Structural Problems of System Integration, of Containment and Shielding Defining the Mechanical Configuration of the Future, Tokamak Type, Experimental Power Reactors

F. Farfaletti-Casali

Commission of the European Communities, J.R.C. Ispra Establishment,
Engineering Division, I-21020 Ispra, Italy

Abstract

The paper reviews the structural mechanics of the overall engineering design of the Tokamak type, experimental power fusion reactors of the next generation, by describing and analysing two of the present major studies, INTOR and NET. Some safety aspects, related to containment and shielding during operation and maintenance, are also described. INTOR and NET are both considered because they constitute two different significant approaches for the definition of the reactor mechanical configuration. The paper introduces the assumptions and the system integration procedures adopted for determining the mechanical configurations. Therefore, the two designs are described and the structural and engineering problems related to the overall architectural aspects are identified. Finally, the main structural problems and the solution adopted are discussed.

1. Introduction

In view of the construction of the next, Tokamak type, fusion reactors, all the critical engineering problems, and among them particularly those of structural nature, and with safety implications, must be identified in order to assess if a sufficient technological capability already exists, or in order to orient the developments which could be needed. This is the aim of the present conceptual and predesign studies, such as INTOR (International TOkamak Reactor) and NET (Next European Torus). This paper, through a description of these studies, will try to provide some basic indications of the structural problems which must be solved.

2. INTOR and NET Mechanical Configurations

The main engineering and structural problems and the reactor configuration are interdependent; from the one side the solutions to the main problems are somewhere related to the overall architectural aspects of the machine, and from the other side these solutions contribute to define in detail the mechanical configuration of the reactor. The configuration of such a complex device, where many different systems must be put together, depends on the basic assumptions and on the systems integration procedures adopted. INTOR and NET used two different approaches in determining their configurations and two different systems integration procedures; although they have many common features, they differ in many aspects.

2.1 Generalities

The basic components of such reactors can be divided into two sections. The superconducting coils, with the associated cryostat and support structure, and the main vacuum containment and shield (vacuum vessel) form a semi-permanent structure which is required to have a high reliability. The vacuum vessel and shield is a modular but continuous structure, it is also called the semi-permanent part of the torus. Within this the internal components (exhaust system, first wall and blanket) form a modular and discontinuous structure different components of which, subject to plasma erosion and/or high thermal and radiation loads, can be removed with relative rapidity. This removable structure is the inner part of the torus.

Because of the hostile environment and high radiation level, the maintenance operations on these internal components, as well as on the vacuum vessel and shield, must be performed fully remotely, avoiding, when possible, any "in situ" repair. For this reason, the internal components are divided into sectors and segments as much as possible independent one from the others; in case of fault they are removed from the inner torus and substituted by spare units through proper access gaps, without disturbing the coils, their cryostat and support structures at cryogenic temperature.

2.2 The INTOR Mechanical Configurations Based on Maintenance Considerations

The INTOR mechanical configurations such as INTOR phase 1 [1] (see Fig. 1) are based on the assumption that the maintenance requirements of the internal components must be the predominant factors in determining the reactor layout and in establishing the systems integration procedures. This produces mechanical configurations where, with the aim of facilitating maintenance as much as possible, the withdrawal and the substitution of the faulty internal components is performed by means of a straight horizontal motion of whole sectors through big access ports located at every interspace between the TF coils, around the equatorial plane of the machine, where the distance between the coils is larger.

In principle, every removable sector of the inner torus has an own access port, which closes with an outer portion of shield integrated in the sector itself, and can be removed without requiring the removal of other sectors, also if, in INTOR, the exhaust system (the divertor region) which is considered to be the most damageable part, is interlinked with the first wall and blanket sectors (consequently the removal of the divertor sectors can be done independently, while the removal of the first wall and blanket sectors requires the previous removal of the corresponding sector of the exhaust system).

For facilitating this maintenance scheme (see Fig. 2) it was decided to use a low number (12) of TF coils; their outer dimensions necessary for sectors removal resulted, at the end, bigger than those necessary for the ripple requirements, increasing cost and technical risk.

The requirement of large access gaps around the equatorial plane of the reactor, introduces severe constraints on the design and the integration of the magnetic systems which must be adapted to this pre-arranged scheme, practically without possibility of optimising their design. The impossibility of having intercoil structures between the adjacent TF coils near the equatorial plane of the machine, for all the height of the access ports, poses severe structural problems for the support of the coils while the impracticability of having outboard poloidal field (PF) coils in this zone makes difficult the optimization of the magnetic system.

2.3 Containment and Shielding Problems in INTOR

The solutions given to the problems of containment affect some reliability and safety aspects of the design. For improving the reliability it was adapted, in the INTOR Phase 1 design, the principle of the complete separation of the torus (the vacuum vessel and shield with the internal components) from the magnetic systems (all the TF coils and PF coils, including their cryostat and the independent vacuum containment). The two main regions are necessarily interlinked, but completely separated by the atmosphere of the reactor hall, and independent wherever possible. The main reason for this was to minimize the interfaces in such a way that the potentially low reliability of the torus would not affect the reliability of the magnetic systems. However, the need for two independent vacuum containments (particularly in the inboard zone) resulted in complications to the design.

Strictly from the safety point of view, it was assumed that the vacuum vessel and shield could constitute a double containment for the plasma chamber everywhere, or at least in the potentially vulnerable parts (such as the thin corrugated structures at the level of the current breakers and the joints between the adjacent segments which are provided for being remotely cut and rewelded). The gaps between the two walls are used for leak detection. Consequently, during machine operation, a triple barrier is foreseen against spread of contamination outside the controlled area of the plant: the first two barriers are constituted of the double walled vacuum vessel and shield and of the enclosures of the associated components, the third barrier being the inner metal liner of the reactor hall.

During maintenance operations implying the opening of the torus and the dismounting of the pipe connections, only a single barrier is envisaged, the reactor hall boundary. The dismountable pipe connections are removed inside the reactor hall, without providing any secondary containment around them; the torus is open and the internal components removed without provision for transfer casks or other maintenance containments.

The main shield is integrated inside the vacuum vessel and shield, with the specific requirements of allowing personnel access in the reactor hall, 24 hours after shut-down, without opening the torus (with a radiation level of 2.5 mrem/h). The remaining part of the biological shield is constituted of the concrete wall of the reactor hall which is designed in such a way so as to determine a radiation level in the range of 0.1 mrem/h at the outer surface of the building, during operation and maintenance.

2.4 Evolution of the INTOR Concept

The INTOR Phase 1 reference design seemed to be too big and expensive. For this reason, INTOR is now evolving towards a more compact configuration. Already in Phase 2a, Part 1, of the INTOR Workshop, a new reference configuration was produced with the same number (12) of TF coils, but with reduced dimensions of these coils, by approaching the ripple limit. The reduction of the outer radius of the magnetic system was about 1.2 m and the corresponding cost reduction was estimated to be of the order of 10%. Two main changes were proposed:

- use of a "combined" vacuum boundary; the distinction between torus and magnetic systems is still present, but the toroidal vacuum containment of the plasma chamber, double-walled, constitutes also the inner vacuum boundary of the magnetic systems. This solution is less costly and less space consuming in the inboard zone, and is consequently particularly relevant to a compact design, but introduces complication at the level of the connection of the vacuum vessel and shield with the outer part of the vacuum boundary of the cryostat, where provisions must be taken for compensating the differential thermal expansions;
- multi-segmentation, at least of the exhaust region; with the reduction of the diameter of the outer legs of the TF coils, it appears impossible to remove whole sectors of the internal components. The sector of the divertor region must be split into two segments, if the full coverage of the region is required. The first wall and blanket sectors can be also split

into two segments of equal span (see Fig. 3), as in the European version of INTOR, Phase 2a, Part 1. Another possibility is that of providing, for each sector, one main segment with the biggest dimensions which can be withdrawn, and one small lateral segment (the so-called "shield post"). In case of multi-segmentation, one segment must be withdrawn first and the other subsequently, but the movements can be relatively simple.

2.5 The NET Mechanical Configurations Derived from the Integration of Optimized Systems

The NET design represents a new evolution in the field of the conceptual studies of the future experimental power reactors twoards more compact and more optimized solutions. In contrast to the approach for the definition of the INTOR configurations, where the maintenance philosophy was the dominant factor, no particular design area (neither maintenance nor others) has been allowed to dominate the overall concept [3]..The major parameters, roughly optimized, are expanded in the various design areas to give an optimized, detailed design of the various systems. By allowing a certain flexibility in maintenance procedures and access requirements, the main systems (in particular torus and magnetic systems), independently optimized for minimum dimensions, cost and technical risk, are assembled together by minimizing the departure from their optimum design. The results of this approach are different compact configurations, with 16 TF coils (ripple-limited), where the internal components are multi-segmented (e.g. 3 segments per sector) and can be removed from the top of the reactor through access ports reduced in dimension and/or number. It appears that the oblique removal of the internal components from the upper quadrant of the torus, where the space for the access above the outboard PF coils can be naturally found, allows a better optimization of the magnetic system. This solution facilitates also the support of the TF coils against the out-of-plane loads because of the reduced height of the access ports and because adequate intercoil structures can be provided in the critical equatorial region.

Fig. 4 shows one of the possible NET configurations, now under investigation. With the single null divertor system located at the bottom of the torus, all 16 main upper access gaps are used for withdrawal of the blanket segments and the corresponding pipe penetrations. Each internal component has an extension or shielding plug located inside the access port used for its removal, and is fed by cooling pipes through this plug. The 16 lower smaller access ports are used for removal of the divertor segments. The 16 main access ports serve each 3 first wall and blanket segments which together form one of the 16 blanket sectors (the total number of segments is therefore 48). From each port they are removed with a proper sequence, first the central ones followed by the lateral ones. Each segment can be directly handled from the top through its upper plug, after opening the upper vacuum door, removing the dismountable pipe connections and cutting of the welded joints at the level of the upper surface of the plugs, which ensures an intermediate secondary vacuum around the pipe connections.

2.6 Containment and Shielding Problems in NET

Being NET an extremely compact design, the solution of a "combined vacuum boundary" between the vacuum vessel and cryostat was adapted as in INTOR Phase 2A, Part 1 (see section 2.4).

During operation, NET adopted the same principle adopted in INTOR, of using a triple barrier against spread of contamination (tritium and activated dust) outside the controlled area of the plant. The vacuum vessel and shield is double-walled, as in INTOR, with possibility of leak detection, and the third barrier is the boundary of the reactor hall. The only difference with INTOR concerns the dismountable pipe connections at the level of the penetrations and the access ports for the removal of the internal segments, which are contained inside separate vacuum enclosures, provided with a secondary vacuum. This ameliorates the reliability and safety conditions, because it avoids contamination from the dismountable connections both of the plasma chamber and of the reactor hall, and facilitates the leak detection.

During maintenance operation, the NET design foresees always the presence of at least 2 barriers instead of 1, as in INTOR. This implies the use of special mobile containers or "Contained Transfer Units (CTU"), during the maintenance operations (disassembly of cooling pipes, opening of the torus, withdrawal and transportation to the hot cells of the faulted segments, etc.) in order to avoid spread of contamination inside the reactor hall. Different types of containers, or of transfer casks, can be used for different operations. They are closed by remotely operated doors and can be tightly attached at the secondary containments of the vessel, before opening the corresponding vacuum door. Their door can be connected by means of a double door system to the access door on the vessel. After opening of the double door, they can work as one unit, under vacuum or under controlled atmosphere, together with the corresponding secondary containment or with the plasma chamber. They are equipped with facilities and tools remotely operated, needed to carry out specific maintenance tasks. They can constitute the first barrier during the maintenance operations, the second barrier being the boundary of the reactor hall.

Another possibility under investigation for NET, for assuring a double barrier during the maintenance operations, is that of providing, around the access ports (e.g. above the upper part of the torus) a fixed "Tight Intermediate Containment (TIC)", inside which to operate for opening the torus, so limiting the volume of the hall exposed to contamination.

As far as the shielding problems are concerned, it is valid for NET what was presented in section 2.3 for INTOR. The main shield is integrated inside the vacuum vessel and shield; in the case that the compactness of the design could not allow to locate in this part all the shield required for the protection of the hall, additional shields could be arranged just outside the magnetic system but in any case as much as possible close to the reactor.

3. Main Structural Problems Encountered for the Definition of the INTOR and NET Design

3.1 Supporting Structures of the TF Coils

In order to minimize the thermal inlets inside the superconducting coils and inside the supporting structures at cryogenic temperature, instead of supporting each coil independently from the outside, the whole system of TF coils is considered as a unique self-sustaining structure of the induced loads. Only the gravity loads are supported from the outside, by means of thermally insulated supports located below the coils, on the basement of the reactor. For the same reason of minimizing the thermal inlets, the torus is supported on the same basement by means of gravity supports independent from those of the coils.

Two main types of induced loads must be considered in the TF coils: the steady in-plane loads and the cyclic out-of-plane loads. The first type of loads produces almost pure tensile stresses inside each coil (due to the proper D-shape of the coil) and gives a centripetal force on each coil (in the order of $4 \cdot 10^8$ N). The centripetal forces can be supported by a backing cylinder or by the central vault formed by the inner legs themselves, kept in touch one with the other. The first solution is adopted in INTOR, while the second one is envisaged for NET, in order to reduce the radial built of the reactor. The cyclic out-of-plane loads, which produce an overturning moment of about 160 MNxm around a radial direction on the equatorial plane of each coil, in conditions inducing fatigue, are supported as internal stresses in the whole system, by restraining the coils, one with the other. This is obtained by putting in contact the coils directly or by means of intercoil structures, and by inserting electrically insulated bolts and shear keys at the interfaces between the adjacent components. The TF coils and the intercoil structures, when assembled together in such a way, form a rigid toroidal body capable of containing, as internal stresses, the out-of-plane loads distributed by mutual interaction between the various components. In these parts where the intercoils structures cannot be located (e.g. where the interspace between the coils must be free for penetrations), the out-of-plane loads are supported as bending stresses of the coil.

In INTOR, the intercoil structures can be located only at the top and at the bottom, in order to leave free access for reactor auxiliaries and maintenance to the ports around the equatorial plane of the machine. In NET, the intercoil structures can have a better distribution, leaving free only penetrations of reduced limensions in the upper and lower parts.

3.2 Structural Problems of the Torus

The torus can be schematized as an assembly of interlinked hollow toroidal components, located one inside the other and constituting different layers surrounding the plasma. The outer most layer is the vacuum vessel and shield; it is provided with penetrations for the access to the inner layers and it includes zones with high electrical resistivity located in vertical planes below the TF coils. By neglecting the exhaust region, the internal concentric layers (first wall, breeding zone, reflector, etc.) can be assimilated to one close slab, the blanket, which encircles the plasma. Both the vacuum vessel and shield and the blanket are divided into toroidal sectors and segments. The segments constituting the vacuum vessel and shield can be considered as welded tanks in stainless steel filled with water and layers of metals. They are rigidly connected together by double systems of welded joints, accessible from the inside, and by mechanical connections. When assembled with the segments clamped together, the vessel behaves like a continuous rigid toroidal body constituted of thick sectors between electrically insulated current breakers (mechanically connected); each current breaker is bridged by two convuluted structures in parallel ensuring the double tightness system and the required toroidal resistivity (in the order of 0.2 mΩ). The blanket sectors are independent one from the other; they are sustained inside the vacuum vessel and shield. During the transients electromagnetic, particularly during the plasma disruptions, severe load conditions are produced by the currents induced in the various layers encircling the plasma. Overturning moments around a radial direction on the equatorial plane in the order of $2 \cdot 10^5$ NXm are expected on each blanket sector, the right value depending on the design and on their span.

Weights and induced loads of the internal sectors, as well as those of the vacuum vessel and shield are supported by the vessel itself; the gravity loads are transmitted on the reactor base by independent supports, while the induced loads produce internal stresses inside the vessel, at the interfaces between its sectors and at the level of the current breakers.

The vacuum vessel and shield appear to be a critical component for which many engineering problems must be solved; among these are the problems related to the feasibility of the supports for the internal segments, which must be congruent with the sealing points of the plugs inside the access ports, where differential thermal dilatations must be accommodated, and the problems related to the feasibility of convoluted structures and current breakers of large dimentions, using inorganic insulating materials.

3.3 Structural Problems of the Vacuum Boundary of the Cryostat

Two options have been considered in INTOR and NET. The first solution envisaged for INTOR

Phase 1 and described in section 2.3, foresees the adoption of a complete independent vacuum boundary for the cryostat. The intention was that of avoiding any interaction between magnetic systems and torus and of allowing the complete construction and the test of the magnetic systems before assembling the torus inside. This concept has many conceptual advantages and is well suited for reactors of large physical size, such as INTOR Phase 1, but poses problems for the construction, in a limited space, of the inboard zone, covering the inner surfaces of the TF coils and facing the vacuum vessel and shield of the torus. Mainly the cylindrical innermost part, enveloping the inner legs of the coils, which must support the external atmospheric pressure, with the presence of current breakers and thin convoluted structures, appears to be a duplicate of the containment given by the vacuum vessel and shield, so resulting in an additional space requirement and in a structural complication. These considerations led to assume, for INTOR Phase 2a, Part 1, and for NET, the other approach, in which the vacuum boundary of the cryostat is foreseen only outside the magnetic systems and is tightly joined with the extensions of the vessel penetrations, so realizing a separate vacuum enclosure, whose inner boundary is "combined" with the containment of the vacuum vessel. No particular problems of design and feasibility result, in this case, for the construction of the vacuum boundary outside the coils, but critical feasibility problems, not yet investigated, appear to arise at the level of the tight joints between this part and the vacuum vessel. The necessity of compensating the differential thermal expansions, mainly during the heating of vessel for tritium out-gassing, can require the use of special strain compliant thin structures, which must be expressely developed. Conventional bellows probably cannot be used in some cases (e.g. at the level of the access ports), where the big dimensions impose the compensation of combined expansions.

3.4 Engineering Problems of Containment During Maintenance Operations

These problems were not considered in INTOR, where it was assumed the possibility of opening, during the maintenance operations, the torus inside the reactor hall. The main structural problems in this case concern the transportation of big and heavy components, by means of fully remotely operated facilities inside the reactor hall. The movements for the withdrawal of the blanket segments (weighing 150-300 tons) are in INTOR translational movements in horizontal direction, avoiding rotation and tilting. The maintenance operations are more complex in NET, because of the reduced dimensions of the reactor and mainly because of the use of tight containers inside which these operations must be carried out. This allows the substitution of the damaged components in vacuum or controlled atmosphere, without spread of tritium contamination and activate dust inside the reactor hall, and avoiding or reducing the time consuming procedures for the complete outgassing and reconditioning of the plasma chamber or for the decontamination of the reactor hall. The NET geometry seems to be appropriate for the use of transfer casks, which could be attached above the torus extensions on access ports of reduced dimensions, for withdrawing inside the blanket segments, by raising them in oblique direction by means of lifting equipment contained inside the cask. The main engineering problems of remote handling concern the maintenance operations, performed inside the tight containers, under controlled atmosphere.

References

[1] INTOR Phase 1, IAEA, Vienna, 1982, STI/PUB/619-ISBN 92-0-131082-X.

[2] INTOR Phase 2a, part 1, IAEA, Vienna, 1983, STI/PUB/638-ISBN 92-0-131283-0.

[3] FARFALETTI-Casali, F., MITCHELL, N., SALPIETRO, E., BUZZI, U. and GRITZMANN, P., "NET System Integration", 13th SOFT, 1984, Varese (Italy).

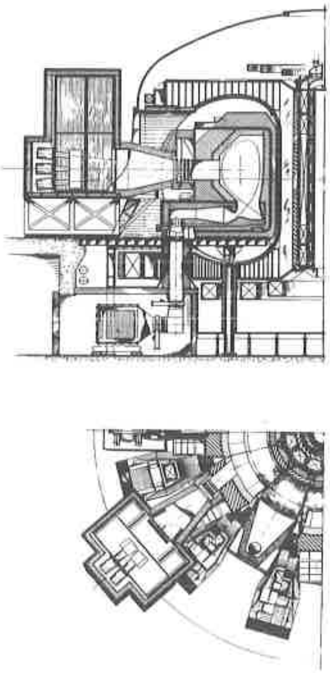

Fig. 1 - INTOR Phase 1 reference design

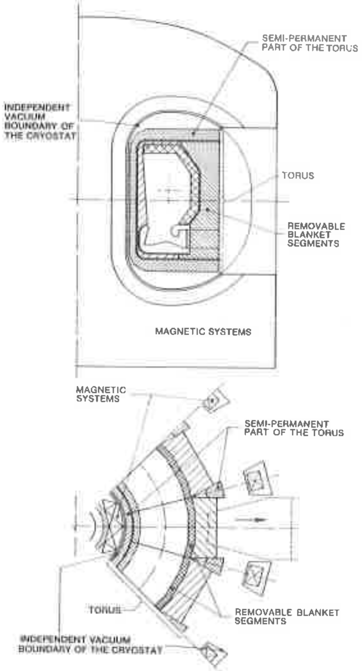

Fig. 2 - Maintenance scheme of INTOR Phase 1

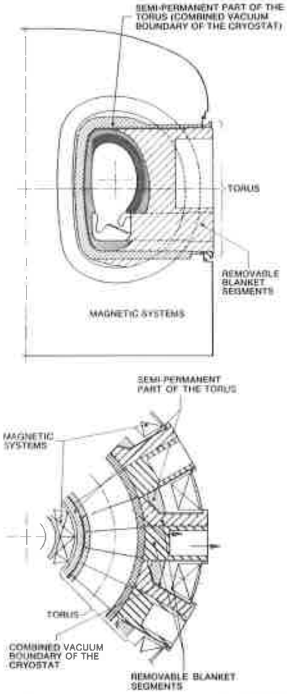

Fig. 3 - Maintenance scheme of INTOR Phase 2A part 1

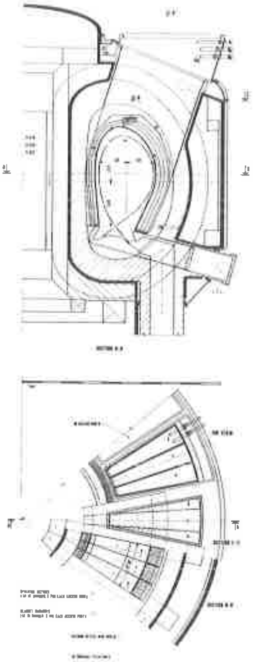

Fig. 4 - A possible NET configuration