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DESIGN AND FABRICATION OF THE MFTF-B MAGNET SYSTEM

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ABSTRACT

The MFTF-B superconducting magnet system consists of 40 NbTi magnets and two Nb₃Sn magnets. General Dynamics (GD) designed all magnets except for the small trim coils. GD then fabricated 20 NbTi magnets, while LLNL fabricated 20 NbTi magnets and two Nb₃Sn magnets. The design phase was completed in February 1984 and included the competitive procurement of magnet structural fabrication, superconductor, G-10CR insulation, support struts and bearings, vapor-cooled leads, and thermal shields for all magnets. Fabrication of all magnets was completed in March 1985. At GD, dual assembly lines were necessary during fabrication in order to meet the aggressive LLNL schedule. The entire magnet system has been installed and aligned at LLNL, and Tech Demo tests will be performed during September-November 1985.

INTRODUCTION

Before magnetically confined nuclear fusion can be commercialized, it will be necessary to demonstrate the ability to control the fundamental fusion processes and achieve the required level of performance with simplified reactor designs. The Mirror Fusion Test Facility (MFTF-B) is a major step in the tandem mirror concept and is such a machine.

The tandem mirror was conceived in 1976 and has evolved into the current MFTF-B symmetrical magnet configuration (Fig. 1). The plasma is contained within the long central cell, constrained by twelve 5.5-meter solenoids, and is then throttled by the two axicells, the second one having a 12-tesla Nb₃Sn insert coil. Two transition coils convert the circular plasma into a fan shape prior to its entering the Yin-Yang end plugs. The major hardware components now nearing completion are the cryogenic plant, control and diagnostic center, vacuum vessel, vacuum pumping station, and the superconducting magnet system. All these systems will be operated and proofed during the Tech Demo tests. Only the superconducting magnet system will be discussed here, with emphasis on the procurement and fabrication processes.

Coil	Qty	Major Radius (M)	Minor Radius (M)	Sweep Angle (Deg)	Coil Cross-section (M x M)	Turn Length (M)	Turn For "C" Coils
T2	2	1.20	1.375	108.75	0.3371 x 0.3400	17.75	15.23
T1	2	0.85	0.700	100	0.4215 x 0.2038	10.51	11.86
A20/A1	4	0.928	—	—	0.9390 x 0.4073	5.83	10.107.88
A21	2	0.3883	—	—	0.6572 x 0.3523	2.44	10.10
S5/S6	4	2.50	—	—	0.163 x 0.336	15.71	6.875/5.625
S3/S4	4	2.50	—	—	0.163 x 0.336	15.71	4.375/3.125
S2/S1	4	2.50	—	—	0.163 x 0.336	15.71	1.875/0.625

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Fig. 1. The design requirements specify the magnet geometry required to produce desired field distributions.

General Dynamics responsibilities included the design and confirmatory analysis of the entire structural support system, the LN₂ and H₂O thermal shields, and all magnets except the 16 trim coils. GD also initiated and awarded all major procurements to support these components. Fabrication of the two Yin-Yang pairs, the 16 trim coils, and the two high field Nb₃Sn insert coils was accomplished by LLNL in-house. GD, with major support from Chicago Bridge & Iron Company (CBI), fabricated the 12 solenoid coils, four axicell coils, and four transition coils in its San Diego facility. Installation of the thermal shields and the magnet/support system was performed by LLNL prior to and during magnet installation and alignment in the vessel.

This work was performed by General Dynamics under LLNL Subcontract 9591309 & 7721805.

A simplified program schedule is shown in Fig. 2. Based on a firm LLNL requirement to achieve this aggressive program schedule, GD chose to facilitate and use four magnet fabrication lines. All magnets were delivered on or before their schedule dates at slightly below cost, a fact of which GD is extremely proud. The performance of each magnet will be demonstrated and evaluated by LLNL during the Tech Demo tests in September-November of this year. The principal magnet characteristic is magnetic field vs current. In addition, the temperature profile during cooldown and warmup and the stresses at critical locations will be carefully monitored.

Fig. 2. MFTF-B schedule.

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DESIGN

LLNL developed the conceptual arrangement of the magnets, including their general configuration, spatial locations, and the internal amp turns to achieve the magnetic field necessary for plasma confinement. Based on this conceptual data, GD performed preliminary analyses and design. After formal review and approval by LLNL, GD proceeded with the detailed design and analysis. It was often necessary to conduct interim workshops (reviews) prior to the early procurement of specific major components required to support the aggressive magnet fabrication schedule. While this mode of operation had potential for error, we were able to achieve the required subcontractor deliveries with only minor contractual adjustments. We attribute this to our thorough, careful analysis leading to timely, decisive actions by both GD and LLNL, and to a cooperative attitude and diligent attention by most subcontractors.

Basic data for each magnet type designed by General Dynamics is shown in Fig. 1. The detailed design requirements were defined by LLNL in a Design Requirements Document. The significant requirements were geometry, design stress, magnet heat load limitations, and conductor requirements.

The M1 and M2 coils have the same geometry as those used in the MFTF-A Yin-Yang magnet. Both are "C"-shaped coils with two major and two minor radius segments. The plane of the major radius arcs (as in all of the "C" coils) are parallel to either 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 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 fan shape that enters the M1/M2 Yin-Yang magnets. The T1 and T2 coils differ from the M1 and M2 coils in that their major radius arcs span more than 180 degrees. 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 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 about 6 kG. The A2 axicell coil, however, has an insert coil designated A21 (insert) that fits inside of the A20 coil and raises this on-axis field to 12 tesla.

The twelve 5.5M central-cell solenoid coils provide most of the plasma containment volume in the MFTF-B system. These coils are identical except for their external support structures and, in the case of the 56 coils, their case structures.

The schedule demands left virtually no time for development work relating to the insert coil; so we relied on the expertise in Nb₃Sn technology in existence at LLNL. The prime concern in using multifilamentary Nb₃Sn was to ensure that the conductor strain from all sources did not exceed the allowable limits, which typically are 0.6 to 0.8%. For these coils we were able to limit the total conductor strain to less than 0.4%, with the winding process contributing about 0.3%.

The two MFTF-B operating modes produce on-axis field distributions whose primary difference is in the central cell field (1.0T for the MARS mode and 1.6T for the Kelley mode). This also affects the operating currents in the solenoids and in the axicell coils.

PROCUREMENT

Approximately 22M of the contract value was subcontracted to nine major vendors (Table 1). All contracts were fixed price with deliveries timed to support the GD/LLNL fabrication and assembly schedule. Great care was taken during the competitive procurement cycle to ensure that all factors were considered that could affect the ability of the bidders to perform these fixed price procurements within the specified schedule. While most subcontractors encountered numerous delays due to late materials delivery, equipment problems, and changes by GD, most of them performed admirably in supporting the aggressive schedule. At the initiation of the procurement cycle, GD generated a detailed technical specification on each item to be procured. As is usually the case, this specification was written to cover the "worst case" use of the material. The GD program office established a procedure wherein any material not meeting the contractual specification was documented on a Waiver Authorization Request Form (WARF) by the subcontractor. This WARF was then transmitted to the GD program office QA manager, who directed the appropriate technical personnel to evaluate the deficiency based on the exact intended use and placement within the magnet system. If sufficient safety margin remained, GD accepted the questionable item for its intended use. While this process often resulted in additional GD record keeping and fabrication effort (such as cutting and splicing), we believe it was beneficial to both GD and our subcontractors. It served the purpose of avoiding rejection of usable material and thus imposing additional demand on the subcontractor to reprocure and refabricate the rejected part. It also assisted GD in maintaining fabrication schedule flexibility. In no case was any item accepted for use that compromised the structural integrity or performance of any component or system.

Table 1. General Dynamics used nine major subcontractors on MFTF-B.

Subcontractor	Responsibility	Contract Value (\$)
1. Chicago Bridge & Iron Co.	Material procurement & fabrication of structural components	9.5M
2. Spaulding Fibre	G-10CR insulation for all magnets	9.7M
3. Interimagnetic General	NbTi conductor core for axicell & transition magnets	2.2M
4. Oxford Superconductor	Wrapping all NbTi cores for axicell & transition magnets	1.6M
5. Supercon	NbTi superconductor for solenoid magnets	1.3M
6. Furukawa Electric	Nb ₃ Sn superconductor for insert coil	1.4M
7. Kobe Steel	Support struts for all magnets	1.2M
8. Mueller	Thermal shields for all magnets	1.0M
9. Meyer Tool Co.	VCL for all magnets	1.0M

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CBI was responsible for all structural fabrication and assembly and also had procurement responsibility for the 304LN structural steel and the weld rod used. This technique was used to give CBI maximum control over all actions that affected their ability to perform within this major subcontract and meet the fabrication schedules in their Salt Lake City and Birmingham facilities. This action was critical to the support of the GD coil winding and manufacturing schedules. In total, CBI procured about 1,400 tons of 304LN from Eastern Steel and performed all closeout welding of the magnet cases after GD completed the winding of the coils and installed the plenum insulation. CBI also installed all clevises for the struts.

Three types of superconductor were procured from four vendors. Table 2 identifies the magnet, conductor type, length, cross-sectional dimensions, I_c , and vendor. All procurements were competitive except for the core wrap, which was a LLNL-directed procurement to utilize a LLNL-owned wrapping line at Oxford. Note that the axicell and transition superconductors were of the Yin-Yang type, varying only in I_c . All superconductors were delivered in

specified lengths corresponding to their use within the magnet. The ends of each length were subjected to short-sample tests to verify conformance to specification. Of 446 lengths procured, only two were rejected, one for insufficient I_c and the other for solder disbond. The Nb₃Sn superconductor manufactured by Furukawa was dimensionally the most accurate, varying less than a mill in any dimension.

Table 2. Three types of superconductors were used.

Magnet	Superconductor Material	Total Footage	Cross-Sectional Dimensions	I_c at 4.5K	Subcontractor
Solenoids	NbTi	436,304	0.197 x 0.492	3,400 at 3.1T 3,190 at 3.1T	Supercon
Axicell	NbTi	158,300	0.256 x 0.258 0.490 x 0.490	8,930 at 7.5T 7,200 at 5.1T	IGC
Insert	Nb ₃ Sn	28,828	0.295 x 0.433 0.083 x 0.272	3,200 at 12.75T	Furukawa
Transition	NbTi	105,942	0.256 x 0.258 0.490 x 0.490	8,930 at 7.5T	IGC
Yin-Yang	NbTi	360,000	0.256 x 0.258	5,775 at 7.5T	IGC Oxford Supercon Oxford

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The G-10CR procurement was one of the most difficult for GD to monitor and for the vendor, Spaulding, to perform, since there were many pieces of multiple configurations. The difficulties arose due to the GD specification delivery schedule by lots consisting of specific numbers of pieces of different configurations. This was specified to support scheduled GD magnet fabrication. The vendor desired to complete the fabrication of the total required pieces of a given configuration and set-up before proceeding to the next configuration. This was often resolved by the vendor having to utilize air shipments on Friday to support the next week's fabrication at GD.

Procurements of three components were transferred to LLNL after contract award, since these components were to be installed at LLNL after delivery of the magnets by GD. They were the vapor-cooled leads, the thermal shields, and the support struts.

The vapor-cooled leads were of the same type as previously procured by LLNL for the first Yin-Yang. The GD-procured leads varied only in size and in the number of Cu tubes, varying from 14 tubes in the Nb₃Sn lead to 57 tubes in the T2 lead.

The 90 struts comprising the structural support system for the MFTF-B were fabricated from 304LN for the turnbuckle tube and A286 for the rod ends, bearing balls, and pins. Kobe Steel was selected to fabricate and assemble the struts, with bearings furnished to Kobe by Lear Siegler. Kobe was competitively selected due to their total in-house capability, including the capability to make the materials, verify the materials properties, and proof test the completed struts before shipment.

The thermal shield system for the MFTF-B consisted of LN₂ shields over the entire magnet surface, plus H₂O shields between the LN₂ shields and the plasma. The procurement consisted of 2,489 panels of 552 different configurations totaling 29,863 ft². The large number of configurations resulted from the necessity to avoid numerous stay-out zones, thus forcing a customizing of the shields for each magnet. This factor also made it extremely difficult to standardize the shield stand-off supports. These two factors resulted in our not achieving the desired degree of commonality and resulted in an increased number of design drawings, a more complex and time-consuming fabrication and installation monitoring system, and many disruptions to the GD/LLNL desired fabrication sequence and schedule. All of these items contributed to making this subcontract with Paul Mueller Company difficult to perform.

FABRICATION

All NbTi magnet manufacturing occurred at the GD Harbor Drive facility in San Diego, CA. The manufacture of the 20 coils (12 solenoids, four axicells, and four transition coils) was accomplished by GD with major support from CBI. CBI fabricated all the magnet structural components, including the coil form, case closure sections, and clevis fittings in their Salt Lake City and Birmingham facilities. GD performed coil winding and plenum insulation closeout prior to the case closeout welding by CBI. Magnet manufacturing consisted of: off-site composite fabrication by CBI, off-site superconductor and insulation fabrication by vendors, coil form true-up by GD, coil ground insulation by GD, coil winding by GD, plenum insulation closeout by GD, case closeout welding by CBI at GD, clevis installation by CBI at GD and LLNL, and shipment of coils by GD and LLNL.

**BLDG 52
HARBOR DRIVE FACILITY**

TRANSITION COIL WINDER (HIGH-BAY)

TENSIONER

2-TON HOIST

WINDER

2-TON HOIST

WINDING STATION NO. 1

WINDING STATION NO. 2

TENT ENCLOSURE

AXICELL WINDING LINES

LAYER - WIND POSITION

2-TON HOIST

CONDUCTOR POOL

5-TON HOIST

TENSION COIL TRUE-UP STATION

TENSION COIL WINDER (LOW BAY)

TENSIONER

LOW BAY 36 FT HIGH

HIGH BAY 56 FT HIGH

Upon receipt of the coil forms at GD, they were leak checked to a tolerance of 1×10^{-4} torr liters/sec at room temperature. No leaks were ever detected. Repair of the coil forms after winding would not be possible. The coil forms were then trued up so that their winding cavity would be in a consistent position relative to the window. The true-up material used was 50 parts Epon 828 epoxy, 50 parts Versamid hardener, and 100 parts 3/4-inch-long fiber-

All winding was performed within a protective tent, which was maintained at a slight positive pressure using air conditioners. Winding of the solenoids and axicells involved a weld positioner as the coil turntable, an insulation pot band dispensing machining, a tensioner, a conductor cleaning station, and a conductor reel and stand. Two parallel winding lines were required to meet the solenoid delivery schedule established by LLNL. This resulted in the last solenoid being completed more than three months before the LLNL need date. During coil winding, layer gap (< 5 mil) compaction was achieved and maintained with tension, tapping, and clamps. After winding, sloped and perforated G-10CR insulation was installed in the coil annulus area, resulting in a solid pack. The steel case cover compressed the pack and was then welded into place by CBI.

The solenoid total fabrication time span averaged 119 M-days and improved from 188 M-days on S1 to 80 M-days on S12. Of the 119 M-days, nine days were devoted to alignment of the coil form on the holding fixture, 14 days to true-up, 11 days for ground insulation, 36 days for winding, 17 days for plenum insulation, and 32 days for closeout weldline.

Axcell manufacture was basically the same as the solenoids, except that a single pancake was used to bring in the emerging conductor. All solenoids and axcells were layer-wound. The axcell total fabrication time span averaged 155 M-days, improving from 176 M-days on coil 1 (A2W) to 129 M-days on coil 4 (A2E). Of the 155 days, three days were devoted to coil alignment on the holding fixture, 16 days for true-up, 17 days for ground insulation, 74 days for coil winding, 16 days for plenum insulation, 14 days for case close-out welding, and 15 days for clevis installation.

A key feature of the Harbor Drive facility was its ability to accommodate the two large, heavy winders and tensioners (Fig. 5) needed to wind the four transition coils (two T2s and two T1s). The two winders were identical in height relative to platform rotation and coil tilt, varying only in the platform height. Both winders were procured from Trelodyne Redco. LNLN procured the lower platform machine to wind the two Yin-Yang pairs at LNLN, after which it was disassembled, shipped on trucks in GD, and reassembled. The use of two transition winding stations was also dictated by the need to meet the aggressive transition coil delivery schedule established by LNLN. The two T2 coils were wound in parallel first, followed by the parallel winding of the two T1 coils. These transition coils were always anticipated to be the most aggressive schedule—*i.e.*, but not to the extent experienced. Coil winding and plenum insulation were each considerably more difficult and time consuming than the solenoids or axiscells. Difficulties were also experienced due to electrical shorts in the joint area, excessive equipment breakdown, and a strike. To recover from these setbacks, it was necessary to initiate two 10-hour shifts, six days a week. After six weeks, this was relaxed to two 8-hour shifts, six days a week, and after six more weeks, we resumed our normal two 8-hour shifts, five days a week.

The total manufacturing time span for the T2 coils averaged 237 M-days, increasing from 234 M-days for T2W to 240 M-days for T2E. Since both coils were being manufactured essentially in parallel, little learning is apparent. However, if the 19 M-days lost due to winter downtime are removed from the T2E time span, a total of 221 M-days results, which is a small improvement over the 234 days for T2W. Both T2 coils were shipped to LLNL on the last possible day on which GD could earn the schedule fee.

The coil manufacturing time span for the T1 coils averaged 150 M-days, improving from 166 M-days for T1W to 134 M-days for T1E. Experience

Fig. 5. Transition coil winding machine/thermocon.

gained on the T2 coils enabled the T1 phase to proceed more smoothly. Bolt T1 coils were delivered significantly ahead of the required schedule.

A LLNL winder, used to construct the Nb₃Sn coils for the High Field Test Facility, was modified for winding the high field insert coil. A double pancake wind was used, primarily to avoid joints in the high field region. A unique feature of the Furukawa conductor was a black oxide (CuO) coating to prevent the solder from wetting and coating the external conductor surfaces. This technique virtually eliminated any post-solder clean-up and resulted in a conductor that was absolutely free of solder lumps. This greatly facilitated the winding.

INSTALLATION AND ALIGNMENT

The coil installation at LLNL proceeded rather smoothly, although schedule pressure tended to make the pace hectic. The general plan in installation and alignment was first to position the coils in the vacuum vessel, using specially designed transporters, then affix the coils to the vacuum vessel with the various adjustable hangers and struts, and finally move the coils into the final position by jacking the transporters and/or adjusting the hangers and struts. The central cell was the exception; in this case, a pair of solenoids was installed in each section of the center cell vacuum vessel in the magnet fabrication yard. Each vessel module with the coils inside was then installed as a unit.

The final coil position at room temperature is actually a "misaligned" position, which takes into account motion expected during cooldown and magnet energization such that the coils are properly positioned during LHe operation. The required misalignment offsets were calculated by GD for the magnets and support system and by the LLNL Mechanical Systems group for the vacuum vessel.

The first coils to be installed were the Yin-Yangs. These magnets, which weighed approximately 400 tons with their transporters, were moved from the magnet yard into the vessel building by two methods. The first was to skid the assembly on greased steel plates using hydraulic rams as the driving force, and the second was to roll it onto a trailer-type platform with 144 tires. The

first method, which worked well for moving the magnets short distances in the magnet fabrication yard, was not very well suited for the long move. The trailer, on the other hand, worked quite well for the two-block trip. The trailer had several hydraulic systems: three leveling and two for steering. The Yin-Yangs were rolled into the vacuum vessel across a bridge on a series of 100-ton Hillman rollers.

The remaining magnets were transported to the building on a low-boy trailer. The transition and axicell coils were installed by first positioning the coils on a rail system leading into the vacuum vessel; rolling them into position on Hillman rollers; and finally installing the struts, hangers, and links. The solenoids were put directly into position with the overhead bridge crane.

Installing the axial links turned out to be more difficult than originally anticipated because of interferences between the axial links and coil cases and also interferences between coils. Fortunately, there was sufficient safety margin in the links, which allowed for machining to remove the interference.

LESSONS LEARNED

As in any endeavor, hindsight is better than foresight. It is useless to say that the overall program schedule should have been less aggressive. That schedule was what the customer wanted and what GD agreed to meet. However, in retrospect, there are several items and events that confirm the importance of approaches chosen or offer a chance to do better next time.

1. During the design phase, strive for maximum commonality. This is easy to say but difficult to achieve with large programs and numerous participants. However, it can save considerably in reducing the number of drawings and results in simpler/cheaper procurement and manufacturing, with less need to store, control, and use multiple, similar parts.
2. During the design phase, require manufacturing personnel to critique and evaluate the designs as they evolve in order to force the designs to reflect the simplest, most cost-effective manufacturing techniques.
3. Review with all manufacturing personnel, engineers, technicians, and engineering liaison what is to be done, why it must be done in the specified way, and the necessity for following the specifications and procedures until they are officially changed.
4. Use strict specifications for all procurements and select subcontractors most likely to meet them. However, retain the flexibility and willingness to reevaluate the rejection or use of sub-spec material.
5. As a program office, retain and do not share information relative to your financial and schedule reserves.

ACKNOWLEDGEMENTS

None of the General Dynamics performance would be achieved without the dedicated commitment of full-time program personnel both at LLNL and GD. In addition, GD provided early, generous support in the use of capital equipment that has future use on magnet programs, as well as in other areas of our business. LLNL personnel leading the MFTF-B program had an unwavering and unyielding commitment to the achievement of the technical objectives within the framework of the funding provided and the schedule required. With these demands upon LLNL, as well as upon GD, we all succeeded.

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