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A brief summary of the work carried out during the construction phase of JET is first given. This period was successfully concluded due to the well timed delivery by industry of all the major parts of the machine and power supplies. This could be achieved because of the excellent technical co-operation between the JET team and the firms involved in construction work.

The assembly of the JET machine started on site in January 1982 immediately after civil engineering work was completed. Great attention was devoted to the preparation of the vacuum vessel octants. After delivery, they were carefully cleaned, baked and leak tested at 500 °C, and then fitted with instrumentation, electrical heater cables and thermal insulation, in view of the bake-out of the complete vessel after final assembly.

The assembly of the large D-shaped toroidal field coils into their supporting mechanical structure presented specific handling problems due to their size and the accurate positioning required. Massive assembly tools specially designed for the handling of pieces up to 120 tons, in the case of a machine octant, had to be used for those operations. The whole assembly of the torus went smoothly and the vessel was closed in December 1982 and vacuum first established early in 1983.

The period from January to April 1983 was devoted essentially to the connection of services to the machine. This work which had been initially somewhat underestimated required a large effort in terms of work preparation, detailed routing design and overall coordination.

The vacuum system was commissioned without problems. The first torus pump-down by turbomolecular pumps took place at the end of May. Subsequent partial bake-out and glow discharge cleaning at 200 °C led to a total impurity pressure lower than 1×10^{-8} m bar, measured at 80 °C vessel temperature and 4500 litre/s effective pumping speed.

All subsystems commissioning tests, vacuum systems, power supplies and services always included the testing of the computer interface and the integration of the subsystem within the central control and data acquisition system (CODAS).

The successful completion of subsystems commissioning enabled the start in June 1983 of integrated tests with the power supplies connected to the coils. The toroidal field and the ohmic heating circuits were both tested up to currents of 40 kA. Field mapping experiments were also carried out to check the poloidal field configuration. This led to a first plasma discharge in the JET apparatus on June 25.

Between July and November 1983, more systems have been commissioned with a view to improve the performances. In particular, the cleaning methods for the vacuum vessel have been optimized, the plasma position control feedback system has been put into operation and the level of field has been raised. With these improvements plasma discharges with peak currents of 1.9 MA and a total discharge duration of 5 seconds have been obtained.

1. Introduction

The Joint European Torus (JET) is a large tokamak, the design of which is described in several reports [1 - 3]. Although the project was officially established in June 1978, the design study started in October 1973. Manufacturing contracts for long delivery items such as the toroidal field coils and the vacuum vessel were placed as early as 1976. To make it possible to place contracts for these items before the decision to build JET was taken, the contracts were split into stages where the first and second stages would usually include development and design work, and in some cases the construction of prototypes. Stage 3 of the manufacturing contracts covering the main production were released only after 1978 but the firms were already committed to it at the signature of the contract. Other components with shorter delivery times were ordered shortly after the decision to build JET was taken because the design had already reached a very advanced state in 1978.

The manufacture of the major components of the machine and of the power supplies was characterized by an excellent spirit of co-operation between JET and the European Industries. In general, the firms became committed to the success of JET and took a pride in delivering good quality components as quickly as possible. There were of course difficulties in all contracts, technical problems and organizational problems to meet the time schedule, but in all cases JET and the firms involved have worked out solutions which have always resulted in a satisfactory conclusion to both parties. The deliveries of the major components suffered some inevitable delays but their final timing between the end of 1981 and the second half of 1982 was never a cause for delays during the assembly at the JET site.

Excellent financial control has also been achieved as at the end of the construction phase the expenditure budget is within a few per cent of the original estimates.

2. The assembly of JET

This paper describes only the assembly of the machine itself. (Figure 1). Details on the assembly of power supplies and the control system are given in other papers presented at this conference.

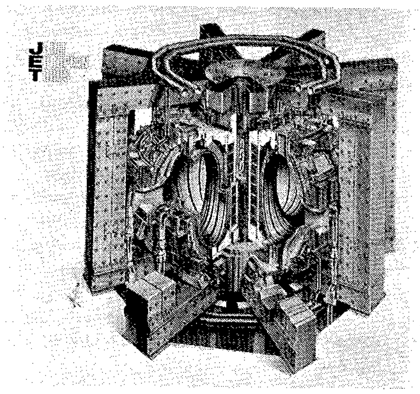

Figure 1. The JET machine. Overall height 12 metres. Overall diameter 15 metres.

The machine consists of a large, double-walled, inconel vacuum vessel made up of alternate rigid sectors and thin flexible bellows welded together. This vessel is made up of 8 octants welded together from the inside by a special lip joint. [4].

The toroidal magnetic field is generated by 32 D-shaped water cooled coils [5] which are supported against the large electromagnetic forces by a mechanical structure [6]. This structure consists essentially of 2 parts:

The inner structure including the lower and upper rings and collars and the inner cylinder.

The external shell enclosing the outer part of the toroidal field (TF) coils is, similarly to the vacuum vessel, also split into 8 octants. Thus, one JET octant is composed of one octant of the vacuum vessel, 4 toroidal field coils and one octant of the mechanical structure.

The poloidal field (PF) system includes the primary winding or coil no 1 made up of 8 small diameter coils stacked along the vertical axis of the machine. The coupling between primary winding and plasma is improved by means of an iron magnetic circuit with a highly saturated central core and eight return limbs. The other poloidal field coils with a much larger diameter (nos 2, 3 and 4) control the shape and position of the plasma cross section. [7].

From the end of 1981 till the end of 1982, the assembly of components of the machine was carried out in the JET assembly hall and in the experimental cell called the torus hall.

Because of the compact design of JET and of tokamak machines in general, the amount of assembly work to be carried out on the machine itself was reduced as much as possible, to alleviate access and safety problems related to work in confined areas, to reduce delays due to shortage of cranage facilities, and in general to allow parallel activities to take place without interfering with one another. For these reasons, the assembly hall was used for all the preparatory work such as the inspection of components after their delivery to the site, the installation of instrumentation sensors, and also the erection of sub-assemblies such as the machine octants. In general, components or sub-assemblies were not transferred to the torus hall before their preparation was complete, all tests satisfactorily passed, and acceptance documents signed off.

2.1 Preparation of machine parts in the assembly hall

2.1.1 The vacuum vessel

After delivery to the JET site each vessel octant has been washed internally with high pressure water jets and detergents. Hot leak tests were then carried out. For this, the octant was closed by two end plates welded on the octant lip joints. This assembly was placed in the JET oven and the main volume and the interspace between the two walls was evacuated. The temperature was raised in 36 hours to 520 °C and maintained for 70 hours. Leak tests were carried out first between the outside and the interspace (the oven was partially filled with helium), and then between the interspace and the main volume by injecting helium in the interspace. All octants had some leaks ranging from 10^{-7} to 4x10^{-9} mbar. $\ell.s^{-1}$. These leaks were localized at lower temperature and repaired. One of the octants was submitted to three further baking cycles but no additional leaks were found. After repairs all octants were accepted with leak rates close to 1x10^{-9} mbar. $\ell.s^{-1}$.

After baking, the octants were checked dimensionally using a photogrametric method but no significant distortion could be found. On the outside wall of the vessel, flux loops and field probes were then fitted for plasma diagnostics and plasma position control. Thermocouples and electrical heaters for the bake-out of the complete vessel were also assembled. All these instruments were covered with special insulation panels selected for their very low thermal conductivity (0.025 W/cm. °C) at 500 °C. The insulation panels were precisely made to measure and fitted in two overlapping layers. The second layer was secured by means of glass fibre tape bands to ensure no local high temperature contact with the electrical insulation of the toroidal field coils. (Figure 2).

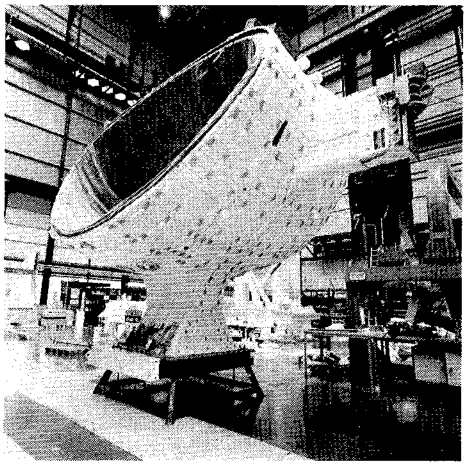

Figure 2. Vacuum vessel octant with thermal insulation

2.1.2 Preparation of octants

On delivery to the JET site, the TF coils and the octants of the mechanical structure were fitted with instrumentation transducers such as resistance thermometers, strain gauges, crack detectors, flux loops and Rogowski coils.

The assembly started by splitting the mechanical structure octant into 2 halves or 1/16 octants along the middle meridian plane and fitting these 1/16 octants into a cradle-shaped jig. Two TF coils were then lowered by means of a special handling tool and locked in position into grooves on the inside surface of the structure (Figure 3). This unit, was then lifted, rotated to an upright position and fixed on one of the sliding tables of the octant assembly fixture. This procedure was repeated for the other unit.

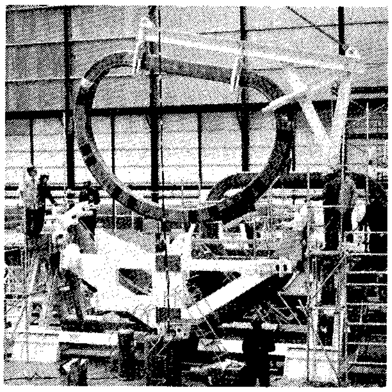

Figure 3. Assembly of a toroidal field coil in the mechanical structure

The octant of the vacuum vessel complete with thermal insulation was inserted on the central support of the assembly fixture between the two sliding tables, and these 2 tables were then rotated so that the half octants of the structure together with the toroidal field coils, enclosed the vessel (Figure 4). These two half octants were then bolted and keyed together to ensure a strong shear joint.

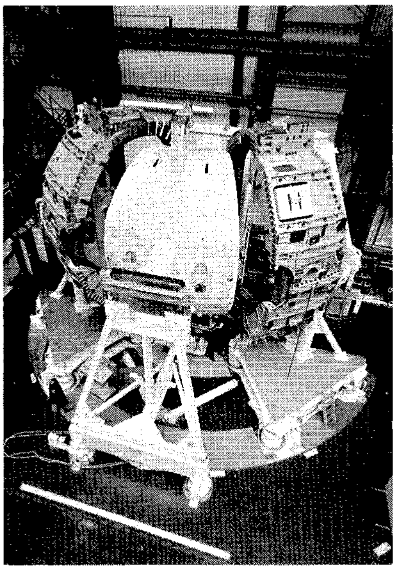

Figure 4. Assembly of a machine octant. The vacuum vessel in between the 2 half octants which are ready to be closed.

At this stage the machine octant was lifted from its assembly fixture, using the rigid stiffening frames bolted on either side of the mechanical structure, and the octant was relocated at another station for finishing work and tests. Busbars and water manifolds were assembled and tested there. Inside the vacuum vessel, several types of penetrations, namely, small vertical diagnostic ports, limiter guide tubes and gas feed pipes, were fitted and welded. Most welds are made on the inside of the vessel and are inaccessible from the outside. For leak testing, helium spray tubes ending close to the outside of the welds have been fitted, and a local vacuum is created on the inside by means of small pumping boxes sealed with silicon rubber gaskets. For all work inside the vessel, strict clean-conditions procedures were enforced.

Some of the limiter units were also installed at this stage. For the initial operation, 4 graphite radiation-cooled limiters, and 8 nickel-clad, water cooled limiters have been installed [8]. Each limiter is located in the equatorial plane at the outside wall and its position can be adjusted in the radial direction. For assembly, each unit weighing approximately 400 kg was inserted in the vessel through a main horizontal port, the supports and feed-throughs were threaded through the penetrations and welded. The nickel limiters were assembled first, the late ones were in fact assembled in the torus hall, and the assembly of the graphite limiters was delayed until after the final water wash of the completely welded vessel in the torus hall.

The assembly of the octants was organized as a series production with a peak period in August 1982 when six octants at various stages of assembly could be seen at the same time. Although it took 7 months to complete the first octant, the improvement in speed and efficiency was such that the 8 octants were all completed and transferred to the torus hall within 12 months after the start of the assembly work.

2.1.3 The poloidal field coils

Coil no 1 consists of 8 sub-coils stacked vertically at the center of the machine. Before delivery, the sub-coils were stacked and shimmed using an epoxy paste on their horizontal face to give good contact and ensure verticality. The 6 central coils were then assembled and their outside diameter was machined on a vertical axis lathe to give an accurate surface for the TF coils and the inner cylinder to press against. After machining the surface was coated with a low friction material so that the coils can expand in the vertical direction during a pulse. After delivery at Culham, the stack was rebuilt and bus bars and water manifolds fitted inside the bore. Dimensional surveys showed that the 4 metres high stack was vertical within 1 mm with steps from coil to coil smaller than 0.25 mm (Figure 5).

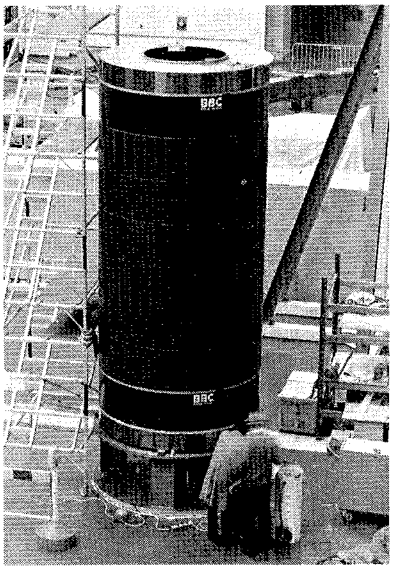

Figure 5. The poloidal field coil no 1

Coils no 3 and 4 were manufactured as half pancakes, preassembled at the factory, dismantled and delivered to JET as half pancakes. The pancakes were stacked on an alignment tool in the assembly hall, coating the mating surfaces with epoxy resin and a glass wool mat. When stacking was complete, the pancakes were clamped and the epoxy resin allowed to cure at room temperature. After completion of water manifolds and electrical connections, the coils were heated by circulating hot water at 60 °C for 24 hours to complete curing of the pancake adhesive. The pancakes were aligned within ± 2.5 mm of the nominal radius, and coil clamps and mounting plates were positioned within ± 0.5 mm (Figure 6).

To move these large coils (up to 12 m in diameter and 80 tons in weight), the JET crane is equipped with 4 separate ropes with an hydraulic load balancing mechanism. These ropes fit into special lifting points spaced around the coil periphery. This system was used to transfer the coils to the torus hall and lower them into their final position on the machine.

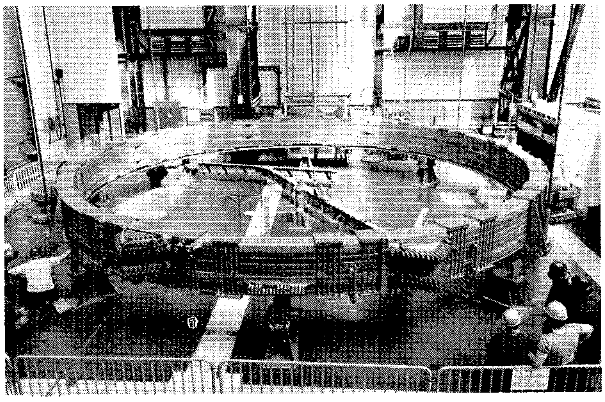

Figure 6. A poloidal field coil no 4

2.2 Assembly of the machine in the torus hall

Assembly work in the torus hall started by mid January 1982 as soon as civil engineering work was completed. Table I shows the milesones of the work.

Table I. Assembly of JET in the Torus Hall

Date	Event
Jan 15 1982	Torus Hall handed over. Start of installation of large pipe rings in the pit under the machine
Feb 1 1982	First lower limb of the magnetic circuit installed
Feb 21 1982	All 8 lower limbs installed
Mar 24 1982	All 8 vertical limbs installed
Mar 26 1982	Lower centre piece of the magnetic circuit installed
Apr 27 1982	Lower PF coil no 2 in position
May 20 1982	Lower ring installed and aligned
Jun 8 1982	Upper ring aligned
July 25 1982	Lower PF coils no 3 and 4 lowered on lower limbs
Aug 4 1982	First octant installed
Oct 26 1982	Five octants installed
Nov 8 1982	Mechanical joint between adjacent octants closed for the first time
Nov 12 1982	Vacuum lip joint between adjacent vessels welded for the first time
Dec 2 1982	PF coil no 1 installed
Dec 13 1982	Eight octants in position
Jan 20 1983	Upper PF coils no 3 and 4 in position
Jan 30 1983	Upper limbs of the magnetic circuit installed.

Figure 7 shows the magnetic circuit and the internal parts of the mechanical structure, namely, the lower ring and collar, and the upper ring and collar, here on its temporary support columns. One segment of the inner cylinder joining the upper and lower collars can be seen with the vertical grooves which locate and support the straight part of the toroidal field coils.

For the transfer of the octant to the torus hall, the side stiffening frames had to be removed, and the complete octant weighing 120 tons was lifted by crane and by a large C-shaped frame able to 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 a whole had to be accurately adjusted to permit the insertion of the octant into its final position. The upper part of the C frame structure with the crane hook attachment is above the upper PF coils, thus allowing the assembly or dismantling of an octant with the PF coils in their parking position (Figure 8).

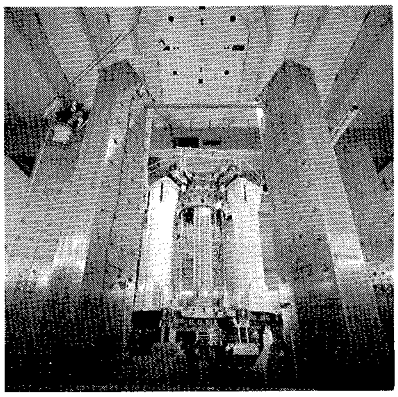

Figure 7. The internal part of the mechanical structure

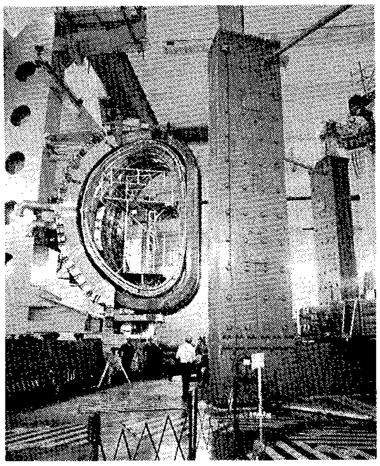

Figure 8. Insertion of a machine octant on the torus. The octant is lifted by the C frame

The mechanical joint between octants is provided by bolts across the adjacent flanges and mechanical keys which resist the large shear forces between octants. These keys have been designed with spherical bearings and retractable wedges so that small misalignments between octants could be accommodated by the keys. After assembly, all bolts and keys were preloaded to provide the required torsional stiffness of the mechanical structure.

To facilitate the insertion of the vessel octants in the congruent space between already assembled octants, the vessels were slightly reduced in width by evacuating the interspace volume. Prior to welding, the lip joints between octants were prepared using a remotely-controlled nibbler. The welding itself was performed with the remotely-controlled welding tool developed by JET (Figure 9). These welds were then leak tested using local pumping boxes on the inside and the helium spray pipes on the outside. After leak testing the internal protection plates and the nickel limiters were fitted.

From January to May 1983 the installation of services to the machine took place. These services included water pipework and bus bars to the coils, gas pipes for the baking of the vessel and for the gas introduction system, and the pulling and terminating of power and instrumentation cables. The pumping chambers with their turbo-pumps were also installed and connected to the primary pumping system (Figure 10).

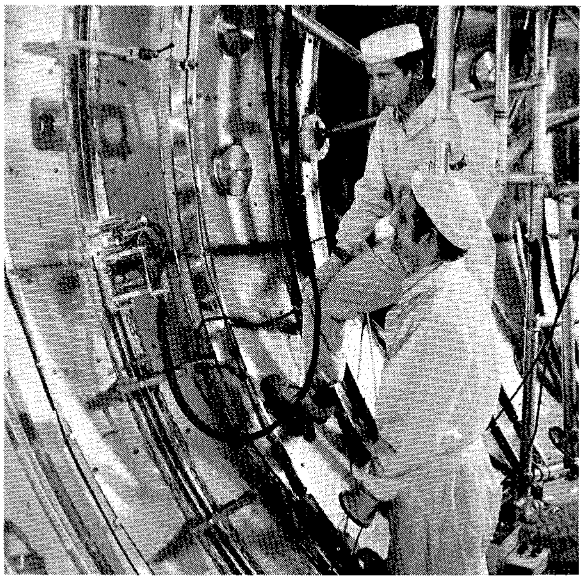

Figure 9. Octant lip joint welding

2.3 General remarks on the assembly of JET

For the assembly of the machine, JET has placed a contract with an industrial firm for the supply of labour and some supervision. It was the responsibility of JET to define the assembly procedures and tests required, and up to the contractor to prepare the work in detail and organize the labour force. For each operation, detailed procedures were prepared and carefully checked through a strict system of review meetings and interface documents to be signed off. For each operation, responsible officers from JET and from the contractor were nominated. This organization proved successful and the detailed preparation of the assembly work made it possible to assemble the machine in a remarkably short time.

Regarding the services, piping and cabling, the level of preparation of the work was not sufficient when assembly started. In particular the amount of work related to the routing of services near the machine had been underestimated. This resulted in four hectic months from February to May to make the machine ready for first operation in June. This kind of experience is not specific to JET but demonstrates again the importance of an early and detailed definition of services.

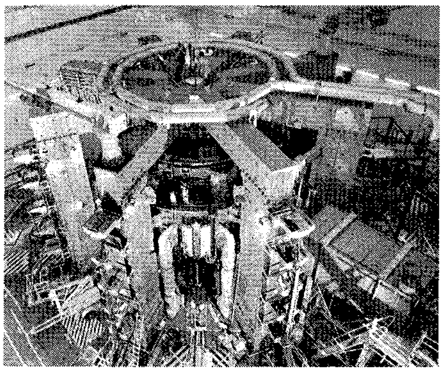

Figure 10. Status of the JET machine in March 1983. Pipework and cables installation is progressing

3. The commissioning of JET

JET subsystems or parts of subsystems were commissioned from January till May 1983 before integrated tests could start. The main JET subsystems are: General services, Toroidal field, Poloidal field, Vacuum, Diagnostics.

In general the components (local units) of each subsystem were commissioned initially in local mode, that is without the use of the CODAS subsystem computers. This was possible because most of the local units have been designed with the capability to operate on their own. Operation sequences, interlocks and in the case of power supplies, simple pulse waveforms, are generated in the local unit cubicles. From June 1983 onwards, commissioning tests always involved several subsystems simultaneously and these were of course carried out under computer control.

For each subsystem, commissioning tests and the associated written procedures were divided into 4 classes depending on the hazards and interfaces involved. This classification was for planning purposes in order to monitor better the commissioning procedures and the progress of commissioning tests. It also helped to establish a formal system for the approval of commissioning procedures.

Class 4 was for local tests (not involving CODAS) and without power or any other serious hazard

Class 3 was for local tests (not involving CODAS) but with power

Class 2 was for tests involving the CODAS interface but without power

Class 1 was for the complete system with power and under computer control.

The procedures for class 3 and class 1 tests were subjected to a very close scrutiny before they were formally approved. In particular safety precautions which were an integral part of the procedure were assessed by a set of JET senior staff (JET Safety assessors) before final approval was given.

3.1 General services

The 400 kV connection, the 400 kV/33 kV substation and the power distribution at 33 kV, 11 kV, 3.3 kV and 415 V were among the first systems to be fully commissioned with CODAS for initial operation. The water cooling system for site water, water treatment and demineralized water systems were operational early in 1983. An emergency cooling system powered with diesel engines was commissioned in May 1983 to guarantee water cooling to the TF coils during bake-out of the vacuum vessel.

3.2 Toroidal field (TF)

The rectifier static unit was commissioned with a dummy load and later with the TF coils up to a current of 25 kA. There were some difficulties during the commissioning of the TF flywheel generator due to a lateral displacement of the shaft induced by magnetic forces in the pony motor. This problem was solved by an electrical reconnection of the motor stator winding [9]. The generator has now been accelerated up to and operated at a speed of 200 rpm (maximum speed is 225 rpm), and tested in short circuit up to 100 kA. In combined operation, the static unit and the generator have delivered a current of 53 kA to the coils (full design value is 67 kA) with a flat top of 10 seconds.

The commissioning of the TF coils started by the final positioning of the coils within the mechanical structure. The straight part of each TF coil fits into a cylindrical groove on the inner cylinder so that the coil is located and supported against lateral forces. The coils were initially pressed mechanically and then magnetically using coil currents up to 15 kA. In this way, centripetal forces of 100 tons per coil were produced. Shims and wedges which locate and support the coils along their outer contours were then made according to the actual measured gaps between coils and structure, and inserted. The accuracy of positioning is about 0.4 mm for the straight part and 1 mm for the outer contour. This accuracy is not dictated by field perturbations or associated forces but by assembly requirements.

At 40 kA and 53 kA the coil expansion has been measured in the vertical and radial directions and agrees with calculated values confirming that bending stresses are effectively eliminated by the D shape. The cooling water temperature peaks 30 seconds after the pulse and returns to its average level within 3 minutes. The coils instrumentation includes also surface temperature gauges to check the temperature of the insulation facing the vessel during bake-out [10].

The short circuit detection system (DMSS) was operational. It protects the coils by de-exciting the generator and closing a crowbar switch (not operational yet) when a voltage imbalance is detected. The earth fault detection system which measures fault currents circulating between the machine earth and the mid-point of the rectifier bridge of the generator, was also operational. Earth fault currents are limited to a small safe value by a 1 kΩ resistor.

3.3 Poloidal field (PF)

The PF flywheel generator was accelerated up to a speed of 211 rpm (maximum speed is 225 rpm). The problem of the magnetic pull and difficulties with the lubrication system of the top guide bearing were solved [9]. The ohmic heating circuit was commissioned in several modes of operation, namely, premagnetisation, fast rise and slow rise, under computer control. For the fast rise, a current up to 40 kA (maximum design value 80 kA) was commuted into the resistive load. The slow rise mode has been commissioned up to a current of 48 kA in the coils. The vertical field (PVFA) and the radial field amplifiers (PRFA) for plasma position control were operated initially using preprogrammed waveforms but the feed-back systems which use flux signals from the magnetic diagnostics were successfully introduced in July 83 for the PVFA and in October for the PRFA. [9].

The PF coils were high voltage tested at 45 kV D.C. to earth when dry, and at 25 kV pulsed after the filling of the water cooling circuit. Interturn insulation tests were made by discharging a 45 µF capacitor into the coil to produce an inter-turn voltage of 560 volts for the no 1 coils and 2800 volts for the outer coils nos 2, 3 and 4. During these tests a short circuit was found between 2 turns in the lower PF coil no 4. The reason for this is not fully explained, but it is thought that break-downs to earth during D.C. ground insulation tests may have generated fast voltage transients able to puncture the interturn insulation. The short circuited turn has now been excluded from the coil.

The coil short circuit detection system (DMSS) which detects current imbalance between symmetrical coils above and below the equatorial plane, was partially commissioned in October but not fully integrated in the poloidal field system.

The field configurations in the plasma region have been measured using the magnetic diagnostics. In the pre-magnetisation mode, the leakage flux from the iron is very small as expected. The field maps for the vertical and radial equilibrium fields show excellent agreement with predicted values. The double flux swing in the central core is 3.8 volt.sec. before saturation of the core, and this value is slightly lower than expected, but this is explained by the magnetic properties of the steel used for the support rings of the ohmic heating coils.

The plasma fault protection system, the main purpose of which is to safeguard the machine from damaging plasma behaviour, was not fully commissioned in November 1983. However, the interlock inhibiting the operation of the poloidal field power supplies when the gas introduction valves do not open, was operational in order to prevent the generation of energetic run-away discharges. In its final form, the plasma fault protection system will receive signals from several diagnostics, and detect the precursor signs of a disruption.

3.4 Vacuum

The high vacuum turbo-pumps and associated systems and the primary pumping systems have all been commissioned and their operational sequences are now computer controlled.

Because of the contamination of the surface of the vacuum vessel during assembly, the vessel was carefully washed before pump-down. The cleaning was carried out manually with high pressure jets (150 bars) of water and a detergent solution at a temperature of 80 °C. Rinsing was made with demineralized water. The bellows protection plates were then installed and a final rinsing was done using an automatic high pressure sprinkler system.

By the end of May 1983, the turbo pumps were brought into operation and after the repair of two leaks on external welds a total pressure of 3×10^{-6} mbar was achieved (90 % of the pressure was due to water). The vessel was heated at 120 °C in order to pump away the water and this resulted in the following partial pressures: 5×10^{-7} mbar H_2, 5×10^{-8} mbar H_2O and small values of O_2 and N_2. The final cleaning before the first plasma operation was glow discharge during 30 hours with the vessel walls at 200 °C but the ports were kept cold because electrical heaters had not been made operational yet. This reduced the water partial pressure to 1×10^{-8} mbar at 100 °C.

The baking plant which circulates hot gas in the vessel interspace had to be fitted with a temporary blower unit because the original blower could not be balanced properly. The plant has been using hot air instead of CO_2 and provides a temperature ramp rate and cool-down rate slower than originally foreseen. The vessel has been maintained for long periods at 300 °C while the ports which are heated by electrical elements have been baked at 200 °C. It is not possible to exceed a baking temperature of 300 °C as long as the nickel limiters are not water cooled because the copper chromium cooling structures of these limiters would be softened.

The drainage and refilling system will cool the limiters, neutral beam scrapers, glow discharge electrodes and some elements of the rotary valve. This system will provide a complex sequence of water cooling and nitrogen gas cooling during a bake-out cycle. The installation of the system is now essentially complete and commissioning tests will take place early in 1984.

The gas handling and gas introduction system is not complete yet as only 2 modules out of 4 have been installed, each equipped with a fast on/off valve, and a dosing valve. This system is computer controlled and both pulsed filling and pre-programmed wave form filling have been tested.

Glow discharge cleaning has been operated successfully with a wall temperature of 300 °C and has proved quite effective to condition the walls. The parameters required to achieve pulse discharge cleaning have been explored (section 4.2) but pulse discharge cleaning has not been used as a cleaning method due to the lack of time. The residual gas analyser system has been available from June onwards to assist wall conditioning operations.

3.5 Diagnostics

Some essential diagnostics were available for day one (July 1983) operation, other diagnostics were brought into operation during the August machine shutdown period or during the period from September to November. The list of diagnostics operational in November 1983 is given below.

- Magnetic diagnostics including flux loops and discrete coils (day one)
- 2 mm single chord interferometer (day one)
- Hα monitors and visible light spectrometers. This include 8 vertical channels and 2 horizontal channels looking at carbon and nickel limiters (day one)
- Spectrometer (2000 Å - 7000 Å)
- Bolometers. One vertical channel was available for day one. There are now 8 vertical individual channels and a camera with 14 vertical spatial channels.
- Hard X-ray monitors (day one)
- Soft X-ray diodes (not day one)
- Infra red camera viewing a carbon limiter (day one)
- Neutron yield monitors (day one)
- Health physics instrumentation (day one)

These diagnostics are fully operational with all data acquisition and interpretation codes.

3.6 CODAS (Control and Data Acquisition System)

The computer configuration is in its final form and the computers required for initial operation are fully commissioned. The main consoles are operational and display facilities are constantly being improved. The level 3 software which provides basic data acquisition and control facilities within subsystems is operational and has been used in commissioning and operation. Level 2 software which provides more ellaborate control functions within a subsystem and level 1 software related to the combined operation of several sub-systems are being implemented. All three levels of the data acquisition software have been in operation since the very first experiment with automatic transfer of experimental data from the interface electronics up to the centralized files permanently held in the off-site IBM-CRAY mainframe. Details of the CODAS system are given in a paper presented to this conference [11]. The Central Interlock and Safety System (CISS) backs up CODAS to guarantee the safe operation of the machine. It is based on programmable logic controllers and is structured into subsystems similarly to CODAS [11]. CISS is not fully implemented yet but is operational for some subsystems.

3.7 Integrated tests

Before plasma operation, tests were carried out to check the combined operation of the toroidal field and poloidal field systems. During these tests a vertical field was generated in order to produce some twisting moment on the toroidal field coils and the mechanical structure. At the low level of the test (2000 ton-metres, ie. 1/10 of the maximum design value) the rotational deflection of the shell was 0.23 mm, in accordance with calculations.

4. First JET operation

4.1 The first phase of operation (June - July 1983)

Before the first plasma operation, the vessel was baked at 200 °C and discharge cleaning was established for 30 hours (section 3.4).

On 25 June the first plasma discharges were generated and after a few discharges at low current, peak plasma currents of 100 kA during 100 ms were measured. The loop voltage during these initial discharges was very high, i.e. 40 volts, indicating a very resistive plasma.

Baking and glow discharge cleaning improved the conditions and allowed in July peak plasma currents of 230 kA during 300 ms with a loop voltage of 26 volts. During this period, the plasma radial position feed back control was in operation but not optimized and the vertical position control was not working leading to vertical displacements of the plasma. [12].

Further baking and glow discharge cleaning resulted in a peak plasma current of 625 kA with a loop voltage of 14 volts. The toroidal field was 1.5 T. Due to the strong elongation of the plasma ($a = 1.15$ m and $b = 1.57$ m) and the lack of vertical position control, the vertical instability limited the discharge to approximately 225 ms. Operation was then interrupted because of problems with power supply control systems and could not be resumed before the planned switching off of the 400 kV power to the JET Laboratory. This switching off had been agreed well in advance with the Electrical Authority for maintenance work on the 400 kV grid system.

4.2 The second phase of operation (October - November 1983)

During the period, from October to November 1983, the machine has been operated on a 2 weekly schedule where one week was devoted to commissioning, in order to improve machine sub-systems and extend the machine operation modes, and the other week was for plasma operation.

4.2.1 Wall conditioning and limiters

During this period, the wall conditioning procedures which have been regularly followed were bake-out assisted by glow discharge. Five days before plasma operation, a bake-out cycle was started by raising the ports temperature and the vessel walls temperature to respectively 200 °C and 300 °C in approximately 30 hours. At this temperature the pressure took typically 24 hours to settle and glow discharge was switched on. Glow discharge is assisted with RF power in order to allow a lower pressure during cleaning and therefore a higher removal rate of impurities. Typical pressures during glow discharge are 5.10^{-3} mbar. Glow discharge cleaning was kept running for 3 complete days before plasma operation. This resulted in barely detectable (less than 10^{-9} mbar partial pressure) impurity levels measured with the residual gas analyser, the only impurities observed being CH_4, H_2O and C_2H_4/CO. The vessel and the ports temperatures were then reduced to 100 °C and maintained at this level for the week of plasma operation. Further glow discharges were carried out every night between operation sessions to remove impurities due to leaks or generated during the discharges.

These procedures have been successful in the sense that low loop voltage discharges have been achieved, and a reasonable reproducibility of discharges has been observed.

Pulse discharge cleaning has not been used so far and the commissioning of this mode of operation has not been carried out yet. Nevertheless, the parameters required to achieve pulse discharge cleaning have been explored and it has been found that a toroidal field of 1500 Gs and a breakdown loop voltage of 7 volts were sufficient to generate cleaning discharges with a current of 120 kA and a duration of 150 ms.

From July to November 1983, only the 4 carbon limiters have been used. The nickel-clad, water-cooled limiters were retracted 10 cm behind the line of the carbon limiters. During discharges, one of the four carbon limiters was viewed by an infra-red camera. There were some indications of arcing especially during the early phases of operation. Later, arcing ceased to be as frequent and some limiter surface heating was observed. The surface temperature never rose above 500 ^{o}C.

No attempt was made to try the nickel-clad limiters because of the satisfactory behaviour of the carbon limiters and the lack of time to investigate and compare results with different types of limiters. In addition, some leaks have opened up between the main vacuum and the water cooling circuits of 3 of the limiters and these circuits have now been blanked and pumped down. The leaks are probably due to a metallurgical problem and the leaky limiters will have to be dismantled during the next shut-down period.

4.2.2 Fast rise discharges

Initially, plasma discharges were obtained in the so-called fast rise mode which involves the premagnetization of the magnetic circuit and the commutation, by means of circuit breakers, of the premagnetization current into a resistive load. A break-down loop voltage in the range of 50 volts was used first but it became clear that better quality discharges were obtained with a lower initial voltage and lower current rate of rise. A discharge of this type is shown in figure 11. For this type of discharge, the gas filling was performed by a single initial gas puff from a fast valve. Position control was achieved by feed-back loops both for the radial and vertical position.

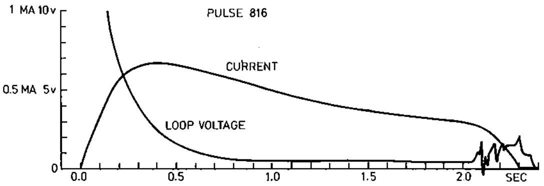

Figure 11. Shot no 816. Fast rise discharge
Toroidal field: 2.08 Tesla
Peak current: 700 kA

Loop voltage at $\frac{dI}{dt} = 0$, 2.5 volts

4.2.3 Flat top discharges

In November, the discharge duration was extended by applying a driving voltage after the fast rise phase. A typical discharge obtained at a toroidal field of 2.08 Tesla is shown on figure 12. Figure 13 shows the discharge with the highest plasma current achieved so far (shot 983). For these discharges the current time evolution was controlled by a pre-programmed wave form as current feed-back control was not operational yet. The gas filling was performed by a gas puff giving typically a filling pressure of 4.10^{-5} mbar followed by a continuous injection of gas throughout the discharge.

All discharges were disruptively terminated with a current quench lasting typically 100 to 300 ms. Some discharges quenched more rapidly, the fastest recorded so far is pulse 807 with a quench time of 45 ms. Some of these disruptively terminated discharges gave rise to a copious production of hard X-rays and photo neutrons (up to 10^{13} neutrons during a disruption) but that could be controlled by an adjustment of the filling pressure. It is hoped that when the dosing valves for gas injection are commissioned late in November, the better control of the gas flow and the density will help in achieving smooth discharge terminations.

The radial position control was operating in its final form and was very successful. The system controls the inner position, in the equatorial plane, of the magnetic surface which originates at the edge of the limiter. It is therefore possible to control the size of the plasma, and the rate of increase of the size of the plasma, by pre-programming the position of the magnetic surface. The position computed from magnetic measurements showed an evolution which followed very precisely i.e, with an error less than 2 cm, the preprogrammed values.

The vertical plasma position control was also operational and kept all discharges exactly centered. Figure 14 shows the magnetic surfaces for shot 983.

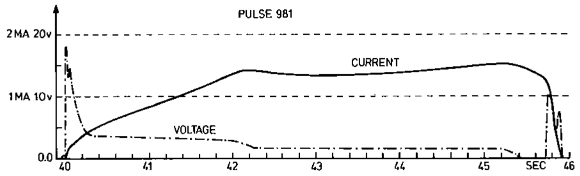

Figure 12. Shot no 981
Toroidal field 2.08 Tesla
Peak current 1.5 MA
Total duration 5.8 sec.

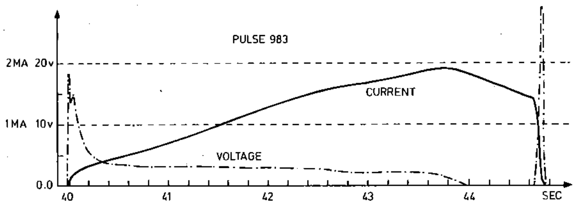

Figure 13. Shot no 983
Toroidal field 2.08 Tesla
Peak current 1.9 MA
Total duration 4.7 sec.

Preliminary analysis of shot 983

All diagnostics indicate a fairly quiet behaviour throughout the discharge. The loop voltage is smooth, the visible light is limited to peaks at the beginning and the end of the discharge, and hard X-rays are practically absent. Soft X-rays show a sawtooth activity which indicates that q(0) = 1, throughout most of the pulse.

The density increases regularly because of the constant gas inlet and reaches its maximum value at the end of the pulse. The maximum integral line density measured along a vertical chord is $7x10^{19}$

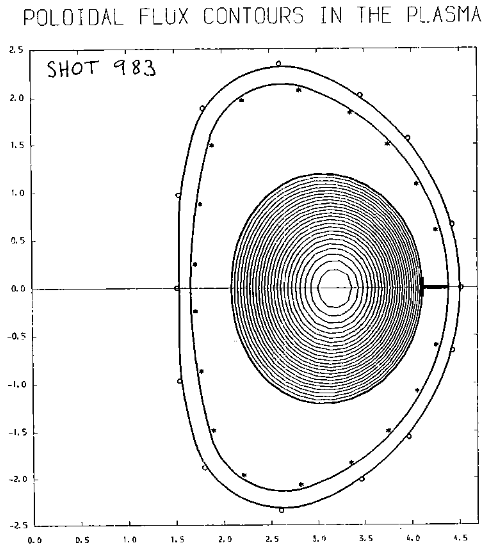

Figure 14. Shot no 983
Plasma cross-section
Horizontal: 2.03 m
Vertical: 2.4 m at time 42 sec.
Ellipticity: 1.18

to 8×10^{19} m^{-3}. From this, the average density is estimated to be 3.10^{19} m^{-3}.

The radiation profile, measured with the vertical bolometer camera, is hollow, indicating that high Z metallic impurities are not dominant. The ratio of the total radiated power to the ohmic heating input power is estimated to be near 0.6. Calculations of Z_{eff} give values between 2 and 3.

The temperature profile cannot be measured yet but the electron temperature obtained from the soft X-rays spectrum is about 900 eV. This value is in good agreement with the ion temperature measured by the broadening of H_{α} lines. Assuming a parabolic density profile and a gaussian temperature profile, the energy replacement time should be in the range of 150 to 300 ms.

Although of a preliminary nature, these results compare very favourably with predictions and represent an encouraging first step of the JET programme.

5. Outlook for the operation programme

The JET operation programme has been divided into a certain number of phases which are essentially determined by the availability of additional heating.

The first phase or the ohmic heating phase, started in October 1983 and aims at reaching the design limit of 5 MA plasma current at a toroidal field level of 3.5 Tesla. This phase should end during the second half of 1984 when the first neutral injection system will become available and provide 5 MW of neutral power at 80 keV with hydrogen beams. By the end of 1985 more power will be available when the second identical neutral injection system will become operational and a further 3 MW of Ion Cyclotron Resonance Frequency heating will be made available. The ICRF heating system will be gradually upgraded to a maximum power of 15 MW, bringing the total additional heating power to 25 MW by 1987. At the same time, the neutral beam injection voltage will be increased to 160 kV for operation with deuterium.

Limiters able to sustain long and powerful discharges have also to be developed. "Belt limiters", ie continuous axisymmetric limiter rings in the toroidal direction, will be fitted inside the vessel by the end of 1985. As a low Z material for these limiters it is proposed to use beryllium.

Preparation for the active phase will take place throughout this programme and will include the development of remote handling techniques for maintenance, and the installation and commissioning of the tritium-associated systems. A period of operation at full performance with deuterium plasma from mid 1988 to mid 1989 should be followed by the tritium phase with D-T plasmas and the study of alpha particle heating and the approach to ignition.

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