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Design, Manufacture and Assembly of the JET Machine [and Discussion]

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Design, manufacture and assembly of the JET machine

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[Plates 1–4]

The design principles that have been followed during the conceptual phase are described first. In particular, it is shown that the machine parameters have been optimized to achieve a high value of plasma current at minimum cost. The expected use of deuterium–tritium mixtures has had a major impact on the basic design and many detailed features of the machine.

For each of the main components of the machine, the design and manufacturing techniques are reviewed in some detail. The vacuum vessel is an all-welded Inconel structure, bakeable at 500 °C to achieve a base pressure in the region of 10^{-7} Pa. The coils are water-cooled copper coils with epoxy-resin-based insulation systems. The mechanical structure includes massive castings and stainless steel parts.

The assembly of JET took one year and involved the use of specially designed lifting and assembly jigs. The first plasma was achieved in June 1983 and the machine has since been run to its maximum design level of performance.

1. General description of the JET design

1.1. *Introduction*

JET belongs to the family of tokamak fusion machines that was first developed in the U.S.S.R. In these machines, the torus-shaped plasma is confined within a magnetic field configuration made up of the combination of two fields. The toroidal field is produced by a set of magnetic coils in toroidal geometry. These coils are called the toroidal-field (TF) coils. The poloidal field is essentially produced by a current that flows through the plasma itself. This plasma current is induced by means of a transformer that includes a primary winding and an iron circuit. The conducting plasma acts as the secondary of the transformer. Other components of the poloidal field are used to control the position and shape of the plasma cross section and are produced by other coils running all around the torus. The primary winding and these other coils are called the poloidal-field (PF) coils.

The JET apparatus is illustrated in figure 1, plate 1, and consists essentially of a vacuum vessel, which contains the plasma and isolates it from atmosphere, a toroidal-field magnet, a set of poloidal-field coils and an iron transformer, which improves the coupling between the primary and the plasma. In addition, massive structural components are required to resist the large mechanical forces resulting from the interaction of magnetic fields and electrical currents. The total height of the apparatus is 12 m and its overall diameter is 15 m. Table 1 gives important parameters of the basic JET machine. It will be seen that the maximum design values of the plasma current and toroidal field are, respectively, 4.8 MA and 3.45 T. It is important to note that the machine operates in a pulsed mode. One of the main reasons for this is the limitation in the magnetic flux required to drive the plasma current (the JET project 1976, 1977, 1980).

Table 1. Main JET parameters

plasma minor radius (horizontal)	1.25 m
plasma minor radius (vertical)	2.10 m
plasma major radius	2.96 m
flat-top pulse length	20 s
mass of the vacuum vessel	100 t
mass of the toroidal-field coils	384 t
mass of the iron core	2700 t
toroidal-field coil power (peak on 13 s rise)	380 MW
total magnetic field at plasma centre	3.45 T
plasma current (D-shape plasma)	4.8 MA
volt-seconds available to drive plasma current	34 Vs
additional heating power	25 MW

1.2. *General technological concepts and design principles*

Operation with deuterium–tritium mixtures, so as to achieve a significant heating of the plasma by the α-particles of fusion reactions, is one of the main objective of the JET experiment.

JET and the American machine TFTR (Tokamak Fusion Test Reactor) built at Princeton University, are the first, and to date, the only large tokamak machines that have been built for active operation with tritium. In JET, the expected release of fast neutrons and the consequent activation of the components of the machine will prevent personnel access, not only to the inside of the vacuum vessel but also to the torus hall where the machine has been built. Maintenance inspections and repairs will have to be carried out by using remote-handling techniques. Tritium itself also presents a radiological hazard and calls for special precautions and specific equipment to handle radioactive gasses.

The use of tritium and remote-handling requirements have had a profound impact on the design principles of the machine.

For operation in active conditions, reliability is at a premium, and the design philosophy has been to achieve the JET objectives with a machine based as far as possible on established engineering techniques, in order to minimize the technological risk. For example, conventional water-cooled coils have been selected for JET rather than superconducting coils.

From this, one should not conclude that no development work has been required for the construction of JET. On the contrary, a large technological programme has been initiated during the design period and has resulted in the placing of a large number of study contracts aimed at assessing the feasibility and checking the specific design features of the JET components. In general, the basic techniques to be used were available in industry, but in almost all cases these techniques had to be considerably extended and improved in order to meet the JET requirements, which were of an exceptional nature because of the size of the components and the level of quality required. The manufacture of the main components, such as the toroidal-field coils and the vacuum vessel, took no less than four years and represented a major challenge for European industries.

Another basic concept has been to use a modular design that involves a number of identical components suited to serial production. This not only facilitates the task of industry for manufacture but is also essential to permit efficient assembly, dismantling and maintenance. For any apparatus of large size, ease of maintenance is desirable to reduce the down time. For JET, ease of maintenance is not only convenient but is an essential feature of the design because remote-handling techniques have to be used during the last phase of operation when the components of the machine are activated.

This modular concept is apparent in the basic design of the vacuum vessel and the mechanical structure, which have been split into eight identical sectors or octants, and in the design of the poloidal-field coils, which are made up of a number of subcoils or pancakes. The modularity has proved its worth during the manufacture and also during the assembly of the JET machine and has made it possible in both cases to derive the benefits from production lines.

Remote maintenance requirements have also dictated a number of essential design features.

The poloidal-field coils are outside the toroidal-field coils in order to ease assembly and maintenance.

The vacuum-vessel octants have been provided with large ports for internal access and special U-joints, which can be welded or cut remotely from the inside.

Only essential parts have been retained on the apparatus itself. Whenever possible ancilliary equipment has been kept outside the torus hall.

1.3. *Optimization of the design*

Within the framework of the design principles described above, great attention has been paid to achieving the most cost-effective design, or in other words, to obtain the best possible performance for a specified construction budget.

An important figure of merit for a tokamak is the plasma current, which controls the confinement of charged particles and in particular the confinement of the energetic α-particles resulting from fusion reactions. The JET philosophy has been to maximize the plasma current at minimum cost. Optimization studies have shown that the aspect ratio R/a of the torus, has a major impact on the cost and should be kept to a minimum value compatible with the flux swing necessary to induce the plasma current.

The JET aspect ratio is 2.4 and is much smaller than the value achieved for other tokamaks (3.1 for TFTR and 3.2 for JT60). Such a low value of R/a is not trivial to achieve and has been made possible by means of a combination of unconventional and sometimes novel design solutions, which all tend to make the best use of space in the centre of the machine.

(*a*) The ohmic-heating coils are used as a central structural support and take up the centripetal forces acting on the toroidal-field coils without space-consuming structures (the inner cylinder is very thin, see §3.3).

(*b*) An iron magnetic circuit is used to reduce magnetizing currents and therefore save on the size of the ohmic-heating coils.

(*c*) The toroidal field coils are designed to be very thin in the radial direction and without any reinforcing steel casing. This slender construction made it necessary to select a bending-moment-free design, i.e. D-shaped coils. This D-shape is also a desirable feature because of the possibility of investigating non-circular plasma cross sections.

It is important to note that not only the central part of the machine, but also the magnetic configuration as a whole, and the complete apparatus, have a very compact design. By comparison with other existing tokamaks (this comparison holds only for machines where the poloidal-field coils are outside the toroidal-field coils), JET is the machine where the poloidal-field coils are, in relative terms, closest to the plasma. This again, is a measure of the cost effectiveness of the design, where the size of the coils, both toroidal and poloidal, has been minimized, together with the magnetic energy required to operate the machine. This cost optimization is not restricted to the machine but extends of course to the whole project concept including power supplies.

The compactness of the design results in part from the use of a large number of thin toroidal-field coils fitting tightly around the plasma. The large number of coils is important as it keeps the field ripple to a low value in spite of the small distance between the coils and the plasma surface. The design of the JET mechanical structure, which holds the coils in position, also contributes to the compact design. For this structure, the novel concept of a shell with minimum thickness in the radial direction has been used.

1.4. *Mechanical problems of the JET assembly*

Large forces are generated by the interaction of the magnetic fields and electrical currents. These forces act not only on the magnets but on all the structural components because of eddy currents induced by the variation of the magnetic fields. The most severe transient forces are those associated with plasma disruptions (rapid change of the poloidal field) and vertical instabilities (rapid vertical motion of the plasma).

The major force systems of the JET assembly are briefly described below.

(*a*) In addition to the atmospheric pressure, the vacuum vessel is subjected to a magnetic pressure during the rise and decay of the toroidal field and during plasma disruptions (partial transfer of the plasma current to the vessel). A vertical instability (see §4.1) gives rise to a very large vertical force on the vessel (in the range of 10^7 N).

(*b*) The toroidal-field coils are pressed towards the centre of the machine with a force of 2.10^7 N per coil. This force is resisted by the central poloidal coils (primary winding).

(*c*) The interaction between the poloidal magnetic field and the current flowing in the toroidal-field coils results in azimuthal forces on the coils. These forces act in opposite directions above and below the equatorial plane and produce therefore an overall twisting moment around the vertical axis of the machine. This twisting moment can reach the value of 10^8 N m in normal conditions but may increase suddenly to twice that value when a plasma disruption occurs. The dynamic effect of this impact loading are severe. The twisting moment is resisted by a mechanical structure which is a tightly fitting mechanical shell surrounding the toroidal-field coils.

The following sections describe the major components of the machine, i.e. the vacuum vessel, the toroidal-field magnet, the mechanical structure and the poloidal-field system.

2. The vacuum vessel

2.1. *Design*

The vacuum vessel that contains the plasma is an all-metal, all-welded, double-containment toroidal structure (Duesing 1983). The vessel is composed of eight identical octants, each octant consisting of five rigid box sections joined together by bellow units. The bellow units consist of two bellows welded concentrically one inside the other.

The double containment was selected as the most effective way to solve a combination of mechanical, ultra-high vacuum and radioactive safety problems as explained below.

(*a*) The double-walled structure with stiffening ribs between the inner and outer skin provides a high mechanical rigidity and strength for minimum mass. The structure must withstand the forces of atmospheric pressure and the additional transient forces resulting from the eddy currents induced in the vessel during operation. The most severe of these transient forces are those associated with plasma instabilities or disruptions.

(*b*) Ultra-high vacuum conditions are essential to obtain clean, impurity-free plasmas. On JET a base vacuum of 10^{-9} mbar† at room temperature has been specified. Baking the vessel at temperatures in the range of 300–500 °C is essential to outgas the walls. This is achieved on JET by the circulation of a hot gas (nitrogen or helium) through the interspace between the inner and outer skins.

(*c*) The gas flowing through the interspace allows the removal of the heat released by the plasma and deposited on the wall.

(*d*) The interspace is an independant vacuum chamber that can be evacuated by its own pumping system. Should a leak develop between the main vacuum and the interspace, operation could continue within the limits imposed by the power deposition on the walls and cool-down time of the vessel.

(*e*) Finally and perhaps most importantly, the double-walled structure constitutes a safeguard against the possible accidental release of tritium in the experimental hall. Moreover, the double wall eliminates any external contamination due to tritium permeation. Tritium permeating through the first wall will be contained within the interspace and diluted in the heat transport gas. The tritium concentration in the gas will be kept low by a clean-up system based on the oxidation of tritium and subsequent absorbtion of tritiated moisture.

Because the vessel will become highly radioactive, remote-handling requirements have dictated many design features. In particular, the chamber is equipped with eight large horizontal ports to allow access to its interior. All the internal equipment, such as limiters, RF antennae, wall-protection tiles can be fitted and dismantled by using specially designed remote-handling tools. If necessary the lip welds joining adjacent octants can be remotely cut and rewelded.

2.2. *Manufacture and assembly*

The vessel is manufactured in octants. Each octant consists of five double-walled rigid sectors and four double bellow assemblies (figures 2 and 3). The rigid-sectors material is vacuum melted Nicrofer 7216 LC equivalent to Inconel 600, and the bellows material is Inconel 625. Those materials were chosen for good mechanical properties at elevated temperature, good weldability and high electrical resistivity of the bellows. This latter property is essential to increase the electrical resistance of the vessel and bring it to a level high, compared with that of the plasma.

The rigid sectors were produced under clean working conditions. Plates were plasma cut and inner walls were electropolished to minimize the true physical surface area, which determines the outgassing rate. About 1 km of welds of ultra-high vacuum quality had to be done for each octant, thus requiring strict quality control procedures and special care in the design to avoid trapped volumes. Machining was carried out with carefully selected (sulphur-free) cutting fluids.

For the bellows, 2 mm thick Inconel sheets were butt welded to form a cylinder and then hydraulically rolled into bellows.

When the octants were completed, surveys revealed only small deviations (a few millimetres) from nominal dimensions.

† 1 bar = 10^5 Pa.

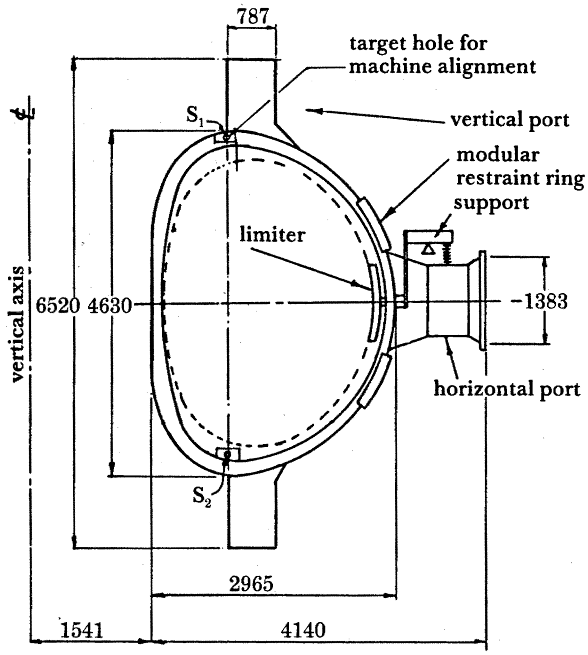
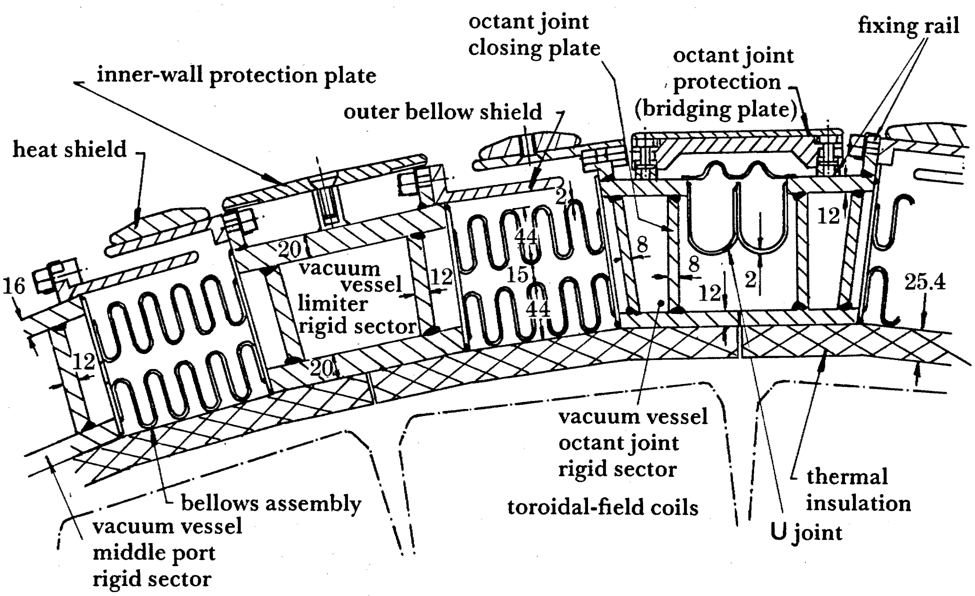


FIGURE 2. One octant of the JET vacuum vessel.



After delivery to the JET site, each octant was washed internally with high-pressure water jets. Hot leak tests were then carried out in an oven at a temperature of 520 °C. All octants showed some leaks ranging from 10^{-7} to 4×10^{-9} mbar l s^{-1}. After repair, the octants were accepted for final assembly on the machine with leak rates close to 1×10^{-9} mbar l s^{-1}.

Before assembly on the machine the vessel octants were covered with special insulation panels selected for their low thermal conductivity. This was to reduce heat losses during baking and protect the electrical insulation of the TF coils. Once assembled into a toroidal vessel, the octants were welded together from the inside. The welding of the lip joint was performed with the remotely controlled welding trolley developed by JET. This first welding was done manually inside the vessel, but tools are being developed so that future cutting and rewelding of the joint can be carried out remotely.

2.3. *Pumping, baking and operation*

In order to facilitate maintenance during the active phase, ancillary equipment for pumping and baking has been installed, as far as possible, outside the torus hall.

Pumping the torus is achieved by four turbo molecular pumps with an effective pumping speed at the vessel of 8500 l s^{-1} for hydrogen. This pumping speed requires a large conductance, and it was therefore necessary to install the pumps on the machine itself. The roughing and backing pumps on the contrary have been installed outside the torus hall in a service area that will remain accessible when the machine becomes active. The baking plant, which circulates and heats the gas in the interspace of the vessel is sited in the same service area. After baking at 300 °C and glow-discharge cleaning, a high-quality vacuum is achieved. Impurity partial pressures are barely detectable (less than 10^{-9} mbar), the only impurities observed being CH_4, H_2O and CO/C_2H_4. The hydrogen pressure is in the range of 10^{-7} mbar at 300 °C and less than 10^{-9} mbar at room temperature. These impressive results, achieved with a very low pumping speed, in relation to the volume and wall area of the vessel, give a measure of the vacuum quality of the vessel and the effectiveness of the cleaning methods.

2.4. *First wall*

Impurity control, which aims at reducing radiation losses from the plasma and dilution of the thermonuclear fuel, is one of the key issue to approach reactor conditions in fusion machines. An important aspect of impurity control is the choice of materials that are directly facing the plasma (Rebut & Dietz 1983; Huguet 1986).

JET started operation in 1983 with graphite limiters, Inconel walls, and some Inconel wall protection tiles. Plasma operation for one and a half years under these conditions resulted in the following observations.

(*a*) Wall material is removed during plasma discharges by sputtering and evaporation, and is redeposited on the graphite limiters. The metallic deposits on the limiters can result in a severe metallic contamination of the plasma.

(*b*) The Inconel wall protection can be severely damaged during plasma disruption. The most severe damage, which shows as craters of melted metal, is attributed to runaway electrons impacts.

In order to eliminate the source of metallic contamination, it was decided to cover large areas of the inner wall with a low-Z refractory material. Graphite has been selected for this purpose. Graphite has excellent thermomechanical properties and resists localized heat impacts very well. At present up to 20% of the inner wall surface is covered with graphite and further protection is planned for installation in 1987 (figure 4, plate 2).

A large fraction of the power injected into the plasma is directly conducted to the limiters. At full performance, when the injected power reaches 40 MW, the graphite limiters have to be replaced by new larger limiters. These new limiters called the belt limiters are planned for installation in 1987 and will consist of two toroidal belts above and below the equatorial plane.

Beryllium and graphite are the two materials which are being considered for the limiter tiles. Beryllium is particularly attractive because of its very low Z and its property to act as an oxygen absorber.

3. The toroidal-field system

3.1. *Design of the toroidal-field coils*

The JET toroidal field (TF) magnet comprises 32 D-shaped coils designed to produce a field of 3.45 T at a radius of 2.9 m (Huguet *et al.* 1977). The coils are conventional water-cooled copper coils. The main parameters of the coil system are shown in table 2.

Table 2. Parameters of the toroidal-field coil system

(Data is given for maximum performance.)

number of coils	32
total number of ampere turns	51 MA
magnetic field at a radius of 2.9 m	3.45 T
current	67 kA
flat-top time of pulse	10 s or longer at lower current
resistive power	280 MW
energy dissipated per pulse	5.4 GJ
dimensions of one coil (vertical/horizontal)	5.68/3.86 m
mass of one coil	12 t
number of turns per coil	24
copper cross section per turn	3900/2700 mm^2

The coils are D-shaped to eliminate bending moments due to the magnetic pressure of the toroidal field. The D-shape is the natural equilibrium shape of a flexible coil subjected to the pressure of the toroidal field. This choice of a D-shape was not only dictated by mechanical consideration but has also played a key role in achieving a tight aspect ratio of the torus. The coils could be designed to be very thin in the radial direction and without any steel casing.

Each coil consists of two pancakes with 12 turns per pancake as shown in figure 5. In order to limit the peak temperature and reduce thermally induced stresses, the copper conductors include two parallel cooling channels symmetrically located in the cross section. All turns are cooled in parallel and the water is flowing in the same direction to avoid temperature gradients between turns. Figure 5 shows that the width of conductor is reduced by machining along the straight portion in order to permit close stacking round the vertical column. The symmetry of the cooling channel is also preserved there by means of a joggling operation whereby the conduction is bent sideways so as to shift the position of the cooling channel. The conductor is subsequently machined on both sides to obtain the required width.

A feature of the conductor is the provision of a longitudinal keyway to receive an epoxy–glass key that is part of the interturn insulation. This key helps in resisting the large lateral loads on the coil due to the interaction with the poloidal field, especially in areas where it is possible to support only the outer turn.

The insulation is a vacuum-impregnated epoxy–glass system. The epoxy resin used has been selected for its good radiation resistance among established and well-tested resin systems.

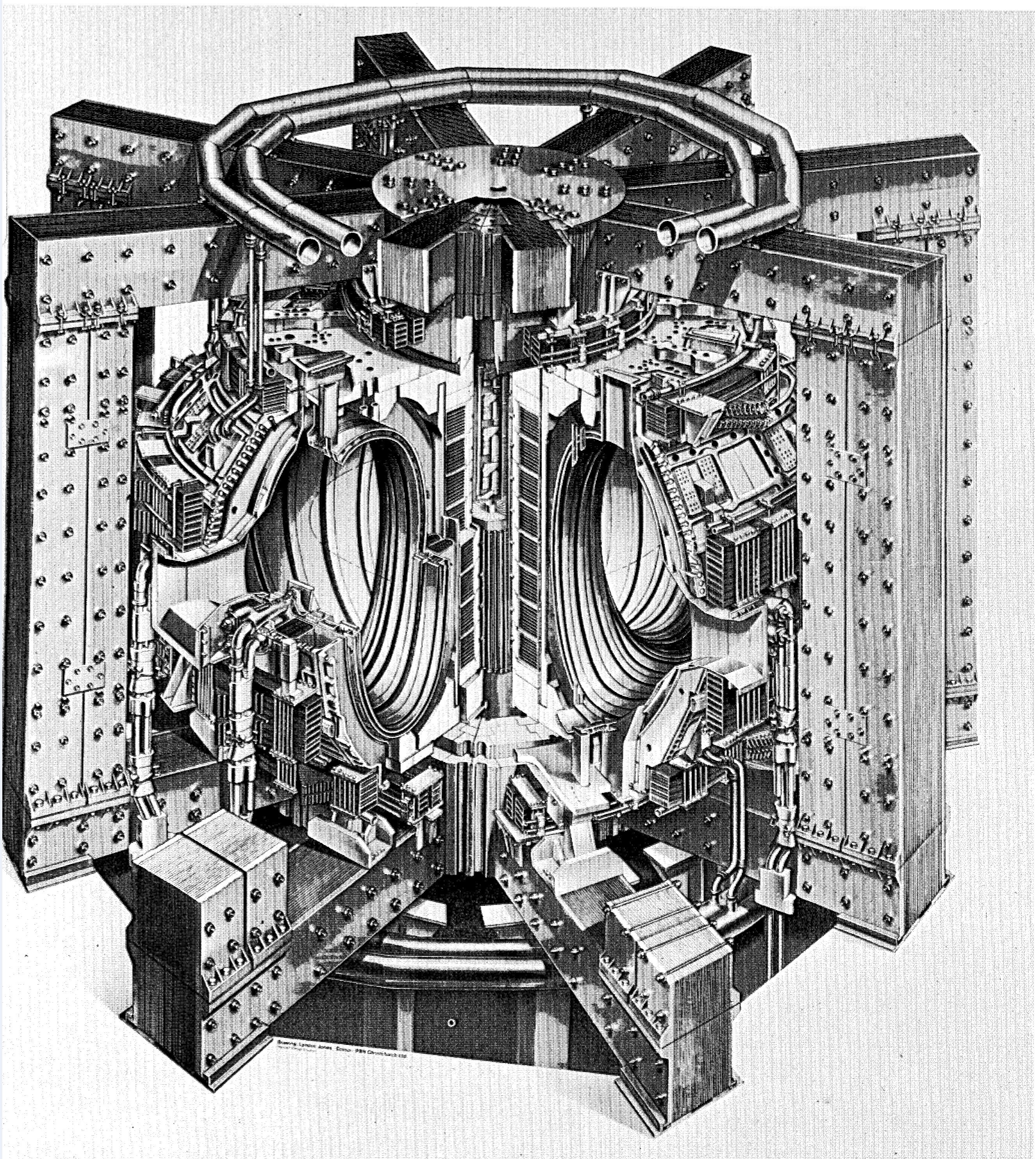


FIGURE 1. The JET machine.

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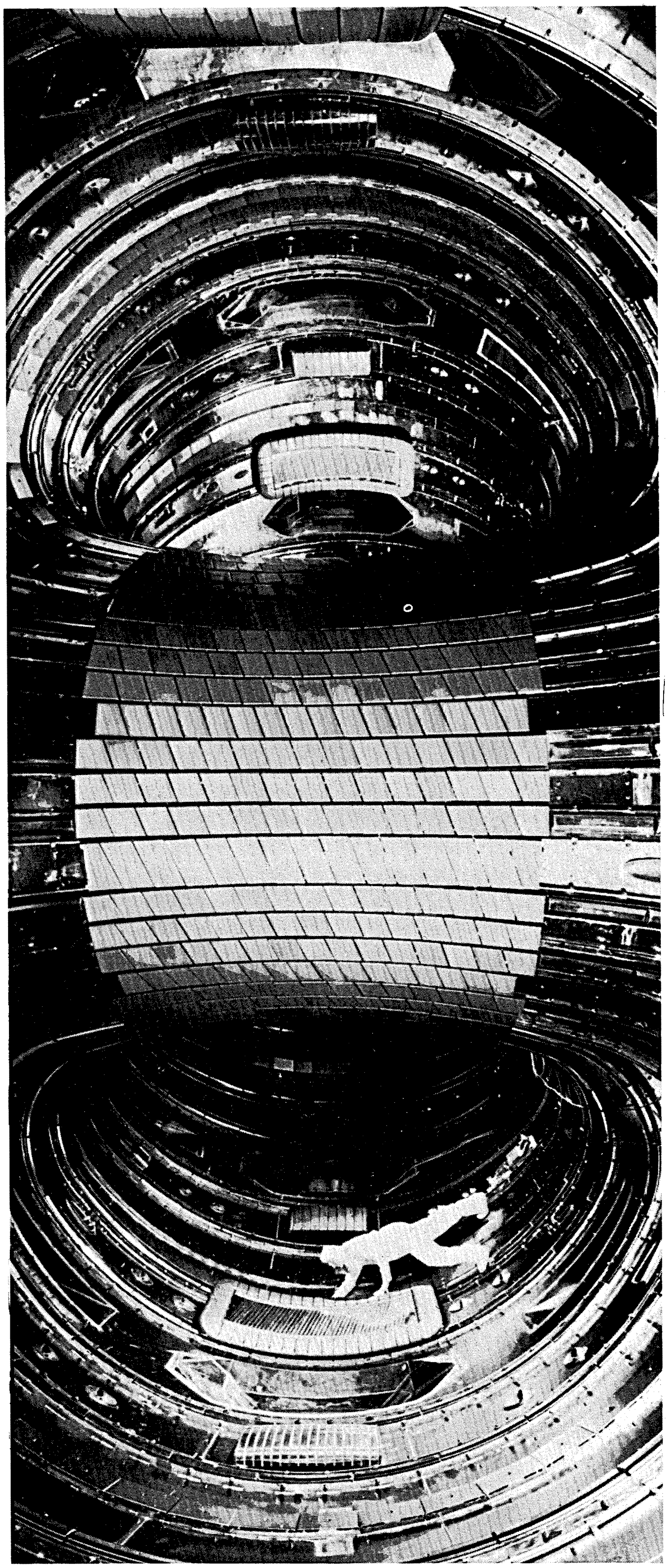

FIGURE 4. View of the inside of the JET vacuum vessel showing graphite protection tiles at the inboard wall.

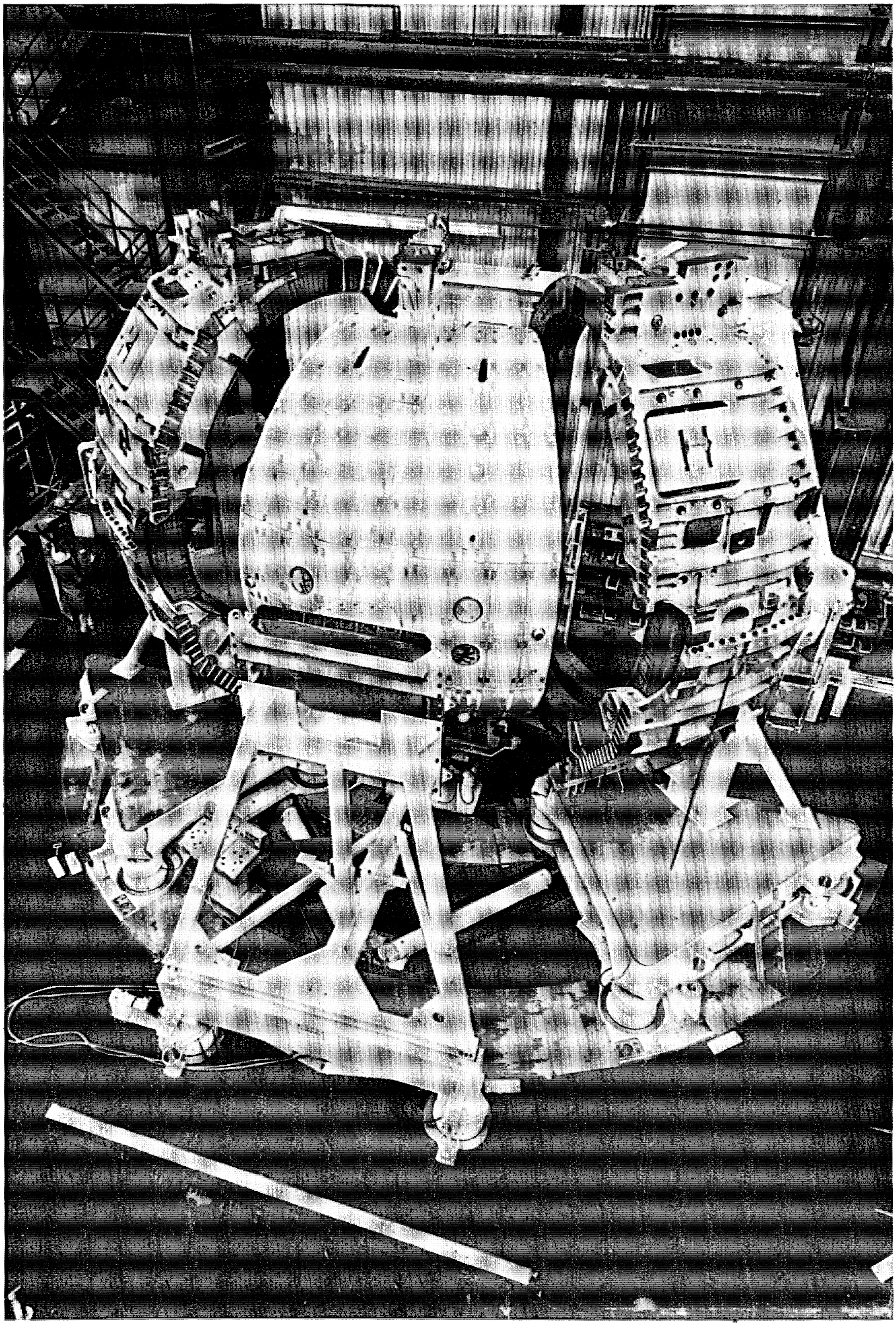

FIGURE 7. Assembly of one machine octant, showing the vacuum vessel octant in the centre and half octants of the mechanical structure on either side.

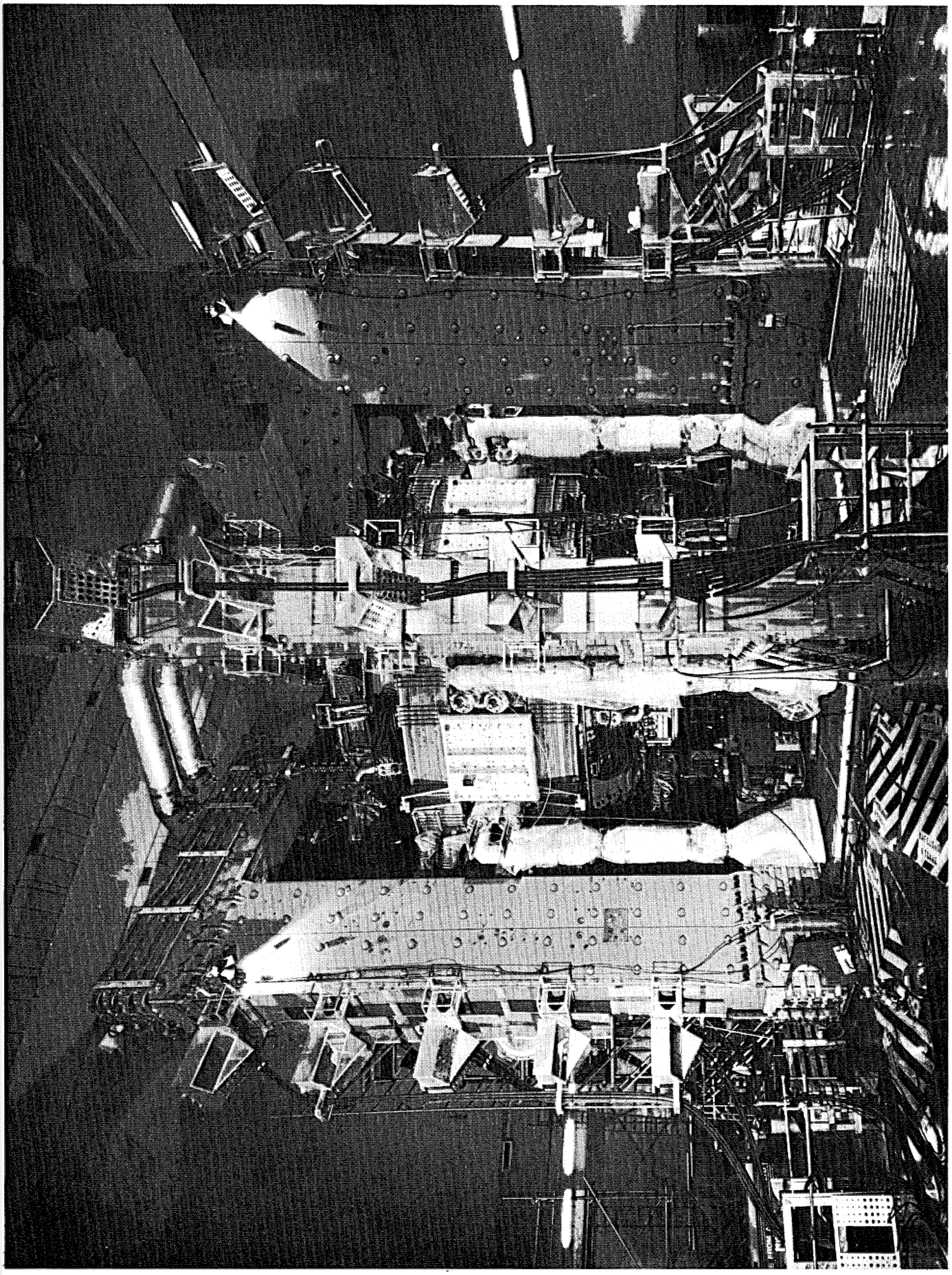

Figure 8. The JET machine in June 1983.

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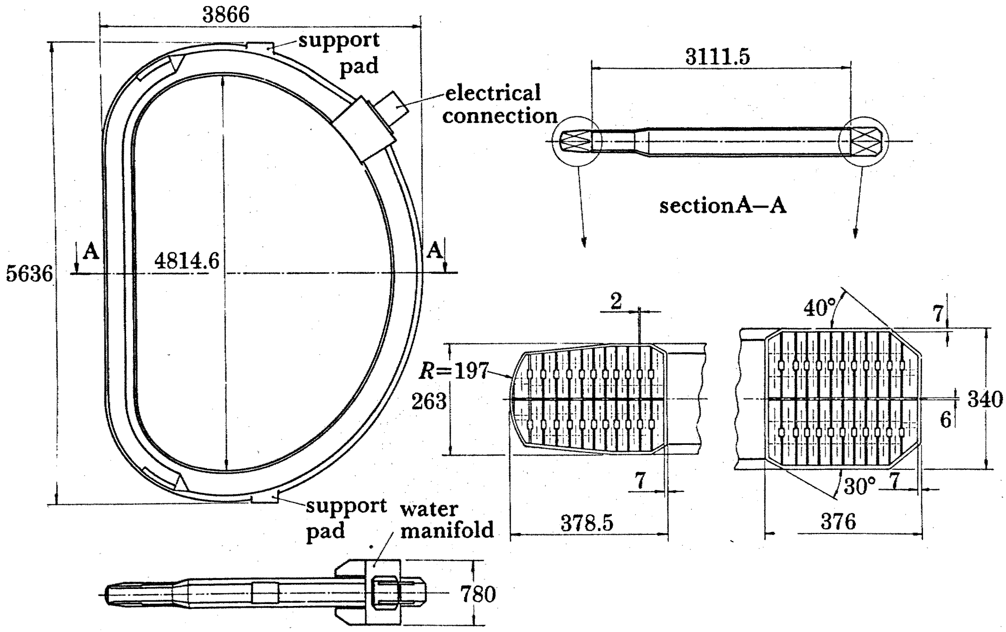

FIGURE 5. A JET toroidal-field coil (all dimensions are in millimetres).

Because the mechanical properties of the resin start degrading only when the radiation dose exceeds 10^7 Gy, it is not expected that radiation damage will endanger the integrity of the coil insulation for the specified D–T operation of 10^4 discharges of 10^{20} neutrons.

3.2. *Manufacture of the toroidal-field coils*

The copper conductor has a special cross section with an area of 4000 mm² and two cooling holes. It is made in 15 m lengths, which means that one brazed joint per turn is required for the coils. The conductor is extruded and then drawn in the half-hard condition.

The main problem in winding D-shaped coils with hard copper is that of springback. The method used has been to wind the coil under tension on a former which is not made to the final shape but is so formed that the coil takes up the correct shape on removal from the winding table. In particular, a concave shape was required on the former in order to obtain the straight portion of D.

The conductor was wound under a tension of 25 t, the maximum tension that will be experienced by the conductor during operation at full field. This ensured that there would be no further yield and deformation when the coil is in service.

After winding, the coil is vacuum impregnated with epoxy resin and baked in a mould to achieve tight dimensional tolerances.

3.3. *Design of the mechanical structure*

The principle function of the mechanical structure is to resist the torsional forces acting on the toroidal-field coil set.

The structure has been designed as a metallic shell which encloses completely the toroidal-field coils. Although very thin in the radial direction this shell exhibits a very high torsional rigidity (figure 6).

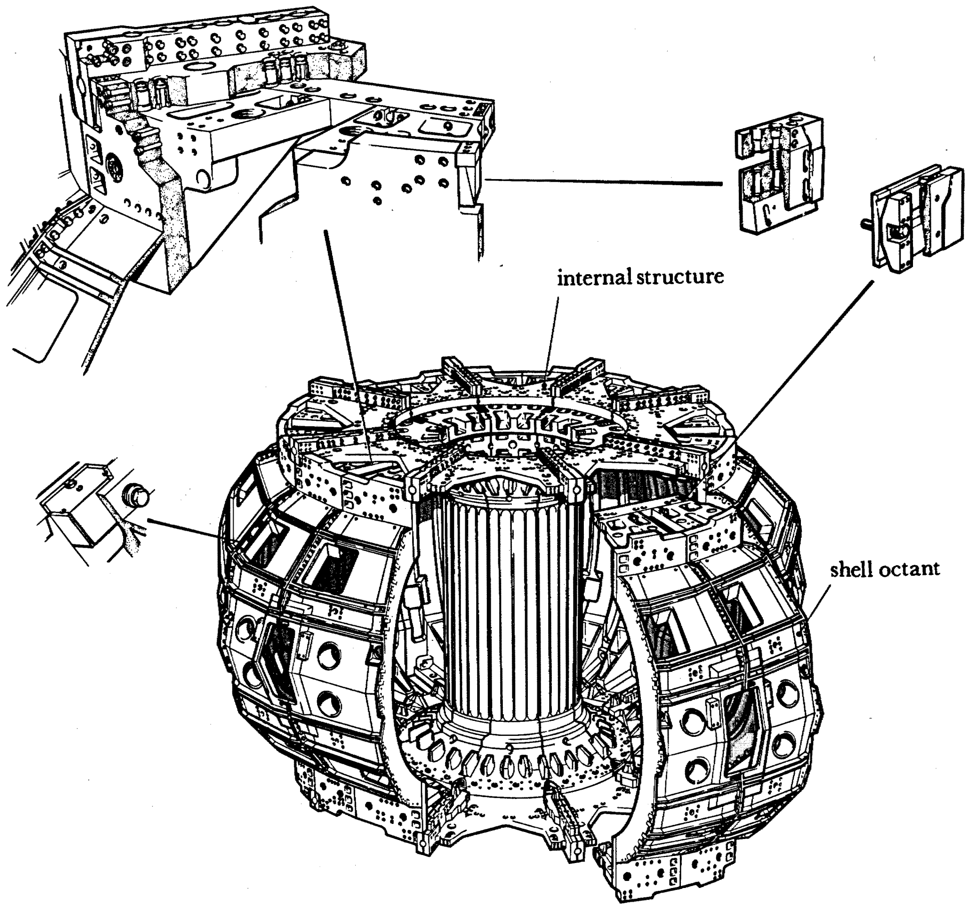

FIGURE 6. JET's mechanical structure.

The stiff part of the shell, which actually resists the torsional load, is the external part. The inner part of the structure (inner cylinder) can be made very thin, thus saving space in the centre of the apparatus and keeping to a minimum the aspect ratio of the torus. The only function of the inner cylinder is to keep the inner portion of the toroidal-field coils straight.

The main components of the mechanical structure are now briefly described.

The external shell is split into eight sectors or octants for assembly reasons. At the mechanical joints between octants, very large tensile and shear loads are resisted by a combination of high tensile strength bolts and shear dowels. The cylindrical shear dowels are of a special design and are expandable to make up for assembly mismatches.

The rings and collars at the bottom and top are stiff members of the structure that transmit the torsional stiffness of the shell towards the centre of the machine.

The inner cylinder is made up of eight sectors dowelled at the bottom and top ends to the collars. The cylinder sectors include machined cylindrical grooves, which locate the toroidal field coils and support them against lateral forces.

3.4. *Manufacture of the mechanical structure*

The material selected for the manufacture of the external shell and the rings is an austenitic nodular cast iron, similar to DIN 1694, GGG – Ni Mn 13-7. The suitability of this material

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for the JET structure was checked extensively. The development work included fatigue and fracture mechanics characterization tests, the production of prototype pieces and the fatigue testing of a large sample cut from the prototype.

For the inner cylinder the material used is an austenitic stainless steel. The plates were cold rolled and welded to form a complete tube. The tube was then cut into eight sectors and after machining to very accurate dimensions both surfaces of each sector were polished ($Ra < 0.4$ μm) to provide an adequate sliding surface for the toroidal and poloidal field coils.

4. The poloidal-field system (Last *et al.* 1981)

4.1. *Introduction*

The poloidal field in a tokamak has the following functions:

(i) to develop an EMF that drives the plasma current by transformer action;

(ii) to control the shape and position of the plasma.

The first function is achieved by making the poloidal-field coils the primary windings, and the plasma the secondary, of a transformer. In JET, an iron transformer core is used to reduce magnetizing currents and external fields.

The magnetizing current of the transformer is mainly carried by the inner coils. The flux of these coils is carried by the iron core and does not pass through the plasma.

The shape and position of the plasma is controlled by the outer coils whose magnetic flux passes through the plasma and returns via the outer limbs of the iron core. The shaping fields are of two types, vertical and radial, to control, respectively, radial and vertical motion of the plasma. The vertical field is provided to counteract the natural tendency of the plasma to expand along the major radius of the torus, under the action of plasma self-magnetic hoop forces and internal gas pressure. Feedback amplifiers are used to control actively the radial position of the plasma.

The radial field is also feedback controlled to keep the plasma in the equatorial plane of the machine. In JET, because of the elongated shape of the plasma cross section, the configuration of the poloidal field makes the plasma naturally unstable against vertical displacements. Feedback control is therefore essential. Any failure of the control system leads to a vertical instability whereby the plasma moves vertically at high speed (*ca.* 50 m s^{-1}) and crashes against the walls of the vacuum vessel. This phenomena gives rise to large vertical forces acting on the vacuum vessel.

The iron transformer has been provided to improve the coupling between the primary winding and the plasma and reduce magnetizing currents. The central core of the transformer is highly saturated up to 8 T. Eight external branches have been provided for the return of the flux. Table 3 gives some parameters of the poloidal-field system.

4.2. *Design of the poloidal-field coils*

4.2.1. *Coil insulation*

All the coils are water cooled through hollow copper conductors and insulated with epoxy-resin-impregnated glass and polyimide tape.

The high voltage gradients (maximum, 7 kV mm^{-1}) in these coils means that epoxy–glass insulation was not considered sufficiently reliable. Mica–glass–epoxy had insufficient shear strength, so an insulation system with interleaved glass tape and polyimide (Kapton) tape,

TABLE 3

	transformer coil	outer coils number 2	outer coils number 3	outer coils number 4
number of coil	8			
total number of turns	568	—	160	122
outer diameter/m	2	5	8	11
total mass/t	90	36	90	160
maximum current/kA	40	45	45	45
maximum voltage to earth/kV	20	20	20	20
duration of pulse/s	20	20	20	20

vacuum impregnated with epoxy resin was developed. The coils have typically 1 mm of insulation wrapped on each conductor (including one layer of polyimide and two of glass) and 6–8 mm of ground insulation (including 6–8 layers of polyimide and 12–15 layers of glass).

4.2.2. *Transformer coil*

The transformer coil is the primary of a transformer, the secondary of which is the plasma. The turns ratio of the transformer is 568/1.

The plasma discharge is initiated, and the plasma current driven, by the electrical field resulting from the magnetic flux change through the primary coil. In the case of JET, a negative-bias flux is first established, and this flux is then driven to a positive value throughout the plasma discharge. This involves a reversal of the current flowing in the primary coil. The power supplies for this circuit include a flywheel generator and a switching network for the current reversal (JET Project 1976).

An unconventional feature of the JET transformer is that its central iron core is highly saturated with a maximum field of 8 T. This enables the central section including the coil to be made much smaller and in turn enables the design of the whole tokamak to be more economical.

A consequence of the high magnetizing field is that the coil carries high current and is therefore subject to outward magnetic forces equivalent to an internal pressure of about 14 MPa. Additionally the coil also has to support an inward pressure of 30 MPa on its outer radius due to the toroidal coils and a vertical pressure of 22 MPa due to transformer weight and magnetic forces.

In principle, the poloidal and toroidal pressures offset each other but either field can be applied separately during test sessions and the waveforms of the two fields are different so the coils must be able to withstand any loading combination. As the external inward pressure gives the highest stresses, the coils are supported on their inner radius by steel support rings. These steel rings also form part of the magnetic circuit.

4.2.3. *Large outer coils*

These coils include independent sections to provide magnetizing, vertical and radial fields and are made of electrically separate pancakes. Some pancakes have adjustable tapping points to allow the number of turns in use to be adjusted.

The pancakes are made in halves and are joined by clamped connectors. The reasons for

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using half pancakes are: (i) to allow transport from the manufacturer to the JET site; (ii) to allow faulty regions of the coil, if they develop, to be isolated and (iii) to facilitate selection of numbers of turns in use.

4.3. *Manufacture of the poloidal-field coils*

Most of the copper conductor for these coils was in the half-hard condition. It was delivered in lengths between 5 and 14 m so in general had to be joined to make coils. This was done by a brazing technique. The sequence of operations was as follows:

(i) clean, sandblast and prime copper conductor;
(ii) apply glass–Kapton tape on conductor;
(iii) wind conductor in tension on former;
(iv) overwrap with glass–Kapton ground insulation tape;
(v) place coil in mould and impregnate with epoxy resin;
(vi) cure for about 16 h at about 150 °C.

For the large outer coil operation, (iii) was 'form the conductor' and preceded operation (ii).

4.4. *Assembly of the poloidal-field coils*

The transformer coil consists of eight identical subcoils stacked vertically at the centre of the machine. After manufacture the coils were stacked and shimmed by using an epoxy paste on their horizontal faces to give good contact and ensure verticality. The six central coils of the eight were then machined on their outside diameter on a vertical axis lathe to give an accurate surface (cylindrical within 0.2 mm) for the inner cylinder and TF coils to press against.

The large outer coils were manufactured as half pancakes so that they could be transported to the JET site. These half pancakes were stacked and glued together at JET to make up complete coils.

5. Mechanical assembly of JET

5.1. *Assembly of machine octants*

The JET toroidal assembly consists principally of the toroidal coils, the mechanical shell structure and the vacuum vessel. The toroidal assembly is split into eight identical sectors or octants comprising four TF coils and one octant of the mechanical structure and of the vacuum vessel.

Assembly started by fitting the toroidal field coils into the half octants of the mechanical structure.

The octant of the vacuum vessel was then inserted and the two half octants rotated so that the structure and coils enclosed the vessel (figure 7, plate 3). The two half octants were then bolted and keyed together to ensure a strong shear joint. Auxiliaries such as bus bars, water manifolds, hoses and instrumentation were then assembled to make up a complete machine octant.

5.2. *Erection of the machine in the torus hall*

At the same time, the magnetic circuit and the central part of the mechanical structure were being erected in the torus hall. These parts, which include the lower and upper rings and collars, and the inner cylinder, were optically aligned as they are the mechanical reference for the whole machine.

Each completed octant, with mass of 120 t, was transferred into the torus hall by means of a large C-shaped frame able to lift and hold the octant in the upright position. The frame lifts an octant from the bottom and maintains it in an accurate vertical position by means of an adjustable restraining arm at the top. The verticality of the coils and the octant as whole has to be accurately adjusted to permit the insertion of the octant into its final position. After assembly the vessel octants were welded together from the inside (see §2.2) and the octants of the mechanical structure were bolted and keyed together to provide the overall torsional stiffness. The mechanical assembly took one year, from January 1982 to January 1983, and was followed by the assembly of all services and auxiliaries (piping and cabling) (figure 8, plate 4). The successful completion of the assembly enabled the start of commissioning tests of subsystems up to May 1983 and then integrated tests which culminated into the production of a first plasma in June 1983 (Huguet *et al.* 1984).

6. Operations

Since June 1983, the machine has been progressively run up to its full design performance. The toroidal-field magnet has been used routinely at its maximum design field and pulse duration. The plasma current and position control have been optimized. Shape control has been successfully introduced in order to control better the elongation of the plasma cross section and reduce the risk of vertical instability. All these improvements resulted in good overall machine performance as illustrated in figure 9. JET has now been operational for nearly three years and the sound technical behaviour of the machine has made it possible to fulfil the planned experimental programme.

The physics results in the ohmic heating conditions, exceeded expectations, allowing a fusion product

$$\hat{n}_i \times \tau_E \times \hat{T}_i = 0.5 \times 10^{20}\ \mathrm{m^{-3}\ s\ keV},$$

to be reached (Rebut *et al.* 1984). This is a clear indication that the basic design choices, which were made ten years before operation started, contained enough forward thinking to keep JET at the forefront of fusion research. The design contains, also, enough intrinsic flexibility to allow new programme orientations and new operation scenarios to be implemented without affecting the basic structure of the machine. Operation with plasma currents in excess of 5 MA, X-point operation, current profile control are but a few examples of recent additions to the JET experimental programme.

The ultimate challenge for the JET machine will be operation with tritium. The JET policy there, is that a meaningful study of α-particle behaviour and heating requires several thousand plasma shots, that is one to two years of operation with deuterium–tritium mixtures. As already mentioned in §1, remote-handling requirements have been incorporated in all components of the machine. The effort already invested is now being followed up by the development of remote-handling tools and procedures. Many such tools are already available and have been used as a help for hands-on work (Dean 1986).

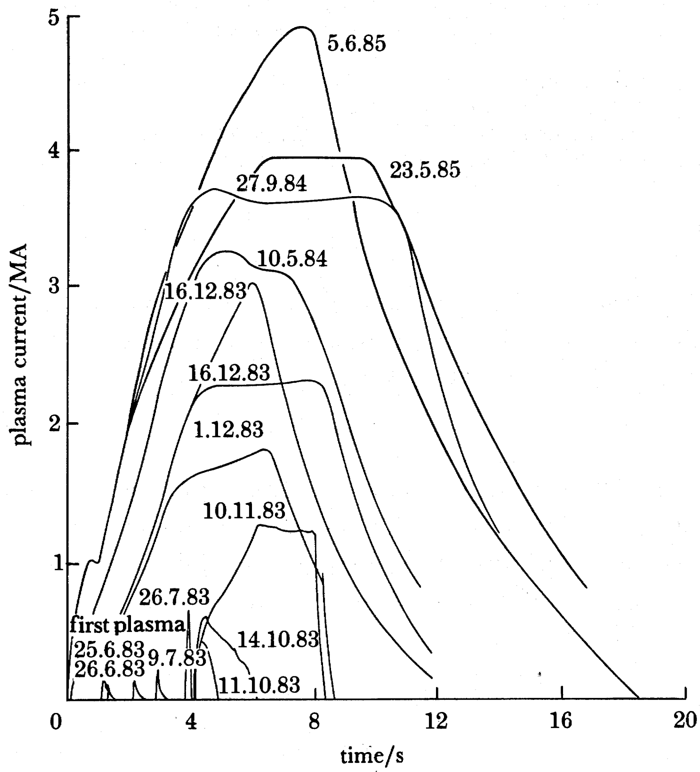

Figure 9. Typical plasma current pulses achieved on JET from 26 June 1983 to 23 June 1985.

The tritium plant is also fully defined and should be operational in 1989. The plant will operate in a closed loop and separate for re-use the hydrogen isotopes from the gas mixtures coming from the machine.

The active-operation phase is the final stage of the JET operation programme and will hopefully lead to further development on the way towards a fusion reactor.

This paper reports the work of the whole JET team under the leadership of Dr P. H. Rebut.

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Discussion

R. S. Pease (*UKAEA, Culham Laboratory, Abingdon, Oxfordshire*). In the design of JET, many detailed and difficult calculations of stresses, temperature and mechanical strains in this three-dimensional structure are made. Can Dr Huguet say anything about the reliability of these calculations?

M. Huguet. More than 500 instrumentation channels monitor the mechanical, thermal and electrical behaviour of the machine. All measurements show good agreement with predictions. This has made it possible to commission and use the machine up to its maximum design performances. Because there appear to be no unforeseen problems, operation of the machine above design values is being considered.

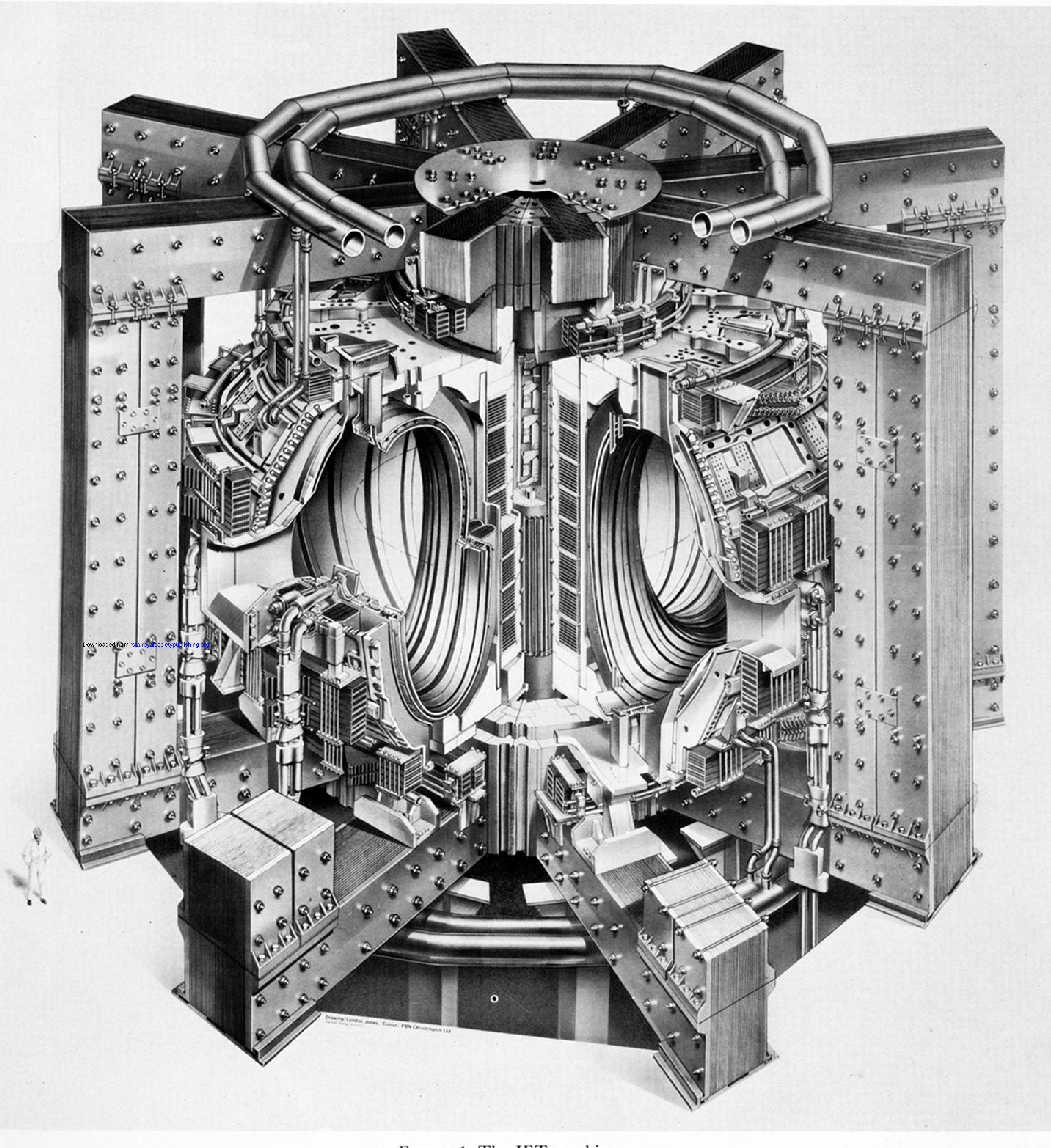


FIGURE 1. The JET machine.

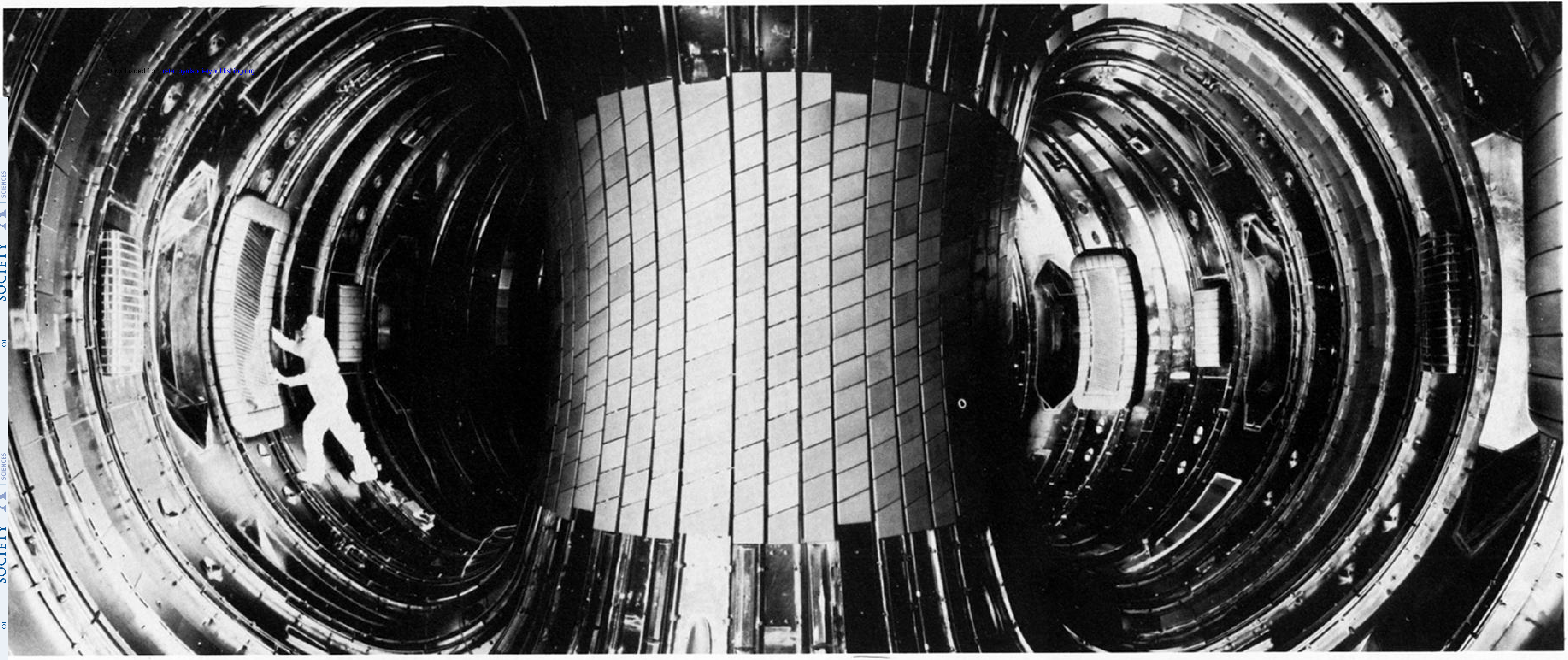
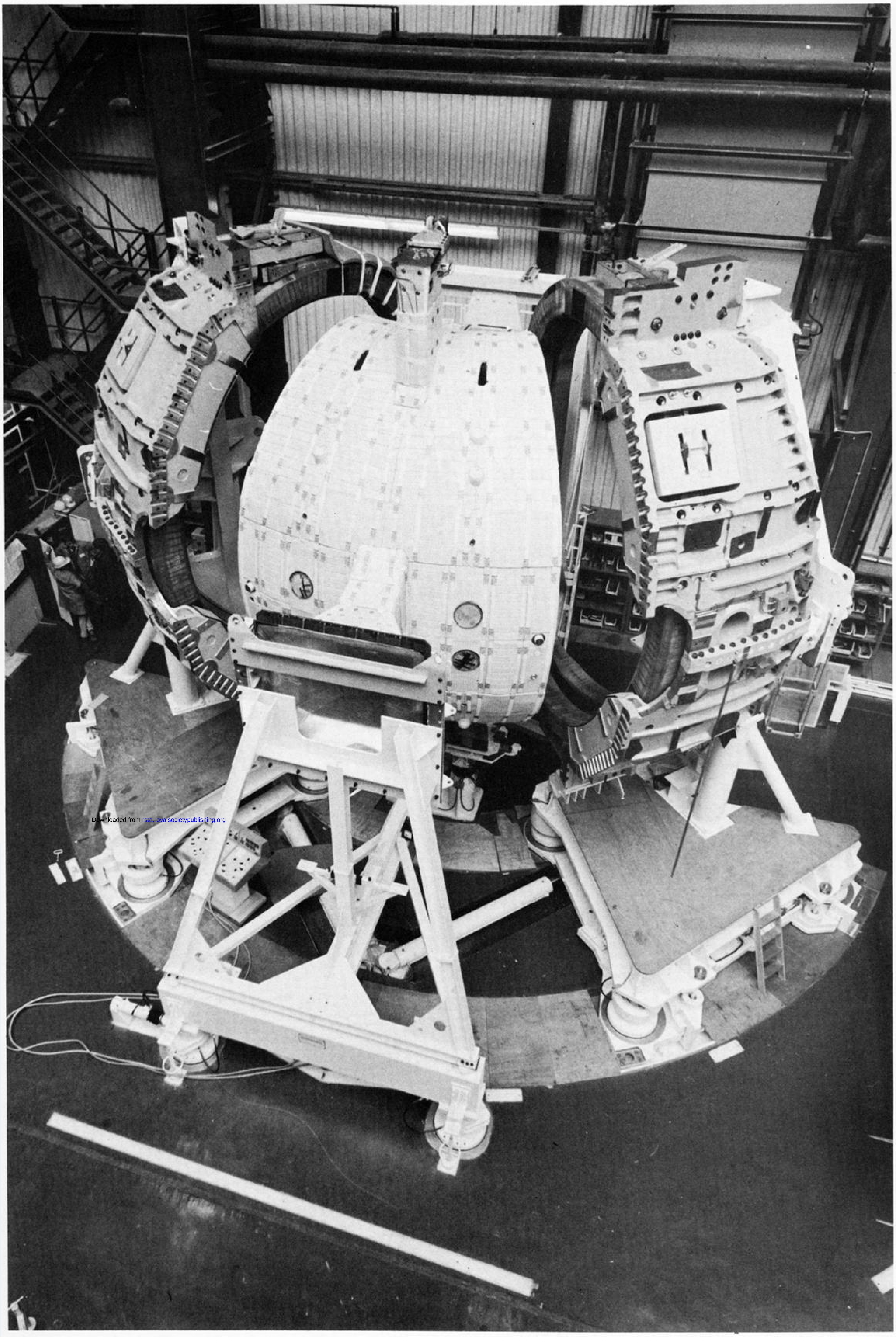


FIGURE 4. View of the inside of the JET vacuum vessel showing graphite protection tiles at the inboard wall.



IGURE 7. Assembly of one machine octant, showing the vacuum vessel octant in the centre and half octants of the mechanical structure on either side.

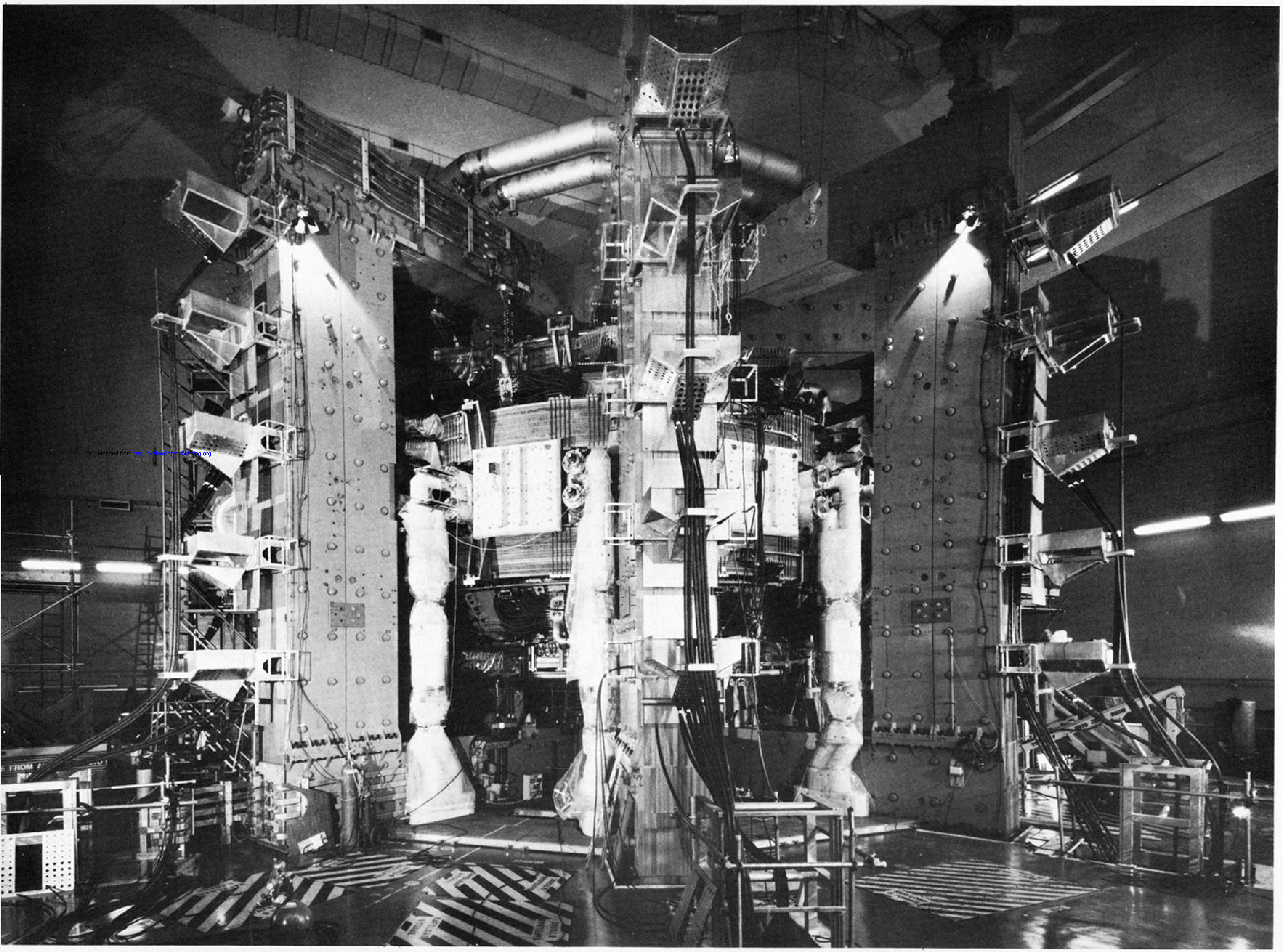


FIGURE 8. The JET machine in June 1983.