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# LARGE COIL TEST FACILITY*

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## Summary

Commercial tokamak power reactors will require confining fields of such large volume, field strength, and duration that superconducting magnets appear to be the only economic means of their production.

Although both small high-field coils and large low-field coils have been successfully operated, total requirements for the Fusion Engineering Device (FED) and subsequent tokamak coils are different, and in many ways, far beyond anything that has been accomplished so far. In addition, the history of superconducting magnets shows that, when large but seemingly straightforward extrapolations in size or complexity were attempted, previously negligible phenomena often interfered with successful operation until the new problems were recognized and solved.

A wide variety of design concepts have been proposed for reactor and FED coils. They employ different combinations of coolant conditions (forced and natural convection, boiling and single phase), conductor configurations (laminated, open or solder-filled cable or braid), superconductor material (NbTi or $Nb_3Sn$), methods of winding or installation or conductor, and ways of incorporating structural materials (holding individual turns separately, structure distributed through the winding or lumped on the outside, welded or bolted). Because there is presently insufficient experimental or theoretical basis for choosing the best design for reactor coils and concentrating all efforts on it, the development of a superconducting TF magnet for the FED tokamak reactor requires several different TF coils, about half the size to be used in the FED, to be built and tested to permit selection of a design and fabrication procedure for the full scale ETF, now FED, coils.[1] The Large Coil Test Facility (LCTF is the facility in which subsize (2.5 x 3.5 m) coils would be tested and system operation demonstrated to such levels of confidence that the full-size FED coils could then be designed and a prototype fabricated.

1. Accept test coils of 2-1/2 m by 3-1/2 m bore.
2. Provide design peak field in the test coil winding when the test coil current is at design value.
3. Produce a pattern of stresses and strains in the test coil similar to that in a full size coil of a tokamak.
4. Produce maximum strains in the conductor of the test coil the same as in the full-size coil.
5. Provide pulsed field in the test coil winding equal in magnitude and ramp rate and similar in orientation to those in a tokamak application.
6. Provide specific stored energy of 9 J/g in the test coil.
7. Accommodate the test coil in a vertical plane, with its longer axis vertical, which is the case for a tokamak coil.

In contrast to the test coils, there appear to be no major technical uncertainties in the design, fabrication, and operation of the test facility. The only advanced technology equipment required is the helium portion of the cryogenic system.

The facility, shown in Fig. 1, is being fabricated in an existing building in the Y-12 Plant of DOE's facilities at Oak Ridge, Tennessee. Final design is nearing completion, and 20% of the construction has been accomplished. A large vacuum chamber, houses the test test assembly which is coupled to appropriate cryogenic, electrical, instrumentation, and diagnostic systems. Adequate assembly/disassembly areas, shop space, test control center, offices, and test support laboratories are located in the same building. Assembly and installation operations are accomplished with an overhead crane. The major subsystems are the vacuum system, the test stand assembly, the cryogenic system, the experimental electric power sys-

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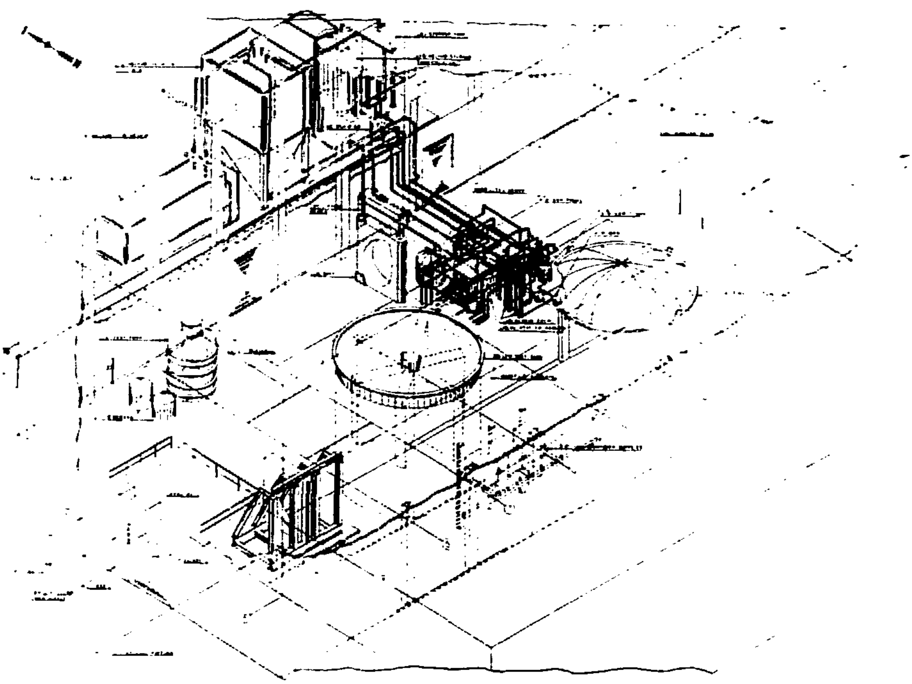

Fig. 1

Overview, ↓CTF Large Coil Test Facility

tem, the instrumentation and controls system, and the data acquisition system.

Vacuum System

A large vacuum tank, Fig. 2, is used to provide thermal isolation for the test coils. The tank is a 35-foot-diameter cylinder with flat bottom and a removable torispherically shaped head. The weight of the experimental equipment is carried through the tank bottom to the foundation which rests on bedrock. Construction is conventional, except that stainless steel is used throughout to provide low outgassing rates, tolerance for cryogenic fluid spills, and absence of significant attractive reaction to magnetic forces. Coolant, electrical, and instrumentation leads are connected through ports in the sidewall and head. The foundation for the vessel is a reinforced concrete slab placed on bedrock. Foundation preparation required some earth excavation and "dental work" on the bedrock to insure minimum settlement of the foundation. The bearing capacity of the bedrock is approximately 15,000 psf. To make room in the building for the tank, ten reinforced concrete columns and sufficient concrete floor area

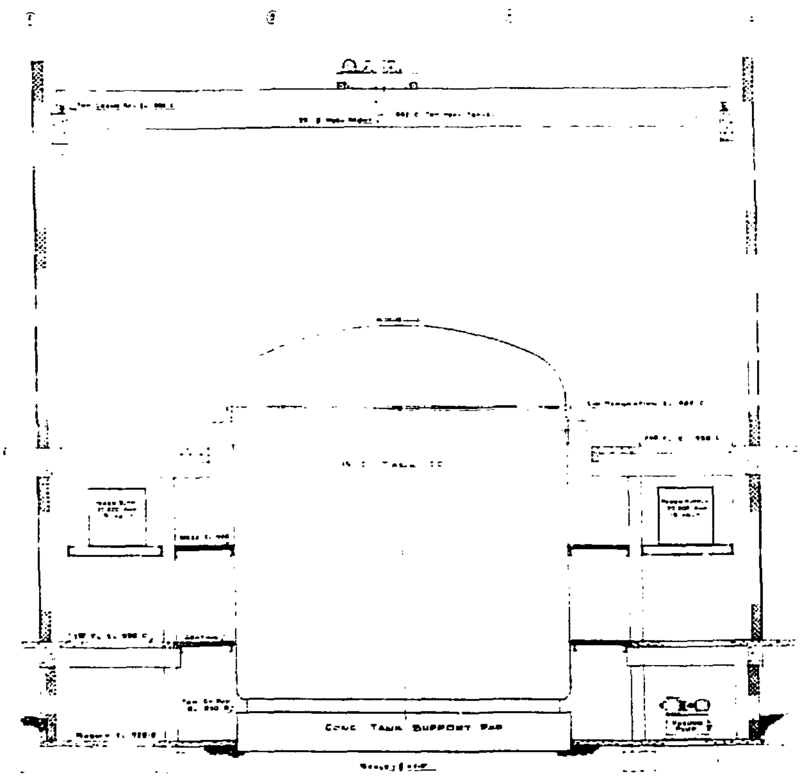

Fig. 2

Vacuum Tank Elevation

to provide a 45-foot square around the 35-foot-diameter vessel were removed at both floor levels.

The perimeter of the opening around the large vessel is supported by reinforced concrete beams and columns which were added for this purpose.

The pumping system has three 1000-cfm/175-cfm blower/mechanical pump, one 600-cfm/110-cfm blower/mechanical pump and two 35-inch oil diffusion pumps. The diffusion pumps are mounted on right angle valves which allow each one to be isolated from the vacuum vessel. There is a liquid nitrogen-cooled baffle between the right angle valves and the pumps to prevent oil back-streaming and thermal radiation into the vacuum vessel. This combination of pumps results in a theoretical pumpdown time of five hours. With only half the system operating, experience has shown that the tank can be pumped down in eight hours when empty of experimental hardware. The ultimate base pressure of the system is $5.2 \times 10^{-5}$ torr with an outgassing rate of 2.6 torr ℓ/sec. The 600/110-cfm blower/pump unit is used to back the diffusion pumps once the vessel reaches $10^{-2}$ torr.

It is possible for leaks to develop from several sources during the operation of this vessel. These include the liquid helium system, liquid nitrogen system, and air leakage. To reduce leak hunting time, a leak detector that can distinguish between these gasses has been included.

## Test Stand Assembly

The coil support structure is designed to support the gravity loads and magnetic loads on the toroidal field coil being tested.[3] Details on the major structural items are shown in Fig. 3.

The bucking post is designed to take up to six coils and is constructed as a forging of 304 series stainless steel. The post has a hexagonal cross-section over its entire length. Each TF coil bears against one of these six faces and transmits the centering force of the coil to the post. A portion of the out-of-plane forces is carried by a groove which runs the full length of each of the six faces. A matching tongue running the full length of each coil nose fits into the post groove and provides support against the out-of-plane forces. The TF coils are attached to the top and bottom of the post using a key and slot connection. The post is cooled with liquid helium which runs through coolant holes in the interior of the post. These holes run the full length of the post and were drilled after forging.

The entire weight of the toroidal coil system is supported by a six-legged base. The base contains a central socket and flange into which the bucking post is attached. The base legs provide long thermal paths which aid in isolating the helium-cooled bucking post from the 300K temperature of the vacuum tank floor. The end of each leg rests on an expansion roller which, in turn, rests on a liquid-nitrogen-cooled pad providing a thermal intercept between the base and the floor.

## Cryogenic System

The cryogenic system is comprised of two subsystems, the helium system and the nitrogen system. The helium system furnishes primary cooling for the coils, test stand, and vapor-cooled leads. The nitrogen system cools a low temperature shield (cold wall) which is interposed between the coils and the vacuum tank wall, provides secondary cooling of gas phase helium during cooldown from ambient temperature to 85K, and provides for $LN_2$ tracing of all cold helium lines.

The specification for the TF coils established the cryogenic conditions to be used in the facility design. An option given to the coil designers is to use either pool boiling of 4.2K, 1 atm helium, or forced convection cooling using supercritical helium at 3.8 K minimum and 16 atm maximum pressure. The return fluid is to be no hotter than 6K and at a minimum pressure of 10 atm. The three U.S. made coils include two pool-boiling and one forced-flow design, and the three foreign made coils include two forced-flow and one pool-boiling design, so both forms of cooling must be provided in the facility.

In addition to the cooling required for the coils and their associated supporting test structure, cooling of the electrical leads feeding energy to the coils is necessary. A transition from the nominal 4K of the coils to room temperature at the power supply must be made with helium cooling at the coil-lead interface being the first step in the provision of this gradient.

Figure 4 is a schematic of the helium system. The helium stream emerges from the primary cold box at 15 atm and 4.4K and is routed to the first station of the auxiliary cold box. It emerges at 15 atm and 3.8K and is routed to the first forced flow cooled coil (FFCC). Emerging from this coil the stream is routed to the second station of the auxiliary cold box where heat picked up from the first FFCC is removed. In similar fashion the stream passes through the second FFCC, the auxiliary cold box, and finally the third FFCC. The

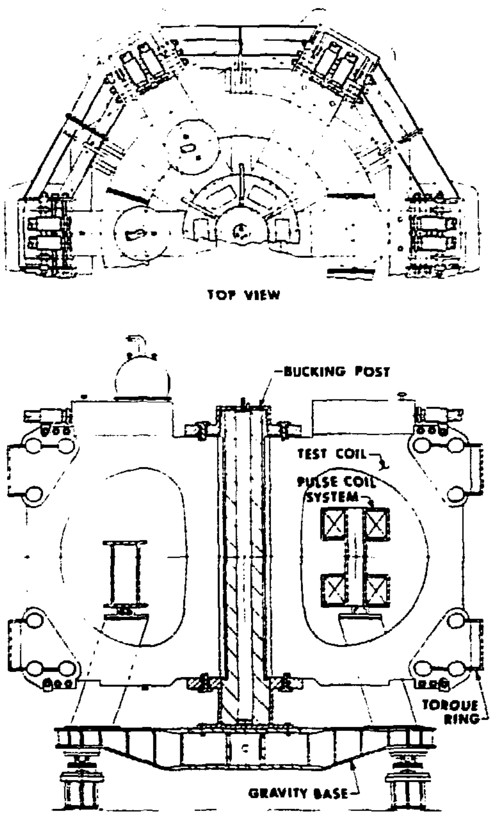


Fig. 3

Test Stand Assembly

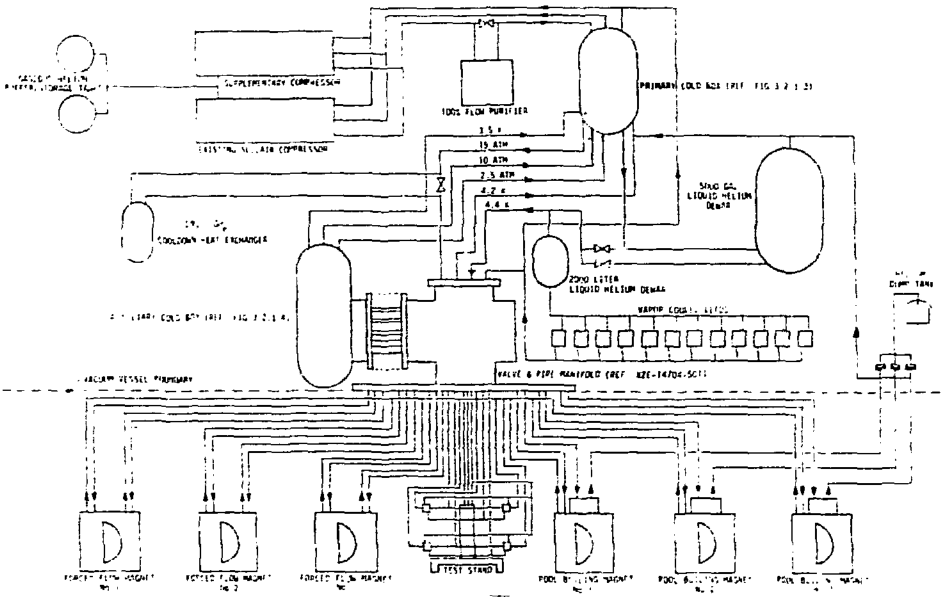


Fig. 4

Liquid Helium System

FFCC's always receive the stream at 3.8K and usually reject it at 4.1 to 4.2K depending on the coil. The first FFCC receives the stream at 15 atm, pressure at the exhaust end of the third coil will be about 10 atm.

From the last FFCC the stream is routed back through the primary cold box, and the flow is split. Two-thirds goes to turbine No. 1 and back through a heat exchanger to the compressor. The other third goes to turbine No. 2 and then to the 4.3K J-T valve which puts liquid into the 5000 gal. dewar. From there the liquid divides; part to the J-T valve feeding the 3.5K bath of the auxiliary cold box. The second part is used to feed the 2000 ℓ dewar for the leads, and also to supply the pool boiling cooled coils and the test stand.

All helium cold lines outside the vacuum tank are vacuum jacketed and nitrogen traced in order to minimize heat leak. Inside the tank only a few layers of MLI is required to insulate the lines.

Table 1 shows system steady-state performance requirements, and Table 2 shows anticipated thermal loads of the coils. The refrigeration values shown in Table 1 are useful refrigeration values after providing for all system losses.

Liquid nitrogen cools the cold wall of the vacuum tank, gaseous helium used for cooldown of

Table 1

Refrigerator Steady-State

Performance Requirements

Forced-Flow Cooled Magnet Test

The refrigerator will provide the following simultaneously with any forced-flow cooled magnet in the test mode and the remaining five (5) magnets in the background mode:

| | |
|---|---|
| Liquid helium production @ 4.4K | 12.5 g/s |
| Refrigeration @ 3.56K | 1470 Watts |
| Refrigeration @ 4.2K | 170 Watts |
| Supercritical helium @ 15 atm and 3.7K | 300 g/s |

Pool-Boiling Cooled Magnet Test

The refrigerator will provide the following simultaneously with any pool-boiling cooled coil in the test mode and the remaining five (5) magnets in the background mode:

| | |
|---|---|
| Liquid helium production @ 4.4K | 12.5 g/s |
| Refrigeration @ 3.56K | 1270 Watts |
| Refrigeration @ 4.2K | 326 Watts |
| Supercritical helium @ 15 atm and 3.7K | 300 g/s |

Liquid nitrogen cools the cold wall of the vacuum tank, gaseous helium used for cooldown of the coils, and intermediate pads on the heat conduction path coming up through the floor at the tank. It is also used to trace all cold helium lines. Nitrogen is delivered to the facility in over the road tank trailers and is piped to points of application via a fixed system using tank pressure to propel the liquid. The piping is vacuum jacketed.

Table 2

Design Thermal Loads For LCTF

Liquid Helium System

(Coil Loads in Watts)

U.S.

| | GE | GD | W |
|---|---|---|---|
| As test coil | 169 | 104 | 114 |
| As background coil | 26 | 27 | 36 |
| Standby | 20 | 20 | 20 |
| Nominal Temp K | 4.2 | 4.2 | 3.7 |

Foreign

| | Euratom | Japan | Swiss |
|---|---|---|---|
| As test coil | 150 | 208 | 150 |
| As background coil | 30 | 52 | 30 |
| Standby | 20 | 20 | 20 |
| Nominal temp K | 3.7 | 4.2 | 3.7 |

Vapor Cooled Leads

The coil current is supplied through current lead assemblies which are cooled with helium vapor. The lead assemblies are built as a combined vapor cooled lead and dewar unit which is bolted to the vacuum vessel. Superconductor is used in a bus connecting the coil interface to the current lead assemblies. The current lead assemblies are universal in the sense that this interface is compatible for use with both the pool-boiling and subsequent forced-flow coils. The lead assemblies have helium reservoirs separate from the coil coolant, and the vapor-cooled section is matched with the coil design current to minimize the helium boil-off. The current leads are of the thermal inertia type to allow a safe discharge of the coil if the lead coolant is lost.

Experimental Electric Power

Four of the TF coils are supplied from separate 15 kA, 12-V dc power supplies. The other two coils are supplied from 25 kA, 12-V units. Aluminum bus will be installed from each power supply to a specified coil connection at the tank wall. A panel for each supply to control the output of the power supply is installed in the control room. Remote operators are installed on the 480-V breakers which feed the power supplies, and the breakers are operated from the control room. The power supply output current is controlled either manually from the control panel or by a computer.

Additional dump circuits (for emergency use) which limit the voltage and discharge the coil within a specified time are installed for each coil. The dump resistors are cooled by natural convection.

The pulse coils are powered by two 300-V dc, 2-kA units. Duty cycle is about 30 sec repeated every three minutes.

Instrumentation and Controls and DAS

Instrumentation and controls for the facility are divided into two parts, coil diagnostics and process instrumentation.

The coil diagnostic instrumentation consists of signal conditioning and analog-to-digital conversion equipment required to monitor the various types of sensors located inside and on the test coils.

Processes, or subsystems requiring I&C are the test stand assembly, the vacuum system, the cryogenic system, the vapor-cooled leads, and the electrical power system.

The outputs of the signal conditioning equipment are high level analog signals. For strain, field, and displacement measurements, ac carrier amplifiers are required to reduce errors to acceptable levels. These are fed into a number of multiplexing analog-to-digital converters, each controlled by a small processor. Data is continuously taken and stored at high speed in buffer memory while a test is underway. Samples of the data are also sent to the diagnostic computer for processing and display.

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