charged individually, in groups, or all simultaneously in less than four hours. In normal operation, the MFTF-B magnets will be charged simultaneously. LLNL, however, will charge specific groups of coils during acceptance testing. All coils charged from common power supplies, therefore, are designed to be operated as a group.

c) Discharge Time

The MFTF-B magnets are designed to be discharged (fast dump, slow dump, freewheeling) either simultaneously or in groups (operated by common power supplies). The designed time constants are not necessarily the same for each coil and are limited by the maximum voltages and temperature limits defined below.

d) Maximum Voltage (Coil-to-Ground) <1000 Volts

The MFTF-B magnets are designed for a maximum voltage between the coil and ground of 1000 Vdc in room-temperature, 1-atmosphere helium gas. Actual fast dump coil-to-ground voltages are much less than the maximum and are defined in Table 9-8 in Section 9-5.

e) Maximum Dump Voltage Across Coil Leads <1000V

The MFTF-B magnets are designed for a maximum voltage between the coil terminals of 1000 Vdc in room-temperature, 1-atmosphere helium gas. Actual voltages, however, are much less.

f) Maximum Conductor Temperature Rise

The calculated hot spot temperature of the conductor during a magnet quench and subsequent fast dump shall be 200K or less based on a two-dimensional coil heat conduction model.

g) Design Life

The MFTF-B coils are designed for 550 electrical cycles including 500 normal operating mode cycles; 145 maximum load fault modes, and 5 maximum load fault-fault modes.

Table 9-1. MFTF-B Magnet Parameters.

Parameter	Units	Mode	T1	T2	A1	A20	S1/S2	S3/S4	S5/S6
NA	10^6 Amp Turns	Mars	2.35	3.71	8.37	9.09	1.006	1.014	1.058
		Kelley	2.35	3.75	1.30	9.25	1.647	1.667	1.720
N	Turns ⁽²⁾ (Nominal)	All	447	597	1975 ⁽³⁾	1975 ⁽³⁾	597	597	597
I _o	Amps	Mars	5266	6222	4238	4600	1684	1699	1772
		Kelley	5258	6278	658	5681	2760	2793	2880
J _o (Unit Cell)	A/cm ²	Mars	2759	3260	2220	2409	1845	1861	1942
		Kelley	2755	3289	344	2542	3023	3058	3156
B _o	Tesla	Mars	5.53	5.25	7.68	7.51	(1)	(1)	(1)
		Kelley	5.52	5.29	(1)	7.48	3.17	3.18	3.183

- (1) Not critical.
- (2) Based on number of turns on design drawings (does not account for any turns lost due to manufacturing variations such as added splices).
- (3) Based on average number of splices in axicell magnets (the actual number of splices varied depending on which conductor lengths were used in which magnets). The maximum difference in number of turns between magnets is one turn.

Table 9-2. Conductor Stability Requirements

	A1/A20	T1/T2	Solenoids (S1-S6)
$\frac{I_{cr}}{I_{op}} - 1$	.15	.10	.10
$\frac{B_{cr}}{B_{op}} - 1$	.10	.10	.10
$\frac{I_s}{I_{op}} - 1$	.15	.10	.10

B_{op}, I_{op} = Operating Field and Current

I_{cr} = Critical Current at B_{op}

B_{cr} = Critical Field at I_{op}

I_s = Maximum Cryostable Current at B_{op}

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9.2 Conductor Designs

Two different types of conductor are used in the MFTF-B NbTi magnets. The twelve 5-m diameter solenoid magnets utilize the simple conductor illustrated in Figure 9.1 (a) while the four axicell (A1, A20) and four transition coils use the type of conductor shown in Figure 9.1 (b) which was developed by LLNL for the MFTF-A yin-yang magnet.

9.2.1 5-M Solenoid Conductor Design

General Dynamics specification 71E0005 defines the requirements for the conductor used in the 5-M diameter solenoid magnets. The conductor utilizes a small monolithic NbTi/copper superconductor soldered into a grooved 1/4-hard OFHC copper stabilizer. The NbTi superconductor material has 46.5 percent Ti and a maximum tantalum content of 2500 ppm. For soldering the superconductor into the stabilizer, 50/50 PbSn solder is used. Significant parameters associated with the solenoid conductor are summarized in Table 9-3.

The two grades of conductor on the solenoid magnets are identical except for the critical current requirements. The requirements for Grade I were established for the first eight layers of conductor in the magnets and the Grade II requirements were established for the remaining 16 layers in the coils. The two grades were established after the start of solenoid conductor fabrication when it was decided by LLNL and GDC to change the definition of critical current to the one given in the footnote to table 9.3. The decision to use .3 V as a limiting voltage in the I_c test rather than a voltage based on a superconductor resistivity of 10^{-11} cm (which was the original definition of critical current) had the effect of lowering the measured critical current of the Solenoid conductor. Therefore, to avoid having to evaluate the acceptability of every length that did not meet the originally contracted

(same as Grade I) critical current level, we established the slightly slower critical requirement (Grade II) that was adequate for the outer 16 layers of the solenoid coils.

For each length of MFTF-B conductor, short-sample tests were conducted by LLNL on a five-foot length of conductor from each end of the length. The tests include physical measurements such as filament numbers, filament size and twist pitch, Cu/Sc ratio, and electrical measurements such as critical current and stabilizer Residual Resistivity Ratio (RRR). The test requirements are specified in the conductor specification. The tests were coordinated and performed by LLNL, except for some SC core tests by MIT.

9.2.2 Transition Coil and Axicell Coil Conductor Design

General Dynamics specifications 71E0003, 71E0004, and 71E0006 define the requirements for conductor used in the MFTF-B transition and axicell coils. This conductor utilizes a square monolithic NbTi/copper superconductor surrounded and soldered to a ventilated copper jacket. This conductor configuration was originally developed by LLNL for use on the MFTF-A yin-yang magnets and has the characteristics of excellent cryostability (due to its ventilated jacket) and of being easy to wind in two directions (necessary for "baseball" or "C"-type coils. GDC modified this design for use in the MFTF-B coils by adjusting the NbTi content (and the resulting critical current) to suit the requirements of the MFTF-B coils based on the needs of the A-Cell and transition magnets in the original MFTF-B A-Cell configuration. When the MFTF-B program was redirected to the Axicell configuration in August of 1982, this conductor was then utilized without change in the axicell and transition coils in the MFTF-B (Axicell configuration) design.

The NbTi superconductor in the yin-yang-type conductor has 46.5 percent Ti and has a maximum tantalum content of 2500 ppm. 50/50 PbSn solder is used to solder the Cu jacket to the superconducting core. Significant parameters associated with the transition and axicell conductor are listed in Table 9-4.

There are two grades of conductor used on the axicell and transition coils. The only difference between the two grades is in the copper-to-superconductor ratio in the .256-inch square monolithic core. The Grade I conductor specification, which is nearly the same as the specification for the original MFTF-A yin-yang conductor, was developed to meet the requirements of the now defunct MFTF-B A-Cell magnet. When the MFTF-B program was reoriented to the Axicell configuration, the Grade I A-Cell conductor was then utilized in the high field regions of the axicell and transition coils. The Grade II conductor requirements were established based on the needs of the original MFTF-B (A-Cell configuration) transition magnet. With the Axicell redesign, this conductor was utilized in the low-field regions of the axicell and new transition coils. Both grades of conductor have excess margins of safety in the Axicell configuration magnet systems.

For each length of MFTF-B conductor, short-sample tests were conducted by LLNL on a five-foot length of conductor from each end of the length. The tests include physical measurements such as filament numbers, filament size and twist pitch, Cu/Sc ratio, and electrical measurements such as critical current and stabilizer Residual Resistivity Ratio (RRR). The test requirements are specified in the conductor specification. The tests were coordinated and performed by LLNL, except for some SC core tests by MIT.

Table 9-3. Solenoid Conductor Data			
Parameter	Units	Grade I	Grade II
Cu/Sc (Core)	--	2:1	
(Stabilizer)	--	28.8:1	
RRR (Stabilizer)	--	110	
Filament Twist Pitch	Inches	4.0 $\pm$ 2.0	
Filament Diameter	Inches	.009 $\pm$.001	
I _c (4.2K & 3.1T)*	Amps	3730	3500
I _c (4.5K & 3.1T)	Amps	3400	3191
F _{ty} (Stabilizer @ RT)	KSI	28.0 - 34.0	
Area (Cu only)	in ²	.0930	
Wetted Area	in ² /in	.9528	
*I _c is defined as the development of .3 μ V over a 1-inch test length of conductor.			

Table 9-4. Axicell and Transition Coil Conductor Data			
Parameter	Units	Grade I	Grade II
Cu/Sc (Core)	--	1.70:1	6.00:1
(Overall)	--	6.40:1	18.70:1
RRR (Core)	--	150	150
(Stabilizer)	--	220	220
Filament Twist Pitch	Inches	7.0 ± 2.0	
Filament Diameter	Inches	$.009 \pm .001$	
I_c (4.5K)	Amps	8930 @ 7.5 T	7200 @ 5.1 T
Area (Copper only)	in ²	.1665	.1810
Wetted Area	in ² /in	3.216

(a) Solenoid Conductor

(b) Axicell and Transition Coil Conductor

Figure 9-1. MFTF-B Conductor Designs.

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9.3 Critical Current Margins

MFTF-B design requirements establish critical current margins that are adequate to accommodate the current peaking expected for any normal fast-dump condition and most fault conditions as well as accounting for normal uncertainties in magnetic field calculations or coil geometric tolerances. The required stability margins are shown in Table 9-2 in Section 9-1.

Magnetic field distributions and peak fields were calculated by LLNL using the EFFI computer code and are based on the nominal coil pack geometry and cross sections. Actual coil cross sections are slightly different from those analyzed for the following reasons:

- o Transition Coils (T1, T2) -- Three turns were eliminated from the nominal coil cross sections at one corner of the coils to prevent the possibility of unwetting of the conductor at a local high spot in the coil.
- o Axicell Coils (A1, A20) -- Six turns were removed from each of layers one and two at one side of the coil due to the requirement for a thicker case thickness at that point. Also, approximately fourteen turns are lost in each coil due to the space occupied by conductor splices.
- o Solenoid Coils (S1-S6) -- Three turns are lost in the coil winding due to the space occupied by the conductor splices.

These differences are assumed to have no effect on the magnetic field distributions and peak fields in the coils for the purposes of the critical current margin calculations. The conductor currents used in the margin calculations, however, do reflect the actual number of turns in the magnets.

The following sections summarize the magnetic fields and critical current margins for each of the MFTF-B NbTi coils.

9.3.1 Transition Coil Critical Current Margins

The peak magnetic fields in the T1 and T2 magnets occur at the centerlines of the major and minor radii in the coils. Figures 9-2 and 9-3 illustrate the magnetic field distributions, coil forms, and dividing line between the Grade I (two layers) and Grade II conductors for the T1 and T2 coils. The peak fields on the T1 coil Grade I and Grade II conductors occur at the center of the coil minor radius for the MARS operating mode. The peak fields on the T2 coil Grade I and Grade II conductors occur at the center of the coil major radius for the Kelley operating mode.

Table 9-5 summarizes the operating conditions, capabilities, and critical current stability margins for the transition coil conductors. The required .10 stability margins ($I_{cr}(B_0)/I_0 - 1$, and $B_{cr}(I_0)/B_0 - 1$) are exceeded in both grades of conductor in both the T1 and T2 coils. It should be noted that the ($I_{cr}/I_0 - 1$) stability margin is included only for reference and is based on the assumption that B_0 is a linear function of I_0 (the margin is calculated along a theoretical load line).

Figure 9-4 illustrates the transition coil conductor operating points and conductor capabilities.

9.3.2 Axicell Coil Critical Current Margins

The critical axicell coil (A1, A20) magnetic field distributions are illustrated in Figures 9.5 and 9.6. The grading line between the minimum required layers of Grade I conductor (10 layers) and the Grade II conductor is illustrated by a dashed line in both figures. The A1 coil field distribution is axisymmetric. The peak field occurs in the MARS operating mode near the center of Layer 1 for the Grade I conductor and on the side of the coil

nearest the solenoid coils for the Grade II conductor. The A20 coil field distribution is not exactly axisymmetric due to the proximity of the T1 transition coil. The peak fields occur at $\theta = 0$ degrees for the Kelley operating mode.

Table 9-6 summarizes the operating conditions, capabilities, and critical current margins for the axicell coil conductors. The required .15 critical current margin of safety $(I_{cr}(B_0)/I_0 - 1)$ and the required .10 critical field margin of safety $(B_{cr}(I_0)/B_0 - 1)$ are exceeded in both grades of conductor in both A1 and A20. Note that the $(I_{cr}/I_0 - 1)$ stability margin is included only for reference and is based on the assumption that B_0 is a linear function of I_0 (the margin is calculated along a theoretical load line).

Figure 9-7 illustrates the axicell coil conductor operating points and conductor requirements.

9.3.3 5M Solenoid Coil Critical Current Margins

The minimum critical current margins in the 5M solenoid coils occur in the Kelley operating mode. Although the field distributions in all of these solenoids are very similar, the slightly higher operating currents in the S5 and S6 coils cause the peak fields to occur in those magnets. The field distributions for these magnets are shown in Figure 9-8. The dividing line between the Grade I and Grade II conductor requirements (Reference Section 9.2.1) is represented by a dashed line in that figure.

Table 9-7 summarizes the operating conditions, capabilities, and critical current margins for the critical solenoid coils. The required .10 critical current margins of safety $(I_{cr}(B_0)/I_0 - 1)$ and $(B_{cr}(I_0)/B_0 - 1)$ are exceeded in all coils. Note that the

$(I_{cr}/I_0 - 1)$ stability margin is calculated along a theoretical load line (that assumes B_0 is a linear function of I_0) and is included only for reference and is not a design requirement.

Figure 9-9 illustrates the solenoid coil conductor operating points and conductor requirements.

Table 9-5. Transition Coil Critical Current Margins

	T1 (2)		T2 (3)	
	Grade I	Grade II	Grade I	Grade II
<u>OPERATING CONDITIONS</u>				
- I Amps	5266	5266	6278	6278
- J Amps/cm ²	2759	2759	3289	3289
- B Max Tesla	5.53	5.17	5.29	4.80
<u>CONDUCTOR CAPABILITY (4.5)</u>				
- I _{cr} (Spec) Amps	8930@7.5T	7200@5.1T	8930@7.5T	7200@5.1T
- I (B _{oper}) Amps	Large	7080	Large	7080
- B _{cr} (I _{oper}) Tesla	8.68	6.36	8.37	5.70
<u>STABILITY MARGINS</u>				
- I _{cr} (B ₀)/I ₀ -1	>1	.34	>1	.22
- B _{cr} (I ₀)/B _{oper} -1	.57	.23	.58	.19
- I _{cr} /I ₀ -1 (1 Ref)	.44	.14	>.40	.10

(1) Assuming B₀ is linear with I₀

(2) T1 parameters are for the Mars mode.

(3) T2 parameters are for the Kelley mode.

Table 9-6. Axicell Coil Critical Current Margins

		A1 (2)		A20 (3)	
		Grade I	Grade II	Grade I	Grade II
<u>OPERATING CONDITIONS</u>					
- I	Amps	4238	4238	4689	4689
- J	Amps/cm ²	2220	2220	2452	2452
- B Max	Tesla	7.68	4.95	7.48	5.64
<u>CONDUCTOR CAPABILITY (4.5K)</u>					
- I _{cr} (Spec)	Amps	8930@7.5T	7200@5.1T	8930@7.5T	7200@5.1T
- I _{cr} (B _{oper})	Amps	8400	7420	>8970	6360
- B _{cr} (I _{oper})	Tesla	8.98	7.03	8.85	6.73
<u>STABILITY</u>					
- I _{cr} (B _o)/I _o -1		.98	.75	.92	.36
- B _{cr} (I _o)/B _{oper} -1		.17	.42	.18	.19
- I _{cr} /I _o -1 (1)		.14	.26	.15	.12

(1) Assuming B_o is linear with I_o.

(2) A1 parameters are for the Mars mode.

(3) A20 parameters are for the Kelley mode.

Table 9-7. Solenoid Coil Critical Current Margins

		S5/S6 (2)	
		Grade I	Grade II
<u>OPERATING CONDITIONS</u>			
- I	Amps	2880	2880
- J	Amps/cm ²	3156	3156
- B Max	Tesla	3.19 (S5)	2.78 (S6)
<u>CONDUCTOR CAPABILITY (4.5K)</u>			
- I _{cr} (Spec)	Amps	3400 @ 3.1T	3191 @ 3.1T
- I _{cr} (B _{peak})	Amps/cm ²	3330	3430
- B _{cr} (I _{oper})	Tesla	3.735	3.49
<u>STABILITY MARGINS</u>			
- I _{cr} (B ₀)/I ₀ -1		.156	.191
- B _{cr} (I ₀)/B _{peak} -1		.171	.255
- I _{cr} /I ₀ -1 (1)		.080	.110

(1) Assuming B₀ is linear with I₀.

(2) Solenoid parameters are for the Kelley mode.

MFTF-B Model L141 (Mars Mode) T1
Grid 1, X- 0.000

MFTF-B Model L141 (Mars Mode) T1
Grid 2, Y- 0.000

$$B_{\text{Peak}} (\text{Gr I}) = 5.53 \text{ T} \quad \otimes$$

$$B_{\text{Peak}} (\text{Gr II}) = 5.17 \text{ T} \quad \otimes$$

----- = Grading Line

Figure 9-2. T1 Magnetic Field Distributions (Mars Mode).

MFTF-B Model L142 (Kelley mode) T2
Grid 1, Y- 0.000

B_{Peak} (Gr I) = 4.795 T $\otimes$
 B_{Peak} (Gr II) = 5.29 T $\boxtimes$
 ----- = Grading Line

MFTF-B Model L142 (Kelley mode) T2
Grid 2, X- 0.000

Figure 9-3. T2 Magnetic Field Distributions (Kelley Mode).

Transition for Conductor Operating Condition.

MFIF-B Model L141 (Mars Mode) WA1
Grid 1, T= 0.000

$B_{Peak} (Gr I) = 7.68T$
 $B_{Peak} (Gr II) = 4.95T$
 ----- = Grading Point

View Looking West

Figure 9-5. A1 Coil Magnetic Field Distribution (Mars Mode).

MFTF-B Model L142 (Kelley Mode) WA2
Grid 1, T- 0.000

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MFTF-B Model L142 (Kelley Mode) WA2
Grid 10, T- 90.000

VIEW LOOKING WEST

$B_{\text{Peak}} (\text{Gr I}) = 7.48 \text{ T}$

$B_{\text{Peak}} (\text{Gr II}) = 5.64 \text{ T}$

----- = Grading Line

Figure 9-6. A20 Coil Magnetic Field Distribution (Kelley Mode).

Figure 9-7. Axicell Coil Conductor Operating Conditions.

MFTF-B Model L142 (Kelley Mode) WS5
Grid 1, T- 0.000

VIEW LOOKING WEST

MFTF-B Model L142 (Kelley Mode) WS6
Grid 1, T- 0.000

$B_{\text{Peak}} (\text{Gr I}) = 3.19 \text{ T}$

$B_{\text{Peak}} (\text{Gr II}) = 2.78 \text{ T}$

----- = Grading Point

Figure 9-8. Solenoid Coil Conductor Magnetic Field Distributions (T = 0.00 Degrees)

Figure 9-9. Solenoid Conductor Operating Conditions.

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9.4 Conductor Cryostability

The MFTF-B design requirements establish conductor cryostability margins that are adequate to accommodate the current peaking expected for any normal operating or fast-dump conditions. The required stability margins are shown in Table 11-6 in section 11.2. The MFTF-B conductors must be unconditionally cryostable at a minimum of either 1.10 or 1.15 (depending on the coil) times the operating current. Unconditionally cryostable is defined as when the generated joule heating in the conductor in W/cm^2 is less than the minimum film boiling recovery flux for the conductor.

The MFTF-B magnet conductor cryostability analysis is discussed in Section 11.2 of this report and is summarized in Tables 11-8 and 11-9. All of the MFTF-B conductors and their splices meet these cryostability requirements.

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9.5 Conductor Temperature Rise Analysis

MFTF-B design criteria requires that the maximum hot-spot temperature rise in the conductors should not exceed 200° for the following conditions:

- a. 1.0M initial normal zone.
- b. 10-second delay before initiation of a dump.
- c. Based on two-dimensional coil heat conduction model.

We have calculated conservative adiabatic temperature rises in the MFTF-B conductors using a GDC computer program called SUPERQ. The program SUPERQ calculates the time and temperature evolution of system parameters by numerically integrating the basic equations governing the power balance and voltages during a dump condition. The actual integration is performed by using temperature steps, calculating current from temperature and time from current. The magnetic field is allowed to vary with the current. SUPERQ makes the following conservative assumptions:

- 1) There is no liquid helium replenishment in the neighborhood of the normal zone. That is, SUPERQ assumes helium gas is trapped in the region of the normal zone and its temperature tracks that of the conductor.
- 2) The temperature is uniform throughout the normal zone.
- 3) The normal zone does not propagate.
- 4) Eddy currents are ignored.
- 5) The normal zone is assumed to occur in the peak field region.

The program commences with a segment of the conductor going normal. The joule heat generated causes a rise in the normal zone temperature. The resistive voltage drop across the normal zone is calculated at each temperature step and compared to the dump initiation voltage. An emergency dump is initiated by introducing a dump resistor in the circuit at a given time after the normal zone voltage equals or exceeds the dump initiation voltage. The integration is terminated with the stored energy in the magnet has been dissipated. Specific heats of the copper, super-

in the magnet has been dissipated. Specific heats of the copper, super-conductor, G-10 insulation, and helium gas are all included in the calculation. The temperature variation of these specific heats are included.

The data in table 9-8 shows that the design requirements can only be met by the proper selection of dump voltage. The actual dump voltages selected by LLNL result in temperatures that meet the design requirements.

Table 9-8. MFTF-B Conductor Temperature Rise

COIL	(OHM) ⁽¹⁾	(SEC)	(VOLTS)	T _{MAX} (K)
T1	.148	17.5	250	58
	.0096	80.3	50	145
T2	.040	68	250	263
A1/A20	.054	112	250	168
S1-S6 ⁽¹⁾	.029	124	83	358
	.035	103	100	149
	.044	82	125	176

⁽¹⁾ Different dump resistances were evaluated for some of the coils.

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10.0

STRESS ANALYSIS

10.1 Introduction and Criteria

10.1.1 Introduction

The stress analyses of the MFTF-B magnets, support systems, and current leads are documented in a multivolume report entitled "MFTF-B Axicell Final Stress Report." A complete listing of the thirteen volumes is included in this report in Section 10.8, along with the report references (References, Section 10-5). The intent of this report, however, is to summarize only those significant details required to 1) understand the general structural behavior of the magnets, and 2) demonstrate the structural integrity of the system.

When the MFTF-B system evolved from the A-Cell to the Axicell configuration, some of the solenoid magnet structures and some of the design criteria were unchanged. The MFTF-B Axicell Final Stress Report, therefore, occasionally refers to the earlier stress report written for the A-Cell configuration (Reference 10-1). That report, however, is not referred to in this analysis summary.

10.1.2 Basic Analysis Approach

As is typical of most structures, conceptual design and analysis of the superconducting magnets was accomplished with simplified hand solutions. However, as the final engineering phase was approached, increasingly heavy dependence upon computerized analysis was needed. Figure 10-1 illustrates the techniques used for the MFTF axicell configuration. The primary analysis tool was

the NASTRAN finite-element computer code (Reference 10-2). A given MFTF magnet was modeled with the appropriate elements, with NASTRAN providing deflections, internal forces, and stresses. These results were then further expanded upon to ultimately calculate safety margins. The entire process required such information as properties, design criteria, and applied loads.

10.1.3 Design Criteria

A Design Requirements Document (Reference 10-3) was provided by LLNL and outlined basic considerations for safety factors, loads to be evaluated, and other structural requirements. The LLNL guidelines were adapted and expanded upon by General Dynamics.

Loads and safety margin calculations were divided into two basic categories: room temperature (RT) conditions and 4K (-452°F) conditions. The need for separate calculations was due to the enhanced 4K material strength properties which were taken advantage of in the design of the magnets. In addition, electromagnetic loads were divided into normal conditions and abnormal conditions. Abnormal conditions are low-probability electrical fault events for which reduced safety factors are utilized. The magnets were designed to survive an abnormal condition, but applied stresses may be as high as the engineering yield stress. There are some short-circuit or open-circuit fault conditions for which design is impossible, and these were not considered in this analysis.

Safety factors for normal and abnormal load cases differ as shown in Table 10-1. These safety factors are represented by percentages of material strength. (The numeric safety factor is actually the reciprocal of these percentages, i.e. 2/3 yield $\rightarrow$ SF = 1.5). To calculate a margin of safety for a given load case, it is first necessary to choose the appropriate temperature-dependent material properties and apply the appropriate safety factor:

$$MS = \frac{(\% \text{ value}) \times (\text{material strength})}{\text{applied stress}} - 1.0$$

$$MS_{\text{example}} = \frac{(2/3) (100 \text{ ksi @ 4K})}{61.72 \text{ ksi applied}} - 1$$

For the magnet case walls, note that the allowable yield stress for plate bending is 9/10 fty. The ASME code allows 100 percent fty but LLNL defined a slightly lower allowable for MFTF-B. Because a biaxial stress state consisting of membrane stresses combined with plate bending stresses (see Figure 10-2), exists in a typical magnet case, a procedure was derived to "normalize" bending stresses to equivalent membrane stresses. The normalized stress is expressed as:

$$\sigma = \sigma_{\text{membrane}} \quad 0.741 \quad \text{bending} \quad \frac{2/3}{9/10} = 0.741$$

$$\text{Thus} \quad \sigma_x = \frac{N_{xx}}{t} \quad 0.741 \quad \frac{6M_{xx}}{t^2}$$

$$\text{Thus} \quad \sigma_y = \frac{N_{yy}}{t} \quad 0.741 \quad \frac{6M_{yy}}{t^2}$$

$$\text{Thus} \quad \sigma_{xy} = \frac{N_{xy}}{t} \quad 0.741 \quad \frac{6M_{xy}}{t^2}$$

Using principal stress and Von Mises stress equations, $\bar{\sigma}$ can be calculated from the above components. Since the components have been normalized to equivalent membrane stresses, the safety margin can now be calculated directly using the allowable membrane working yield stress:

$$MS = \frac{2/3 \text{ fty}}{\bar{\sigma}} - 1.0$$

A complete description of this procedure, along with explicit instructions for its use, is contained in Appendix A of Reference 10-1.

Another aspect of the design criteria involves stability considerations. For buckling critical components, standard textbook solutions using appropriate knockdown factors are used. When end conditions, effective lengths, etc., are not clearly defined, a buckling factor (BF) of 4.0 is selectively superimposed (GDC requirement). Otherwise a $BF = 2.0$ is acceptable.

For fatigue, the principles of fracture mechanics are applied to the steel components of the magnets. Actual cryogenic tests are run for conductor splice joints since analytical approaches are not practical here. The design requirement for fatigue is that factor of safety of 4 is required on life predictions and fatigue tests. The Design Requirements Document specifies that 500 cycles of load are expected, thus analyses or tests must demonstrate adequate strength for 2000 cycles. A complete description of the fracture mechanics is contained in Volume IV of Reference 10-5.

For cooldown/warmup, the goal is to keep the stress level below the instantaneous allowable yield stress. The allowable f_{ty} is established based on the current temperature of the component of interest. The f_{ty} is assumed to vary linearly between 300K and 4K. Thus, for any given instant, a certain applied stress can be compared to the current local yield stress

10.1.4 Material Properties

Basic material properties are needed to calculate structural safety margins and to predict deflections. For MFTF, all magnet cases are made up of 304LN stainless steel using E316L weld wire at joints. The RT and 4K properties of steel and other magnet materials are listed in Table 10.2.

Generally, these numbers represent average values and do not reflect of statistical basis. One exception is the 304LN stainless

steel, where the material specification calls out the Table 10-2 numbers as minimum requirements. Each of the plates used for MFTF has a 4K yield and ultimate test run to verify compliance. If the 4K yield strength is unusually high, then the fracture toughness tests are also run to verify compliance. The weld wire used for MFTF must qualify to minimum strength and toughness requirements.

Another quantity specified as minimum is the RT yield strength of the "quarter-hard" copper. In the solenoid conductor specification, the 0.2 percent offset minimum RT yield strength is given as 28 ksi. Using test data generated at General Dynamics, this value is enhanced to 35 ksi when the copper is cooled to 20K (Reference 10-4).

10.1.5 Loads and Load Combinations

Superconducting magnet loads are made up of various effects. Table 10-3 presents basic loads, plus compatible combinations of these loads, for the MFTF axicell configuration. When the facility is at room temperature, the only expected loads are dead weight combined with seismic events.

On the MFTF-B project, GDC developed an innovative technique for determining the worst electromagnetic loads and then generating the electromagnetic forces for input to the NASTRAN models. Generally, electromagnetic loads are the major design driver for superconducting magnets and, thus, it is vital that accurate data be generated. General Dynamics' approach was to couple the LLNL EFFI (Reference 10-5) fields and forces model directly to the NASTRAN models. A detailed EFFI model of the western half of the magnet array was built such that the center of each EFFI segment coincided directly with a NASTRAN conductor pack node. Thus, loads generated by EFFI could be directly input to the finite-element model. This process is thoroughly documented in Volume III of Reference 10-5.

Considerable detailed calculations were needed to derive strut and link loads. Many load components exist and must be combined in the appropriate manner with the appropriate safety factors. For each coil, GDC generated a strut loads table which summarized compatible load types and applied appropriate safety factors. This data is included in Volume II of Reference 10-5.

GDC built stick models of each coil type to assist in the calculation of strut loads. Although closed-form solutions are practical for statically determinate support systems, the models allowed quicker iterations and provided valuable deflection data. Also, vacuum vessel stiffness parameters at strut attach points were accounted for in the models.

Axial electromagnetic forces are generally very large compared to other load types. Substantial attractive forces between coils are transferred through the links and, eventually, into the vacuum vessel. Loading situations were developed based on the criteria in the LLNL Design Requirements Document. Loads were calculated for various combinations of coil groups on/off, and transient current peaking during fast dumps was accounted for. Because the current peaking analysis had not been completed at the beginning of the strut sizing, we used conservative ground rules in the design analysis.

Seismic forces used in strut sizing were obtained from LLNL. LLNL built a stick model of the vacuum vessel/coils and applied site seismic excitations. Dynamic SRSS loads in the struts were determined and submitted to GDC. This data superseded the preliminary ± 0.75 quasi-static criteria previously used.

Misalignment of coils causes kick loads in struts. For the hanger struts, these kick loads can be on the same order of intensity as all other load types, thus, the kick loads are important design drivers.

As the MFTF axicell configuration magnet designs matured, it became apparent that tight tolerances would be difficult to maintain. Because improperly located coils in the system could give rise to secondary loads in support struts and could cause physics problems with the plasma, GDC and LLNL established a list of sources of potential physical and magnetic misalignments (see Table 10-4) for consideration in the design. Although trim coils were added to correct for plasma misalignment effects, however, the physical alignment of the coils must be structurally compensated for. In particular, axial links not parallel to the Z axis could impose kick loads in the X-Y plane. Although these kick loads are a very small fraction of the axial link load, they this can be on the same order of magnitude as the design loads for hangers as shown in the Figure 10-3 example.

Table 10-1. Material Properties for MFTF Axicell
are Based on Test Data

THE DESIGN STRESS FOR STRENGTH ANALYSIS IS BASED ON:		
ITEM	NORMAL OPERATION (HIGH PROBABILITY)	ABNORMAL OPERATION (LOW PROBABILITY)
Membrane Stresses, σ_m	2/3 Yield	100% Yield
Bending Stresses, σ_b	90% Yield	
Membrane + Bending	$\sigma_m + 0.741 \sigma_b$ $\leq 2/3$ Yield	$\sigma_m + \sigma_b \leq$ Yield
Ult. Stress, Magnets	1/2 Tensile Ultimate	60% Ultimate
Ult. Stress, Supports	33% Tensile Ultimate	60% Ultimate
Seismic Stress	120% of Above Allowables	100% of Above Allowables
Stress Cycles	At Least 4 x Operating Cycles	

Table 10-2. Material Properties Used for MFTF-B Are Based on Test Data and are Mutually Agreed Upon by GDC/LLNL

MATERIAL	CONDITION	USAGE	MODULUS-MSI		CTE (RT-4K) 10 ⁻⁶ IN/IN/°F	YIELD-KSI		ULTIMATE-KSI		4K TOUGHNESS K _{IC} KSI √IN
			RT	4K		RT	4K	RT	4K	
304LN Stainless	Annealed	All Magnet Cases, Clevises, Turn-buckles	28.	30.	5.9	35.	100.	90.	170.ST 200.L LT	200. (But use 120.)
Welds	As Welded	All Magnet Cases	--	30.	---	50.	100.	70.	150.	120.
A286	Stainless	Rod End Forgings	29.	31.	5.5	85.	125.	105.	190.	90.
OFE	Annealed 1/4 Hd	Y-Y Type Conduct. Solenoid Conduct.	-- 17.	17. 18.	6.2 6.2	-- 28.	18. 35.	23. 34.	59. 66.	-- --
NbTi	--	Superconductor	--	11.4	---	--	--	--	2% E	--
Fiberglass Epoxy G-10CR	Cured	Insulation Warp Fill Norm	4.3 3.9 2.0	5.0 4.8 3.2	4.5 5.1 14.0	-- -- --	-- -- --	60. 43. -61.*	125. 78. -109.*	-- -- --
Epon 828 Versamid 115 30% 1/4* Fibers	Cured	Coil Form True-Up	--	1.2	~29.0	--	--	--	-34.*	--
Epon 815 Versamid 125 50% 1/32* Fibers	Cured	Coil Form True-Up	--	1.7	~29.0	--	--	--	-38.*	--

* Compression Only Allowables

Table 10-3. Loads on the MFTF-B Magnets are Composed of a Combination of Various Effects

INDIVIDUAL LOAD CONDITIONS			LOAD COMBINATIONS		
CATEGORY	LOAD CASE	LOAD CONDITION	CATEGORY	LOAD CASE	LOAD CONDITION
Electro-magnetic	1	Normal Operation	4.2K Opr.	11	1 + 3 + 4 + 8
	2	Individual Fault Conditions and Transients		12	2 + 3 + 4 + 8
	3	Trim Coil Loads	Seismic	13	8 + 9 (at room temperature)
Thermal	4	Residual Cooldown (R.T. to 4.2K)		14	11 + 9 (@ 4.2)
	5	Quench (Pack Locally Warm)		15	12 + 9 (@ 4.2)
	6	Cooldown/Warmup (Gradients)			
Other	7	Internal Pressure (Quench)			
	8	Gravity Dead Load			
	9	Seismic Excitations			
	10	Winding Loads			

Table 10-4. Misalignment of Coils Affects Both the Plasma and the Support Strut Loads

LLNL and GDC have evaluated sources of coil misalignment and have tabulated the various contributions. The total effect has been conservatively estimated by simple addition of components:

MAGNET TRANSLATIONAL ALIGNMENT ERROR						
CAUSES OF MAGNET MISALIGNMENT	ERROR BAND (INCHES)					
	SOLN	A1	A2	T1	T2	Y-Y
Mechanical Location of Coil Pack	±.10	±.10	±.10	±.10	±.10	±.25
Cooldown	±.10	±.11	±.11	±.10	±.14	Note 1
Magnetic Forces	0.	0.	0.	±.03	±.03	Note 1
Gravitational Forces						
Magnet:	±.01	±.01	±.01	±.01	±.01	Note 1
Vessel:	±.02	±.02	±.02	±.02	±.02	.02
Temperature change of Vessel (Cooling by M.B. c. panel)	±.04	±.04	±.04	±.04	±.04	±.04
Creep (Magnet & Vessel)	±.10	±.10	±.10	±.10	±.10	±.10
Vacuum Load on Vessel	±.03	±.03	±.03	±.03	±.03	±.03
Reproducibility of Alignment Target	±.03	±.03	±.03	±.03	±.03	±.03
Alignment of Targets during Installation	±.03	±.03	±.03	±.03	±.03	±.03
TOTAL	±.46	±.47	±.47	±.49	±.55	

Note 1: To be provided by LLNL.

T1/T2 ANGULAR MISALIGNMENT			
CAUSE OF MAGNET MISALIGNMENT	ERROR BAND (DEGREES)		
	RX	RY	RZ
T1: Cooldown	±.004	.0	±.018
Magnetic Forces	.0	.0	±.018
Gravitational Forces	.0	.0	±.010
TOTAL	±.004	.0	±.046
T2: Cooldown	±.014	±.003	±.043
Magnetic Forces	±.001	±.003	±.017
Gravitational Forces	.0	±.002	±.005
TOTAL	±.015	±.008	±.065

Figure 10-1. Our General Approach to Magnet Structural Analysis Relies Upon Extensive Usage of Computer Codes

Figure 10-2. Plate Elements are Loaded by Combined Membrane and Bending Forces.

$$\text{KICK LOAD} = (\text{AXIAL LOAD})(\text{NO. LINKS}) \sin \theta$$

$$\sin \theta = \theta \text{ FOR SMALL ANGLES}$$

$$\text{KICK LOAD} = (970 \text{ kips})(8) \frac{.46^\circ}{57.3}$$

$$\text{KICK LOAD} = 147 \text{ kips}$$

$$\text{HANGER REACTION} = \frac{147 \text{ kips}}{2 \text{ hangers}} = 74 \text{ kips}$$

$$\text{SIDE STRUT REACTION} = \frac{147 \text{ kips}}{1 \text{ strut}} = 147 \text{ kips}$$

$$(\text{REF SINGLE COIL WT} = 30 \text{ kips})$$

Figure 10-3. Kick Loads are Induced by Small Misalignments of Axial Loads

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10.2 Transition Coils

The generalized criteria and analysis approach established for structural analysis of the MFTF-B magnets was followed in the transition magnet design. The detailed analyses of the transition coils are contained in Volumes X and XI of Reference 10-5. Highlights of the analyses, however, are presented here for the major structural components of the transition coils, T1 and T2.

10.2.1 Magnet Case

Finite-Element Modeling -- Most of the case stress analysis results for coils T1 and T2 were derived from the large 3-D NASTRAN models of the structures. The finite models are documented in volume V of Reference 10-5, and the element analyses were verified by closed-form hand solutions of major structural effects. Stress output was refined in critical areas to determine safety margins. The 3-dimensional, quarter-symmetric NASTRAN models shown in Figures 10-4 and 10-5 simulate the T1 coil 4.0-inch case with no superstructure and the T2 coil 4.0-inch case with tie straps. The basic modeling scheme for these coils is similar to the procedure used in modeling the other "C-shaped" coils in the MFTF magnet system. Plate elements represented the magnet case, and a 3-dimensional network of rod elements represented the conductor pack's axial and transverse stiffness properties. Transverse conductor pack rods were selectively disconnected when they were found to be reacting tension loads since the actual conductor pack can react only compression in the transverse directions.

Electromagnetic loads established the primary structural requirements for the case. These loads produce overall (primary) bending of the case, as well as local (secondary) bending of the case walls due to the conductor pack bearing pressure, as shown in Figure 10-6. The electromagnetic loads applied to the 3-dimen-

sional transition coil NASTRAN models were from the LLNL Electromagnetic Fields, Forces, and Inductances (EFFI) program model L-141.

T1 Case Analysis -- The design load condition for the T1 coil is the normal operating MARS mode. The total major radius spreading load is 1.93 million pounds, and the total minor radius spreading load is 1.52 million pounds. Although the MARS abnormal operating condition generates a major radius spreading load of 2.36 million pounds and a minor radius spreading load of 1.66 million pounds, the steady-state loading condition is more critical because of the higher stress allowables for abnormal operating conditions

In the T1 major radius, the dominant case stress is the hoop (longitudinal) stress shown in Figure 10-7. This stress is caused by the 1.66×10^6 lb pounds trying to spread apart the minor radius lobes and is affected by the presence of case chamfers at the major radius plane of symmetry. The minimum margin of safety in the major radius is .26.

Hoop stress is also the dominant part of the minor radius stresses shown in Figure 10-8. In the minor radius, however, the transverse stresses and the secondary plate bending stresses caused by the 6300 psi magnetic pressures on the case are more significant than in the major radius. The minimum margin of safety in the minor radius is .80.

In addition to stresses, we evaluated the deflections of the T1 coil under the highest loading condition (abnormal operating conditions). The tendency of the T1 coil upon being charged is to circularize itself. The major and minor radius lobes tend to spread apart as shown in Figure 10-9. The major radius spreads a maximum of .38 and the minor radius spreads a maximum of 0.39 inches. These values are reasonable. The angular rotation is counterclockwise as expected. Local bowing of the case is minimal, because the case material is 4.0 inches thick.

T2 Case Analysis -- The worst condition for the T2 coil is the normal operating Kelley mode. This condition has a major radius lobe spreading force of 1.95×10^6 lb, and a minor radius lobe spreading force of 4.11×10^6 lb. The worst abnormal condition occurs when M1 quenches. This results in a major radius lobe spreading force of 2.78×10^6 lb and a minor radius lobe spreading force of 4.41×10^6 lb.

The T2 minor radius spreading loads are reacted at the major radius plane of symmetry and at the tie straps. For the normal operating condition, the tie straps react approximately 83 percent of the minor radius spreading loads with the remainder reacted at the major radius symmetry plane (Figure 10-10). All of the major radius spreading forces are reacted at the minor radius symmetry plane.

The vertical chamfer area at the minor radius symmetry plane is the most critical area of the T2 coil case. The high stress at this point is a result of large secondary bending moments caused by curved beam effects which tend to make the inner and outer rings bulge outward. These moments peak in the corner where the minimum thickness occurs causing the increases in the Von Mises stresses shown in Figure 10-11. The minimum margin of safety in the minor radius is .10.

The stresses in the T2 major radius are low. Stresses in this area are generally low because the tie straps, which restrain minor radius spreading, react most of the load that would otherwise be reacted at the minor radius symmetry plane.

The highest T2 case stresses, other than the minor radius chamfer area, occur at the tie strap locations. There are high longitudinal stresses at this point, as shown in Figure 10-12, caused by the peak case bending moments caused by the minor radius spreading forces.

The T2 case tie strap stresses are highest for an abnormal operating condition. The minimum margin of safety, however, occurs if the magnet is operated normally after 140 hours of cooldown when the tie strap has not reached its steady-state temperature. At this time, the minimum margin of safety, as shown in Figure 10-10, is .01.

We evaluated the T2 magnet deflections for normal operating conditions. The analysis results show clearly the tendency for "C" coils to circularize themselves under electromagnetic loading. The major radius lobe deflects .204 inches at the symmetry plane and the minor radius deflects .361 inches at the symmetry plane. These deflections are due to the normal operation of electromagnetic loads and residual cool-down effects. Case shrinkage due to thermal contraction accounts for part of the inward deflections (Figure 10-13).

10.2.2 Conductor

The yin-yang type of conductor is used in both the T1 and T2 magnets. The conductor is under a triaxial state of stress caused by longitudinal and transverse loads due to electromagnetic loads and relative thermal contraction of the case and conductor. The longitudinal loads are carried by axial stresses in the Cu/Nb core and Cu jacket of the conductor. The transverse stresses are imposed as bearing stresses on the sides of the conductor by the G-10CR insulation.

The highest transition coil conductor stresses occur in the T1 coil minor radius where there are very high transverse stresses which are illustrated in Figure 10-14. The high bearing stresses at that point can cause coining (local yielding) of the soft conductor jacket for fault-type conditions. There is no coining (yielding) for normal operating conditions.

In an effort to limit the amount of fault-condition "coining" to an acceptable level, the T1 layer-to-layer insulation was graded. The inner 14 layers feature 48 percent bearing areas and the outer 15 layers have 57 percent bearing area. For the worst-case fault condition, the maximum conductor interface stress is 12.2 ksi and the maximum coining per conductor is .003 inches (layers 27 through 29 at the minor radius plane of symmetry). The cumulative pack deformation at the minor radius plane of symmetry normal to the layer-to-layer insulation is .035 inches.

10.2.3 Insulation

The insulation system includes button-on-a-string, chevron, layer-to-layer, offsets, joggle pieces, plenums, clamp blocks, clamp plates, etc. Fiberglass G-10CR is used for insulation and exhibits high strength at 4K. The primary loading direction is generally through the thickness under direct bearing. Strength in this direction is 109 ksi (compression), and the design allowable is taken as 36 ksi bearing. (The factor of safety of 3.0 accounts for the linear elastic behavior of this composite material.)

Analysis of insulation was conducted using results from early finite element model runs. In some instances loads from EFFI L72 were used. This is somewhat conservative as loads from EFFI Model L141 are somewhat lower. Positive margins exist in all parts.

10.2.4 Support System

The T1 magnet is supported within the vacuum vessel via seven support struts. There are two vertical hanger struts, one lateral side strut, and four axial struts. The four axial struts tie coil T1 to coil A20. (Coils S6, A1, A2, and T1 comprise an axial load grouping and the axial load from T1 is eventually transmitted to the vacuum vessel via drag struts from S6 to the vacuum vessel.) The two hanger struts and the side strut primarily react dead

weight, seismic, and electromagnetic "kick" loads and are attached to the vacuum vessel (see Figure 10-15).

The T2 transition coil is also supported in the vacuum vessel by seven struts (Figure 10-16). Four axial links which react the axial load are connected to M1. Two hanger struts and one lateral strut react the coil weight and lateral seismic loads. The three hanger/lateral struts lie in the same plane. Because the coil center of gravity is offset from this plane, however an overall moment exists which must be reacted by the axial struts.

The support system analysis is summarized in Section 10-5.

10.2.5 Summary

Structural analysis of the transition coils has shown sufficient strength in all areas. Because the coil case is primarily stiffness critical, the state of stress is relatively low throughout most of the case. The presence of chamfers, however, increases stress levels locally.

On the T1 coil at the major radius plane of symmetry, the outer ring scarf causes an equivalent stress of 52 ksi for the MARS normal operating condition. The margin of safety of 0.26 is the smallest for the case structure.

The vertical chamfer area at the minor radius symmetry plane is the most critical area of the T2 coil case. The corner at the scarf has a stress of 78 ksi for the Kelley mode abnormal operation. The margin of safety is 0.28. The T2 tie strap has a minimum margin of safety of 0.0 at 169 hours after start of cooldown.

The yin-yang-type conductor in the T1 coil experiences high triaxial stresses. Some yielding will occur on the first load cycle and some embossing of the layer-to-layer insulation on the conductor stabilizer jacket surface will occur for abnormal conditions. No performance degradation is expected. Insulation in the transition magnets shows positive margins of safety using conservative analysis approaches.

Figure 10-4. NASTRAN 3-D Model of T1 Case and Conductor Pack.

Figure 10-5. NASTRAN 3-D Model of T2 Case and Conductor Pack.

Figure U-6. The Electromagnetic Loads Establish the Primary Structural Requirement for the Transition Coils

Figure 10-7. T1 Major Radius Perimeter Stress Plot

- NORMAL OPERATING CONDITION GOVERNS.
- MINIMUM MARGIN OF SAFETY = .80.
- THE SIDE PLATES CARRY MORE BENDING LOAD WITH A SHARP NONLINEAR TENSION PEAK IN THE CORNERS.
- FLAT PLATE BC EXPERIENCES HIGH ELECTROMAGNETIC TRANSVERSE LOADING.

Figure 10-8. T1 Minor Radius Perimeter Stress Plot

DEFLECTIONS ARE IN INCHES.

- COIL CASE IS DEFLECTING IN THE MANNER EXPECTED.
- MAXIMUM SPREADING DEFLECTION = 0.39 INCHES.

Figure 10-9. T1 Case Deflections for Abnormal Operation

- Tie straps carry 80 percent of electromagnetic spreading load.
- Inner straps carry 55 percent of total strap load.
- Inner strap margin-of-safety:

	140 Hours	Steady State
Normal Operation $\sigma = 55.7 \text{ ksi}$	$M.S. = \left(\frac{56.0}{55.7} \right) - 1 = +.01$	$M.S. = \left(\frac{63.6}{55.7} \right) - 1 = +.14$
Abnormal Oprtn. $\sigma = 68.6 \text{ ksi}$	$M.S. = \left(\frac{84.0}{68.6} \right) - 1 = +.22$	$M.S. = \left(\frac{95.4}{68.6} \right) - 1 = +.39$

- Full penetration, fully inspected strap welds show positive safety margins.

Figure 10-10. The T2 Tie Strap Carries Most of the Minor Radius Spreading Load

Figure 10-11. T2 Minor Radius Perimeter Stress Plot.

- STRESS PEAK AT STRAP LOCATION IS FROM MOMENT DUE TO TIE STRAP RESTRAINT
- MAJOR RADIUS STRESS IS LOW BECAUSE STRAP REACTS MOST OF SPREADING LOAD

Figure 10-12. T2 Case Stresses Peak at the Tie Strap Attach Point.

- Deflections shown are for normal operation.
- Higher spreading forces in minor radius causes larger deflections.
- Thick plate inhibits cross-section distortions arising from secondary bending.

Figure 10-13. T2 Case Deflections for Normal Operation.

- Hoop force is due to the reaction of outward electromagnetic forces, and is also due to differential thermal contraction between conductors and magnet case (winding forces are small).
- Transverse forces are due to electromagnetic construction and are also due to conductors bearing against one another after cooldown.
- Transverse forces are transmitted to the conductors via intermittent G-10CR insulation bearing surfaces.

Figure 10-14. T1 Conductor Triaxial Stresses

- Centroid Translation:
 - Up = .299 inches
 - South = .208 inches toward A2 coil
 - East = .598 inches
- Upon installation, coil must be located such that upon cooldown and EMF loading it will be correctly aligned.
- Centroid offset $\sim .70$ inches.

Figure 10-15. T1 Coil Motions for Normal Operating Conditions

- NASTRAN model used for analysis.
- Worst condition occurs when M2 is on, T2 is off.
- Results show clearance is maintained.

Figure 10-16. The Deflections of T2 and M1 are Within Acceptable Limits.

10.3 Axicell Coils

The structural analysis of the axicell (A1 and A20) coil case, conductor pack, support system, and other structural entities incorporated extensive computer and hand analysis. The computer work consisted of several detailed finite element models and STANSOL models. Design guidelines, material allowable stresses, and safety factors for analysis of the different structural components are specified and discussed in Reference 10-5. The load cases that the axicell coil was analyzed for include normal operating electromagnetic forces and several critical abnormal load cases. Internal pressure due to coil quench, seismic and weight loads, and loads due to thermal effects were also considered.

10.3.1 Magnet Case

The magnet case for the axicell coils is one of the major critical structural components. Abnormal load cases can cause the conductor pack to impart 3 million pounds of force against the case sidewall. In addition to the loads from the magnets own conductor pack, A20 magnet cases must also react the electromagnetic loads of the insert coil (A21). The large loads reacted by the case cause severe stress peaking in the case corners, as is typical with most magnets. The corners on the inner ring of the axicells proved to be the highest stressed, and local stiffening by corner buildups was necessary.

The analysis of the case structure was based on a combination of two detailed finite element models. The first of these models is a 2-D axisymmetric GDSAP model which is illustrated in Figure 10-17 and described in detail in Reference 10-5. This model is, in some ways, more accurate than the 3-D model discussed later (finer mesh, better load definition). Figure 10-18 shows some typical results of this model for two normal load cases. Abnormal load cases were also applied to this model to verify the structural design.

The 3-D cyclic symmetric NASTRAN model which was used in conjunction with the 2-D model is presented in Figure 10-19. Details of this model can also be found in the Reference 10-5, Volume V. Load cases consistent with the 2-D model were run and a comparison of the results were made. The two models agreed extremely well, as illustrated in Figure 10-20. From these results and the results of the 2-D model, and in conjunction with the design requirements, it was determined that the minimum margin for the case is +.12. Appendix A of this volume contains the hand calculations, results, load scan, and margin of safety calculations in conjunction with this analysis.

10.3.2 Conductor

The analysis of the axicell conductor pack and the resulting testing proved to be one of the biggest structural challenges of the MFTF-B+ system. The location of the coils in the high field region combined with the relatively high currents and soft annealed copper make significant conductor yielding on the first load cycle imminent. This becomes a problem, not only from the conductor standpoint, but also from the conductor splice point of view since typically the splice is a potential weak point. Due to the nonlinear behavior of the conductor in this situation, conventional analysis tools had to be expanded to provide at least a piecewise linear analysis. In addition, significant testing was necessary to insure the structural adequacy of the conductor pack components. The analysis and testing details are contained in Reference 10-5, Volume 5, Appendices B and C respectively. The following is an overview of this information.

The axicell coil design calls for the use of the yin-yang-type conductor. The conductor core consists of niobium titanium filaments in a copper matrix. The core is then wrapped by a copper stabilizing jacket. Figure 10-21 shows the composite conductor in detail and present the important specifications of the conductor.

As mentioned, this conductor will be subjected to stress and strain levels in the axicell barrier coils that exceed the original yin-yang design intentions. Linear analysis shows these levels to be well past the yield point; thus, nonlinear analysis was required to determine stress and strain. The basic worst-case levels of stress and strain are shown in Figure 10-22. Two types of operation modes are identified in this table: normal and abnormal. In normal operation, the conductor must survive and remain superconducting, whereas in abnormal operation the conductor must only survive without filament damage. The strain quantities in brackets in 10-22 are the amount of plastic strain. The stresses and strains shown in the table correspond to the innermost turn of conductor since the maximum loading occurs there. The distribution through the pack is illustrated in Figure 10-23.

The results presented here were determined from the program STANSOL. This program represents one slice of the conductor pack cross-section, and a depiction of the model is shown in Figure 10-24. Since this is a linear analysis program, additional software was written in order to post-process STANSOL results so that a piecewise linear analysis could be performed. This analysis involved increasing the applied load until a turn reached the yield point. The elastic modulus was then changed to the plastic modulus and the load increased further until the next turn reached yield. This simulated each conductor's tracking of the stress-strain curve and was simplified since turns yielded in order starting with the innermost turn. To verify the final result, a linear STANSOL model and a corresponding GDSAP finite model were run, each using secant modulus values for each turn (as determined from the piecewise linear analysis). Correspondence between the nonlinear piecewise approach and the secant approach were essentially exact.

The previous discussion only accounts for the first portion of the load cycle; that is, the stress and strain levels shown will occur when the magnet is operating or "loaded up." When the magnet is turned off, elastic deformations will try to be recovered. If no plastic deformation had taken place, the coil pack would return to its previous position. However, the piecewise linear analysis shows that plastic deformations will take place in the inner layers and the innermost turns will have the largest amount of nonrecoverable strain. As a result, the outer layers will clamp down on the inner turns causing them to go into hoop compression. The compressive stress levels that occur in this instance are shown in Figure 10-25. These results were determined from a GDSAP axisymmetric model where deformations were modeled by thermal deflections.

The levels determined in this analysis were used to support extensive verification tests. Four splice joint tests were performed and six current fatigue and critical current tests were performed. Two of the splice joint tests were performed in liquid nitrogen and two were performed in liquid helium temperatures. Each specimen was cycled at conservative worst-case load cycles and survived. Ultimate pulls on several of the specimens after fatigue cycling demonstrated significant reserve strength. Additional evidence of the splice joint design acceptability was provided by ultrasonic inspection which showed acceptable solder bonds even after fatigue cycling. The splice joint test specimen used is depicted in Figure 10-26.

The six conductor specimens were also subjected to fatigue cycling at liquid helium temperatures. Before and after the structural testing, critical current tests on the specimens were performed and compared. The specimens showed no critical current degradation even after conservative loading. The conclusion from this testing, as with the splice testing, is that the conductor pack design is structurally adequate.

The above discussion only accounts for the hoop direction which is the major design driver and does not address the radial and transverse directions. These forces were also determined and found to be at low levels. Some conductor coining will occur from the transverse loading as with most yin-yang-type conductor magnets; however, the levels are within acceptable limits.

10.3.3 Insulation

The insulation system includes button-on-a-string, snow fence layer-to-layer, offsets, joggle pieces, plenums, etc. Fiberglass G-10CR is used for insulation and exhibits high strength at 4K. The primary loading direction is generally through the thickness under direct bearing. Strength in this direction is 109 ksi (compression) and the design-allowable is taken as 36 ksi bearing. (The factor of safety of 3.0 accounts for the linear elastic behavior of this composite material.) Each insulation piece was checked in relation to its position in the magnet to insure adequate bearing area. All insulation has positive margins of safety

One G-10CR piece which required more extensive analysis is the lead anchor block which bolts to both the lead and case sidewall and provides insulation between these pieces. Since this part carries more than just bearing loads, a relatively fine meshed NASTRAN model was constructed of the lead and anchor block. The conclusion from this model was that the anchor block provided adequate strength for this loading situation.

10.3.4 Stick Model Analysis

The axicell magnets are supported in a group with the T1 and S6 magnets. This system is illustrated in Figure 10-27. This configuration of struts is a statically determinate structure and will not produce thermal lock-in during cool-down or warm-up. The major analysis tool used to determine strut loads and coil dis-

placements was the stick model which is illustrated in Figure 10-28. This model contains all of the magnets in the group except T2. Loads from T2 were fed directly into the model. Many different critical load cases were run on this model including both normal and abnormal electromagnetic loads, seismic, and thermal loads. The resulting loads, as determined by this model, were used to size struts, rod ends, and lugs. The results for the struts are contained in Reference 10-5 Volume II. The lug analysis is presented in Appendix G of Reference 10-5, Volume V. It was determined from this support system that the S6-to-vacuum vessel rod end was the critical item as it showed a zero margin with reduced safety factors. The use of the reduced margins was justified and accepted by LLNL (reference memo MFTF-1210-M-661-DSR). All other components showed adequate strength with standard allowables.

The stick model was also used to perform extensive misalignment calculations. Again, a variety of load cases was analyzed and the displacements of the coils tabulated. This information will be utilized during installation so that coils can be pre-misaligned such that they are in the proper location and orientation during operation.

10.3.5 Axicell Structural Analysis Summary

Structural analysis of the axicell coils showed sufficient strength in all areas, although many major components are highly stressed and show small or zero margins. Corner buildups were necessary on the case inner ring to provide local stiffening and material to control stress peaking. The yin-yang-type conductor in the axicell will experience hoop direction yielding on the first load cycle as well as some embossing of bottom insulation onto the jacket surface. However, tests have demonstrated the conductor's ability to survive. Tests have also proven the strength of the critical splice joint.

BASIC MODEL:

- 148 nodes.
- 296 degrees of freedom.
- 148 2-D Linear strain elements.
- 28 boundary springs.
- Axisymmetric solution mode.

MODEL MODIFIED TO ACCOUNT FOR TRIMMING OF SIDE WALLS.

Coil case trimmed by .53" To clear coil T1 (slots for leads not coincident with .59" trimback are shown only for illustration.)

Figure 10-17. 2-D Axisymmetric GDSAP Model

Figure 10-18. 2-D Model Results.

S6/T1/A1 TO A2 LUG

780 NODES
762 ELEMENTS
4,057 D.O.F.

Figure 10-19. 3-D Cyclic Symmetric Model

Figure 10-20. 2-D and 3-D Comparison

- Monolithic core with wrapped copper stabilizer.
- NbTi superconductor contains 46.5 ± 1.5 percent titanium.
- Cu/Sc : 1.70:1 (Gr I) (volumetric ratio)
Core : 6.00:1 (Gr II) (volumetric ratio)
Cu/Sc : 6.4:1 (Gr I) (volumetric ratio)
Overall: 18.7:1 (Gr II) (volumetric ratio)
- RRR Core = 150. Stabilizer = 220.
- 50/50 Pb Sn Solder.
- ICR = 8930 A at 4.5K, 5.1T (Grade I)
= 7200 A at 4.5K, 5.1T (Grade II)
- Copper Area: 1.074 Cu^2 (Grade I)
 1.168 Cu^2 (Grade II)

(a)

CONDUCTOR CORE CROSS-SECTION

(b)

Figure 10-21. Description of Conductor.

STRESS AND STRAIN LEVELS				
	Stress (ksi)		Strain (μ in/in)	
	Normal	Abnormal	Normal	Abnormal
Grade I	20.0	25.0	3200.0 (1526.0)	5100.0 (3030.0)
Grade II	16.0	21.0	1800.0 (444.0)	3500.0 (1720.0)

Figure 10-22. Operating Stress and Strain Levels.

Figure 10-23. Stress and Strain Levels Through the Pack.

Figure 10-25. Compressive Stress Levels

Figure 10-24. STANSOL Model

Figure 10-26. Splice Joint Specimen

Figure 10-27. Axice11 Support System

Figure 10-28. Stick Model

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10.4 Solenoids

This is a summary of the stress analysis which was performed to verify the structural integrity of the twelve solenoid coils of the MFTF-B axicell magnet system. The analysis of the solenoid coils was done using the design criteria and methods of analysis given in Reference 10-5, Volume I.

The ten central solenoid coils (S1 through S5) have 1.0-inch thick coil cases; coil S6 has a 1.5-inch thick coil case. From the standpoint of coil case stresses, the WS2 is the most critically loaded coil. Therefore, the case stress analysis results are given for coils WS2 and S6 (East or West).

The conductor pack including the plenum insulation is identical for all twelve solenoids. From the standpoint of the conductor pack alone, the S5 is the most critical since S5 has both the maximum current and the maximum peak field.

Analysis of the solenoid coil box beams was done using loads from the WS1/WS2 module. These loads are highest since these box beams attach to the axial drag struts for the central ten solenoids.

10.4.1 Conductor Pack STANSOL Analysis

The STANSOL II computer code was used to calculate the internal loads and deflections in the solenoid conductor pack. The input to the STANSOL code consisted of the conductor pack geometry and physical properties, conductor current, and magnetic field data for coil S5 of the L72 EFFI configuration (shown in Figure 10-31). The latest EFFI configuration was L142 for the solenoid coils. The STANSOL analysis model was made up of 25 layers of conductor, as shown in Figure 29, separated by .057-inch thick G-10CR layer insulation. The radial stiffness of the layer insulation was modeled to represent a winding gap of .004 inch between layers.

The conductor pack radial deflections and hoop stresses are shown in Figure 10-30. These values are given for both normal operation and a fault load condition. The fault load condition assumed that both current and field increased by 15 percent. The maximum conductor hoop stress was 17.0 ksi at the inner layer. The conductor at this point has no radial pressure and a 561 psi lateral pressure. This yields a Von Mises stress of 18.6 ksi for a resulting M.S. = +.25 when compared to the 23.3 ksi allowable stress for the quarter-hard copper.

10.4.2 Coil Case Axisymmetric Analysis

The solenoid cases are large rings which are for the most part axisymmetric in cross section and in loading. The nonaxisymmetric portion arises from the four support reaction locations which are around the coil. For this reason, the coil case stress analysis was made up of a linear combination of an axisymmetric analysis and a beam-bending analysis to account for the beaming of loads between support points.

The coil case axisymmetric analysis was done with a finite element model using GDSAP axisymmetric elements. The model was run for each of the four loading conditions shown in Figure 10-32. The stresses in both the hoop and radial directions were included in the table of Figure 10-33.

10.4.3 WS1/WS2 NASTRAN Stick Model Analysis

A "stick" model was constructed to represent the WS1/WS2 solenoid coil module together with the box beams, clevises, and support struts. The WS1/WS2 module was represented since this module had the attachments for the axial drag struts which support all ten central solenoids for Z-direction loading. Representation of only the WS1/WS2 module for the stick model was sufficient since 1) there is no interaction of mechanical stiffnesses from module to

module, and 2) the statically determinate loads from the other three models and the S5 coils were input as point loads onto this model.

The loads for the stick model analysis were:

- o Weight - 1G down.
- o Seismic - 0.75G, RSS from X, Y, Z directions.
- o Thermal contraction.
- o Axial magnetic loads (Kelley mode critical).

An isometric view of the stick model, together with an overlay of deflections for one combination of loading, is shown in Figure 10-34. The data items derived from this model were:

- o Thermal deflections of all points on the module.
- o Deflections of all points on the module due to mechanical loading.
- o Support strut loads.
- o Bending, shear, and axial loads on the coil cases and box beams.

The detailed deflections are given in Reference 10-5.

10.4.4 WS2 and S6 Case Stress Analysis

Solenoid coil case stresses were calculated for all loading conditions through a linear combination of stresses from the case

axisymmetric analysis plus beam bending stresses from the stick model analysis. Beam bending stresses for S6 were derived from the S6 stick model and the axicell coils given in Reference 10-5.

A summary of the WS2 and S6 case stresses are given in Figure 10-33. The margins of safety shown are based on a maximum allowable fault load stress of 100 ksi for the 304LN.

10.4.5 Box Beam Stress Analysis

The box beam stress analysis was done using box beam internal loads calculated by the solenoid coil WS1/WS2 stick model analysis. Figure 10-35 shows the sections of the box beams used to define these elements in the stick model.

The minimum margin of safety for the box beams is +.29. This margin is for a maximum principal stress of 33.4 ksi which occurs at corner C in the weld where the box beam joins the coil case side plate.

Winding Load - 300-lb tension.

COOLDOWN LOADS

Differential thermal contraction of pack and bobbin at 4K.

Figure 10-29. Load Conditions Used for STANSOL Analysis of Solenoid Conductor Pack

Figure 10-30. Solenoid Coil Conductor

Figure 10-31. Conductor Hoop Stress and Radial Deflections from STANSOL Analysis.

100 PSI Internal Pressure

Conductor Pack Side Load

Sidewall Pressure Due to Conductor Torquing

Outer Ring Pressure Causes by Side Hoop Expansion

Figure 10-32. These Load Cases Were Used for the Axisymmetric Analysis of the Coil Case

Kelley Mode
Single Cault

CASE STRESSES (KSI)

LOC	MS2			S6		
	RAD	HOOP	V.M.	RAD	HOOP	V.M.
11	48.7	4.7	46.6	43.8	14.9	38.5
12	-46.2	-36.1	42.1	-40.1	-17.6	34.8
21	-46.6	-49.7	48.3	-24.9	-17.7	21.8
22	50.1	-29.0	69.4	27.6	-3.1	29.3
31	45.0	-40.6	74.2	25.0	-4.8	27.7
32	-41.7	-72.8	63.3	-22.2	-20.5	21.4

Figure 10-33. Solenoid Case Total Stresses (Axisymmetric Stresses Plus Beam-Bending Stresses).

Figure 10-34. WS1/WS2 Stick Model Deflections

The box beam sections correspond to the elements used in the WS1/WS2 stick model.

The box beam loads were obtained from the WS1/WS2 stick model analysis.

Figure 10-35. Box Beam Modeling Used for the WS1/WS2 Stick Model

10.5 Supports

10.5.1 Introduction

MFTF-Axicell superconducting magnets are mounted within the system's large vacuum vessel using a number of steel struts and links. These members react dead weight and seismic forces as well as electromagnetic forces. Figures 10-36 and 10-37 illustrate the overall approach. Volume II Reference 10-5 provides the analysis details and safety margins for these attachments.

10.5.2 Analysis Ground Rules

From the beginning of the MFTF program, the basic philosophy in supporting the magnets has been to maintain a statically determinate system. This avoids huge locked-in residual cool-down loads (RT to 4K), allows ease of mechanical loads calculation, and minimizes heat loads on the coils. To offset the lack of redundancy, higher safety factors and proof loads are utilized. Also, geometric ground rules used for sizing assure adequate strength and fatigue life.

The primary ground rules used for the attachments relate to safety factors. A complete discussion of safety factors and load types is given in Volume I of Reference 10-5. The service load for each load type is calculated and the component is sized to carry this load times its appropriate safety factor. The following is reflected in LLNL's Requirements Document (Reference 10-3).

Operating Loads include dead weight and normal (Class I) electromagnetic forces. Ultimate SF = 3.0, Yield SF = 1.5.

Design Loads are the same as operating loads except seismic forces are added in. Ultimate SF = 2.5, Yield SF = 1.25.

Abnormal Loads include dead weight, seismic loads, and abnormal (Class II) electromagnetic forces. Ultimate SF = 1.67, Yield SF = 1.0. (The low probability abnormal loads use an ultimate safety factor of 2.0 divided by the 1.20 seismic factor. Only ten of these unlikely loading events are assumed during the lifetime of MFTF.)

In addition to the above safety factors, incidental loading is accounted for. Compression loads used in sizing are assumed to be a minimum of 50 percent of the tension load. This assures that "tension only" attachments will carry unexpected compression loads. Also, clevis fittings welded to the coils are sized for an incidental 5 percent side load at the pin center. This is especially important for those locations which have unusually long fittings. The 5 percent side load corresponds to a 3° strut cant which is theoretically possible based on clearances.

Proof loads are applied to each strut assembly to assure that gross manufacturing defects which somehow escaped NDE testing won't cause failure. Proof loads do not assure that fatigue requirements will be met, but provide confidence that hidden defects or material embrittlements aren't present. The proof load is set at 125 percent of the worst of operating, design, or abnormal loads; and is run at room temperature. The maximum allowed applied proof stress is 90 percent of RT yield, thus a few assemblies have had their proof loads reduced from the 125 percent value. LLNL also has required (Reference 10-3) that clevis attachments to the magnet cases which primarily react dead weight be proof loaded to 150 percent of the dead weight or to the 100 percent of design load, whichever is greater. (The GDC criteria is generally more stringent.)

All attachments which anchor to the vacuum vessel use room temperature values for modulus, yield strength, and ultimate strength for all load types. Even though one end of these struts is cold (4K) during worst loadings, no attempt has been made to taper the strut or to use smaller cold end lugs.

Struts or links which attach cold structure-to-cold structure use 4K material properties for 4K load conditions. Only one strut type (A20-to-S6) fits this category, but all the links do. Links (Figure 10.37) are used when the pin-to-pin length is so short that a turnbuckle-type strut is not practical.

Materials used for the struts and links have evolved simply to 304LN stainless steel and alloy A286. The specially processed (nitrogen-controlled) 304LN used for the magnet cases is also specified for the link bodies and tube portions of the struts. A-286 is used for the rod end bodies, pins, and monoballs.

10.5.3 Clevis, Rod End Stress Analysis Methods

Figure 10-38 presents the details of the A-286 rod ends and a sample 304 LN magnet clevis. Details of the stress analysis are discussed here and are completely documented in Volume II, Reference 10-5. Note that the 304LN clevis analysis shown here applies only to the magnet side of the attachment because the vacuum vessel clevis and its backup structure are the responsibility of the vessel contractor.

To minimize the number of different parts used in the support system, GDC established the list of standard attachment sizes referenced to pin diameter, shown in Table 10-5. The range of sizes accommodates the full range of MFTF-B support loads. Yield and ultimate tension load capabilities were calculated for each standard configuration and are shown in Table 10-6.

The basic starting point in the stress analysis of MFTF attachments is the monoball bearing. GDC established desired load capabilities for bearings of various bore sizes. Lear-Siegler designed a slotted bearing for use in the coil-to-coil links and a slotted rod end/monoball for use in the struts that meet the GDC load ratings.

Sizing of the rod end eye is centered about the dimensions of the monoball. Originally, when the race concept was employed, the rod end thickness was set equal to the monoball race thickness. Also, the rod end radius was set equal to $0.875 \times$ the race diameter. When the race was discarded, the rod end thickness and radius were left unchanged. The housing hole diameter decreased slightly, and some bearing area was lost due to the installation slot. The simple, straight-thru hole for the race was changed to a spherical radius with a slot 50 percent into the thickness.

Thus, the finalized edge distance ratio increased slightly from a standardized 0.875 to a range of 0.886-0.907 (using the slot diameter as the hole diameter). The bearing area decreased by 13-15 percent; the net tension area increased slightly. For ease of calculation, the original configuration's geometry is used for analysis but with a 15 percent reduction in bearing area for the installation slot. The following equations apply (Reference 10-4):

$$\begin{aligned} P_{\text{TENSION}}^{\text{ULTIMATE}} &= K_t f_{tu} A_t \\ P_{\text{BEARING-SHEAROUT}}^{\text{ULTIMATE}} &= K_{bru} f_{tu} A_{brg} (.85) \\ P_{\text{BEARING}}^{\text{YIELD}} &= K_{bry} f_{ty} A_{brg} (.85) \end{aligned}$$

The lug efficiency factors (K) are dependent upon edge distance; and for $e/D = 0.875$, the following values apply:

$$\begin{aligned} K_t &= 0.93 \\ K_{bru} &= 0.67 \\ K_{bry} &= 0.70 \end{aligned}$$

Using the original race diameter for area calculations is not much different from using the current slot diameter dimension, thus the following method was used:

t	= rod end thickness	This data is available in Table 10-5
D	= original race diameter	
A_{tension}	$= [2(.875)(D) - D]t = Dt(.75)$	
A_{brg}	$= Dt$	

Concerning the rod end threads, a relatively low average shear stress exists in the threads. However, the softer mating 304LN turnbuckle is the design driver and a threaded overlap of 1.50 x the major diameter is needed. In addition, another 3 inches of thread length is added to each rod end for adjustment capability.

Of next consideration is the 304LN clevis welded to the coils. Again, the monoball size establishes most of the dimensions. First, the gap between the blades is set at $0.10 \pm .06$ inches over the ball width. The end radius is 1.50 times the monoball bore diameter (i.e., pin diameter). The thickness is calculated to at least match the monoball strength.

After clevis drawing signout, we were informed by CBI that the best tolerance they could hold on edge distance would be $\pm .12$ inches. Rather than redesign released hardware, we chose to recalculate lug strengths using the new minimum edge distances. A loss of 6 percent in strength for the smallest lug, and 1 percent for the largest lug was imposed. Analysis for the 5 percent lug side load and the lug welds is shown in volumes relating to the individual coils' detailed stress analysis.

Finally, the A-286 attachment pin is reviewed. This pin is loaded in double shear and shows relatively high margins for shear. Pin bending is the critical failure mode, and standard procedures are

used for analysis. It is assumed the rod end is shimmed in order to be reasonably centered between the clevis blades to maximize pin bending strength.

10.5.4 Link Stress Analysis Methods

Links are used to axially couple some of the coils as shown in Figure 10-36. The pin-to-pin length is too short for an adjustable turnbuckle, thus a solid body attachment is used. Adjustment capability of a link is limited to initial installation when the exact pin-to-pin length is determined and the blank end of the link is drilled to accommodate its monoball/race assembly. Future changes would require the replacement of the link body, but the monoballs should be reusable.

The original intent was to design the lug ends of the links to have the same dimensions as a corresponding standard MFTF rod end. A considerable loss of room temperature strength is apparent since the rod ends are A286 and the link bodies are 304LN. This is of no consequence because room temperature seismic loads in links are small compared to 4K seismic + electromagnetic forces. At 4K, the links would be 80 percent as strong for yield loads as a geometrically equivalent rod end, and 105 percent as strong for ultimate loads. However, the design of link bodies progressed to a slightly different configuration from an equivalent rod end. The thickness remained the same, but the edge distance increased from $e/D = .875$ to $e/D = 0.96$.

Detailed capabilities are summarized in Table 10-7. Note that the 71E3606-10 link is necked down in its central region due to tight clearances with A1-A2 stayout zones. The minimum section was set equal to the section across the eye of the link to assure compatible strength.

10.5.5 Turnbuckle Stress Analysis Methods

As was mentioned in another section, the monoball is the basic starting point in the stress analysis of attachments. The monoball leads to the geometric construction of the rod end, which in turn leads to a starting point for sizing of the turnbuckle. The turnbuckle (Figure 10-39) is sized quite simply by first setting the inside diameter at 0.50 inches less than the rod end threads major diameter. The turnbuckle threads, of course, mate to the rod end threads. Next, the outer diameter is increased in 1/8-inch increments until tension and compression load requirements are satisfied. To minimize heat loads, turnbuckles were sometimes sized to specific load requirements rather than attempting to match the strength of mating rod ends and clevis attachments.

In the beginning, the tube is sized for tension loads (with the appropriate safety factors). The thread major diameter (D_{MAJOR}) determines the deepest cut into the tube wall along the threaded portion of the turnbuckle. However, a short thread relief zone (dimension D_2 on drawing 71E3608) has a slightly deeper cut ($D_{MAJOR} + .033 (+.500/-0.000)$). In conjunction with the outside diameter, this zone establishes one of the minimum tension areas. The tolerance on the outside diameter used for analysis was $\pm .065$ inches.

Room temperature yield/ultimate properties are used for all struts except the A20-S6 station where 4K properties are used for 4K loads (the entire strut is cold, all others have a warm end).

Compression load analysis for turnbuckles is somewhat complex. The total struts must resist both column buckling and beam column stresses. The minimum compression loads for analysis purposes is set at 50 percent of the tension load. This is somewhat of a traditional structural ground rule and assures that minimal

compression capability exists even if compression loads are not expected. In conjunction with this, the tube's slenderness ratio is controlled.

Johnson-Euler column analysis is used to establish the buckling capability of the pinned-end strut. The Euler equation is applicable only when L/p exceeds 126 for room temperature applications and 77 for 4K applications. Reduced capabilities based on the Johnson steel tube approach are calculated for RT $L/p < 126$ and 4K $L/p < 77$.

The MFTF strength criteria (Reference 10-5, Volume I) states that a buckling factor of 2.0 shall be used when end conditions, effective lengths, etc., are clearly defined. For the MFTF struts, $BF = 2.0$ is appropriate and is used for all three load types (normal, design, abnormal). Thus, the following must be satisfied:

$$\frac{P_{J-E}}{2.0} \geq P_{\text{APPLIED COMPRESSION}}$$

Beam column action occurs when compression loads cause bending moments due to load offsets. These offsets are due to rod end - turnbuckle misalignment and crookedness in the turnbuckle. The end moments are amplified due to lateral deflection of the strut. This action induces $P/A \pm Mc/I$ stresses which must be compared against allowable stresses (accounting for appropriate safety factors). Drawing requirements show that the monoball center may be offset from the turnbuckle end-of-part center by 0.10 inch maximum. In addition, the turnbuckle may be crooked by a maximum of 0.0025 inch per inch of turnbuckle length. For analysis purposes, the axial compression load is offset by 0.10 inch from each pin center and the entire column is crooked by 0.0025 inch x L.

10.5.6 Axicell Attachment Loads

Considerable detailed calculations were needed to derive strut and link loads. Many load components exist, and must be combined in the appropriate manner with the appropriate safety factors.

The primary sources of strut loading include:

- 1) Axial electromagnetic attractive forces between coils.
- 2) Dead weight.
- 3) Seismic forces.
- 4) Misalignment kick loads/restoring forces.
- 5) Trim coil side loads/trim coil torques.

Inconsequential sources of strut loading include:

- 1) Vacuum vessel external pressure.
- 2) Residual cool-down (RT - 4K) (loads negligible only if strut system is statically determinate).

GDC built stick models of each coil type to assist in the calculation of strut loads. Although closed-form solutions are practical for statically-determinate support systems, the models allowed quicker iterations and provided valuable deflection data. Also, vacuum vessel stiffness parameters at strut attach points were accounted for using the models. For each coil, a strut loads table was generated which properly adds compatible load types and applies appropriate safety factors.

Axial electromagnetic forces are generally very large compared to other load types. Substantial attractive forces between coils are transferred through the links and eventually into the vacuum vessel. Loading situations were developed based on criteria in the LLNL Design Requirements Document (Reference 10-3); electromagnetic loads analysis details are shown in Volume III of Reference 10-5. Loads were calculated for various combinations of coil

groups on/off, and transient current peaking during fast dumps was accounted for. The current peaking analysis had not been completed during strut sizing, thus, we worked to conservative ground rules which included:

- 1) Current in magnets adjacent (one each side) to a quenched coil is assumed to peak to 15 percent above the design operating current.
- 2) If one of the adjacent coils is a solenoid (S1-S6), then all solenoid coil currents peak to 15 percent above the design operating current.

Dead weights of coils were obtained from the GDC Design Group. Generally, the load in main hanger struts due to dead weight is obtainable by hand. The stabilizing couple in axial supports (due to off-cg Z locations of hangers) is also easily calculated.

Seismic forces used in strut sizing were obtained from LLNL. LLNL built a stick model of the vacuum vessel/coils and applied site seismic excitations. Dynamic SRSS loads in struts were determined and submitted to GDC.

Improperly located coil in the MFTF-B system could give rise to secondary loads in support struts. In particular, axial links not parallel to the Z axis could impose kick loads in the X-Y plane. These kick loads are a very small fraction of the axial load, and are reacted by hanger/side struts. Even a small part of an axial load, however, can be on the same order of magnitude as design loads for hangers.

Detailed analysis of sources of coil misalignment was accomplished and kick loads were calculated similar to the methods shown in Figure 10-3. The key to the analysis is the maximum off-center condition of a coil. The following values were used:

Solenoids	<u>+ 0.43"</u>
A1/A2	<u>+ 0.47"</u>
T1	<u>+ 0.49"</u>
T2	<u>+ 0.55"</u>
Y-Y	<u>+ 0.55"</u>

If an active coil is misaligned, the neighboring coils will apply a restoring force which tends to drive the coil back to on-center. LLNL made an assessment of restoring force magnitudes. A conservative approach was taken using offsets greater than predicted misalignments (2 cm for "C" coils, 1.27 cm for "O" coils).

At first glance, one might use the restoring force to relieve misalignment kick loads. However, it is recognized that the two load types were not calculated based on equivalent assumptions. More importantly, a condition could exist whereby a misaligned coil is at zero current. Its restoring force is thus zero, but neighboring active coils could still be imposing kick loads trying to squeeze the inactive coil out of the system. Our approach was to choose the maximum of either the restoring force or misalignment kick load in calculating strut loads.

Physics requirements conflict with misaligned coils. In particular, the transition coils can be misaligned by no more than 0.04 inch (1 mm) for the machine to still produce plasma. Reality exceeds this requirement by a factor of ten, thus LLNL added four racetrack-type trim coils to each transition coil. Electric current magnitude (and direction) can be adjusted in the trim coils to correct the magnetic field for physical misalignments in the main coils. These trim coils not only increase the weight of T1 and T2, but also impose electromagnetic side loads (X-Y plane). These side loads are due to the ability to reverse the current direction in some of the trim coils - asymmetric forces are possible which must be reacted externally via support struts. Equilibrium is established by equal and opposite side forces in neighboring main coils.

An interactive trim coil force matrix was calculated by LLNL and is reproduced in Table 10-8. These loads are for one trim coil at positive current. Multiple possibilities of trim coil +/- currents and main coils on/off were examined to find worst trim coil side loads.

Another consideration involving trim coils concerns torques about the Z axis. Each of the four trim coils on a transition magnet imposes a rotation of about Z since the X-Y forces do not pass through the machine center. If all four of the trim coils are at positive current, then all forces and rotations mutually cancel. If two trim coils are at negative current, a worst case torque can be formulated. This torque is reacted by a couple in the main hanger and the stabilizing hanger of the affected transition coil.

10.5.7 Axicell Attachment Sizes

Table 10-9 summarizes basic dimensions for individual applications and is useful as a quick reference.

10.5-8 Axicell Attachment Safety Margins

Calculation of safety margins for support hardware is basically a simple matter of comparing "yield capability needed" to "yield capability available" (and likewise for ultimate capability). A margin of safety (MS) is thus based on:

$$MS = \frac{(\text{capability load})}{[(\text{safety factor})(\text{actual load})]} - 1.0$$

Tables 10-10, 10-11, and 10-12 present margins of safety for the individual MFTF axicell support stations.

Table 10-5. Standard MFTF-Axicell Attachment Configurations

(Dimensions are inches)

IDENTIFICATION			MONOBALL CONFIGURATION						A-286 ROD END CONFIG.				304LN CLEVIS CONFIG.			
MFTF I.D.	PIN DIA. REF.	IS THIS SIZE USED FOR MFTF AXICELL ?	BORE DIA. (PIN) D	HOUS- ING THICK.	BALL WIDTH W2	RACE DIA. (IF USED)	NO- RACE HOUS. DIA.	NO- RACE SLOT DIA.	RAD- IUS E2	HOUSING DIA. FOR ANALYSIS B	THICK- NESS T2	SHANK MAJ. DIA. --	RAD- IUS (+/-12) E1	PIN DIA. D	THICK- NESS (EA.) T1	CLEVIS GAP G
A	1.750	Yes	1.750	1.312	1.531	2.8125	2.7515	2.770	2.46	2.8125	1.312	2.250	2.63	1.750	0.75	1.63
B	1.875		1.875	1.343	1.625	3.1250	--	--	2.73	3.1250	1.343	2.375	2.81	1.875	0.75	1.73
C	2.000	Yes	2.000	1.500	1.750	3.1875	3.1015	3.120	2.79	3.1875	1.500	2.500	3.00	2.000	1.00	1.85
D	2.250	Yes	2.250	1.678	1.969	3.5625	3.5015	3.520	3.12	3.5625	1.678	2.750	3.38	2.250	1.00	2.07
E	2.500		2.500	1.875	2.187	3.9375	--	--	3.45	3.9375	1.875	3.000	3.75	2.500	1.25	2.29
F	2.750	Yes	2.750	2.062	2.406	4.3750	4.2020	4.220	3.83	4.3750	2.062	3.375	4.13	2.750	1.25	2.51
G	3.000	Yes	3.000	2.250	2.625	4.7500	4.5920	4.610	4.16	4.7500	2.250	3.625	4.50	3.000	1.50	2.73
H	3.250		3.250	2.437	2.844	5.1250	--	--	4.48	5.1250	2.437	3.875	4.88	3.250	1.50	2.94
I	3.500		3.500	2.625	3.062	5.5000	--	--	4.81	5.5000	2.625	4.375	5.25	3.500	1.75	3.16
J	3.750	Yes	3.750	2.812	3.281	5.8750	5.7530	5.770	5.14	5.8750	2.812	4.625	5.63	3.750	1.75	3.38
K	4.000		4.000	3.000	3.500	6.2500	--	--	5.47	6.2500	3.000	4.875	6.00	4.000	2.00	3.60
L	4.250		4.250	3.187	3.719	6.6250	--	--	5.80	6.6250	3.187	5.125	6.38	4.250	2.00	3.82
M	4.500	Yes	4.500	3.375	3.937	7.0000	6.8030	6.820	6.13	7.0000	3.375	5.500	6.75	4.500	2.25	4.04
N	4.750		4.750	3.562	4.156	7.3750	--	--	6.45	7.3750	3.562	5.750	7.13	4.750	2.25	4.26
O	5.000	Yes	5.000	3.750	4.375	7.7500	7.6040	7.620	6.78	7.7500	3.750	6.000	7.50	5.000	2.50	4.48
P	5.500	Yes	5.500	4.125	4.938	8.6250	8.4040	8.420	7.55	8.6250	4.125	6.625	8.25	5.500	2.50	5.04
U	6.000		6.000	4.500	5.438	9.5000	--	--	8.31	9.5000	4.500	7.250	9.00	6.000	2.75	5.54

MONOBALL,
USES OUTER
RACE

Table 10-6. Overall Load Capabilities for Standard
MFTF Attachment Configurations

(Safety Factory = 1.0)

MFTF I.D.	PIN DIA. REF.	IS THIS SIZE USED FOR MFTF AXICELL?	YIELD CAPABILITY		ULTIMATE CAPABILITY	
			RT KIPS	4K KIPS	RT KIPS	4K KIPS
A	1.750	Yes	132	229	275	344
B	1.875		142	263	307	394
C	2.000	Yes	202	281	360	449
D	2.250	Yes	228	369	442	553
E	2.500		3.8	443	548	685
F	2.750	Yes	351	556	667	834
G	3.000	Yes	460	642	800	1000
H	3.250		500	794	952	1190
I	3.500		628	881	1100	1375
J	3.750	Yes	675	1000	1267	1584
K	4.250		823	1155	1440	1800
L	4.250		877	1354	1630	2038
M	4.500	Yes	1044	1467	1820	2275
N	4.750		1104	1666	2000	2500
O	5.000	Yes	1292	1814	2250	2813
P	5.500	Yes	1423	2263	2750	3438
Q	6.000		1710	2660	3340	4175

Detailed breakdown by components is shown in
Table 3-6. Table does not include turnbuckle)

(1 kip = 1000-lb force)

Table 10-7. Link Body Capabilities for MFTF Axicell Attachment Configurations.

(Safety Factor = 1.0)

LINK P/N 71E3606	GOES WITH STD. ATTACHMENT TO	YIELD		ULTIMATE	
		RT KIPS	4K KIPS	RT KIPS	4K KIPS
-7, -8, -10	M	686	1961	1456	3639
-9	J	480	1371	1018	2544

Table 10-8. Trim Coil Interactive Force Matrix

COIL	EXTERNAL FORCE ON TR5 (KIPS)			EXTERNAL FORCE ON TR7 (KIPS)		
	X	Y	Z	X	Y	Z
M2	0	0	0	.22	-.90	-1.35
M1	-.45	0.22	-0.25	2.25	8.54	-11.69
T2	20.68	11.02	-35.07	X	X	X
T1	X	X	X	-0.90	0	-1.35
A20/A21	4.04	-5.84	-13.27	0	0	0
A1	0.22	0	-0.22	0	0	0
S6	0.67	0	-0.45	0	0	0
TR1	-0.22	0	0	X	X	X
TR2	0	0	0	X	X	X
TR3	0	0	0	X	X	X
TR4	0	0	0	X	X	X
TR5	X	X	X	0.22	0	0
TR6	X	X	X	0	0	0
TR7	X	X	X	0	0	0
TR8	X	X	X	0	0	0

Table 10-9. Basic Sizes for MFTF Axicell Attachments.

COIL	STRUT	71E3647		MFTF I.D.	L	OD	DI	O MAJ
		P/N	PIN					
WS1,3 ES2,4	Side	-17	2,250	D	37.50	4,750	2,250	2,750
WS1,3 ES2,4	Hang	-16	1,750	A*	49.19	3,375	1,750	2,250
WS5, ES5	Side	-20	1,750	A*	37.50	3,000	1,750	2,250
WS5, ES5	Hang	-18	1,750	A*	49.19	2,750	1,750	2,250
WS1,2 Axial	Axial Drag	-22	5,500	P	53.54	10,500	6,125	6,625
WS6, ES6	Hang	-16	1,750	A*	49.19	3,375	1,750	2,250
WS6, ES6	Side	-21	2,250	U	37.50	4,375	2,250	2,750
WS6, ES6	Axial Drag	-19	5,000	O	71.96	9,500	5,500	6,000
T2 Trans	Hang 01	-9	3,750	J	119.99	6,750	4,125	4,625
T2 Trans	Hang 02	-10	1,750	A	178.72	5,000	1,750	2,250
T2 Trans	Side	-11	2,250	D	113.48	5,000	2,250	2,750
T1 Trans	Hang 22	-6	3,000	G	81.34	5,625	3,125	3,625
T1 Trans	Hang 23	-7	1,750	A	139.47	4,500	1,750	2,250
T1 Trans	Side	-8	2,750	F	93.95	5,750	2,875	3,375
A1 Axicell	Hang	-12	1,750	A	92.74	3,375	1,750	2,250
A1 Axicell	Side	-13	1,750	A	95.48	3,625	1,750	2,250
A2 Axicell	Hang	-14	2,000	C	92.74	4,000	2,000	2,500
A2 Axicell	Side	-15	2,250	D	95.48	5,000	2,250	2,750
A2 Axicell	Axial to Sb	-23	4,500	M	80.15	7,750	5,000	5,500
Yin-Yang	Hang 01	-1	4,500	M	185.23	7,500	5,000	5,500
Yin-Yang	Hang 02	-2	5,500	P	120.81	9,250	6,125	6,625
Yin-Yang	Hang 05	-3	4,500	M	113.62	7,500	5,000	5,500
Yin-Yang	Side 07	-5	3,750	J	124.76	8,500	4,125	4,625
Yin-Yang	Axial U3,4	-4	5,500	P	135.14	10,250	6,125	6,625
LINKS FOLLOW		71E3606						
EST-WS5	Coil to Coil	-7	4,500	M	24.21	(LINK)		
T2 Trans	Axial to TT	-9	3,750	J	26.87	(LINK)		
T1 Trans	Axial to A20	-8	4,500	M	25.36	(LINK)		
A1 to A20	Axial	-10	4,500	M	26.00	(LINK)		

*Uses 1.00-inch clevis instead of 0.75-inch.

Table 10-10. MFTF Axicell Safety Margin Summary for Attachments
(Loads are Kips)

IDENTIFICATION				FROM APPENDIX D INCLUDES SAFETY FACTOR			YIELD STRENGTH CHECK @ DSN TEMP.					ULTIMATE STRENGTH CHECK @ DSN TEMP.					OVERALL M.S.
COIL	STRUT	71E- 3647 P/N	PIN	YIELD CAPAB. NEEDED	ULT. CAPAB. NEEDED	DSN TEMP.	MONO- BALL TAB 3	ROD END TAB 4	304LN CLEVIS TAB 5	A286 PIN TAB 6	MIN. YIELD M.S.	MONO- BALL TAB 3	ROD END TAB 4	304LN CLEVIS TAB 5	A286 PIN TAB 6	MIN. ULT. M.S.	
WS1,3 ES1,4	Side	-17	2.250	199	332	RT	295	303	228	281	.15	442	494	497 ^a	495	.33	.15
WS1,3 ES2,4	Hang	-16	1.750	177	196	RT	183	187	176 ^c	172	.47	275	304	382 ^a	303	.40	.40
WS5, ES5	Side	-20	1.750	54	91	RT	183	187	176 ^c	172	2.19	275	304	382 ^a	303	2.02	2.02
WS5, ES5	Hang	-18	1.750	41	77	RT	183	187	176 ^c	172	3.20	275	304	382 ^a	303	2.57	2.57
WS1,2 Axial	Axial Drag	-22	5.500	902	1506	RT	1833	1799	1423	1675	.58	2750	2938	3113	2953	.83	.58
WS6, ES6	Hang	-16	1.750	103	206	RT	183	187	176 ^c	172	.67	275	304	382 ^a	303	.33	.33
WS6, ES6	Side	-21	2.250	149	298 ^b	RT	295	303	228	281	.53	442	494	497	495	.48	.48
WS6, ES6	Axial Drag	-19	5.000	1401 ^a	2802 ^a	RT	1500	1470	(36900 K)	1343	.00	2250	2400	(706204K)	2368	.00	.00
T2 Trans	Hang 01	-9	3.750	429	858	RT	845	836	675	781	.57	1267	1364	1475	1377	.48	.48
T2 Trans	Hang 02	-10	1.750	55	110	RT	183	187	131	172	1.40	275	304	286	303	1.50	1.40
T2 Trans	Side	-11	2.250	175	350	RT	295	303	223	281	.30	442	494	497	495	.26	.26
T1 Trans	Hang 22	-6	3.000	352	704	RT	533	541	460	475	.31	800	882	1004	838	.14	.14
T1 Trans	Hang 23	-7	1.750	110	220	RT	183	187	132	172	.20	275	304	286	303	.25	.20
T1 Trans	Side	-8	2.750	262	523	RT	445	456	351	420	.34	667	745	766	741	.28	.28
A1 Axicell	Hang	-12	1.750	103	206	RT	183	187	132	172	.28	275	304	286	303	.33	.28
A1 Axicell	Side	-13	1.750	73	145	RT	183	187	132	172	.81	275	304	286	303	.90	.81
A2 Axicell	Hang	-14	2.000	153	307	RT	240	241	202	208	.32	360	394	439	367	.17	.17
A2 Axicell	Side	-15	2.250	204	408	RT	295	303	228	281	.12	442	494	497	495	.08	.08
A2 Axicell	Axial to S6	-23	4.500	857	1713	4K	1516	1757	2984	1467	.71	2275	2556	5708	2343	.33	.33
Yin-Yang	Hang 01	-1	4.500	580	1160	RT	1213	1195	1044	1086	.80	1820	1951	2283	1915	.57	.57
Yin-Yang	Hang 02	-2	5.500	930	1860	RT	1833	1799	1423	1675	.53	2750	2938	3113	2953	.48	.48
Yin-Yang	Hang 05	-3	4.500	579	1158	RT	1213	1195	1044	1086	.80	1820	1951	2283	1915	.57	.57
Yin-Yang	Side 07	-5	3.750	631	1262 ^b	RT	845	836	675	781	.07	1267	1364	1475	1377	.00	.00
Yin-Yang	Axial 03,4	-4	5.500	1185	2370	RT	1833	1799	1423	1675	.20	2750	2938	3113	2953	.76	.76
LINKS FOLLOW				71E3606			LINK TAB 7					LINK TAB 7					
ES1-W55	Coil-to-Coil	-7	4.500	1035	1728	4K	1516	1961	2984	1467	.42	2275	2544	5708	2343	.32	
T2 Trans	Axial to YY	-9	3.750	717	1434	4K	1056	1371	1930	1055	.47	1584	2544	3687	1685	.10	
T1 Trans	Axial to A20	-8	4.500	841	1682	4K	1516	1961	2984	1467	.74	2275	2639	5708	2343	.35	
A1 to A20	Axial	-10	4.500	1010	2021	4K	1516	1961	2984	1467	.45	2275	2639	5708	2343	.13	

- a) Per LLNL, use reduced safety factors. Replace 1401/2802 with 1343/2250.
b) Used GDC seismic loads.
c) Uses 1.00-inch clevis for 1.75-inch pin size.

Table 10-11. MFTF Axicell Safety Margin Summary for Turnbuckles

IDENTIFICATION						From App. D. w/SF				DSN TEMP	Yld Chk. @ DSN Temp.		Ult. Chk. @ DSN Temp.		OVERALL M.S.					
COIL	STRUT	71E P/N	PIN	MFTF I.D.	L	DO	YLD. CAPAB. NEEDED	ULT. CAPAB. NEEDED	T		C*	T	C	T		C				
WS1,3 ES2,4	Side	-17	2.250	D	37.05	4.750	199	199	332	332	RT	341	341	.71	.71	780	441	1.35	.33	.12***
WS1,3 ES2,4	Hang	-16	1.750	A*	49.19	3.375	117	59	196	98	RT	152	135	.30	1.29	348	185	.78	.89	.30
WS5, ES5	Side	-20	1.750	A*	37.50	3.000	54	54	91	91	RT	91	91	.69	.69	208	134	1.29	.47	.28***
WS5, ES5	Hang	-18	1.750	A*	49.19	2.750	41	21	77	39	RT	54	54	.32	1.57	124	90	.61	1.31	.32
WA1,2 Ax.	Ax. Drag	-22	5.500	P	63.54	10.500	902	902	1506	1506	RT	1753	1666	.94	.81	4007	1909	1.66	.27	.06***
WS6, ES6	Hang	-16	1.750	A*	49.19	3.375	103	56	206	108	RT	152	135	.48	1.41	348	185	.69	.71	.48
WS6, ES6	Side	-21	2.250	D	37.50	4.375	149	149	298**	298**	RT	289	275	.94	.85	660	349	1.21	.17	.17
WS6, ES6	Ax. Drag	-19	5.000	D	71.96	9.500	1401	702	2802	1401	RT	1427	1325	.02	.89	3261	1555	.16	.11	.02
T2 Trans	Hang 01	-9	3.750	J	119.99	6.750	429	266	858	533	RT	622	487	.45	.83	1421	634	.66	.19	.19
T2 Trans	Hang 02	-10	1.750	A	178.72	5.000	55	55	110	110	RT	224	167	3.07	2.04	511	209	3.65	.90	.90
T2 Trans	Side	-11	2.250	D	113.48	5.000	175	175	350	350	RT	341	267	.95	.53	780	371	1.23	.06	.06
T1 Trans	Hang 22	-6	3.000	G	81.34	5.625	152	176	704	352	RT	471	392	.34	1.23	1077	510	.53	.45	.34
T1 Trans	Hang 23	-7	1.750	A	139.47	4.500	110	97	220	194	RT	224	159	1.04	.64	511	213	1.32	.10	.10
T1 Trans	Side	-8	2.750	F	93.95	5.750	262	262	523	523	RT	523	420	1.00	.60	1195	558	1.28	.07	.07
A1 Axicell	Hang	-12	1.750	A	92.74	3.375	103	52	206	103	RT	152	90	.48	.73	348	127	.69	.23	.23
A1 Axicell	Side	-13	1.750	A	95.48	3.625	73	73	145	145	RT	197	113	1.70	.55	451	160	2.11	.10	.10
A2 Axicell	Hang	-14	2.000	C	92.74	4.000	153	77	307	154	RT	241	155	.58	1.01	550	218	.79	.42	.42
A2 Axicell	Side	-15	2.250	D	95.48	5.000	204	204	408	408	RT	341	302	.67	.48	780	414	.91	.01	.01
A2 Axicell	Axial-S6	-23	4.500	M	80.15	7.250	857	857	1713	1713	4K	1635	1471	.91	.72	3270	1760	.91	.03	.03
Yin-Yang	Hang 01	-1	4.500	M	185.23	7.500	580	290	1160	580	RT	671	450	.16	.55	1533	595	.32	.03	.03
Yin-Yang	Hang 02	-2	5.500	P	120.81	9.250	930	465	1860	930	RT	1091	956	.17	1.06	2491	1174	.34	.25	.17
Yin-Yang	Hang 05	-3	4.500	M	113.62	7.500	579	290	1158	579	RT	671	581	.16	1.00	1533	733	.32	.27	.16
Yin-Yang	Side 07	-5	3.750	J	124.76	8.500	631	631	1262	1262**	RT	948	948	.50	.50	2166	1308	.72	.04	.04
Yin-Yang	Ax. 03,4	-4	5.500	P	135.14	10.250	1185	653	2370	1305	RT	1613	1340	.36	1.05	3688	1656	.56	.27	.27

* Minimum compression = 50 percent of tension. Minimum tension = 100 percent of compression.

** Used GDC seismic loads.

*** See Euler check in Table 10-10c.

Table 10-12. MFTF Axicell Safety Margin for Turnbuckles - Euler

IDENTIFICATION							DSN TEMP	COMPRESSION LOADS W/O SAFETY FACTOR - KIPS			EULER COLUMN CAPABILITY KIPS	MS = $\frac{\text{CAPAB.}}{\text{BF(LOAD)}} - 1$ BF = 2.0
COIL	STRUT	71E P/N	P1N	MFTF I.D.	L	DO		NORMAL	DESIGN	ABNORMAL		
WS1.3 ES2.4	Side	-17	2.250	D	37.05	4.750	RT	47	109	199	444	.12
WS1.3 ES2.4	Hang	-16	1.750	A*	49.19	3.375	RT	28	36	59	193	.64
WS5. ES5	Side	-20	1.750	A*	37.50	3.000	RT	18	29	54	138	.28
WS5. ES5	Hang	-18	1.750	A*	49.19	2.750	RT	13	14	21	95	1.26
WA1.2 Ax.	Ax. Drag	-22	5.500	P	63.54	10.500	RT	185	216	901	1913	.06
WS6. ES6	Hang	-16	1.750	A*	49.19	3.375	RT	32	43	56	193	.72
WS6. ES6	Side	-21	2.250	D	37.50	4.375	RT	90	119	145	353	.22
WS6. ES6	Ax. Drag	-19	5.000	D	71.96	9.500	RT	467	500	631	1561	.24
T2 Trans	Hang 01	-9	1.750	J	119.99	6.750	RT	150	213	255	659	.29
T2 Trans	Hang 02	-10	1.750	A	178.72	5.000	RT	22	44	50	247	1.47
T2 Trans	Side	-11	2.250	D	113.48	5.000	RT	87	140	150	408	.28
T1 Trans	Hang 22	-6	3.000	G	81.34	5.625	RT	110	141	162	524	.62
T1 Trans	Hang 23	-7	1.750	A	139.47	4.500	RT	42	77	91	257	.41
T1 Trans	Side	-8	2.750	F	93.95	5.750	RT	137	209	253	580	.15
A1 Axicell	Hang	-12	1.750	A	92.74	3.375	RT	27	41	45	146	.62
A1 Axicell	Side	-13	1.750	A	95.48	3.625	RT	47	58	71	183	.29
A2 Axicell	Hang	-14	2.000	C	92.74	4.000	RT	51	58	63	240	.90
A2 Axicell	Side	-15	2.250	D	95.48	5.000	RT	123	163	183	441	.20
A2 Axicell	Axial-56	-23	4.500	H	80.15	7.250	AK	571	622	706	1811	.28
Yin-Yang	Hang 01	-1	4.500	H	185.23	7.500	RT	111	232	234	640	.37
Yin-Yang	Hang 02	-2	5.500	P	120.81	9.250	RT	195	372	374	1190	.59
Yin-Yang	Hang 05	-3	4.500	H	113.62	7.500	RT	117	232	233	749	.61
Yin-Yang	Side 07	-5	3.750	J	124.76	8.500	RT	45	505	519	1342	.29
Yin-Yang	Ax. 03.4	-4	5.500	P	135.14	10.250	RT	213	522	522	1681	.61

Minimum compression = 50 percent of tension.

Figure 10-36. Turnbuckle-Type Struts and Links Support the MFTF-Axicell Coils Within the Large Vacuum Vessel

Figure 10-37. Turnbuckles are Used Wherever Practical; Short Pin-to-Pin Lengths Require Utilization of Fixed-Length Links.

Figure 10-38. Special A-286 Forging Processes are Used to Produce the MFTF Rod End. These Attach to the Coils Via 304LN Clevis Fittings.

Figure 10-39. The Turnbuckle Portion of the Struts Has ± 3 Inches of Adjustment Capability Built In.

10.6 Leads/Stacks

10.6.1 Introduction

A detailed stress analysis of the stacks on the solenoid, axicell, and transition coils was performed. The primary analysis tools used were the NASTRAN finite-element stick models of the WS5 solenoid coil stack, A20 axicell stack, and T2 transition coil stack.

The finite-element models included all primary structural components of the stacks: the inner stack pipe, G-10CR divider plank, current lead bus bars, vapor-cooled lead assemblies, vacuum enclosure outer pipe, and double bellows.

The load cases considered in the finite element analysis were: (1) forced deflections at the base of the stack corresponding to the movement of the coil during operation; (2) thermal contraction of the stack components resulting from steady-state cooldown; (3) atmospheric pressure outside the vacuum enclosure outer pipe acting on the top of the stack; (4) dead weight; and (5) seismic load of $\pm .75$ Gs in each of the three orthogonal directions.

10.6.3 Solenoid Coil Stacks

Stress analysis of the stack assemblies for solenoid coils WS1-WS6 and ES1/ES6 was performed. The analysis was done specifically for WS5 since this coil has the most severe displacements of any of the solenoids. WS5 analysis results showing the displacements at the top of the stack and the component stresses are shown in Figure 10-40.

10.6.3 Axicell Coils A1 and A20 Stacks

The A1 and A20 stacks are identical and have a straight vertical pipe run similar to the solenoid stacks. The only significant differences between the solenoid and the A1 and A20 stacks are: (1) the total length of the 10-inch diameter inner stack pipe and (2) the cross-sectional areas of the leads.

The types of loads applied to the axicell coil stacks are the same as for the solenoids. The larger rotations of the axicell coils are the most significant difference in the loading. These larger rotations made it necessary to use a stronger material for the stack bellows. These bellows are Nitronic 40 stainless steel vs. 304L for the solenoid stacks. The transition coils also use Nitronic 40.

10.6.4 T1 Coil Stack

The T1 coil stack is shown in Figure 10-41. Like the axicell and solenoid stacks, the T1 stack is a straight pipe length. The T1 stack, however, is installed 45 degrees from the vertical and is approximately 15 inches longer at the base than the axicell stacks.

All margins of safety for the T1 stacks are positive.

10.6.5 T2 Coil Stack

The geometry of the T2 stack is shown in Figure 10-42. Unlike the other stacks, the T2 stack has a much more complicated shape. This complicated shape makes the stresses much more severe for the T2 lower stack pipe. The bends in the pipe not only intensify the pipe stresses, but also increase the moments due to offsets in the load path.

In order to carry the large bending moments, the lower stack pipe on T2 is made from 12-inch diameter schedule 100 pipe. Also, gusset plates are used to reinforce the pipe at the 90° bend. The gusset plates prevent local overstressing of the pipe due to stress intensification at the 90° bend.

Additional analysis was required to investigate the current lead contraction relative to the stack pipe on T2. Upon steady-state cooldown, the leads will contract more than the stack pipe. However, the leads are prevented from contracting freely relative to the pipe by bends in the pipe and leads. Stresses in the leads were kept within acceptable levels by controlling the clearance between the leads and the lead clamps. Thermal strains can be absorbed as elastic strains in the leads.

10.6.6 A21 Coil Stack

The A21 coil is attached to the inside of the A20 coil as shown in Figure 10-43. The principal difference between the A21 and A20 stacks is the 23-inch lateral offset in the A21 lower stack pipe. All the individual components are the same as A20 except for the leads. The A21 copper leads are 3.50 inch by .75 inch and the A20 leads are 4.0 inch by 1.375 inch. The cross-sectional areas of the VCL's also differ.

In order to prevent thermal contractions of the leads at the 23-inch offset from being restrained by the stack and binding, a .063-inch clearance has been provided between the current lead and the G-10 is provided between the divider plank and the stainless steel guides.

STRESSES IN STACK COMPONENTS

	$\sigma_{V.M.}$ (ksi)	σ_{All} (ksi)	M.S.
Lower He Pipe (10"φ)	4.85	20.0	3.12
Upper He Pipe (12"φ)	5.62	20.0	2.56
G-10CR Divider Plank	Negligible	37.0	Large
Copper Lead	Negligible	18.7	Large
V.C. Lead (Outer Tube)		20.0	Large
Outer Vacuum Pipe (22"φ)	Negligible	20.0	Large

MAXIMUM DEFLECTIONS AT TOP OF STACK

Δ_x	= - .2740 Inches
Δ_y	= - .4936 Inches
Δ_z	= - .849 Inches
θ_x	= - .00175 Radians
θ_y	= - .00163 Radians
θ_z	= $\pm$.00028 Radians

Figure 10-40. The Solenoid Stack Components Have Large Design Margins of Safety

T1 Stack Assembly

View Looking West

Figure 10-41. The T1 Stack is Similar to the Solenoid Stack.

Figure 10-42. The T2 Lower Stack Pipe has a Complex Geometry.

Figure 10-43. The A2I Stack is Similar to the A20 Stack

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10.7 Yin-Yang Modifications

10.7.1 Introduction

The modification of the MFTF-B superconducting magnet system into the Axicell configuration required significant structural changes to the yin-yang magnet structure. In order to utilize the existing yin-yang pair, changes were required which called for detailed structural analysis. Volume VI of Reference 10-5 documents the analysis procedure and stress results which were called for due to yin-yang modifications for the axicell configuration.

The primary structural modification to the yin-yang pair was the result of an increased spacing between coils M1 and M2. In order to accommodate the 1.7-meter coil separation, it was necessary to replace the existing case extension and intercoil beam. Several NASTRAN finite element models were constructed to analyze this modification and to iterate on the extension/intercoil region. Additional stress analysis of the yin-yang magnets was required to assess the effects of a slot cut in the M1 major radius to allow for neutral beam passage. Local effects in the region of the notch were investigated as well as overall behavior due to structural asymmetry.

As a result of the increased coil spacing and neutral beam slot, it was necessary to redesign the yin-yang support system. In addition, the adjacent transition coil (T2) now overlaps the M1 major radius, requiring removal of a previously existing MFTF-B strut.

10.7.2 Case Extension and Intercoil Beam Redesign

The primary consideration in the yin-yang extension/intercoil redesign was that a maximum capability of load sharing between coils be achieved. As in previous yin-yang configurations, electromagnetic forces cause a gross spreading tendency of the

major radius lobes. This load is transferred from the minor radius of one coil through the intercoil structure, and is reacted by the major radius of the other coil, as shown in Figure 10-44. A greater magnet flexibility, however, is apparent now due to the increased coil spacing, which means that less major radius spreading force is reacted by the opposing coil. Without sufficient "clamping" restraint provided by the reacting coil, major radius lobe spreading deflections increase, causing minor radius stresses to peak up. For this reason, the prime design consideration was that the new yin-yang extension/intercoil achieve maximum load sharing between coils.

Initial sensitivity studies were conducted by iterating on the coil extension stiffness to determine its affect on intercoil load. Iterations were performed using a NASTRAN finite element "stick" model (beam element model). Results showed that intercoil load remained insensitive to extension stiffness, or, that beyond a certain point, increasing the coil extension cross section did not pay off with an increase in load sharing between coils. The point at which this occurred was when approximately 20 percent of the major radius spreading load was transferred through the intercoil beam into the reacting minor radius. The goal, then was to redesign the extension/intercoil to 20 percent load sharing and verify it with detailed analysis.

Detailed analysis was performed, not only to insure proper load sharing, but also to establish extension/intercoil plate thicknesses and to determine minor radius stresses. The analysis tool used was the 6600 degrees of freedom NASTRAN quarter-symmetric model created originally for MFTF-A analysis. With exception to separating the coils 1.7 meters and removing the intercoil beam, the coil portion of the model is identical. This model is shown in Figure 10-45.

Due to applied inside barrier electromagnetic loads, a critical longitudinal stress (hoop direction) develops on the inner case

plate 40° from the minor radius plane of symmetry. The maximum MFTF-A element stress peaked at 79.8 ksi, while that for Axicell yin-yang is 56.7 ksi.

Since stress output is given only at element centers, and because both axial and plate bending peak sharply in corner regions, it was necessary to extrapolate the element stress plot into the case corner. Figure 10-46 depicts such a stress extrapolation. Peak equivalent membrane stresses were calculated which account for a higher allowable stresses (9/10 fty), on the bending component (see Volume 1 of the FSR). Although the axicell extrapolated equivalent membrane stress is 67.8 ksi, which slightly exceeds the 67 ksi allowable stress specified under Axicell ground rules, the difference is within the accuracy of the analysis. Also, the critical stresses are highly localized and, with the assurance of a sufficient yield strength in the affected area, the described coil extension/intercoil box beam is structurally sufficient to minimize coil stresses.

Load paths in the separated yin-yang pair differ from that in the original MFTF-A configuration. As seen in the analysis results, a smaller percentage of major radius spreading load is now reacted by the opposing coil. This is due to the greater magnet pair flexibility caused by the increased coil spacing. The reduced "clamping" force of the reacting magnet results in peak stresses located in the minor radius of the coil with the highest spreading force. For MFTF-B, on the other hand, peak stresses occurred in the minor radius of the coil reacting the coil with the greater spreading force.

10.7.3 Effect of P2B2 Beam Slot

Additional stress analysis of the Axicell yin-yang coils was required in order to assess the effects of a reduction in the M1 radius cross section due to neutral beam passage. The area affected is shown in Figure 10-47. Analysis was performed once

again using the detailed finite element model with necessary grid and element refinement in the notched region.

Locally, the "notched" region is structurally adequate using 3-inch plate. Stress results obtained from the detailed run are shown in Figure 10-48. Membrane stresses were plotted in the side plates of the M1 major radius, one plot to either side of the plane of change in section. These curves show stress distributions of similar shape and magnitude to either side of the change in section, indicating a good transmittal of load across it. Examination of the triangular-shaped plates indicates that they achieve load transfer in the inner cover plate through transverse shear (see Figure 10-49). Bending stresses in this plate were hand calculated based on the moment induced by the difference in shear at each end. Resulting stresses are less than the allowable based on 2/3 fty.

10.7.4 Final Yin-Yang Axicell Run

Once it was determined that the stretched, slotted yin-yang part was structurally adequate, the detailed finite-element model was converted back to a quarter-symmetric model and run for final results. The M1 major radius lobe included the notch and L-141 electromagnetic loads were applied. Three (3) loading conditions (NASTRAN subcases) were applied to the model: (1) Worst Normal Operation, (2) Worst Abnormal Operation, and (3) Worst Condition.

The peak minor radius stress, once extrapolated into the corner, still slightly exceeds the 67 ksi (2/3 fty) work allowable specified in the design ground rules. A worst finite-element hoop stress of 63.95 ksi (which includes bending) develops in the inner side plate of coil M2 on a plane 70° from the minor radius plane of symmetry. Each stress component (inner and outer surfaces in both the longitudinal and transverse directions) was

extrapolated into the case corner to calculate the peak equivalent membrane stresses. The axicell equivalent membrane value, thus, was 71.9 ksi, while the worst equivalent membrane value for MFTF-A was 92.9 ksi. The worst analytical safety margin for axicell -0.068.

In summary, stresses in the Axicell yin-yang pair are considerably (approximately 25 percent) lower than MFTF-A operating stresses due to electromagnetic loads. The axicell design ground rules, however, derate the 304LN yield strength from 120 ksi to 100 ksi, which results in peak stresses which slightly exceed the new allowable stress. This was considered acceptable, however, due to the local nature of the high-stress region, the questionable accuracy of the extrapolation, and most importantly, the inability to lower the stresses with any reasonable structural modification.

10.7.5 Yin-Yang Support System Redesign

A new yin-yang support system was necessary due to the T2 coil presence and the intercoil structure revision. A six-strut system was maintained to alleviate high strut forces which occurred in the previous MFTF-A seven-strut systems due to thermal cool-down.

A NASTRAN finite element "stick" (beam element) model was constructed in order to analyze the new support system. Coils M1, M2, and T2 were included in the model to determine overall structural behavior (deflections) of the three-coil module when subjected to thermal cool-down, and seismic accelerations (0.75G) in the lateral, vertical, and axial directions. NASTRAN graphics plots of the model are shown in Figure 10-50.

Results from the yin-yang supports "stick" model show no high strut loads due to thermal cool-down, and deflections were small enough to cause no interference between coils. Strut loads due to dead weight, magnetic loads, and seismic effect compare favorably to the hand solution, as shown in Table 10-13.

Table 10-13. Yin-Yang Strut Forces (Kips). No Safety Forces are Applied.

Strut No.	Dead Weight	Vertical Seismic 0.75G (F_v)	Lateral Seismic 0.75G (F_L)	Axial Seismic 0.75G (F_A)	Magnetic	Total Load*	Total Hand
1 (Hanger)	195.2	146.4	-146.3	0.0	0.0	402.2	402
2 (Hanger)	207.2	155.4	-155.5	0.0	0.0	427.0	402
3 (Hanger)	352.1	254.1	167.5	0.0	0.0	564.8	73
4 (Sidel)	0.0	0.0	434.5	0.0	0.0	430.6	46
5 (Axial)	0.0	0.0	366.9	-328.9	433.0	917.6	91
6 (Axial)	0.0	0.0	-366.4	-329.3	433.0	934.8	91

$$\text{Total load} = Wt + \sqrt{(F_v^2 + F_L^2 + F_A^2)} + MAG$$

Figure 10-44. The Electromagnetic Loads Spread the Major Radius Lobes Apart

Axicell Yin-Yang
NASTRAN 1/4-Symmetric
Finite Element Model
with Extension.

PLATE	THICKNESS (IN)
A	0.75
B	0.5
C	1.75
D	3.0
E	4.0
F	4.0
G	4.0
H	1.75
I	1.5
J	3.0

Figure 10-45. The Yin-Yang Extension Structure Maximizes Load Sharing and Utilizes Existing Plate Thicknesses.

Figure 10-46. Comparison of MFTF-A and MFTF-Axicell Yin-Yang Side Plate Stresses

Figure 10-47. The P2B2 Beam Reduces the M1 Major Radius Cross Section.

Figure 10-48. Comparison of Yin-Yang Pair with Notched M1 Major Radius to Yin-Yang Pair Without Notched M1 Major Radius.

Figure 10-49. Load Transfer in the Notched Major Radius is Achieved by Transverse Shear.

Figure 10-50. NASTRAN Stick Model of Yin-Yang and T2 Coils.

10.8 References

- 10-1 MFTF-B Final Stress Report, GDC-LLNL-82-002, Volumes I - XI, 1982.
- 10-2 Astronautic Structures Manual, Marshall Space Flight Center, Vol I, 1975.
- 10-3 MFTF Design Requirements Document, LLNL, revised 20 May 1983, updated 12 August 1983 via LLNL memo.
- 10-4 Astronautic Structures Manual, Marshall Space Flight Center, Vol. I, 1975.
- 10-5 MFTF-Axicell Final Stress Report, GDC-LLNL-84-002, Volumes I-XIII, 1984.

Volume Number	Title
I	MFTF-B Structural Analysis Approach
II	Support Struts Analysis
III	Electromagnetic Loads Analysis
IV	Fracture Mechanics Analysis
V	Documentation of Finite-Element Models (Separate sub-volumes for each coil type)
VI	Yin-Yang Modifications Detailed Stress Analysis
VII	Solenoid Coils Detailed Stress Analysis
VIII	Axicell Coils Detailed Stress Analysis
IX	Insert Coil Detailed Stress Analysis
X	T1 Coil Detailed Stress Analysis
XI	T2 Coil Detailed Stress Analysis
XII	Leads/Stacks Detailed Stress Analysis
XIII	Cooldown-Warmup Stress Analysis (Separate subvolume for each coil type).

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THERMAL ANALYSIS

11.1 Introduction

The Design Requirements Document (DRD), Reference 11-1*, sets forth the requirements and criteria for the magnets, interfaces, and system level considerations influenced by the magnets. Every engineering task in general is directed at satisfying these requirements, identifying where cost considerations may require a change to the requirements, and what the consequences might be. The thermodynamically related requirements have been extracted from the DRD and categorized under the major thermodynamic task headings. The DRD paragraph or auxiliary reference is indicated. Every thermodynamic design analysis effort is directed at establishing an answer, developing a criteria, target, or guideline for the design of the magnets to permit them to satisfy the intent of the requirements, and defining the requirements on the interfaces and facility systems.

The cryostability requirements and criteria have been extracted and condensed from the Design Requirements Document (DRD). These are shown with DRD reference on Table 11.1. All conductors and windings are designed to be everywhere unconditionally cryostable (no cold end conduction benefit) with at least the indicated margins. Because of high neutron heating in the windings and potential cryostability degradation at walls, special ventilation techniques were incorporated at the structural case/winding interface zones. Poolboiling LHe heat transfer is defined for general windings, conductor, and interface zones by the extensive test data survey and correlations of Reference 11-2.

* In the thermodynamic analysis section, 11.0, references are identified by Arabic numeral (11-4) for general references and by Roman numeral (11-IV) corresponding to volume numbers of the detailed Final Thermal Analysis Report for Axicell.

Thermal conditioning requirements are shown on Table 11-2. The magnets are designed to be cooled down or warmed up within 120 hours. The inlet helium profile is a time-compressed version of the facility ramp-down profile experienced with the MFTF-A cryogenic system and was jointly determined and agreed to between LLNL and GDC. Time-compression is mandatory to cool the magnets in 120 hours. The fast cool-down maximizes gradients and differential temperatures. Support system components and extended structures are cooled by passive conduction to the winding cavity coolant whenever possible. This transient cooling continues on the longer, heavier supports after 120 hours. The terminal portion of the transient contributes a distributed incremental 1100 watts to the helium at 140 hours when the magnets are full of LHe. This additional initial operation heat load decays to the steady-state value in several tens of hours and is acceptable from refrigeration capacity, helium quality, and cryostability considerations.

Design of the thermal protection systems for the supports and liners are directed at the general requirements of minimizing heat loads within cost and "good" thermal design constraints. Of course these systems have to meet structural load requirements which have grown and are generally contrary to the requirement of lowest heat loads, hence compromise of the "minimizing of" heat loads. In the face of high instantaneous neutron heat loads, natural circulation reduction by individual dewars with low head, and liner clearance limitations on pipe sizes, the helium quality limit has been interpreted to be that in contact with the winding. A goal of the last requirement has been to keep higher vapor content circulated out of and away from the winding by using more open channel boundary and plenum zones and insulations. LHe heat load requirements are summarized on Table 11-3.

The leads design analysis and developmental testing, much of which was accomplished for earlier MFTF magnet configurations, has shown conformance with the requirements as shown in Table 11-4. Early thermally isolated lead analysis established the specific flow rate parameter which was anticipated to provide safety margin and became a DRD requirement.

Final integrated stack/VCL analysis has required a higher specific flow rate as the lead size reduced. The heaters are mandatory and increased in size to provide environmental control for the enclosure and components on the top of the stacks and external to the vacuum chamber.

Thermodynamic aspects of magnet safety fail in the areas of maximum realistic winding temperature predictions and design analysis of the quench venting system and associated maximum pressure loading in the magnet and of pressure envelope components. Both of these become more intense, critical, and important as peak dump voltage is reduced. However, the consequences of higher dump voltages which could mitigate the thermodynamics criteria are less predictable, less certain, less easy to design for, and less forgiving of unidentified flaws in design or fabrication, hence the press toward lesser induced peak voltages. These magnet safety requirements are summarized in Table 11-5. A maximum effort was required to provide realistic but maximum safety margins in these magnets for high reliability.

This summary report highlights the detailed analyses made during the design phase of the project for the MFTF-B axicell configuration magnet set and associated interfaces with the facility. Throughout this period the information has been reported as part of design reviews and action items to LLNL. The sections that follow summarize the efforts in these thermally related topics.

<u>Section</u>	<u>Topic</u>
11.2	Cryostability
11.3	Cool-down/Warm-up Including Supports
11.4	Heat Loads
11.5	Thermosiphon
11.6	Quench Venting
11.7	Lead and Stack Thermal Performance
11.8	References

Table 11-1. Cryostability Requirements

Item/Description		DRD Paragraph																																
•	Cryostatically stable copper stabilized NbTi axial heat conduction omitted.	2.2.2 2.2.4																																
•	Pool boiling, 4.5K saturated helium at bottom of magnet, natural convection through magnet.	2.2.3																																
•	Ventilation and helium natural flow distribution design to preclude vapor accumulation in contact with conductor.	2.7.5																																
•	Conductor temperature less than superconductor transition to current sharing with design current at maximum magnetic field.	2.2.4																																
•	Minimum superconducting margins:	2.4.6																																
	<table><tr><td></td><td>Critical Current</td><td>Critical Field</td><td>Cryostable Current</td></tr><tr><td>Coil</td><td>$\Delta I_c / I_{op} (\%)$</td><td>$\Delta B_c / B_{op} (\%)$</td><td>$\Delta I_c / I_{op} (\%)$</td></tr><tr><td>T1</td><td>10</td><td>10</td><td>10</td></tr><tr><td>T2</td><td>10</td><td>10</td><td>10</td></tr><tr><td>S1-S6</td><td>10</td><td>10</td><td>10</td></tr><tr><td>A20</td><td>15</td><td>10</td><td>15</td></tr><tr><td>A2I</td><td>100</td><td>7.5</td><td>15</td></tr><tr><td>A1</td><td>15</td><td>10</td><td>15</td></tr></table>		Critical Current	Critical Field	Cryostable Current	Coil	$\Delta I_c / I_{op} (\%)$	$\Delta B_c / B_{op} (\%)$	$\Delta I_c / I_{op} (\%)$	T1	10	10	10	T2	10	10	10	S1-S6	10	10	10	A20	15	10	15	A2I	100	7.5	15	A1	15	10	15	
	Critical Current	Critical Field	Cryostable Current																															
Coil	$\Delta I_c / I_{op} (\%)$	$\Delta B_c / B_{op} (\%)$	$\Delta I_c / I_{op} (\%)$																															
T1	10	10	10																															
T2	10	10	10																															
S1-S6	10	10	10																															
A20	15	10	15																															
A2I	100	7.5	15																															
A1	15	10	15																															
•	Superconducting design margins include trim coil super-imposed fields.	2.4.6																																

Table 11-2. Requirements for Pre- and Post-Operation Thermal Conditioning

Item/Description	ORD Paragraph																								
<ul style="list-style-type: none">Coils capable of cool-down/warm-up in 120 hours.	2.4.7																								
<ul style="list-style-type: none">Inlet Temperature Profiles:<table><tr><th colspan="2">Cool-Down</th><th colspan="2">Warm-Up</th></tr><tr><th>Time, Hr.</th><th>Temp., K</th><th>Time, Hr.</th><th>Temp., K</th></tr><tr><td>0 Hr</td><td>220</td><td>0 Hr</td><td>80</td></tr><tr><td>35 Hr</td><td>95</td><td><65 Hr</td><td>300</td></tr><tr><td>55 Hr</td><td>95</td><td></td><td></td></tr><tr><td><80 Hr</td><td>5</td><td></td><td></td></tr></table>	Cool-Down		Warm-Up		Time, Hr.	Temp., K	Time, Hr.	Temp., K	0 Hr	220	0 Hr	80	35 Hr	95	<65 Hr	300	55 Hr	95			<80 Hr	5			Letters JHV to JWW
Cool-Down		Warm-Up																							
Time, Hr.	Temp., K	Time, Hr.	Temp., K																						
0 Hr	220	0 Hr	80																						
35 Hr	95	<65 Hr	300																						
55 Hr	95																								
<80 Hr	5																								
<ul style="list-style-type: none">LN₂ Liners at 80K and water liners flowing during cool-down warm-up reversed with LN₂ liners at 300K.	D.I.a.d.																								
<ul style="list-style-type: none">Temperature differentials not exceeding stress limits accommodate distortion associated with temperature differentials,	2.4.7																								
<ul style="list-style-type: none">Specify helium flow rates for coils' cool-down/warm-up in 120 hours.	2.4.7																								
<ul style="list-style-type: none">Passive cooling of supports heat load delta 1100 watts acceptable at 140 hours cool-down.	Memo JHV to TAK 8/12/83																								
<ul style="list-style-type: none">400 regeneration cycles - warm case to 80K followed by cool-down.	2.4.10.1																								
<ul style="list-style-type: none">100 full thermal cycles - 300K to LHe to 300K.	2.4.10.1																								

Table 11-3. LHe Heat Load Requirements.

Item/Description					DRD Paragraph
<ul style="list-style-type: none"> Minimize heat load to reduce helium requirements. 					2.2.7
<ul style="list-style-type: none"> Finish and clean to minimize emissivity and thermal radiation. 					2.6.2.6
<ul style="list-style-type: none"> Supports designed to minimize heat load. 					2.7.4
<ul style="list-style-type: none"> LN₂ intercepts and internal shields required. 					2.8.2
<ul style="list-style-type: none"> LN₂ intercepts optimum location design. 					2.2.4.2
<ul style="list-style-type: none"> Passive cooling of supports heat load delta 1100W acceptable at 140 hours CD. 					Memo JHV to
<ul style="list-style-type: none"> LN₂ liners conduction and radiation <0.80 W/M² 					2.8.2
<ul style="list-style-type: none"> Maximum allowable helium heat load: 					2.7.5
Coil Group	Thermal Load Limit (W)	Averaged 10% Duty Cycle Time Neutronic Heating (Determined by LLNL)	Instantaneous Neutron Heating Total Within Winding		2.8.4
T1 (2)	140	7.4	74	31	
T2 (2)	200	4.5	45	24	
A1 (2)	180	343	3430	2300	
A2I (2)	40	98	984	616	
A20 (2)	200	149	1486	800	
S1 - S6 (12)	650	225	2251	1442	
Total for Entire System	1410	827	8270	5213	
<ul style="list-style-type: none"> Natural convection through magnets is bouyancy driven by magnets as heat source, return to dewar at top, dewar helium 4.35K saturated. 					2.2.3
<ul style="list-style-type: none"> Liquid helium return lines from lead duct near the top of the structural case of each magnet. Sized jointly by LLNL and magnet and cryogenic system subcontractors. 					2.10.5.1
<ul style="list-style-type: none"> Helium quality at exit of each coil 2.5% by weight. 					2.7.5
<ul style="list-style-type: none"> Internal ventilation to inhibit vapor accumulation in contact with conductor. 					2.7.5

Table 11-4. Lead Safety-Related Thermal Requirements

Item/Description	DRD Paragraph
<u>CURRENT LEADS</u>	
● Separate leads for each magnet.	2.4.4
● Thermal inertia design to operate without cooling for 10 minutes or longer at rated current.	2.7.13.4
● Voltage taps on VCLs are monitors for VCL safety (overheat).	2.9.1.1
● Coolant helium vapor through each VCL pair = 0.11 g/s/kA/Pair flow control by LLNL.	2.7.5
● Electrical heater at top of VCLs to maintain coolant helium exit temperature of $296 \pm 5K$ at 0.11 g/s/kA/Pair flow rate and all levels of current (including zero). (Heaters are sized for all other losses at minimum environment.)	2.10.5.2
● Thermocouple on bus at heater for feedback on-off control of heater by computer.	--
● Magnet subcontractor specify required VCL flow rate as a function of current to maintain 300K coolant exit temperature (software).	2.10.5.2

Table 11-5. Magnet Safety-Related Thermodynamic Requirements

Item/Description	DRD Paragraph
<ul style="list-style-type: none"> Fast energy dump resistor circuit for quench protection. 	2.2.5
<ul style="list-style-type: none"> Voltage taps on leads for magnet protection. Also, voltage taps in the magnets. 	2.10.4
<ul style="list-style-type: none"> Design for fault mode constraint. Maximum voltage across terminals or any point in coil to ground during fast dump ≤ 1000 VDC. 	2.7.13.2 2.4.5
<ul style="list-style-type: none"> Design dump system for maximum voltage to ground during fast dump ≤ 500 VDC. 	2.10.3.5
<ul style="list-style-type: none"> Environment for coil insulation: Helium gas at 1 atm and 300K. 	2.4.5 2.7.9.3
<ul style="list-style-type: none"> Hot-spot temperature rise during quench, 10-second delay and fast dump 200K based on 2-D heat conduction model. 	2.7.13.1
<ul style="list-style-type: none"> Design to include worst-case fault pressure during magnet quench and venting. Pressure is determined by maximum voltage safety parameters (dump time constant) and helium/vent system design. 	2.5.6
<ul style="list-style-type: none"> Joint function of return lines as quench vent lines influences sizing jointly by LLNL and magnet and cryogenic system subcontractors. 	2.10.5.1

11.2 Cryostability

The MFTF-B Axicell configuration magnets cryostability analysis examines the thermodynamic behavior of the MFTF conductor and leads below the superconductor critical temperature. All MFTF superconducting magnets are unconditionally cryostable within the prescribed cryostability current margins listed in Table 11-1 of section 11.1, reprinted in this section with margin definitions in Table 11-6.

11.2.1 Solenoids

References 11-VIII and 11-IX establish central cell solenoid conductor fabrication criteria and early insulation/ventilation design and cryostability analysis. Changes in the operating/peak conditions and insulation/ventilation designs made after the earlier analyses are reflected in the reevaluation of the cryostability of the solenoid coil conductor presented in Reference 11-X. Table 11-7 is a solenoid magnet-by-magnet listing of those changes for the current Axicell versus the earlier A-Cell configuration. Note that there is no longer an S7 coil and that there is increase in both current and peak field. In the process of the transition, LLNL found and GDC agreed that the criterion for the critical current of $10^{-11} \Omega\text{-cm}$ was unacceptable and consequently the criterion was changed to $5 \times 10^{-13} \Omega\text{-cm}$ or $0.3 \times 10^{-6} \text{ V}$ over 2.54-cm length. The critical current criteria of $10^{-11} \Omega\text{-cm}$ used for the Yin-Yang conductors is still acceptable for high field application where the voltage take-off is very pronounced. The same criterion when used for the solenoid conductors in lower field can allow unacceptably high heat generation because the voltage take-off is much more gradual. Along with the change of the criterion, the critical current margin for solenoids was changed from 25 percent to 10 percent. A few ventilation/insulation changes also have been made during the winding of the solenoid coils.

Based on the new criteria of $5 \times 10^{-13} \Omega\text{-cm}$, some of the initially produced conductor did not meet the critical current requirement in the old specification (3400A at 3.1T and 4.5K, or 3730A at 3.1T and 4.2K). GDC changed the specification and labeled the marginally acceptable conductors Grade II and used them for winding the outer layers at lower fields. The specifications at 4.2K now appear as:

<u>Grade</u>	<u>Critical Current (A)</u>	<u>Magnetic Field (tesla)</u>
I	3730	3.1
II	3500	3.1

The Grade II conductors are to be used in the layers whose peak field is less than 2.78 tesla or approximately the 9th layer and out.

After incorporation of the design and fabrication changes and under the new set of operating/peak conditions, the solenoid coil is found to be unconditionally cryostable everywhere in the winding. The cryostability margins of conductor segments are smaller at the new operating conditions, but they are larger at the new peak conditions. The cryostability of all of the conductor segments analyzed in the early report, Reference 11-IX, are re-evaluated and two new locations, a Grade II conductor in the 9th layer and a Grade I conductor against the entering lead cover, are additionally analyzed. Table 11-8 lists the cryostability parameters that resulted from the as-built solenoid configurations most recent analysis, Reference 11-X.

11.2.2 MFTF Conductor Magnets

Cryostability analysis of the magnets using MFTF NbTi conductor is presented in Reference 11-XI. This group of magnets includes the Transitions, T1 and T2, and the Axicell Barrier coils, A1 and A20.

Within the scope of this subject was to identify and eliminate, through interaction with the designers, potential problem areas that might jeopardize the required cryostability margins.

Special ventilation features that influence cryostability were required for the transition (T1 and T2) coils. Double-layer, 1/4-inch cross-grid plenum insulation was selected to encourage helium flow to the inner ring during cool-down operation, to converge steady-state flow through the intermediate vent located at the high point of the inner ring of the upper lobe of the lower minor radius, and to provide deep helium channels and nondegraded heat transfer in the high field region. Solid plenum insulation was extended over 75 and 90 degrees in the major radius outer ring of the T1 and T2 magnets, respectively, to baffle the high plenum flow into the conductor pack. Cross-slotted insulation was provided between the conductor pack and solid plenum insulation for positive ventilation at the outer conductor layer.

The AxiCell (A1 and A20) coils receive very high neutron heating during the plasma shots. Strong, intermittent vapor generation and high vapor quality due to the neutron heating called for generous bubble passages around the conductor pack and large vapor accumulation volume at the top portion of the plenum. The deep channel insulation (0.31 inch) at the inner ring provides a generous bubble passage as well as some storage for the vapor that is generated intermittently from the lower portion of the magnet. The 0.15-inch deep channel insulation at both sides of the single inlet pancake and 0.375-inch deep post insulation along the sidewall of the layer conductors promote the transport of bubbles and compensate for the degradation of the recovery heat flux at the surface of the conductors adjacent to the wall.

Discovery of potential solder blockage occurring in the Grades I and II YY-type conductor channels prompted reassessment of the conductor wetted perimeter. A revised wetted perimeter of 7.42 cm²/cm, lower than the original 8.17 cm²/cm, was calculated

assuming the channels between the core and the stabilizer on one side of the conductor were blocked.

To identify the degree of cryostability, margins of cryostability are calculated at worst-case local environments throughout the conductor pack of the magnets as well as throughout the lead buses up to the stack assembly. The margins are then used to assist in determination of the adequacy of the insulation design and ventilation configuration. Tables 11-9 and 11-10 are examples of cryostability margin results for the maximum current/maximum field service for this type of conductor and splices represented by A20 in this magnet set. Similar considerations were examined for the remaining magnets with NbTi conductor and are presented in greater detail in Reference 11-XI. Additionally, a section on design recommendations that assure the cryostability of the magnets was presented to guide design.

11.2.3 Transition Leads

Also included in Reference 11-XI is the cryostability analysis of the transition lead configurations. This report includes design recommendations that enable the leads to comply with the cryostability specifications set forth by LLNL.

For the Transition magnets, Kapton insulation is wrapped around the inlet lead to provide electrical protection from the conductor pack. Two cooling channels are provided for helium flow along the lead from the entrance in the winding to an exit at the vapor-cooled lead (VCL) stack. If the lead goes normal, helium vapor formed in the channels induces a flow by thermosiphon action that removes all of the generated energy without allowing vapor to accumulate in the channel and avoids film boiling heat transfer. These leads have been designed and shown by thermosiphon analysis to be very cryostable.

The pancake inlet leads on the Axicell A1/A20 Barrier coils, unlike the Transition inlet leads, are not internally helium cooled, but receive external helium cooling through the 0.25-inch space on each side, and at least two criss-crossed layers of slotted plenum insulation at the inboard and outboard edges. Ventilation conditions are similar for the exit lead. The exiting and entering leads are fixed to the sidewalls of the case structure by bolting to G-10CR anchoring pads. The other three surfaces of the lead are wetted by helium.

The portions of all leads that extend from anchored zones to the stack outlet are all afforded liberal ventilation by the adjacent insulation and G-10 clamps.

Table 11-6. Minimum Superconducting Margins

COIL	$\Delta I_c / I_{op} (\%)$	$\Delta B_c / B_{op} (\%)$	$\Delta I_s / I_{op} (\%)$
T1	10	10	10
T2	10	10	10
S1-S6	10	10	10
A20	15	10	15
A21	100	7.5	15
A1	15	10	15

$$\text{Critical Current Margin} = \frac{\Delta I_c}{I_{op}} = \frac{I_c - I_{op}}{I_{op}} \bigg|_{B_{op}}$$

$$\text{Critical Field Margin} = \frac{\Delta B_c}{B_{op}} = \frac{B_c - B_{op}}{B_{op}} \bigg|_{I_{op}}$$

$$\text{Cryostable Current Margin} = \frac{\Delta I_s}{I_{op}} = \frac{I_s - I_{op}}{I_{op}} \bigg|_{B_{op}}$$

$I_{op} \equiv$ Operating Current

$B_{op} \equiv$ Maximum Operating Field

$I_c \equiv$ Critical Current

$B_c \equiv$ Critical Field

Table 11-7. Comparison of Operating Parameters of Solenoids

	Axicell Configuration (Kelley)		A-Cell Configuration	
	Current (amp)	Peak Field (tesla)	Current (amp)	Peak Field (tesla)
S1	2746	3.17	2668	2.938
S2	2746	3.17	2668	2.938
S3	2778	3.18	2668	2.938
S4	2774	3.18	2668	2.938
S5	2866	3.19	2668	2.938
S6	2866	3.19	2624	2.955
S7			2590	2.932

Table 11-8. Cryostability Parameters of Solenoids

	Recovery Flux, W/cm ² ①	Operating Joule Heat Flux @ 2866 A, W/cm ² ②	Peak Joule Heat Flux @ 3153 A, W/cm ² ③	Operating Stability Margin $\frac{① - ②}{①} \times 100\%$ Percent	Peak Current Stability Margin $\frac{① - ③}{①} \times 100\%$ Percent
Basic Conductor	0.22	0.154	0.186	30.00	15.45
High Current Lead	0.30	0.005	0.006	98.33	98.00
30° Lead-in	0.30	0.149	0.180	50.33	40.00
Splice	0.17 ⁽¹⁾	0.047	0.057	72.35	66.47
Rise-up - 1st Layer	0.29	0.174	0.210	40.00	27.59
Rise-up - 3rd Layer	0.22	0.171	0.207	22.27	5.91
Joggle - 1st Layer	0.30	0.149	0.180	50.33	40.00
Joggle - 4rd Layer	0.22	0.147	0.178	33.18	19.09
Basic Conductor with Maximum Wall Degradation	0.195	0.150	0.180	23.08	7.70

(1) Average for nearly square cross section of splice section.

Table 11-9. Margins of Cryostability of MFTF Grades I/II Conductor for Various Local Environments of the Axicell A20 Coil

Location of Conductor	Field Strength (tesla)	Wetted Perimeter (cm ² /cm)	Degraded Resistivity (nΩ-cm)	Conservative Margin of Cryostability for Normal Operating Current (For $I = 1.15 I_{\text{operating}}$)
Peak Field in Magnet for Grade I Conductor	7.48	8.17	41.00	47.5% (30.6%)
	7.48	7.42	41.00	42.2% (23.6%)
Peak Field in Magnet for Grade II Conductor *	5.64	8.17	32.46	61.7% (49.3%)
	5.64	7.42	32.46	57.8% (44.2%)

* Grading line occurs at 10th layer for analysis.
Actual grading occurs in 14th layer.

Table 11-10. Margins of Cryostability of Eighth-Hard Conductor
Splices for the Axicell A20 Coil

Location of Splice	Produced Due to Cold Welds (Watts)	Field Strength (tesla)	Degraded Resistivity ($n\Omega$ -cm)	Conservative Margin of Cryostability of Worst Case Location on Splice for Normal Operating Current (For $I=1.15 I_{\text{Operating}}$)
Inner Ring Grade I Conductor High Field Mid-Layer Splice	0.196	7.48	42.65	63.3% (51.5%)
Side Plate High Field Grading Splice *	0.124	5.64	34.80	70.1% (60.4%)
Outer Ring Grade II Conductor Low Field Mid-Layer Splice	0.036	0.00	11.56	90.1% (86.8%)
Outlet Lead Grade II Conductor Splice	--	3.00	22.79	80.2% (73.8%)

* Grading splice occurs at the end of the 10th layer for analysis.
Actual grading occurs away from wall in 14th layer.

11.3 Cool-down/Warm-up Analysis

The general objectives of the thermal conditioning of the Axicell configuration magnets is to reach cool-down steady-state conditions in the magnet and warm up to ambient conditions within 120 hours without exceeding structurally acceptable gradients. Inlet temperature schedules and flow rates were proposed. Table 11-11 lists the recommended flow rates and cooling periods for the different magnets for the design inlet temperature schedule of Table 11-2. Models of each magnet type were developed in accordance with the Convair Thermal Analyzer Computer Program, Reference 11-3, and the simulations were performed. The working heat transfer medium for both warm-up and cool-down is helium which will flow through the magnets. Liquid nitrogen is used to cool radiation shields that significantly decrease the radiation heat gain on the magnets from the vacuum vessel.

Analysis on the Solenoid magnet group is included in Reference 11-I and 11-II. Reference 11-I presents documentation of the flow resistance test of a typical solenoid magnet. Reference 11-II documents the thermal conditioning modes. Included in this report are the recommended flow rates and distributions for the Solenoids, gradients and profiles experienced during the simulations, observed heat loads, descriptions of the models, and design recommendations.

An important issue in the cool-down of the solenoid coils is the lagging cool-down rate of the Solenoids' support members. In particular, the box beams with drag struts attached must use copper conduction paths to improve cool-down performance. This, along with other design recommendations, is presented in greater detail in Reference 11-II.

Because of the complex geometries of some of these magnets, in particular the C-shaped Transitions and Yin-Yangs, it was necessary to analyze for flow distribution to the various flow paths of the magnets. These distributions should assure the uniform cool-down and warm-up of the respective magnets while reducing the severity of cross-sectional gradients.

Figure 11-1 is the cool-down temperature history for the T1 Transition coil for the recommended helium flow rate of 13.85 G/sec. This example is representative of the histories exhibited for all of the magnets with few exceptions.

Analysis of the Transition coils for thermal conditioning presented problems unique only to these C-shaped coils which were the first coils where the major radius curvature exceeded 180° . The documentation of the Transition coils' cool-down/warm-up analysis is presented in References 11-III for T1 and 11-IV for T2.

Suitable cool-down flow distribution called for the utilization of solid insulation in the major radii plenums of both T1 and T2 to prevent excessive gas bypassing of the winding. The solid insulation was included in both magnets to the extent necessary for suitable flow distribution and thermal conditioning. As a result of several parametric runs at the flow distribution models, it was recommended that T1 use a solid plenum insulation that extends 75° through the major radii symmetric about the horizontal axis. T2 requires a 90° expanse of the same solid insulation. Figure 11-2 shows selected time-slice temperature profiles during cool-down on T1.

The magnet supports are standardized throughout the MFTF system. Because of the shape of T2, additional supports were required to constrain the magnet to its "C" shape. These supports take the form of straps located on the outer and inner side plates stretching from end to end of the major radii.

These straps are completely passively cooled and caused a lag in the cool-down process. To bring the cool-down within the prescribed 120-hour requirement it was necessary to increase the theoretical flow rate, based on an enthalpic energy balance, by 30 percent - from 24.0 G/sec to 31.2 G/sec.

Both References 11-III and 11-IV list the design recommendations for each of the respective coils, T1 and T2.

The Axicell Barrier coils and their performance was analyzed and is documented in Reference 11-V. See Table 11-11 for simulated cool-down results/parameters. The thermal conditioning requirements remain consistent with the other magnets, that is 120-hour cool-down and warm-up with structurally acceptable gradients.

An additional consideration for these Axicell coils is that A20 must cool at a rate comparable to that of A21 which lies "nested" inside of A20. As the magnets cool, they contract and therefore control of the coils' relative contraction during cooling and the relative expansion during warming must be controlled.

With the recommended flow rates the temperature difference between the two nested coils during a nominal cool-down or warm-up will be within the allowable temperature difference boundaries. However, separate flow controls to the nested coils are necessary to control their temperatures in response to monitored temperature differentials and levels. A time interval of several hours is available to correct a condition such as flow stoppage in one of the nested coils.

There was an additional consideration for the cool-down rate of A20. There are 15 support clevises on the coil so, as in the case of T2, a higher flow rate is recommended to extract the heat out of the peripheral structure.

Modifications of the Yin-Yang magnet pairs coupled with the new, more realistic helium inlet temperature profiles made it necessary to determine an acceptable method of thermal conditioning of the new case extension and intercoil member. These "as-built" changes included the minor radius glue block dimensions, guard vacuum considerations, the major radius solid insulation transitioning to the perforated plenum insulation toward the minor radius, new winding/plenum cross-sectional flow distribution based on the T2 pressure drop analysis (Reference 11-IV), the

final case dimensions, the effect of the LN-cooled shields, and the dimensions as well as the number of stiffening ribs. The model includes the P2B2 beam notch and the new supports and attachments.

Design recommendations included in Reference 11-VII, the thermal conditioning documentation of the Yin-Yang magnets, describe baffle plates, cool-down flow rates, sensor placement, and other features requested to provide satisfactory operation.

An in-depth study was conducted as a result of an action item which requested "redline" minimum temperatures for the helium inlet. A detailed model of the helium inlet region was constructed and its thermal behavior was simulated and documented in Reference 11-VI. For this study the inlet region was subjected to inlet flows that varied parametrically in initial temperature from 220K to 80K in order to document the resulting temperature gradients and differentials. This included total longitudinal temperature differences estimated between winding and case. The stress and deflections accompanying the different temperatures were studied by the stress group. They have since found that all of the structure can tolerate initial helium temperatures as low as 80K (LN_2) temperature.

As can be seen on Table 11-11, for each magnet of the MFTF-B Axicell configuration there is at least one support on that particular coil that requires in excess of the specified 120 hours to reach steady-state operation conditions. All of these supports, except the tension straps on T2 and box beams on Solenoids, are attached to the coils using triangular plate clevises. Figure 11-3 shows temperature profiles on the shorter hanger of T2 at different time intervals during cool-down.

These members are all passively cooled except the warm-to-cold supports which have an LN_2 intercept constrained at 80K and an LN_2 -cooled liner covering the strut from the intercept to the magnet. This intercept and liner aids in reducing the conduction heat load from the vacuum vessel to the magnet by at least a factor of three. Radiation down the hollow

strut tube is significantly reduced through the utilization of a series of circular disc shields connected via a low conductivity rod located in the hollow annulus of the tube.

Additionally, the warm end of these struts above the intercept is covered by a passive radiation shield to stabilize its temperature profile in the variable-temperature vacuum vessel and liner radiation environment and to reduce intercept heating to ensure vapor-locking-free cooldown.

Detailed design analysis of the supports thermal concept is analyzed and presented in Reference 11-XII. References 11-XIII and 11-XIV present a more detailed evaluation of the strut steady-state and transient heat loads response, respectively. Each of these reports presents correlation developed to conservatively estimate the steady-state heat loads as a function of their geometries (Reference 11-XIII) and transient heat loads and passive conduction cool-down response as a function of their geometries and time (Reference 11-XIV). These tools will allow estimates to be performed without the future need to set up detailed models and simulate these supports which is both time consuming and expensive.

As mentioned earlier, all of these supports are passively cooled. This causes them to lag the magnet in cool-down rate during the terminal portion of cool-down. One approach to this problem was to increase the helium flow rate to hasten the active thermal conditioning. This was done to the extent that the magnets themselves were at steady-state operating condition by 120 hours in accordance with specifications.

Operation of the magnets cannot begin until the cryostats are filled with liquid helium and are charged. These activities require an additional 20 and 4 hours respectively (total of 140 hours). The extra time allows the supports to essentially approach their steady-state temperature profiles in all cases except for the two longest supports to the vacuum vessel of the system - one on T2 and one on M1. Operation before being fully cooled means that the supports are still contracting and thus the magnets

are not completely aligned. The shifting that takes place axially is more tolerable than lateral shifts.

Monitoring of behavior during thermal conditioning and operation is achieved through the placement of instrumentation on strategic places in the magnet system, both on the magnets and on their supports. The temperature sensor plan is outlined in Reference 11-XXI.

FLOW RATES FOR:

T1 COIL

CONDUCTOR PACK = 8.24 G/SEC

OUTER RING/
PLENUM = 5.61 G/SEC

TOTAL = 13.85 G/SEC

Figure 11-1. Temperature Histories at Top of Transition Coil T1 Indicate Satisfactory Cool-down in 120 Hours with 13.85 G/sec Total Mass Flow

Figure 11-2. Transition T1 Coil Longitudinal Temperature Differentials During 120-Hour Cool-Down are Moderate with 13.85 G/sec Total Mass Flow

HANGER (01) STRUT TEMPERATURE HISTORIES VS. DISTANCE FROM CASE-31.2 G/SEC TOTAL HE FLOW

Figure 11-3. T2 Upper Hanger (01) Strut Temperature Histories

Table 11-11. Recommended Helium Cool-down Flow Rates and Cool-down Response

Coil	Flow Rate (G/sec)	Time to Reach Steady-State (Hours)		
		Coil	Vessel Supports	Axial Cold-to-Cold Supports
M1	125	92	230	180
M2	125	92	160	N/A
T2	32.0	120	200	225
T1	13.85	120	200	225
A20	24.0	120	140	260
A21	4.0	100	N/A	N/A
A1	21.0	120	140	200
W, E S6	7.4	120	110	260
W, E S5	6.5	105	110	180
W, E S4	6.5	105	110	180
W, E S3	6.5	105	110	180
WS2	8.5	105	110	180
WS1	8.5	105	110	180
ES2	6.5	105	110	180
ES1	6.5	105	110	180

11.4 Heat Loads

The MFTF-B Axicell configuration heat load summary is an accounting of all the contributing heating components of the magnet system. It is presented in Reference 11-XVI.

Thermal loads are defined for helium, nitrogen, and water fluid systems for each specific magnet. Helium heat load values include contributions from: shields, struts, intercoil supports, conductor splices, instrumentation, lead stack, current leads, and neutronic heating. Further, contributions from the shields are itemized by panel radiation, inter-panel shield radiation, and support conduction. Heat loads from struts include combined radiation and conduction contributions.

Total nitrogen heat loads include magnet, lead duct, and strut panels and stack and strut intercepts. Also, nitrogen and water flow requirements are defined for individual magnets and struts. Magnet surface areas used in thermal radiation load calculations are also given.

In accordance with established design requirements (Reference 11-1) the Axicell final heat load summary includes a revised thermal data log of the component heat loads for the entire MFTF-B Axicell magnet configuration (Appendix A) of Reference 11-XVI.

In that same reference, the categorical summaries of helium heat loads to Transition (T1/T2), Barrier (A1/A20), Insert (A2I), Solenoid (S1-S6), and spread Yin-Yang (M1/M2) coils for the MFTF-B Axicell configuration are tabulated. Table 11-12 is extracted from Reference 11-XVI and is typical of the format used. Each component thermal load is itemized into three heating levels: maximum, nominal, and plasma shot heat rates, where the latter classification includes the instantaneous neutron and gamma collision energies within each magnet. Maximum heating represents the time averaged steady-state refrigeration load on the facility. The nominal heat load corresponds to thermal control performance before components subject to thermodynamic performance degradation are degraded

such as liner and magnet surface emittance and for the most realistic performance of other components. These discrete heat load classifications define thermodynamic and refrigeration tolerances expected in the system.

Revised magnet component helium heat load summaries prove that, while the loads for Solenoids and the Insert coils exceed their individual specified maximum heat loads, maximum total steady-state thermal loads still conform to the maximum allowable helium refrigeration total requirements (Table 11-13) recommended by Lawrence Livermore National Laboratory (Reference 11-1). However, nominal heating conditions, specified in Tables 1 - 8 of Reference 11-XVI, will prove more realistic for early start-up helium refrigeration operation. The dispersion of heating rates provides a measure of the degree of conservatism in the maximum heating category.

Helium mass quality is directly determined from the plasma shot heat load for each magnet. The heat to the return, lead duct, and stack is assumed to not contribute to quality in the magnet and, furthermore, instantaneous neutron heating of the case (outside the wall insulations) is assumed diffused over the entire duty cycle.

Steady-state heat loads were generated during the thermal conditioning, cool-down/warm-up, phase of analysis. A more detailed description of the assumptions made and the simulation models employed is presented in References 11-II, 11-III, 11-IV, 11-V, and 11-VII, the respective cool-down/warm-up reports for the Solenoids, T1, T2, Axicell coils, and Yin-Yangs.

As mentioned earlier, some of the heat loads were generated during the thermal conditioning phase of analysis which was prior to all designs being finalized. In most cases, the changes were not severe enough to warrant complete revision of analysis. This, however, was not the case for the cold mass support heat loads. These loads play a significant role in helium refrigeration requirements and any changes in helium capacity needs should be made known.

A formidable data base exists because of the earlier analysis of A-cell configuration supports as well as Axicell configuration supports. A simplified approach to determining steady-state heat loads was developed; results took the form of correlations for heat loads as a function of either two or three parameters of the supports. These correlations are documented in Reference 11-XIII. Revised support heat loads based on finalized design correlations are presented in Reference 11-XIV.

It is also noteworthy that a similar, more detailed tool that characterizes the transient behavior of the supports during the terminal time periods of the cool-down process has been developed. These correlations also appear in Reference 11-XIV.

Original requirements stated that steady-state operation levels were to be reached within 120 hours after start of cool-down. This requirement was easily met in the actively cooled magnets, but presented a problem for the passively cooled supports. Because LHe filling of the cryostats requires an additional 20 hours once the magnets have cooled to steady-state, these requirements were relaxed to the point that the transient support heat load, exceeding steady-state by approximately 1.1 KW at 140 hours, has been deemed acceptable by LLNL. Relaxation of requirements in the interests of simplified support cooling systems took into account that all cryostability specifications were met at the higher distributed heat loads and that the refrigeration system can meet these short term incremental loads for several tens of hours.

Maximum heat loads through the 304LN support struts, from the LH₂-cooled liners (radiation shields) to the external support beams (Transition T2 coil) and intercoil box beams connecting the solenoid coils were calculated using a combined conduction/radiation heat flux of 0.8 W/m². Nominal support heating rates (evaluated at a gray-body shape factor $\epsilon = 0.18$) which included combined conduction/radiation loads is only about 5/6 of the maximum support heating rate (evaluated at $\epsilon = 0.27$).

Heat transfer from the LN liners to each coil were calculated using a maximum combined conduction/radiation heat flux of 0.8 W/m^2 for Transition coils, 1.07 W/m^2 for solenoids, and 1.14 W/m^2 for Axicell and Yin-Yang magnets. Emittance of CRES surfaces were considered to be an undegraded $\epsilon = .18$ for the nominal case yielding a heat flux of 0.55 W/m^2 during steady state.

Plasma "shot" heating rates were defined to include maximum steady-state heating rates for all magnets, plus instantaneous maximum neutron heating. The refrigeration contribution of neutron heating has been defined as 10 percent of the heat rate produced during a "plasma shot" sequence (30-second pulse), or simply, a time-averaged plasma heat rate over the 5-minute cycle.

Coil splice heat load values for MFTF conductor were obtained from earlier research, Reference 11-4, which furnishes a realistic cold-weld joint resistance plot in terms of NbTi superconductor current at selected field strengths. The resultant heat load is the joule heat rate (I^2R).

Stack and lead components for the stack/lead configurations of the magnets were analyzed in detail and the summary appears in section 11.7 (including Table 11-19). Analysis and results are presented in References 11-XI and 11-XV. The stack and VCL heat loads are also presented in Reference 11-XVI.

External instrumentation heat load analysis required determination of the thermal response of the temperature sensor installation which was provided in Reference 11-5. The thermal instrumentation locations and plans are shown in Reference 11-XXI. These analyses provided guidelines for sensor location. Installation guidelines are presented in Reference 11-5 of the A-Cell Configuration final thermal analysis report and modified slightly in Reference 11-6, an action item memo from an instrumentation workshop.

Table 11-12. MFTF-B Axicell T1 Transition Coil Component
Helium Heat Load Summary

Transition Coils (2) Source	Steady-State Heat Load (Watts)		
	Maximum	Nominal	Plasma Shot
Support Heat Loads (304LN)***	11.22	9.35	11.22
Coil LN ₂ Shields (0.80 W/m ²)	42.12	28.96	42.12
Coil Splices (30/T1 Coil)	14.40	8.99	14.40
Lead Splices (4/Coil)	10.00	5.56	10.00
Fluid Lines	12.72	8.26	12.72
Stacks (Including Internal Instrumentation)*	29.00	19.00	29.00
External Instrumentation	12.35	12.35	12.35
Total T1 Transition Coil Heat Load	131.81	92.47	205.81**
Neutron Heating	7.40		74.00

* Add liquefaction - 1.27 G/sec (2 T1 coils).

** Includes instantaneous neutron heating.

*** Includes support neutron heating.

Table 11-13. MFTF-B Axicell Configuration - Total LHe Heat Loads Summary

Magnet Group	Heat Load*	Neutron Heating (Watts)	Maximum Allowable Helium Refrigeration (Watts)	Maximum Allowable For Neutron Heating (Watts)
Transition (T1/T2)	312.51	11.9	340	11.9
Barrier (A1/A20)	277.12	492.0	380	492
Insert (A2I)	43.62	98.0	40	98
Solenoid (S1 thru S6)	716.47	225.0 ***	650	225***
Total	1349.72		1410	
Yin-Yang (M1/M2)**	1060.20	22.80 30.00 X-Ray		

* Not including vapor-cooled lead coolant liquefaction.

** This total is composed of new support loads from the large modified Yin-Yang thermal model and LLNL 8/03/83 MFTF-B Magnet System Thermal Data Estimates - J. Van Sant.

*** Not including box beams and links direct neutron heating which adds 35 watts.

11.5 Thermosiphon

The primary objective of the thermosiphon analysis was to size the supply and return line system to provide satisfactory supply and exit quality while balancing the supply flow between magnets grouped on a common dewar while also being compatible with the vent system sizing of the magnets. Extensive vapor pockets would produce a "dried-out" region which would result in degraded heat transfer in these areas. This, in turn, could threaten the cryostability requirements of the conductor pack.

Additionally, for a given heat input, either steady-state or neutronic radiation, the specific enthalpic increases along the length of the helium flow path must be sufficiently small to preclude excess vapor generation. This criteria can be maintained only by providing a sufficient LHe flow rate. The flow rate is directly a function of helium heat input and the distribution system fluid impedance. The only available variable in the natural circulation systems of the MFTF-B configuration is the impedance of the distribution lines. The magnet impedance is a function of the winding and cryostat design and is fixed for each as-built magnet. This characteristic was measured for the C-shaped magnets by LLNL (Reference 11-7) and for the solenoids by GDC (Reference 11-1). The dewar location relative to the magnets is also fixed.

The sizing of the supply and return lines is the critical objective of the thermosiphon task. The documentation of this task is presented in Reference 11-XX with the theoretical discussion of the computer code developed, THERMOSIPHON, to simultaneously solve the equations that formulate the problem described in Reference 11-XIX. Distribution line sizing, system configuration, inlet helium conditions, quality levels, and helium refrigeration capacity were all directly (or indirectly) obtained from this overall systems level task.

Analytical models representing the solenoids, the transition coils, and the barrier coils were developed for input in accordance with the format required for the THERMOSIPHON computer program which was utilized for

each respective analysis. Table 11-14 lists the pertinent input parameters and final line size parameters after iteration to the final configurations. Although the computer code requires a steady state heat input while the coils experience a transient due to the cyclic nature of neutron heating, a method was developed to find an equivalent heat input that will simulate the worst vapor generation in the magnet at the end of the 30-second neutron heating pulse. While all of the steady-state non-neutron heating is continuously absorbed by the helium, only a fraction of the transient neutron heating is required to balance heat generated flow rate against temperature rise toward saturation and subsequent vapor generation. Iteration in the THERMOSIPHON program results in the final percentages of neutron heating that simulate the worst case vapor generation at the end of the 30-second neutron pulse. These equivalent fractions are footnoted in Table 11-15.

Another integral part of the thermosiphon analysis involved the selection of flow parameters, i.e., fluid flow frictional losses. For the transition coils, the Yin-Yang empirical friction factor was employed (Reference 11-7). The solenoid insulation and flow characteristics varied enough from the Yin-YANG to warrant a separate flow resistance test to be performed by GDC, Reference 11-I. The two correlations appear as:

$$f = 69.2 \text{ Re}^{-.46} - \text{LLNL Yin-Yang}$$

$$f = 1.947 \text{ Re}^{-.233} - \text{GDC Solenoid}$$

where: f = friction factor

Re = Reynolds number

The Yin-Yang data is considered characteristic of all the C-shaped magnets (M1, M2, T1, T2) which have solid insulation blocking the major radius section of the slotted plenum insulation. The solenoid data is considered characteristic of the solenoid-type magnets which have more liberally ventilated peripheries with continuous open grid, plenum, and post insulations (S1-S6, A1, A21, A20).

Specific parameters and performance results for the finally selected configurations are summarized in Table 11-15. It should be noted that plumbing for the transition magnets includes allowances for the trim coils. Exit quality levels are well within the conservative value of 2.5 wt% established in the MFTF Design Requirements Document, Reference 11-1. Recommendation of the results of this study were made to Livermore for their facility plumbing in ongoing communications and design reviews and are detailed in the analysis documentation of Reference 11-XX.

Table 11-14. Thermosiphon Analysis Input Parameters

Magnet System	Heating Parameters (watts)				
	Coil		Supply	Return	Stack
	Steady-State	Neutronic			
A1	52.0	1715	1.23	1.0	15.0
A2G	55.0	743	1.23	0.76	15.0
A2I	8.6	492	0.55	0.61	9.0
Solenoid	30.4	235	1.96	0.44	9.7
T1	50.8	54	1.4	1.5	15.3
T2	77.1	33	2.5	1.8	15.3

Magnet	Coil Parameters		
	Flow Area (cm ²)	Coil Length (cm)	Hydraulic Diameter (cm)
A1	1280	298	0.29
A2G	1280	298	0.29
A2I	439	135	0.16
Solenoid	99	785	0.16
T1	288	527	0.29
T2	370	885	0.29

Magnet	Distribution Line Parameters				
		Length (cm)		Diameter (cm)	
		Common	Branch	Common	Branch
A1	Supply	183	610	11.0 (4"ø)	11.0 (4"ø)
	Return	190	387	16.3 (6"ø)	16.3 (6"ø)
A20	Supply	183	610	11.0 (4"ø)	8.5 (3"ø)
	Return	190	387	16.3 (6"ø)	11.0 (4"ø)
A2I	Supply	-	792	-	3.9 (1.25"ø)
	Return	500	197	11.0 (4"ø)	5.7 (2"ø)
Solenoid	Supply	173	1140	5.7 (2"ø)	4.5 (1.5"ø)
	Return	183	184	11.0 (4"ø)	8.5 (3"ø)
T1	Supply	-	1050	-	5.7 (2"ø)
	Return	180	439	16.3 (6"ø)	8.5 (3"ø)
T2	Supply	-	1209	-	8.5 (3"ø)
	Return	180	394	16.3 (6"ø)	11.0 (4"ø)

Table 11-15. MFTF-B Axicell Configuration Line
Size Comparative Results

Axicell Magnets	Supply Line (nom-inch)	Heating *	Magnet Heat Rate (W)	Flow Rate (g/sec)	Exit Quality (wt%)
A1	3	Steady-State	52	331	0
	3	Peak (Pseudo)	652	794	2.68
	4	Steady-State	52	428	0
	4	Peak (Pseudo)	652	1052	1.60
A20	3	Steady-State	55	295	0
	3	Peak (Pseudo)	315	696	0.81
A21	1.25	Steady-State	8.6	98	0
	1.25	Peak (Pseudo)	152	241	2.10

Solenoid Magnets	Friction Factor	Supply Line (nom-in)	Heating *	Magnet Heat Rate (W)	Flow Rate (g/sec)	Exit Quality (wt%)
S2	LLNL	1.5	Steady-State	30.4	60.2	1.61
	LLNL	1.5	Peak (Pseudo)	65.65	77.8	3.40
	GDC	1.5	Steady-State	30.4	92.1	0.64
	GDC	1.5	Peak (Pseudo)	65.65	121.8	1.74

Transition Magnets	Port Location (Return)	Magnet Peak (Pseudo) Heat Rate * (W)	Flow Rate (g/sec)	Exit Quality (wt%)
T1	Main	77.8	165.0	0
	Aux. (Comb.)		25.2	0
T2	Main	93.6	250.4	0
	Aux. (Comb.)		35.0	0

* Steady-state heating excludes all neutronic heating while peak (pseudo) heating simulates the quality and flow conditions at the end of the 30-second pulse which translates to steady-state + 35 percent neutron heating rate for Axicell magnets, +15 percent neutron heating rate for central cell solenoid magnets, and +50 percent neutron heating rate for transition magnets.

11.6 Quench Venting

Quench analysis of the MFTF-B Axicell configuration magnets is required to predict magnet quench pressure histories corresponding to assumed line sizes for a given magnet vent system. A comfortably safe vent system design would limit peak magnet quench pressures to that of the burst disk (under worst-case conditions) while minimizing the cost of the system. Analysis and conclusions are presented in Reference 11-XVIII and include realistic predictions for quench propagation, energy dissipation in the magnet, and winding temperature rise mapping.

The quench pressure analysis of all four magnet groups, the axicells, the transition magnets, the Yin-Yangs, and the solenoids was performed using Convair's "MAGPRS" computer program. Heating scenarios, initiated by a failure in the vacuum with subsequent air condensation on the helium supply/return lines and magnet surfaces, were developed separately for each magnet. (M2 and the S5/S6 pair have identical quench plumbing configurations with M1 and the remaining solenoids respectively, but experience the larger magnetic fields so these were selected for analysis as worst-case conditions.) These scenarios accounted for lateral as well as longitudinal normal zone propagation and temperature dependent copper residual resistivity ratios (RRR). These analyses include realistic time phasing of the maximum heat deposition and the techniques and analysis tools are presented in Reference 11-XVII.

The axicell and transition magnets were both analyzed with a 10.16-cm (4-inch) and a 15.24-cm (6-inch) dewar inlet, dewar vent, and burst disc. Peak secondary axicell coil pressures of 99.0 psia and 57.0 psia were developed for the 10.16-cm and 15.24-cm vent line sizes, respectively. The 15.24-cm line is recommended for the axicell vent system.

Secondary pressures of 82.5 and 54.5 psia were experienced by the transition coil's 10.16-cm and 15.24-cm vent lines, respectively. Based on the assumed single magnet group quench and assumed pressure drops, the 10.16-cm vent line provides an adequate pressure safety margin.

The solenoids and Yin-Yangs were analyzed using the same procedure. Instead of varying the line size, however, the underlying assumption of single magnet group quench was augmented. A second analysis was performed on these magnets to simulate quenching by all of the magnets simultaneously. This case is highly unlikely.

For the Yin-Yang magnet, which vents through a 15.24-cm (6-inch) line, secondary pressures of 56.87 and 74.09 psia were developed for the individual and simultaneous vent analyses, respectively. Figures 11-4 and 11-5 show the characteristic behavior of some pertinent parameters during the individual and simultaneous quenches.

The solenoid pair, S5 and S6, developed pressures of 74.65 and 102.13 psia, respectively, for individual and simultaneous vent cases venting through a 10.24-cm line. The design criteria for the magnets is met for the Yin-Yangs, but a design criteria of 103 psi (7 atmospheres) is necessary for the solenoids.

An additional quench pressure analysis was performed to determine if a 5.08-cm (2-inch) vent line from the insert magnet, A21, would provide an adequate pressure safety margin during a quench. Analysis shows that peak secondary A21 pressures of 28.0 psia and 19.5 psia were developed when quench venting through a 5.08-cm (2-inch) and 7.62-cm (3-inch) line, respectively. The 5.08-cm line does provide an adequate pressure safety margin and is therefore recommended for use as the A21 branch vent line. Table 11-16 lists the recommended vent line sizes, peak pressures and time for the magnet to expel 90 percent of its helium mass. One hundred psia is used for strength and deflection analysis internal to the magnets.

The study reported in Reference 11-XVII evaluates how winding temperatures might be reduced by more realistic (less conservative) simulation of the thermodynamic responses within the magnet and how normal zones develop and propagate.

Also addressed in this study is how the joule heating spreads through the winding, what influence the helium has in storing and transporting energy, and what is the nature of liquid helium replenishment and boundary wetting. To expand the survey of vapor and thermal front propagation in the lateral directions, a 2-D model of broader lateral extent with field gradients was found to be necessary.

The goal of this detailed analysis was expected to be parametrically varied detailed simulation results of winding quench propagation and temperature rise. These results would augment and correlate with the very sparse data in the superconducting magnet community. First, the detailed analytical results along with the sparse test data for multi-dimensional propagation were fit with propagation velocity equations. These equations were then used to predict normal zone growth rates, progressively follow the normal zone growth and its associated temperature rise effect on resistivity in any winding, and to predict heat dissipation as a function of time during quench. This joule heat rate history may then be used to drive the energy and flow balances in dewar and vent system to predict quench venting and pressure histories.

Secondly, the analytical results would show the winding temperature rise relative to the single-node adiabatic model. The resulting temperature reductions from the single-node adiabatic model should be applied directly to the results of the single-node adiabatic model such as output by the programs SUPERQ or SYSCAP. The degree of benefit applied is a function of thermodynamic boundary parameter and may be judged based on the winding configuration, degree of knowledge of the hydrodynamics, and degree of conservatism desired.

Results of this study include the generating of correlation equations for propagation velocities, both along the conductor length and transversely across the conductor. The study also provides a tool for prediction of maximum conductor pack temperature rise for comparison with results obtained from quench programs such as SUPERQ. Figure 11-6 shows the reduction of maximum quench temperature which results from boundary wetting and rewetting during current dump in such large, high static head magnets.

Table 11-16. Summary of Quench Vent System Parameters and Results

Coil System *	Common Vent Line Size cm (inch)	Peak Pressure** (psia)		Time to 90% Empty+ (sec)
		Individual Group	All Magnets Simultaneous	
Transitions (T1/T2)	10.16 (4.00)	82.5	113	21.3
Axicells (A1/A20/A21)	15.24 (6.00)	57.0	78	22.8
Yin-Yang (M2)	15.24 (6.00)	56.9	74	24.5
Solenoid Pair++ (S5/S6)	10.16 (4.00)	74.7	102	21.5

* These magnets share a common vent system and are therefore presented together.

** Secondary peak pressures in magnet after burst disc rupture. Peak pressure when burst disc ruptures is burst disc setting ≈ 80 psia (5 atmospheres ± 5 psia)

+ Includes 10-second dump delay after first normalization plus dump time.

++ Each pair of solenoids S6/S5, S4/S3, and S2/S1, both east and west, share a dewar. S5/S6 pair was analyzed as the worst case.

Figure 11-4. Thermodynamic Characteristics of Yin-Yangs (M2) Quench Vent System for Worst-Case Individual Magnet Quench.

KEY

1. Check Valve
2. 22-Inch
3. 16-Inch
4. 7-Inch, 5 ATM Burst Disc
5. 1500-Liter Dewar
6. M2-Coil
7. 6-Inch Thru Vacuum Vessel

Figure 11-5. Thermodynamic Characteristics of Yin-Yang (M2) Quench Vent System for Worst-Case Simultaneous Multiple Magnet Quench

Figure 11-6. Multi-Dimensional Heat Transfer Reduces Quench Temperature Rise Slightly While Boundary Wetting or Rewetting During Current Dump Yields Greater Reduction for A-Cell and Axicell Magnets.

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11.7 Lead and Stack Thermal Performance

The stack/VCL thermal performance analysis objectives were two-fold: Satisfy all Lawrence Livermore National Laboratory (LLNL) requirements set forth in Reference 11-1 and summarized in Table 11-4, and attain the thermal considerations necessary to achieve a satisfactory stack design. The final analysis results are presented in Reference 11-XV.

In the course of these analyses, GDC also established design targets and objectives to maintain the thermal design integrity of the stacks. These considerations are listed below.

- Number of copper tubes in the vapor-cooled lead for operating current shall be based on no more than 110 amps/tube. Minimum open area inside structural stainless steel tube should be maintained.
- Helium coolant flow rate must be sufficient to provide a safety margin on runaway condition on the VCL, as well as positive control of top VCL temperature by ambient bus heaters.
- Stack volume filler inside helium vessel must provide thermal insulation; and must minimize helium percolation, circulation, and natural convection.
- Thermal radiation shield situated between concentric helium and vacuum vessels provides the primary insulation to minimize stack heat transfer into the vapor-cooled leads from ambient, and to minimize transverse and shield support conduction.
- Ambient bus heaters maintain the upper end of the vapor-cooled leads and environmental box at 300K and make up all heat losses from this zone.
- Breathing holes at the upper end of stainless steel housing tube promoting convective heat transfer coupling of copper tubes for flow stability, as well as heat transfer to the side of the vapor-cooled lead yielding thermal anchoring for stabilization and mitigation of runaway potential.
- Liquid level control bypass tube is located to minimize unwetted bus length and still meet vacuum chamber routing requirements.
- Bus superconducting insert must remain superconducting for steady-state and 10-minute uncooled operation.
- Copper transition bus must remain superconducting, accommodate long, unwetted lengths, and transfer sufficient heat for VCL coolant supply.

- Positive, but minimum, vapor bypass refrigeration load attained for positive control of liquid level in concert with compromise sizing of transition bus for superconducting maintenance.
- LN₂-cooled liner around lead duct in conjunction with an anti-shine-through shield closure between liner and 6-foil stack shield to minimize heating of LHe and especially unwetted bus zone ullage gas.

Satisfaction of all these thermal requirements was accomplished in three phases. First, the vapor-cooled leads were analyzed as thermally isolated leads since the stacks were not designed at that time (References 11-8 and 11-9). Secondly, individual component analyses were conducted as design progressed and, finally, an accurate integrated thermal model depicting the actual total physical characteristics and operating conditions of the stack assembly and inner components was analyzed. Design differences in the respective stacks are identified in Tables 11-17 and 11-18.

A rigorous thermal design analysis of the Mirror Fusion Test Facility-"B" (MFTF-B) Axicell configuration stacks and vapor-cooled leads (VCL) for the solenoid, transition, barrier, and insert coils was conducted. All lead and stack-related thermal requirements of Reference 11-1 have been met with the exception of the 0.11 G/sec-kA-Pair specific coolant flow rate specification by LLNL.

Investigation of the combined thermal performance of the stacks and vapor-cooled leads demonstrates considerable interdependency. For instance, the heat transfer to the VCL from warm bus heaters, environmental box, and stack is a significant additional heat load to the joule heating in the leads and is proportionately higher for the lower current leads that have fewer copper tubes. Consequently, the specific coolant flow requirement in G/sec-kA-Lead Pair increases as the current decreases. For example, the 6 kA-Transition T2 leads only require the specified 0.11 G/sec-kA-Lead Pair while the 1.5 kA insert magnet A21 requires 0.14 G/sec-kA-Lead Pair. The definition of this interdependency and the definition of the necessary thermal management has required an integrated thermal model for the entire stack/VCL assembly.

The selection of common-size stacks for manufacturing economy are thermally inefficient for the lower current leads of the insert magnets and solenoids resulting in disproportionately high helium heat load. This yields an operation liquefaction penalty for all but the highest current stacks, but affords manufacturing savings.

The long unwetted cold bus lengths required by the vacuum chamber port configurations also contribute a heat load penalty in that the bus cross-sections had to be upsized. This was necessary to maintain, by bus conduction to the LHe level, the upper end of the bus sufficiently below its Nb₃Sn insert current-sharing temperature to accommodate 10 minutes of uncooled operation before going normal. Urgency for copper procurement required this upsizing be accomplished conservatively by hand analysis scaling. The upsizing contributes LHe heating in excess of that required to provide vapor flow for coolant. Some buses have been enlarged above these conservative sizes to make bus sizes common to the next higher current magnet, benefitting procurement and manufacturing efficiency, but further aggravating excess heat load problem.

Table 11-19 summarizes the aggregate stack/VCL performance for each magnet configuration. This shows the growth in specific coolant flow rate as lead size decreases which is an increase in liquifaction load on the system of about 14 percent above that which would have achieved if the DRD specified specific flow rate could have been safely used. Accompanying the increase in liquefaction load is a decrease in the excess refrigeration load that gets bypassed to the refrigerator from the lead duct. The increase in liquifaction load is within the facility refrigerator capacity.

The resulting numerous design and facility interface recommendations that have been incorporated are listed in Reference 11-XV, along with a discussion of the detailed analyses.

Table 11-17. Major Design Parameter Differences for the Different Magnet Stacks/VCLs/Buses

DESIGN PARAMETER	SOLENOID STACKS S1 - S6	BARRIER STACKS A1/A20	INSERT STACK A2I	TRANSITION STACK T1	TRANSITION STACK T2
Geometry	Vertical Stack	Vertical Stack	Vertical With 23.0" Offset	Stack 45° Slope to Horizontal	Stack 51° Slope to Horizontal
Current (A)	2866	4208/4648	1517	5266	6278
Outside Diameter of VCL Outer Tube - Inches	2.25	3.25	2.25	3.25	3.25
Number of .25 O.D. VCL Copper Tubes	26	42	14	48	57
Non-Wet Bus Length - Inches	41.0	42.0	46.8	21.9	34.0
Size of Copper Bus Leads - Inches	3.50 x .75	4.00 x 1.375	3.50 x .75	4.00 x .75	4.00 x .75 4.00 x 1.375
Size & Material of Superconductor - Inches	.200x.067 Nb ₃ Sn	.436x.214 Nb ₃ Sn	.256x.256 NbTi .272x.083 Nb ₃ Sn	.438x.214 Nb ₃ Sn	.256x.256 NbTi .436x.214 Nb ₃ Sn

Table 11-18. Selection of Transition Bus Superconducting Inserts

MAGNET	OPERATING CURRENT A	Nb ₃ Sn INSERT	PERFORMANCE TEMPERATURES*	
			CURRENT SHARING** (K)	CRITICAL (K)
INSERT A2I	1517	6.9x2.1 mm FURUKAWA COND. (CRITICAL 3200 A @ 12.7T)	17.3	17.8
SOLENOID	2866	1.7x5.08 mm CONDUCTOR (RATED 1000 A @ 12T)	14.2	17.8
AF0 (A1)	4648	5.4x11 mm HFTF CONDUCTOR (RATED 5000 A @ 12T)	17.2	17.8
T2 (11)	6246	5.4x11 mm HFTF CONDUCTOR (RATED 5000 A @ 12T)	17.0	17.8

* Performance temperatures are 1/4 tesla field and operating current.

** Provides superconducting temperature margin relative to 4.5K bath temperature for steady-state temperature rise plus 10-minute uncooled operation rise at upper end maximum temperature location on bus.

Table 11-19. Summary of Stack/VCL Liquefaction and Refrigeration Heat Rates

MAGNET	CURRENT KA	PREVIOUS DESIGN REVIEWS (TARGET) REFRIG. LOAD (1) WATTS	CURRENT STACK FINAL DESIGN ANALYSIS (2)				
			EXCESS HEAT TO LHe ABOVE BOILING 0.11 G/S/KA/PR WATTS	MINIMUM SPECIFIC FLOW ROT G/S/KA/PAIR	MAXIMUM STACK REFRIG. WATTS	RECOMMENDED SPECIFIC FLOW (3) (4) G/S/KA/PAIR	STACK REFRIG. LOAD FOR REC. FLOW WATTS
A2I	1.52	11.4	16.0	0.130	12.0	0.14	11.0
S1-S6	2.87	9.7	13.5	0.1225	10.0	0.13	8.0
A7	4.21	15.4	14.0	0.110	14.0	0.12	10.0
A20	4.65	15.4	13.5	0.115	11.0	0.12	9.0
T1	5.27	15.4	14.5	0.1125	13.0	0.12	9.5
T2	6.28	15.4	16.0	0.110	16.0	0.12	10.5

- (1) All design review magnet heat load tabulations gave excess stack/VCL refrigeration load above the heat transferred to boil off specific coolant of 0.11 G/s/KA/Pr.
- (2) With current design size buses.
- (3) Yields similar safety margins ($\Delta T = 35K$ or $W = 0.015$ G/s/KA/Pr) against runaway as before, considering stabilizing influence of stack heating of VCL and maintenance of VCL top temperature to nominal of 315K by heaters.
- (4) Aggregate total flow increase to these magnets of 14 percent.

11-8 References

References for the thermodynamic analysis summary are divided into two groups. Those which are not specifically volumes of the detailed Final Thermal Analysis Report (FTAR) for the Axicell Magnet System are designated as General References and given Section - Arabic numbers. Those that are volumes of the FTAR are given Section - Roman numbers.

General References

- 11-1 Lawrence Livermore National Laboratory, MFTF Design Requirement Document, revised May 20, 1983.
- 11-2 Christensen, E. H., "Pool Coiling Helium Heat Transfer from Magnet Conductor Surfaces," AIChE Symposium Series, Cryogenic Processes and Equipment 1982, No. 224, Volume 79:120-125, 1983.
- 11-3 O'Neill, R. F., "Convair Thermal Analyzer Computer Program P4560D," 696-O-T-80-737, 30 June 1980.
- 11-4 Cornish, D. N., et al, "Developmental Work on Superconducting Coils for a Large Mirror Fusion Test Facility (MFTF)," Lawrence Livermore National Laboratory, UCRL-78881, 17 July 1977.
- 11-5 Liggett, M. W., and C. A. Sink, "MFTF-B Thermal Instrumentation Final Analyses and Configuration," Final Thermal Analysis Report for A-Cell, Volume XVII, GDC-LLNL-82-003, June 1982.
- 11-6 Wohlwend, J. W., Memo to T. A. Kozman, "GDC Action Items Resulting from MFTF-B Instrumentation Workshop," MFTF-84-M-1034-JW, 2 May 1984.
- 11-7 Van Sant, J. H., "MFTF East Yin-Yang Magnet Flow Resistance Measurements," ENC 82-19, Lawrence Livermore National Laboratory, November 1982.
- 11-8 Bartkowski, J. F., "Design of Counter Flow Vapor-Cooled Leads (VCL) for MFTF-B A-Cell and Transition Magnets," Final Thermal Analysis Report for A-Cell, Vol. XIII, GDC-LLNL-82-003, June 1982.
- 11-9 Bartkowski, J. F., Design Analysis of Counter Flow Vapor-Cooled Leads (VCL) for Solenoid Coils Using 104-cm Long Bus Bar," Final Thermal Analysis Report for A-Cell, Vol. XIV, GDC-LLNL-82-003, June 1982

References from FTAR Volumes

Detailed thermal analysis was reported topically during the course of the MFTF-B Axicell design phases in an internal format easily adaptable as chapters of a final report. These individual reports provided working requirements to the designers, provided system level data and thermo-hydraulic parameters comprising the interfaces between magnet system and facility, and verified and confirmed compliance with the specification.

Certain of the earlier A-Cell configuration reports, particularly selected topics pertaining to the initially designed central cell solenoids and the fundamental structural supports, are applicable and included for the Axicell configuration. The FTAR volume reference list is given below and cross-references the serially published reports and numbers to the Axicell NbTi magnets Final Thermal Analysis Report Volumes, including an abbreviated topical title. Organization is first by major topic such as cool-down/warm-up, cryostability, etc., and secondarily in general order from solenoids, transition, barrier, and yin-yang plug magnets. System level analyses complete the list.

<u>FTAR SECTION- VOLUME NUMBER</u>	<u>TOPIC</u>	<u>GDC MFTF NUMBER</u>	<u>COMPLETION DATE</u>
11-I	Solenoid Flow Resistance	MFTF-83-R- 552-KRJ	28 Apr 83
11-II	Solenoid Cooldown/Warmup	MFTF-1220-M- 653-JMO	29 Jul 83
11-III	T1 Coil Cooldown/Warmup	MFTF-5220-M 627-JMO	27 Jun 83
11-IV	T2 Coil Cooldown/Warmup	MFTF-5220-M 654-GRJ	4 Aug 83
11-V	A1 and A20 Coils Cooldown/ Warmup	MFTF-84-R- 972-IKK	16 Mar 84
11-VI	Initial Coolant Inlet Temper- ature Evaluation	MFTF-84-R- 971-GRJ	9 Mar 84
11-VII	Spread Yin-Yang Cooldown/ Warmup	MFTF-84-M- 929-GRJ	18 Feb 84

11-VIII	Required Bond Between Solenoid Superconducting Insert and Copper Stabilizer	MFTF-LLNL-82-003, Vol. VII Final Thermal Analysis Report	Jun 82
11-IX	Preliminary Ventilation Cryostability of the Solenoids (A-Cell)	GDC-LLNL-82-003, Vol. IX Final Thermal Analysis Report	Jun 82
11-X	Revised Cryostability of the Solenoids (As-Built)	MFTF-84-M-1022-IXK	23 Apr 84
11-XI	MFTF Conductor and Leads Cryostability Analysis	MFTF-84-M-876-JMO	30 Sep 83
11-XII	Thermal Design and Heat Loads of Supports (A-Cell)	GDC-LLNL-82-003, Vol. XVI Final Thermal Analysis Report	Jun 82
11-XIII	Support Strut Steady-State LHe Heat Loads	MFTF-1220/6220-M-761-GRJ	3 Oct 83
11-XIV	Support Struts Transient Thermal Performance	MFTF-84-R-1030-GRJ	2 Apr 84
11-XV	MFTF-B Stack/Vapor-Cooled Lead Thermal Performance	MFTF-84-R-970-JMO	1 Feb 84
11-XVI	Final Heat Load Summary	MFTF-84-R-1006-JMO	17 Feb 84
11-XVII	Superconducting Quench Propagation and Conductor Temperature Rise	MFTF-4220/5220/6220-M-717-JMO	26 Aug 83
11-XVIII	Quench Venting and Maximum Pressure Analysis	MFTF-1220/7220-M-708-GRJ	23 Aug 83
11-XIX	Thermosiphon Computer Program	MFTF-4220-M-833-KRJ	16 Dec 83
11-XX	Thermosiphon Design Analysis	MFTF-84-M-880	9 Jan 84
11-XXI	Revised Temperature Sensor Plan (Rev. B)	MFTF-1220-M-795-GRJ	23 Apr 84

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12.0

ELECTRICAL ANALYSIS

The responsibility of General Dynamics for electrical analysis in the MFTF-B magnet system design was limited to a study of the effects of fault conditions occurring in one or more magnets. Fault conditions will give rise to induced currents and hence current peaking in the coils, and to a temperature rise in a conductor hot spot. LLNL was responsible for the design and analysis of the overall electrical circuitry and the quench detection and protection system.

A fault condition usually originates when a length of superconductor goes normal and begins to heat up because of joule heating. The magnet protection system senses the presence of the normal zone and initiates an emergency fast dump of the magnet current through an external dump resistor, within some predetermined time interval. For MFTF-B, the emergency fast dump is initiated within ten seconds of normal zone detection. The discharge time constant is limited by the capability of the magnet insulation to withstand high voltage without arcing or breaking down.

For purposes of analysis, we define two types of fault conditions: fault and fault-fault. A fault condition is one where a normal zone occurs and the protection system functions properly to turn off the magnet power supplies within ten seconds after normal zone detection. A fault-fault condition is that situation where a normal zone occurs, the protection system fails to operate and, consequently, the power supplies are not turned off but continue to supply current to the magnets.

The following sections summarize the coil current peaking analysis.

12.1 Current Peaking Analysis

In the event of a fault condition in one of the magnets of the MFTF-B magnet system, and subsequent fast dump of that magnet, currents will be induced in neighboring magnets. The magnitude of the induced current will depend, in part, on the mutual inductance between the dumped magnet and the particular magnet affected. Since the additional current results

in additional electromagnetic forces acting on the magnets, it is important to calculate these induced currents so the magnets and magnet support structure can be designed to accommodate these added, induced loads.

The current peaking analysis was carried out using a commercially available computer program called SYSCAP. SYSCAP is a system of circuit analysis programs that perform static/dynamic and linear/nonlinear nodal analyses of electric circuits. The analysis was carried out for the circuits shown in Figures 12-1 and 12-2 using the inductance data listed in Section 3-2.

Each of the 26 magnets of the MFTF-B magnet system was modeled for SYSCAP analysis by a circuit similar to that shown in Figure 12.3. The power supply, E , with internal resistance; R_S , provides the initial magnet current; and resistor R_I acts as a switching resistor. R_D is the appropriate dump resistor for the magnet, while the magnet itself is represented by coil "L," having essentially zero resistance, 10^{-10} ohms. The actual magnet resistance is modeled by the series-resistance, R_C , which was chosen to be 10^{-7} ohms, a reasonable value for a large, superconducting magnet.

The circles in Figure 12.3 represent voltage-dependent voltage sources (VDVS) which are used to model the effects of mutual inductances. In any particular magnet circuit there will be one VDVS for each magnet with which this magnet is inductively coupled. For example, the circuit in Figure 12.3 illustrates a magnet circuit that is inductively coupled to three other magnets.

The voltage of a VDVS can be made dependent on the voltage of any given element in any desired circuit. As an example, consider a pair of coupled magnets which we will denote as "A" and "B." The circuit of each magnet will therefore include one VDVS. The voltage of the VDVS in the circuit of magnet "A" is made dependent on the voltage across coil "B," and vice versa. By choosing the DC resistance of the coil to be small, the voltage of the VDVS in the circuit of magnet "A" will be dependent on

the inductive voltage across magnet "B" and hence is proportional to the dI/dt in the circuit of magnet "B." Similar remarks apply to the VDVS in the circuit of magnet "B."

In addition, SYSCAP allows the user to choose a multiplying constant for each VDVS voltage. By choosing this multiplying constant equal to the mutual inductance between magnets "A" and "B," there is obtained in the circuit of magnet "A" a voltage source proportional to the time rate of change in the current of magnet "B," and the mutual conductance between "A" and "B." The circuit of magnet "B" is similar. In this way, any number of mutual inductances can be modeled with the only limitation being the limit on the number of nodes allowed in SYSCAP.

A magnet fault condition is modeled in the following fashion: it is assumed that at quench initiation the entire magnet winding goes normal at a bath temperature of 4.5K. That is, obviously, a worst-case scenario. Thus, at quench initiation, the coil resistance, R_C , is assumed to rise from 10^{-7} ohms to the resistance of the total length of copper stabilizer at 4.5K. This heat is assumed to adiabatically heat the copper stabilizer and the consequent temperature rise due to this heat is then calculated. With the resistivity of copper at this increased temperature, the joule heating for 0.1 second is again calculated and a new temperature is obtained. This sequence of calculations is repeated every 0.1 second. Temperature variations of the copper resistivity and specific heat are taken into account. The magnetic field is allowed to vary with current, and SYSCAP calculates the temporal behavior of the current, voltage, and power of all elements in the circuits.

The dump of a magnet is carried out by SYSCAP in the following manner: at the start of the dump the power supply voltage is switched to zero. At the same instant, R_1 is switched from its nominal value of 10^{-7} ohms to a value of 10^7 ohms, effectively forcing the current to flow through the dump resistor. However, in a fault-fault condition, this sequence of events does not occur and the power supply continues to operate supplying current to the magnet.

in the normal charge and discharge operational modes of the MFTF-B magnet system, all 26 magnets are brought up or down in current simultaneously, but not necessarily with identical time constants. Hence, in the normal charge and discharge modes, induced currents are small. This has been demonstrated by both GDC and LLNL.

Even in a fault condition the induced currents turn out to be quite small. For example, the maximum current rise in coil A2I was investigated during a quench of the three magnets most closely coupled to it, namely, A1, A20, and T1. This situation should result in the maximum induced current in A2I. This peak occurred ten seconds after quench initiation. The results showed that the current increased only 3.3 percent over the operating value. At this time the protective system began to dump all magnets and the peak current A2I dropped rapidly from the peak value. This increase posed no threat to the structural integrity of the A2I magnet.

Therefore, efforts have concentrated on investigating the current peaking in fault-fault conditions only. Table 12.1 lists the fault-fault conditions that were studied.

Table 12-1

Fault-Fault Conditions Analyzed with SYSCAP

NO.	QUENCH/MAGNET	MODE
1)	Quench of M1, M2, T1, A20, A2I, and A1.	Kelley
2)	Only coils T1, T2, M1, and M2 on. Quench of T1 and M2.	Kelley
3)	Quench of A1, A20, A2I, T2, M1, and M2.	Kelley
4)	Quench of A1, A20, and T1.	Kelley
5)	Quench of S6 only	Kelley
6)	Quench of S6 only	Mars
7)	Quench of A20 only	Kelley
8)	Quench of A20 only	Mars
9)	Quench of S4 only	Kelley
10)	Quench of A2I only	Kelley
11)	Quench of S6, A1, A20, A2I, and T1	Kelley
12)	Quench of S6, S5, S4, and S3	Mars
13)	Quench of A20, A2I, T1, and T2.	Mars

Figure 12-1. MFTF-B Magnet Power Supply and Protection Circuits (Except 5M Solenoids).

Figure 12-2. MFTF-B Solenoid Magnet Power Supply and Protection Circuit.

Figure 12-3. SYSCAP Model of Each Magnet.

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13.0

INSTRUMENTATION SUMMARY

13.1 Instrumentation Plan

The MFTF-B instrumentation includes a combination of temperature, strain, voltage, and liquid helium level measurements distributed over selected points on the NbTi magnets and their support systems.

A measurement code number was prepared which assigns measurement numbers to each of the sensor channels. Additionally, vacuum vessel feed-thru connector assignments have been made for those cables that must go through the vacuum vessel ports.

The measurement code numbers are tabulated on the applicable sensor installation drawings. The connector assignments and pin assignments are designated on the applicable instrumentation wiring diagrams for each measurement code number.

All external temperature and strain gage sensors require moisture protection. All temperature sensors mounted on LHe temperature surfaces additionally require thermal radiation shields. All sensors are installed for a 10-year operating life.

All external temperature and strain gage sensor wiring is routed along a magnet case to the top of the magnet including support strut instrumentation. All wiring from the top of the magnet is routed to vacuum vessel penetrations. All vessel penetrations for wiring are located on the top of the vessel.

The temperature and strain measurement instrumentation wiring inside the vacuum vessel will pass through the vacuum vessel ports via a double-

ended hermetic feed-thru designed to meet MIL-C-26482, Series 1. The feed-thru has a jam nut mounting with a silicone rubber seal. The design leakage requirement is 10^{-8} std. cc/sec of helium.

All voltage tap and level sensor wiring exits through the magnet stack through conax fittings which allow for continuous cable runs to the exterior of the vacuum vessel.

Instrumentation cables selected include single-, three-, and four-conductor cable configurations. All cables are Kapton insulated, shielded, and jacketed designs rated for continuous operation at 1000 volts. Single-conductor cables are 30 AWG and are used for voltage taps. Four-conductor cables are 26 AWG and are used for temperature sensors. Three-conductor cables are 26 AWG and are used for strain gages.

Table 13-1 provides a summary of all NbTi coils and their associated support systems, liquid helium line and warm bus lead measurements.

The cryogenic linear temperature sensors (CLTS) are used exclusively for all cryogenic measurements. These sensors are required to be redundant for helium return line and LN_2 -cooled strut measurements which are required for long-term operation of the magnets. The remaining CLTS measurements are required primarily for acceptance testing and demonstration of the magnet system. The CLTS sensors are nickel manganin resistance sensors which provide excellent linear outputs. The temperature range that is to be monitored for all CLTS sensors is 320°K to 4.2°K.

Type E, chromel constantan thermocouples are used exclusively for installation on warm bus high current leads next to heaters. These thermocouples will be used for controlling LLNL coil bus heater power supply circuits.

Karma alloy foil strain gages are used exclusively for all strain gage measurements as specified by LLNL. Both single axis and 3-axis rosettes are utilized. All gages have a self-temperature compensation number of

15 which has been proven to be the most desirable for cryogenic strain measurements. There are no redundant strain gages installed inasmuch as they are primarily required for acceptance testing, design verification testing, and demonstration of the magnet system.

Voltage taps are located on coil windings, entering and exiting warm and cold lead buses for normal zone monitoring, and quench detection circuit inputs. A redundant voltage tap is installed on each entering and exiting cold bus lead and on each entering and exiting warm bus lead. All taps consist of 30 AWG Kapton-insulated wires soldered to conductor surfaces with 36.65% Pb, 63% Sn, .35% Sb solder with the exception of the warm bus lead installations, which may include bolts and terminal lugs when installed by LLNL because of the large warm bus mass.

Liquid helium level sensors are installed in the stack of each magnet. The active level sensing length of NbTi superconductor will extend from the G-10CR feed-thru plate in each stack to approximately twelve inches below the liquid helium bypass line. The installation of one sensor in each magnet stack will provide liquid level monitoring and impending low helium level data in case of helium fill line blockages or accidents.

Liquid helium level sensors are NbTi superconductor wire installed in a perforated fiberglass tube.

Table 13-1. instrumentation Channel Count Summary

MFTF-B System	Voltage Taps	Temperature		Strain Gage	Liquid Level Sensors
		CLTS	T/C		
S1-S6 Coils	203	67	24	32	12
S1-S6 Supports		85		16	
S1-S6 He Lines		36			
A1 Coils	36	15	4		2
A1 Supports		15			
A1 He Lines		6			
A20 Coils	36	19	4	20	2
A20 Supports		12		4	
A20 He Lines		6			
T1 Coils	36	32	4	33	2
T1 Supports		12		4	
T1 He Lines		6			
T2 Coils	36	32	4	40	2
T2 Supports		20			
T2 He Lines		6			
Total	347	369	40	159	20

13.2 Solenoid Coil and Support System Instrumentation

The MFTF-B solenoid coil and support system drawing tree for instrumentation drawings is shown in Table 13-2.

The solenoid coil and support system instrumentation consists of a combination of selected measurement points including temperature, strain, voltage, and liquid helium level.

13.2.1 Temperature Measurements

The total temperature sensor distribution for the S1-S6 solenoid system is summarized in Table 13-3.

There are a total of 67 CLTS sensors located on the outer coil cases of S1 through S6. These sensors are used primarily for monitoring cool-down, warm-up characteristics and to verify analyses. Figure 13-1 depicts the sensor locations and provides additional location rationale.

Support struts with LN_2 intercepts are instrumented with 72 CLTS sensors; 36 of these sensors are redundant due to the operational requirement for these measurements to ensure that the LN_2 intercepts are performing adequately. An additional 13 sensors are distributed on selected interlinks, box beams, cold-to-cold struts, and drag struts as shown in Table 13-3 for the purpose of verifying analytical predictions of heat loads and temperature gradients in a few selected locations.

Each S1 through S6 coil liquid helium supply line is instrumented with one CLTS to ensure that liquid helium has reached the bottom of each coil. These sensors are required for long-term operation, but redundancy is not required since more than one magnet is supplied by the same liquid helium dewar.

Each S1 through S6 coil has 2 CLTS sensors installed near the base of the coil-stack interface for monitoring liquid helium line return temperature. These sensors are required for long term operation to determine the status of the liquid helium at the top of each coil and provide for differential temperature data between supply and return points. Redundancy of these sensors is required due to the operational aspects and inaccessibility for easy placement.

The warm bus leads for S1 through S6 each have a thermocouple installed near their respective heaters to provide inputs to LLNL power supplies used to control warm bus heater inputs. There are 24 thermocouples required for these controls.

13.2.2 Strain Measurements

The strain gage measurements for the solenoid coils and their support systems are summarized in Table 13-4.

The outer coil case strain measurements are located on ES5 and ES6 with 16 channels of data on each coil. The gages are located the same on each of the coils. These gages are required primarily for magnet system demonstration and design verification. The gage locations and orientations are shown in Figure 13-2.

As shown in Table 13-4, there are 6 gages located on selected hanger struts, 6 gages located on selected lateral struts, and 2 gages located on the drag struts of WS6. Hanger and lateral strut gages assure that loads caused by coil misalignment do not exceed strut capabilities. With the additional drag strut gages and other magnet support system gages, the gages will allow the measurement of significant loads for any combination of magnets on or off. Additionally, accuracy of overall load calculations may be verified.

13.2.3 Voltage Taps

The total voltage tap distribution for S1 through S6 coils is summarized in Table 13-5. Each solenoid coil has 9 taps installed in the conductor pack with the exception of WS4 which has 8 taps. One tap was lost on this coil during winding. This tap was identified as measurement V064. Additionally, 2 taps are installed on each entering and exiting cold bus lead making 1 redundant tap for each cold bus. LLNL will later install 2 taps on each bus entering and exiting lead. These taps replace taps that were originally scheduled to be installed on vapor-cooled leads. The voltage taps are installed on each magnet to provide for normal zone and quench detector circuit inputs.

13.2.4 Liquid Helium Level Measurements

NbTi superconducting helium level sensors are installed in the stack of each magnet. The active level sensing length will extend from the GLOCR feed-thru plate in each stack to approximately 12 inches below the liquid helium bypass line. The sensors are insensitive to magnetic fields up to 10 tesla. The 70-milliampere current carried by the NbTi assures resistive operation in helium gas and superconducting operation in liquid helium. The installation of one sensor in each magnet stack will provide liquid helium monitoring and impending low helium level data in case of helium fill line blockages or accidents.

Table 13-2. Instrumentation Drawing Tree for Solenoid Coils and Support Systems

Table 13-3. Temperature Sensors Have Been Located on Solenoid Coils and Their Support Systems for Acceptance Testing and Magnet Cooldown/Warmup Operations

Subsystem	Coil	Qty.	Coil	Qty.	Total
Outer Coil Case	ES1-ES5	23	WS2-WS6	23	46
	ES6	11	WS1	10	21
Box Beams			WS1-WS2	2	2
			WS3-WS4	2	2
Intercoil Links	ES1-WS1	2	WS2-WS3	1	3
Drag Struts	ES6	8	WS1-WS6	20	28
All Hanger Struts	ES2,4,5,6	16	WS1,3,5,6	16	32
All Lateral Struts	ES2,4,5,6	8	WS1,3,5,6	8	16
Axial Struts	ES6-EA20	2			2
Conductor Bus Heaters	ES1-ES6	12	WS1-WS6	12	24
LHe Supply and Return Lines	ES1-ES6	18	WS1-WS6	18	36
Total					212

Table 13-4. Strain Gages for Solenoid Coils and Their Support Systems Have Been Located for Acceptance Testing and Design Verification

Subsystem	Coil	Qty.	Coil	Qty.	Total
Outer Coil Case	ES6	16			16
Outer Coil Case	ES5	16			16
Hanger Struts	ES2,4,6	3	WS1,3,6	3	6
Drag Struts			WS6	2	2
Lateral Struts	ES2,4,6	3	WS1,3,6	3	6
Intercoil Links			WS4,WS6	2	2
Total					48

Table 13-5. Voltage Taps Have Been Distributed on Conductors and High-Current Leads for Protection Circuit Inputs

Subsystem	Coil	Qty.	Coil	Qty.	Total
Conductors	ES1-ES6	54	WS1-WS6	53	107
Bus Lead In	ES1-ES6	12	WS1-WS6	12	24
Bus Exit	ES1-ES6	12	WS1-WS6	12	24
Warm Bus Leads	ES1-ES6	24	WS1-WS6	24	48
Total					203

17 Total taps per solenoid coil, except WS4 has 16 taps total.

1 redundant tap on each warm and cold bus lead, both entering and exiting.

- Five (5) sensors are used on most coils to verify that cooldown flow is splitting symmetrically and reaching the inner ring near the inlet and outlet. Significant gradients can occur if flow does not behave as predicted.
- Five (5) additional sensors are used on WS1 to verify cooldown and regeneration analysis predictions for this coil which is affected by the box beams and large axial struts to the vessel.
- Six (6) additional sensors are used on ES6 to verify analysis predictions relating to the effects of the large extended structures on case temperatures.
- All sensors are also intended to be used in monitoring regeneration temperatures.

Figure 13-1. S1-S6 Outer Coil Case Temperature Sensor Locations.

LOOKING EAST
WS5, WS6 or ES5, ES6

SECTION A-A

- Hoop gages on the sidewalls indicate the case overall out-of-plane bending.
- Hoop gages on the inner and outer rings indicate the case in-plane bending.
- The transverse gages on the sidewalls indicates sideplate bending due to electromagnetic side load.

- * Rosette Gage
- x Transverse Gage
- ◆ Hoop Gage
- Priority 2 Gage

Total Gages = 24

Figure 13-2. Solenoid Coil Outer Case Locations.

13.3 Axicell A1, A20 Coil and Support System Instrumentation

The MFTF-B axicell coil and support system drawing tree for instrumentation drawings is shown in Table 13-6. The A1-A20 coil and support system instrumentation consists of a combination of selected measurement points including temperature, strain, voltage, and liquid helium level.

13.3.1 Temperature Measurements

The total temperature sensor distribution for the A1 and A20 axicell system is summarized in Table 13-7.

There are a total of 34 CLTS sensors located on the outer coil cases of A1 and A20. These sensors are distributed with 8 sensors on EA1, 7 sensors on WA1, 12 sensors on EA20, and 7 measurement points on W20. These measurements are used primarily for cool-down, warm-up characteristics and to verify analysis. Figure 13-3 describes more specific measurement requirements.

The two hanger struts and one lateral strut for each of these 4 coils are instrumented with 2 CLTS sensors each for a total of 24 sensors. These sensors, including one redundant sensor on each strut, monitor operational performance of the LN_2 intercepts. Additionally, there is 1 CLTS installed on 2 interlinks between EA1 and EA20 and on 1 interlink between WA1 and WA20. These sensors will assist in verifying thermal analyses.

Each A1 and A20 coil liquid helium supply line is instrumented with one CLTS to ensure that liquid helium has reached the bottom of each coil. These sensors are required for long-term operation, but redundancy is not required since more than one magnet is supplied by the same liquid helium dewar.

Each A1 and A20 coil has 2 CLTS sensors installed near the base of the coil-stack interface for monitoring liquid helium line return temperature. These sensors are required for long-term operation

to determine the status of the liquid helium at the top of each coil and provide for differential temperature data between supply and return points. Redundancy of these sensors is required due to the operational aspects and inaccessibility for easy replacement.

The warm bus leads for A1 and A20 each have a thermocouple installed near their respective heaters to provide inputs to LLNL power supplies used to control warm bus heater inputs. There are 8 thermocouples required for these controls.

13.3.2 Strain Measurements

The strain gage measurements for the A1 and A20 coils and their support systems are summarized in Table 13-8.

The outer coil case strain measurements are located on EA20 only with 20 channels of data on this coil. The gages are located the same on each of two coil sections. These gages are required primarily for magnet system demonstration and design verification. The gage locations and further measurement rationale are shown in Figure 13-4.

One strain gage is installed on one hanger and one lateral strut on each of the four axicell coils. These measurements will ensure that loads caused by misalignment will not exceed strut design capability. These strut loads must be monitored during the Technical Demonstration since misalignment loads are a substantial portion of strut design loads.

13.3.3 Voltage Taps

The voltage tap distribution for A1 and A20 coils is summarized in Table 13-9. Each axicell has 10 taps installed in the conductor pack. Additionally, 2 taps are installed on each entering and exiting cold bus lead which provides 1 redundant tap for each cold bus. LLNL will later install 2 taps on each warm bus entering and

- exiting lead. These taps replace taps that were originally scheduled to be installed on vapor-cooled leads. The voltage taps are installed and located on each magnet for normal zone and quench detection circuit inputs.

13.3.4 Liquid Helium Level Measurements

NbTi superconducting helium level sensors are installed in the stack of each magnet. The active level sensing length will extend from the GLOCR feed-thru plate in each stack to approximately 12 inches below the liquid helium bypass line. The sensors are insensitive to magnetic fields up to 10 tesla. The 70-milliampere current carried by the NbTi assures resistive operation in helium gas and superconducting operation in liquid helium. The installation of one sensor in each magnet stack will provide liquid helium level monitoring and impending low helium level data in case of helium fill line blockages or accidents.

Table 13-6. Instrumentation Drawing Tree for A1, A20 Axicell Coils and Support Systems

Table 13-7. Temperature Sensors Have Been Located on Axicell Coils and Their Support Systems for Acceptance Testing and Magnet Operation

Subsystem	Coil	Qty.	Coil	Qty.	Total
Outer Coil Case	EA1-EA20	20	WA1-WA20	14	34
Intercoil Links	EA1	2	WA1	1	3
Hanger Struts	ES1-EA20	8	WA1-WA20	8	16
Lateral Struts	ES1-EA20	4	WA1-WA20	4	8
Conductor Bus Heaters	EA1-EA20	4	WA1-WA20	4	8
LHe Supply and Return Lines	EA1-EA20	6	WA1-WA20	6	12
Total					81

Table 13-8. Strain Gages for Axicell Coils and Their Support Systems Have Been Located for Acceptance Testing and Magnet System Demonstration

Subsystem	Coil	Qty.	Coil	Qty.	Total
Outer Coil Case	EA20	20			20
Hanger Strut	EA1-EA20	2	WA1-WA20	2	4
Lateral Strut	EA1-EA20	2	WA1-WA20	2	4
Total					28

Table 13-9. Voltage Taps Have Been Distributed on Conductors and High Current Leads for Protection Circuit Inputs.

Subsystem	Coil	Qty.	Coil	Qty.	Total
Conductors	EA1, EA20	20	WA1, WA20	20	40
Bus Lead-In	EA1, EA20	4	WA1, WA20	4	8
Bus Exit	EA1, EA20	4	WA1, WA20	4	8
Warm Bus Leads	EA1, EA20	8	WA1, WA20	8	16
Total					72

- 18 total taps per axicell coil.
- 1 redundant tap on each bus and warm bus lead.

A1 COIL

A20 Coil

- Seven (7) sensors on each magnet monitor longitudinal and transverse temperature distributions to indicate abnormal flow distributions.
 - Inner ring and side plate at top and bottom reflect flow generation.
 - Outer ring on one side.
 - Outer ring and side plate on other side.
- Five (5) additional sensors are used on EA20 to confirm the effects of extended clevis structures and to supplement strain data on that coil.
- Sensors on A20 and A21 coils are required to control the temperature differences between those coils.
- All sensors will also monitor regeneration temperatures.

Figure 13-3. A1 and A20 Outer Case Temperature Sensor Measurements.

STRAIN GAGES ARE LOCATED ON TWO CROSS-SECTIONAL PLANES.

EACH CROSS SECTION HAS 6 GAGES.

CONSIDERATIONS

- Transverse stress is the major stress component.
- Transverse stress peaks severely in the case corners.
- Case material is worked close to the allowable.
- Strain gages provide a check on the analysis and insure adequate strength is maintained.
- Rosettes are necessary to provide verification in "clean" area.
- Two cross sections are required since critical peaking occurs in both gouged and ungouged regions and is dependent on different load distributions.

Figure 13-4. A1 and A20 Outer Case Strain Gage Locations.

13.4 Transition T1, T2 Coils and Support Systems Instrumentation

The MFTF-B transition coil and support system drawing tree for instrumentation drawings is shown in Table 13-10.

The T1-T2 coils and support systems instrumentation consists of a combination of selected measurement points including temperature, strain, voltage, and liquid helium level.

13.4.1 Temperature Measurements

The temperature sensor system distribution for the T1 and T2 transition coil system is summarized in Table 13-11.

There are a total of 18 CLTS and 14 CLTS sensors located on the outer coil cases of ET1 and T1 respectively. Similarly, there are 19 CLTS and 13 CLTS sensors installed on the outer coil cases of ET2 and WT2 respectively. These temperature sensors are required to monitor cool-down and regeneration temperatures of each T1 and T2 coil case. Figures 13-5 and 13-6 show the sensor locations and location rationale.

Additionally, there are 4 CLTS sensors located on the ET2 structural strap. These straps must be cooled down before coil operation can be started. Figure 13-7 depicts these sensor locations.

The two hanger and one lateral strut for each of these 4 coils are instrumented with 2 CLTS sensors each for a total of 24 sensors. These sensors, including one redundant sensor on each strut, monitor operational performance of the LN_2 intercepts. Additionally, there is 1 CLTS installed on 2 interlinks between ET1 and EMI. These sensors will assist in verifying thermal analyses.

Each T1 and T2 coil liquid helium supply line is instrumented with one CLTS to ensure that liquid helium has reached the bottom of each coil. These sensors are required for long-term operation,

but redundancy is not required since more than one magnet is supplied by the same liquid helium dewar.

Each T1 and T2 coil has 2 CLTS sensors installed near the base of the coil-stack interface for monitoring liquid helium line return temperature. These sensors are required for long-term operation to determine the status of the liquid helium at the top of each coil and provide for differential temperature data between supply and return points. Redundancy of these sensors is required due to the operational aspects and inaccessibility for easy replacement.

The warm bus leads for T1 and T2 each have a thermocouple installed near their respective heaters to provide inputs to LLNL power supplies used to control warm bus heater inputs. There are 8 thermocouples required for these controls.

13.4.2 Strain Measurements

The strain gage measurements for the T1 and T2 coils and their support systems are summarized in table 13-12.

The outer coil case strain measurements are located at 33 points on ET1 and 36 points on ET2 of data on this coil. The gages are located at a major and minor radius, near critical stress corners and near stack exits. These gages are required primarily for magnet system demonstration and design verification. Typical gage locations and further measurement rationale are shown in Figures 13-8 and 13-9. Additionally, four gages are located on the ET2 structural strap.

One strain gage is installed on one hanger and one lateral strut on each of the four transition coils. These measurements will ensure that loads caused by misalignment will not exceed strut design capability. These strut loads must be monitored during the Tech. Demo, since misalignment loads are a substantial portion of strut design loads.

Additionally, two intercoil axial links between E12 and EMI are gaged to assist in checking any asymmetry in strut loads.

13.4.3 Voltage Taps

The voltage tap distribution for T1 and T2 coils is summarized in Table 13-13. Each axicell has 10 taps installed in the conductor pack. Additionally, 2 taps are installed on each entering and exiting cold bus lead which provides 1 redundant tap for each cold bus. LLNL will later install 2 taps on each warm bus entering and exiting lead. These taps replace taps that were originally scheduled to be installed on vapor-cooled leads. The voltage taps are installed and located on each magnet for normal zone and quench detection circuit inputs.

13.4.4 Liquid Helium Level Measurements

NbTi superconducting helium level sensors are installed in the stack of each magnet. The active level sensing length will extend from the G10CR feed-thru plate in each stack to approximately 12 inches below the liquid helium bypass line. The sensors are insensitive to magnetic fields up to 10 tesla. The 70-milli-ampere current carried by the NbTi assures resistive operation in helium gas and superconducting operation in liquid helium. The installation of one sensor in each magnet stack will provide liquid helium level monitoring and impending low helium level data in case of helium fill line blockages or accidents.

Table 13-10. Instrumentation Drawing Tree for T1-T2 Coils and Support Systems

Table 13-11. Temperature Sensors Have Been Located on Transition Coils and Their Support Systems for Acceptance Testing and Magnet Operation

Subsystem	Coil	Qty.	Coil	Qty.	Total
Outer Coil Case	ET1, ET2	37	WT1, WT2	27	64
Structural Straps	ET2	4	WT2	2	6
Hanger Struts	ET1, ET2	8	WT1, WT2	8	16
Lateral Struts	ET2	4	WT2	4	8
Conductor Bus Heaters	ET1, ET2	4	WT1, WT2	4	8
LHe Supply and Return Lines	ET1, ET2	6	WT1, WT2	6	12
Intercoil Links	ET2	2			2
Total					116

Table 13-12. Strain Gages for Transition Coils and Their Support Systems Have Been Located for Acceptance Testing and Magnet System Demonstration

Subsystem	Coil	Qty.	Coil	Qty.	Total
Outer Coil Case	ET1	33			33
Outer Coil Case	ET2	36			36
Structural Straps	ET2	4			4
Intercoil Links	ET2, EM1	2			2
Hanger Struts	ET1, ET2	2	WT1, WT2	2	4
Lateral Struts	ET1, ET2	2	WT1, WT2	2	4
Total					83

Table 13-13. Voltage Taps Have Been Distributed on Conductors and High-Current Leads for Protection Circuit Inputs

Subsystem	Coil	Qty.	Coil	Qty.	Total
Conductors	ET1, ET2	20	WT1, WT2	20	40
Bus Lead-In	ET1, ET2	4	WT1, WT2	4	8
Bus Exit	ET1, ET2	4	WT1, WT2	4	8
Warm Bus Leads	ET1, ET2	8	WT1, WT2	8	16
Total					72

- 18 total taps per transition coil.
- 1 redundant tap on each cold bus lead and warm bus lead.

SENSOR LOCATION:

ET1 - 18 PL

WT1 - 14 PL

Fourteen (14) temperature sensors monitor the cool-down and regeneration temperatures of each T1 coil:

- Two (2) sensors (inner and outer plenum) are used at each major/minor radius tangency point to monitor axial and transverse temperature gradients. These gradients are sensitive to the flow distribution in the coil and auxiliary vents.
- One (1) additional sensor is installed on the outer (glue block) side of the case near the main and upper auxiliary vent to monitor the gradient in this hard-to-cool location.
- Two (2) sensors are used at one major radius center to confirm the effects of solid plenum insulation.
- One (1) sensor is used at the center of one minor radius lobe (inner) and the remaining major radius lobe (outer plenum) to monitor axial gradients affected by flow distributions in the coil and auxiliary vents.

Four (4) additional sensors are added to the east coil (which has strain instrumentation) to confirm analysis predictions of cooldown temperature profiles.

All sensors are usable for monitoring regeneration temperatures.

Figure 13-5. T1 Coil Case Temperature Sensor Locations.

Sensor Location - ●

ET2 - 19 P1

WT2 - 13 P1

Thirteen (13) temperature sensors monitor the cooldown and regeneration temperature of each T2 coil case.

- Two (2) sensors are used at each major/minor radius tangency point to monitor axial and transverse temperature gradients which are sensitive to internal and external flow distributions.
- One (1) additional sensor is used near the main vent to monitor the temperatures at the last point to cool down.
- Two (2) sensors are used at one major radius (a) center to confirm the effect of solid plenum insulation on case temperature gradients.
- One (1) sensor is used in one minor radius and the other major radius (c) to monitor the axial gradients affected by flow distributions in the coil and auxiliary vents.

Six (6) additional sensors are added to the east coil (which has strain instrumentation) to confirm analysis predictions of cooldown temperature profiles.

Figure 13-6. T2 Coil Case Temperature Sensor Locations.

● - Sensor Location

- Straps are cooled by conduction from the cases causing significant temperature gradients and longer cooldown times.
- Coil can not be operated until straps have reached acceptable temperatures (predicted to occur at 140 hours).

Figure 13-7. T2 Support Strap Temperature Locations.

- P1 gages are essential for accurate critical stress determination.
- P2 gage is recommended in addition to P2 to check stack area stresses.
- Gages at both symmetry planes are necessary because all spreading loads are reacted here.
- Corner chamfers are critical stress areas.

Figure 13-8. Typical T1 Strain Gage Locations

- P1 gages are essential for accurate critical stress determination.
- P2 gage recommended in addition to P2 to determine overall stress distribution.
- Minor radius symmetry plane is most highly stressed area, several gages assure good assessment of stresses.
- Tie-strap gages assure accurate E.M. load-sharing determination.
- Tie-strap-attach-area gages are needed to assess overall case bending moment in this region.

Figure 13-9. Typical T2 Strain Gage Locations.

13.5 Sensor Descriptions

The NbTi coil measurement sensors are described in Table 13-14.

The CLTS-2 temperature sensors were procured by General Dynamics and sent to a calibration laboratory for calibration. Each sensor will have a resistance vs. temperature calibration point recorded at 273.15K, 77.37K, 27.1K, and 4.2K, with an accuracy of $\pm 0.15K$.

The liquid helium level sensors will be procured and tested by LLNL. No calibration is required since the sensor is superconducting in liquid and normal above 10K in gaseous helium.

Table 13-14 Instrumentation Sensor Descriptions

<u>Temperature Sensors</u>	
Part No.	CLTS-2
Construction:	Thin foil sensing grids of nickel and manganin laminated into glass fiber-reinforced epoxy resin matrix with integral Cu-printed crkt terminals.
Size:	0.430" long x 0.310" wide x 0.004" thick.
Resistance:	296.9K = 290 ohms $\pm$ 0.5%. 4.1K = 220 ohms (nominal)
Range:	300K to 4.2K
Manufacturer:	Micromasurements

<u>Liquid Level Level Sensors</u>	
Construction:	NbTi superconductor element housed in a perforated epoxy fiber-glass tube with four 28-AWG lead wire exits for signal conditioning
Size:	0.25" OD fiberglass tube x magnet stack length required.
Resistance:	Nominal 5.3 ohms per cm active length @ 300K. Nominal 4.5 ohms per cm active length @ 20K.
Range:	Active sensing length is 53.8 inches.
Manufacturer:	American Magnetics, Inc.

<u>Strain Gages</u>		
Part No.	WK-15-250BG-350	WK-15-250RA-350
Construction:	Thin foil sensing grid of "K" alloy encapsulated in glass-fibre reinforced epoxy resin. Single axis.	Same, but rosette, 3 axis.
Size:	0.375" long x 0.125" wide (overall)	0.550" long x 0.865" wide (overall)
Resistance:	350 $\pm$ 0.3% ohms	Same
Range:	$\pm$ 1.5% strain	Same
Manufacturer:	Micromasurements	Same

13.6 Electrical Wiring and Connectors

The instrumentation and control wiring will be of three configurations: single-conductor, three-conductor, and four-conductor.

Single-conductor 30 AWG wire is used for voltage taps and multiconductor 26 AWG wire is used for the strain and CLTS sensors. All wires are silver-plated copper.

All cables are insulated with Kapton insulation for wires and jackets. Kapton insulation is .010-inch thick over each conductor and .010-inch thick for jackets.

All cables are shielded. The single conductor cable has a silver plated copper served wire shield for added mechanical protection and excellent flexibility properties. The multiconductor cables have silver plated copper foil with a 26 AWG drain wire.

All cables have a voltage rating of 1000 volts rms and will be sample tested by the supplier at 2000 volts from conductor-to-conductor and conductor-to-shield.

The cable usages, descriptions, and part numbers are summarized in Table 13-15.

The four cable termination categories are summarized below:

a) Vacuum Vessel Penetrations

All instrumentation wiring inside the vacuum vessel and sensors mounted on magnet and support system surfaces will pass through the vacuum vessel double-ended through bulkhead connectors.

b) Liquid Level Sensor Cables

All liquid level sensor cables will extend approximately 40 feet beyond each magnet stack and will be terminated by LLNL.

c) Voltage Tap Cables

All voltage tap cables exit each magnet stack through conax fittings which allow for one continuous cable for each voltage tap. These cables will extend approximately 40 feet beyond each stack exit point and will be terminated by LLNL at selected protection circuit inputs.

d) High Current Lead Heater Thermocouple Cables

All high current lead temperature control thermocouple cables (Type E, chromel constantan wiring) will extend as one continuous length from the thermocouple installation on the high current lead to the LLNL heater power supply circuits.

The vacuum vessel electric feedthru connectors were procured from Kyle Technology Corporation, and meet the LLNL requirements summarized below:

- Hermetic double-ended feedthru.
- Per MIL-C-262482, Series 1, bayonet coupling.
- Jam nut mounting with silicone rubber seal.
- 61 contacts of gold-plated beryllium copper.
- Insert material - ceramic devoid of organics.
- Radiation environment - 10^6 rads neutron radiation.
- Vacuum environment - 10^{-8} torr.
- Leakage requirement - 10^{-8} std. cc/sec helium.
- Straight plugs for mating with above feedthru per MIL-C-26482, Series 1.

Table 13-15 Electrical Wire Summary

<u>Function</u>	<u>Part Description</u>	<u>Part Number</u>
Cable for Voltage Taps	One Conductor - Shielded and Jacketed Conductor: 30 AWG, Ag Plated Cu Insulation: .010 Wall Kapton Shield: Ag Plated Cu Served Wire Jacket: .010 Wall Kapton Voltage Rating: 1000 VRMS	KTF 5004
Cable for Strain Gages	Three Conductor - Shielded and Jacketed Conductor: 26 AWG, Ag Plated Cu Insulation: .010 Wall Kapton Drain: 26 AWG, Ag Plated Cu Shield: Ag Plated Cu Served Foil Jacket: .010 Wall Kapton Voltage Rating: 1000 VRMS	KTF 5002
Cable for CLTS Temp. Sensors	Four Conductor - Shielded and Jacketed All other properties same as above.	KTF 5003

13.7 Conclusions

All instrumentation drawings have been completed. All drawings and wiring diagrams utilize a standardized instrumentation channel measurement numbering system in accordance with LLNL guidelines. Additionally, a standardized electrical feedthru pin assignment system has been incorporated on all wiring diagrams per LLNL guidelines.

Electrical wiring and connectors including grounding, shielding, and insulating properties have been incorporated per DRD requirements. Sensor selections and placements follow DRD and LLNL supplemental requirements. Sensor installation testing for long term moisture protection was completed at LLNL and LLNL procedure MEL-78-001435 will be updated at LLNL to include the finalized materials and methods used in sensor installations.

Only LHe supply and return line and LN₂-cooled strut temperature measurements are required for long term operation of the magnets. Redundancy for the LHe supply sensor installations is not required since more than one magnet is supplied by the same helium dewar and all magnets are instrumented with LHe supply line temperature sensors. Redundant sensors are required for all LHe return line and LN₂-cooled strut temperature measurements. The remaining temperature sensors on this coil will be used primarily for acceptance testing, cool-down/warm-up, and demonstration of the magnet cryogenic system.

Procurement orders were placed by General Dynamics for all CLTS temperature sensors, including calibration, all electrical wiring, and all electrical connectors. Remaining instrumentation sensors and materials will be ordered by LLNL. All GDC materials ordered have been received and shipped to LLNL.

14.0

VERIFICATION TESTING SUMMARY

The following section summarizes the testing performed in support of the MFTF-B NbTi coils. Section 14.1 covers Solenoid testing, Section 14.2 covers Transition Coil Testing, Section 14.3 covers Axicell Testing, and Section 14.4 covers in-process testing for all coils.

14.1 Verification Testing performed in Support of Solenoid Coils

Table lists the initial complement of verification tests, along with remarks which describe the final status of the test.

14.1.1 Conductor Coldweld Proof Load Verification

This test was performed to determine the proper value of load to apply to the annealed coldweld joints at the conductor splices. The value was selected, such as to stretch the joints sufficiently so that, following superconductor insert reinstallation, the maximum operating strain would not strain the superconductor excessively in the joint areas. This load value was used in the manufacturing sequence when making solenoid splices.

14.1.2 Entering Lead Splice Verification

This test was performed to verify that the final entering lead splice configuration could withstand the final MFTF-B design loads. Of particular concern was the possibility of the stabilizer separating from the entering lead bus at maximum loads. The final design provided a mechanical lock to insure that this could not occur. Testing was performed at 80K in a tensile test machine and demonstrated adequate margin.

In addition, a production test was performed to demonstrate that the entering lead bus could be formed into its final configuration following installation on the coil. This test was crucial to our entering lead design and was successfully completed.

14.1.3 Case Stiffener Test

As a result of the higher loads in the MFTF-B axicell configuration design (as compared to the original MFTF A-Cell design), the entering lead cutout was redesigned to include a number of external stiffeners. Then stiffeners were to be welded in place following the solenoid fabrication. Questions relative to potential coil damage due to weld heat buildup and due to excessive case deformation caused by weld-induced stresses were answered during the conduct of this test.

The test utilized a built up section which simulated a portion of the solenoid case. Typical epoxy filler and insulation installations were also added. A number of thermocouples were attached to the inner side of the simulated coil can sidewall to measure the weld-induced heat. The case section deflections were measured by making periodic measurements from reference planes to specific points on the exterior of the coil case specimen.

A total of three stiffeners were welded to the coil case exterior, each using a specific credible weld method. The test results showed that the maximum temperatures reached would not cause any damage to the coil interior filler material or insulation. Analysis of the deflection data showed it to be well within the design margins established during the solenoid design phase.

14.1.4 Instrumentation Coupon LHe Cycling Tests

This test was performed by LLNL using coupons that had been prepared by GDC as part of the original MFTF program. The sensors included strain, crack, two types of temperature sensors, and

typical voltage taps. The intent of the LLNL tests was to evaluate the sensor installation techniques used by GDC. The test results were not totally satisfactory. The installation methods, in the opinion of LLNL, needed to be modified to insure sensor reliability.

After these tests were performed, the instrumentation installation task, except for coil-mounted voltage taps, was transferred to LLNL.

14.1.5 Solenoid Flow Verification

This test was performed to determine the flow impedance of a completed solenoid coil to verify the values used in designing the solenoid LHe manifold.

The test used nitrogen gas as a fluid. The test setup included a heat exchanger to keep the gas temperature uniform, several pressure gages, and a flow meter. Test data was taken over a range of flow values and was used to establish the final flow values for the solenoid LHe supply and return manifolding.

14.1.6 Conductor Splice Tensile Test

The original conductor splice design was subjected to tensile and fatigue testing. Following the testing examination revealed that the soldered-on doubler had separated from the conductor at the tips of the doubler. This shear-bond failure was determined to be unacceptable so a new splice design was developed and samples fabricated. The new design used a special stabilizer insert which was coldwelded to the ends of the two conductor lengths. Following annealing and proof loading of the two joints, the superconductor insert was overlapped and resoldered into the special stabilizer insert.

Tests on the redesigned solenoid splice were performed at 4K by LLNL. The specimens passed the tensile-loading and fatigue-loading tests with no failures. Fatigue loading was performed for 5000 cycles on two specimens. Tensile testing was performed to failure on one specimen.

Test data from the redesigned solenoid splice verified the adequacy of the design for all solenoid operational modes.

14.1.7 Solenoid Layer Insulation Bend Test

This test was performed to verify that, under the worst case of conductor layer misalignment, the layer insulation would not fail under maximum expected compressive loads. The test fixture used included curvature equal to the median coil radius and a sidewall-to-sidewall curvature resulting from the maximum credible misalignment due to solenoid layer buildup errors.

Testing of a typical layer insulation showed no insulation failure due to the compressive loading in the compound curvature fixture.

Table 14-7. Initial Solenoid Coil Verification Tests

Test Number	Title	Remarks
6.1.1	Conductor Coldweld Proof Load Verification Memo MFTF-1410-R-429	See 14.1.1
6.1.2	Entering Lead Splice Verification	See 14.1.2
6.1.3	Case Stiffener Tests Memo MFTF-83-M-739-REB	See 14.1.3
6.1.4	Instrumentation Coupon LHe Cycling Tests Report 64A 7574; Memo MFTF-1410-M-201	See 14.1.4
6.1.5	Calibration of Carbon-Glass Sensors	Deleted
6.1.6	Calibration of Production CLTS Sensors	Vendor Task
6.1.7	Solenoid Flow Verification	See 14.1.5
6.1.8	Verification of Lead Splice Fabrication	LLNL Task
6.1.9	Verification of VCL Operation	LLNL Task
6.1.10	Verification of VCL Fabrication	LLNL Task
6.1.11	Conductor Splice Tensile Test Memo MFTF-1412-M-351	See 14.1.6
6.1.12	Solenoid Layer Insulation Bend Test	See 14.1.7

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14.2 Verification Testing in Support of Transition Coils

Table 14-2 lists the initial complement of verification tests, along with remarks which describe the final status of the test.

Table 14-2. Initial Transition Coil Verification Tests

Test Number	Title	Remarks
6.2.1	Conductor Splice Verification	See Axicell Test 6.3.2
6.2.2	Case Corner Weld Tests	Cancelled
6.2.3	Verification of Plenum Stiffness	Cancelled
6.2.4	Verification of Vapor-Cooled Lead Operation	LLNL Task

14.3 Verification Testing in Support of Axicell Coils

Table 14.3 lists the initial complement of verification tests, along with remarks which describe where the final status of the test can be found.

14.3.1 Conductor Mechanical Properties Tests

These tests were performed using six samples of yin-yang-type MFTF-6 conductor. The six samples represent the two conductor grades, three each of Grade I and three each of Grade II. The intent of the test was to verify that the critical current of the test specimens would not be degraded below the specification value following a series of fatigue cycling loads at a test temperature of 4.2K.

All six samples were prepared for the mechanical testing by applying two strain gages to each specimen in a back-to-back configuration. The specimens were shipped to Teledyne Engineering Services Company in Massachusetts for testing at 4.2K. Each specimen was loaded to an initial value determined by the strain values, but in the range of from 3100-4750 lb. Following this initial loading, the specimens were subjected to a total of 2000 cycles of cyclic loading. Loading values were related to the loads obtained from the initial tensile loading test.

Following this loading test, the specimens were sent to LLNL for critical current testing. All specimens had a critical current value in excess of the design specification minimum.

14.3.2 Conductor Splice Verification Tests

These tests were performed to verify that the splice design for both the axicell and transition coils was adequate for the expected high loads in the axicell coil environment. This would

also qualify the splice for the transition coils since their loads were less than for the axicell coils.

A total of four splice specimens were fabricated consisting of a "dog-bone" specimen with the ends of the splice included as part of the machined copper end fittings of the dog-bone specimen. A section of conductor was soldered between the end pieces representing the splice as if it had been cut across its width and each piece rotated 180 degrees. Two of the splice specimens were tested at 80K test temperature including tensile and fatigue loading. For the third and fourth specimens, a section of pipe (3-inch diameter) was fabricated using set screws to support the specimen mounted inside the pipe. This pipe provided structural support against bending during the compression portion of a newly defined fatigue loading cycle.

The third and fourth specimens were tested at Teledyne Engineering Services Company at 4.2K. The splices survived these tests with no apparent joint degradation. A final ultimate tensile test was performed on one of these specimens at the same time that the conductor samples (paragraph 14.3.1) were being tested at Teledyne.

Table 14-3. Initial Axicell Coil Verification Tests

Test Number	Title	Remarks
6.3.1	Conductor Mechanical Properties Tests Memo MFTF-83-M-757-KJH	See 14.3.1
6.3.2	Conductor Splice Verification Tests Memo MFTF-1210-M-677-KJH	See 14.3.2
6.3.3	Verification of Vapor-Cooled Lead Operation	LLNL Task

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14.4 In-Process and Final Acceptance Testing in Support of Solenoid Coils, Transition Coils, and Axicell Coils

The following section summarizes the testing, completed and planned, that supports the production and final acceptance of these coils. Section 14.4.1 covers solenoid coils, 14.4.2 covers transition coils, and 14.4.3 covers axicell coils. Section 14.4.4 summarizes the test methods used.

14.4.1 The twelve solenoid coils were fabricated and delivered to LLNL in 1983. During the coil fabrication a series of tests were performed designed to show that the fabrication was free from flaws which could influence magnet performance. These tests included the following:

- a. Coil case bobbin-to-sideplate leak test.
- b. Ground wall insulation verification.
- c. Coil-to-case high potential tests,
 1. In air,
 2. In helium gas.
- d. Layer turn-to-turn short test.
- e. Coil voltage gradient test.
- f. Voltage tap tests.

Because of the way in which these coils were wound (continuous conductor) the presence of layer-to-layer faults was only detectable using the voltage gradient methods. In similar fashion, the presence of turn-to-turn faults was only detectable by measuring turn-to-turn voltages. In both of these methods, the continual presence of the very low-resistance conductor limits the values of detectable faults to low resistances, of the order of 2-5 percent of the shunting conductor resistance. In spite of these limitations, a number of layer-to-layer and turn-to-turn flaws were found, localized, and following the outcome of remedial action, corrected

Following completion of the case close out welding operations on each coil, the final electrical and leak acceptance tests were performed. These tests included the following:

- a) Coil-to-case high potential test in helium gas.
- b) Final voltage gradient test.
- c) Final voltage tap electrical tests.
- d) Outer ring-to-sideplate closeout weld leak tests.

These tests proved that the completed coils met the LLNL and GDC specifications. The leak test, due to pumpdown time restrictions, could not be performed by evacuating the coil interior and using helium gas around the coil exterior. To minimize testing time, a series of metal tools were fabricated which permitted the establishment of a vacuum on the coil exterior allowing helium gas on the coil interior to be used as the leak test tracer gas. Following completion of testing, the coil parts were sealed in preparation for shipping to LLNL.

Details of these tests, as well as test results for each solenoid coil, can be found in the Solenoid Test Procedure/Report, 71E0011.

The in-process and final acceptance test procedures (71E0041 - T1 Transition Coil and 71E0044 - T2 Transition Coil) were prepared and used during coil fabrication.

Because of the method of winding the T1 and T2 coils, a high potential test, layer-to-coil, can be performed for half of the layers. This test is followed by a splice which connects the layer to the remainder of the coil. The remaining tests, voltage gradient, turn-to-turn, and voltage tap tests, are similar to those described for the solenoid coils. Listed below are the in-process tests for the T1 and T2 coils.

- a. Ground wall insulation verification.
- b. Coil-to-case high potential tests,
 - 1. In air,
 - 2. In helium gas.
- c. Layer turn-to-turn short test.
- d. Coil voltage gradient test.
- e. Voltage tap tests.
- f. Layer-to-coil high potential tests.

Testing to date has been limited to the two T2 coils. A number of layer-to-layer faults have been found and remedied. One particular problem uncovered during this testing was that the residue left from the ultrasonic testing of the conductor splices is conductive and caused a number of the layer-to-layer faults. Splice test procedures were modified to eliminate the acoustic couplant material by improving the cleaning methods.

Final acceptance testing included the tests listed below:

- a. Coil-to-case high potential test in helium gas.
- b. Final voltage gradient test.
- c. Final voltage tap electrical tests.
- d. Coil case leak tests.

The coil case leak tests were performed in a manner similar to the final case leak test described for solenoids. In the case of the transition coils, a number of external test tools are required to cover all of the welded seams. It is to be noted that these tests do not provide a true integrated leak test as would be the case if a vacuum were provided within the coil case with the helium gas on the outside in a bag surrounding the coil exterior. However, this method is acceptable and represents a low risk relative to finding a leak in the case structure.

14.4.3 The in-process and final acceptance test procedure (71E0042) for the axicells were prepared and used in support of the axicell fabrication effort.

The axicell design, like the solenoid design, uses a continuous piece of conductor (with splices) to wind the coil. The test philosophy, therefore, is similar to that used for the solenoids. The layer-to-layer testing used the voltage gradient scheme in a manner similar to that used by the solenoids. This technique located one layer-to-layer fault which was removed. The axicell in-process tests are listed below:

- a. Coil can bobbin-to-sidewall leak test.
- b. Ground wall insulation verification.
- c. Coil-to-case high potential tests,
 - 1. In air.
 - 2. In helium gas.
- d. Layer turn-to-turn short test.
- e. Coil voltage gradient test.
- f. Voltage tap tests.

Following completion of the coil case closeout operations, the final acceptance tests was performed. These tests were similar to the final acceptance tests performed on the solenoids. These final acceptance tests are listed below:

- a. Coil-to-case high potential tests in helium gas.
- b. Final voltage gradient tests.
- c. Final voltage tap electrical tests.
- d. Outer ring-to-sideplate closeout weld leak test.

The final case leak test was performed as outlined for the solenoid tests except that smaller tools were fabricated for leak checking smaller sections of the case and the helium inlet line and vent stack welds.

14.4.4 Following is a brief summary description of the coil electrical tests used in the in-process and final acceptance tests.

a. High Potential Tests

This uses a conventional high potential tester, with a voltage range of 0 to 5000 volts. It is a direct current (dc) device. The current is limited to less than 10 milliamperes in the shorted condition. Metered current ranges are from 2 to 2000 microamperes. This instrument is also used in conjunction with a hollow, insulated probe, through which a flow of helium gas is vented, to locate flaws in insulation systems. It can find small pinholes, cracks, etc., that may compromise the coil insulation if left unrepaired.

b. Turn-to-Turn and Voltage Gradient Tests

These tests use a dc power supply to put a known value of current (1 to 5 amperes) through the portion of coil that is completed. Knowing the current, coil temperature, resistance per foot of the conductor, and length of the conductor, one can compute the starting and ending voltages of the layer under test and the expected turn-to-turn voltages. In practice, it is possible to use a plus or minus 1-2 percent error band for these values. Negative deviations from these values suggest, depending on the actual values, that a shunt path (short) exists which is reducing the measured voltages. Further analysis of such data will indicate the location of the flaw, often to within a few centimeters, along the coil conductor.

The voltage gradient test uses the installed voltage taps as points from which layer voltages can be measured. Using initial values as a reference, subsequent readings are compared to the initial values providing a continuing check

on previously wound layers. Finally, these values are used as reference values for the final acceptance voltage gradient test to prove that there are no faults in the completed winding.

For all the coils, the calculations, predictions, and listing of various data are accomplished by suitable programs that are used on a computer located adjacent to the winding area. The test technician performs the test, obtains the test data, enters it into the computer program and notifies engineering if the computer indicates a potential fault. The computer data sheets are included in the test reports as backup data.