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

PROGRESS REPORT FOR THE TWO QUARTERS ENDING MARCH 31, 1981

by
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INTRODUCTION

This report covers progress by Team One of the DOE/OFE/D&T 12 Tesla Coil Development Program during the first and second quarters of fiscal 1981. General Atomic Company is the Team One leader, with Magnetic Corporation of America (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 toroidal field of 12 tesla in a tokamak reactor.

SUMMARY

On January 27 1981 a review was held at DOE Headquarters (Germantown, Maryland) of the Team One 12 Tesla effort. Don Beard (DOE) and Don Cornish (LLNL) reviewed presentations by John Alcorn (GA) and Harvey Segal (MCA).

At that time, Segal reported upon preliminary performance results of production NbTiTa/Cu to be used in the 12 Tesla Test Coil. Some reduction in short sample critical current was noted, relative to that from 4 in. billet wire, attributed to high Fe content.

Subsequent tests by MCA on 10 in. billet material indicate that the NbTiTa filaments are necking down and even fracturing as the requisite 22 mil diameter is approached. This is evidently due primarily to material inhomogeneities (small Ta and Ti rich inclusions) as well as high iron content.

As a result of the above difficulties, a tentative decision has been made to reconfigure the conductor to a two (vice three) level cable, employing 44 mil, instead of 22 mil composite strands. This represents a compromise between performance enhancement due to area reduction, and degradation due to uneven filament size. At superfluid helium conditions (1.8 K) this conductor is expected to operate satisfactorily at 11-1/2 tesla, as opposed to 12 tesla for the previous configuration. Both are based upon a NbTiTa current density of 50 kA/cm^2; hence the amount of superconductor required is identical. No overall program cost increment is anticipated for this change, and the coil is still scheduled for completion by the end of FY-81.

Meanwhile details of the cryostat neck region have been finalized, and cryostat fabrication is in progress.

THE FY'81 PROGRAM

During FY'81 the Team One (GA/MCA) effort of the 12 Tesla Coil Program consists of the following tasks.

TASK 1: COMPLETE FABRICATION OF TEST COIL CONDUCTOR

This work, performed under subcontract by Magnetic Corporation of America, includes billet extrusion and drawing into wire of the NbTiTa/Cu material, and cabling of the final conductor by New England Electric Wire Co; 275 m of conductor is required, now rated for 10 kA at 11-1/2 tesla and 1.8 K.

TASK 2: FABRICATE TEST COIL ASSEMBLY

The Test Coil Assembly includes the coil itself, helium vessel, vacuum chamber, cryostat neck, current leads and instrumentation, in accordance with GA Drawing MAG–191. The coil will be wound at GA using conductor from Task 1. It will be operated at temperatures from 1.8 K to 3 K; hence the vacuum isolation and cryogenic features (heat exchanger, valves, etc.) in the neck region.

TASK 3: TESTS AT GENERAL ATOMIC

We will perform heat pulse/recovery tests upon prototypical conductor in the He I and He II regimes, using the GA 10 tesla facility. This information will augment, and greatly assist interpretation of the results later obtained with the test coil at LLNL.

The neck region of the test coil cryostat will be pretested within the GA test facility to insure proper functioning of the heat exchanger and valving required for He II and 3 K He I operation.

TASK 4: COMPARATIVE STUDY OF BATH COOLING OPTIONS

Magnetic Corporation of America will perform a parametric and cost tradeoff study of the three bath cooling options now under consideration for a 12 tesla NbTi alloy toroidal field coil:

- He II: 1.8 K, saturated at 12.5 torr
- He II: 1.8 K, subcooled at 1 atm.
- He I: 3 K saturation temperature at 0.24 atm, subcooled to 2.5 K.

TASK 5: INVESTIGATE CERTAIN CRITICAL AREAS OF TF–COIL DESIGN

Recent effort on the ETF/FED, STARFIRE and INTOR reactor studies, and review of the 12 tesla program, has revealed that certain aspects of the Team One TF-Coil concept (Ref. GA-A15974 of July 1980) require further study in order to properly assess its generic viability. Among these are the following:

- Simultaneous support of the hoop, clenching, and PF-coil induced out-of-plane loads by the coil/helium vessel structure.

- Eddy current heat loads induced in the TF-coil/helium vessel by the external PF-coils, and by a plasma disruption.

- Prediction of TF-coil dynamic response to a quench. GA has prepared such an analysis, and applied it to the Team One TF-coil, acting in conjunction with a proposed coil protection circuit. This analysis should be fully presented in a report, for evaluation and use by the fusion magnet community.

- Analysis of the heat propagation from a source within a cabled conductor immersed in a saturated superfluid helium bath.

TASK 6: TEST COIL TESTING PLAN

A plan is required for setup and testing of the Team One Test Coil at LLNL during FY'82. This plan should include:

- A detailed listing of the tests to be performed.

- Listing of GA and LLNL supplied equipment required, including cryogenics, power supplies, instrumentation and data acquisition.

- Test schedule

- Cost estimate.

TASK 7: INTOR MAGNET SYSTEMS

GA is coordinating the magnet systems effort for the U.S.A. portion of the INTOR 1981 design study. This includes preparation of the magnetics sections of the U.S.A. presentation for the Session VI Workshop at Vienna, and participation in that workshop.

Also, GA is providing the conceptual design for an INTOR TF-coil concept employing cabled NbTiTa conductor, immersed in a saturated superfluid helium bath. This is one of three alternatives presented, the others employing 4 K bath cooled Nb_3Sn, and forced flow Nb_3Sn.

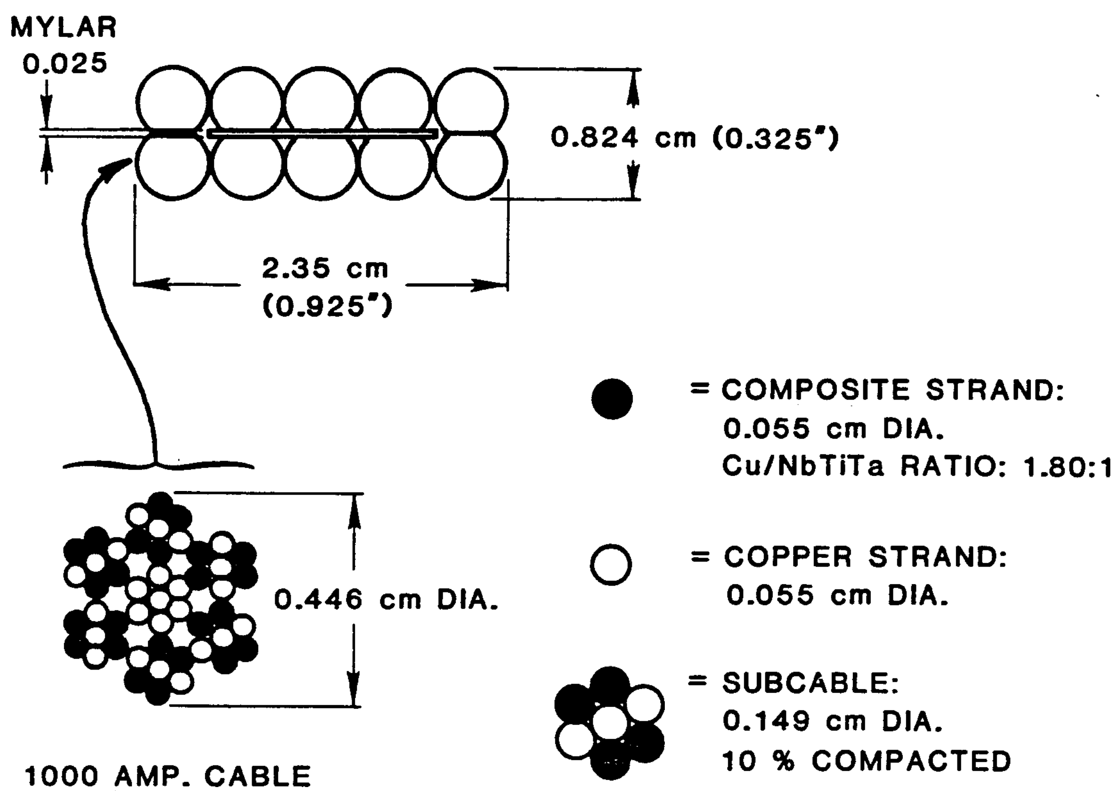
PROGRAM STATUS

STATUS OF TASK 1: TEST COIL CONDUCTOR

Last year (FY'80) MCA fabricated a 4 in. diameter billet (No. 675) using NbTiTa alloy (32/43/25 wt%) obtained in a special melt from Wah-Chang. Wire samples were drawn from that billet without difficulty. A characteristic superconductor critical current density of 75 kA/cm^2 at 12 tesla and 1.8 K was obtained from their sample No. 806 (10 mil wire, equivalent to 23 mil wire from a 10 in. diameter billet).

During the first quarter of FY'81, the 12 tesla test coil design was reconfigured for primary operation in the saturated superfluid helium mode. The three-level cabled conductor design (Fig. 1) was adjusted for 10 kA operating current at 12 tesla and 1.8 K. Its superconductor operating current density of 50 kA/cm^2 was based upon the performance of sample No. 806 from the 4 in. billet; 275 m of this conductor was required by GA for winding the coil, whose cross-section is illustrated in Fig. 2.

CONFIGURATION:



CONDUCTOR PERFORMANCE:

OPERATING CURRENT: 10 KA
OPERATING BATH TEMPERATURE: 1.8 K
SUPERCONDUCTOR CURRENT DENSITY: 50 KA/cm^2
(0.83 x CRITICAL CURRENT DENSITY @ 12 TESLA 2.17 K)

Fig. 1. Test coil conductor, initial superfluid design.

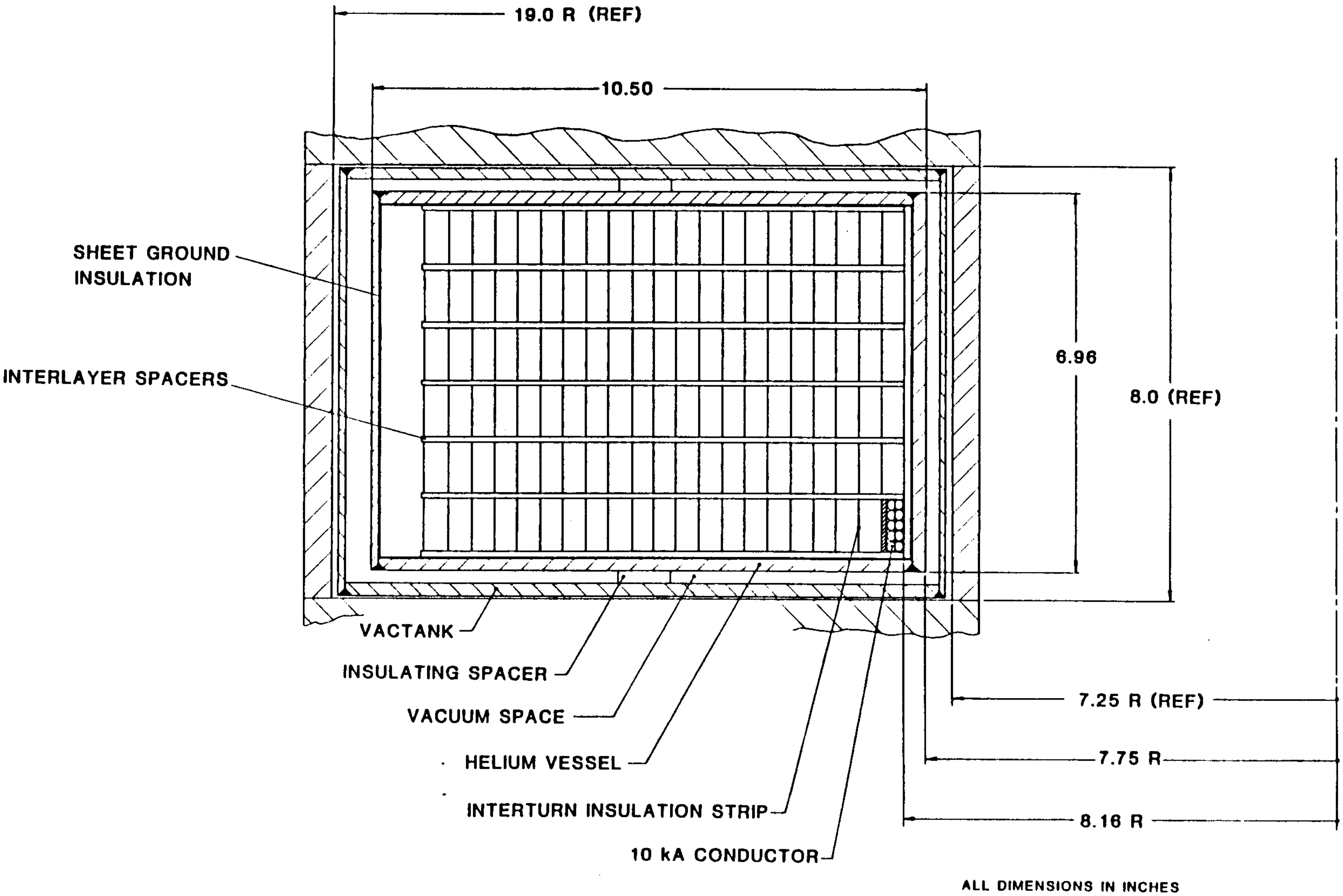


Fig. 2. Team One Test Coil -- cross-section.

Some 150 pounds of NbTiTa rod stock was received by MCA from Teledyne Wah-Chang in October 1980, from which they processed a 10 inch diameter billet (their No. 858).

At the January 1981 review meeting, Segal of MCA presented test results taken from samples of this billet, which indicated significant performance degradation. Based upon results at 4.2 K and 9 T, the predicted critical current density at 12 tesla and 1.8 K was 57 kA/cm^2, down 24% from the 4 in. billet samples. At the time, this degradation was attributed to the fact that chemical analysis of the NbTiTa for the 10 in. billet has revealed an iron content of up to 335 ppm, versus 125 ppm specified maximum.

For subsequent developments, I quote from MCA's 12 tesla progress report for February 1981:

> "At the end of January HIconductor was authorized to proceed with the production of 275,000 feet of 0.0216 inch diameter wire from billet 858. When the wire was drawn to 0.073 inch wire, it started to become very brittle and could not be processed in the Herborn. Production was halted and samples of that billet (at both preheat treatment size and at 0.073 inch) were sent to Pacific Magnetic Structures for analysis. In addition, samples of the 4" diameter billet were also sent to them for comparison. The conclusions of their analysis were that there are large differences between the NbTiTa alloy used in the two billets. The material used in billet 858 contained tantalum inclusions. The copper to NbTiTa interface contained stringers that protrude into the copper in billet 858, but billet 675 had smoother interfaces typical of NbTi to copper boundaries. Finally, they observed that α-titanium was more uniformly distributed in billet 675 than in billet 858.
>
> During the manufacture of the NbTiTa, Wah Chang did inform MCA that there were tantalum inclusions in the billet. At that time we instructed Wah Chang to proceed with the production of that material since (1) it would have delayed the program 7 to 8 months if a new batch of NbTiTa were processed, and (2) it was assumed that Ta inclusions would not be detrimental to the processing or performance of the conductor as long as all the Ti was in solution. It now appears that the tantalum inclusions are also accompanied by a non-uniform distribution of titanium. This has produced a brittle material with non-uniform filaments.
>
> In order to determine whether the material of billet 858 can be processed to 0.0216", two additional samples were made. These samples were drawn using single die passes rather than using a multiple die machine. The only difference between those two samples was in the die schedule. The sample drawn with the smaller reduction was processed in a single length to final size whereas the other sample could not be processed and broke into many small pieces.
>
> HIconductor was then instructed to process the shortest length of material from billet 858 (approximately 8,800 ft. @ .073") using single die passes. After the sixth die pass, the conductor began to break up into short lengths (less than 100 ft.). One of those short lengths was given a brief heat treatment to anneal the copper. However, that length also began to break after two additional die passes.
>
> It now appears that the wire should not be drawn to a diameter less than 0.0440 inch. In order to determine the effect of twisting on the wire, a 100 ft. length sample was given 1 TPI in the twister at .0479" and was then drawn to .0440". The wire did not break. A short sample test was performed on that sample at MCA. At 7 T and 4.2 K,

the conductor had a critical current density of 8.5×10^4 A/cm^2 compared to 7.9×10^4 A/cm^2 for .0216" wire. This unexpectedly higher current density at the larger wire diameter most likely is due to fewer broken filaments at .0440" than at .0216". It can only be hoped that the remainder of the conductor can be processed with a minimum number of breaks. In order for this conductor to be acceptable, it is necessary for General Atomic to approve a modified cable design. The 10,000 A conductor should consist of a 2 level cable using 0.0440" diameter strands...."

Photomicrographs of an etched 22 mil diameter sample from billet No. 858, taken by Pacific Magnetic Structures, are shown in Fig. 3. They reveal the variations in filament size and surface roughness.

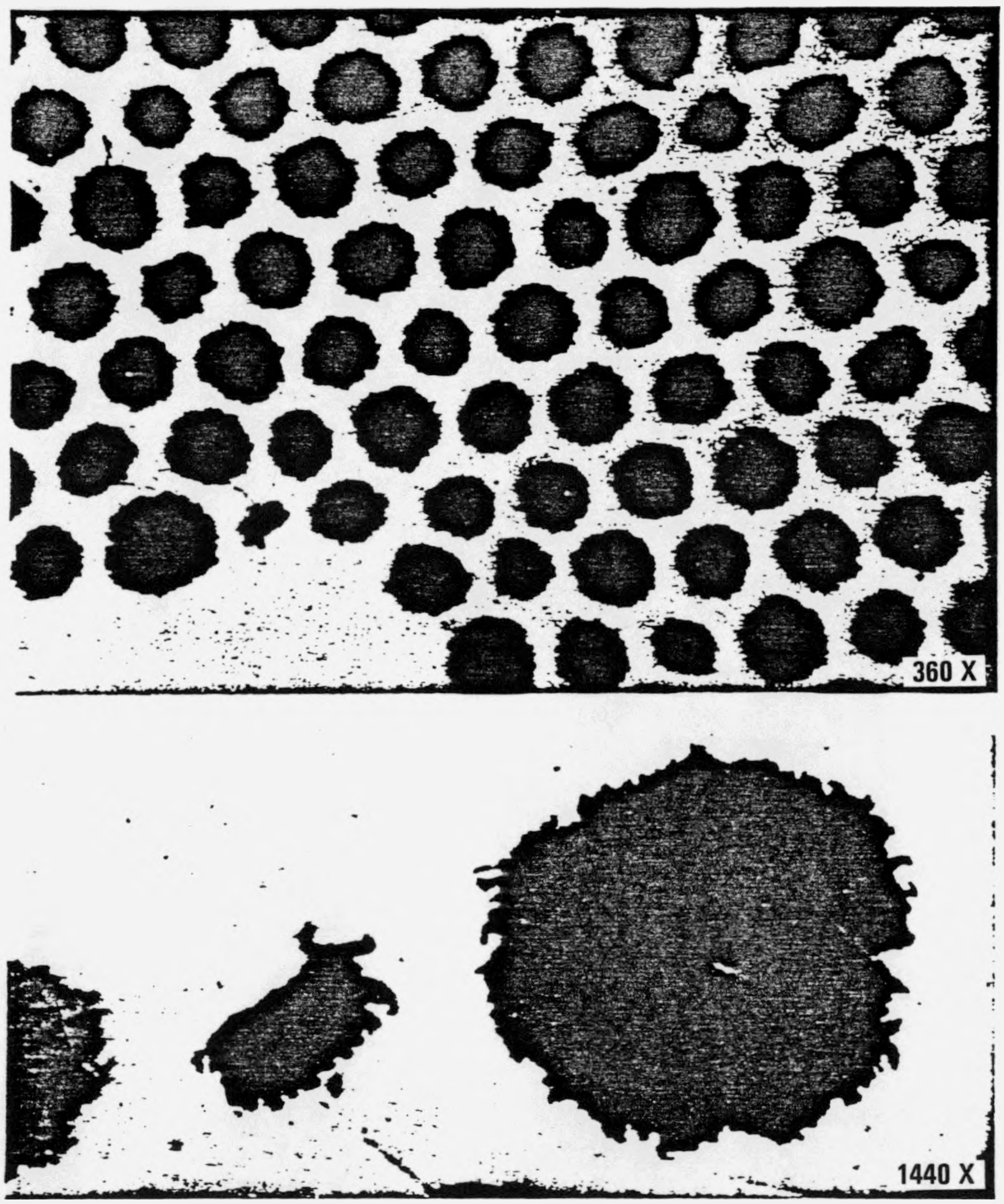


Fig. 3. Photomicrographs of 22 mil diameter sample from billet 858.

Following considerable discussion between GA and MCA (and with Don Beard of DOE) it was agreed that MCA should proceed on a revised, two level conductor design using 44 mil composite wires. We have evolved the design shown in Fig. 4. The overall conductor cross-section of 2.40 x 0.82 cm closely matches that of the previous design, so that the coil design remains unchanged. Also, the amount of NbTiTa superconductor required is almost identical. However, the conductor is now rated for 10 kA at 1.8 K and 11-1/2 tesla, with a somewhat reduced critical current margin. Therefore, nominally the coil will perform as before in a superfluid helium bath, but at 1/2 tesla less peak field. Since some uncertainties yet remain as to actual conductor performance, current and background field can be adjusted as necessary during the test.

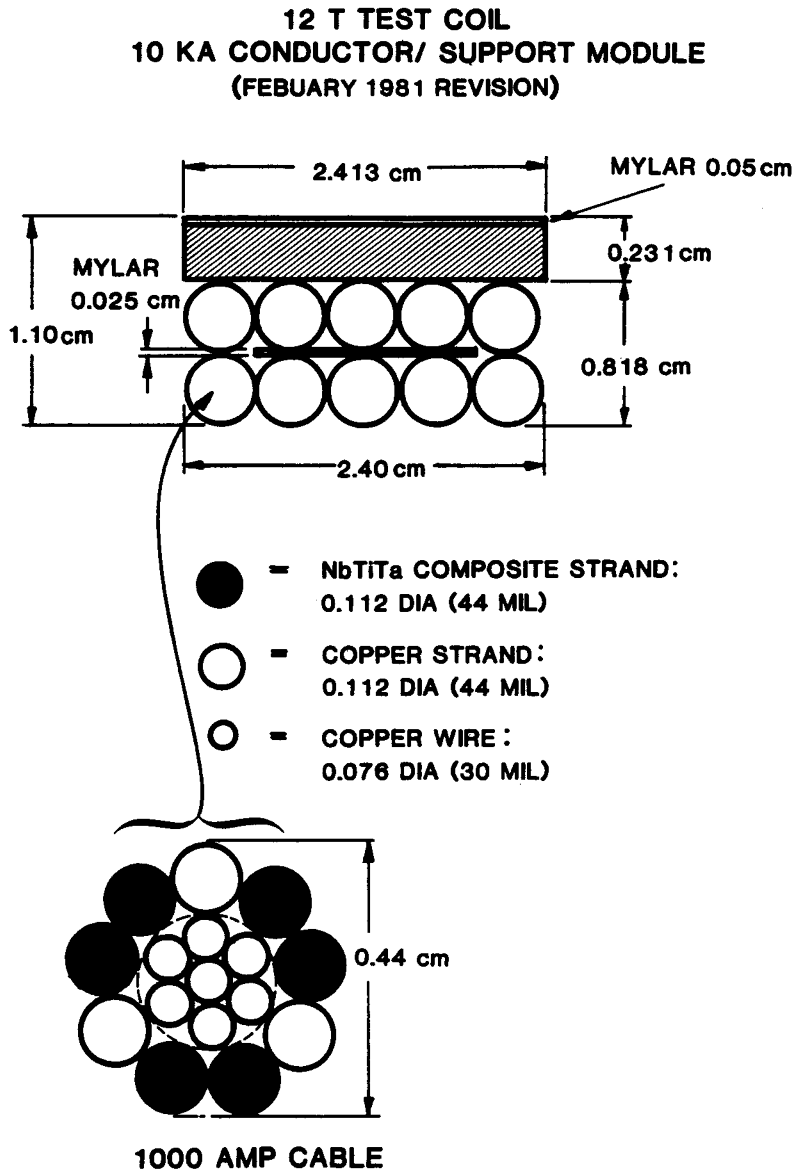


Fig. 4. Conductor/support strip module, revised design.

As of this writing (3/23/81), MCA has completed processing of one batch of 44 mil wire, representing about 1/4 of the total requirement. Although considerable breakage has occurred, the wire will be physically acceptable for cabling, following cold welding. High field critical current tests will be performed by MCA (at MIT) on six or more samples from this batch. If performance is as anticipated (that is, around 55 kA/cm^2 at 12 tesla and 1.8 K, or equivalent), then the remainder of the wire will be processed to 44 mils.

It is now (3/23/81) anticipated that conductor fabrication, including cabling, can be completed by mid–May.

STATUS OF TASK 2: FABRICATION OF TEST COIL ASSEMBLY

The test coil cryostat vessels have now been fabricated. The cryostat neck design has now been completed, and construction will soon commence.

The coil fabrication schedule is paced by delivery of the revised 10 kA cabled conductor, now expected by the end of May 1981. If this occurs, coil/cryostat fabrication can be completed by the end of FY'81.

It is still necessary for certain Test Coil to Test Facility interface details to be resolved with LLNL. To this end, John Purcell and Yen-Hwa Hsu will visit LLNL soon for discussions with Don Cornish.

STATUS OF TASK 3: TESTS AT GENERAL ATOMIC

No tests in support of this effort have been performed at the GA High Field Test Facility since last year.

New England Electric Wire Co. is now (3/23/81) preparing a 50 foot length of two level cable, rated for 1 kA at 10 tesla and 1.8 K. The first level (sub) cable consists of four 22 mil composite wires (1.8:1 Cu/SC ratio) plus two 22 mil copper wires around one 22 mil copper core. The second level cable consists of six such subcables around one all copper subcable.

Five (or more) turns of this cable will be wrapped upon a mandrel to form a coil for testing within the 20 cm diameter "coldfinger" insert of the GA test apparatus. The coil will be superfluid helium bath cooled, and covered on its outer and side regions to simulate flow conditions within a toroidal field coil configuration. A constantan heater wire will be embedded in a portion of the cable as a heat source.

STATUS OF TASK 4: STUDY OF BATH COOLING OPTIONS

MCA is presently gathering background information for this study.

STATUS OF TASK 5: CRITICAL AREAS OF TF–COIL DESIGN

At the January program review, Don Cornish expressed concern over two aspects of our TF-coil conceptual design, urging us to investigate each in detail.

Coil/Case Integrity

His first area of concern was whether the coil winding pack, especially in the outer region, can simultaneously bear the hoop, clenching and out-of-plane loads without suffering excessive relative motion (distortion). In response, Lew Creedon of our staff has performed a preliminary, but detailed analysis of the conductor support/case response to the imposed outer region loads. This study has indeed revealed the need for three significant design modifications, to wit:

- In the outer coil regions, the self-generated "clenching" forces result in a 5000 psi (max) pressure exerted by each coil half against the central radial web of the helium vessel. Since the self-supporting (in hoop load) coil grows significantly relative to the helium vessel, and since no practical means has been postulated for assuring coil/web interface sliding under such clenching pressure, it was necessary to redesign the central radial web as a series of "floating" plates in the outer region. This feature is depicted in Fig. 5. Incidentally, despite this complication, the central web offers significant advantages in terms of coil fabrication and dimensional stability.

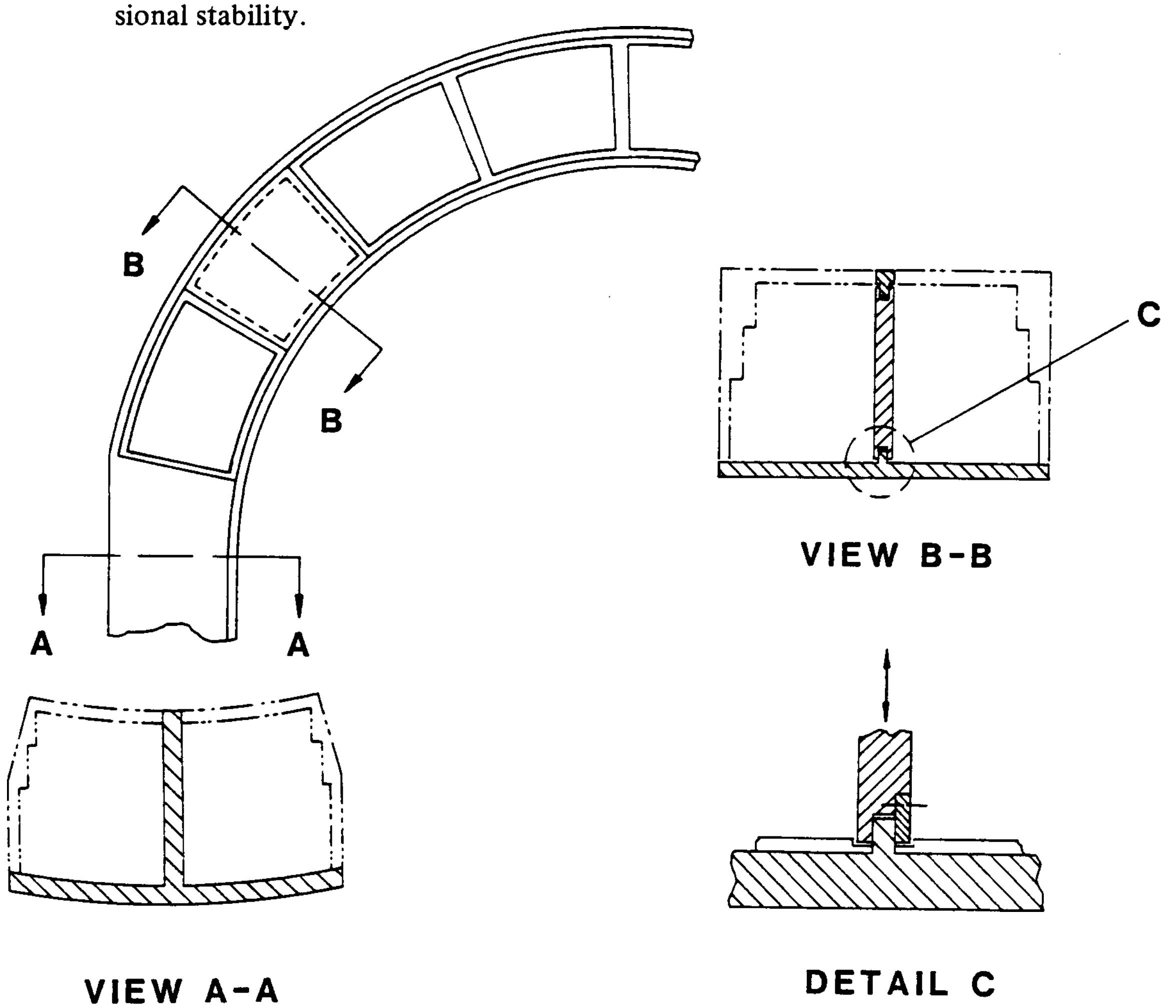


Fig. 5. TF-Coils floating central flange concept.

- When the TF-coil system is energized, the coil expands radially in the outer, curved regions, carrying the central web plates with it. Subsequently, when the external EF-ring coils are energized, the resultant out-of-plane loads will cause the TF-coil pack to bear against one helium vessel sidewall. For this reason the outer, full height coil portion must be supported by "shelves" projecting inward from the helium vessel sidewalls, as shown in Fig. 6. Incidentally, the coil helium vessel does not carry the longitudinal out-of-plane running loads in bending; these are borne by an intercoil support structure such as presently envisioned for INTOR. Thus the helium vessel walls can be of modest (~ 5 cm) thickness.

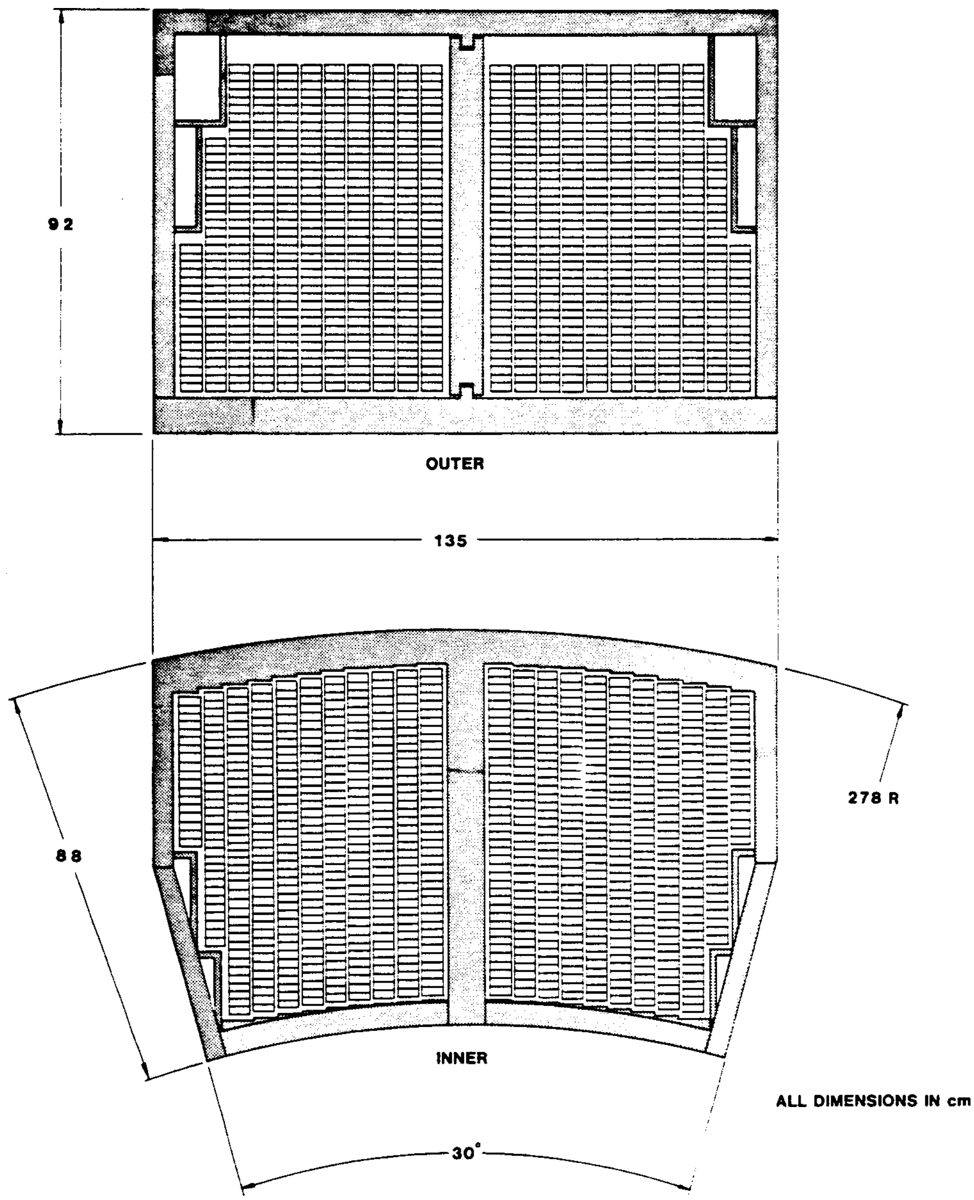


Fig. 6. TF-Coil sections.

- The GA TF-coil concept has previously featured a frame type conductor support, consisting of four co-wound stainless steel strips; "over" and "under" strips for hoop and circumferential bearing load support, and flanking strips for centerpost radial bearing load support. Detail analysis has revealed that this configuration may be unstable against the large accumulated circumferential (clenching and out-of-plane) loads in the outer coil regions. In order to insure such stability, the conductor is now encased within two opposing channel strips, as shown in Fig. 7. The channel flanges provide the requisite restraint against tipping under the circumferential loads. The channel web thickness is sized primarily for hoop load support at 60 kspi; it also possesses adequate transverse column strength, aided by its longitudinal curvature and radial compression from adjacent turns.

  A copy of the preliminary analysis for this condition is being sent to Don Cornish of LLNL for review.

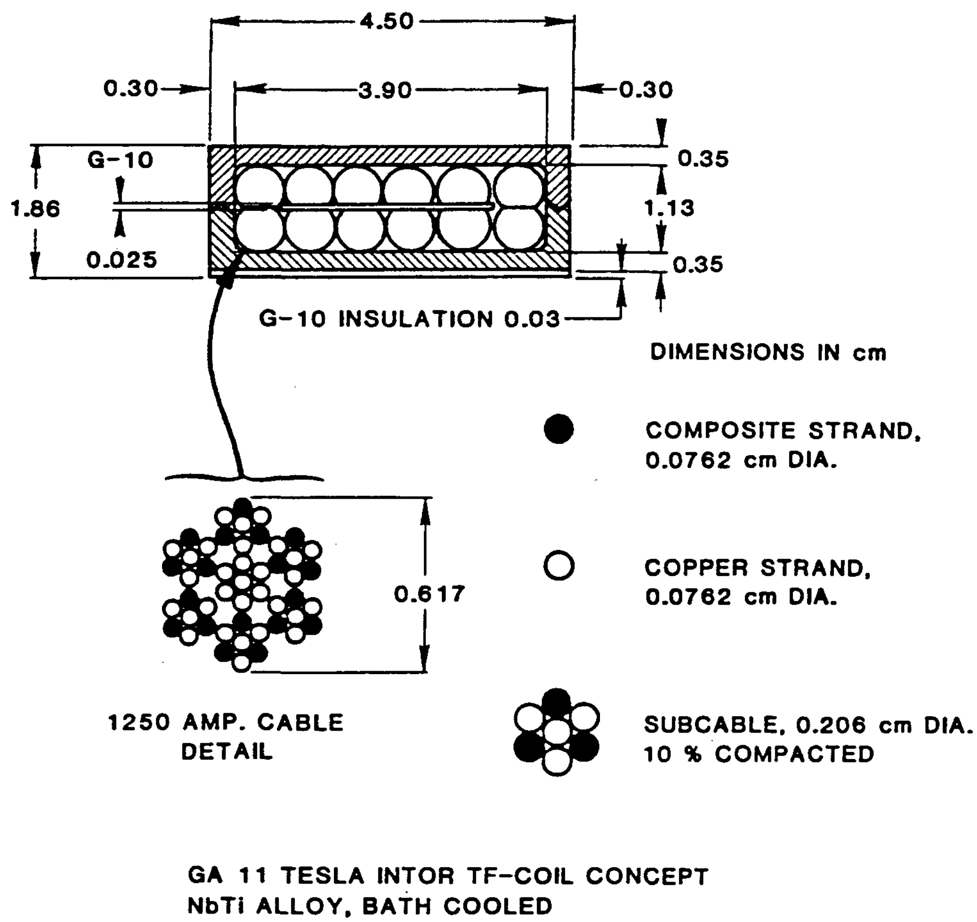


Fig. 7. Conductor/support strip module, high field region.

Eddy Current Heat Loads in Coil Case

Further analysis of this important consideration is now underway by Wilkie Chen, partly in support of our INTOR effort (Task 7).

Prediction of TF-Coil Dynamic Response to a Quench

This analysis will be written up, and published as a GA–A by Yen-Hwa Hsu. Some additional work must yet be done to adequately predict a quench from saturated superfluid bath conditions.

Heat Propagation From a Superfluid Helium Bath Cooled Cable Type Conductor

Acting upon Don Cornish's suggestion, Yen-Hwa Hsu has given a closer analytical look at such a condition within our TF-coil winding concept. This work is discussed in a technical memorandum dated February 17, 1981, a copy of which is being forwarded to Don Cornish for review.

Her analysis addressed the three aspects of this question, assuming static (non-connective) conditions, and that all the liquid remains He II; heat transfer to the liquid from the conductor; He II heat transfer through the interstrand and intercable channels; He II heat transfer throughout the bath volume from interlayer channels. In a cabled design, the wetted surface is extensive, so solid-liquid heat transfer rate is not high. The thermal conductivity of He II is very high, some 10^3 times that of high purity copper. Nevertheless the interstrand channels are quite small, as is the source to sink temperature gradient – assuming that the lambda point (2.17 K) is not exceeded. As a result, such an analysis, based entirely upon thermal conductivity, indicates that the joule heating within the normal region of a conductor is considerably greater than the heat transport capacity of the conductor channels.

In fact however, the coolant very close to the heated conductor may be well above the lambda point – that is, He I. Nucleate or film boiling will probably occur at the solid/liquid interface, resulting in convective as well as conductive heat transport. In this case we picture the gas being rather violently expelled from the source zone, and recondensed in the He II bath within a short distance. Concurrently, He II with near zero viscosity flows towards the heat source, replenishing the expelled coolant.

This dynamic He I/He II behavior is difficult to analyze. However, heat pulse/recovery tests in superfluid helium at GA and elsewhere indicate that the heat transfer, even from cable, is considerably greater than for He I. It is our intent to quantify this behavior in our Task 3 tests at General Atomic, and during the FY'82 tests at LLNL.

STATUS OF TASK 6: TEST COIL TESTING PLAN

This work has been initiated at General Atomic.

STATUS OF TASK 7: INTOR MAGNET SYSTEMS

At the behest of Bill Stacey (Georgia Tech) and with DOE approval, GA is coordinating the magnet systems effort for the U.S.A. portion of the INTOR '81 design study.

John Alcorn and others at GA worked with the Design Center INTOR participants (Tom Shannon, Tom Brown, et al.) to prepare the Magnetics portion of the U.S.A. document for the INTOR Session VI Workshop. Alcorn will participate in Session VI at Vienna (March 30 – April 10).

During the course of this effort, a number of basic magnetics design issues were addressed, which are common to both INTOR and FED. Most of them are the result of external location of the main equilibrium field (EF) coils. Among the key issues under review are the following:

- Support of the TF-coils against the immense out-of-plane loads generated by interaction with the poloidal field.

- Accommodation of the large eddy current heat loads generated within the TF-coil helium vessels and support structure by the poloidal coils and during a plasma disruption. (External PF-coils dictate the use of cabled conductor for the TF-coils in order to avoid excessive eddy current heating within the coils themselves.)

- Design of the immense outer EF-ring coils, which are necessarily superconducting to avoid excessive power consumption. This is an aspect of tokamak reactor magnet design which has received scant attention to date from the fusion community, despite the fact that the ETF, INTOR, STARFIRE and FED design studies all employ external PF-coils. For INTOR the situation is exacerbated by the requirement for a poloidal divertor, with a consequent separatrix and 60 cm vertical displacement of the plasma axis, relative to the machine midplane. As a result, the lower, outer EF-ring coil must carry 26 megamp-turns, at a 10 meter radius, and 7-1/2 tesla peak field. This is a coil of heroic proportions and large self-generated loads. We have evolved a tentative design concept for such a coil, employing cabled 50 kA conductor, co-wound stainless steel support strip, and a constant tension coil shape.

As part of our contribution to INTOR '81, we have also prepared the conceptual design of a superfluid helium bath cooled, cabled NbTiTa conductor TF-coil. This is one of three TF-coil options carried in the INTOR U.S.A. design.