Structural problems of the NET basic machine

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The NET basic machine provides a framework inside which ignited plasmas can be confined while nuclear components testing is performed. The magnetic containment of the plasma is provided by the coil systems ; the vacuum containment is provided by the vacuum vessel, which has also to provide the shielding against radiations to protect the toroidal field (TF) coils. The TF coil system has to contain a magnetic energy of ~25 GJ in addition to the ability to carry the electric current necessary to produce a maximum magnetic field of ~12 Tesla. The TF coils have also to support the forces generated by the transversal field due to the poloidal field coils. While the self field is stationary the transversal loads are of cyclic nature. The poloidal field coils necessary to shape the plasma and to induce the plasma current are also experiencing quite high magnetic fields (e.g. ~12 T in the central column) and associated mechanical loads, which are cyclic in nature.

These coils are made up of several components connected together by different means and they have to act as structural elements. During cooling from room to operating temperature 4.2 °K and during quench significant thermal gradients will be experienced by the coils with consequent thermal stresses. This coils should also resist to forces raising in case of accident such as short circuit of one or more coils.

The Vacuum Vessel (V.V.) is about 600 mm thick and is the primary containment of activated material, then it is designed to resist not only the loads experienced during normal operation but also in accident condition. Main loads for the V.V. are the atmospheric pressure, the electromagnetic loads due to plasma disruption, thermal stresses due to nuclear heat deposition, overpressure and localised impact forces during accident.

The structural assessment of these components will be presented in the paper, taking into account also the nuclear effects.

1 INTRODUCTION

In the European fusion programme it is envisaged to built in addition to the devices foreseen in the basic Tokamak program three major devices before the construction of the prototype fusion commercial reactor : JET, NET and Demo. JET should establish scalings of plasma heating and confinement sufficiently reliable to determine the main parameters of NET. NET has the objective to demonstrate the feasability of fusion in both physics and technological aspects, Demo should demonstrate the commercial, reliable, safe and environmentally acceptable fusion reactor operation. NET shall obtain self sustaining fusion reactions for long pulses in a controlled way. NET shall qualify the nuclear components and demonstrate the safe and reliable operation of the basic machine. NET is a Tokamak like machine ; in a Tokamak a current flows, in the plasma around a circular loop, induced by transformer action from external coil. Magnetic confinement and stability is provided by sets of external coils, arranged both toroidally and poloidally around the plasma.

Three phases of operation (Table 1) are envisaged for NET.

Table 1 Operation Phases of NET

Phase	I	II	III
Duration (Calendar years)	2	4	7
Fluence (MWa/m^2) (*)	-	0.1	0.7
Integral operation time (days)	-	70	300
No. of pulses ($x\ 10^4$)	1	4	5
Breeding ratio required (**)	-	-	0.3-0.4

(*) Based on an average wall loading of 1 MW/m^2
(**) T supply : ~6 kg from blanket and ~20 kg from external source (~1.5 kg/y)

The operation of NET will go from the maximum of flexibility with different plasma shape and plasma currents up to 15 MA to the maximum of availability up to 25% for long periods (e.g. one calendar year). The operating cycle is pulsed with start-up, burn, quench and dwell time.

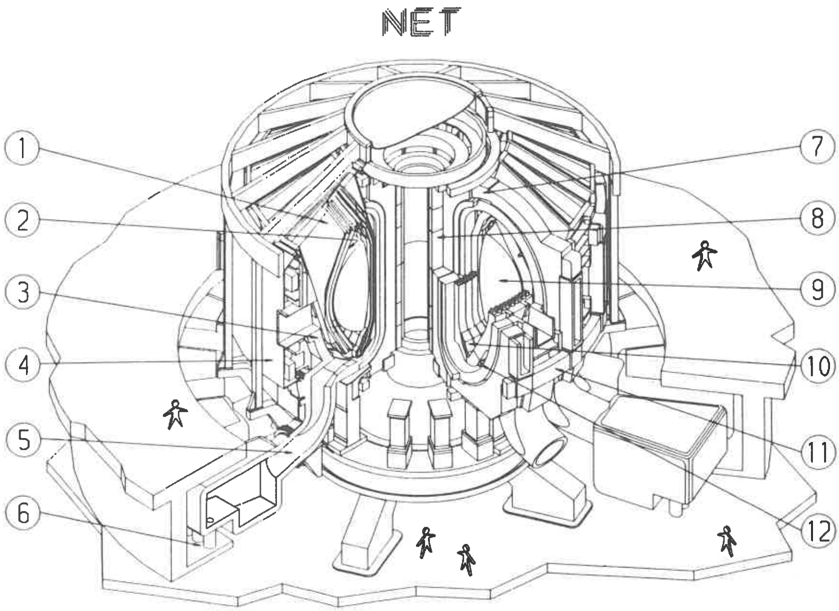
2 THE TOROIDAL FIELD COILS

The overall layout of the toroidal and poloidal field coils within the NET machine is shown in Figure 1. Both sets of coils are superconducting and enclosed within a common cryostat, with penetrations to allow access to the machine interior. The toroidal field coil cases act as supports for the poloidal coils.

The toroidal coils are individually supported against gravity on a flexible multiplate support which allows easy radial movement but is stiff in other directions (Figure 2).

The magnetic forces are supported on the inside by a vault formed from the noses of the coils and on the outside by an intercoil structure in the region of the outer equator. Since the coils are an elongated form of the bending moment free D shape, both inner and outer supports play a part in supporting the in-plane coil forces due to the self field as well as the out of plane forces due to the poloidal field coils.

Each coil consist of a winding pack (8 MAT/coil) contained inside a stainless steel (316LN) case. The case thickness varies around the coil perimeter, being concentrated at the nose in the straight inner leg to provide greater protection for the winding pack against the coil centring forces.



1	Blanket	7	Toroidal Field Coils
2	First Wall	8	Inner Poloidal Coils
3	Shield	9	Plasma
4	Cryostat	10	Divertor Plates
5	Plasma Exhaust	11	Outer Poloidal Coils
6	Vacuum Pump	12	Active Coils

Fig. 1 NET Lay-out

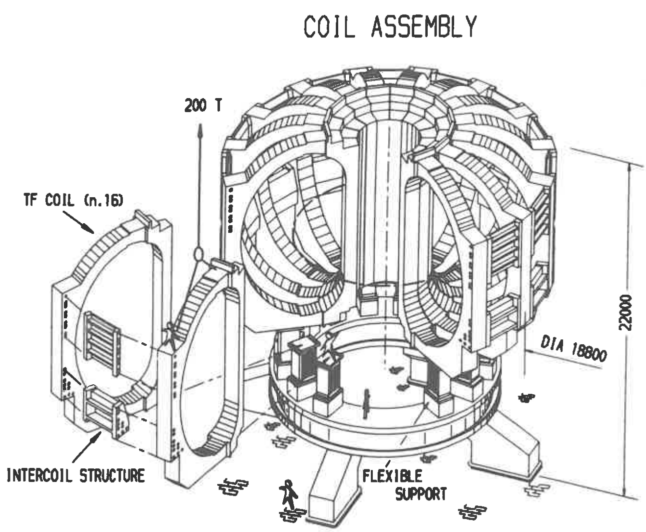


Fig. 2 TF Coil Assembly

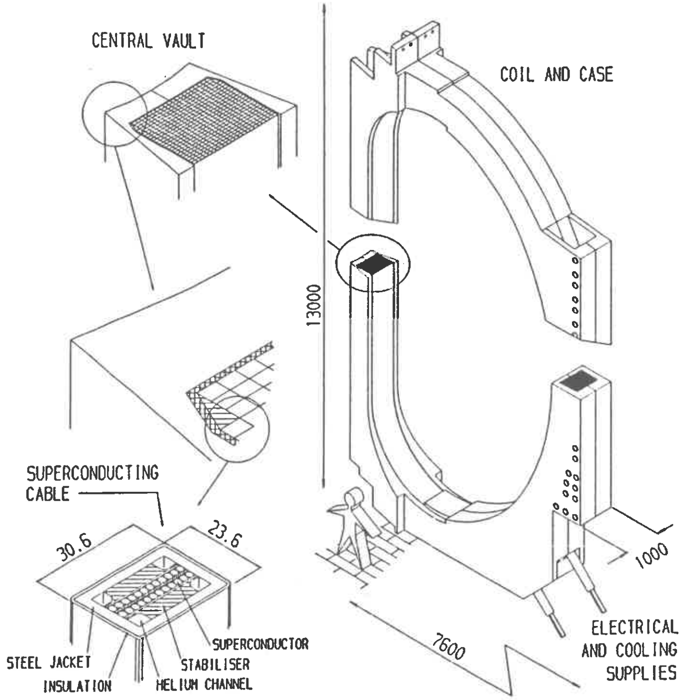


Fig. 3 TF Coil

Table 2 TF Coils characteristics

Inside dimension	: Bore 6 m Height 11.2
Weight (incl. case)	: 200 t
Conductor	: Nb_3Sn superconductor at 4.2 K, force flow cooled, contained in steel jacket
Insulation	: Vacuum impregnated glass fibre reinforced epoxy (maximum voltage to ground 20 kV, across terminals 9 kV)
Conductor current	: 16 KA
Maximum field	: 11.4 T
Maximum rate of change of field	: 1 T/s
Total magnetic energy	: 25 GJ
Radiation life	: 5 x 10^8 rads
Fatigue life	: 10^5 full power burn cycles
Average current density	: 13.7 MA/m^2 (over case and winding pack)
Average stresses tension	: 130 MPa (over case and winding pack)
Hoop compression (in vault)	: 170 MPa
Operating conditions	: Toroidal field on continuously (several months at a time) Poloidal field pulsed during burn

The design of the outer intercoil structure is critical, since this structure must support both tension and shear forces while the stiffness of the structure must match that of the toroidal field coils to avoid the introduction of extra bending stresses allowing some equatorial access to the machine interior.

It consists of a steel box fitting between the coils, and secured to the coil and the next intercoil structure by bolts. This design allows insulated gaps to be placed between coil case and structure to avoid short circuiting the plasma.

The winding pack will be inserted into the steel case with a good matching on the contact surfaces. The winding pack is made up of the conductor and epoxy glass vacuum impregnated as electrical insulator.

Typical A15 conductor is shown in Figure 3. The A15 superconducting strands are mechanically brittle. However before brittle fracture can occur, the electrical properties will be degraded, and it is this which gives the limiting strains on the strands.

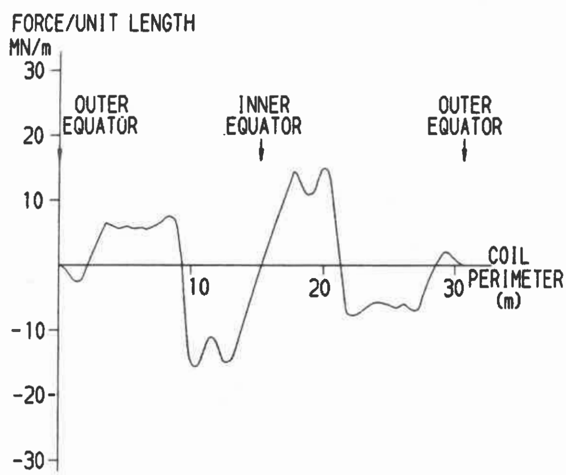
2.1 TF coil analyses

The analyses of the TF coil shall follow all stages of fabrication from the formation of the A15 compound at 700+800 °C till the coil is completed. Then when the coil is put in service the cooldown and warming up to 300 °K shall be carefully analized. During operation the loading on the coils is determined by the current in the winding pack crossing the magnetic field. The loading due to the self field is a bursting force confined to the plane of the coil, which gives a resultant centring force towards the machine axis. This loading is steady, since the TF coils will remain charged for many months. The loading due to the poloidal field coils acts normal to the plane of the coil and varies substantially around the coil perimeter.

The total out of plane coil loading is summarized in Figure 4.

The quench of a coil in NET is regarded as an abnormal condition, during such accurance the coil will increase the temperature and bearable thermal stresses will raise.

A coil fault in NET shall not develop in a release of active



Total overturning moment on 16 coils	124 MNm
NET centring force on one coil	341 MN
Average hoop force at equatorial crossection	75 MN

Fig. 4 Out of plane TFC loading

material in the reactor hall. During a fault non symmetric load can occur on the TF coil system. The mechanical analyses shall follow the fault tree and the electrical analyses of the system.

Preliminary analyses of the fabrication, cooling and quench phase have been carried out for NET with satisfactory results. The fault analysis is being carried out.

Global coil analysis during normal operation

A finite element stress analysis of a single coil in normal operation (with the poloidal field at the end of burn condition) has been performed with a model containing about 4000 nodes. The model was sufficiently fine to separately represent winding pack and case (Figure 5).

This allowed some iteration with the design to determine the necessary case thickness, the load conditions for the intercoil structure and the areas where further analysis/design was necessary to resolve possibly high stress levels. The analysis showed that

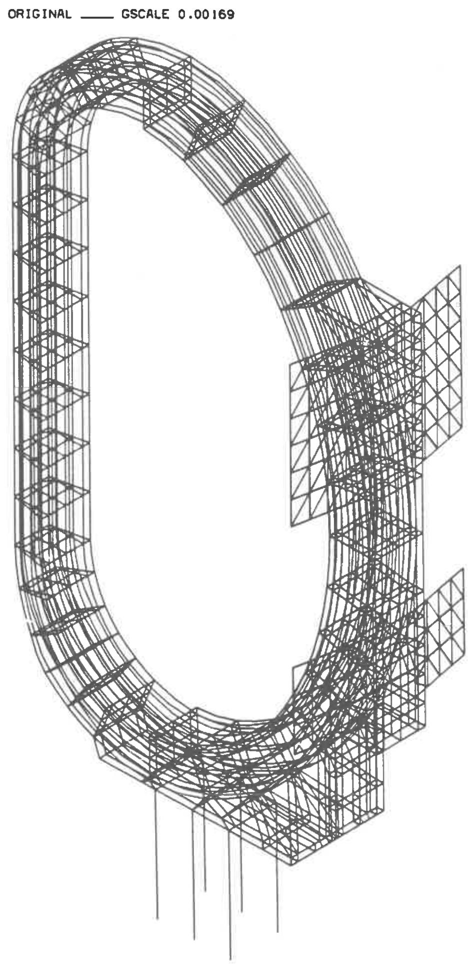


Fig. 5 FE model of the TF coil

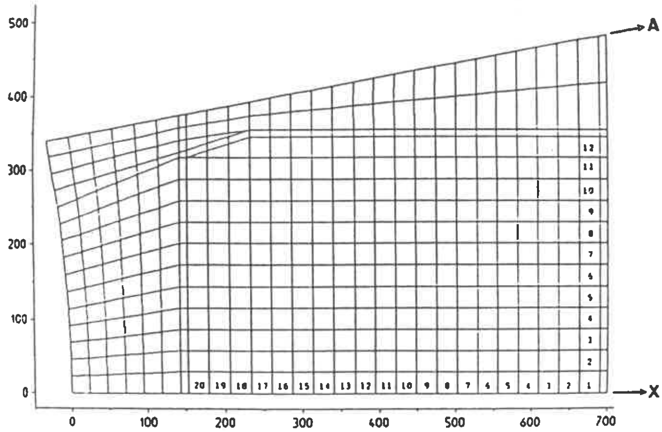


Fig. 6 Finite element mesh winding pack and conductor

broadly stress levels were acceptable, but that the central vault required further design and analysis attention. The general results from this analysis are given in Table 3.

Table 3 Results from global stress analysis

	Predicted	Allowed
Peak tension strain along conductor	0.15%	0.2% (design specification)
Peak insulator shear outside central vault	30 MPa	30 MPa, failure >70 MPa
Peak case tensile stress outside vault (alternating component)	250 MPa	425 MPa 8 mm initial crack
Peak case tensile stress in vault (alternating component)	200 MPa	600 MPa (1/2 UTS)

Central vault analysis

The most critical stress region as regards the conductor occurs within the central vault, where there is not only a tensile strain but also high compression in two directions due to the centring force on the coil and the resultant hoop compression of the vault. Some arrangements of winding pack and case also give high insulation and case stresses in this region.

A series of two dimensional stress analyses have been performed at the equator in the central vault, using various case/winding pack layouts and the loading strain conditions from the global analysis. The analyses considered variations in the thickness of the nose of the coil, in the winding pack shape, in the conductor jacket thickness, and in the effective winding pack elasticity. The winding pack was represented by global elastic properties derived from detailed conductor analyses, with separate representation of the ground insulation layer and the case (Figure 6).

A friction coefficient of 0.2 prevents slip at the sides between case and winding pack, but slip can still occur at the nose. This will only happen as the toroidal field is energised, and not as the poloidal field is pulsed and so is judged not to be a problem.

Conductor analysis

A detailed stress analysis has also been performed on a single conductor. The object of this was firstly to determine the elastic properties for use in the global and central vault analyses, and secondly to interpret the stress/strain conductor loadings from the central vault analysis. The results show that the jacket has Von Mises stresses in the range 500-600 MPa peak (in the corner regions) and that some initial plastic deformation of the stabiliser is possible. A detailed assessment of the superconducting cable has been made, taking into account the effect of the twist of the superconductor around the core. This has been used to derive an equivalent stiffness matrix for the cable which can be used in future for a more precise analysis of the core region.

3 POLOIDAL FIELD COILS

In a tokamak the poloidal field (PF) coil system has to provide the

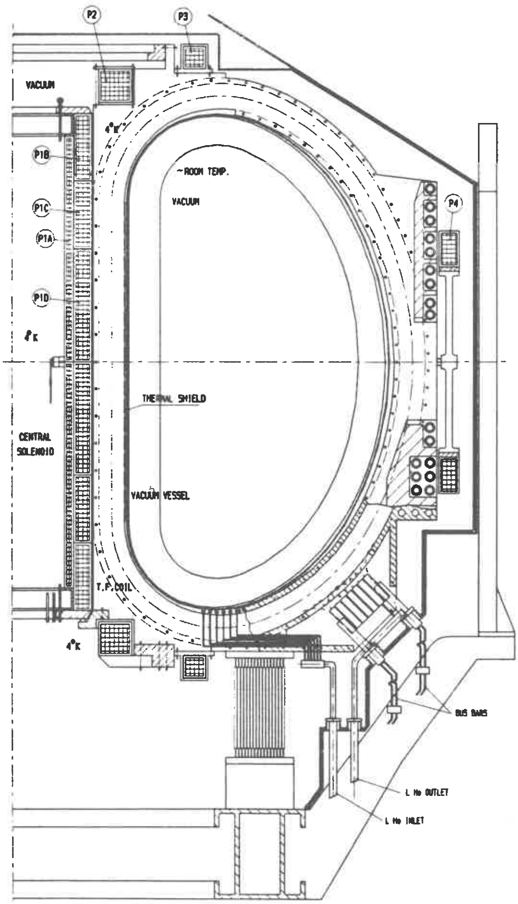


Fig. 7 PF coil cross-section

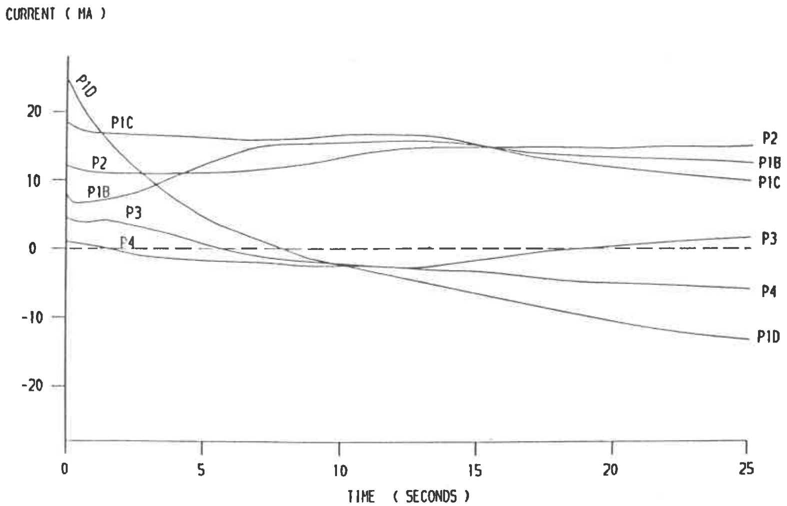


Fig. 8 Current variation in PF coils during start-up

magnetic flux, to drive the plasma current, and the magnetic field to shape the plasma. In an elongated plasma the two requirements are in competition for the same space, then in NET the currents flowing in the PF coils have both functions. The PF coils and currents time dependance are shown in Figure 7 and 8.

High current density and magnetic field is required in the central solenoid to reduce the overall machine size. Consequently the design of the central solenoid (C.S.) is the most critical. A pure superconducting C.S. would require an excessively high field even for an A15 conductor. A hybrid configuration of the central column with a nitrogen cooled copper insert inside a superconducting stack offers the best possibility to minimize the machine size.

The copper coil insert is only energized at the start of each NET operating cycle, its fast discharge causes the plasma initiation. In this way the copper insert reduces both the maximum field and the maximum rate of field change at the superconducting winding to acceptable values.

The outer poloidal field coils design is easier than the one for the C.S., the P2 and P3 coils are directly supported by the TF coils and the P4 are linked together by sixteen pillars supported by the TF coils.

The conductor current is identical for the whole set of superconducting coils with a maximum transport current of 40 KA. Several options are at present considered.

3.1 Central solenoid (C.S.) analyses

The central solenoid analyses shall be carried out following the same pattern as for the TF coil analyses.

The electromagnetic load acting on the C.S. during operation are vertical and radial. The radial forces are resisted by hoop stresses in the coil and the vertical compressive forces require thick conductor jackets (5 mm). The compressive stresses are the most critical.

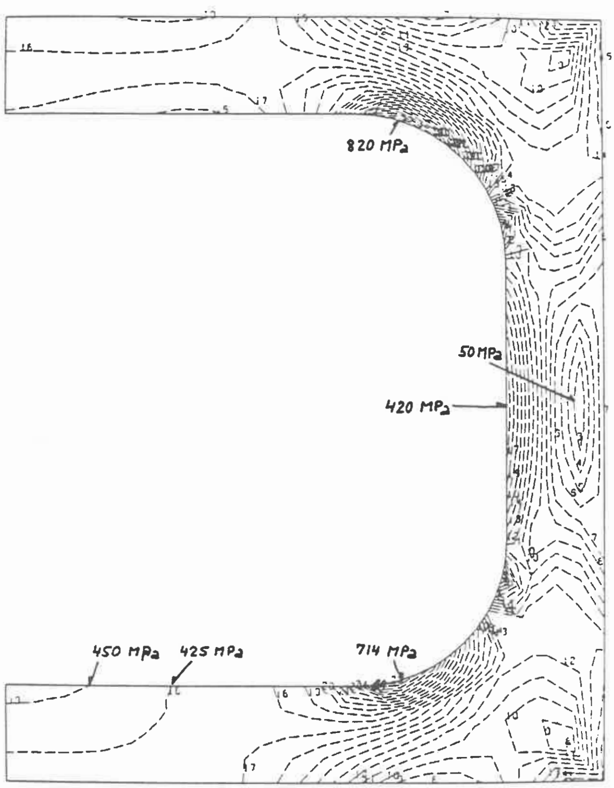


Fig. 9 Von Mises stresses in PFC conductor jacket

A finite element model of the conductor jacket and insulation has been produced and the analyses has shown Von Mises stresses (Figure 9) as high as 800 MPa, in case of plasma disruption which are probably above the allowable stresses.

The allowable stresses in the conductor jacket are not well defined because of the uncertainty on the degradation of the mechanical caracteristics of the jacket material, due to the heat treatment at 700÷800 °C for several hours to form the A15 compound, when the coil is already wound. An investigation of the most suitable material for the jacket is underway. The jacket material shall be non magnetic (hysteresis losses), thermal expansion from 1070 °K to 4 °K compatible with A15, high tensile strength at 4 °K $\sigma_{02} > 1000$ MPa, shall be resilient at low temperature ; candidates are : Aisi 316LN, inconel and incoloy.

4 R & D PROGRAMME FOR THE COIL SYSTEM

The use of A15 superconductor and size of the NET coils represent a substantial advance on existing technology, and therefore an extensive research and development programme is underway within Europe to demonstrate such coils are feasable and can operate safely and reliably. The superconducting caracteristics of the coils have to be tested (e.g. critical current, AC losses, stability, quench behaviour) as well as the more conventional one (e.g. mechanical resistance, insulation capability). The R & D programme started in 1982 foresees several steps to reach the feasability demonstration. The superconducting materials are developed from the filament to the strand, subsize conductor, full size NET conductor. There are tests going on to qualify the insulators under irradiation at 4 °K from the mechanical and electrical point of view. Tests are also being carried out to qualify the manufacturing processes and the materials (e.g. steel jacket welding).

The final conductors will be tested to demonstrate the feasability of the coils and validate the design tools. A prototype poloidal field coil is being developed by CEA and KfK for testing on Tore Supra to gain experience in operating superconducting coils on a real tokamak environment.

The magnets R & D programme is a joint effort of all the laboratories associated with the European Commission for the fusion programme.

5 VACUUM VESSEL

The design of the NET bulk shield integrated into the vacuum vessel must not only provide the necessary shielding to reduce the neutron and gamma doses and fluxes to acceptable level for the superconducting coils but also must fulfill the structural, electromagnetic and thermal requirements.

Therefore the structure must withstand the atmospheric pressure and electromagnetic loads, contain the tritium in case of accident, be fully remotely maintainable and have a controllable global toroidal electrical resistance of approx. 0.2 mΩ.

The main vacuum vessel seal must also be provided by a continuously welded metal wall, where all welds at the segment joints should be double contained with interspace pumping for leak detection.

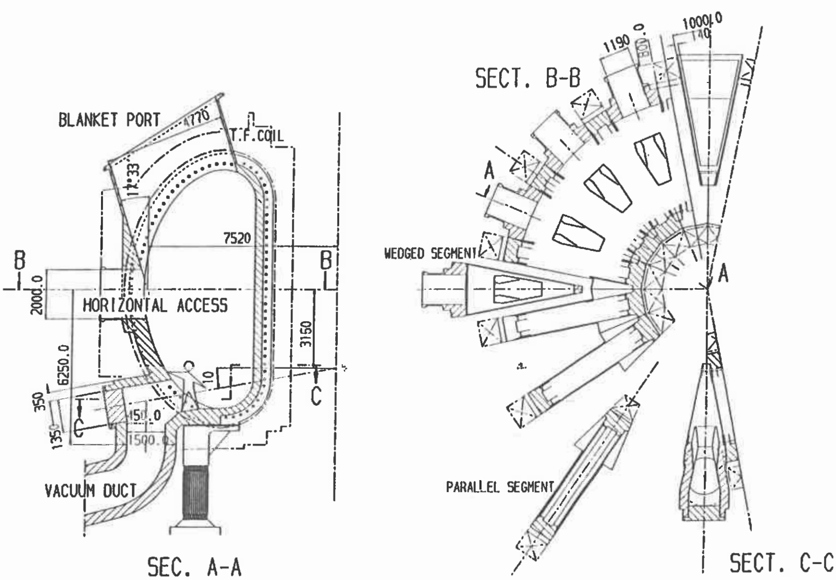


Fig. 10 Vacuum vessel general assembly

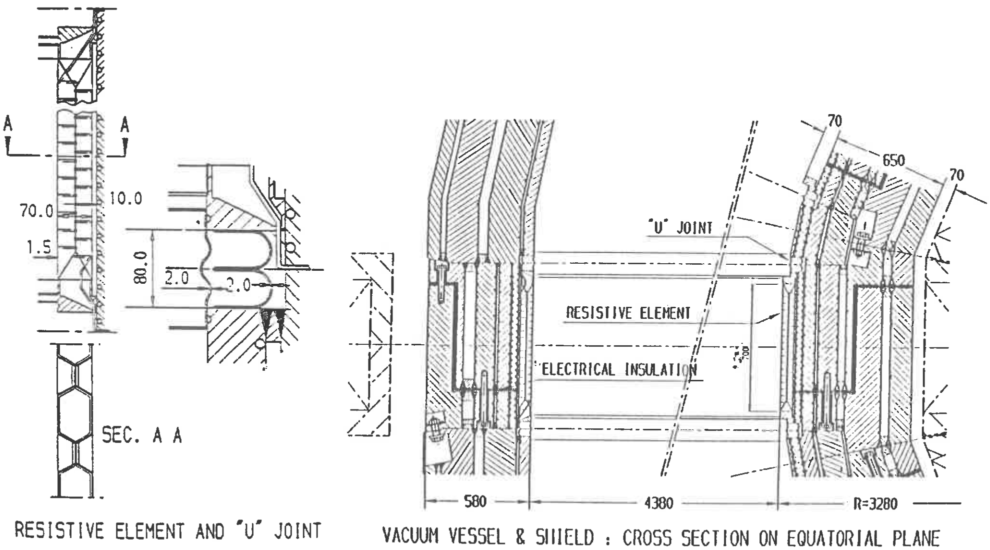


Fig. 11 Vacuum vessel segments details

The NET V.V., made of 32 segments (16 parallel and 16 wedge-shaped), is a toroidal chamber with a D-shaped cross-section which completely fills the inner bore of the toroidal field coils (TFC) leaving a gap to allow thermal expansion and the location of the thermal shield (Figure 10).

The thickness and composition of the V.V. walls are determined by the shielding requirements. The reference solution is a welded structure made of multiple water cooled steel layers alternated by layers of water flowing at very low velocity (Figure 11), casting solution as back-up is investigated.

The parallel segments are divided in two rings which are mechanically connected but electrically insulated. The electric break, due to radiation problems must be made of inorganic material and inserted between the two rings. The feasability of such break is being investigated as well as the use of a varistor (Silicon Carbide or Zinc oxide) as insulator to reduce the currents in the resistive element during plasma disruption.

The wedged segments are mechanically joined to the parallel ones by captive bolts which are distributed along the abutment flange and located inside the wall thickness. The seal is realized by "U"-shaped joints welded with remote handling techniques.

Since it is likely that the "U"-joint must be protected from tritium contamination and an interspace for leak detection must be provided, a steel covering plate to be remotely welded/cut has been foreseen.

A list of the V.V. main parameters is shown in the following table:

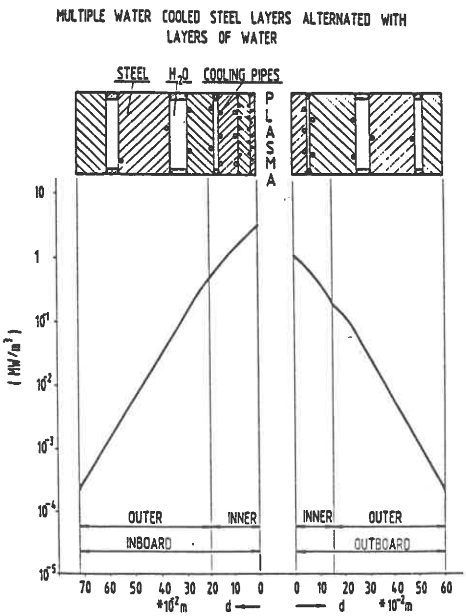
Table 4 V.V. and shield main parameters

Cross-section internal vertical height	9.59 m
Cross-section internal horizontal dimension	4.38 m
Typical thickness (including shield) inboard	0.7 m
outboard	0.59 m
N° of oblique ports	16
N° of pumping duct access	16
N° of ports on equatorial plane	8
Base pressure	1.33×10^{-6} Pa
Electrical resistance in toroidal direction	0.2 mΩ
Maximum baking temperature	180 °C
Weights : parallel segment	1.1×10^{6} N
wedged segment	1.15×10^{6} N

5.1 Nuclear and thermal analysis

Since the vessel is shielded from the plasma by the internal components, the heat load is mainly due to the nuclear heat generated within the V.V. because of neutron and gamma radiations.

Figure 12 shows the power density distribution in the NET DN bulk shield in the case of a homogeneous steel and water shielding mixture, considering a $Li_{17}Pb_{83}$ water cooled blanket.



Power density profile in the NET DN bulk shield for a homogeneous steel and water shield mixture

Fig. 12

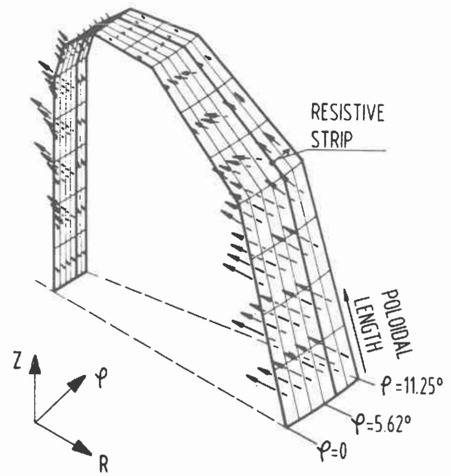


Fig. 13 Electromagnetic force on VV

The necessity of having a good neutron reflector in the inner shield (only 10% water) explains why water is mostly concentrated in the outer shield (25%) which acts as moderator.

The pitch of the cooling pipes inside each layer has been optimized to have a small difference of temperature $\Delta T\psi$ in the toroidal direction between two adjacent cooling channels. The temperature of the V.V. during operation will be kept as low as possible (~70 °C) to allow low pressure in the coolant.

5.2 Electromagnetic analysis

The most severe V.V. loading condition arises when a plasma disruption occurs. In this case, the eddy currents induced on the vessel give rise to large electromagnetic loads, lasting several tens of milliseconds, which are of major concern in the V.V. design.

The eddy currents and the related electrodynamic forces were computed by means of the code UNISH and Cariddi. UNISH is based on a thin shell approximation so that the complex V.V. structure had to be schematized by 16 thin SS toroidal sectors joined by thin resistive strips. Cariddi is a truly 3D code and has been used to check the UNISH results.

Having assumed a plasma current linearly decaying to zero in 20 ms, the V.V. eddy currents reach their maximum value when the plasma disappears. At this time a total induced current of 6.6 MA flows into the vessel. This current, interacting with the poloidal and toroidal magnetic fields, gives rise to the electromagnetic forces distribution shown in Figure 13. In Figure 14 the symmetric and antisymmetric components of the electromagnetic pressure $J_s \times B$, (J_s is the surface current density vector), at t = 20 ms, are shown as a function of the poloidal coordinates, for different axial planes. It can be seen that the first one reaches its maximum value (P_{nsymm} = -.36 MPa) on the outward side of the vessel, while the second one is larger on the inward side of the rigid sector ($P_{nantisymm}$ = 1. MPa).

The screening effect of the first wall, not considered in this analysis, seems to be negligible, since the first wall time constant is very short compared to that of the V.V.

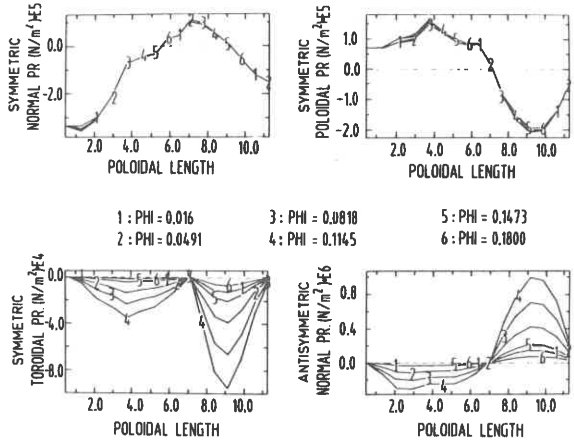


Fig. 14 Symmetric and antisymmetric components

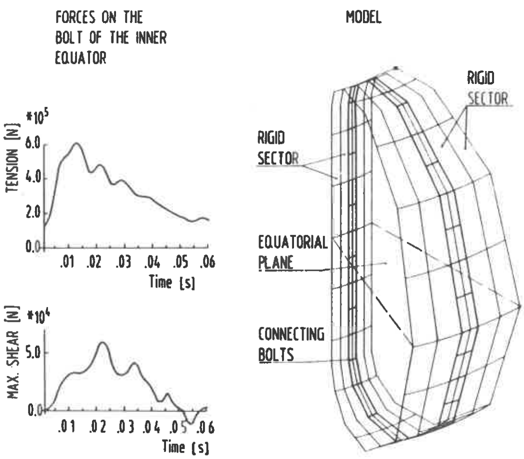


Fig. 15 Finite element stress analysis

As far as the main access ports are concerned, their effect is to reduce by about 15% the induced current and by even more the pressures along the vertical side of the hole, but to concentrate the pressures around the ports, giving rise to a local pressure magnification of about a factor of two.

5.3 Preliminary stress analysis

A simple model (Figure 15) has been adopted for the structural analysis performed with the ADINA finite element code. The rigid sectors are represented by shell elements with a stiffness corresponding to 0.2 m thickness and a weight to 0.4 m thickness.

The resistive elements are represented by shells of 0.006 m thickness and the bolts by beams of area 0.01 m^2 fixed to flanges. The model is subjected to a static atmosphere loading of 1 atm together with the time varying disruption forces which decay to zero in 0.06 s. No damping is included.

The results show that the natural frequencies of the structure are higher than the frequency of the exciting force, and so the displacement consists of a static response with a superimposed oscillation.

The acceleration due to the dynamic response of the vessel to the applied force is small (up to about 2.5 $m.s^{-2}$) and is submerged in most cases by the natural vibrations. The peak acceleration in the region of the exhaust duct appears to be up to about 10 $m.s^{-2}$.

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