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NON-SUPERCONDUCTING MAGNET STRUCTURES FOR NEAR-TERM, LARGE FUSION EXPERIMENTAL DEVICES

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ABSTRACT

Water cooled copper magnets provide a means of producing high magnetic fields for tokamaks using a well developed existing technology. The basic function of these magnets is to provide reliable, both time varying and steady state, magnetic fields. Copper electrical properties, insulation, and water cooling systems play major roles in design selection. Aside from being electro-magnetic devices, coils designed for tokamaks must be self-supporting structures, capable of resisting large I x B magnetic forces. These magnets require the integration of both electrical and structural design considerations.

Magnet integrity is enhanced by the presence of structures which lend additional external support. These external structural systems are highly stressed and, often, deflection limited.

This paper describes the magnet and structural design in the following American tokamak devices: the Princeton Large Torus (PLT), the Princeton Divertor Experiment (PDX), and the Tokamak Fusion Test Reactor (TFTR). The Joint European Torus (JET), also presented herein, has a magnet structure evolved from several European programs and, like TFTR, represents state of the art magnet and structure design.

The PLT device was designed in 1971 as a high plasma current tokamak. At the time it incorporated the latest in copper magnet and structure technology. Design features on this machine have in some fashion subsequently been incorporated on every major device built within the tokamak fusion community.

1. INTRODUCTION

Since the early part of the 1950s scientists and engineers have been performing experiments with the ultimate goal of achieving fusion energy. Experiments have taken several different approaches to meet that objective, the major approaches are: magnetic mirrors, magnet pinches, laser fusion, and toroidal confinement.

In early experiments toroidal confinement was investigated in devices known as stellerators. Later, as we will see, the devices used to study plasma physics were tokamaks. The basic difference lies in the manner by which the rotational transform, or twisting, of the confining magnetic field is produced. In the tokamak the twisting of the confining magnetic field is produced by the poloidal fields from a toroidal current carrying plasma - the so-called discharge current. In the stellerator the twisting of the confining field is produced by means of conductors placed outside the plasma. These conductors are usually wound in helices of large pitch around the donut-shaped volume containing the plasma and produce a multipole poloidal magnetic field.

The first series of successful plasma physics experiments performed with a tokamak was reported by scientists of the Soviet Union in 1969. The reported encouraging results caused the emphasis of magnetically confined toroidal systems to shift to the development of tokamaks for fusion research. Toroidal confinement devices require relatively high toroidal fields (3-6 T at the plasma axis, 6-12 T at the inner conductor) coupled with the need for pulsed vertical fields of moderate to high strengths (typically from 2-7 T in 1-10 s). The vertical fields are required for ohmic heating, plasma equilibrium, impurity control, etc. The combination of the vertical and toroidal fields of the magnitudes shown above provide the major cause for design specification of tokamak magnets. Some of the more recent experimental devices are reported in this paper. These include the Princeton Large Torus (PLT), and the Poloidal Divertor Experiment (PDX), as examples of successfully operating tokamaks. We present the Tokamak Fusion Test Reactor (TFTR) and the Joint European Tokamak (JET) as examples of the next generation of tokamaks now in the advanced design stage which, if successful, should provide the scientific feasibility of fusion. Those devices will be discussed in subsequent sections.

2. SHORT HISTORY OF TOKAMAKS

Soon after the 1969 disclosure by the Soviet scientists, and in an attempt to correlate the results, scientists and engineers of the Princeton Plasma Physics Laboratory designed a modification to the then operating C-stellerator, which converted that device into the first American tokamak, the Symmetrical Tokamak (ST), see Fig. 1. Initial experimental results from ST substantiated the earlier Soviet optimism for confinement of plasmas in Tokamaks. Previously, in stellarators, confinement experiments showed that confinement time ran counter to theory, and decreased with increasing electron temperature. Initial experiments in the ST confirmed Soviet results and showed that the confinement did indeed increase with temperature [1]. Fig. 2 shows the dramatic comparison of plasma confinement experiments in the C-stellarator with initial ST experiments. These results were direct cause for scientists and engineers at Princeton to design a new tokamak, a plasma heating experiment called the Adiabetic Toroidal Compressor (ATC), see Fig.

3. ATC became operational in May 1972, and continued to produce new promising experimental evidence that tokamaks should be pursued as a possible fusion reactor. Consequently, in the early 1970s, a new generation of tokamaks was designed. These devices listed below were much larger both in size and magnetic field than previous tokamaks. They are all operational and were designed to test plasma physics scaling laws, and to gain more confidence in the quest to show scientific feasibility. They are Princeton's PLT, see Fig. 4, Princeton's PDX, see Fig. 5, and the Soviet T-10, see Fig. 6. PLT and T-10 became operational in late 1975. In July 1978 PLT, using neutral beam heating, was able to achieve a plasma temperature of about 6 KeV (60 x 10^{-6} K), a very important accomplishment indeed. PDX became operational in early 1979 and preliminary experiments have yielded highly satisfactory results. While these larger experiments were being designed, many other tokamaks were fabricated and operated throughout the world to supplement the experiments being performed on the larger machines. Some of the major devices are ALCATOR A and C at MIT, ORMAC and ISX at Oak Ridge National Laboratory, the University of Texas tokamak at Austin, Texas, Doublet II and III at General Atomic, DITE at Culham, the Frascati Tokamak (FT) at Laboratori Nazionali de CNEN, Italy, a series of tokamaks, T-3, T-4 and T-7 in the Soviet Union, and ASDEX at Max Planck Institut für Plasmaphysik, Garching, Germany.

Experimental results from all the above machines are being used in the design of a third generation of tokamaks, designed to demonstrate scientific feasibility. These devices, TFTR in Princeton, JET in Culham, and J-60 in Japan, should be operating between 1981 and 1984. All the devices mentioned above have used normal, and in most cases, water cooled copper conductors. Plans for the fourth generation of tokamaks are to use superconducting coils. It is now universally accepted that economics dictate that tokamak fusion reactors must use superconducting magnets.

The authors will limit themselves to discussion of only one of the myriad of technical problems associated with the design of tokamaks; that of specifications and motivations for the design of toroidal field and poloidal field, normal, water cooled copper coils. Although the problems in all tokamak designs are similar, the solutions are manifested in slightly different ways. We illustrate these variations by using the PLT, PDX, JET and TFTR as specific examples. We point out, however, that the principles illustrated by these examples are applicable to any tokamak regardless of the physical size, operating magnetic fields, and type of coils either copper or superconducting.

3. FORCE SYSTEMS

The purpose of the mechanical structure in a tokamak is to provide support for the toroidal field (TF) and poloidal field (PF) coil systems. These coil systems are subjected to forces produced by the interaction of their currents with the various magnetic fields. The largest forces by far are those produced by the toroidal field coils. Consequently, the supporting structure for the toroidal field coils accounts for much of the mechanical structure.

When arranged in a torus, the interaction of the TF coil current with its own axial field produces an outward force perpendicular to the curvature of the TF coil. The resultant field within the torus is proportional to I/R (where I is the current and R the radial distance from the central axis of the torus). Since this field is greater at the inner radius of the coil, a net imbalance results which is termed the "centering force". This force tends to move the coils radially inward.

The currents in the plasma and the various PF coils produced fields with a vertical and radially outward component. These fields are generally not tend to rotate each TF coil about its horizontal axis. These lateral forces produce what is referred to as the "overturning moment". These moments are resisted by structures usually referred to as "torque frames". These are either external to the TF coils or are an integral part of the TF coil case structures.

Both the TF and PF coils are subjected to forces which tend to expand them and are resisted by the coil copper as hoop stresses. Coil cases, or partial coil cases, are sometimes utilized to assist in support for the hoop stresses. These are the basic force systems which motivate and dominate all tokamak designs. The subsequent sections will illustrate different methods of solving those problems.

4. PRINCETON LARGE TORUS (PLT)

The PLT device was designed in 1971 as a high plasma current tokamak. At the time it incorporated the latest in copper magnet and structure technology. Design features on this particular machine have subsequently been incorporated on every major device built within the tokamak fusion community.

4.1 Principal of the Mechanical Structure

The major structural components of the PLT are the torque frame, the center column, and the poloidal field coil support system.

The interaction of the TF current on the PF vertical field causes each TF coil on PLT to experience an out-of-plane lateral force. Because the TF current is in opposite directions at the top and bottom of the coil, these out-of-plane loads result in a net "overturning moment". This moment is counteracted by the steel anti-torquing structure shown in Fig. 7.

Each TF coil is anchored to the upper and lower shelves by means of wedge castings, see Fig. 8. Since lateral forces at the tops and bottoms of all TF coils are in opposite directions, upper and lower shelves experience opposing rotational forces. To restrain these rotations the shelves are connected by type 304,8 in. dia. stainless steel diagonal struts [2]. Although the forces in each strut are rather high (about 160,000 lb.), it is interesting to note that the design is deflection limited. Each TF coil is limited to a rotation of less than 1 mrad about its horizontal center line.

Detail design features of this anti-torquing structure were included to aid installation. Diagonal struts were attached to the upper and lower shelves by means of a close fitting clevis and pin arrangement. This construction not only facilitated a piece-by-piece assembly of large components, but also limited relative rotation of the top and bottom shelves. The method employed to anchor the TF coils to the upper and lower shelves is unique. Each TF coil is laterally anchored by means of wedge castings between adjacent coils, see figs. 7 and 8. Each wedge casting contains an integral worm-and-gear arrangement which is accessible from above and below the machine. Rotating the worm provides a lateral shim adjustment, tightening the TF coils against their wedge casting neighbor. Wedge castings are type HF stainless steel; this selection was predicated by low permeability and high strength requirements.

Another highly stressed structural element provided radial restraint for the large toroidal field coil magnets. Termed the "center column", this massive three-piece Inconel forging contacts the TF coils in an area of particularly high bending moment [3], see Fig. 8. The coils are relieved of a vertical component of force in their contact with the center column. This minimizes a relatively high tensile stress in the inboard portion of the coils by transfering it into the column. The center column was designed as large as possible consistent with available space in order to maximize its stiffness. For this reason it took on an hourglass shape. The stiffness of this structure was carefully designed to provide the correct proportion of horizontal and vertical components of force to restrict bending. Several design interactions, including various spring stiffnesses for center column action, were necessary to arrive at a final design.

Design features of the center column included the unique ability to assemble the three-piece structure in place. This is illustrated in Fig. 9 which shows the thread engagement of the two outer hubs and the center stud. The sloping concave ends of the stud were designed to avoid first thread shear stress build-up. The hubs themselves have infinitely adjustable stainless steel wedge mechanisms incorporated into their design. These mechanisms provide a shimless way of containing the TF coils in the previously mentioned high bending moment area.

The PF coil system on PLT exists entirely within the toroidal volume created by the bore of the 18 TF coils. Owing to space limitations, the support structure for these coils presented a very difficult machine design problem [2]. The previously mentioned wedge castings provided anchor points to restrain the mutual attraction of PF coils above and below the horizontal mid-plane of the device. Stainless steel sheet 1/8 in. thick, was used to clamp the coils to every wedge, see Fig. 10.

4.2 Stress Analysis

Two areas in the PLT device were analyzed to be relatively highly stressed. The toroidal field coils were designed on the basis of a maximum allowable combined stress (no plasma) in the copper [4]. This occurs at one inner turn 13.5° above the horizontal bisector of a coil, see Fig. 11. The total stress predicted was 16.9 ksi from hoop tension, 5.7 ksi from radial bending and 9.2 ksi from other less severe loadings. This adds up to a maximum predicted combined stress of 31.8 ksi.

The previously mentioned center column was analyzed as the most highly stressed structural member. The stress in this three-piece member results from the 2.1 x 10^6 lb axial force placed on it by the 18 toroidal field coils. The basic tensile stress in the "stud" is 60 ksi. With a stress concentration factor of 1.9 at the threads, the maximum predicted stress in this part is 114 ksi.

4.3 Toroidal Field Coils

The toroidal field coil system on the PLT was considered unique for its time [5] (see Table 1 for coil specifications). These large magnets (see Fig. 11) were mandrel wound from insulated hard copper bar. A B-stage fiberglass epoxy insulation system served as a bond scheme to make the copper windings into true monolithic structures. After winding two pancakes of 21 turns each, the press cured pair was joined and vacuum impregnated with epoxy resin. The resulting copper/epoxy coil was then face machined in the nose area to a wedge shape. The resulting nested wedge shapes of all the TF coils provided flat supports for each coil under the 3.24 x 10^6 lb centering force. During construction accurate positioning of these large coils insured a solid, well nested, coil group.

5. POLOIDAL DIVERTOR EXPERIMENT (PDX)

5.1 Purpose

The PDX was primarily designed to study the effectiveness of poloidal divertors in controlling impurities in large, high temperature plasmas. The large impurity concentrations in recent tokamaks have contributed to energy losses which will become even more severe in the next generation of reactor-like devices. The PDX design is unique in providing considerable flexibility for both study and comparison of the most promising poloidal divertor geometries and techniques known at present. An artist's view of the PDX device, Fig. 12, indicates the plasma in the center of the elongated toroidal vacuum vessel. The magnetic divertor coils appear in the four corners of the plasma enveloped by the plasma separatrix. The magnetic divertor has two main functions: first, it defines the size and shape of the plasma without the need of a mechanical limiter and, secondly, it carries the escaping plasma from the plasma edge, where impurities tend to concentrate, to a separate burial chamber. By capturing 95% of the escaping plasma and preventing its return into the discharge chamber, it is anticipated that the impurities generated will be reduced by a factor of ten.

5.2 Principal of the Mechanical Design

The mechanical design of the PDX device [6], in responding to the physics requirements, was predicated upon repeated rearrangement and replacement of the divertor field coils located within the vacuum vessel and consequently within the bore of the TF coils. To provide access to the divertor field coils it was decided to make the TF coils demountable. This aspect of the TF coils became a major consideration in both the design of the coils and the design of the supporting mechanical structure. It should be noted that the demountable design had an additional advantage to the fabrication schedule as it permitted the work on major sub-systems to proceed in parallel.

5.3 Toroidal Field Coil System

An elevation view of the PDX device is shown in Fig. 13. The individual TF coils are not circular in shape but consist of two straight sections (legs) joined by two semicirclar arcs forming what is commonly referred to as a race-track coil [7]. Each coil has 20 turns of copper conductor arranged in two layers of ten turns each. The conductor material is silver bearing copper worked to a yield strength of greater than 35 ksi and drawn with a central elliptical hole for water cooling. The insulation scheme for each turn elliptical hole for water cooling. The insulation scheme for each turn consists of 0.044 in. of B-stage epoxy glass applied over 0.007 in. of polyester tape and press cured to 0.042 in. The insulation is tested to 2500 V DC. See Table 2 for coil specifications.

The demountable design requirement resulted in the location of an electrical-mechanical joint in the semicircular regions of the TF coils. The design considerations of the joint presented one of the most difficult design problems in the PDX device [8]. The combination of radial, lateral and thermal loads in conjunction with the TF coil support structure produced a complex force and moment condition in the joint region resulting in critical stresses. The electrical requirements and space restriction further complicated the problem. A number of alternatives were considered and investigated in a lengthy joint testing program. The resulting design (Fig. 14) utilizes captive expandable pins in a lap joint configuration. Each lap joint contains two pins per turn and the individual turns are nested together in a clevis-type arrangement, thereby reducing the bending moments produced by the non-axial tension forces. A hydraulic clamping device surrounds the lap joint assembly providing mechanical support as well as the necessary pressure of 1500 psi to maintain the electrical current carrying capability of 43.7 kA across the surface of the lap joint. A hydraulic design was utilized in order to ensure the clamping pressure would remain essentially unchanged during lateral coil motions, as well as displacements caused by temperature changes and creep. The clamp, shown in Fig. 15, is a structural box frame consisting of two side members and a top and bottom bridge member. The frame is mechanically isolated from the main structural components to prevent the transmission of lateral forces through the hydraulic clamp. This is necessary to maintain a uniform and positive pressure distribution through the coil joint. Each of the clamp side members contain two nitrile rubber tyres which move the metal pistons against the sides of the coil when pressurized. This hydraulic system operates at a pressure of 8000 psi and is constantly monitored at each clamp by the computer controlling the PDX operation.

A preload force was necessary in order to reduce bending stresses in the joint to a reasonable limit. A low pressure hydraulic preload system, see Fig. 13, was designed and installed on each of the coil cases supporting the outer legs of the TF coils and anchored to the upper and lower shelves. The pistons develop a force of 65,000 lb. which is then maintained by a mechanical locking device. The preload system prevents stresses from exceeding 20,000 psi in the TF coil joint.

The 20 TF coils are arranged around the center column assembly which consists of a center shaft with a large thrust assembly mounted on each end. On the rim of the thrust assembly are located adjustable pads which contact each TF coil at a point carefully chosen to reduce the bending moment in the lap joint area. The reaction at each thrust pad location is 130,000 lb vertical (outward), 64,000 lb radial (inward). In addition, the center column thrust assembly provides a vertical clamping force reducing the tensile stresses on the inner legs of the TF coils. The vertical reaction from each TF coil is transmitted through the thrust assembly to the center shaft. The total tensile load on the center shaft is 2.6×10^6 lb resulting in a stress of 7000 psi.

The centering force on the PDX TF coils is 1.8×10^6 lb per coil and is resisted by the mutual support the coils give each outer through the wedge-shaped inner legs. The outward magnetic force on the other leg of the TF coil is supported by a coil case which encloses the outer legs of the coil. The coil cases are anchored to the shelves and, in addition, two large rolled centerline further restrain the radial motion of the coil and case. These rings have a 6 in x 6 in cross-section and exert a force of 72,000 lb at each coil location. If unsupported, the yield stress in the outer leg of the TF coil would be exceeded.

The total overturning moment of 4.96×10^6 ft lb is transferred through the coil cases to the shelves and is ultimately resisted by the diagonal members of the torque frame. In addition to the coil case, a portion of the overturning moment is transferred to the shelves through the piers. The piers are wedge-shaped in cross-section and are both pinned and bolted to the shelves and provide additional support to the coils in the vicinity of the lap joint. The piers also serve to align the TF coils.

Surrounding the center shaft and splined to the thrust assemblies is the torque tube. Between the wedge faces of the inner legs of the TF coils are spacers which extend into keyways machined into the torque tube outer diameter. Wedge shaped blocks in the keyway lock the spacers to the torque tube. These tapered steel spacers serve two functions. First, they provide the necessary space for assembly or removal of the TF coil turns. Secondly, they transmit the lateral forces resulting from the inner legs of the TF coils to the torque tube and thrust hubs. The torque tube has vertical insulated joints to prevent the induction of eddy currents. The joint is castellated to transmit torque. A spline near each end of the torque tube provides alignment and transmits the torque into the thurst hub assembly. These forces are ultimately transmitted through the shelf to the torque frame. The torque frame is a deflection limited design, the criterion being to limit rotation of the TF coils to less than 2 mrad during normal operation.

5.4 Poloidal Field Coil System

The PF coils [9] are divided into three categories: the external PF coils, the PF solenoid, and the internal PF coils or canned coils. All of the PF coils are located within the bore of the TF coils, Fig. 16. The external coils, homic heating (OH), centering field (CF), equilibrium field (EF), and nulling field (NF), are located around the domes and outer wall of the vacuum vessel. These coils are of a conventional water cooled copper design and are supported by a cage-like structure surrounding the vacuum vessel. The PF solenoid is a self-supporting glass epoxy cylinder containing windings of each of the four PF systems noted above plus a divertor field coil (DF). The solenoid forms an integral part of the PF supporting cage connecting the inner rim of the upper and lower arch assemblies. The outer solenoid, which connects the outer rim of the arch assemblies, support the largest diameter PF coils thereby completing the cage.

The internal PF coils primarily generate the poloidal DF and are encased in stainless steel containers to prevent outgasing of the electrical insulation inside the vacuum vessel. The internal coils utilize water cooled copper turns which are vacuum impregnated with urethane after being enclosed and sealed in the containers. The canned coil assemblies are attached by metal straps to adjustable brackets and supported by radial I-beams in each dome of the vacuum vessel.

5.5 Other Structural Considerations

The upper and lower shelves serve several important functions. As already noted, the shelves transmit torque from the thrust hubs, piers and coil cases to the torque frame. The upper and lower shelves also provide reference surfaces for alignment of the structural components of the PF and TF coil system. In addition, the lower shelf supports the gravitational loads from the PF and TF coil systems. The shelves are of a box beam construction welded from 305 stainless steel. Each shelf consists of two major welded sections, two pie-shaped insulated sections and five extensions which connect the torque frame. A substructure supports the lower shelf on pylons and provides additional support to the torque frame and center column assembly. The vacuum vessel is supported directly from the substructure base plates to eliminate transmittal of forces between the vacuum vessel and the TF support system through the shelves.

5.6 Stress Analysis

The major factor governing the design is the limitation of stresses in the TF coils to an acceptable level. As noted previously, the highest stresses in the TF coils occur in the lap joint area and are limited to approximately 20,000 psi by the preloaded system. Stresses in the remaining areas of the TF coils do not exceed 15,000 psi. An area of concern, however, is the non-linear variation of the epoxy shear modulus with temperature. This could result in radial deformations of the individual turns of the TF coils in the wedge-shaped inner leg. Increased deformation in this area would bring about a corresponding increase in the inplane bending stresses.

By comparision, stresses in the PF coils are lower. The highest stressed PF coils are located in the outer solenoid where the combined hoop and bending stresses in the copper are less than 6000 psi. Stresses in the steel of the major structural components rarely exceed 7000 psi. In fact these components are generally deflection limited in design. Two notable exceptions were the TF coil spacers and the hydraulic clamp side members where high stresses necessitated the use of Nitronic 33 material.

The TF coils were originally analyzed using the ANSYS finite element code. Individual structural components were studied utilizing SAP IV programs. A finite element model simulating one-fifth of the five-fold symmetry of the machine has been developed by Grumman Corporation. Their in-house code, known as COMAP-ASTRAL, will be used to investigate the nonlinear behavior of the TF coil and the interaction of the various structural components.

The power tests of the PDX machine have been completed and all specifications were met. A good correlation between the test results and design calculations was achieved. A first plasma was obtained on the PDX machine on 29 November 1978.

6. JOINT EUROPEAN TORUS (JET) [10]

6.1 Principle of the Mechanical Structure

The mechanical structure must have sufficient stiffness, particularly against torsion, to ensure that no excessive deformation occurs to the toroidal field coils. As stated previously, each coil is subjected to large radial centripetal forces, as well as to azimuthal forces which appear in both normal operation and under fault conditions. The JET device is shown in Fig. 17.

In order to a[illegible]d bending stresses in the TF coils the mechanical structure, shown in Fig. 18, must provide supports all the way around the TF coils; also provision is made to support the thermal expansion. Insulation gaps are built into the structure to reduce eddy currents, and large ports are designed through which the neutral beam vacuum pumping ducts and other diagnostics are fitted. The design must be such that the strucure can be easily assembled and disassembled both for hands on and later during D-T experiments for remotely controlled maintenance, see figs. 19 and 20 (a).

The structure consists of three main components: the inner cylinder, the upper and lower rings, and the outer sheil which is split into octants.

The inner cylinder supports the TF coils, and its only function is to keep the inner portion of the coils straight. For this purpose vertical cylindrical grooves are machined into its outside diameter, into which the rounded nose of each coil fits. The inner cylinder consists of eight identical sectors of an average thickness of 4 cm, the dowel connection permits the inner ring to expand radially with the temperature change of the inner poloidal field coils.

Since each TF coil is supported by its outer turns resting in the vertical groove of the inner cylinder, shear stresses are induced in the insulation layer between turns of the torus. To compensate for this the shear strength of the coils has been increased by means of interlocking keys between turns. The bearing surface of the TF coils must conform closely with the inner cylinder to avoid local crushing of the coil insulation, or bending stresses within the coils. Calculations which take into account the low shear modulus of the insulation layers between turns have shown that the requirements on straightness and surface finish are within manufacturing capabilities for both the coils and the inner cylinder.

Reinforcing steel rings have been fitted inside of the inner PF coils in order to decrease the compression stresses in them when they take up centripetal forces. These coils are energized in series so that they all expand similarly and thus provide a straight homogeneous support for the toroidal field magnet. The free vertical expansion of both toroidal and poloidal magnets is made possible by means of thin layers of a material with a low friction factor.

The straightness of the inner cylinder has been specified to be within 0.4 mm along the 3.5 m bearing surface; deviations from straightness must be smooth with slopes which do not exceed 0.3 mm/m. Under these conditions the shear stresses induced in the TF coils should not exceed 0.5 kg/mm^2 (710 psi).

The rings are composed of two parts, an inner conically-shaped collar and an outer supporting ring. The collar is made of magnetic steel and can therefore be considered a part of the magnetic circuit. It is split into eight equal sectors and insulated between each sector. Retractable side supports on the collar are provided for the coils. These supports are designed as teeth which are mounted vertically between coils by means of screw mechanisms from the outside. The outer part of the ring is also made up of eight identical insulated sectors with large openings in each sector to accommodate the vertical parts of the vacuum vessel. It is joined on to the collar by means of bolts and steel dowels. The sectors are clamped by insulated bolts and the shear forces are transmitted by cylindrical shear keys made of steel and insulated with glass cloth epoxy. A high degree of accuracy can be achieved on these joints because the rings and collars are pre-assembled by the contractor in a jig where the key holes are drilled together.

The outer shell, see Fig. 20(b), is made up of identical octants which are split into two parts for ease of assembly. These segments are large units extending from top to bottom of the shell and bolted and keyed together by means of flanges along the meridian line. Inside of the shell, the side supports for the coils are provided by a box section which also stiffens the shell against bending and torsional deformations. Thermal expansion for the TF coils is accommodated by a gap between the periphery of the coils and the extended shell. The insulated shear connections between octants must be of an adjustable type to allow for minor misalignments at assembly. This will probably be accomplished by using insulated bolts and keys, and with the shear keys of prismatic shape and shimming devices to make up for the remaining gaps.

It is proposed to manufacture the inner collar from cast carbon steel and the rings from stainless steel or austenitic nodular cast iron, while the outer shell will be fabricated from type 304 stainless steel, stress relieved to 500°C after welding, see Fig. 21.

6.2 Stress Analysis

The highest stresses in the ring assembly arise in the contact surfaces of the dowel joint between the collar and the outer part of the ring. The peak bearing pressures on the dowels of this joint are of the order of 14 - 17 kg/mm^2 (20 - 24 ksi). This value includes the stress concentration effects due to the non-uniformity of the bearing pressure on the dowel.

The dowel connection between the inner cylinder and the collar has a stress range of 10 - 17 kg/mm^2 (14 - 24 ksi), in the joints between the octants of the outer shell the shear is transmitted by insulated hexagonal keys, the bearing pressure on these insulated keys if uniformly distributed so that the average value for the joint is less than 6 kg/mm^2 (8.5 ksi). Owing to stress concentrations in the shell in the vicinity of the openings some keys will experience higher loads, but the maximum stress anywhere is expected to be less than 15 kg/mm^2 (21.2 ksi). The three-dimensional finite element model calculations performed indicated that in the most severe case the overall rotational deformation can be kept below 3 mm on the periphery of the rings which is acceptable for the TF coils.

6.3 Toroidal Fields Coils (TF)

There are 32 D-shaped TF coils required for the JET machine, see Fig. 22. They are 224 in overall height by 152 in overall width. Each coil weighs 12 tons and consists of two pancakes of 12 turns per pancake. The copper cross-section varies from 37 cm^2 (4.2 in.^{2}) on the inner part to 39 cm^2 (60 in.^{2}) on the outer part. The coils are not cased. See Table 3 for a list of TF coil specifications.

The copper bars are wound under tension on a kidney-shaped mandrel. The amount of overbend on the straight side of the coil will be evaluated during several full scale winding tests. The straight lengths of copper bar of approximately 11 m (36 ft.) will be prebent before winding in order to keep the cooling holes at the machined portion of the coil in a symmetrical position. As winding proceeds, additional lengths of copper bar are brazed on until a complete coil is wound.

There is an interlocking key between turns which consists of preimpregnated glass fabric, where the fibers are arranged at right angles but not interwoven, the whole banded together by adhesion. The interturn insulation on both sides of the key consists of ten layers of dry glass sheet and two layers of prepreg. One or two layers of these dry glass sheets extend around the key, see Fig. 23.

The advantages and disadvantages of D-shaped coils were evaluated before the final design of D-coils was accepted for JET. The stresses and deflections of the TF coils under varying load and support conditions were checked by using two- and three-dimensional finite element computations (STRUDL and ASKA).

There exists a general agreement that D-shaped coils can:

(1) better accommodate non-circular plasmas and plasmas of low aspect ratios;

(2) considerably reduce the bending stress and the shear stress inside the windings; and

(3) alleviate the support problem.

On the other hand, of course, circular coils are better suited for fabrication.

The reduction of shear stress between turns of a multi-turn coil is helpful because of the poor bond strength between the interturn insulation and the copper turns.

Circular coils of approximately this size would exhibit high bending and shear stresses up to approximately 2 kg/mm^2 (2.8 k[illegible]) shear stress in the insulation layers between turns. In order to decrease these shear stresses, the circular coils would have to be designed thicker in the radial direction or supported externally by a structure or coil case. Both of these solutions are at the cost of an increased aspect ratio or, in other words, at the cost of reduced performance for a machine of the same overall size.

6.4 Poloidal Field Coils (PF)

The inner poloidal coil stack consists of 12 identical coils mounted one above the other at the center of the machine. In addition to their own electromagnetic forces, they support the inward force of the toroidal field coils in the radial direction and the weight and the magnetic force of the transformer core in the vertical direction. Each coil consists of an eight-layer six-turn, water cooled copper winding, see Fig. 24 for details.

The conductor is extruded copper with 0.1% silver added to improve the creep properties and reduce the amount of softening adjacent to the brazed joints. It is available in 8 - 17 m lengths and will be jointed by butt brazing during winding to make the total length per coil of 270 m (880 ft.).

The insulation between turns is to be either glass fiber and mica tape or glass fiber interlaced with kapton tape; in either case the whole will be vacuum impregnated with epoxy resin.

The outer poloidal field coils consist of two circular coils (number 3) of 7.88 m (25.8 ft) mean diameter and two coils (number 4) of 10.49 m (31.3 ft) mean diameter; the weight of copper per coil is 20.2 tons and 35.9 tons, respectively.

6.5 The Transformer Core

The present design consists of a structure weighing 2500 tons. The radial legs and eight outer vertical limbs are made of insulated steel laminations held together by thick side plates, with strong feet bolted to the foundations. The upper legs must be able to accommodate the thermal expansion of the inner poloidal field coils. The legs are assembled from thin electrical-type steel sheets stacked by hand.

Three-dimensional flux calculations were carried out. The coil and plasma currents, as calculated by POTENT and EQUILI, have been used as data in the Rutherford Laboratory, both as a check and to enable the effect of stray fields to be studied.

The stray field significantly reduces the flux which must be carried in the iron, and can also affect diagnostic equipment and neutral beam injection sources.

7. TOKAMAK FUSION TEST REACTOR (TFTR)

The principal structural problem in the TFTR is the design of the TF coils and the method of supporting them for the centering forces and overturning moment. The three principal structural elements which perform this function are the 20 TF coils and their cases, the inner support structure, and the shear compression panels, see Fig. 25 for a composite view of the TFTR.

7.1 Principle of the Mechanical Structure

The inner support structure is a vertical cylinder which has four horizontal stiffening rings and is located at the center of the machine. Each of the 20 TF coils contacts the inner support structure at these stiffening rings. The inner support structure is split into four vertical insulated elements to minimize the eddy currents caused by the time varying magnetic field produced by the ohmic heating coils. There are teeth in the insulated surfaces to transfer mechanical stresses across these boundaries. The elements of the inner support structure are made of diffusion bonded titanium pieces. Titanium was chosen because of its low modulus of elasticity and high strength.

The shear compression panels are large box-like Nitronic 33 stainless steel weldments. They fit between the TF coils and are bolted to the side covers of the TF coil cases at the outer radius of the machine. These boxes, together with the TF coils, form a ring around the machine with the shear compression panels acting as blocks in an arch.

A top view of the TFTR device shows the three elements of the main structure, see Fig. 25. The inner support structure appears like the hub of a wheel. The 20 toroidal field coils are the spokes of the wheel and the shear compression panels with the coils form the outer rim.

7.2 Stress Analysis

The action of the centering force is to move the TF coils radially inward toward the center of the machine. This action is resisted by the hoop compression in both the inner support structure and the shear compression panels. The centering force load is approximately 6 x 10^6 lb on each TF coil. The proper sharing of this load between these two elements must be carefully regulated to minimize stress levels in the coils. The centering force is the sum of the magnetic body forces generated in the coil copper. These body forces must be transmitted through the copper and case to the support points at the inner support structure and shear compression boxes. A consequence of this loading is a horizontal shear stress which appears across the relatively weak epoxy-fiberglass insulation between the copper layers of the coil. Advanced finite element stress codes have recently become available to determine these shear stresses in the insulation [11]. The selection of titanium for the inner support structure was necessary in order to prevent this member from becoming overly stiff with respect to the shear compression panels.

Both the inner support structure and the shear compression boxes also support the TF coils against the overturning moment. The overturning moment on each coil is 80 x 10^6 in. lb. The TF coils are keyed to the inner support structure at the horizontal stiffening rings. For this loading condition the inner support structure acts as a cylinder carrying torsion. The shear compression panels resist the overturning moment by shearing action. This is of course not as efficient as the more common bracing as seen on the PLT and PDX, but does permit greater access to the interior of the machine for neutral injection beams, pump ducts and diagnostics. The shear compression panel is similar to the panels used on the torque frame of the ATC.

7.3 Toroidal Field Coils (TF)

Each TF coil [12] is wound with two coil pancakes consisting of 22 turns of hard copper bar approximately 6 in. x 4/3 in. cross-section, see Fig. 26. The turns of copper are electrically insulated from each other with epoxy-fiberglass insulation. Both the copper and the insulation, in addition to performing their functions as electrical conductor and insulation, are load carrying members. The coils receive additional support from a case of Nitronic 33 stainless steel. The case consists of a 2 in. thick inner ring which fits into the bore of coil, an outer ring 8 in. thick which fits over the outside diameter of the coil, and two side covers which are bolted into the inner and outer rings; the side covers are nominally 3/4 in. thick. See Table 4 for a list of TFTR TF coil specifications.

7.4 The PF Coils and their Structural Supports

The PF coils are wound from hard copper with vacuum impregnated epoxy fiberglass insulation which also acts as a structural bond for the coils. These coils are not in a case. There are 18 discreet coil groups with nine above and nine below the horizontal mid-plane of the machine, see Fig. 27. Every coil of this system lies in a horizontal plane with its center line co-axial with the vertical center line of the machine. The coils are subjected to radial and vertical magnetic forces. The radial forces are reacted by hoop stresses in the coil copper. The vertical forces are reacted by support from external structures. Coils in the inner group are supported from the inner support structured and the outer group coils are supported by either the floor or the superstructure, depending upon whether the coils are above or below the mid-plane. Between supports the coils behave as curved beams with tension and compression stresses in the copper, and shear stresses in the epoxy-fiberglass insulation. The support brackets of these coils are designed to give minimum restriction to the radial deformation of the coil and still give full vertical support.

In any particular coil group there may be as many as three distinct coils. However, owing to the close grouping of the coils' magnetic centers, the three coils must share one support system and the cast as a monolithic stack. At any particular time the different coils within a stack are subjected to different loadings. One coil may not be carrying any current and not be subjected to any loads while its neighbor will be carrying full current and be experiencing full loading, including thermal expansion. The fiberglass bond between coils is designed to transmit the necessary stresses to force both coils to experience the same deformations.

8. CONCLUSION

The structrual and coil designs of four tokamaks have been presented. Each illustrates variation of designs to fit the particular parameters of the specific experiment. For example, owing to the complexity of the PF coils in PDX, an elaborate method of assembling demountable TF coils was designed. These demountable coils simplify the assembly, maintenance and possible replacement of the PF coils. On the other hand, the engineering problems associated with designing the demountable joint for the TF coils were among the most difficult encountered in manufacturing the device. As indicated in the text, trade-offs are often made to accommodate the specific requirements of the experiments. Table 5 lists the major design parameters and objectives for each of four tokamaks reported for comparison with each other.

As we move into the design and construction of the next generation of tokamaks, more than likely an engineering test facility (ETF), even larger coils, probably superconducting coils, in a 14 MeV neutron environment, will tax the state of the art of tokamak structure and coil design. However, the basic methods and principles described above, properly modified for specific requirements, are applicable, regardless of size of coil, material used, and strength of the magnetic field.

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FIGURE CAPTIONS

Fig. 1 The ST-tokamak after conversion.

Fig. 2 Confinement as a function of electron temperature in the C-stellarator compared to the ST-tokamaks.

Fig. 3 The Adiabetic Toroidal Compressor (ATC).

Fig. 4 The Princeton Large Torus (PLT).

Fig. 5 The Poloidal Divertor Experiment (PDX).

Fig. 6 The Soviet Union's T-10 tokamak.

Fig. 7 An exploded view of the PLT device showing: 1. toroidal field coil; 2. upper shelf halves; 3. split wedge castings; 4. center column hubs; 5. diagonal bracing; 6. vertical bracing; 7. torque tubing; 8. center column plug; and 9. center column stud.

Fig. 8 Cross-section of PLT.

Fig. 9 Center column assembly.

Fig. 10 Section showing poloidal field coils.

Fig. 11 PLT - toroidal field coil.

Fig. 12 Artist's view of PDX: 1. Plasma; 2. divertor coils; 3. separatrix; 4. burial chamber.

Fig. 13 Cross-section of PDX.

Fig. 14 PDX TF coil joint detail.

Fig. 15 PDX TF coil clamp.

Fig. 16 PDX poloidal coil system layout.

Fig. 17 The JET apparatus - elevation. (Reproduced by courtesy of the Commission of the European Communities.)

Fig. 18 The JET apparatus - plan. (Reproduced by courtesy of the Commission of the European Communities.)

Fig. 19 Mechanical structure design. (Reproduced by courtesy of the Commission of the European Communities.)

Fig. 20 (a) Mechanical structure method of assembly. (b) Outer part of the mechanical structure. (Reproduced by courtesy of the Commission of the European Communities.)

Fig. 21 Coil case structures. (Reproduced by courtesy of the Commission of European Communities.)

Fig. 22 JET TF coils. (Reproduced by courtesy of the Commission of European Communities.)

Fig. 23 JET TF coil insulation scheme. (Reproduced by courtesy of the Commission of European Communities.)

Fig. 24 General arrangment of the poloidal field system. (Reproduced by courtesy of the Commission of the European Communities.)

Fig. 25 TFTR

Fig. 26 TFTR toroidal field coil.

Fig. 27 A photograph of the TFTR mockup, section view showing the PF coil system and its supports outside of the TF coil.

Table 1

Specifications for PLT TF Coil

Shape of coil	circular, wedge-shaped nose
Maximum design current, A	42,800
Number of turns per coil	42
Number of pancakes per coil	2
Total number of coils	18
Build of coils, m	0.4
Max width of coils, m	0.25
Type of conductor	C.D.A. no. 104, 8 oz silver/ton
Method of cooling coils	water
Conductor cross section, cm	width = 12.01, thickness = 3.175 (2 turns), 2.54 (2 turns), [illegible].47 (13 turns)
Shape and size of waterhole, cm	0.310 in. i.d./360 in. o.d. copper tube brazed into conductors
Maximum temperature rise	limit = 100°C (copper)
Coil cases	no
Turn to turn insulation	two layers 0.040 in. B stage epoxy +0.015 m conolite (one layer between two turns)
Pancake to pancake insulation	four layers 0.030 in. B stage.
Ground insulation	3/16 in. dry glass tape, vacuum impreg./w no. 820 shell epoxy.
Maximum stress in conductor	31.8 ksi (plasma disrupt.)
Weight per coil, tons	5.5

Table 2

Specifications for PDX TF Coils

Shape of coil	racetrack
Maximum design current, A	43.7 kA
Number of turns per coil	20 turn double layer solenoid coil
Total number of coils	20
Build of coils, m	0.20
Max width of coils, m	0.29
Type of conductor	copper alloy no. 104 worked to yield strength >35 ksi.
Method of cooling coils	deionized H_2O 11°C.
Conductor cross section, cm	outer leg, outer turn - 11.1 x 2.5, inner turn - 8.6 x 2.5.
Shape and size of waterhole, cm	elliptical - 1.6 x 0.6.
Maximum temperature rise	25°C.
Coil cases	yes
Turn to turn insulation	1.0 mm mylar and epoxy glass
Ground insulation	1.0 mm mylar and epoxy glass
Maximum stress in conductor	20 ksi
Weight per coil, tons	4.0

Table 3

Specifications for JET TF Coils

Shape of coil	D
Maximum design current, A	41 MA extended 51 MA
Number of turns per coil	12
Number of pancakes per coil	2
Total number of coils	32
Build of coils, m	5.68 x 3.86
Max width of coils, m	338 mm
Type of conductor	silver/copper
Method of cooling coils	water cooled
Average cross-section	inner: 2700 mm^2, outer: 3900 mm^2
Shape and size of waterhole	oval
Maximum temperature rise	71°C.
Coil cases	no
Turn to turn insulation	2 mm
Pancake to pancake insulation	8 mm
Ground insulation	6 mm
Maximum stress in conductor	5.9 kg/mm^2 (tensile inside winding)
Weight per coil, tons	12

Table 4

Specifications for TFTR TF Coils

Shape of coil	circular
Maximum design current, A	73,300
Number of turns per coil	44
Number of pancakes per coil	2
Total number of coils	20
Build of coils, m	0.38
Max width of coils, m	0.339
Type of conductor	copper CDA 104
Method of cooling coils	water
Conductor cross section, cm	16.63 x 1.42; 16.63 x 1.54; 16.63 x 1.73
Shape and size of waterhole, cm	2.04 x 0.711
Maximum temperature rise	92°F.
Coil cases	yes
Turn to turn insulation	epoxy-glass laminate
Pancake to pancake insulation	epoxy-glass laminate
Ground insulation	epoxy-glass laminate
Maximum stress in conductor	25 ksi
Weight per coil, tons	26.8

Table 5

Comparison of Tokamaks

Item	PLT	PDX	JET	TFTR
Number of TF coils	18	20	32	20
Shape of TF coils	circular wedge-shaped nose	racetrack	D-shaped	circular wedge-shaped nose
Bore of coils, m	1.6	3.6 x 1.88	4.9 x 3.1	2.8
Major radius of torus, m	1.4	1.49	3.0	2.65
Minor radius of plasma, m	0.45	roughly square 0.8	1.25 horizontal 2.10 vertical	0.85
Plasma current, kA	480	500	3000	2500
Field at plasma, I	4.96	2.35	2.7	5.2
Field at inside conductor of TF coils, T	10.6	6.4	5.6	9.75
Centering force per coil, tons	1620	900	1220	3000
Overturning moment, per coil, 10^6 in.	10.2	2.98	16.1	80
Method of initial plasma breakdown	air core solenoid	air core solenoid	iron core transformer	air core solenoid
Location of PF coils	inside TF bore	inside TF bore	outside TF coils	outside TF coils
Anticipated plasma temp with neutral beam heating, KeV	6[a)]	8-10 keV	>5	>5

a) Achieved on 28 July 1978.

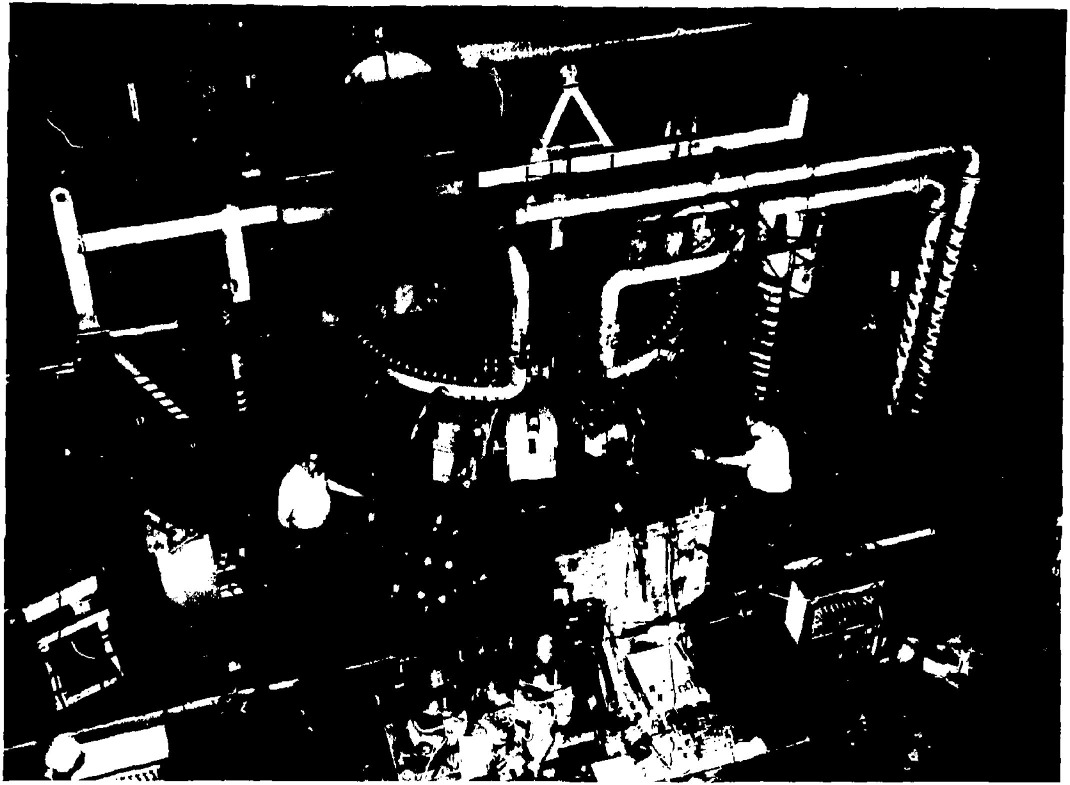


Fig. 1. The ST Tokamak after conversion.

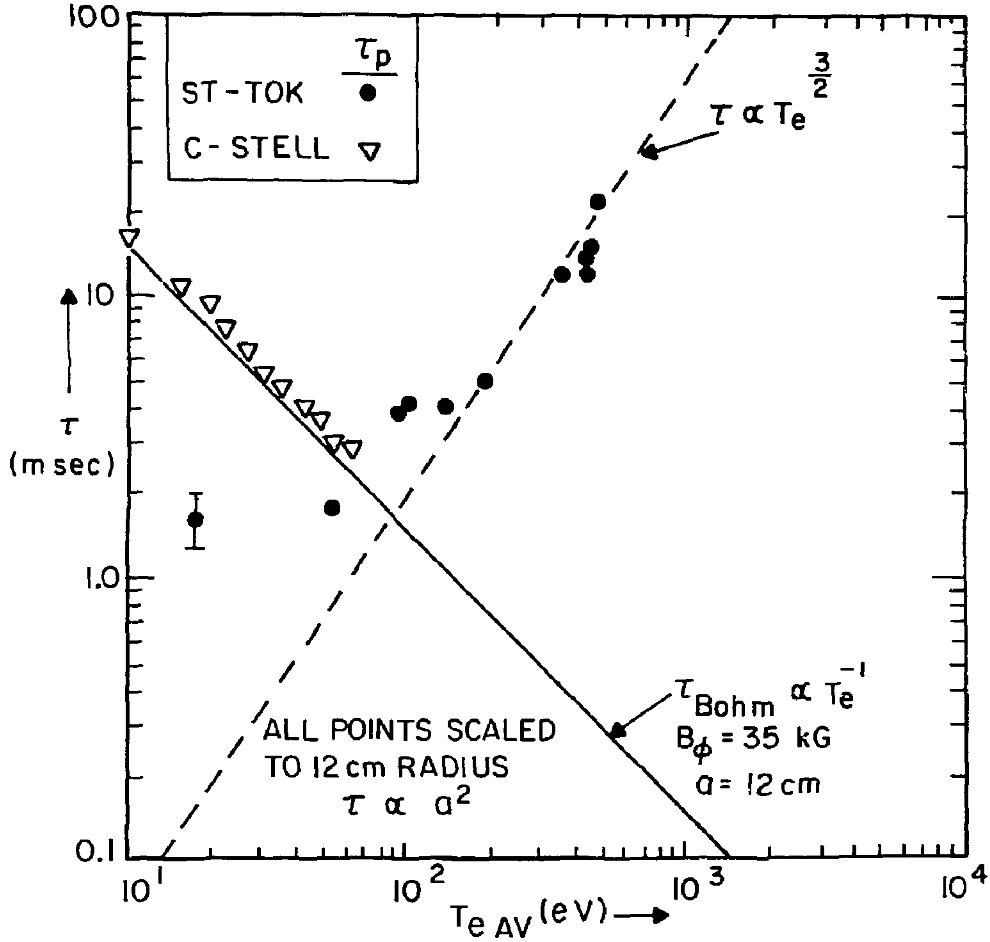


Fig. 2. Confinement as a function of average electron temperature in the C-Stellarator compared to the ST Tokamak.

Fig. 3. The Adiabetic Toroidal Compressor (ATC)

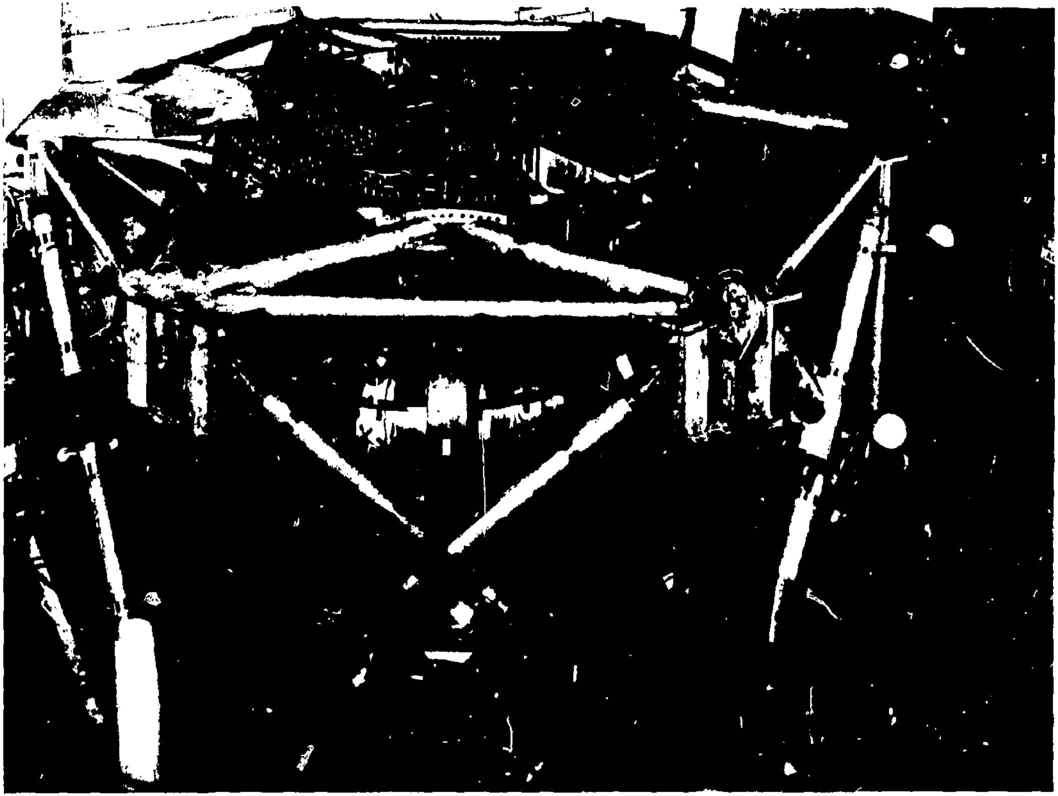


Fig. 4. The Princeton Large Torus (PLT)

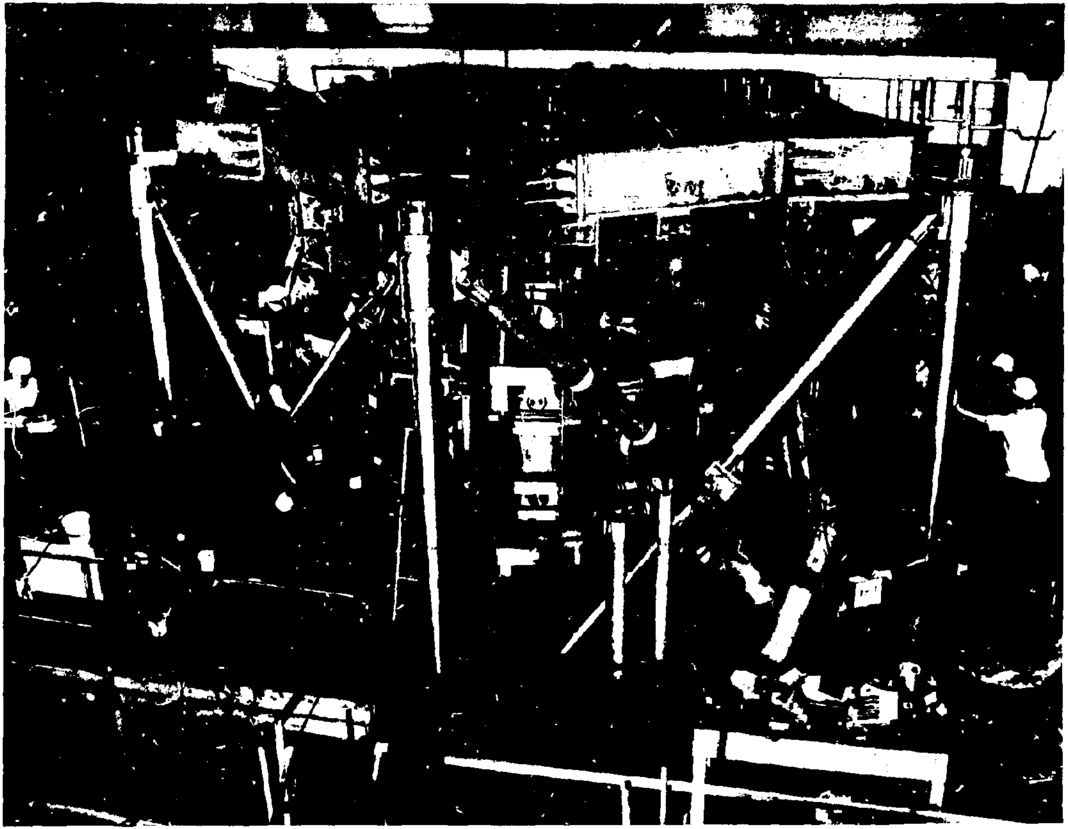


Fig. 5. The Poloidal Divertor Experiment (PDX).

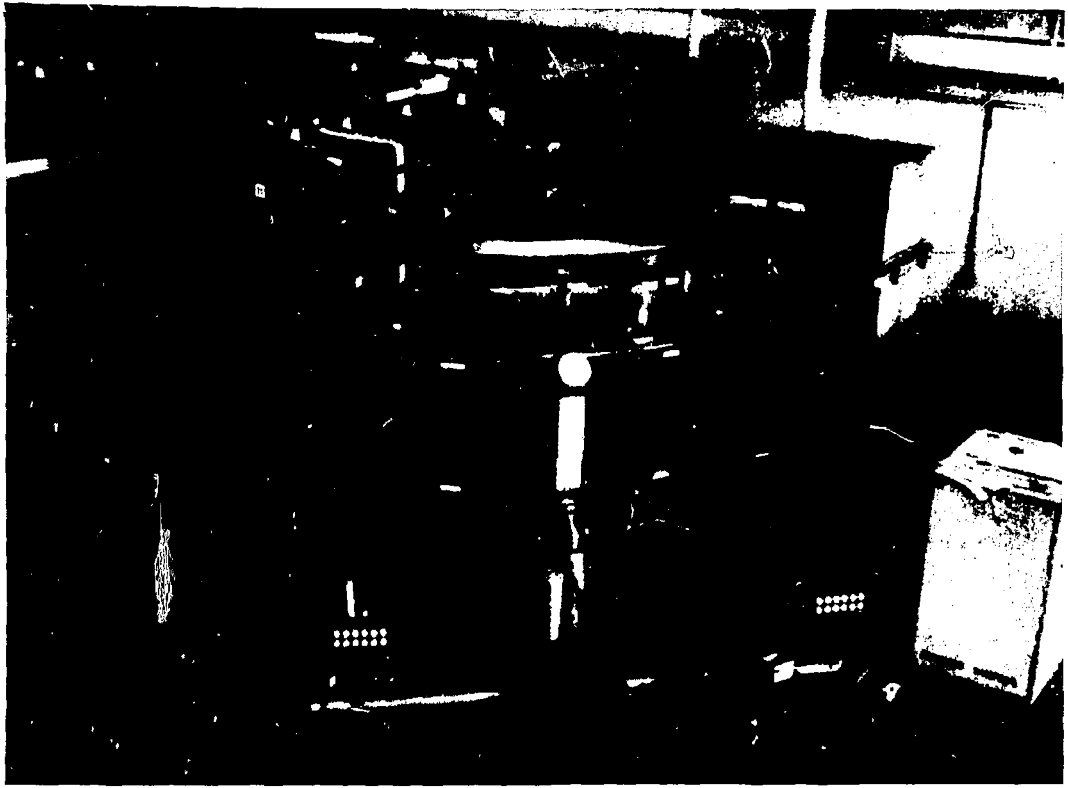
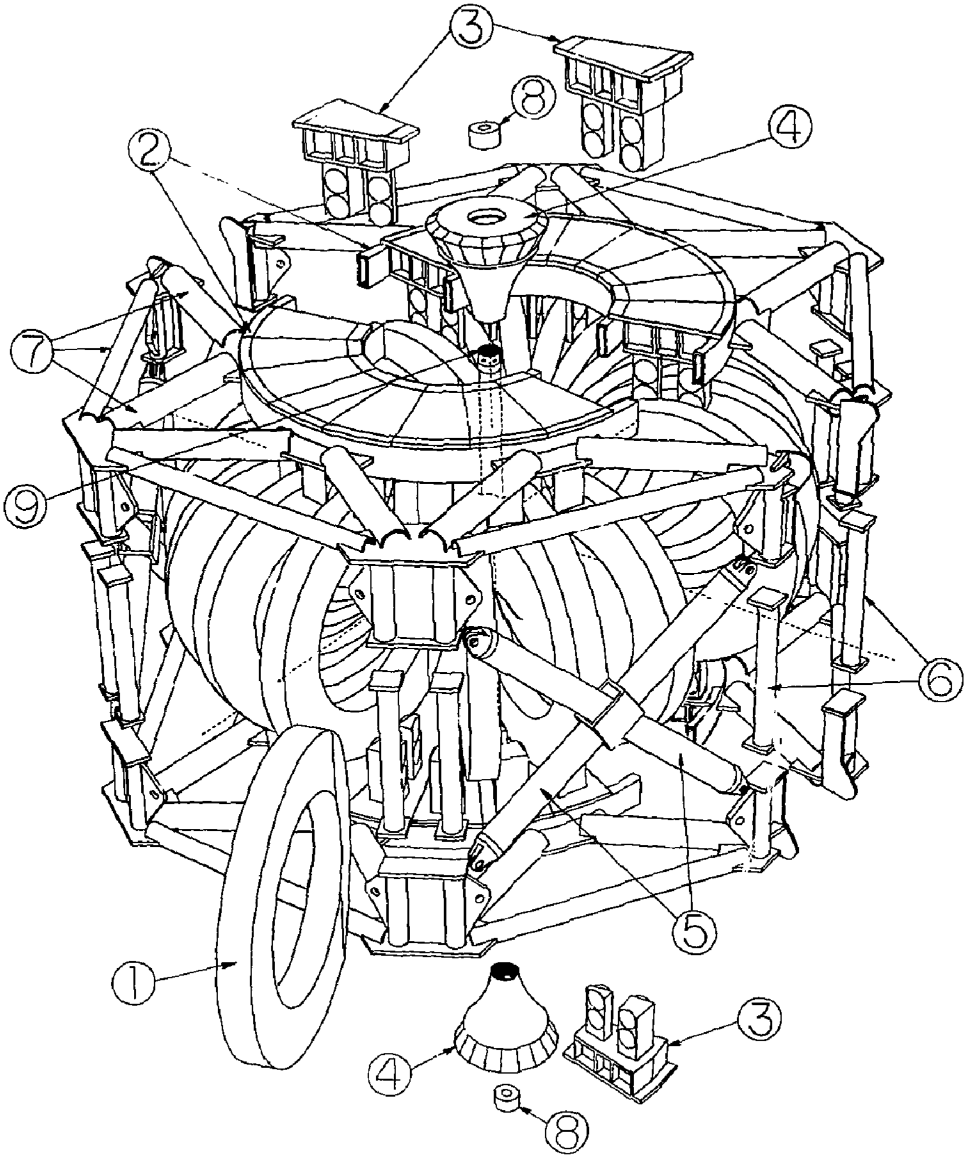


Fig. 6. The Soviet Union's T-10 Tokamak.



An exploded view of the PLT device showing:

1. Toroidal Field Coil
2. Upper Shelf Halves
3. Split Wedge Castings
4. Center Column Hubs
5. Diagonal Bracing
6. Vertical Bracing
7. Torque Tubing
8. Center Column Plug
9. Center Column Stud

Fig. 7.

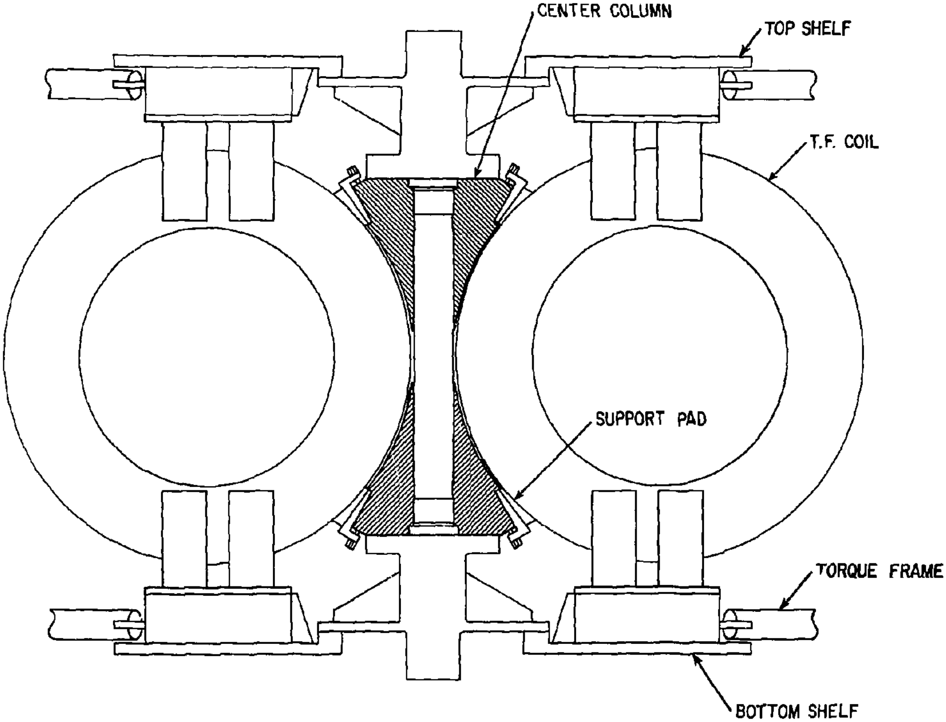


Fig. 8. Cross -ection of PLT.

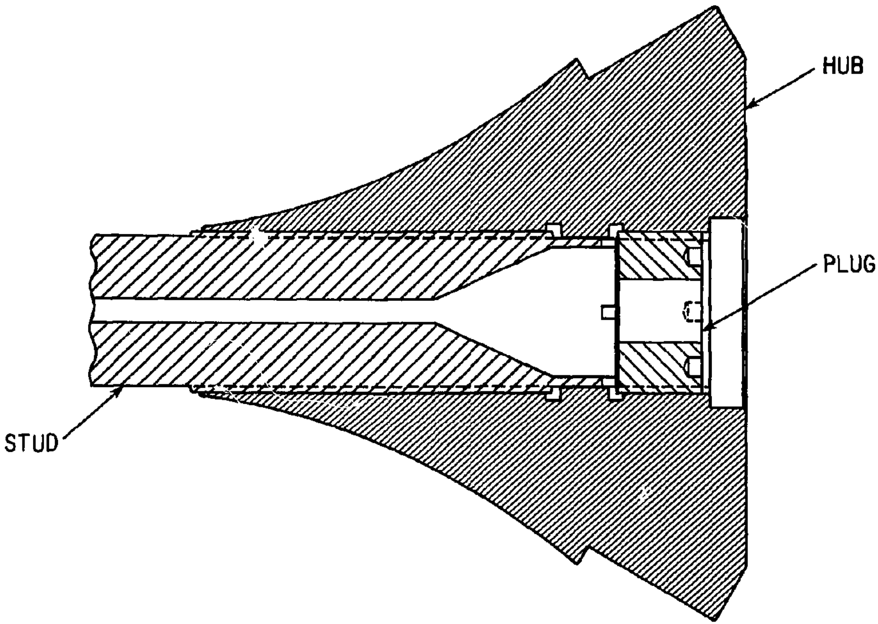


Fig. 9. Center Column Assembly.

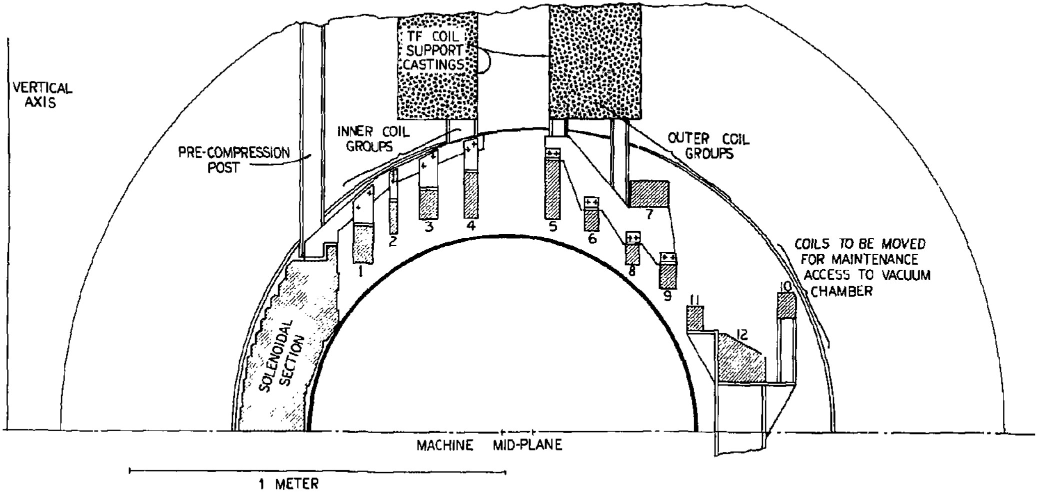


Fig. 10. Section showing poloidal field coils.

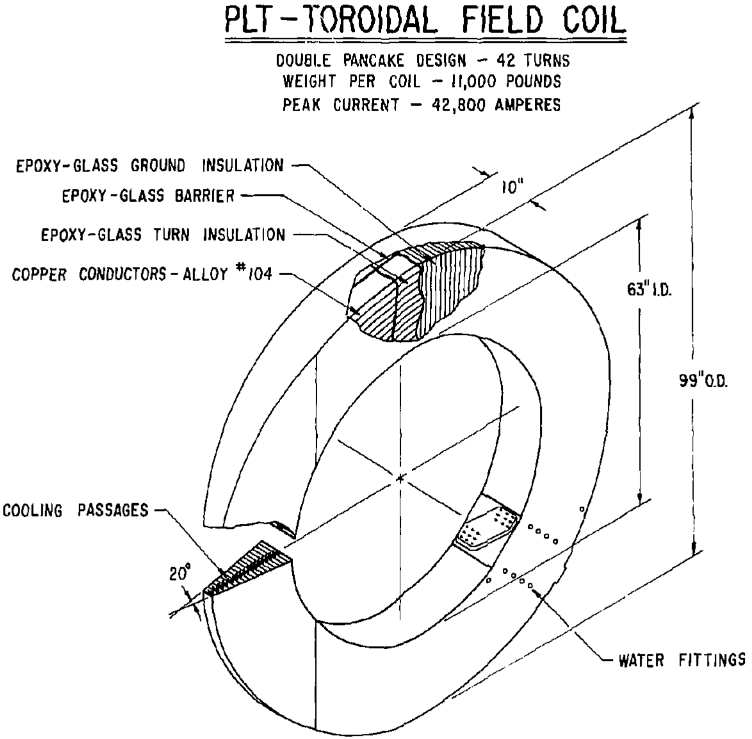
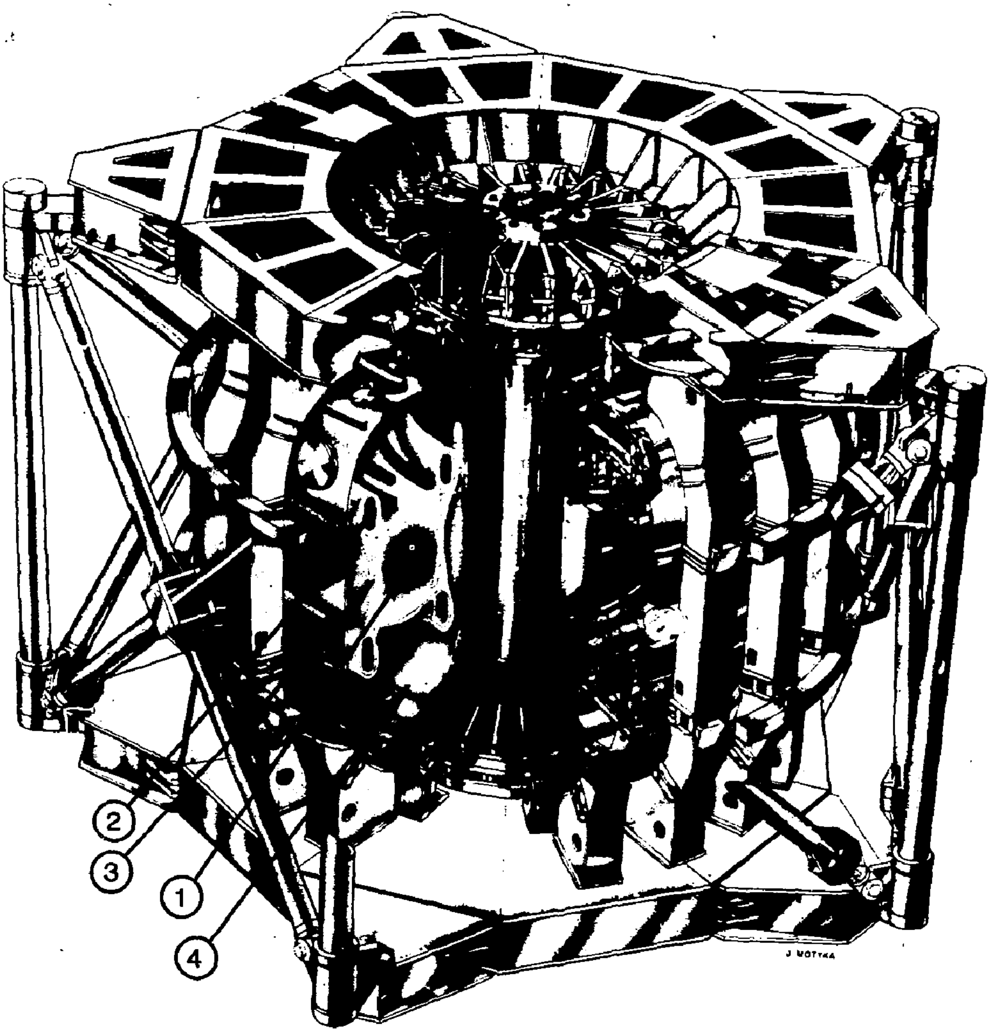

PLT-TOROIDAL FIELD COIL
DOUBLE PANCAKE DESIGN - 42 TURNS
WEIGHT PER COIL - 11,000 POUNDS
PEAK CURRENT - 42,800 AMPERES
EPOXY-GLASS GROUND INSULATION
EPOXY-GLASS BARRIER
EPOXY-GLASS TURN INSULATION
COPPER CONDUCTORS - ALLOY #104
10"
63" I.D.
99" O.D.
COOLING PASSAGES
20°
WATER FITTINGS

Fig. 11.



1. Plasma
2. Divertor Coils
3. Separatrix
4. Burial Chamber

Fig. 12. Artist's view of POX.

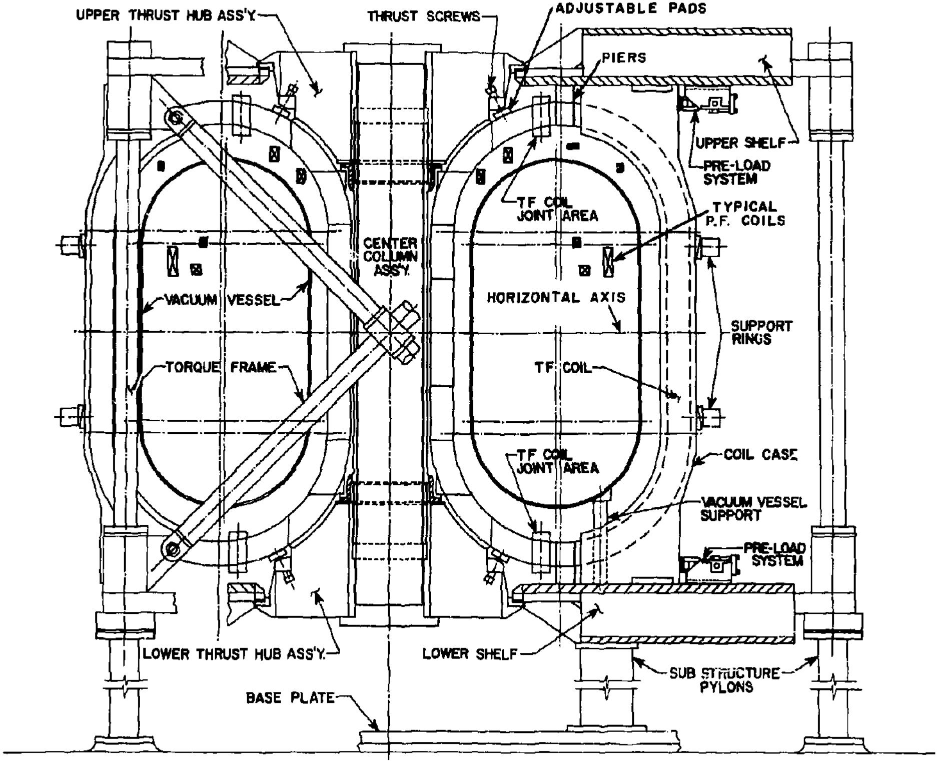


Fig. 13. Cross section of PDX.

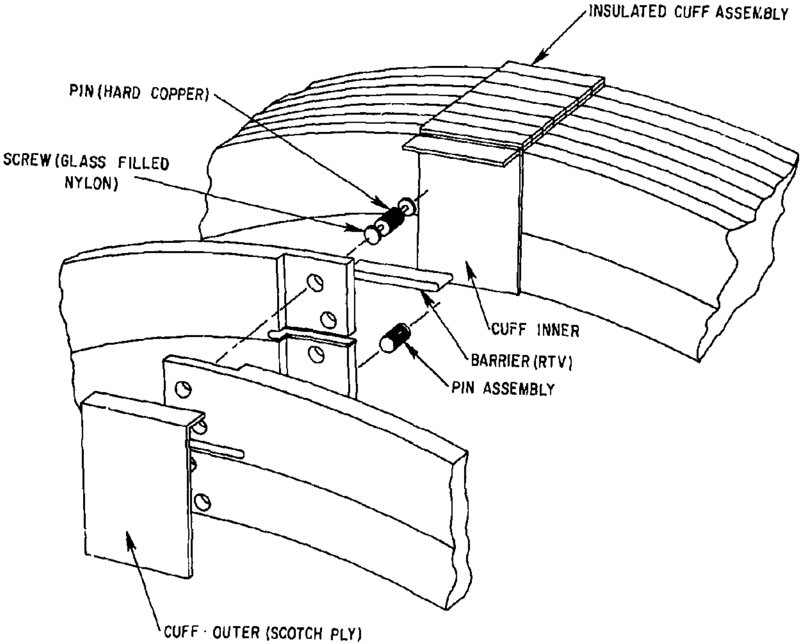


Fig. 14. PDX TF Coil Joint Detail.

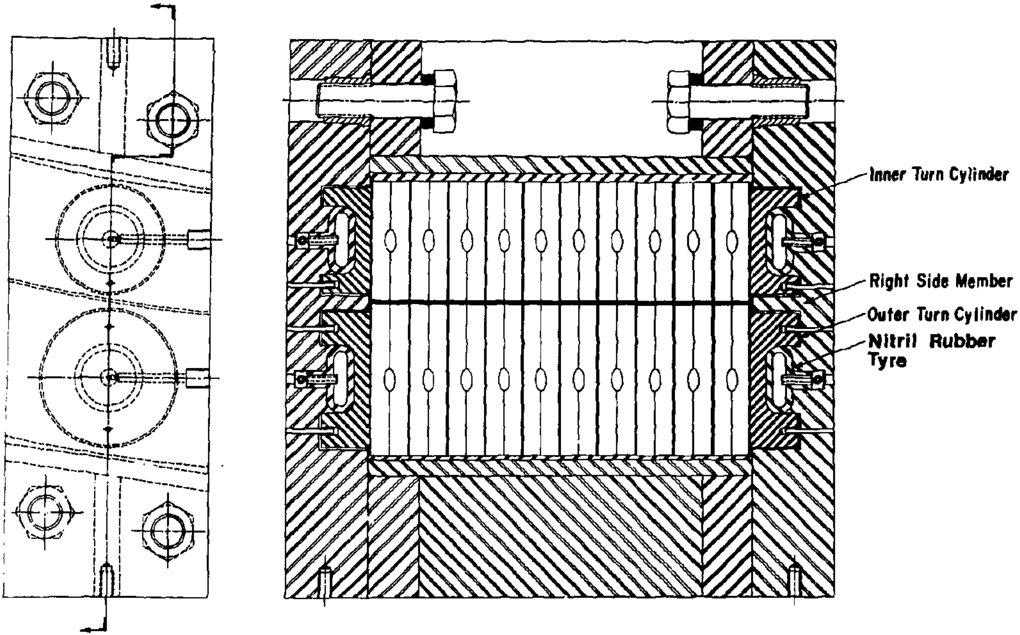


Fig. 15. PDX TF Coil Clamp

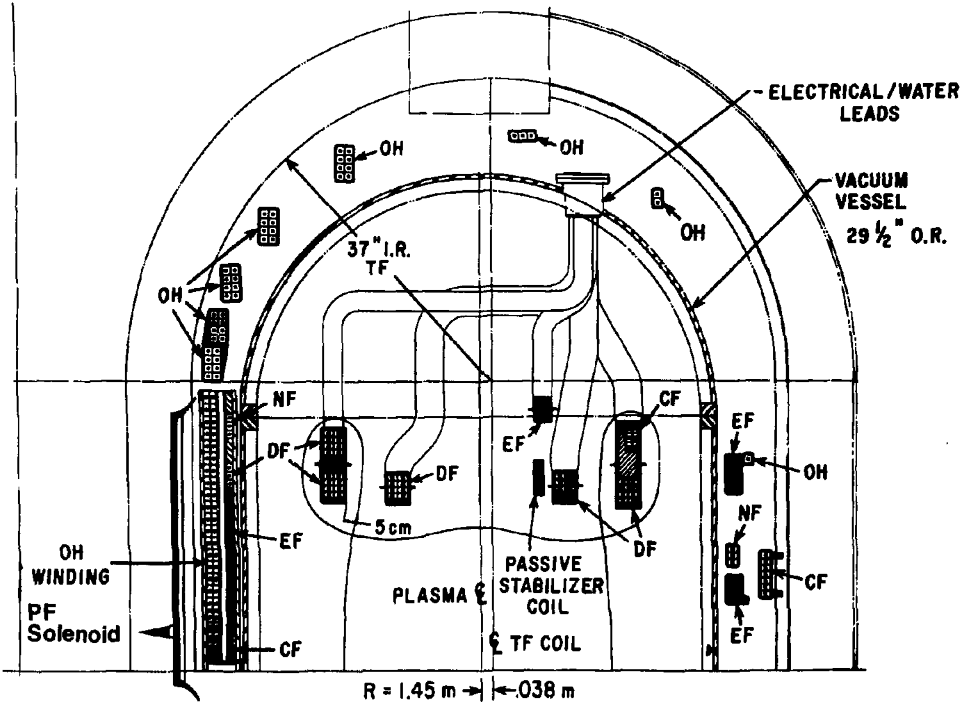


Fig. 16. PDX POLOIDAL COIL SYSTEM LAYOUT

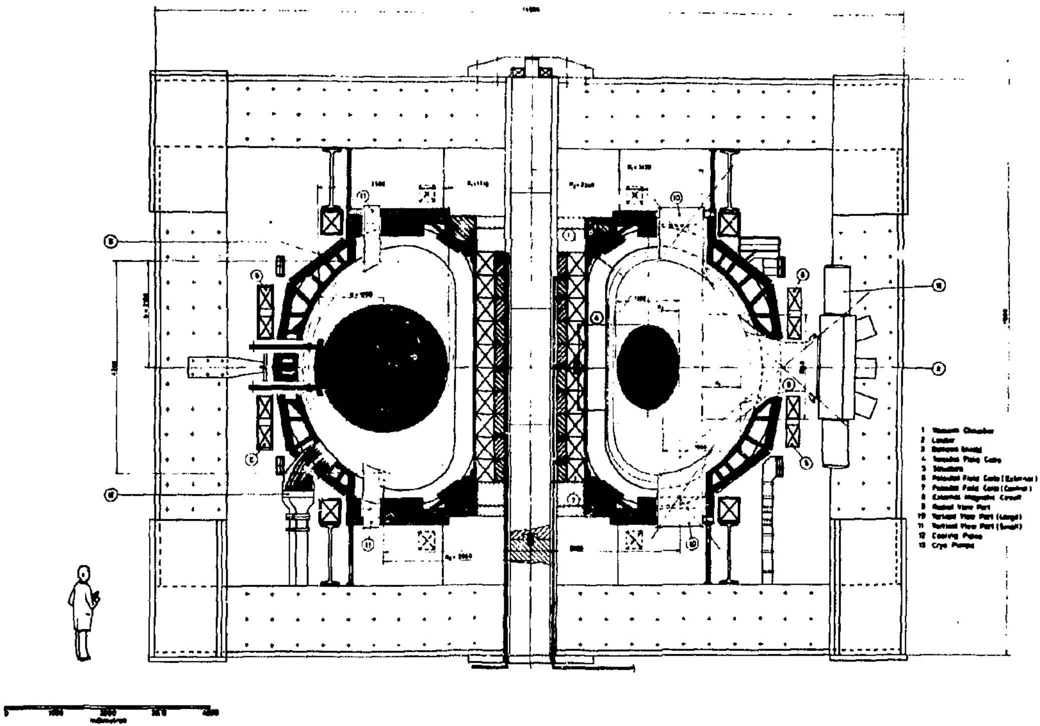


Fig. 17. **The JET Apparatus – Elevation**

Courtesy: Commission of the European Communities.

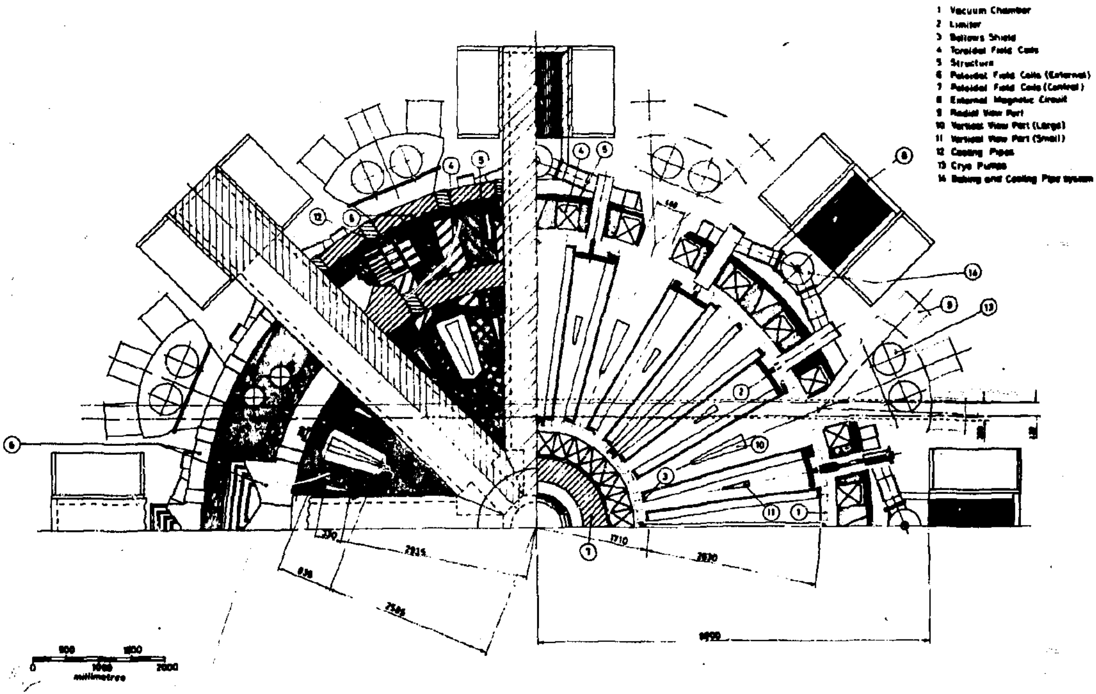


Fig. 18. **The JET Apparatus – Plan**

Courtesy: Commission of the European Communities.

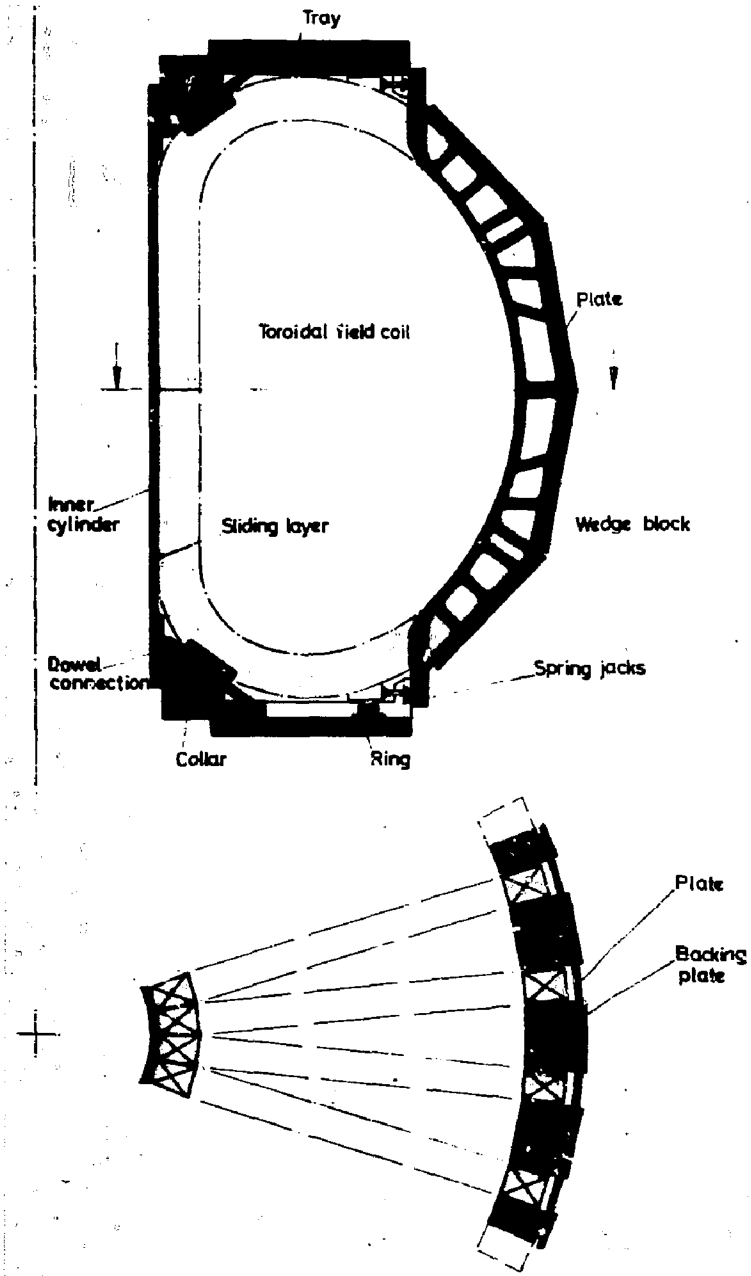


Fig. 19. **Mechanical Structure Design**

Courtesy: Commission of the European Communities.

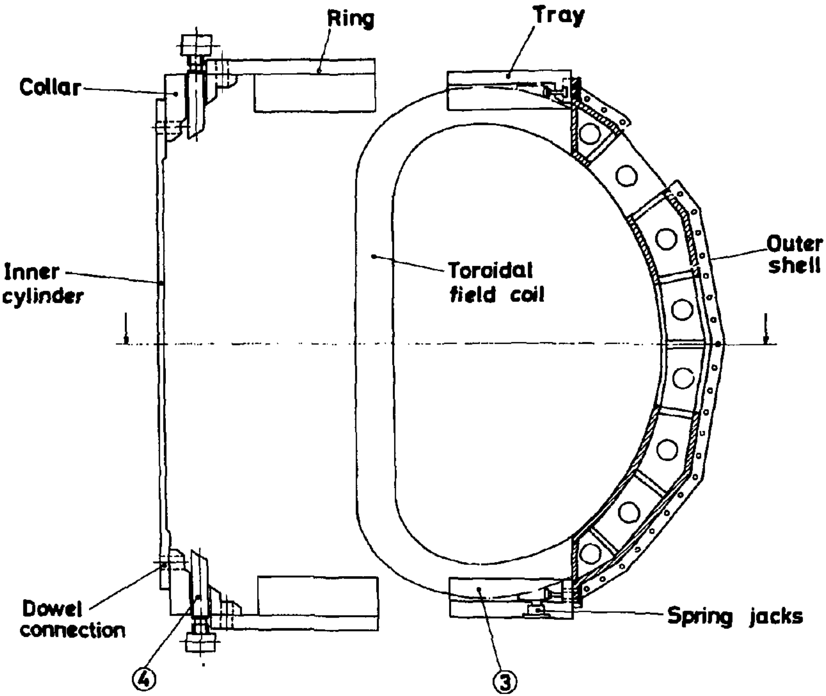


Fig. 20. Mechanical Structure
Method of Assembly

Courtesy: Commission of the European Communities.

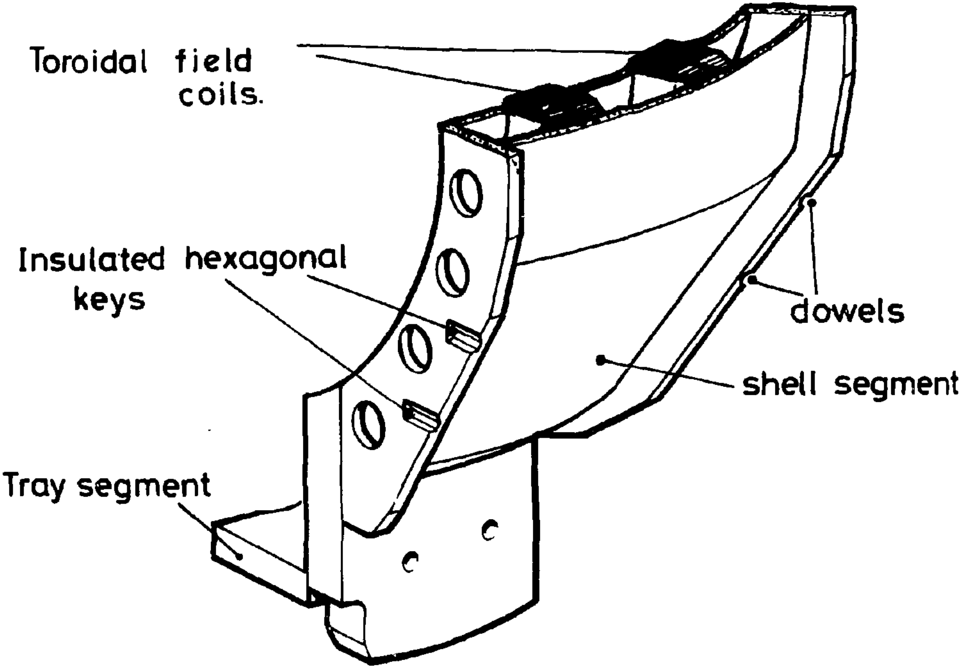


Fig. 20a. Outer part of the Mechanical Structure

Courtesy: Commission of the European Communities.

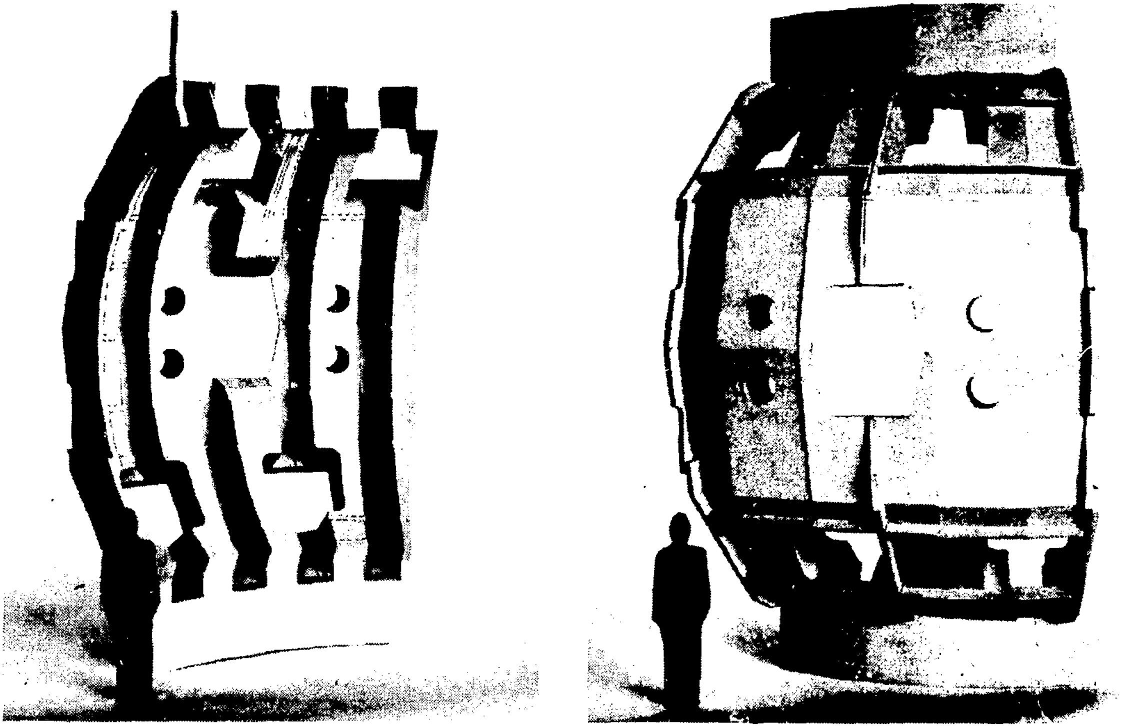


Fig. 21. Coil Case Structures

Courtesy: Commission of the European Communities.

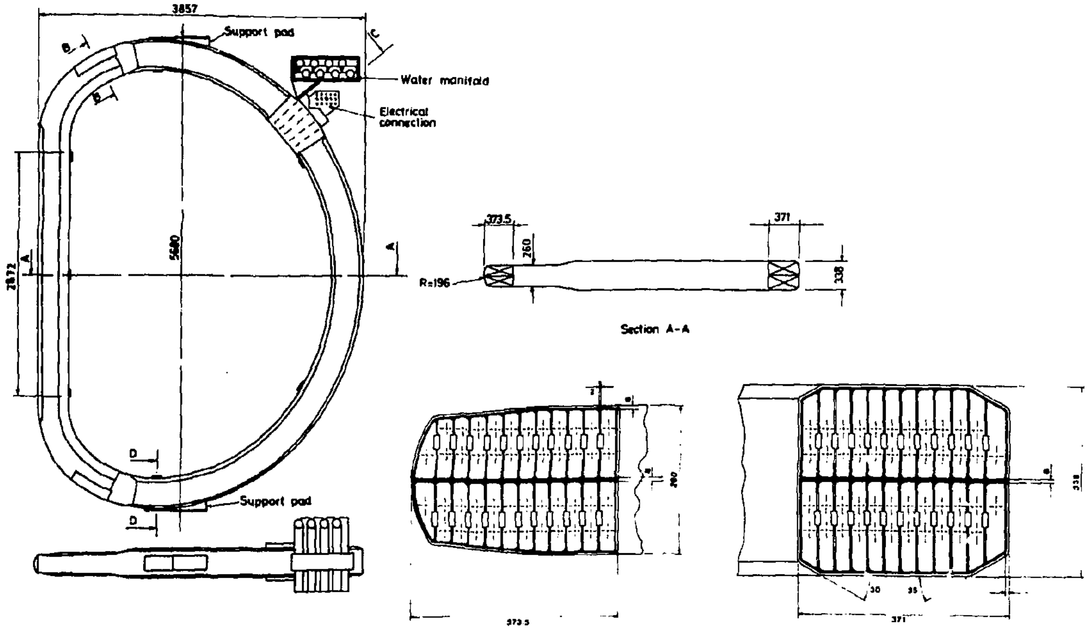


Fig. 22. JET TF Coils

Courtesy: Commission of the European Communities.

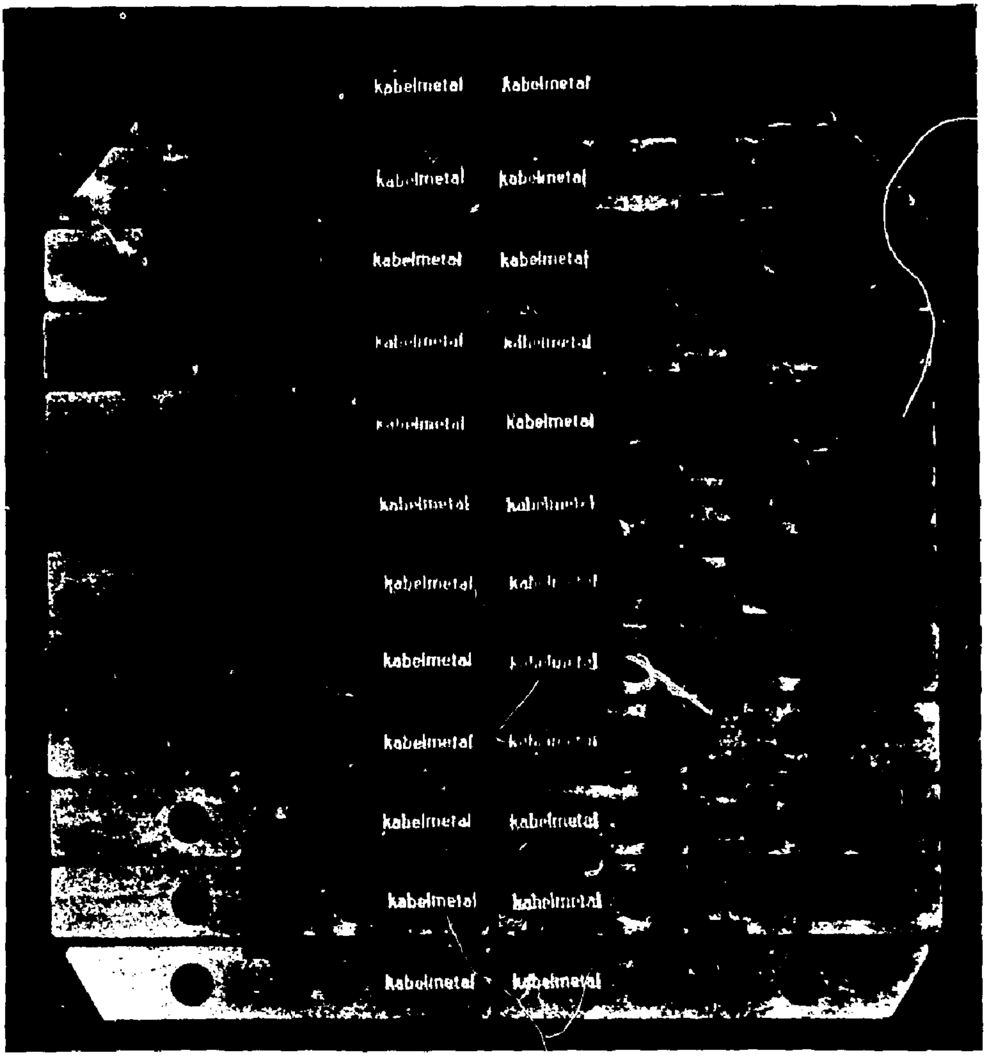


Fig. 23. JET TF Coil Insulation Scheme

Courtesy: Commission of the European Communities.

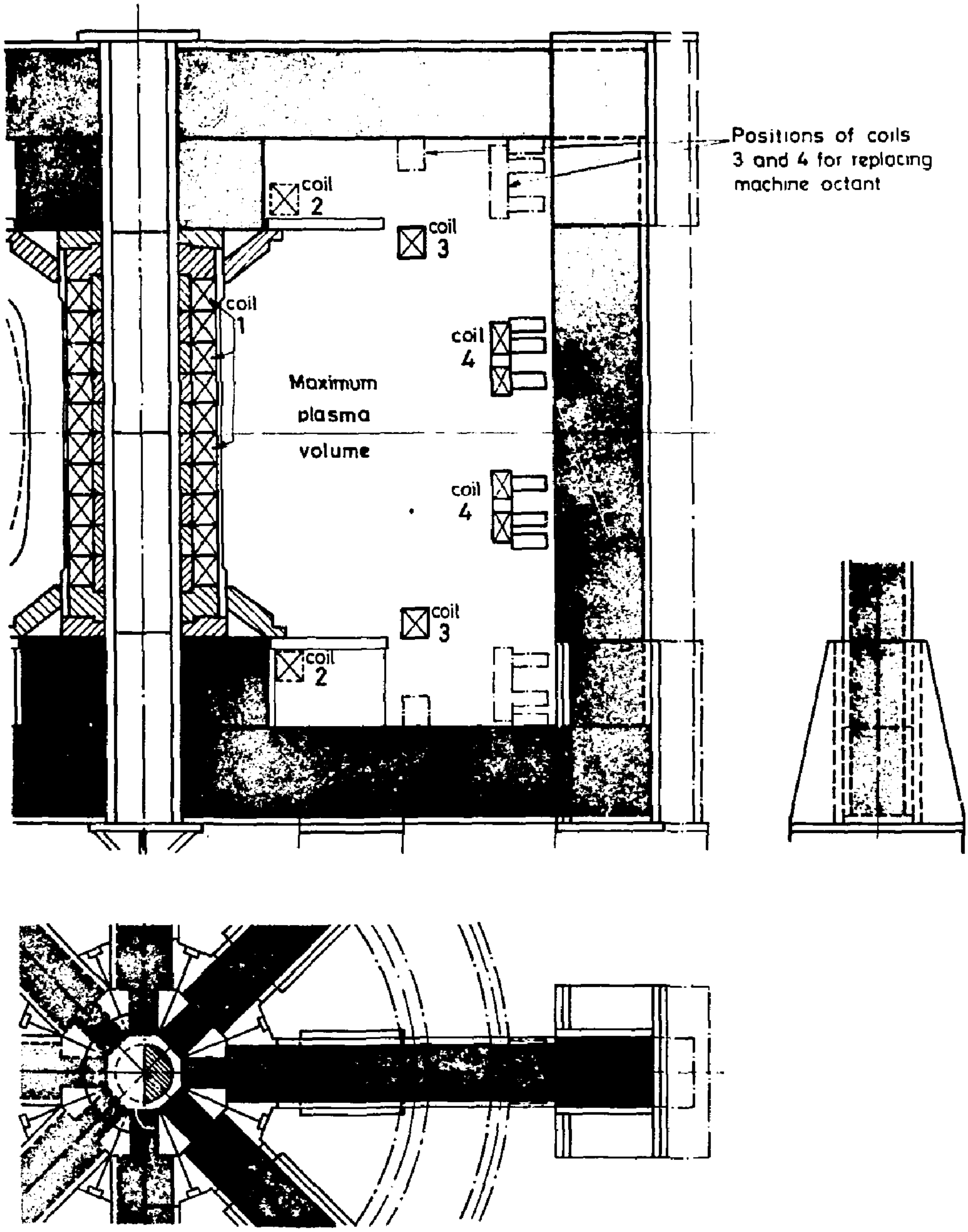
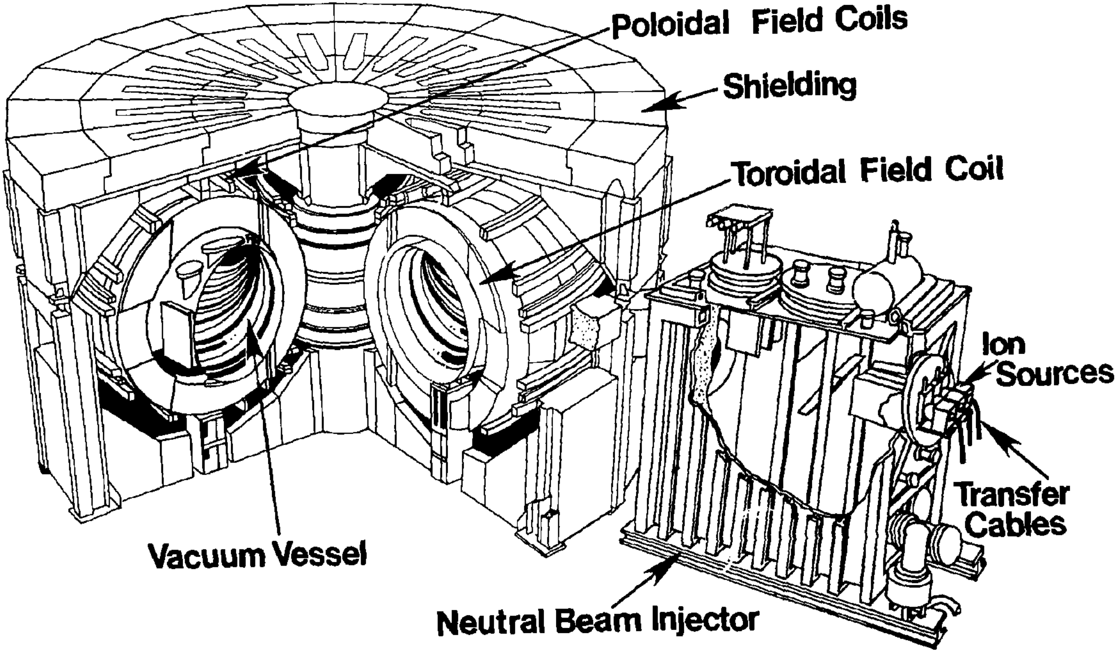


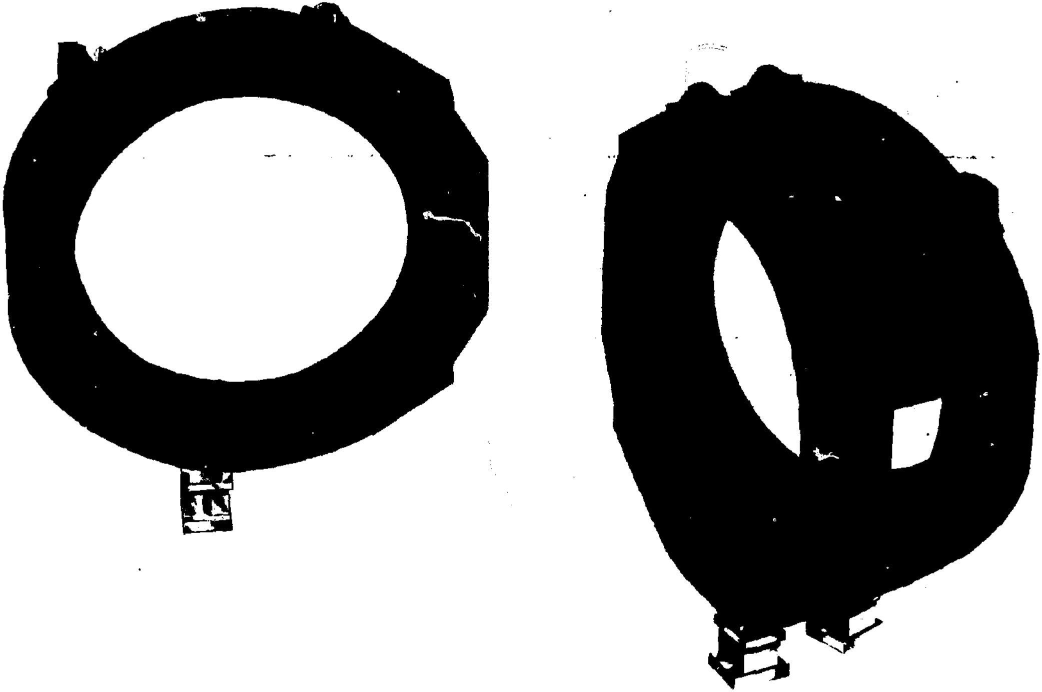
Fig. 24. General Arrangement of the Poloidal Field System

Courtesy: Commission of the European Communities.


Poloidal Field Coils
Shielding
Toroidal Field Coil
Ion Sources
Transfer Cables
Vacuum Vessel
Neutral Beam Injector

TFTR

Fig. 25



TFTR TOROIDAL FIELD COIL

Fig. 26

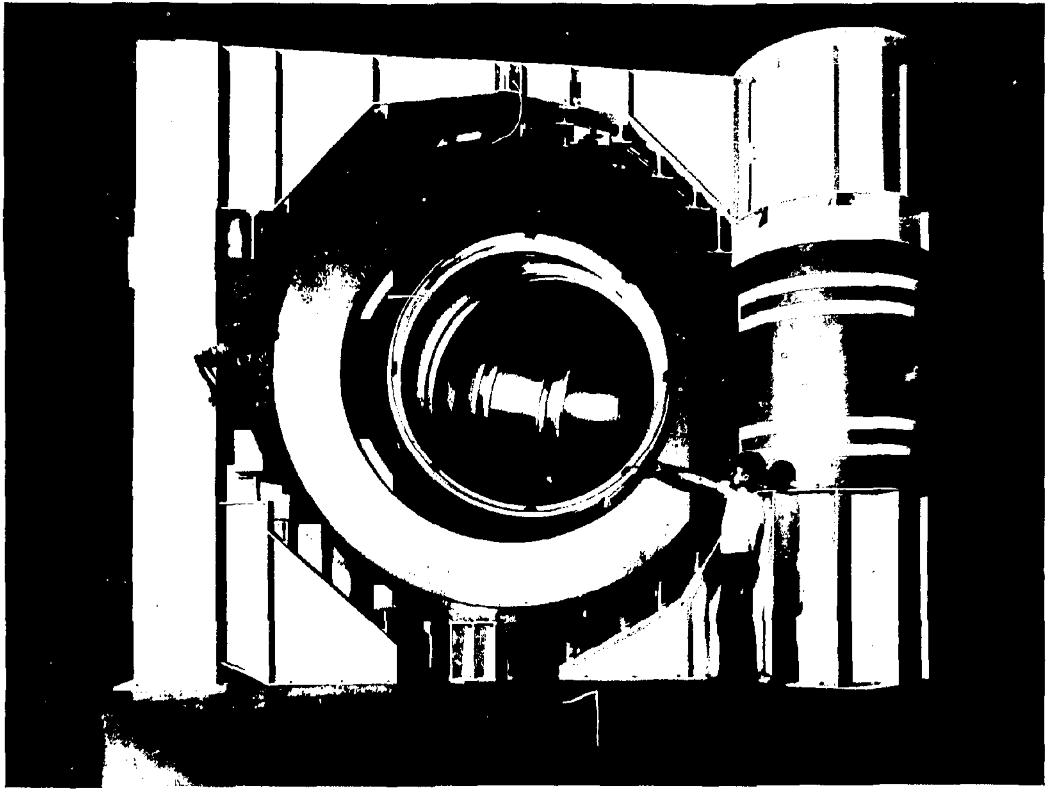


Fig. 27. A photograph of the TFTR Mockup, Section view showing the PF Coil System and its supports outside of the TF Coil.