INTERNATIONAL THERMONUCLEAR EXPERIMENTAL REACTOR

ITER EDA NEWSLETTER

VOL.6, NO. 3 MARCH 1997

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, AUSTRIA

ISSN 1024-5642

CENTRAL SOLENOID MODEL COIL PROJECT *

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The Full Size Central Solenoid

Function of the Central Solenoid

The central solenoid (CS) provides the majority of the magnetic flux change needed to initiate the plasma, generate the plasma current and maintain this current during the burn time. It contributes towards the fields needed to confine the plasma, but is not used for plasma control. The CS supports a large fraction of the centripetal force from the TF coils, which, in turn, support part of the radially outward load on the CS.

Conductor for the CS

The CS design uses three different conductors so as to reduce the amount of superconducting material used in lower field sections and thus reduce cost. Each conductor is in the form of a cable in conduit (the jacket material is Incoloy 908) with a square outer cross section and a circular cable cross section. The cable uses about 1000 Nb_3Sn strands and features a cooling channel (for supercritical helium) at the centre.

CS Design

The CS is layer wound along its entire height. Each of the 14 layers is wound with 4 conductors in hand to reduce cooling channel lengths to a limit of about 1 km. Layers are alternately wound from bottom to top and top to bottom to allow series connections. Electrical terminals are located at the bottom about 1.5 m below the bottom turns, and interlayer series connections are at the top and bottom about 1.5 m from the ends of the windings. Cooling is provided by supercritical helium flow and coolant entry and exit are in the joint regions. Parameters for the central solenoid are given in Table 1.

The preload structure is not integral with the CS, but is assembled to it when installed in the machine. It consists of a large flange at each end of the CS and tie plates between the flanges. It provides a vertical precompression of the CS and prevents vertical tension in the CS during a pulse.

CS Model Coil Programme; Large R&D Project-1 (L-1)

Objectives

The technology required to build the CS represents a significant advance on that existing today for conductor manufacture using Nb_3Sn in a large, heavy-walled conduit and for fabricating the conductor into a large piece of electrical equipment, the CS. The objective of the model CS programme is to develop magnet technology to a level which will allow the CS to be built with confidence. It should provide for the validation of design and analysis, demonstration of industrial manufacturing methods, the performance of each component integrated in the magnet and demonstration of reliable operation. This programme (and the TF model coil programme, ITER Large R&D Project L-2) also drives the development of ITER full-scale conductor including strand, cable, conduit and terminations. Further, the model coil programmes serve to integrate the supporting R&D programmes on insulators, joints, material characterization, ac losses and stability/ramp rate effects.

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* This is the fourth article in a series describing the Seven Large ITER R&D Projects. For the previous articles in the series, see Newsletters Vol. 5, Nos. 8 and 9, and Vol. 6, No. 2.

Table 1 Central Solenoid-Geometrical data

Height of Winding	12.116 m
Inner Radius of Winding	1.919 m
Outer Radius of Winding	2.700 m
CS Subassembly (approximate weights):	
Cable	273 t
Conduit	457 t
Insulation	53 t
Buffer Zone, etc.	67 t
TOTAL Winding Pack	850 t
Outer Cylinder	358 t
Inner Cylinder	242 t
TOTAL Weight of CS	1,450 t
Preload Structure Weight	710 t
Number of Turns	3,356
Maximum Field at Conductor	13 T
Total Current*	127.7 MA
Current per Conductor*	38 kA
Radial Force Integrated Over 2 pi*	10.5 GN
Total Vert. Comp. Force at Mid-Plane**	1.0 GN
Self Inductance	14.9 H
Total Stored Energy*	10.8 GJ
Average Voltage per Turn	15 V
Operating Voltage to Ground	+/- 6.3 kV
Maximum Voltage to Ground (fault : 1 Terminal to Ground)	12.6 kV

* Initial Magnetization ** End of Burn

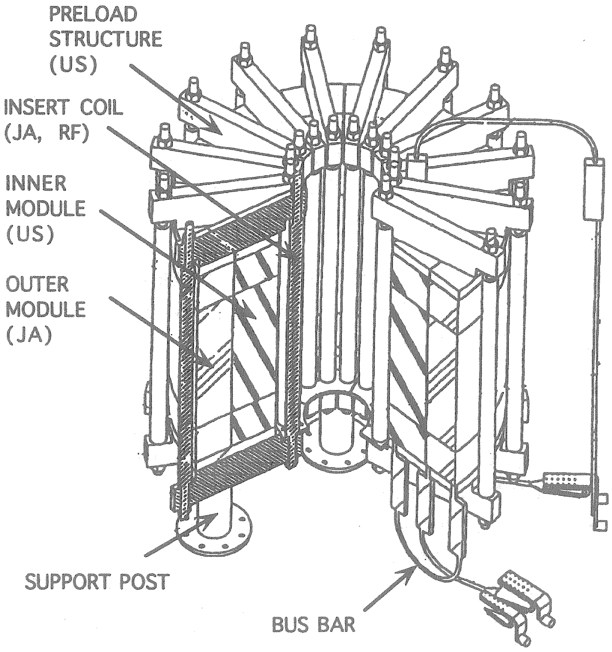

Figure 1. The CS Model Coil Assembly showing the inner and outer modules, an insert coil and the structure

Design

The CSMC is illustrated in Figure 1. It will be layer wound with two grades of heavy-walled square conductor, reflecting the winding of the ITER CS. It will have an inner diameter of 1.6 m, an outer diameter of 3.6 m and a winding height of 2.8 m. The CSMC will produce a 13 T magnetic field with a 46 kA conductor current. The CSMC consists of two nested modules (which are electrically connected in series) and is capable of accepting insert coils for full-scale conductor performance testing. Key parameters of the CSMC modules are given in Table 2.

Project Management

The Project Responsibility lies with the Naka JWS Deputy Director and the US and JA Home Team (HT) Leaders. The Project Management is also a joint responsibility of the JCT, the US and the JA HTs. The project management scheme is summarized in Figure 2.

Table 2 Summary of Key Parameters of the CSMC

Model Coil characteristics	Inner Module	Outer Module
No. of layers	10	8
No. of turns/layer	31-34	34
Total no. of turns	328	272
Inner radius (incl. ground ins.)	0.79 m	1.367 m
Outer radius (incl. ground ins.)	1.357 m	1.800 m
Height (winding)	1.775 m	1.775 m
Height (incl. ground ins.)	2.795 m	2.795 m
Conductor length (inc. joints)	2288 m	2687 m
Total module weight	46 t	52.6 t
Operating current	46 kA	46 kA
Operating field	13 T	7.3 T
Self inductance	606 mH	
Stored energy at 13 T	641 MJ	
Ground insulation thickness	10 mm	

Under the guidelines provided by the responsible Deputy Director and the US and JA HT Leaders, the project L-1 HT managers are responsible for implementation of project L-1, in close collaboration with the project L-1 JCT contact persons.

The project L-1 JCT manager is responsible for defining the technical specifications and the interface issues, for assessing the overall progress made and the results obtained against the ITER needs, for the integration of the results into the design, and for the identification of any new inputs for the implementation stage.

The HT Project managers are supported by the HT Work Area Coordinators and by a project staff for planning, schedule control and QA. The JCT Project Manager is supported by the JCT Task Officers.

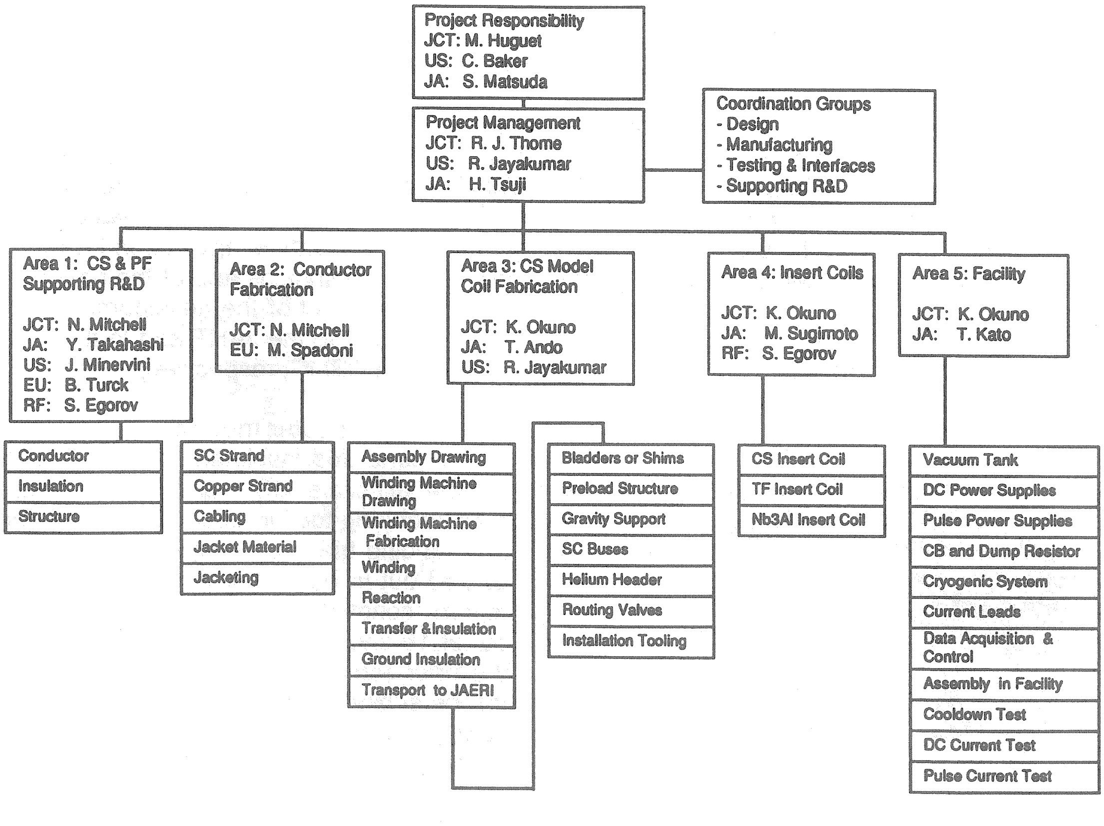

Figure 2. The L-1 (CS Model Coil R&D) Project Management Scheme

Work Organization and Status

The organization of the CSMC project work among the HTs is illustrated in Figure 3.

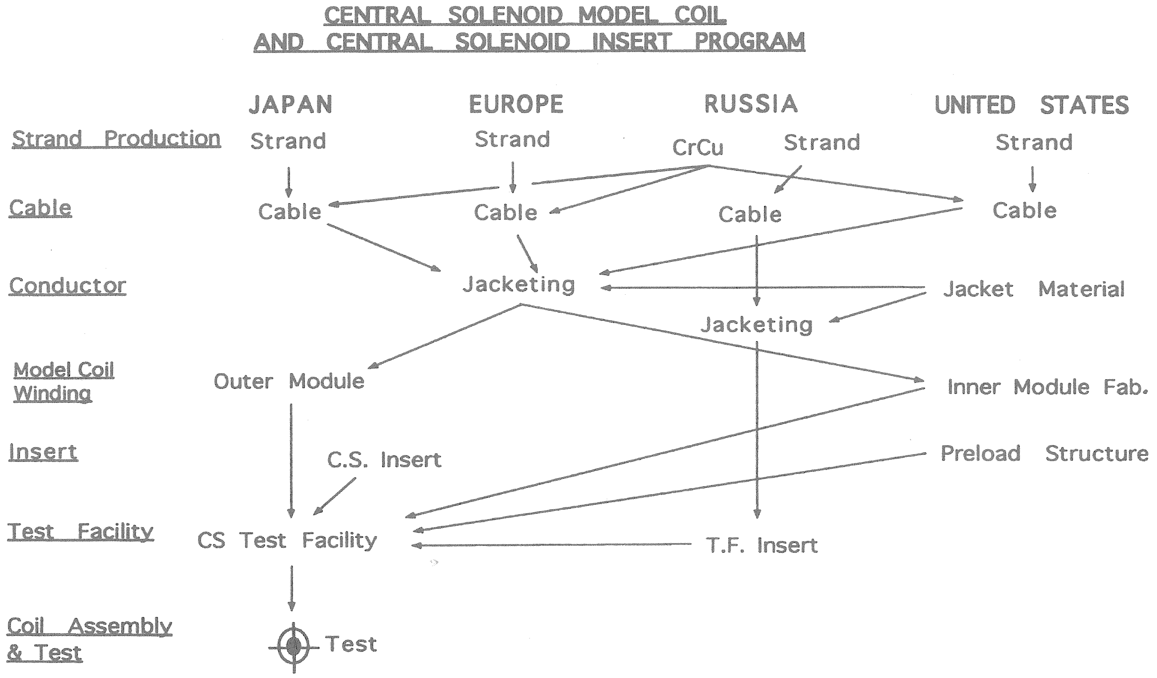

Figure 3. The CS Model Coil and CS Insert Coils Work Programme showing the movement of constituent items between Home Teams

Nb_3Sn strand is being manufactured and cabled in all four Parties, in recognition of the need to develop multiple strand suppliers for the full-scale requirements. Thus far, about 25 tonnes of Nb_3Sn strand have been produced to an ITER specification, five 100 m and one 1,000 m dummy copper cables have been produced for jacketing and winding trials, and 33 of 37 cables for the final conductor are complete.

Heavy-walled, square Incoloy 908 jacket material from the USHT, as well as cabled superconductor from the EUHT, JAHT and USHT, are supplied to the EUHT for jacketing. The jacket is supplied in lengths of 8-10 m and is butt welded to obtain the required length. The finished cable is then pulled into the jacket and the jacket is rolled to compact the inner diameter around the cable and control the final void fraction for helium access in the cross section (see Figure 4). Thus far, five 100 m dummy cables have been jacketed and 23 of 37 final cables have been jacketed. Quality control of component dimensions and of the final product, as well as examination of welds and leak testing, have been an important part of the development effort. The jacketed conductor for each layer of the CSMC is supplied by the EUHT to the JAHT and to the USHT, who have responsibility for fabrication of the outer and inner modules of the CSMC, respectively.

The inner and outer modules will each be wound two in hand and insulated in a manner designed for the full-scale CS. A significant part of the manufacturing tooling has already been procured, and winding trials (see Figures 5 & 6) have been carried out in both HTs with steel bar or full size dummy conductor. Thus far, the final winding of 2 out of 10 and 2 out of 8 layers has been done for the inner and outer modules, respectively. Tooling for the subsequent stages of manufacture is near completion and includes: heat treatment (reaction to form Nb_3Sn), turn insulation, and module assembly.

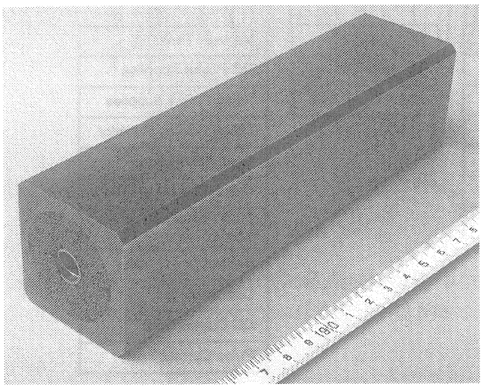

Figure 4. CS Model Coil Incoloy 908-jacketed conductor sample

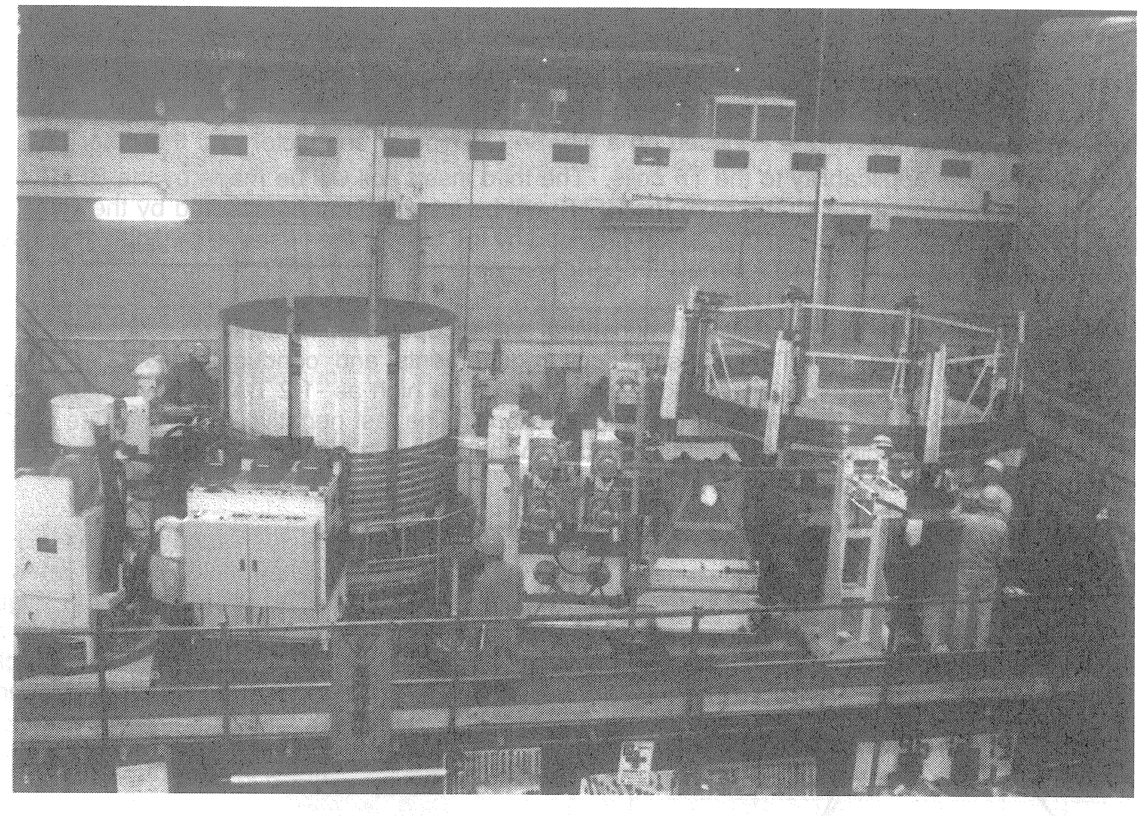

Figure 5. Winding the outer module (axis vertical) at Toshiba Corporation(Tokyo, Japan). A conductor travels from the spool on the right to the mandrel on the left through the bending rollers. A second conductor is wound in the space to form a 2-in-hand winding.

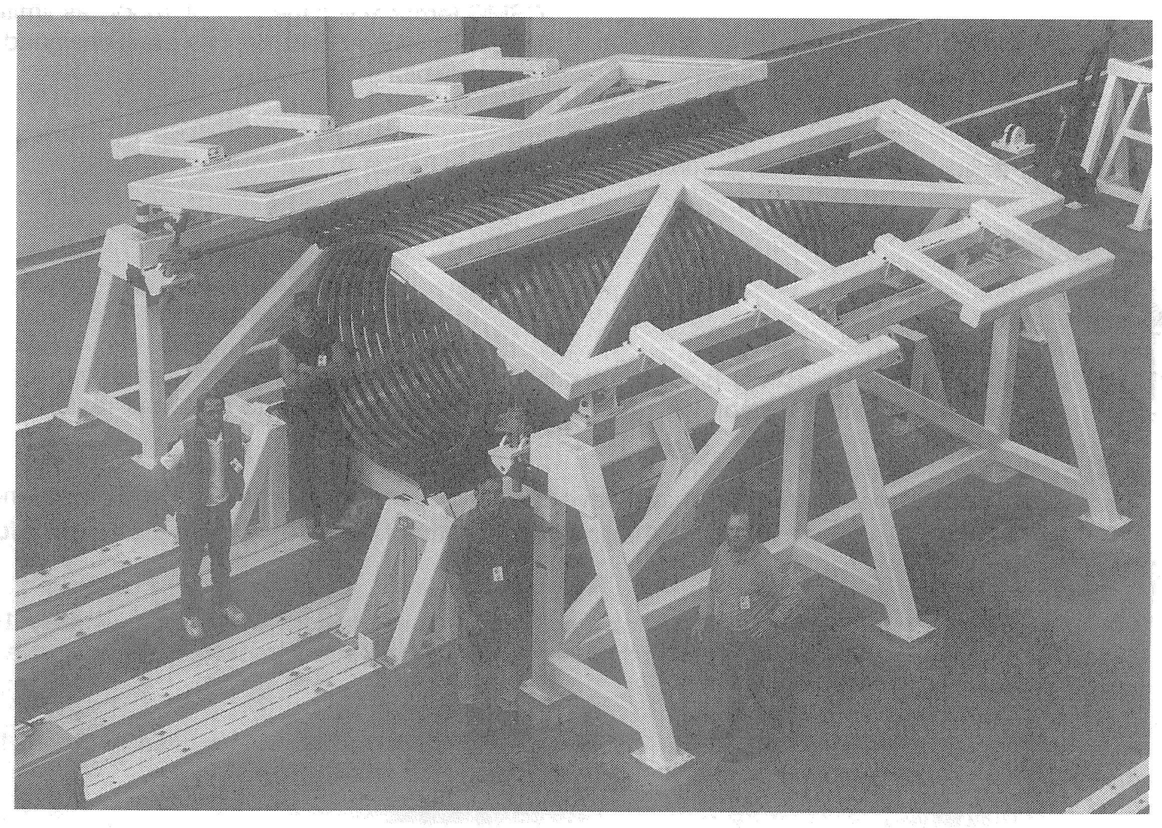

Figure 6. Two coils are wound independently then corkscrewed together at Lockheed Martin, San Diego, USA, to form a 2-in-hand layer for the inner module.

Testing

Upon completion of the manufacture, the inner and outer modules will be shipped to JAERI for assembly and testing. The testing program will revolve around the performance of the CSMC and of insert coils. Two insert coils will be made by the JAHT: one is based on a Nb_3Sn CS type of conductor and the other on a Nb_3Al conductor with potential applicability to the TF coils. The third insert coil will be made by the RFHT to study TF conductor performance. The strand from the RFHT will be inserted and compacted by the RFHT into a thin-walled, circular, Incoloy 908 conductor jacket provided by the USHT, then used to fabricate the insert coil that will demonstrate full-scale ITER TF conductor performance under simulated operating conditions.

The CSMC test facility has the capability of supplying pulsed operation to allow investigation of CSMC performance consistent with the ITER full-scale coil requirements and conductor design criteria. For example, the full-scale CS will experience field discharge rates as high as -1.2 T/s for several seconds and field change rates of about 0.3 T/s for relatively long durations. The fast negative discharge rate of -1.2 T/s for the full scale CS is associated with plasma initiation in the full-scale system and will be achieved in the CSMC test by a fast discharge through a resistive load.

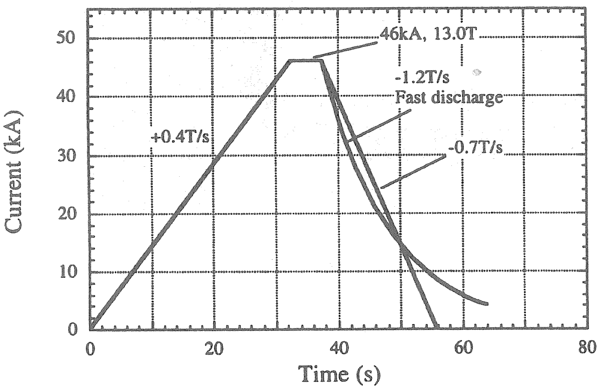

Figure 7. Typical magnet current (and field) pulse capability for the CSMC.

One of the power supplies available at the JAERI facility will allow field change rates up to +0.4 T/s or -0.7 T/s as illustrated in Figure 7. Another power supply will pulse the CSMC and/or insert coil up to 13 T at a maximum field change rate up to 2 T/s, which substantially exceeds the ITER requirement and design criteria for the CSMC, but will be useful in determining design margin and operational limits.

A resistor in the test facility can provide a variety of fast discharge time constants for testing performance under rapid ramp-down conditions and also protect the coil in the event of a quench. Discharge time constants are chosen to be below a CSMC terminal voltage limit of 10 kV, as limited by the facility. The CSMC is, however, designed for a terminal voltage of 15 kV.

The CSMC Test Facility at JAERI, Naka, is complete and shown in Figure 8.

Conclusions

The ITER EDA design and R&D activity is a collaborative effort among four Home Teams and the Joint Central Team. The effort in the superconducting magnet Model Coil program to date has resulted in the following:

Approximately 25 tonnes of Nb_3Sn strand have been produced to date in all four Parties and the balance will be produced by mid 1997. Cabling is underway of full size cross-section cables for the CSMC.

A 300 m jacketing line has been set up for the CS type of conductor. Five, approximately 100 m lengths of dummy cable have been pulled through CSMC jackets and compacted. These have been used in trial winding procedures.

About 4900 m of the Incoloy 908 jacket material for the CS Model Coil have been delivered to the jacketing line and the balance of about 1800 m will be delivered by mid 1997.

The design of the CSMC is essentially complete.

23 conductors have been jacketed out of the 37 required.

Trials of winding, heat treatment, lead preparation and insulating have been performed with five dummy cables with Incoloy 908 jackets, each 100 m long.
Winding of the first layers of the inner and outer modules of the CS Model Coil has been performed.
The test facility for the CSMC is ready at the Japan Atomic Energy Research Institute in Naka.

In addition, there has been extensive progress in supporting R&D activities on components and material properties.

Effective collaboration has resulted in significant strides in developing the ITER design and establishing the R&D program that is essential to verify design parameters.

Acknowledgments
The Home Teams are implementing the R&D programs. The model coil programs, in particular, require extensive coordination and are being performed with close collaboration among them. The JCT acknowledges the continuing efforts of the Home Teams and extensive support from their industrial partners.

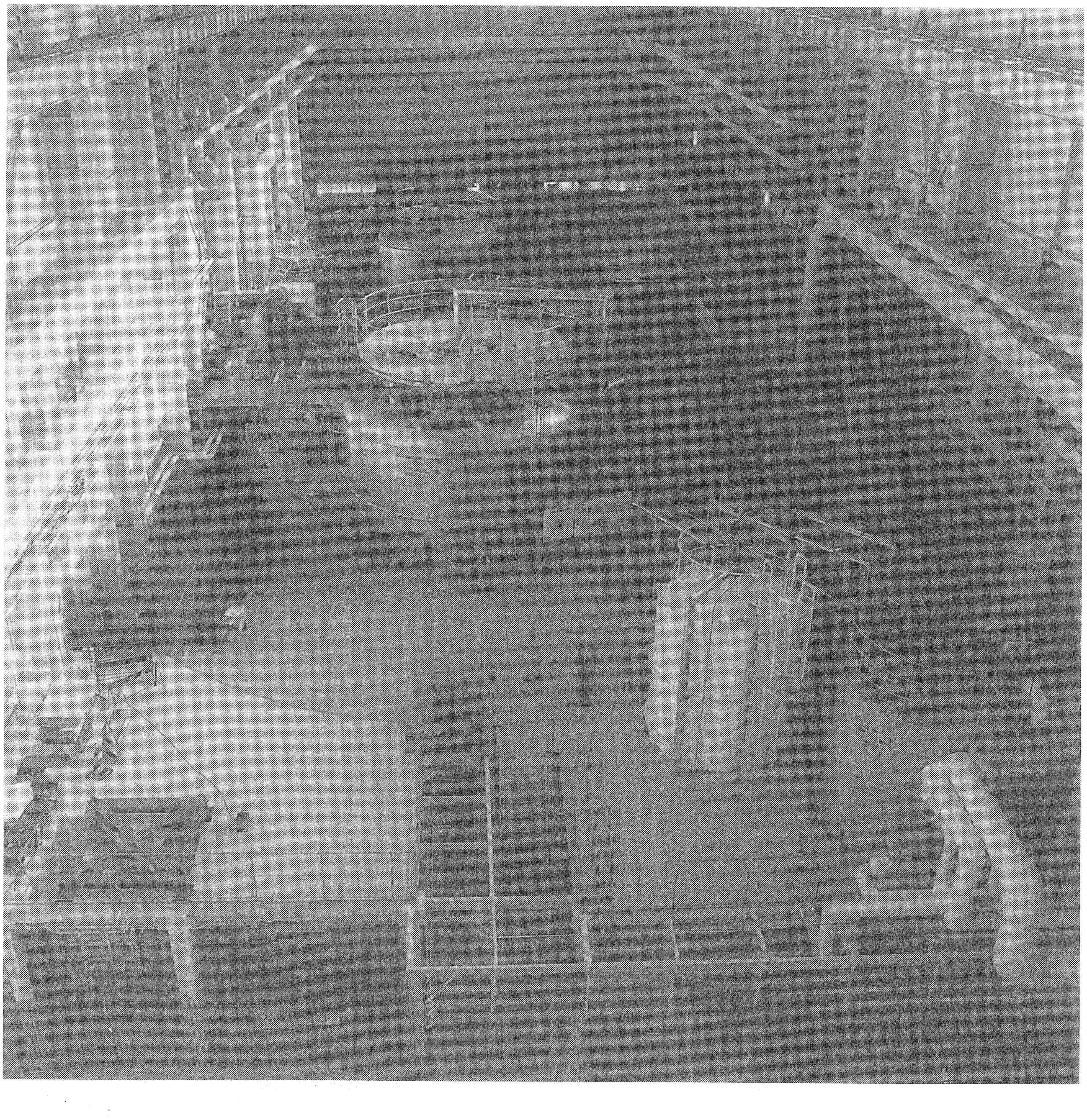

Figure 8. The CSMC cold test facility at the Japan Atomic Energy Research Institute, Naka, Japan

Items to be considered for inclusion in the ITER Newsletter should be submitted to B. Kouvchinnikov, ITER Office, IAEA, Wagramerstrasse 5, P.O. Box 100, A-1400 Vienna, Austria, or Facsimile: +43 1 237762, or e-mail: basaldel@ripo1.iaea.or.at (phone +43 1 206026392).

Printed by the IAEA in Austria
May 1997