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THE TEAM ONE (GA/MCA) EFFORT OF THE DOE 12 TESLA COIL DEVELOPMENT PROGRAM

by
J. S. ALCORN

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GENERAL ATOMIC COMPANY

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GENERAL ATOMIC COMPANY

THE TEAM ONE (GA/MCA) EFFORT OF THE DOE 12 TESLA COIL DEVELOPMENT PROGRAM*

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Progress to date on the Team One effort of the DOE/OFE/D&T 12 Tesla TF-Coil Development Program is presented. General Atomic is the Team One leader, with the Magnetic Corporation of American (MCA) as industrial subcontractor. The basic mission of this effort is to demonstrate the feasibility of, and establish an engineering data base for utilizing bath cooled NbTi alloy to generate a peak field of 12 tesla in a tokamak reactor. The 1980 effort has been concentrated upon four major tasks: completion of the conceptual design of an ETF reactor compatible TF-coil employing helium bath cooled NbTi alloy conductor; procurement of conductor for the coil to be tested at the LLNL HFTF during FY 82; design of the test coil; and a series of relevant tests using the GA HFTF. The ETF TF-coil concept employs cabled NbTiTa/copper conductor, immersed in a helium bath subcooled to 2.5 K from a saturation temperature of 3 K. A saturated superfluid (He II) bath cooled option is also under consideration. Hoop, radial and circumferential bearing loads are borne by a multicomponent frame of stainless steel strips which surround the pancake (spiral) wound conductor. Magnetic Corporation of America is providing the 10 kA, three level, unsoldered, uninsulated Rutherford cable for the test coil. Meanwhile, at GA, a series of heat pulse/recovery tests are being performed upon samples of cabled conductor, at 2.5 - 3 K, and in the He II range. These tests will guide the test coil cryogenic design, and provide improved insight into results later obtained with that coil at Livermore. The 0.4 m I.D. x 1 m O.D. Test Coil has been designed. Its salient features are presented.

The Program

The objective of the Team One effort is to demonstrate the feasibility of, and establish an engineering data base for utilizing bath cooled NbTi alloy to generate a peak field of 12 tesla in a tokamak reactor.

This four year effort is being implemented in four closely related phases:

I. Experimental development of a NbTi alloy, compositionally and process optimized for 12 tesla operation at bath temperatures below 4 K.

II. Conceptual design of an ETF reactor compatible toroidal field coil system, employing the NbTi alloy selected by Phase I, and an appropriate bath cooling regime.

III. Design, construction and testing of a solenoid test coil utilizing the selected reactor prototypical conductor and bath conditions. This coil will be tested at the LLNL high field test facility.

IV. Tests performed at the GA high field test facility to supplement, and aid interpretation of results from the Phase III coil tests at LLNL.

The present schedule for this program is shown in Table 1.

TABLE 1
TEAM ONE SCHEDULE

TASK	PARTICIPANT	FY-79	FY-80	FY-81	FY-82
PROJECT MANAGEMENT	GA				
PHASE I: NbTi ALLOY COMPONENT AND PROCESS OPTIMIZATION	U OF W + MCA				
PHASE II: ETF TF-COIL CONCEPTUAL DESIGN	GA + MCA				
PHASE III: TEST COIL					
•CONDUCTOR DESIGN	MCA/GA				
•COIL DESIGN	GA				
•CONDUCTOR FAB.	MCA				
•COIL FAB., ASS'Y	GA				
•TEST AT LLNL	GA/MCA				
•ANALYSIS, REPORT	GA/MCA				
		LLNL HFTF AVAILABLE			

*Work supported by Department of Energy, Contract DE-AT03-76ET51011.

Phase I: NbTi Alloy Development

The NbTiTa alloy employed in this program was selected during Phase I, completed during FY 79. Dr. David Larbalestier, et al., of the Materials Science Center, University of Wisconsin, working under subcontract to GA, performed upper critical field (H_{c2}) tests upon a large number of candidate NbTi binary, ternary and quaternary alloys with the goal of selecting one or more possessing the best high field performance at temperatures below 4 K. Eventually a ternary alloy of NbTiTa, 32/43/25 by weight percent, was found to exhibit the most promising H_{c2} performance; specifically 13.85 tesla at 3 K. This indicated that such material would offer acceptable design current densities at 12 tesla and practical bath temperatures (1.8 – 3 K). This study was reported upon in Refs. 1 and 2.

In order to verify and optimize the selected material's J_c performance, and ensure its manufacturing practicality, MCA performed process parameter tests upon a series of composite filamentary wire samples. J_c was determined over a range of magnetic fields and temperatures, as a function of heat treatment and cold work. No unusual manufacturing difficulties were encountered, and as anticipated, cold area reduction of 10^5 or more is desirable for J_c optimization. This work was reported upon in Ref. 3.

The MCA performance data upon which the Phase II and III designs are based is shown in Fig. 1. This data is based upon an area reduction of 1.6×10^5:1 from an initial 4-inch diameter billet.

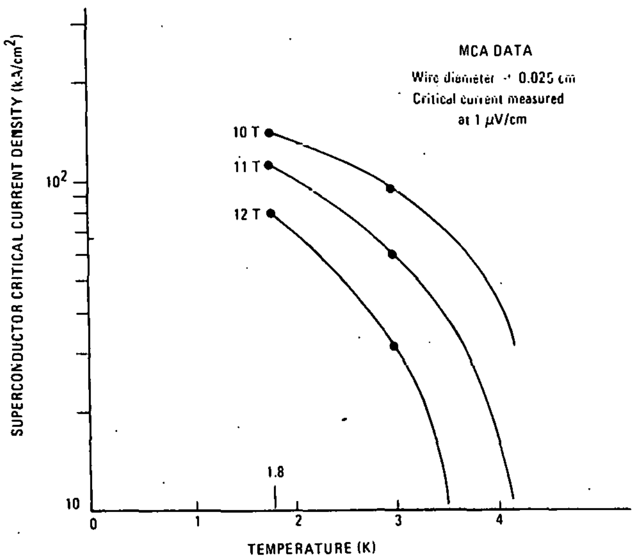

Fig. 1. Short sample performance of 32 Nb/43 Ti/25 Ta.

Phase II: ETF TF-Coil Concept

Fulfillment of Phase II is provided by the report GA-A15974, "12 Tesla ETF Toroidal Field Coil; Helium Bath Cooled NbTi Alloy Concept."[4] This study provides continuity of the entire Team One 12 tesla effort, ensuring that the prototypical conductor as developed is reactor compatible, and establishing the viability of an actual reactor TF-coil employing such conductor.

Overall Design Parameters. Although this design concept has been under development for over a year, it was adjusted in mid-1980 to reflect the ETF Design Center Interim "Design No. 1" parameters as regards number (10) and size of TF-coils.[5] Also, the peak field was reduced to 11-1/2 tesla, since it now appears that ETF will not require more than this. The 10 kA current was selected primarily upon the basis of compatibility with the conductor to be used in the Test Coil of this program; optimal current for an ETF TF-coil may be somewhat higher.

Figure 2 is an elevation view of ETF Design 1 showing one TF-coil. The number (10) and overall dimensions of the Team One coil shown match those of ETF. However, its 11-1/2 tesla peak field (at 2.87 m R) corresponds to a major axis field (B_t) of 6.1 tesla.

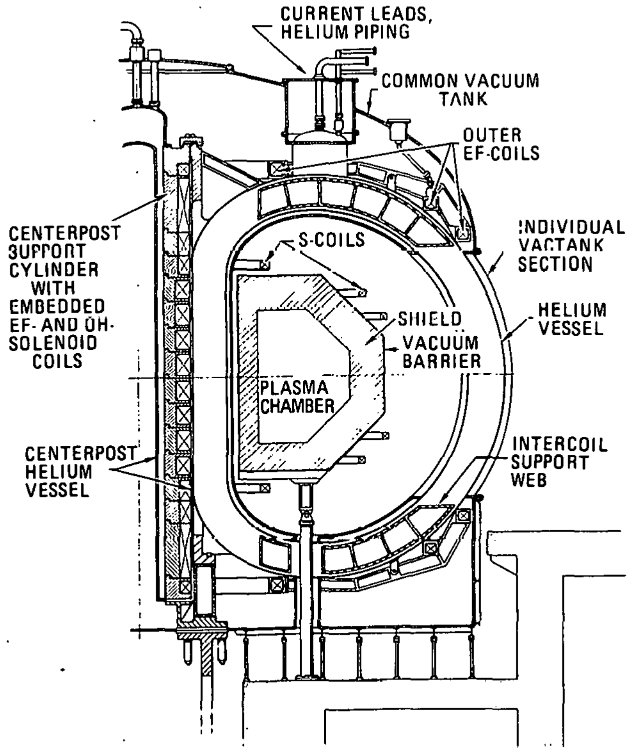

Fig. 2. TF-coil in ETF Interim Design 1.

The coil shown is 110 cm thick in the centerpost region, corresponding to its overall coil/helium vessel current density of 1000 A/cm^2. This necessitates embedding the solenoidal OH- and EF-coils within the center-post support cylinder, as shown. This concept was employed for the superconducting OH-coils of the General Atomic TNS Reactor Study, as described in Ref. 6.

In the ETF Interim Design, cold intercoil web structures connect adjacent upper (and lower) coil regions to resist the out-of-plane loads (as shown in Fig. 2). An immense vacuum tank encloses all of the TF-coils, except for the 8 m high outermost region of each, which is individually enclosed. However, GA believes that five intercoil diagonal braces (or shear panels) may be required to resist opposing torsional loads of the upper and lower regions. Although not shown in Fig. 2, such a scheme is illustrated in Fig. 13 below.

Table 2 summarizes the basic parameters of the Team One TF-coil concept.

TABLE 2
ETF 12 TESLA TOROIDAL FIELD COILS – TEAM ONE CONCEPT
BASIC PARAMETERS

NUMBER OF COILS	10
TOTAL AMPERE TURNS	165×10^6
TOTAL STORED ENERGY	40 GJ
TOTAL INDUCTANCE	800 H
PEAK FIELD	11–1/2 T
CURRENT	10 kA
TOTAL WEIGHT (10 COIL/He VESSELS)	3.42×10^6kg
COIL STRAIGHT SECTION HEIGHT	7.2 m
MEAN RADIUS OF OUTER COIL LEG	11.5 m
CONDUCTOR:	
SUPERCONDUCTOR	NbTiTa
STABILIZER	COPPER
CONFIGURATION	UNSOLDERED, 3-LEVEL RUTHERFORD CABLE
COIL COOLING	ℓHe BATH, 3 K SATURATION TEMPERATURE, SUBCOOLED TO 2.5 K
STRUCTURAL MATERIAL	AUSTENITIC STAINLESS STEEL

Conductor. The 10 kA conductor is a three-level, unsoldered, uninsulated "Rutherford cable," whose general structure is depicted in Fig. 3. The conductor consists of ten 1000 ampere cables, each of which is a six-around-one bundle of similarly configured subcables. Four conductor grades are employed, the high and low field grades being shown in Figs. 4 and 5. Grading is based upon three centerpost region parameters: amount and type of superconductor required (as a function of magnetic field), amount of copper stabilizer required (a function of magnetoresistance, radiation

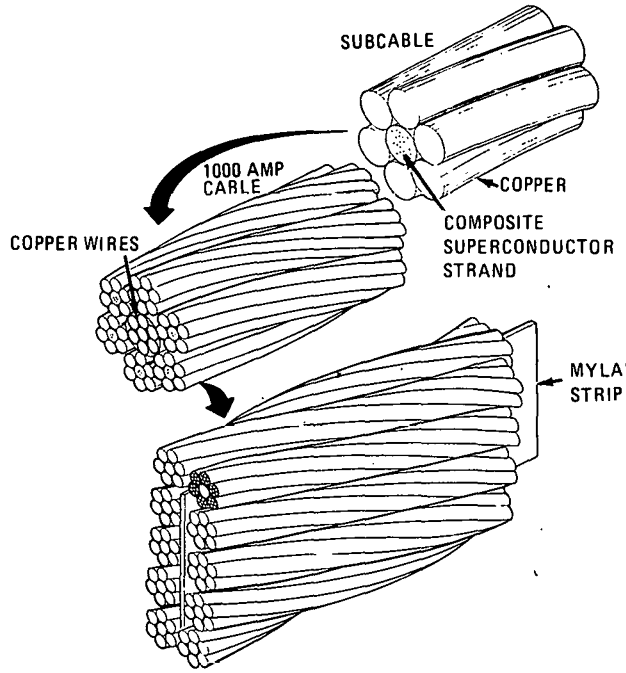

Fig. 3. Three-level cabled conductor, low field region.

degradation, cryostability and/or protection criterion limit), and required bearing load support (a function of cumulative radial bearing load).

Conductor Support. The conductor is housed within a multi-component stainless steel strip support frame. Collectively, these support elements carry almost all of the hoop, radial bearing (centerpost) and circumferential bearing (outer region) loads generated within the coil. Allowable combined stress is 80 Kpsi (316 LN, or equivalent).

Coil/Cryostat Design. Figure 6 shows cross-sections of one coil/helium vessel in both the centerpost and outer region. Each coil is independently immersed in liquid helium within its own stainless steel helium vessel. However, all 10 coil/helium vessels (plus the centerpost support cylinder, and superconducting OH- and EF-coils) share a common vacuum volume. In the centerpost region, all 10 TF-coils are surround by a common vacuum tank; in the outermost 8 m high region each coil/helium vessel is surrounded by, and supported within its own vacuum tank leg.

Figure 7 is a cross-section of half of one coil/helium vessel in the centerpost region showing the field graded regions.

Figure 8 is an isometric view illustrating the transition of the helium vessels from the centerpost to outer regions.

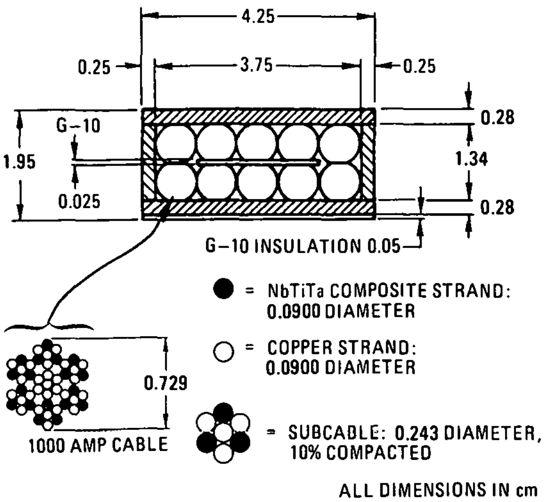

Fig. 4. 10 kA conductor/support module, high field region (10 to 11-1/2 tesla).

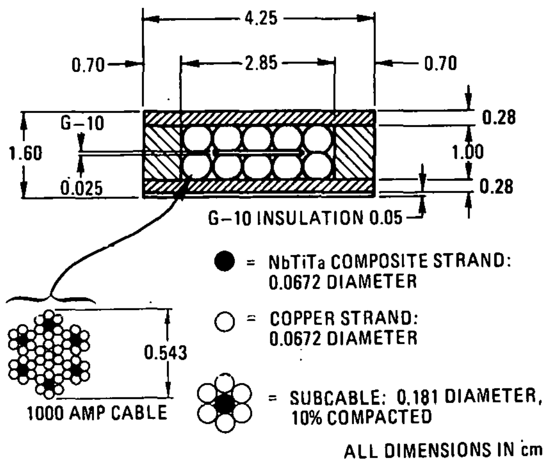

Fig. 5. 10 kA conductor/support module, low field region (0 to 5 tesla).

The coils are spiral wound, the 22 full height pancakes having 58 turns each. The pancakes are wound directly onto the weldment consisting of the minimum perimeter wall (the outer radius element shown in the centerpost section), and the central radial spine of the helium vessel. Thus, one-half of a coil is wound and its side and outer perimeter wall elements installed. The coil/helium vessel is then inverted, and the process is repeated for the other half.

Figure 9 is a detail section of the coil/helium vessel, at the inner corner of the outer coil region. Shown here are detail relationships of the cabled conductor/support modules; interturn, interlayer and ground insulation, and the helium vessel.

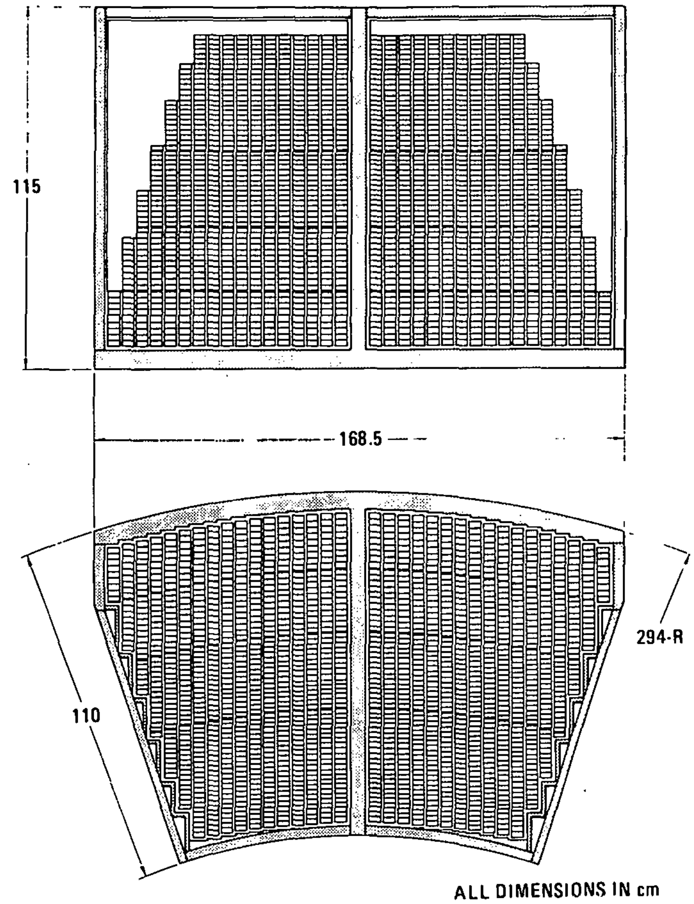

Fig. 6. Coil cross-sections in centerpost and outer regions.

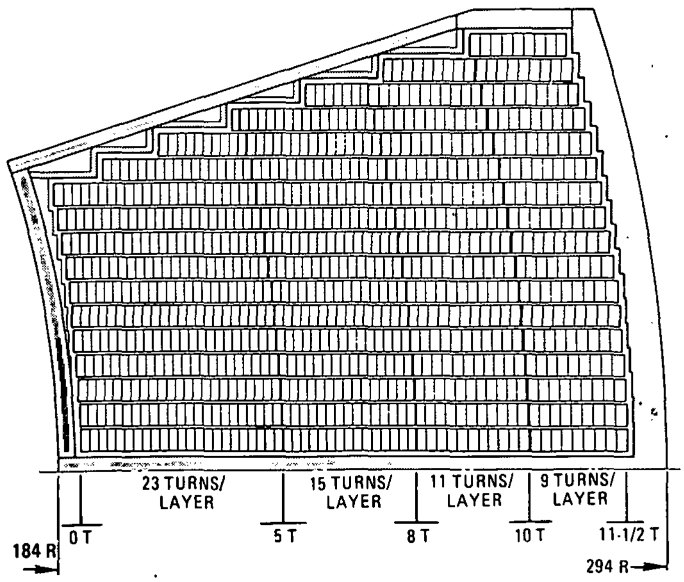

Fig. 7. Toroidal field coil/helium vessel half section in centerpost region.

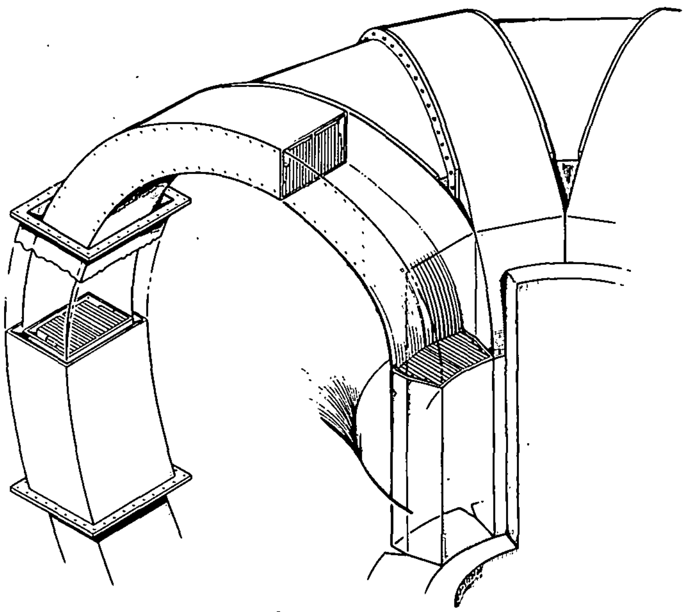

Fig. 8. Cryostat details.

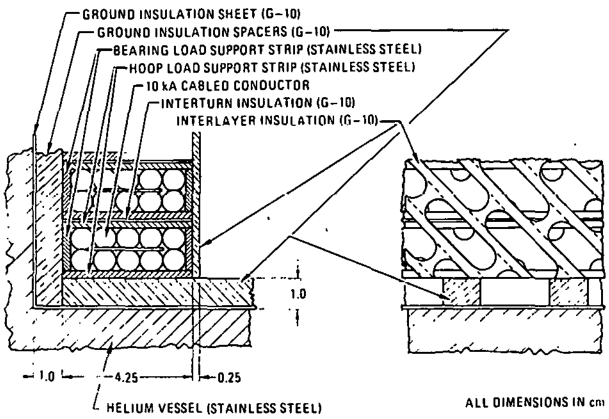

Fig. 9. Coil detail: high field conductor region.

Transverse helium migration through each conductor/support module is allowed by the twist pitch of the cabled conductor and by the cutouts (or "mouseholes") in the stainless steel side strip. Vertical helium flow is allowed by the diagonal perforation and radial groove pattern in the interlayer insulation, and by the diagonal, interrupted pattern of the coil-to-helium vessel (ground) insulation.

Table 3 shows the coil/helium vessel component fractions in the centerpost cross-section.

TABLE 3
COIL/HELIUM VESSEL COMPONENT FRACTIONS IN CENTERPOST REGION

	AREA (cm^2)	FRACTION PERCENT
CONDUCTOR, NET	3,442	20.8
SUPPORT STRIP	5,447	33.0
INSULATION	698	4.2
HELIUM VESSEL	2,635	16.0
HELIUM	4,297	26.0
	16,519	100.0

Coil Cooling Method. Bath cooling has been selected in lieu of forced flow, based upon considerations of design simplicity and operational reliability.

A bath saturation temperature of 3 K was selected, which corresponds to the current sharing temperature of NbTiTa superconductor at 4/3 times its design current density of 30 kA/cm^2 and 11-1/2 tesla. The corresponding operating bath pressure is 182 torr (0.24 atm, or 3.5 psia). During normal operation, the bath is subcooled to a nominal temperature of 2.5 K. This is achieved through a heat exchanger located in the outer leg of each TF-coil. Natural convection, driven by the subcooler and centerpost neutron heat load, should be sufficient to ensure a reasonably uniform bath temperature. This operating mode is shown on the helium phase diagram, Fig. 10.

At the subcooled temperature, the superconductor is operating at about 60% of its short sample current density. During a local thermal disturbance (a conductor motion induced normal zone), the helium adjacent to the conductor will heat beyond the saturation temperature. The resulting vapor (bubbles) will migrate out into the bulk liquid and recondense. The cooling versus heat generation characteristics of the conductor in the high field region are shown in Fig. 11.

The relatively modest neutron heat load of 5 kW to the centerpost region can easily be accommodated, without bubble evolution, by natural convection within the coil.

In the event of a plasma disruption, the total field change of 0.5 tesla will generate about 7.0 MJ of eddy current heating in the ten TF-coil helium vessels (only a small amount of heat is generated in the cabled conductor). This heat can be absorbed by the coil helium volumes without raising their temperature above the 3 K saturation point. Thus the coil will not quench, and the bath operating temperature of 2.5 K can be restored in 4 hours by the refrigeration capacity required to absorb the neutron heating.

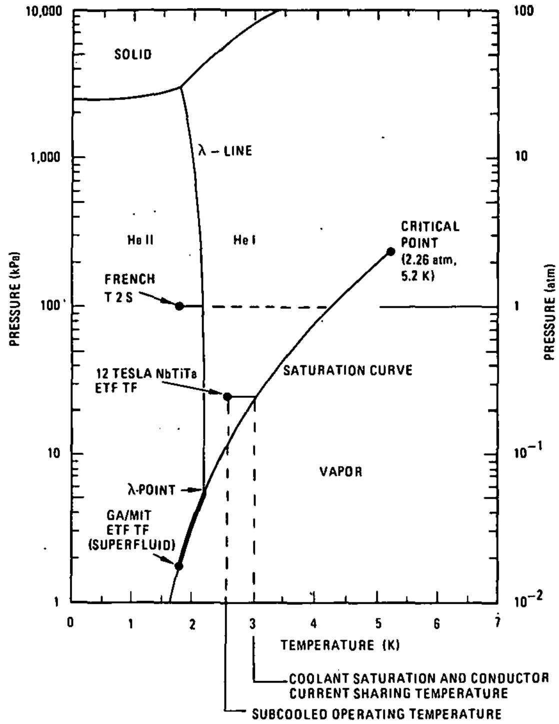

Fig. 10. Helium phase diagram.

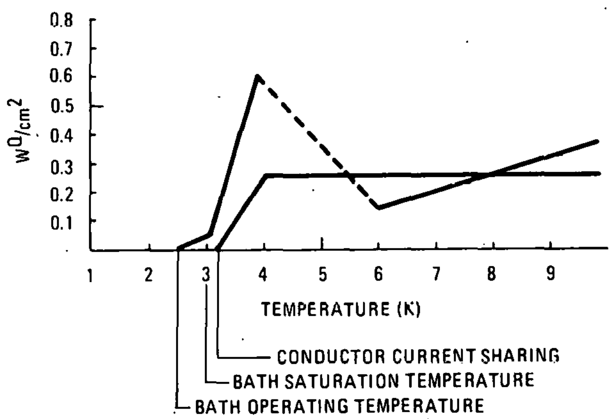

Fig. 11. Cooling versus heat generation in 12 T conductor normal zone.

Alternative Superfluid Helium Operation. A bath cooling alternative worthy of serious consideration is employment of superfluid helium. Preliminary investigation of an ETF-like TF coil, bath cooled with saturated He II at 1.8 K, was presented in Ref. 7.

The key characteristics of saturated super-fluid helium bath cooling are: high thermal conductivity (10^4 W/cm-K at 1.9 K and q = 0.5 W/cm^2); high heat transfer rate to coolant; and near zero viscosity. As a result of the high thermal conductivity, almost all of the enthalpy of the entire bath volume up to the lamda point (2.17 K) is available to absorb heat from a local source. Heat transport takes place so rapidly that it is almost impossible to sustain an appreciable temperature gradient. Hence, all vapor evolution takes place at the liquid surface.

Load Support. In the straight, centerpost region the i dl x B (Lorentz) forces on each conductor are directed radially inward towards the machine axis. This accumulated load of about 12,400 psi average at the coil inner radius must be borne by the centerpost support cylinder (Fig. 2).

In its outer, curved portion, the coil is self-supporting against hoop loads by virtue of the conductor support strip. Therefore, the coil layers do not bear against the outer helium vessel wall except in the straight centerpost region, as seen in Fig. 6 (above).

The out-of-plane (overturning) loads as a function of perimeter are shown for one coil half in Fig. 12.

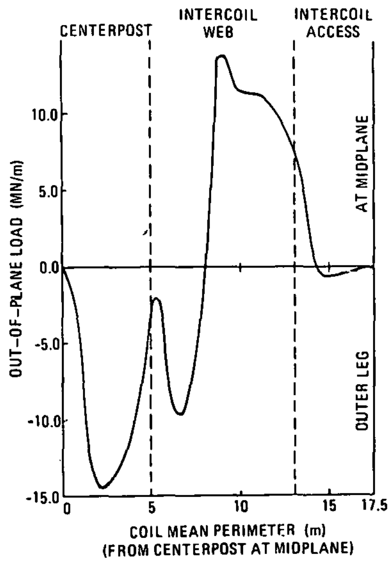

Fig. 12. Out-of-plane loads.

In the ETF Design Center Interim Design concept of July 1980, this load is borne entirely by the upper and lower intercoil web structure, and by bending in the outer coil legs. In the upper, and lower, outer coil regions, the helium vessels are supported by the intercoil web structures. These elements will indeed constrain the upper (and lower) regions of all ten TF-coils to rotate about the machine vertical axis as rigid "wheels," in response to the out-of-plane loads. However, it appears necessary to connect the upper and lower web supported regions with diagonal intercoil struts (or shear panels) in order to resist the torsional moment between them. Such a strut is shown diagrammatically in Fig. 13.

It is recognized that such intercoil struts (or shear panels) would interfere with machine access for the bundle divertor and neutral beams, and with torus sector removal. However, since the upper, and lower, TF-coil regions are rigidly interconnected by the web structures, diagonal struts need be included only in the five intercoil bays not required for beam and divertor access. Though necessarily at liquid helium temperature during operation, they must be demountable for torus sector removal.

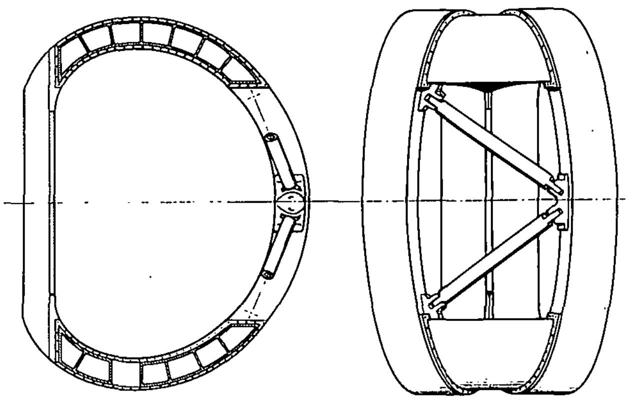

Fig. 13. Out-of-plane load bearing structure.

Quench Protection

The circuit diagram for the TF-coil power supply leads and energy dump system is shown in Fig. 14. The coils are charged in 12 hours during plant startup but function in a steady state mode during normal operation.

Since the stored energy of the fully charged TF-coil system is 40 GJ, coil damage would result in the event of a single coil quench if this energy were dissipated internally. To avoid this, the system is discharged rapidly by forcing the current to flow through resistors placed between the coils in the circuit and activated by mechanical switches. The 10 water cooled resistors and mechanical switches are located above the reactor, between the coil "chimneys."

During startup and normal operation, the power supply charges the coils with the dump resistors (R) bypassed by the closed switches (S). If a coil is detected to be quenching (by a voltage signal) the switches are opened, forcing the current to flow through the dump resistors.

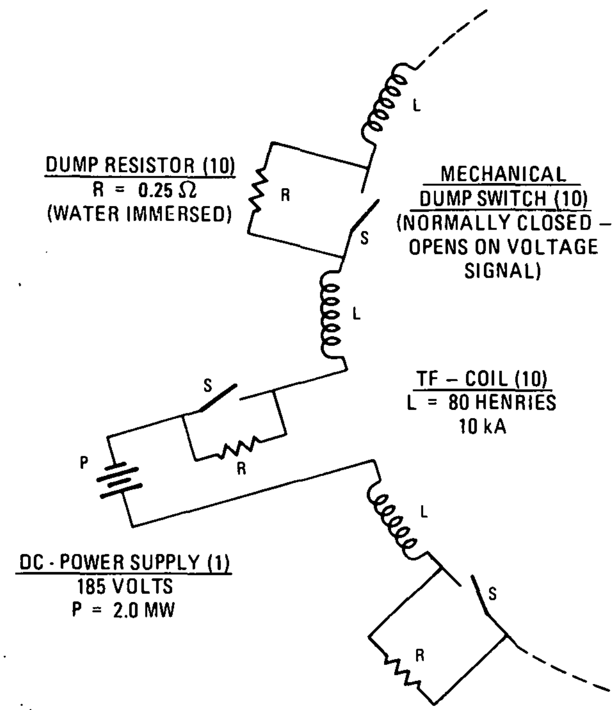

Fig. 14. TF-coil operating/protection circuit.

A magnet quench analysis for the case of a low liquid level and a normal region starting in the gas space has been performed using the GA developed code QUENCH. This computer program accurately accounts for all the important processes in the cryostat during a magnet quench. It tracks liquid level, cryostat pressure, coil temperature, normal region dissipation, energy deposited into the helium bath, current decay, etc. The results show that the magnet will not suffer damage, provided intercoil dump resistors are utilized.

The computer program is basically a two-dimensional, time-dependent thermal transient code with liquid helium cooling in the region just below the liquid level. The magnet is assumed uniformly anisotropic with simplified geometry consisting of an arc at the top and bottom and two straight sections. The thermal conductivity is assumed to be temperature independent. The heat capacities of the support structure, copper and superconducting material are integrated. Local temperature dependent resistivities and specific heats enable the calculation of ohmic heating in the winding structure as the stored energy of the field is dissipated in the equivalent LR circuit. The compressibility of liquid helium is also accounted for. The pressure relief valve is set at 3 atm absolute.

Figure 15 shows the coil parameters as a function of time for a conductor with a copper

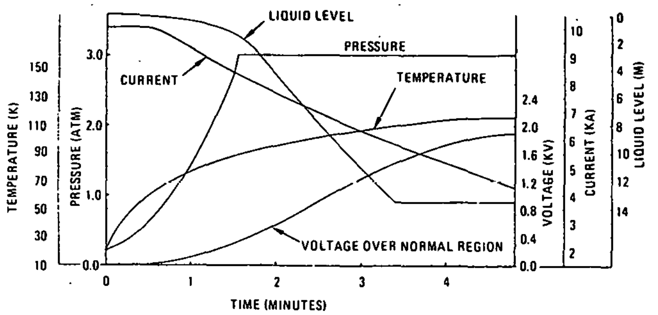

Fig. 15. Coil quench data.

current density of 6000 A/cm^2 and an average field of 5 T. It shows that peak resistive voltage over the normal region is 1.9 kV, while the peak temperature is 115 K at that time. The peak temperature rises up to 115 K in 380 seconds and would probably not exceed 130 K when the current has decayed to zero. The voltage over each 0.25 Ω dump resistor is initially 2.5 kV, being opposed by the inductive reactance of each coil, as indicated in Fig. 16. The IR drop of each turn is almost cancelled by its inductive rise. Thus, the net accumulated voltage relative to ground is controlled by the dump resistor.

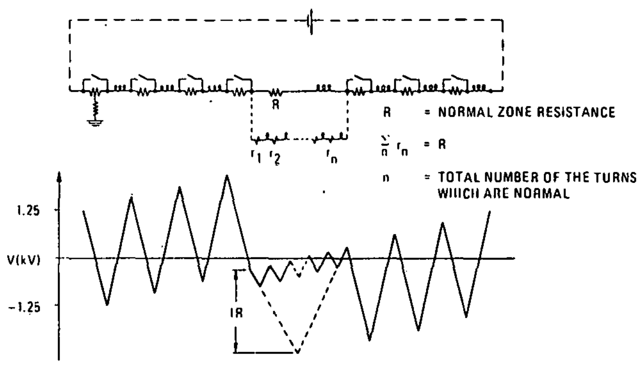

Fig. 16. Distributed quench voltages (shown for seven-coil circuit)

Phase III: 12 Tesla Test Coil

The 12 tesla coil to be tested during FY 82 at the LLNL High Field Test Facility has been designed. NbTiTa superconductor was ordered from Wah-Chang in February 1980, and received by MCA in September. Completion of the cabled conductor is now anticipated by February 1981.

Conductor. The 10 kA conductor for the test coil was jointly developed by GA and MCA. As shown in Fig. 17, it is a three level, unsoldered uninsulated "Rutherford" cable, employing the NbTiTa alloy developed during Phase I. It is similar to the conductor for

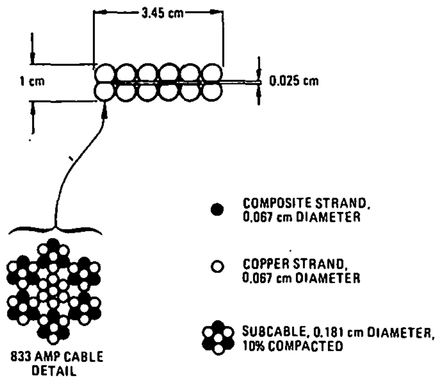

Fig. 17. Team One test coil conductor.

the 12 tesla ETF-TF-coil concept described above, except that the number of subcables has been increased from 10 to 12 (for coil space reasons), and its copper area has been reduced in proportion to its lack of neutron radiation degradation.

Test Coil. A cross section of the test coil is shown in Fig. 18. The coil is wound onto the "bobbin" weldment of the helium vessel as two double pancakes having 21 turns per layer. After closure, the helium vessel is installed within a vacuum tank. Location and support of the helium vessel is provided by a pattern of alumina/polyimid insulators, as indicated. Thus the coil can be operated at temperatures down to 1.8 K without excessive heat leak from the surrounding 4.2 K helium bath of the LLNL background field coils.

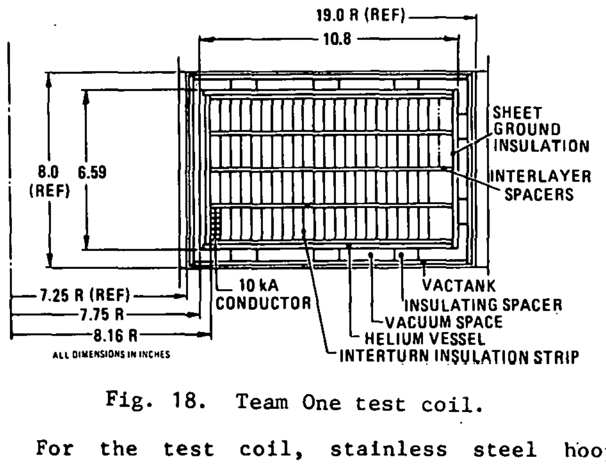

Fig. 18. Team One test coil.

For the test coil, stainless steel hoop load support is provided by banding around the outer diameter of each coil layer, rather than by distributed support as specified for the ETF TF-coil concept. However, the coolant passage geometry of an actual TF-coil application is simulated by the G-10 interturn strip, and perforated interlayer insulation.

The cryostat neck is shown in Fig. 19. In addition to the current leads, this region

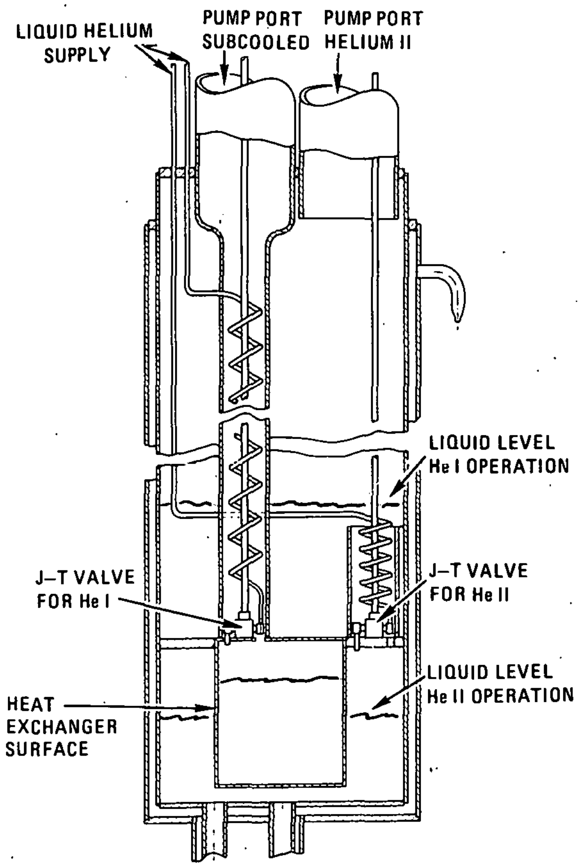

Fig. 19. Cryostat neck.

includes a J-T valve fill line, and a heat exchanger.

Coil Operation. The basic mode of operation for the test coil will be at a temperature of 2.5 K, subcooled from bath saturation conditions of 3 K and 1/4 atmosphere. Subcooling will be provided by the heat exchanger located within the coil helium vessel neck.

The coil and cryogenic system are designed to also permit operation in the saturated He II regime. This is achieved by pumping the coil down to 12.5 torr and replenishing liquid as required through the heat exchanger/J-T fill line.

The conductor is rated for 10 kA operation at 11-1/2 tesla, since that is the maximum field which it will experience in the LLNL HFTF. At the normal operating temperature of 2.5 K, the NbTiTa superconductor is at about 60 percent of its short sample performance, rising to about 90 percent at 3 K.

Phase IV: Tests Performed at the GA HFTF

A test facility has been established at GA having the capability of generating 10 tesla within the 22 cm bore of its nested solenoid pair. Both background field coils employ NbTi; the 40 cm bore 8 tesla coil, built by MCA, is intrinsically stable, and without internal cooling; the insert coil was "dry" wound by GA using "barber pole" wrapped cable, supported by stainless steel strip wound on its O.D. A vacuum insulated tube (coldfinger"). can be inserted within the 22 cm bore for testing samples at subatmospheric pressure, and temperatures down to 1.8 K.

With this apparatus, heat pulse/recovery data is being obtained on various cable samples, which will augment, and greatly assist interpretation of the FY 82 LLNL HFTF results. Also, a series of saturated superfluid helium tests are being performed to better understand the parameters of this bath cooling option.

Figure 20 is a semi-schematic cross section of the background field coil/cryostat, showing also the coldfinger bore insert.

Recently, a series of heat pulse/recovery tests have been performed on cabled conductor samples installed within the "coldfinger" insert of this apparatus. Data was obtained for sample environments of 8-10 tesla, and temperatures between 1.8 and 3 K. Results of these tests are reported in Refs. 8 and 9.

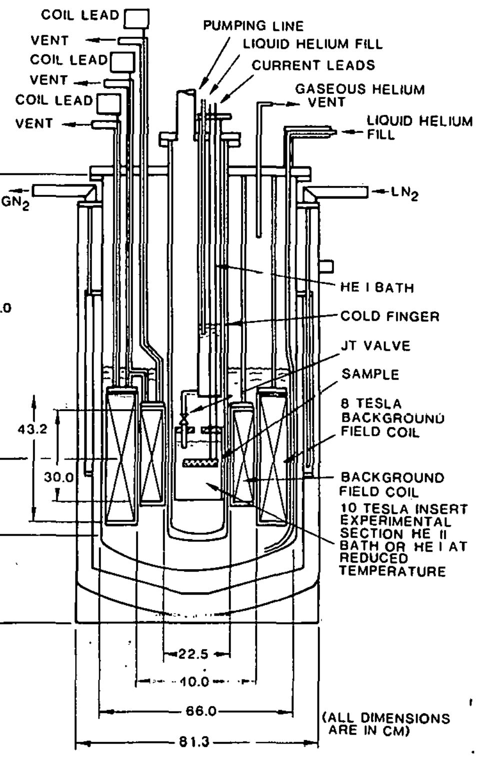

Fig. 20. GA high field test facility coil/cryostat.

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