JAPANESE CONTRIBUTIONS TO CONTAINMENT STRUCTURE, ASSEMBLY & MAINTENANCE AND REACTOR BUILDING FOR ITER

June 1991

Kiyoshi SHIBANUMA, Tsutomu HONDA, Naokazu KANAMORI
Takuya TERAKADO, Yoshinao OHOKAWA, Hideo HOSOBUCHI
Eisuke TADA, Koichi KOIZUMI, Fushiki MATSUOKA, Satoshi NISHIO
Keisuke SATOH, Koichi SATOH, Junichi ADACHI*¹, Keizo HONDA*²
Makoto HIRUCHI*³, Souji KAJIURA*², Takeshi KOBAYASHI*³
Mitsunori KONDOH*⁴, Tadashi MUNAKATA*⁵, Shin MURAKAMI*⁶
Masao OBAMA*⁵, Hideki OGAWA*⁶, Masayoshi SASAKI*²
Nobuo TACHIKAWA*⁶, Toshiaki WAKe*¹ and Masao YAMADA*²

日本原子力研究所
Japan Atomic Energy Research Institute
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Japanese Contributions to Containment Structure, Assembly & Maintenance and Reactor Building for ITER

Kiyoshi SHIBANUMA, Tsutomu HONDA, Naokazu KANAMORI, Takuya TERAKADO
Yoshinao OHOKAWA, Hideo HOSOBUCHI, Eisuke TADA, Koichi KOIZUMI
Fushiki MATSUOKA, Satoshi NISHIO, Keisuke SATOH, Koichi SATOH
Junichi ADACHI*3, Keizo HONDA*5, Makoto Horiuchi*1, Souji KAJIURA*2
Takeshi KOBAYASHI*3, Mitsunori KONDOH*5, Tadashi MUNAKATA*5
Shin MURAKAMI*5, Masao OBAMA*5, Hideki OGAWA*5, Masayoshi SASAKI*2
Nobuo TACHIKAWA*5, Toshiaki WAKUI*1 and Masao YAMADA

Fusion Experimental Reactor Team
Naka Fusion Research Establishment
Japan Atomic Energy Research Institute
Naka-machi, Naka-gun, Ibaraki-ken

(Received April 12, 1991)

Joint design work on Conceptual Design Activity of International Thermonuclear Experimental Reactor (ITER) with four parties, Japan, the United States, the Soviet Union and the European Community began in April 1988 and was successfully completed in December 1990. In Japan, the home team was established in wide range of collaboration between JAERI and national institutes, universities and heavy industries. The Fusion Experimental Reactor (FER) Team at JAERI is assigned as a core of the Japanese home team to support the joint Team activity and mainly conducted the design and R&D in the area of containment structure, remote handling and plant systems. This report mainly describes the Japanese

*1 Hazama Corporation
*2 Hitachi, Ltd.
*3 Kawasaki Heavy Industries, Ltd.
*4 Mitsubishi Atomic Power Ind., INC.
*5 Toshiba Corporation
contribution on the ITER containment structure, remote handling and reactor building design. Main areas of contributions are vacuum vessel, attaching locks, electromagnetic analysis, cryostat, port and service line layout for containment structure, in-vessel handling equipment design and analysis, blanket handling equipment design and related short term R&D for assembly & maintenance, and finally reactor building design and analysis based on the equipment and service line layout and components flow during assembly and maintenance.

Keywords: ITER Containment Structure, Assembly & Maintenance, Reactor Building
ITER 炉構造・遠隔保守及び炉建屋の設計

日本原子力研究開発機構研究所核融合実験炉特別チーム
柴沼 清・本多 力・金森 直和・寺門 拓也
大川 慶直・細田 英男・多田 栄介・小泉 豊一
松岡 不識・西尾 敏・佐藤 琪介・佐藤 浩一
安達 潤一・本多 啓三・堀内 誠一・根浦 宗次
小林 武司・近藤 光昇・宗像 正・村上 伸
小浜 正夫・小川 秀樹・佐々木正祥・立川 信夫
浦井 俊秋・山田 政男

（1991年4月12日受理）

国際熱核融合実験炉（ITER）の4か国共同概念設計活動は1988年4月に始まり、1990年12月を以て3年間に渡る共同設計活動を終了した。日本においては核融合実験炉特別チームが中心となり、国立研究機構、大学、企業と協力し、共同設計作業をサポートした。特別チームは主に炉構造、組立保守、炉建屋、プラントを担当した。この報告書は、ITERの概念設計の内、炉構造、遠隔保守及び炉建屋に対する日本のコンクリーツーションをまとめたものである。日本チームの主なコンクリーツーションは炉構造では、薄肉真空容器構造設計、電磁気解析、プラント固定概念、クライオスタットコイル真空容器、ポート及び周辺機器配置及びサービスラインレイアウト、遠隔保守では全体メンテナンス概念、炉内ハンドリング装置、炉外ハンドリング装置の設計解析及び関連したR & Dによる炉構造設計への反映、炉建屋は機器配置及びメンテナンス時の物流を反映した設計とその解析である。

【資料】

*1（株）問組
*2（株）日立製作所
*3川崎重工業（株）
*4三菱原子力工業（株）
*5（株）東芝
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I. Introduction

International Thermonuclear Experimental Reactor (ITER) was initiated at summit meetings of governmental leaders and it was decided to extend fusion research development activities in worldwide. In response to the summit initiatives, joint design work on ITER Conceptual Design Activities (CDA), under the auspice of the IAEA in collaboration with four parties, Japan, the United States, the Soviet Union and the European Community, was began in April 1988 and was successfully completed in December 1990.

In CDA, a guiding document, called "Terms of Reference", was issued and constituted the basis for the ITER activities. The Terms of References call for an integrated international design activity which shall:

1) define a set of technical characteristics of an ITER and subsequently to carry out the design work necessary to establish its conceptual design;

2) define future research and development needs and draw up cost, manpower and schedule estimates for the realization of such a device;

3) define the site requirements for ITER and perform a safety and environmental analysis;

4) carry out in a coordinated manner specific validating research and development work supportive of the design activities.

This work included two phases, the definition Phase performed from May to October 1988, and the Design Phase completed in December 1990. During the definition phase, a set of ITER technical characteristics was developed and reported in the document "ITER Concept Definition". In addition, preliminary plans for coordinated R&D in support of ITER were developed and subsequently carried out.

The Design Phase produced a conceptual design, a cost estimate, a description of site requirements, a preliminary construction schedule, and an ITER R&D plan. All information produced within the CDA has been made available for all ITER Parties and the following documents that summarize the results of the CDA co-operated with 4 Parties is being published by IAEA:

a) Conceptual Design Report

b) Physics and Technology R&D for Conceptual Design
During the CDA, the International Design Joint Team was organized by participating 10 members from each party and conducted the ITER Conceptual Design Activity based on the technical contribution from the home team in each Party. In Japan, the home team was established in wide range of collaboration between JAERI and national institutes, universities and heavy industries. The Fusion Experimental Reactor (FER) Team at JAERI is assigned as a core of the Japanese home team to support the Joint Team activity and mainly conducted the design and R&D in the area of containment structure, remote handling and plant system. In addition, many hardware laboratories, such as superconducting magnet, heating and current drive, and tritium technology laboratories were also involved to perform the corresponding design and R&Ds.

This paper mainly describes the Japanese contribution on the ITER containment structure, remote handling and reactor building design. In addition to this report, the following reports (JAERI-M Reports) will be published in order to summarize the Japanese contributions to the ITER Conceptual Design Activity.

1) Japanese Physics Contributions to ITER Conceptual Design Activities and Physics Issues to Be Resolved in Engineering Design Activities (EDA)
2) Japanese Contributions of Poloidal Field Systems to ITER Conceptual Design Activities
3) Systematic Study of ITER Operation Scenario
4) System Design - Parametric Study -
5) ITER Neutral Beam Injection System - Japanese Design Proposal -
6) Conceptual Design of SC Magnet System - Concepts -
7) Conceptual Design of SC Magnet System - Stress Analysis -
8) Conceptual Design of SC Magnet System - AC Loss -
9) Conceptual Design of SC Magnet System - Utility -
10) Conceptual Design of SC Magnet System - Material -
11) Conceptual Design of SC Magnet System - R&D Proposal -
12) トーラス中心構造の機械試験
13) 巻線剛性試験
14) 絶縁キーの開発
15) 耐放射線性絶縁材料の開発
16) Japanese Contributions to Blanket Design for ITER
17) Japanese Contributions to ITER Testing Program
18) Solid Breeder Blankets for DEMO, JAERI-M 91-063
19) Japanese Contributions to ITER Shielding Neutronics Design, JAERI-M 91-046
20) Conceptual Design of Fusion Experimental Reactor - Conceptual Design of Electron Cyclotron Wave System -
21) Conceptual Design of Fusion Experimental Reactor - Conceptual Design of Low Hybrid Wave System -
22) Conceptual Design of Fusion Experimental Reactor - Conceptual Design of Ion Cyclotron Wave System -
23) Conceptual Design of Fusion Experimental Reactor (ITER/FER) - Plasma Facing Component -
24) 核融合実験炉の概念設計 - 割れ系の概念設計 -
25) 核融合実験炉における炉心部の遮蔽設計、JAERI-M 91-017
26) 核融合実験炉の概念設計 - 安全性の解析・評価 -
II. Key Parameters

The major parameters for the present ITER design are given in Table II-1[1,2]. More detailed informations about the design in Containment Structure[3] and Assembly & Maintenance[4] are given in Table II-2 to Table II-8. ITER Plant design parameters are described in ITER Plant technical report[5].

Table II-1 ITER design parameters

<table>
<thead>
<tr>
<th>BASIC DESIGN PARAMETERS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Radius, R, (m)</td>
<td>6.0</td>
</tr>
<tr>
<td>Minor Radius, a, (m)</td>
<td>2.15</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>2.8</td>
</tr>
<tr>
<td>Plasma Current, (MA)</td>
<td>2 (nominal)</td>
</tr>
<tr>
<td>Elongation, k, (95%)</td>
<td>~2</td>
</tr>
<tr>
<td>Triangularity, δ, (95%)</td>
<td>~0.4</td>
</tr>
<tr>
<td>Safety Factor, qφ,(95%)</td>
<td>~3.0</td>
</tr>
<tr>
<td>Toroidal Field on Axis, (T)</td>
<td>4.85</td>
</tr>
<tr>
<td>Plasma Volume (m^3)</td>
<td>~1100</td>
</tr>
<tr>
<td>Pulse duration, (s)</td>
<td>&gt;200</td>
</tr>
<tr>
<td>steady-state(ultimate goal)</td>
<td></td>
</tr>
<tr>
<td>Wall Loading, (MW/m^2)</td>
<td>~1.0</td>
</tr>
<tr>
<td>Fusion Power, (MW)</td>
<td>~1100</td>
</tr>
<tr>
<td>Total Fluence, (MWa/m^2)</td>
<td>1.0</td>
</tr>
</tbody>
</table>
## Table II-1  ITER design parameters (cont'd)

### SYSTEM PARAMETERS

#### TOTORIDAL FIELD COILS

<table>
<thead>
<tr>
<th>Number</th>
<th>Conductor</th>
<th>Stabilizer</th>
<th>Maximum field, (T)</th>
<th>Bore height, (m)</th>
<th>Bore width, (m)</th>
<th>Average cable current density, (MA/m²)</th>
<th>Inner leg overall current density, (MA/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>Nb₃Sn, force-cooled</td>
<td>Cu</td>
<td>11.2</td>
<td>14.8</td>
<td>7.1</td>
<td>35.1</td>
<td>14</td>
</tr>
</tbody>
</table>

#### POLOIDAL FIELD SYSTEM

<table>
<thead>
<tr>
<th>Total volt seconds available, (V-s)</th>
<th>325</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor:</td>
<td></td>
</tr>
<tr>
<td>inner coils</td>
<td>Nb₃Sn, force-cooled</td>
</tr>
<tr>
<td>outer coils</td>
<td>Nb₃Sn for NbTi, force-cooled</td>
</tr>
<tr>
<td>Maximum field at coil:</td>
<td></td>
</tr>
<tr>
<td>inner coils, (T)</td>
<td>13.5 (at prebias)</td>
</tr>
<tr>
<td>outer coils, (T)</td>
<td>7.9 (PF5, during disruptions-others in the range of 5-6)</td>
</tr>
<tr>
<td>Available one turn voltage, (V)</td>
<td>25</td>
</tr>
<tr>
<td>Maximum allowable error field at break-down, (T)</td>
<td>&lt;10⁻³</td>
</tr>
</tbody>
</table>
Table II-1  ITER design parameters (cont'd)

CURRENT DRIVE AND HEATING
(reference system)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total injected power, (MW)</td>
<td>145</td>
</tr>
<tr>
<td>Number of ports</td>
<td>3</td>
</tr>
<tr>
<td>Beam energy, (MeV)</td>
<td>1.3</td>
</tr>
<tr>
<td>Power, (MW)</td>
<td>75</td>
</tr>
<tr>
<td>LH:</td>
<td></td>
</tr>
<tr>
<td>Number of launchers</td>
<td>2</td>
</tr>
<tr>
<td>Frequency, (GHz)</td>
<td>5</td>
</tr>
<tr>
<td>Power, (MW)</td>
<td>50</td>
</tr>
<tr>
<td>EC:</td>
<td></td>
</tr>
<tr>
<td>Number of ports</td>
<td>1</td>
</tr>
<tr>
<td>Frequency, (GHz)</td>
<td>120</td>
</tr>
<tr>
<td>Power, (MW)</td>
<td>20</td>
</tr>
</tbody>
</table>

IMPURITY AND PARTICLE CONTROL

| Mode of impurity control   | double/semi- |
|                            | double null  |
|                            | poloidal divertor |
| Mode of fueling            | gas puffing, pellets |

FIRST WALL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>austenitic ss</td>
</tr>
<tr>
<td>Coolant</td>
<td>H\textsubscript{2}O, 50-150\textdegree C, 1.5 MPa</td>
</tr>
<tr>
<td>Maximum temperature of</td>
<td></td>
</tr>
<tr>
<td>structure, °C</td>
<td>300</td>
</tr>
<tr>
<td>Protection</td>
<td>C-based, 20 mm</td>
</tr>
</tbody>
</table>
Table II-1 ITER design parameters (cont'd)

<table>
<thead>
<tr>
<th>DIVERTOR PLATE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface material</strong></td>
</tr>
<tr>
<td>physics phase</td>
</tr>
<tr>
<td>technology phase</td>
</tr>
<tr>
<td><strong>Heat sink material</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Coolant</strong></td>
</tr>
<tr>
<td><strong>Coolant temperature, (°C)</strong></td>
</tr>
<tr>
<td><strong>Coolant pressure, (MPa)</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SHIELD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inboard material</strong></td>
</tr>
<tr>
<td><strong>Inboard thickness (incl. blanket &amp; v.v. &amp; cryostat)(m)</strong></td>
</tr>
<tr>
<td><strong>Outboard material</strong></td>
</tr>
<tr>
<td><strong>Outboard thickness (incl. blanket &amp; v.v. &amp; cryostat)(m)</strong></td>
</tr>
<tr>
<td><strong>Coolant</strong></td>
</tr>
<tr>
<td><strong>Maximum temperature of structure</strong></td>
</tr>
<tr>
<td>for operation, (°C)</td>
</tr>
<tr>
<td>for baking, (°C)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TEST FACILITIES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
</tr>
<tr>
<td><strong>Location</strong></td>
</tr>
<tr>
<td><strong>Number of modules</strong></td>
</tr>
<tr>
<td>physics phase</td>
</tr>
<tr>
<td>technology phase</td>
</tr>
</tbody>
</table>
### Table II-1 ITER design parameters (cont'd)

<table>
<thead>
<tr>
<th>TRITIUM FUELING SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-T flow rate (mbar.l/s)</td>
</tr>
<tr>
<td>Consumption</td>
</tr>
<tr>
<td>(at 25% availability), (kg/a)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TRITIUM-BREEDING BLANKET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of segments</td>
</tr>
<tr>
<td>inboard</td>
</tr>
<tr>
<td>outboard</td>
</tr>
<tr>
<td>Structural material</td>
</tr>
<tr>
<td>Coolant</td>
</tr>
<tr>
<td>Coolant temperature</td>
</tr>
<tr>
<td>(inlet.outlet),(°C)</td>
</tr>
<tr>
<td>Thickness (incl. first wall)</td>
</tr>
<tr>
<td>inboard, (m)</td>
</tr>
<tr>
<td>outboard, (m)</td>
</tr>
<tr>
<td>Tritium breeding ratio</td>
</tr>
<tr>
<td>Tritium breeding material</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VACUUM SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum boundary material</td>
</tr>
<tr>
<td>Plasma chamber exhaust composition;</td>
</tr>
<tr>
<td>D-T in molecular form, (%)</td>
</tr>
<tr>
<td>He, (%)</td>
</tr>
<tr>
<td>Other, (%)</td>
</tr>
<tr>
<td>Initial base pressure, (mbar)</td>
</tr>
<tr>
<td>Pre-shot base pressure, (mbar)</td>
</tr>
<tr>
<td>Nominal pumping speed at entrance</td>
</tr>
<tr>
<td>of divertor chamber pumping duct</td>
</tr>
<tr>
<td>for He and D-T during burn, (m³/s)</td>
</tr>
</tbody>
</table>
Table II-1  ITER design parameters (cont'd)

### CRYOGENIC REQUIREMENTS

HE refrigeration requirement, at 4k, (kw):

<table>
<thead>
<tr>
<th>Component</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnets w/o sweeping</td>
<td>85</td>
</tr>
<tr>
<td>Additional due to sweeping</td>
<td>25</td>
</tr>
<tr>
<td>Other (NBI, cryopump etc.)</td>
<td>20</td>
</tr>
</tbody>
</table>

**Total**

### MAJOR DIAGNOSTIC SYSTEMS

- Magnetic diagnostics
- Fusion product diagnostics
- Interferometry and polarimetry
- Bolometer arrays
- ECE diagnostics
- Thomson scattering system
- Collective Thomson scattering system
- Microwave reflectometry
- Visible and crystal spectoscopy
- CHERS
- Motional Stark effect
- Neutral particle analysis
- Langmuir and calorimeter probes
- Tile markers
- Infrared and visible inspection periscopes
- IR thermometers
- Plasma facing component thermocouples
- Pressure gauges and residual gas analyzers
Table II-1  ITER design parameters (cont'd)

PLASMA DISRUPTION AND VERTICAL DISPLACEMENT EVENTS
(Tentative characterization)

<table>
<thead>
<tr>
<th>Number of disruptions:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics Phase, (% of shots)</td>
<td>5</td>
</tr>
<tr>
<td>Technology Phase, (% of shots)</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thermal quench during disruption:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>time, (ms)</td>
<td>0.1-1.0</td>
</tr>
<tr>
<td>energy deposition</td>
<td></td>
</tr>
<tr>
<td>- first wall, (MJ)</td>
<td>250</td>
</tr>
<tr>
<td>- divertor, (MJ)</td>
<td>250 (cover also 500)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Current quench during disruption:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>time, (ms)</td>
<td>20 to several 100</td>
</tr>
<tr>
<td>energy deposition</td>
<td></td>
</tr>
<tr>
<td>- first wall (radiation), (MJ)</td>
<td>300-500</td>
</tr>
<tr>
<td>- divertor plate, (MJ):</td>
<td>up to 200</td>
</tr>
<tr>
<td>- runaway electrons:</td>
<td></td>
</tr>
<tr>
<td>particle energy, (MeV)</td>
<td>up to 300</td>
</tr>
<tr>
<td>total energy, (MJ):</td>
<td>100</td>
</tr>
<tr>
<td>peak load, (MJ/(m^2))</td>
<td>30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Poloidal currents</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>through first wall elements due to plasma motion</td>
<td>up to 0.2 (I_p)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vertical displacement events (combined thermal and current quench due to loss of vertical position control):</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>time (ms)</td>
<td>20-several 100</td>
</tr>
<tr>
<td>energy deposition, (MJ)</td>
<td>1000</td>
</tr>
<tr>
<td>runaway electrons:</td>
<td>same as regular current quench</td>
</tr>
<tr>
<td>- poloidal currents through first wall elements due to plasma motion</td>
<td>up to 0.2 (I_p)</td>
</tr>
</tbody>
</table>
Table II-2 Vacuum vessel parameters and working conditions

Internal vacuum: $4 \times 10^{-7}$ mbar
Internal overpressure in case of accident: 2 bar abs

External pressure: $10^{-5}$ mbar to 1 ATM
in case of accident: 2.0 bar abs
1.2 bar abs (in interspace used for leak detection)

Max adm. leak rate: $10^{-6}$ mbar/s

Electromagnetic Disruption loads

<table>
<thead>
<tr>
<th>$F_R$ (MN)</th>
<th>$F_Z$ (MN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+10</td>
<td>+10</td>
</tr>
<tr>
<td>-20</td>
<td>+2</td>
</tr>
</tbody>
</table>

Note: These loads are typical values for reference plasma disruption scenario, and include effects of inductive currents only. (see ITER-IL-PC-1-9-11,17 and PFDU technical report)

Weight of the in-vessel components in one sector: TBD (560 tonne approx)

Earthquake acceleration:
- vertical TBD (0.2g tentatively)
- horizontal TBD (0.3g tentatively amplitude and frequency TBD)

Accidental loads during assembly/maintenance of vacuum vessel/ internal components: TBD

Baking temperature: $180^\circ$C
Operating temperature: 90-100$^\circ$C
Stand by temperature: 90$^\circ$

Number of equatorial ports: 16 (for dimensions see reference drawings)

Number of vertical access ports: 16

Vacuum pumping ports:
- number 16
- conductivity TBD (indicatively $100 \, m^3/s$) cross section is determined
Table II-2 Vacuum vessel parameters and working conditions (cont'd)

Total toroidal electrical resistance: 20 micro-ohm (uniform current distribution)

Electromagnetic pressure on resistive elements: TBD (tentatively 10 bar see PFDU technical report)

Disruptive heat load on resistive elements for non-uniform current distribution: 1.5x10^6 J/m
(for 4x10^8 J with energy peaking factor 4)

Min. shielding thickness for re-welding stainless steel: (see note below)

Note: A more detailed recommendation on the minimum shielding thickness (80% SS+20% H_2O) to limit helium production and allow for stainless steel rewelding have been formulated by NEG in October 90, which gives the different required distances between V.V. face surface and rewelded joint position for the different machine areas depending on the geometry factors:

<table>
<thead>
<tr>
<th>appm in the metal</th>
<th>0.1 appm</th>
<th>1 appm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inboard area, midplane</td>
<td>150</td>
<td>0</td>
</tr>
<tr>
<td>Divertor area*</td>
<td>350</td>
<td>200</td>
</tr>
<tr>
<td>Inside NBI port</td>
<td>500</td>
<td>350</td>
</tr>
<tr>
<td>For NBT ports interface</td>
<td>400-450</td>
<td>250-300</td>
</tr>
<tr>
<td>NEG recommendations on joints rewelding</td>
<td>acceptable</td>
<td>upper limit</td>
</tr>
</tbody>
</table>

* Assumes additional shielding inside vessel of 210-230 μm.
Table II-3 Attaching locks interface parameters and operational conditions

Reference EM forces on the inboard and outboard blanket segments

- Loads acting on inboard blanket segment (electrical segmentation is 96, assembly segmentation 32)
  * forces on the: radial, MN vertical, MN
  - quarter of segment 1.0 2.55
  - half of segment 0.6 3.0
  * maximal pressure on front plate 0.7 MPA

- Loads acting on outboard blanket segment (electrical segmentation 48 assembly segmentation 48)
  * forces on the radial, MN vertical, MN
  - quarter of segment 10 20
  - half of segment 2.6 35
  * pressure on the front plate:
    - average 0.3 MPA
    - peak 2.6 MPA

**BS weight**

<table>
<thead>
<tr>
<th>NUMBER</th>
<th>WEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>40 Tonne</td>
</tr>
<tr>
<td>16</td>
<td>45 Tonne</td>
</tr>
<tr>
<td>16</td>
<td>70 Tonne</td>
</tr>
<tr>
<td>32</td>
<td>130 Tonne</td>
</tr>
<tr>
<td>32</td>
<td>15 Tonne</td>
</tr>
<tr>
<td>16</td>
<td>25 Tonne</td>
</tr>
</tbody>
</table>

(Values calculated assuming composition of 85% SS and 15% H₂O of the total volume).
<table>
<thead>
<tr>
<th>Table II-3 Attaching locks interface parameters and operational conditions (con'd)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AL (Attaching Locks) temperature</strong></td>
</tr>
<tr>
<td>- normal operation</td>
</tr>
<tr>
<td>- baking regime</td>
</tr>
<tr>
<td>- conditioning between two pulses</td>
</tr>
<tr>
<td><strong>Mutual BS/VV thermocontraction in the:</strong></td>
</tr>
<tr>
<td>- normal operation</td>
</tr>
<tr>
<td>- baking regime</td>
</tr>
<tr>
<td>- accidental conditions</td>
</tr>
<tr>
<td><strong>Allowable assembly tolerances of BS position (radial/toroidal/vertical)</strong></td>
</tr>
<tr>
<td>including divertor requirements</td>
</tr>
<tr>
<td>if divertor is supported on blanket</td>
</tr>
<tr>
<td><strong>Allowable maximum operating gaps to prevent dangerous dynamic shocks</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Allowable flexible BS displacement under the disruption dynamic loads (mainly radial value)</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Distance from first wall for rewelding of stainless steel</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Volumetric nuclear heating as a function of distance from first wall</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Primary vacuum</strong></td>
</tr>
<tr>
<td><strong>Required lower limit of the gaps/holes sizes for good vacuum pumping</strong></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

* Thickness is consistent with helium production limit as established by Nuclear Group (approx. 0.1 appm He in metal on the machine mid plane).
Table II-4 Cryostat vessel requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner radius</td>
<td>13 m</td>
</tr>
<tr>
<td>Outer radius</td>
<td>13.7 m max</td>
</tr>
<tr>
<td>Inside total height</td>
<td>27.3 m</td>
</tr>
<tr>
<td>Operating pressure inside</td>
<td>10^-5 mbar</td>
</tr>
<tr>
<td>Operating pressure outside</td>
<td>1 bar abs</td>
</tr>
<tr>
<td>Accidental pressure inside</td>
<td>2.0 bar abs(1 bar design press.)</td>
</tr>
<tr>
<td>Accidental pressure outside</td>
<td>1.3 bar abs(1.3 bar design press.)</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>20-35°C</td>
</tr>
<tr>
<td>Maximum temperature</td>
<td>TBD</td>
</tr>
<tr>
<td>Maximum leak rate</td>
<td>10^-5 mbar.l.s^-1</td>
</tr>
<tr>
<td>Toroidal electrical resistance</td>
<td>equivalent of 10 mm of SS</td>
</tr>
<tr>
<td>of cylindrical section</td>
<td></td>
</tr>
<tr>
<td>Minimum electrical resistance</td>
<td>100 micro Ohm/sector</td>
</tr>
<tr>
<td>for all ties to WV</td>
<td></td>
</tr>
<tr>
<td>Port requirement*:</td>
<td></td>
</tr>
<tr>
<td>1) Ports interfacing to vacuum vessel:</td>
<td></td>
</tr>
<tr>
<td>16 midplane-horizontal</td>
<td>3.3 m(W)x5.8m(H)</td>
</tr>
<tr>
<td>16 upper side-horizontal</td>
<td>3.1 m Dia</td>
</tr>
<tr>
<td>16 lower side-pumping</td>
<td>3.3 m Dia</td>
</tr>
<tr>
<td>16 top head - vertical</td>
<td>1 m dia permanent and a large trapezoidal cover for blanket segments replacement</td>
</tr>
<tr>
<td>16 bottom head-vertical</td>
<td>1 m Dia</td>
</tr>
<tr>
<td>2) Other Ports/penetration:</td>
<td></td>
</tr>
<tr>
<td>1 top head-centre</td>
<td>6.3 m Dia</td>
</tr>
<tr>
<td>1 bottom head-centre</td>
<td>14 m Dia</td>
</tr>
<tr>
<td>TBD piping penetrations</td>
<td>TBD</td>
</tr>
<tr>
<td>TBD coil elect. leads</td>
<td>TBD</td>
</tr>
</tbody>
</table>
Table II-5  Weight support system design and interface specifications

<table>
<thead>
<tr>
<th>Earthquake accelerations</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>TBD (0.2 g assumed @ TBD Hz)</td>
</tr>
<tr>
<td>Horizontal</td>
<td>TBD (0.3 g @ assumed TBD Hz)</td>
</tr>
<tr>
<td>Position</td>
<td>See Reference drawing</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Magnet weight support system</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total magnet weight</td>
<td>12,000 ton</td>
</tr>
<tr>
<td>Normal operating temperature</td>
<td></td>
</tr>
<tr>
<td>Coil</td>
<td>4.5°K</td>
</tr>
<tr>
<td>Base of the support</td>
<td>Ambient</td>
</tr>
<tr>
<td>Allowable total heat leak to coil</td>
<td>5 kW at 4.5°K</td>
</tr>
<tr>
<td></td>
<td>(To be minimized by design)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tolerances at installation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil-to-Base</td>
<td>TBD</td>
</tr>
<tr>
<td>Coil-to-Coil</td>
<td>TBD</td>
</tr>
<tr>
<td>Maximum deflection</td>
<td>20-30 mm</td>
</tr>
<tr>
<td>Maximum external load</td>
<td>TBD</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vessel weight support system</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total supported weight</td>
<td>16500 ton</td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
</tr>
<tr>
<td>Vessel (normal operation)</td>
<td>90°C</td>
</tr>
<tr>
<td>Vessel (bakeout)</td>
<td>180°C</td>
</tr>
<tr>
<td>Base of the support</td>
<td>Ambient</td>
</tr>
<tr>
<td>Allowable total heat flow</td>
<td>TBD</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tolerances at installation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>VV-to MWS (Magnet Weight Support)</td>
<td>TBD</td>
</tr>
<tr>
<td>VV-to-VV sector</td>
<td>TBD</td>
</tr>
<tr>
<td>Maximum deflection</td>
<td>20-30 mm</td>
</tr>
<tr>
<td>Maximum external load</td>
<td>TBD</td>
</tr>
</tbody>
</table>
Table II-6 Equatorial ports allocation

<table>
<thead>
<tr>
<th>PORT NO</th>
<th>PHYSICS PHASE</th>
<th>TECHNOLOGY PHASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NBI</td>
<td>NBI</td>
</tr>
<tr>
<td>2</td>
<td>Diagnostics</td>
<td>Diagnostics</td>
</tr>
<tr>
<td>3</td>
<td>RH+IVVS</td>
<td>RH+IVVS</td>
</tr>
<tr>
<td>4</td>
<td>LH</td>
<td>LH</td>
</tr>
<tr>
<td>5</td>
<td>LH</td>
<td>LH</td>
</tr>
<tr>
<td>6</td>
<td>EC</td>
<td>EC</td>
</tr>
<tr>
<td>7</td>
<td>RH+IVVS</td>
<td>RH+IVVS</td>
</tr>
<tr>
<td>8</td>
<td>Diagnostics</td>
<td>Diagnostics</td>
</tr>
<tr>
<td>9</td>
<td>Diagnostics</td>
<td>Diagnostics</td>
</tr>
<tr>
<td>10</td>
<td>Diagnostics</td>
<td>Diagnostics</td>
</tr>
<tr>
<td>11</td>
<td>RH+IVVS</td>
<td>RH-IVVS</td>
</tr>
<tr>
<td>12</td>
<td>TM</td>
<td>TM</td>
</tr>
<tr>
<td>13</td>
<td>TM</td>
<td>TM</td>
</tr>
<tr>
<td>14</td>
<td>PI+Diagnostics</td>
<td>NBI+Diagnostics</td>
</tr>
<tr>
<td>15</td>
<td>NBI+RH+IVVS</td>
<td>NBI+RH+IVVS</td>
</tr>
<tr>
<td>16</td>
<td>NBI</td>
<td>NBI</td>
</tr>
</tbody>
</table>

NBI: Neutral beam injection  
IVVS: In-vessel viewing system  
RH: Remote handling  
PI: Pellet injection  
TM: Test module  
EC: Electron cyclotron  
LH: Lower hybrid  
NT: Nuclear testing
### Table II-7 Component classification for maintenance

<table>
<thead>
<tr>
<th>Class 1</th>
<th>Class 2</th>
<th>Class 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Scheduled maintenance)</td>
<td>(Semi-permanent components)</td>
<td>(Permanent components)</td>
</tr>
<tr>
<td>Divertor plate</td>
<td>Blanket</td>
<td></td>
</tr>
<tr>
<td>First Wall armor</td>
<td>Divertor shield</td>
<td></td>
</tr>
<tr>
<td>IC Faraday shield</td>
<td>Shield plug</td>
<td></td>
</tr>
<tr>
<td>LH launcher surface</td>
<td>RF launchers</td>
<td></td>
</tr>
<tr>
<td>Diagnostics I</td>
<td>Diagnostics IV</td>
<td></td>
</tr>
<tr>
<td>EC Window</td>
<td>Diagnostics IV*</td>
<td></td>
</tr>
<tr>
<td>Test modules</td>
<td>Diagnostics IV</td>
<td></td>
</tr>
<tr>
<td>NBI ion sources</td>
<td>Diagnostics V*</td>
<td></td>
</tr>
<tr>
<td>EC mirror</td>
<td></td>
<td>TF coils</td>
</tr>
<tr>
<td>Diagnostics II*</td>
<td></td>
<td>PF coils</td>
</tr>
<tr>
<td>Gate valves</td>
<td></td>
<td>Vacuum vessel</td>
</tr>
<tr>
<td>Cryopump</td>
<td></td>
<td>Bellows</td>
</tr>
<tr>
<td>Diagnostics III*</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Center solenoid</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Note: Examples:

**Diagnostics I**
- Wall tile probes
- Divertor probes
- Divertor thermocoupling
- Movable probes

**Diagnostics II**
- Mirrors
- Bolometers
- Micro-fission chamber components

**Diagnostics III**
- Window
- Optical
- Corner

**Diagnostics IV**
- Many

**Diagnostics V**
- Many

---

- 18 -
Table II-8 Components configuration, size and weight

- Machine gravity support (1/16)
  configuration, size: see reference drawing 20 ton (each)

- Cryostat
  segmentation: TBD

- TF coils (1/16) 470 ton

- Vacuum vessel (1/16)
  Wedged segment 180 ton
  Parallel segment 80 ton

- Intercoil structure (1/32) 45 ton

- Center solenoid 720 ton

- PF coils
  PF5(1/2) 140 ton
  PF6(1/2) 380 ton
  PF6(1/2) 230 ton
  PF magnet support (1/16) 19 ton

- Horizontal ports (1/16) TBD

- Pumping ducts (1/16) TBD

- In-vessel components
  Inboard blanket/shield (1/32) 40 ton
  Outboard side blanket/shield (1/32) 80 ton
  Outboard center top and bottom (1/32) 64/35 ton
  Shield plug (1/16) 5 ton
  Divertor plate (1/64) 1.5 ton
  Active coils TBD
  Service line TBD
  Connection boxes TBD
  Lower divertor shielding (1/32) 20 ton

Surrounding equipments see chapter IV.
References

III. Containment Structure

III.1 Introduction

(1) GENERAL

This report describes brief summary of the Containment Structures Design Unit (CSDU) arising from the work carried out for the ITER Conceptual Design Phase and Japanese Home Team contributions for it. The Containment Structures Design Unit activity area is the following: the primary vacuum vessel (VV), attaching locks (AL) of the in-vessel components, plasma passive and active stabilizers design, cryostat vessel (CV) and machine gravity supports.

The aim of the ITER conceptual design phase has been to identify and analyse the main design requirements, interface parameters and possible design solutions for each component of the system with the purpose of selecting reference or possible candidate designs to carry forward to the next stage, the Engineering Design Phase.

Reference designs have been chosen, but for some components, alternative design options are described and retained for further consideration into the next design phase. These are essentially components critical for the working of the basic machine for which unresolved problems still exist and for which further research and development is necessary before a final choice can be made.

Section 2 of this report gives a summary of the CSDU activity and results reached during ITER Conceptual Design Phase [1]. Section 3 to 10 give the design description of the Japanese proposals. In section 11, Future R&D plan is described. In section 12, the conclusions and recommendations for future design development are stated in terms of what has been accomplished to date, the acceptability of the designs including any alternatives, to what extent the design requirements have been met and areas of concern remaining.

(2) ITER OBJECTIVES

The overall objective of ITER is to demonstrate the scientific and technological feasibility of fusion power. ITER will accomplish this objective by demonstration of controlled ignition and extended burn of a deuterium-tritium plasma with steady state as an ultimate goal, by demonstrating technologies essential to a reactor in an integrated
system, and by performing integrated testing of the high-heat-flux nuclear components required to utilize fusion power for practical purposes.

To reach this objective ITER will be operated in two phases:
- a physics phase focused mainly on achieving the plasma objectives,
- a technology phase devoted mainly to engineering objectives and the testing programme.

The engineering and testing objectives are to validate design concepts and qualify engineering components, to demonstrate the reliability and maintainability of the reactor systems, and to test the main nuclear technologies (blanket modules, tritium production, extraction of high-grade heat appropriate for the generation of electricity, etc.). Specifically it is hoped that the device can provide:

1) testing conditions with the average neutron wall loading of about 1 MW/m²,
2) a neutron fluence of about 1 MWa/m² but with the design allowing for the possibility of a higher neutron fluence in the range of 3 MWa/m²,
3) a tritium breeding blanket that aims at achieving a breeding ratio as close to unity as possible, and
4) an overall availability of ITER of at least 10%, but which should reach a level of 25% and provide continuous operation for a period lasting one to two weeks.

(3) ITER CONFIGURATION[1]

During the concept definition phase, the configuration development studies were aimed at deriving a reactor concept that integrated the results of several concurrent efforts. Information derived from the efforts of other ITER engineering groups and design units with specific system responsibilities was combined with efforts within the maintenance and containment structures design units to arrive at the proposed configuration. Specifically, the issues addressed included:

1) The design of integrated vacuum vessel/bulk shield and its interface to the TF and PF coil systems, blankets, active and passive plasma stabilizers, all port penetrations, etc.
2) The evolution of the maintenance schemes for key components.
3) The principal design solutions of the cryostat and machine gravity
supports.

4) Initial concept and layout of the reactor buildings that affect the ITER configuration.

The reference ITER configuration, based on the final required machine parameters and the results of the design efforts to date, is shown in Figs III.1-1 to III.1-5.

Several reactor configurations with variants have been considered for the concept definition phase. All the solutions investigated have some common requirements:

1) The basic machine is the semi-permanent or permanent part of the reactor and it is designed for the lifetime of the plant: it must have high reliability. It consist of the magnet system, vacuum vessel and shield structures and cryostat in a VV configuration which allows for separate assembly and repair/reassembly as much as possible.

2) The internal (or in-vessel) components, which include the blanket segments, shielding plugs and plasma facing components, are located inside the vacuum vessel and are replaceable. They have necessarily lower reliability and shorter lifetime and must be substituted because of the end of life, or accident, or for experimental purposes during the various operational phase. (During CDA phase this point of design philosophy was reconsidered, and only the divertor plate, the small blanket test modules, and some part of the first wall tiles are considered as scheduled replacement elements. All large blanket segments are considered practically semi-permanent elements with the need for replacement resulting only from accident damage);

3) Access penetrations through cryostat, coils systems, and vacuum vessel and provided for the maintenance and substitution of the internal components and for reactor auxiliary system (exhausting, heating, fueling, etc.);

4) All the main coils are superconducting and the PF coils, located outside the TF coils, can be disassembled with the torus (vacuum vessel and TF coils system) in position;

5) The coils and the intercoil structures, contained in the cryostat vacuum are completely surrounded by a helium gas-cooled thermal shield to reduce the radiation heat losses;

6) The vacuum vessel is a tight structure which separates the plasma
vacuum from the cryostat vacuum, providing the primary containment of activated materials; the vacuum vessel in combination with the shield also provides the nuclear radiation shielding to protect the TF coils.

7) The initial layout of the reactor hall, auxiliary systems and adjoining spaces has been developed with the following criteria as guidelines;
- design for full remote maintenance with hands-on backup wherever possible;
- enable transport of major components into/out of the reactor hall spaces during construction, and after neutron activation;
- basic machine support systems is located in optimal locations for installation, operation, maintenance and safety;
- overall dimensions are kept as small as possible without unduly constraining construction, operation, safety and maintenance.

(4) Japanese Home Team Contributions[2]
Apart from the common cooperative activity in CDA joint work Items extensively contributed by Japanese home team are as follows.
1) Vacuum vessel configuration: Thin double wall vessel as an alternate approach,
2) Electromagnetic analysis,
3) Initial assembly: Thin double wall vessel,
4) Gravity support: Spring plate flexible support,
5) Attaching locks: Hydraulic locking system,
6) Cooling pipe & magnet services: Basic layout, personal access, vacuum & biological shield boundaries,
7) Cryostat: Comparison between a metal and concrete concept,
8) Port penetration: Typical horizontal port penetration,
9) Long Term R&D
THE ITER DEVICE

1- CENTRAL SOLENOID
2- SHIELD/BLEANKET
3- ACTIVE COIL
4- PLASMA
5- VACUUM VESSEL-SHIELD
6- PLASMA EXHAUST
7- CRYOSTAT
8- POLOIDAL FIELD COILS
9- TOROIDAL FIELD COILS
10- FIRST WALL
11- DIVERTOR PLATES

Fig. III.1-1 The ITER device
Fig. III.1-2 Vertical cross section of ITER
Fig. III.1-3 Horizontal cross section of ITER
1- CRYOSTAT

2- VACUUM VESSEL WEDGE SECTION

3- VACUUM VESSEL PARALLEL SECTION

4- VACUUM VESSEL SUPPORT

Fig. III.1-4 The containment structure of ITER
Fig. III.1-5  ITER vacuum vessel segment
III.2 Reference and Alternative Concepts[1]

The main efforts of the Containment Structures Design Unit were concentrated in the following areas [1]:
1) Vacuum Vessel (VV): reference approach choice, design study and development of details (assembly joints, electroinsulating structural connections, resistive elements, cooling channels, etc.)
2) Attaching locks (AL) for the in-vessel components: development and analysis of the candidate design solutions.
3) Plasma passive and active stabilizers: design development and integration into the VV structure.
4) Cryostat: reference design selection and development
5) Machine gravity supports: choice of design and development of details.

During the CDA phase, the following main tasks were confronted by each design unit:
- finding workable and reliable design solutions for all machine components, consistent with the parameters and requirements lists,
- choosing a reference or "first candidate" design option for each component for ITER design integration,
- determining the most critical unresolved design problems for future design and R&D efforts.

Naturally, in the process of choosing the single "reference" or "first candidate" design option from existing workable solutions, the relatively conservative, best known, or standard solution have the best chances to be chosen. These choices are supported by wide and reliable existing manufacturing experience and/or previous R&D results.

However, many new and previously unknown attractive alternative design solutions were also discussed during CDA phase. These can lead to improvements in some parameters of machine components, increase total machine reliability, or operational flexibility. These options were not chosen for reference mainly due to lack of existing manufacturing experience or the necessity of additional R&D study. They should be kept in consideration for the EDA phase, since some part of these options have a good chance to be used in the ITER final design, based on successful future design developments and R&D results.

These alternative options offer a more effective means of solving
the identified critical design issues and improving the existing ITER reference design.

Progress of the ITER design resulting from the CSDU activity can be briefly described as follows:

(1) VACUUM VESSEL

The reference V.V. design approach was chosen in 1989 based on early discussions of options. It was developed in detail during 1990 based on home team design proposals and analytical studies.

The reference thick wall V.V structure consists of 32 rigid thick-wall sectors (16 "parallel", located in the plane of TF coils, and 16 "wedged", located between the TF coils). Each parallel sector has two internal electroinsulating breaks which are structurally connected by toroidally oriented bolts and shear keys with electroinsulating coatings. All connections are located in secondary (cryostat) vacuum and are separated from primary vacuum by 32 corrugated resistive elements which provide a full-metallic welded boundary for the primary vacuum and tritium/radioactive dust containments.

The Vacuum Vessel has 32 assembly joints, located separately from electroinsulating breaks.

The position, shape and design of these assembly joints were chosen (after some iterations) on the basis of existing experience, stress analysis, safety, nuclear shielding and remote handling maintenance requirements. There are double welded joints with additional structural welds and bolted connections to provide sufficient stiffness. The location of the weld joints was chosen to maintain the possibility of cutting/rewelding by remote handling tools after the machine is irradiated (stainless steel rewelding limit ~1 appm He production.

The design of the main VV components (bolts, shear keys, welded joints and resistive elements cross sections) have been chosen (after some iteration) on the basis of numerical studies that determined electromagnetic, overpressure, thermal, gravity and seismic loads. For the latest VV design, all calculated base stresses are within acceptable values, but some critical points with stress concentrations have been identified and need to be improved in future studies and designs.

Critical R&D tasks are required to finalize the VV design, establish its feasibility/reliability, and check its compatibility with remote handling tools. These should be completed during the EDA phase.
to provide the basis for construction of the VV.

In parallel to the reference V.V. design development, the alternative thin-wall V.V. option should be kept in consideration. The thin-wall design is potentially simpler than the reference one and has been a common approach used in existing fusion devices. However, some unresolved problems or technology demonstration tasks exist (e.g. compatibility with twin-loops design, bonding/welding manufacturing choice). If these problems are solved in time, the thin-wall VV has a good chance of being used in ITER. It seems also that the best features from both approaches will probably be combined in the final vacuum vessel design.

(2) ATTACHING LOCKS FOR THE IN-VESSEL COMPONENTS

Many possible design options of the blanket attaching locks was developed and analysed during the CDA phase, but a reference approach was not chosen. One attractive, but not yet verified, option was chosen only for ITER design integration.

This situation is a result of the extremely difficult and significantly contradicting requirements for the locks design. These requirements is briefly summarized below:

- locks must withstand the high electrodynamic loads due to plasma disruption (up to 35 MN shear load between adjacent outboard blanket segments),
- freedom for mutual (blanket-to-vessel and blanket-to-blanket) thermocontraction in normal and accidental conditions without component damage should be provided,
- no clearances or sliding surfaces are allowed in the lock to prevent dynamic shocks, jamming, vacuum welding, etc.; the locks are located in an irradiation area that precludes rewelding of stainless steel,
- locks connection/disconnection must be accomplished by remote handling tools, taking into account the possibility of having to remove damaged (uncooled) blanket segments,
- correct mutual position (a few mm) and small gaps (~20 mm) between all blanket segments must be guaranteed,
- the locks should provide the electroinsulating barrier between blanket segments, if these barriers are not incorporated into the segment structure,
- the design should provide effective nuclear heat removal from all lock elements.
It should be pointed out that the design of the blanket locks has never been addressed previously since there are no analogies on any existing tokamaks.

New engineering approaches and guidelines have been generated by the ITER Team that only partially resolve some of these requirements. For example, electroinsulating breaks located in the mid-portion of the blanket segments combined with electrical conducting connections between blanket segments in the locks area drastically reduce the loads, acting on the attaching locks. This approach (referred to as the separation of electroinsulating breaks and field assembly joints) is used in the inboard blanket and also V.V. structure designs.

A second example is the mutual blanket-to-blanket interlocking scheme, used in ITER instead of the previous blanket-to-vessel locking scheme. This approach simultaneously solves the problem of blanket-to-vessel thermocontraction in normal operation and baking regimes and leads to compensation of the dominant shear electromagnetic loads, acting in opposite directions on the adjacent blanket segments walls. Only non-compensated, relatively small vertical electromagnetic load and blanket dead weight acts on the vacuum vessel.

A list of some of the blanket attaching lock options analysed during the CDA phase is given below.

1) Mechanical bayonets
2) Flexible welded plates
3) Hydraulic jacks
4) Bolted wedges
5) Melted/solidified metal
6) Bolt-to-bolt welded connections
7) Toroidal supporting belts

Approaches 3 through 7 are considered good candidates for use on ITER, however, they all require significant continuing design and R&D.

For ITER design integration in the CDA phase, the bolt-to-bolt welded connection approach was chosen for the inboard blanket segments. Its combination with other approaches seems reasonable for the outboard blanket.

The bolt-to-bolt welded connections approach is based on the welding of specially shaped heads to two bolts, respectively screwed into the side walls of adjacent blanket segments. This approach excludes any gaps and sliding surfaces and it is not sensitive to the tolerances of
the blanket segments manufacturing or installation. If a blanket segment needs to be replaced (this is a possible, but non-scheduled operation), all its welded connections will be cut and all the bolts in the two adjacent segments will be replaced. As a result, no rewelding of irradiated material is required. In the latest design, aluminium-alloy sleeves with Al₂O coating are inserted into the blanket structure prior to inserting of the bolts. They provide the double (or quadruple) electrical barrier and also protect the blanket walls from damage due to relative thermocontraction between adjacent segments that may result from off-normal operating conditions (i.e., loss of cooling).

However, a serious technological problem remains to be solved before this design can be adopted. Welding and cutting tools for operation in the narrow (~20 mm) and deep (~500 mm) gas must be developed. If the feasibility of repeatable, good quality, thick (several cm) welded joints for these conditions can be demonstrated, this concept will be chosen as the reference. If not, other approaches must be considered.

This means that R&D studies during the EDA phase should be conducted on several design approaches with a uniform level of priority.

It is hoped that work on the blanket locking system will develop a concept that can also be applied to the divertors or at least lead to feasible new ideas. As opposed to the blankets, the divertors require scheduled replacement.

(3) PLASMA PASSIVE AND ACTIVE STABILIZERS

One of the principal torus (WV and blanket) functions is to provide the passive and active stabilization of the plasma since the very elongated cross-section is naturally unstable to vertical displacements. To do this, highly conductive passive loops (PL) and in-vessel fast active control coils (AC) must be incorporated in the torus design.

(3.1) Passive stabilizing loops

The conventional saddle passive loops approach was proposed initially for plasma vertical stabilization in ITER. But evolution of the ITER parameters to the highly elongated plasma drastically reduced the saddle loops stability margin to an unreasonably low value (i.e. m ~0.3 for specified plasma parameters and only 1 cm for all electrical gaps). Additionally, design integration problems appeared due to interference
between the vertical legs of the saddle loops and the horizontal ports.

To solve both problems, a new passive stabilization concept, named the twin-loops concept, was conceived and developed by the ITER Team. This approach was approved as the ITER reference design in October 1989.

The twin-loops consist of good conducting plates attached to the outboard blanket segments front face, side, and back walls above and below the horizontal ports area; and of conductive plates attached to the adjacent inner surface of the V.V. bulk structure. There are no special vertical electrical connections between the upper and lower parts of the twin loops. This allows a maximum flexibility in the location of the horizontal parts. There are also no requirements for galvanic connections between blanket segments and V.V. since inductive coupling is used. This solves the problem of different thermoexpansion movements between these structures.

Both simple estimates and detailed numerical studies show, that the twin-loop concept (in comparison with saddle-loops) allows an increase in the allowable gap size between the adjacent outboard blanket segments, electrical gaps can be increased from 10mm to 30mm and geometric gaps from ~5mm to 20mm. Simultaneously, the stability margin is improved from $m_S \sim 0.3$ to the required level of $m_S > 0.5$. It is interesting to note that if the stability margin were kept at the previous level the allowable electrical gap could be increased by a factor of ~10, up to ~100mm.

(3.2) Fast active control coil

A pair of one-turn sectorized coils located in the primary vacuum area with ceramic powder electroinsulation and current joints/cooling water connections was initially proposed for the active control of the plasma vertical position in ITER. A detailed study showed three serious problems:

1) the necessity of full remote maintenance for the in-vessel current joints because they are located in a severe radiation and tritium environment. In the original design, the AC current joints and water connections had to be disconnected before the outboard central blanket segment could be moved, and then had to be reconnected after the new segment was installed, since part of the upper AC was integrated in the central blanket segment structure.

2) extremely severe operating conditions for the AC current joints and
water connections, including high cyclic (N>10^7) dynamic (t_p~30ms) EM loads with a typical amplitude up to F_p~1 MN/m.

3) an unreasonably high value of the AC self-inductance. For the first version it was at least a factor of 2 higher than the "ideal" limit. This resulted in increased requirements for the voltage and power capability of the AC power supply system.

The first step involves relocating the AC to a new position approximately 2.5 meters nearer to the machine mid-place than the previous one. The idea is to use two toroidally continuous spaces for the AC with up-down symmetry. The space is available between the upper-to-horizontal VV ports and horizontal-to-lower VV ports. The new AC position results in no geometrical intersection of the AC with the blanket segment replacement tractors. As a result, the AC can be kept in place during all maintenance operations on in-vessel components. AC static efficiency in the new position is approximately 20% less than ideal but this disadvantage can easily be compensated by the reduction of the AC self-inductance (see steps 2 and 3). The new AC position was adopted as an ITER reference in February-March 1990.

The second step in AC design improvement was the relocation of its current/water terminals from the primary to the secondary vacuum region. In this arrangement the AC can be repaired by remote handling tools without prior blanket segment removal.

The third step involved the reduction of the AC self-inductance by eliminating the long current leads, and more effectively, by replacing the single-turn with multiturn coils. It was shown that reduction of the AC self-inductance by approximately a factor of 2 can be accomplished by these two methods. The required voltage and power of the AC power supply system is reduced correspondingly.

Seven possible AC design options have been analysed by CSDU, and the latest two or three are considered as the most probable candidates for ITER. They are the following:
- single-turn or multiturn sectorized coils
- saddle-type multiturn coils
- flexible multiturn coils.

(4) CRYOSTAT

Several feasible cryostat (CV) design options were discussed and compared during the CDA phase. Options considered were:
concrete wall, up to ~2 mm thick, with continuous inner metallic liner
- full-metallic ribbed welded wall
- metallic, electrically sectorized wall with continuous liner
- metallic rigid, welded structure with local high-resistive elements

It was decided in CDA phase, that the CV should have no specific nuclear shielding requirements. This decision is derived from the fact that sufficient biological shielding for personal access for 24 hours after shutdown will be provided by the outboard blanket / v.v. (thickness ~1.5m) and the shielding around all penetrations (~1.2m close to the machine). Local streaming points should be determined and specially shielded. This means that a biological shielding function is not required for the cryostat of the ITER machine.

The requirement for the CV toroidal electrical resistance (to limit the EM shielding effects) was varied during the CDA phase. Initially, up to 70mm of effective stainless steel wall thickness was allowed, and a simple full-metallic, ribbed, welded CV design was chosen as the reference (25mm sheets, supported on 700mm vertical and toroidal ribs).

In September 1990 the electrical requirements were respecified to be 10mm of effective stainless steel toroidal thickness. The change was based on a better numerical study of the start-up phase. As a result, the previous full-metallic welded CV design has been slightly modified to include four local high-resistive corrugated metallic inserts. Electrically insulated bolted connections are incorporated in the CV cylindrical wall around the resistive insert perimeter to provide structural continuity through the inserts. This design seems feasible and reliable, but limited R&D study is needed for optimization of the resistive inserts design.

An upper cryostat cover, with large trapezoidal openings for blanket maintenance and a central circular cover for the central solenoid and PF 5 replacement, was also designed. Future design optimization is required to reduce the weights of the cover and to provide reliable vacuum sealing around all openings. The multiple penetrations for current leads and cryogenic lines will be incorporated into the bottom portion of the CV.
(5) MACHINE GRAVITY SUPPORTS

In the gravity support area, feasible design options were developed and analysed during the CDA phase. The main requirements for the supports are to provide a reliable machine base for reacting gravity and earthquake loads and for machine assembly and repair. It should occupy the minimum space and provide sufficient freedom for the magnet system and VV thermal expansion and minimize heat leakage to the cold components. Different variations of kinematic rolling and flexible supports were compared. The flexible multi-plate design approach was chosen as the ITER reference. Its major advantages are its simplicity, absence of rolling/sliding surfaces, and a good centering of the magnet set and VV axis. The choice between variants using compressive or tensile flexible plates is still open, but the compressed plates option was chosen for ITER design integration, since it has the stronger basis in current designs and numerical analysis.

(6) LONG TERM R&D PLAN

(6.1) Introduction

The containment structures long-term R&D plan for 1991-1995 was originally prepared during Winter 1990 Joint Work, discussed by Home Teams, and reviewed/updated during the Summer 1990 Joint Work period. A new revised R&D plan was then presented and reviewed at the R&D Specialist Meeting and ISTAC during the week of 27 August and 15 September 90. The main comment was about the full scale mock-up/prototype task description and time schedule. The recommendation to reexamine the full scale vacuum vessel (VV) prototype needs and timing and evaluate cost/benefit of centralized versus distributed efforts was formulated.

After discussion in the CSDU, most of these recommendations have been incorporated into this latest version of the plan (ITER-IL-CS-2-0-38 rev.4).

(6.2) Summary

Key issues of the ITER containment structure are to develop

1) fabricability of large and heavy components (20m, 100ton) with complicated geometry and high accuracy of 2-5mm including on-site thick welding, also cutting and rewelding by remote handling tools,
2) accurate torus structure to allow electromagnetic loading (10 MN/m) due to disruption and to provide flexibility for thermal expansion
due to different operating temperature,
3) tritium containment structure with double seals to be maintained by remote handling.

For this purpose, an overall R&D plan is established and the following 5 specific tasks are addressed in the CSR&D plan 1990-95 (Technical issues are summarized in Section 11). These include:

- Vacuum vessel (COS.1)
- Locks and supports (COS.2)
- Plasma stabilizing elements (COS.3)
- Cryostat elements (COS.4)
- Full scale mock-ups (COS.5)

development Tasks COS.1 - COS.4 will basically proceed in the following three steps.

1. key component development/study
2. scaled and partial models development/study
3. full scale mock-up development

In order to minimize redundancy in test facility costs, the final steps of COS.1 - COS.4 tasks development will be combined in one large mock-up study (COS.5). This full-scale torus sector mock-up should have most of the important features of the critical or undeveloped details. Based on the recommendations of the R&D review meeting, the fabrication of a VV prototype was postponed after 1995, and is now considered as a task of the construction phase.

The needs and time schedule for the torus sector full scale mock-up fabrication/study were discussed in both the CSDU and AMDU. It was decided that a torus mock-up must be at least fabricated before 1995 in order to validate the principal design solution and to receive feedback response in design optimization before starting of the actual manufacturing process. The main requirements for the detailed mock-ups are as follows.

1) The ITER torus system is strongly related to safety problems and a complete full scale test of all joints and potentially unreliable elements is needed in order to assure compliance with established safety requirements and existing practice for nuclear power equip-
ment development.

2) Extremely high electromagnetic (EM) loads acting on the vacuum vessel and in-vessel components that result from plasma disruptions, with the additional constraint of a required limit on the vacuum vessel toroidal electrical conductance, are the main design features of the ITER vacuum vessel that make its requirements different than those of existing fission power reactor vessels. In order to meet the ITER requirements for strength and reliability, all vacuum vessel manufacturing processes (structural and assembly joints, electro-insulating connections, etc.) need to be thoroughly qualified at each fabrication step (Tasks COS 5.1-5.3). Additionally, task COS 5.4 is proposed to help resolve the question of the accuracy of the EM load calculation.

3) Requirements for full remote handling, disassembly and reassembly of the VV and in-vessel components failure increases the importance of compatibility between VV and in-vessel components design and remote handling tools/procedures.

(6.3) R&D schedule

Figure III.2-1 shows the overall R&D plan of the ITER containment structure together with the remote handling development. It is proposed to share development because the full scale mock-up demonstration in the final step and be done as a combination and the resources required can be minimized.

In Fig. III.2-1, the basic functions and feasibility of critical elements and their scalability to partial models can be demonstrated in STEP-1&2, so that the reference configuration can be fixed. In STEP-3, deflection and alignment during manufacturing in factory and initial assembly including on-site welding, cutting and rewelding by remote handling tools can be demonstrated by full scale mock-up manufacturing and as a final step testing.

(6.4) Cost and schedule

The CS R&D program is estimated to cost a total of 43.5 M$ from 1991 through 1995 and the cost of the prototype VV sector will be included only in the Construction Activity Phase (after 1995). The tentative cost break-down and time schedule for all tasks/subtasks are given in Table III.2-1, III.2-2 and Fig. III.2-2.
### Table III.2-1 CSDU R&D COSTS (1991-1995)

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<th>Task No.</th>
<th>Task description</th>
<th>Cost (M$)</th>
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<td>Partial models manufacturing</td>
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Overall Plan for Containment Structure R&D

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**STEP-I**
Component Development

**STEP-II**
Full-scale Partial Model Development

**STEP-III**
Torus Sector Mock-up Manufacturing
- VV 1st Sector Component
- VV 2nd Sector

**AMA-12**
Integrated Mock-up
Mock-up Test Facility

**AMA-9**
VV Handling Prototype

**AMA-5**
Blanket Handling Prototype

**AMA-1,2,3**
In-vessel Handling Prototype

**AMA-4,6,8**
Port Assembling Prototype

**AMA-II**
Standard Component & Process Development

**AMA-10**
Viewing System Prototype

**AMA-7,13**
Vacuum Pump & Heating Devices Handling Prototype

Fig. III.2-1 R&D schedule of CSDU & AMDU
Fig. III.2-2 Overall plan for containment structures and assembly and maintenance tasks
III.3 Thin Double Wall Vacuum Vessel Structure Design[2]

Reference Vacuum Vessel Design Concerns

The ITER vacuum vessel reference design is based on heavy steel sections bolted together across insulated joints. Vacuum integrity is achieved by seal-welding a high resistance corrugation across the structural joint. The advantages for this design include: good shielding characteristics, low deformation under load, good strength, no electrical insulation in the plasma vacuum (except in blanket/shield modules and locks), and adequate, heavy structure for providing attachment points for the blanket modules. Very important advantage of the reference vacuum vessel is a good possibility of twin-loops incorporation that is problematic for alternative option.

As this design concept has progressed, however, several difficulties have been discovered. First, although the heavy sections can be made very robust, the overall strength of the structure is limited to the bolts and shear keys that tie the sections together. The loads from the blanket modules during a plasma disruption are very severe and must be taken primarily by separate structure between adjacent blankets, and not be carried into the vacuum vessel. Second, the seal welds attaching the resistive corrugation to the heavy sections must absorb the shear stress between the cool heavy section and the hot resistive section following a disruption. It is difficult to provide flexibility at this joint to reduce the stress concentration. Third, since the toroidal electrical resistance is concentrated at discrete locations on the inner surface, there is a tendency for radial currents to form in the vessel during a plasma disruption, adding extra vertical shear forces to the structural joint area. Finally, the overall complexity of the design and required manufacturing tolerances could result in a very expensive structure to build and to qualify for tritium containment.

Alternate Vacuum Vessel Design Concept

As a result of the concerns with the reference design, the alternate vacuum vessel design concept is proposed. The alternate concept is based on a thin wall sandwich structure, with continuous inner and outer face sheets separated by rib stiffeners. This is a common design solution for the vacuum vessels of existing fusion devices. The membrane strength of this design is of the same order as the reference design in
that the tensile area of the skin is similar to that of the segment to segment connecting bolts on the reference design. The bending strength of the sandwich design is nearly as great as the solid section design, and does not have the extra bending loads produced by the discontinuity at the joints. Since the sandwich design provides the required electrical resistivity by uniformly distributing it toroidally around the structure, there should be no toroidal gradient in ohmic heating from a plasma disruption. The primary disadvantage of the sandwich structure had been the difficulty of providing structural attachment points for the blanket and shield modules. This problem has been practically eliminated, however, by structurally separating the blanket/shield structure from the vacuum vessel. Most serious concern for the thin-wall design is a difficulty of its integration with twin-passive loops due to unacceptable large electrical gaps value between blanket and double-sheet SS vessel structure. If this gap will be reduced by using of conductive plates, attached to SS, vessel toroidal resistance will be drastically shunted.

The Japanese thin-wall concept has only a 15 cm thickness, and employs an intermediate shield and support structure on which to mount the blanket modules. In Table III.3-1 and Table III.3-2, vacuum vessel configuration comparison and thin double wall vessel concept are shown.

**Thin-wall alternate VV with 15 cm total depth and separate shield structure (Japan proposal)**

This design consists of a relatively thin (15cm) double wall vacuum vessel that has a separate shield structure from which the blanket modules are supported. In this way, the blanket and shield EM forces are not transmitted to the vacuum vessel, except for the residual EM load and the gravity load, which are transmitted through a "shelf" on the outboard lower side of the vacuum vessel. The shield system is structurally continuous in both the toroidal and poloidal directions, but is electrically discontinuous in the toroidal direction. The concept is illustrated in Figs III.3-1 to III.3-8.

The vacuum vessel is constructed of thin face sheets separated by box tubing, which forms the structural core as shown in Fig. III.3-4. As in the other thin wall design, either welding or diffusion bounding can be used to bond the face sheets to the box tubing. The general feasibility of this approach has been demonstrated during the manufac-
turing of JT-60 Upgrade. Heavier rib sections are used at the assembly joints where the double field welds are made. Water between the face sheets serves as coolant and additional shielding material. Calculations show that the shielding effectiveness of this design is comparable to the reference concept.

The vacuum vessel is segmented at the radial planes through the ports (the same as the other thin wall design), and part of the shield structure is preinstalled in the bore of the TF coil. The preinstalled pieces are bolted across an insulated break in the factory. Other pieces are connected by keys in situ, and clearance is provided by a small toroidal shift of the shield structures. The peak calculated Von Mises stress for this design is 199 MPa.

In conclusion, a continuous, thin wall sandwich type vacuum vessel is proposed as an alternative to the thick wall reference design. The alternate concept appears feasible from the standpoint of fabrication, assembly, cooling and structural loading. There are still issues to be resolved, such as the exact composition of the core, the fabrication method (welded, diffusion bonded or other), the worst case temperature distribution due to joule heating from a plasma disruption, and the effect and severity of conductive plasma currents or "halo" currents.
Table III.3-1 Vacuum vessel configuration comparison

[Requirements]
a. Plasma vacuum boundary and tritium containment
b. One turn resistance
c. Magnet and biological shielding
d. Supporting magnetic forces & in-vessel component
e. Passive stabilization

[Thick vessel concept]
a. High stress at mechanical joint
b. Imbalanced force due to non-uniform current distribution
c. Thermal stress due to non-uniform temperature distribution
d. Welding deformation
e. Low reliability to vacuum sealing due to electromagnetic force from blanket

[Thin double wall concept]
a. Low stress due to full penetration welding
b. Low imbalanced force due to uniform current distribution
c. Low thermal stress due to uniform temperature distribution
Table III.3-2 Thin double wall vessel concept

[Key features of thin double wall vessel]

a. Vacuum vessel divided into two components.
   thin double wall vessel
   - vacuum boundary
   - tritium containment
   - one turn resistance (20 micro-ohm)
   - gravity support of in-vessel component
   shield structure
   - support structure of magnetic force
   - magnet and biological shield

b. Thin double wall vessel
   - thin double wall: 15mm thickness
   - square tube : 120mm
   - total thickness : 150mm

c. Shield structure
   - Rigid torus structure
   - one-turn break
   - thickness : 230mm inboard region
   430mm outboard region

d. Thin double wall vessel with full penetration welding

e. Shield structure connected by keys or welding

[Stress estimation]
A preliminary analysis shows that Toresca stress of 100-200MPa will be applied to the port region.
Supporting dead weight of blanket

Fig. III.3-1 Elevation view (thin double wall vacuum vessel)
Fig. III.3-2 Plan view (thin double wall vacuum vessel)
Fig. III.3-3 Detailed plan view (thin double wall vacuum vessel)
Fig. III.3-4 Thin double wall vacuum vessel

Fig. III.3-5 Shield structure (one-turn break)
Fig. III.3-6 Thin double wall vessel configuration
Fig. III.3-7 Shield structure configuration
Fig. III.3-8 Inboard/outboard blanket structure
III.4 Electromagnetic analyses under disruption electromagnetic load[2]

4.1 Electromagnetic load for thick vacuum vessel and blanket

The analyses on EM load on thick vacuum vessel and outboard blanket are performed on the following conditions:
- Reference disruption (fast movement)
- Finite element circuit method
- Shell element
- ITER '89 summer reference drawing
- 3 modules/sector
- Twin loop passive stabilizer (5-mm-thick Cu Plate)
- Electrical gap size: 10, 30 mm
- Vacuum vessel: with, w/o

The models of vacuum vessel and outboard blanket are shown in Figs III.4-1 and III.4-2.

The results for electrical gap: 10mm are shown in Figs III.4-3 to III.4-5 and the results for electrical gap: 30mm are shown in Figs III.4-6 to III.4-9. The total EM loads of outboard blanket for different gap are shown in Figs III.4-10 and III.4-11.

The conclusion obtained from above results are summarized as follows:
- Twin loop can minimize eddy current flowing on side wall from upper to lower part.
- However, a large amount of vertical eddy current is induced within twin loops.
- EM force on outboard blanket cannot be reduced so drastically than expected.
- The effect of the gap size is not so large in the range of 10-30mm.
- Total EM forces on a quarter of an outboard blanket module are
  \[ RF = 12 \text{ MN} \]
  \[ Fz = 22 \text{ MN} \]
  for reference configuration, assuming no electrical contact between vacuum vessel and outboard, and electrical gap size of 30mm.

4.2 Stress Analysis of ITER Vacuum Vessel

(1) Objective

The alternative structural concept of vacuum vessel named "Thin double-wall structure" has an advantages to have larger bending stiff-
ness than that of single solid structure. Also, this concept can avoid the extra bending stress in the bolt joints required for the solid structure. In order to evaluate these advantages quantitatively, the mechanical behaviors of the ITER vacuum vessel under the electromagnetic loading due to plasma disruption has been analyzed by using a simple 3-dimensional finite element model of MSC/NASTRAN.

(2) Finite Element Model

The cross section of ITER vacuum vessel is shown in Fig. III.4-12. The typical structure consists of outer and inner wall of 15 mm thickness separated by rib stiffener of rectangular pipes. Total thickness of typical cross section is 150 mm. The finite element model of ITER vacuum vessel is shown in Fig. III.4-13. The 1/16 sector of vacuum vessel is modeled by using 367 nodes and 276 shell elements (QUAD4 and TRIA3) of MSC/NASTRAN. The mechanical behaviors of whole vacuum vessel was analyzed by using the function of cyclic symmetry of MSC/NASTRAN. In order to evaluate the effects of bending stiffness increased by double-wall structure, two different models were employed for the analysis;

i) Model 1

Total thickness of 30 mm (15.0x2) is assumed for membrane and bending stiffness. Young's Modulus of 190 GPa and the bending inertia per unit length of 2.25x10^3 (mm^4) are also assumed.

ii) Model 2

Total thickness of 30 mm is assumed for membrane stiffness. The bending stiffness increased by thin double-wall structure is assumed by increasing the bending inertia per unit length up to 1.37x10^5 (mm^4) (61 times larger than that of Model 1).

In these models, the consideration of shear modulus, which depends on the geometrical pitch of rib stiffener, was not included in the calculation. Also, the vertical and horizontal port ducts are assumed to be a solid structure of 100.0 mm thickness.

(3) Loading Condition

The electromagnetic loads generated by the plasma disruption are calculated based on the actual geometries of vacuum vessel and the other structural components inside of vacuum vessel. A set of assumption for the plasma disruption is listed in Table III.4-1. The time variation of
electromagnetic loads acts on the vacuum vessel and other components are shown in a series of figures (Figs III.4-14 to III.4-18). As shown in Fig. III.4-14, the maximum load in radial direction which dominates the deformation and stress level occurs at 22.0 msec. Therefore, the electromagnetic load at 22.0 msec was employed for the analysis as nodal point load. Total magnetic loads acts on the 1/16 sector of each component are summarized in Table III.4-2.

(4) Results of the stress analysis

1) Deformation of vacuum vessel

The deformation of the ITER vacuum vessel due to plasma disruption, calculated by Model 1 is shown in Figs III.4-19 and III.4-20. As shown in the figures, the maximum displacement of 16.1 mm, toward the torus center, occurs at the horizontal port. The corresponding figures calculated by using Model 2 are shown in Figs III.4-21 and III.4-22. Because of the increased bending stiffness, the maximum displacement of 10.8 mm is 33% smaller than that obtained by Model 1.

2) Stress in the vacuum vessel

The contour of constant Tresca stress in the vacuum vessel due to plasma disruption, calculated by Model 1, is shown in Fig. III.4-23. The maximum Tresca stress of 246 MPa is calculated at the location near the horizontal port. The corresponding figure calculated by Model 2 is shown in Fig. III.4-24. The maximum Tresca stress occurs at the same location, but the maximum value of 205 MPa is about 83% of the value calculated by Model 1. Therefore, when the same membrane strength is assumed for the vacuum vessel, the structural concept of "thin double-wall" is effective to reduce the stress level. The contour of constant Von Mises stress calculated by Model 2 is also shown in Fig. III.4-25. The effects of thin double-wall structure employed for the vacuum vessel of the FER and ITER are compared in Table III.4-3.

(5) Summary

The mechanical behaviors of the ITER vacuum vessel, which has the "thin double-wall structure" has been analyzed by using MSC/NASTRAN. The preliminary analysis shows that the double-wall structure is effective to reduce the displacement and stress occurs at plasma disruption.
4.3 Simplified Structural Analysis of ITER Outboard Blanket

(1) Objectives

Large electromagnetic (EM) loads induced by the plasma disruption are the major loading condition for the design of containment structures. However, the amplitudes and the distribution of EM loads depend on many factors such as plasma current, plasma motion at disruption, relative gap between structural components, etc., and the quantitative evaluation of EM loads applied to the containment structures has not been completed yet. For this reason, the mechanical behavior of ITER outboard blanket was analyzed by using simplified FEM models and loading conditions.

The major objectives of the analysis are as follows;

a) to examine the effects of support conditions and reinforcement ribs on stress and deformation of outboard blanket box structure under EM loads due to plasma disruption

b) to obtain the implications to mechanical design of outboard blanket against EM loads

(2) Basic FEM Model

The basic FEM model of ITER outboard blanket is shown Fig. III.4-26. The side module of the outboard blanket is modeled by a simple box structure composed of 500 shell elements. The model has a rectangular cross section of 1 m square and length of 10 m. The plate thicknesses of FEM model are, 15 mm for first wall, 30 mm for side plates, 50 mm for rear panel and 30 mm for top and bottom wall.

(3) Support Conditions

In order to obtain the technical implications on the support structure between adjacent modules and components, four kinds of support conditions listed below are employed for the analysis;

a) full constraint of rear panel

b) three lines of rear panel constraint (both side edges and center from top to bottom)

c) two lines of rear panel constraint (both side edges from top to bottom)

Four support conditions are schematically shown in Figs III.4-27 and III.4-28.
(4) Reinforcement Ribs
In addition to the analysis by using the basic model, the three types of reinforcement ribs shown in Fig. III.4-29 were modeled and analyzed.

Regarding the reinforcement ribs, the conditions of the analysis are summarized as follows;

a) No reinforcement rib
b) Lateral ribs of 30 mm thickness, 1 m interval
c) a) and a toroidal longitudinal rib, 400 mm from rear panel
d) b) and radial longitudinal rib, center in toroidal direction

In order to simplify the analysis, the thickness of 30 mm is assumed for all ribs.

(5) Loading Conditions
The three simplified patterns of EM loads on the side wall were employed for the analysis. The EM forces on first wall and rear panel were neglected. The characteristics of each loading conditions are as follows;

a) Vertical EM force: $F_V$ which is uniformly distributed on both side walls, totally 10 MN for a quarter
b) Radial EM load: $F_R$ which is distributed on side wall, totally 10 MN for a quarter
c) Combination of $F_V$ and $F_R$

These loading conditions are shown in Fig. III.4-30.

(6) Results
The maximum displacement and the Tresca stress obtained by a series of analysis are summarized in Figs III.4-31 and III.4-32. From the viewpoint of reducing the displacement and stress due to EM loads, the effects of support conditions and reinforcement ribs are summarized as follows;

a) Regarding the support conditions, the side wall support is the most effective condition. Three different support conditions of rear panel do not show any difference.
b) Lateral ribs are effective against the EM loads in the radial direction. But they are not effective against the vertical EM loads.
c) Longitudinal ribs are effective against the EM loads in the verti-
cal direction and not so effective to radial EM loads.

d) The maximum displacement and the Tresca stresses calculated by a series of analysis are in the range of 0.16-0.33 mm. and 5.5-11.0 kg/mm², respectively.

Table III.4-1 Assumption for plasma disruption scenario

<table>
<thead>
<tr>
<th>Time after Current Decay (msec)</th>
<th>Plasma Current</th>
<th>Plasma Location</th>
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<tr>
<td></td>
<td>I_p (m)</td>
<td>a_p (m)</td>
</tr>
<tr>
<td>0.0</td>
<td>22.0</td>
<td>2.2</td>
</tr>
<tr>
<td>0.1</td>
<td>22.0</td>
<td>2.2</td>
</tr>
<tr>
<td>5.0</td>
<td>17.0</td>
<td>1.93</td>
</tr>
<tr>
<td>11.0</td>
<td>11.0</td>
<td>1.50</td>
</tr>
<tr>
<td>18.0</td>
<td>4.0</td>
<td>0.90</td>
</tr>
<tr>
<td>20.0</td>
<td>2.0</td>
<td>0.66</td>
</tr>
<tr>
<td>22.0</td>
<td>0.0</td>
<td>0.00</td>
</tr>
<tr>
<td>100.0</td>
<td>0.0</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Table III.4-2  Total electromagnetic load of each structural component due to plasma disruption (1/16 sector, at 22.0 msec after disruption)

<table>
<thead>
<tr>
<th>Component</th>
<th>1/32 Right</th>
<th>1/32 Left</th>
<th>Total (1/16 sector)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum Vessel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF (MN)</td>
<td>- 20.23</td>
<td>- 22.68</td>
<td>- 42.91</td>
</tr>
<tr>
<td>FY (MN)</td>
<td>- 2.98</td>
<td>3.13</td>
<td>0.15</td>
</tr>
<tr>
<td>FZ (MN)</td>
<td>7.72</td>
<td>- 8.81</td>
<td>1.09</td>
</tr>
<tr>
<td>Fixed Blanket</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FR (MN)</td>
<td>- 1.29</td>
<td>7.08</td>
<td>5.79</td>
</tr>
<tr>
<td>FY (MN)</td>
<td>0.32</td>
<td>- 0.99</td>
<td>- 0.67</td>
</tr>
<tr>
<td>FZ (MN)</td>
<td>- 9.51</td>
<td>8.82</td>
<td>- 0.69</td>
</tr>
<tr>
<td>Outboard Center Module</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FR (MN)</td>
<td>3.07</td>
<td>- 3.47</td>
<td>- 0.40</td>
</tr>
<tr>
<td>FY (MN)</td>
<td>7.16</td>
<td>- 6.94</td>
<td>0.22</td>
</tr>
<tr>
<td>FZ (MN)</td>
<td>- 27.93</td>
<td>27.74</td>
<td>- 0.19</td>
</tr>
<tr>
<td>Outboard Center Module</td>
<td></td>
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<tr>
<td>FR (MN)</td>
<td>1.11</td>
<td>0.93</td>
<td>2.04</td>
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<tr>
<td>FY (MN)</td>
<td>0.52</td>
<td>0.24</td>
<td>0.76</td>
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<tr>
<td>FZ (MN)</td>
<td>0.002</td>
<td>- 0.0035</td>
<td>- 0.0015</td>
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<tr>
<td>Inboard</td>
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</tr>
<tr>
<td>FR (MN)</td>
<td>- 0.163</td>
<td>- 0.0044</td>
<td>- 0.167</td>
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<tr>
<td>FY (MN)</td>
<td>0.298</td>
<td>0.0102</td>
<td>0.400</td>
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<tr>
<td>FZ (MN)</td>
<td>- 0.065</td>
<td>- 0.052</td>
<td>- 0.0013</td>
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Table III.4-3 Comparison of thin double-wall vacuum vessel for the FER and ITER

<table>
<thead>
<tr>
<th></th>
<th>FER</th>
<th>ITER</th>
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<tr>
<td>1. Plasma Current (MA)</td>
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<td>22</td>
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<td>2. Plasma Center</td>
<td>4.7</td>
<td>6.0</td>
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<tr>
<td></td>
<td>Radius (m)</td>
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</tr>
<tr>
<td>3. Electromagnetic</td>
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<tr>
<td>Load due to Plasma</td>
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<td></td>
</tr>
<tr>
<td>Disruption</td>
<td>(1/12 Sec.)</td>
<td>(1/16 Sec.)</td>
</tr>
<tr>
<td>FR : Radial (MN)</td>
<td>- 20.0</td>
<td>- 42.9</td>
</tr>
<tr>
<td>FZ : Vertical (MN)</td>
<td>- 5.0</td>
<td>- 1.1</td>
</tr>
<tr>
<td>4. Thickness</td>
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<td></td>
</tr>
<tr>
<td>Total (mm)</td>
<td>120.0</td>
<td>150.0</td>
</tr>
<tr>
<td>Membrane (mm)</td>
<td>26.0</td>
<td>30.0</td>
</tr>
<tr>
<td>Port Area (mm)</td>
<td>26.0</td>
<td>100.0 (Solid)</td>
</tr>
<tr>
<td>5. Bending Inertia</td>
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<tr>
<td>per unit length</td>
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<td></td>
</tr>
<tr>
<td>(mm$^4$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Model 1</td>
<td>1.46$x10^3$</td>
<td>2.25$x10^3$</td>
</tr>
<tr>
<td>b) Model 2</td>
<td>7.48$x10^4$</td>
<td>1.37$x10^5$</td>
</tr>
<tr>
<td>6. Maximum Displacement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(in radial direction)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Model 1</td>
<td>21.4 mm</td>
<td>16.1 mm</td>
</tr>
<tr>
<td>b) Model 2</td>
<td>6.2 mm</td>
<td>10.8 mm</td>
</tr>
<tr>
<td>7. Maximum Tresca Stress</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Model 1</td>
<td>370 MPa</td>
<td>246 MPa</td>
</tr>
<tr>
<td>b) Model 2</td>
<td>146 MPa</td>
<td>205 MPa</td>
</tr>
</tbody>
</table>
Fig. III.4-1 Model of vacuum vessel
Fig. III.4-2 Model of outboard blanket
Fig. III.4-3  Electromagnetic force acting on vacuum vessel (gap: 10mm)
Fig. III.4-4 Electromagnetic force acting on center module of outboard blanket (with vacuum vessel) (gap: 10mm)
Fig. III.4-5 Electromagnetic force acting on side module of outboard blanket (with vacuum vessel) (gap: 10mm)
Fig. III.4-6 Electromagnetic force acting on vacuum vessel (gap: 30mm)
Fig. III.4-7  Electromagnetic force acting on vacuum vessel (gap: 30mm)
Fig. III.4-8 Electromagnetic force acting on center module of outboard blanket (with vacuum vessel (gap: 30mm)
Fig. III.4-9 Electromagnetic force acting on side module of outboard blanket (with vacuum vessel) (gap: 30mm)
Fig. III.4-10 Total EM load (in MN) on a quarter of center and side modules of outboard blanket (gap: 10mm)
Fig. III.4-11 Total EM load (in MN) on a quarter of center and side modules of outboard blanket (gap: 30mm)
Fig. III.4-12 Typical cross section of the ITER vacuum vessel

DIMENSIONS SHOWN ARE AT OPERATING TEMPERATURE OF THE COMPONENTS
Fig. III.4-13 Finite element model of the ITER vacuum vessel (1/16 sector is modeled for cyclic symmetry)
Fig. III.4-14 Time variation of electromagnetic load in the 1/16 sector of vacuum vessel after plasma disruption

Fig. III.4-15 Time variation of electromagnetic load in the 1/16 sector of fixed blanket after plasma disruption
Fig. III.4-16 Time variation of electromagnetic load in the 1/16 sector of outboard center-module after plasma disruption

Fig. III.4-17 Time variation of electromagnetic load in the 1/16 sector of outboard side-module after plasma disruption
Fig. III.4-18 Time variation of electromagnetic load in the 1/16 sector of inboard after plasma disruption
Fig. III.4-19 Deformation of ITER vacuum vessel due to plasma disruption calculated by using Model 1
Fig. III.4-20  Deformation of ITER vacuum vessel due to plasma disruption calculated by using Model 1
Fig. III.4-21 Deformation of ITER vacuum vessel due to plasma disruption calculated by using Model 2

Max. Disp. 10.8 mm
Fig. III.4-22 Deformation of ITER vacuum vessel due to plasma disruption calculated by using Model 2.
Fig. III.4-23 Contour of constant Tresca stress in the ITER vacuum vessel due to plasma disruption calculated by using Model 1.

Max. Tresca Stress
246 MPa
Model 2

Contour Level
1. 1.ET
2. 2.ET
3. 5.ET
4. 7.ET
5. 9.ET
6. 1.00E8
7. 1.20E8
8. 1.50E8
9. 1.70E8
10. 1.90E8

Max. Tresca Stress
205 MPa

Fig. III.4-24 Contour of constant Tresca stress in the ITER vacuum vessel due to plasma disruption calculated by using Model 2
Fig. III.4-25 Contour of constant von Mises stress in the ITER vacuum vessel due to plasma disruption calculated by using Model 2
Fig. III.4-26 Basic FEM model of ITER outboard blanket side module
(a) Full constraint of Rear Panel

(b) 3 lines of Rear Panel constraint (both side edges and center line from top to bottom)

Fig. III.4-27 Support condition of FEM model (1)

(c) 2 lines of side wall constraint (0 and 400 mm from rear side edge from top to bottom)

(d) 2 lines of rear panel constraint (both side edges from top to bottom)

Fig. III.4-28 Support condition of FEM model (2)
(A) No reinforcement (B) Lateral ribs of 30mm, 1 m interval
(C) B and toroidal longitudinal rib, 400 mm from rear panel
(D) C and radial longitudinal rib center in toroidal direction

Fig. III.4-29 Concepts of reinforcement ribs

a) Vertical EM Load: $F_v$ uniformly distributed on side plates
b) Radial EM Load: $F_R$ distributed on side plates
c) Combination of $F_v$ and $F_R$

Fig. III.4-30 Loading conditions of the EM force
Fig. III.4-31 The maximum displacements obtained by a series of FEM analysis

Fig. III.4-32 The maximum Tresca stress obtained by a series of FEM analysis
III.5 Assembly scheme for alternative VV[2]

Alternate concept for the design and assembly of the vacuum vessel has been studied by Japanese teams. The design uses double thin walls to simultaneously obtain the required toroidal resistance and the double all welded vacuum/tritium boundary. This concept split the vacuum vessel toroidally into only 16 equal sectors, versus the 16 parallel and 16 wedge sectors of the reference concept. In this segmentation scheme the required field joint in the midplane between the TF coils, and toroidally bisects the ports. In this concept, each vacuum vessel sector is installed into the bore of a TF Coil and assembled into its installed position with the TF Coil.

In addition to the configuration/structural advantages discussed in section 3, this concept has features which can be beneficial to Assembly and Maintenance.
- Fewer, lighter pieces must be handled
- Fewer field joints
- Fit up tolerances at assembly are less severe since sections are welded (i.e. no bolts or shear keys)
- The interspace between walls, usually used for cooling passages, can be evacuated and used for leak checking of the two walls independently while still in the workshop. Since the field joints used to connect adjacent sectors contains independent inner and outer splice plates, a similar void area is formed that can also be used for leak checking. This means that individual vacuum vessel sectors can be leak checked without having a complete toroidal assembly.

(1) Installation of alternate thin double wall VV concept
The steps required to assemble the vacuum vessel are shown Figs III.5-1 to III.5-2.
1) The assembly unit of a TF coil, 1/16 of the vacuum vessel, and a 15.5 degree sector of permanent shield is preassembled.
2) The units are sequentially installed onto the machine support structure.
3) The vacuum vessel sectors are aligned and welded together, inner and outer walls, in the gaps of the shield sectors.
4) The 7 degree sectors are installed to complete the torus and welded.
5) The cooling pipes connecting the 7 degree sectors to the 15.5 degree sectors are installed.

6) Continue the machine assembly as in the reference case.

(2) Initial Assembly of reactor and On-site Testing of SC Coils and VV

The one-site TF and PF coil testing under cryogenic temperature should be performed to find out the initial failure of the magnet and replace the module because some troubles in the magnet are possibly foreseen. The replacement of the magnet, however, suffers from many drawbacks if the connection of the vacuum vessel and port has been completed.

Here proposed are an assembly procedure to have priority on purging the magnet system of the initial failure and making replacement of the magnet module easy, that consequently is preferable for the Containment Structure design, manufacturing and construction. The coil test is carried out by evacuating cryostat vessel and cooling down the magnet system to the cryogenic temperature. The penetrations of the cryostat vessel are covered by the temporary caps to plug them. After the coil test, the VV sectors and ports are connected together. Then the final leak test is performed to check the total outgassing characteristics of the vessel (see Fig. III.5-3).

1. SHOP PREPARATION

1.1 Vacuum vessel sector leak test by evacuating the gap between inner and outer skins.

1.2 Pre-assemble of a TF coil and a vacuum vessel sector including the shield module inside.

1.3 Pre-assemble of the center solenoid.

1.4 Pre-assemble of the EF coil units.

2. ON-SITE PREPARATION

2.1 Construct the cylindrical wall of the cryostat vessel.

2.2 Settle the base plate and generate a levelled reference plane to start assembly.

2.3 A temporary center column is installed on the support frame fixed in the lower hole in order to make a reference pole for assembly.
2.4 The gravity supports of the TF coil and the VV are positioned on the base plate.

2.5 Generate the aligned and levelled reference surface on the top of the supports for further assembly and reassembly procedure.

3. INSTALLATION OF THE TF COIL AND VV

3.1 Start installation of the assembly unit composed of TF coil VV and permanent shield.

3.2 Proceed with assembling.

3.3 Proceed with assembling.

3.4 Complete installation of the TF coil and VV assembly.
   (1) The TF coils are temporarily bound together.
   (2) The VV segments are temporarily fastened together and settled on the gravity support.

4. CENTER SOLENOID AND EF COILS ASSEMBLY

4.1 Remove the temporary center column and its support frame.

4.2 Fasten the TF coils by keys with access from the torus center.

4.3 Install the center solenoid and fix it to the TF coils.

4.4 Connect the TF coils on the outboard side by the inter-coil-structure.

4.5 The upper and lower PF5 coils are assembled from the top and bottom of the reactor hall.

4.6 Put down the lower PF6 and PF7 coil unit and support it briefly.

4.7 Get down the upper PF6 and PF7 coil unit, connect it with the lower unit and fix the outer EF coil assembly to the TF coils by center pins.

5. COIL TESTING

5.1 Connect the coil services (bus bars and cryogenic supply). Lay down the upper frame of the cryostat vessel.

5.2 Provide the vacuum and cryogenic temperature.
   (1) Cover the penetration holes with upper trapezoidal plates and temporary cap flanges.
   (2) Seal the flanges and evacuate inside the cryostat
(3) Cool down the coils to the cryogenic temperature.
(4) Carry out the coil tests such as electrical insulation check, current flow test.
(5) Replace a coil unit if failure is found.

6. VACUUM VESSEL ASSEMBLY
   6.1 Double wall vessel connection
      (1) Warm up the magnets and open the cryostat vacuum by removing the temporary flanges and supper cover plates.
      (2) Weld the outer skin of the double-wall-vessel trough the gap between the shield segments.
      (3) Weld the inner skin of the vessel and perform vacuum leak test of the joint parts by evacuating the void between walls.
      (4) Temporary connectors of the VV segments are removed.
      (5) Install the parallel pieces of the shield structure.

   6.2 Connect the shield segments to generate the in-vessel rigid torus structure.
   6.3 Install the upper vertical ports.
   6.4 Connect the upper ports by stiff weld or mechanical joint + seal weld.
   6.5 Connect the extensions of the ports by mechanical joint + seal weld.
   6.6 Plug the ports by temporary cover flanges and perform the final leak check and total outgassing test of the vacuum vessel.

7. ACCOMPLISHMENT OF THE MACHINE ASSEMBLY
   7.1 Internal components installation
      (1) Remove the temporary flanges.
      (2) Install the internal components, which are in-vessel active control coils, blanket modules, divertor plates, by the remote maintenance equipment.

   7.2 Cover the upper ports by the plates with vertical extension ports.
   7.3 Put down the upper frame and the trapezoidal cover of the cryostat.
**Fig. III.5-1** Assembly of vacuum vessel/shield (1)

**Fig. III.5-2** Assembly of vacuum vessel/shield (2)
ON-SITE PREPARATION

Construct the cylindrical wall of the cryostat vessel.

Settle the base plate and generate a levelled reference plane to start assembly.

A temporary center column is installed on the support frame fixed in the lower hole in order to make a reference pole for assembly.

Fig. III.5-3 (a) Initial assembly of reactor structure
The gravity supports of the TF coil and the VV are positioned on the base plate.

Generate the aligned and levelled reference surface on the top of the supports for further assembly and reassembly procedure.

Start installation of the assembly unit composed of TF coil, VV and permanent shield.

Proceed with assembling.

Fig. III.5-3 (b) Initial assembly of reactor structure
Proceed with assembling.

Complete installation of the TF coil and VV assembly.
(1) The TF coils are temporarily bound together.
(2) The VV segments are temporarily fastened together and settled on the gravity support.

Remove the temporary center column and its support frame.

Fig. III.5-3 (c) Initial assembly of reactor structure
Fasten the TF coils by keys with access from the torus center.

Install the center solenoid and fix it to the TF coils.

Connect the TF coils on the outboard side by the inter-coil-structure.

Fig. III.5-3 (d) Initial assembly of reactor structure
The upper and lower PF5 coils are assembled from the top and bottom of the reactor hall.

Put down the lower PF6 and PF7 coil unit and support it briefly.

Get down the upper PF6 and PF7 coil unit, connect it with the lower unit and fix the outer EF coil assembly to the TF coils by center pins.

Fig. III.5-3 (e) Initial assembly of reactor structure
COIL TESTING

Connect the coil services (bus bars and cryogenic supply). Lay down the upper frame of the cryostat vessel.

Provide the vacuum and cryogenic temperature.

1. Cover the penetration holes with upper trapezoidal plates and temporary cap flanges.
2. Seal the flanges and evacuate inside the cryostat vessel.
3. Cool down the coils to the cryogenic temperature.
4. Carry out the coil tests such as electrical insulation check, current flow test.
5. Replace a coil unit if failure is found.

Fig. III.5-3 (f) Initial assembly of reactor structure
Double wall vessel connection

1. Warm up the magnets and open the cryostat vacuum by removing the temporary flanges and upper cover plates.

2. Weld the outer skin of the double-wall-vessel through the gap between the shield segments.

3. Weld the inner skin of the vessel and perform vacuum leak test of the joint parts by evacuating the void between walls.

4. Temporary connectors of the VV segments are removed.

5. Install the parallel pieces of the shield structure.

Connect the shield segments to generate the in-vessel rigid torus structure.

Install the upper vertical ports.

Fig. III.5-3 (g) Initial assembly of reactor structure
Connect the upper ports by stiff weld or mechanical joint + seal weld.

Plug the ports by temporary cover flanges and perform leak test of the vacuum vessel.

Connect the extensions of the ports by mechanical joint + seal weld.

Fig. III.5-3 (h) Initial assembly of reactor structure
Internal components installation
(1) Remove the temporary flanges.
(2) Install the internal components, which are in-vessel active control coils, blanket modules, divertor plates, by the remote maintenance equipment.

Put down the upper frame and the trapezoidal cover of the cryostat.

Cover the upper ports by the plates with vertical extension ports.

Fig. III.5-3 (i) Initial assembly of reactor structure
III.6 Machine Gravity Support[2]

The total dead weight of the ITER basic machine is estimated to be around 26,000 ton, which should be sustained by the machine gravity support under all load conditions including the event of an earthquake. Since the machine gravity support is the key reference frame of the whole basic device assembly, several concepts and possible locations were proposed and discussed. As a result, the following general concept was tentatively chosen for the purpose of machine integration and the final choice will be made in the next design phase based on detailed analysis:

1) The Poloidal Field (PF) coils are attached to the Toroidal Field (TF) coils and therefore the dead weight of all magnet system is supported by the TF gravity support.

2) All dead weight of in-vessel components is transmitted to and supported by the vacuum vessel gravity supports which are independent from the magnet gravity supports because of different operating temperature. Electromagnetic loads from a plasma disruption are not transmitted to the magnet and vacuum vessel gravity supports except net vertical loads.

3) The vacuum vessel gravity supports and magnet gravity supports are located below TF coils in the 16 trapezoidal zones between an inner radius of 7.0 m and an outer radius of 10 m with toroidal clearance is about 1.4 m for providing sufficient access to the center of the machine and to lower divertor maintenance area.

4) The flexible multi-plate structure without any mechanical kinetics was adopted for providing high reliability and absolute reference point for the machine assembly (i.e. the magnet system and vacuum vessel must be free to expand or contract radially due to temperature changes, but all components must remain good concentric to the common machine vertical axis.).

Based on this general configuration, the structural design for both, magnet system and vacuum vessel gravity supports, was performed. The key design concepts proposed by Japan team are summarized in Table III.6-1 and Figs III.6-1 to III.6-3.
Table III.6-1 Flexible support with spring plates for TF magnet and vacuum vessel

[Requirements]

<table>
<thead>
<tr>
<th></th>
<th>TF magnet</th>
<th>Vacuum vessel</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Load</td>
<td>100 MN</td>
<td>120 MN (dead weight)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80 MN (magnetic force)</td>
</tr>
<tr>
<td>b. flexibility</td>
<td>15 mm</td>
<td>21 mm</td>
</tr>
</tbody>
</table>

[Key features]

a. A flexible structure with spring plates is proposed since the gravity support provides the reference surface for assembly/disassembly and high reliability is required.

b. The gravity supports of TF magnet and vacuum vessel are located under the TF magnet in R=4.8 to R=9 m, so as to keep piping space and maintenance area between TF magnets.

[Structure design]

<table>
<thead>
<tr>
<th></th>
<th>TF magnet</th>
<th>Vacuum vessel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring plate</td>
<td>t = 100 mm</td>
<td>t = 100 mm</td>
</tr>
<tr>
<td></td>
<td>w = 700 mm</td>
<td>w = 700 mm</td>
</tr>
<tr>
<td></td>
<td>l = 4268 mm</td>
<td>l = 2700 mm</td>
</tr>
<tr>
<td></td>
<td>n = 15</td>
<td>n = 15</td>
</tr>
<tr>
<td>Compression stress</td>
<td>6 MPa</td>
<td>15 MPa</td>
</tr>
<tr>
<td>Bending stress</td>
<td>16 MPa</td>
<td>69 MPa</td>
</tr>
<tr>
<td>Buckling factor</td>
<td>56</td>
<td>39</td>
</tr>
<tr>
<td>Bending stress (0.3G)</td>
<td>132 MPa</td>
<td>120 MPa</td>
</tr>
<tr>
<td>Heat lead at 4 K</td>
<td>3 kW</td>
<td></td>
</tr>
</tbody>
</table>
Fig. III.6-1 Basic layout of gravity support
Fig. III.6-2 Details of TF magnet support
Fig. III.6-3 Details of vacuum vessel support
III.7 Blanket Attaching Locks

The design of the attaching locks system for the internal removable components is a critical issue that is still open. According to the design requirements described in [1], the attaching locks should be capable of providing sufficient mechanical stiffness, flexibility, maintainability, and tolerance of nuclear radiation.

For this purpose, five different locking systems have been proposed and discussed [1]. It may be possible to select different attaching locks system for inboard and outboard region due to differences in space, access available, and maintenance procedures. However, no reference solution was selected because several solutions proposed only partially satisfy the requirements and there are large uncertainties in the present data base on technological and material properties as well as feasibility and reliability.

Finally, the bolt-to-bolt welded connector was tentatively chosen as a first option for the purpose of design integration [1], but the selection of reference structure will be made in the next design phase (Engineering Design Phase) based on the R&D results and detailed analysis of all of these concepts.

III.7-1 General approach

(1) General concept

There are three basic design concepts for supporting the blanket/shield modules in the machine. The first is to connect each segment directly to the vacuum vessel and assume that the vessel can carry the resultant loads. A second concept is to carry certain local loads into the vacuum vessel and to react other loads directly between adjacent segments. The third support concept is to tie all the blanket/shield segments together to form an independent structural assembly. Only the net non-compensated vertical load on the blanket/shield assembly would be carried back through the vacuum vessel into the machine gravity support. In general, the third concept (independent support) is preferable to others and the independent support has the following advantages:

1) The vacuum vessel can be much simpler structurally and less accurate dimensionally, since the locations of the blanket/shield
segments are not referenced from the vacuum vessel.

2) Failures from fault loading should not impact the vacuum vessel. If a failure occurs in the blanket/shield structure due to an unexpected electromagnetic or thermal load, it can be repaired or replaced independent of the vacuum vessel. Protecting the vacuum vessel also prevents breaching the tritium barrier.

3) The inherent thermal mismatch between the vacuum vessel and the blanket/shield segments will not be constrained.

4) The vacuum vessel and blanket/shield structure can be analyzed separately.

(2) Vertical load connection

The net vertical load on the blanket/shield segment assemblies must still be carried through the vacuum vessel into the machine gravity support. The vertical connection is made at the bottom of the machine for two reasons. First, in a remote environment, it is probably easier to set a large blanket/shield structure on a shelf than to hang it from a vertical surface. Second, the local path through the vacuum vessel is more direct for both gravity and disruption type loads.

(3) Segment to segment connection

The connection between the blanket/shield segments is the key and the following basic features are desirable:

1) Standard connectors of the same design should be used wherever possible instead of custom connectors at each location. This should provide a better chance of developing remote tooling for assembly and disassembly.

2) Multiple connectors of modest size should be used instead of a few large connectors for two reasons. First, this allows the possibility of operating with one or two connectors improperly installed or broken. Using only a few connectors would probably mean that every one must be functioning correctly. Second, the blanket/shield structure may not be capable of carrying high local loads from a few connectors, but would be more compatible with the distributed load from many connectors.

3) Connectors must have some means of providing assembly clearance during the initial placement of the segments. The size and mass of the segments will make them difficult to handle with precision.
4) Connectors should have a backup method of replacement if primary method fails.

5) Connectors should be located far enough from the plasma to avoid excessive nuclear heating and damage.

III.7-2 Hydraulic connectors[2]

(1) Concept description

The hydraulic connectors proposed by Japan team basically consist of a movable wedge with hydraulic driving system. The hydraulic driving system has flexible part for providing reversible movement for the wedge by changing the cooling water pressure. For example, the wedge is extended to provide locking forces for the blanket segments in the normal operation and is shrunk to provide unlocking and clearance between segments during maintenance. This system has the following advantages:

1) The assembly/disassembly procedure of the blanket segments is very simple since locking/unlocking of this system can be done only by changing the cooling water pressure.

2) This system can basically provide no gaps between the blanket segments during normal operation, so that it is expected to have high mechanical stiffness against the electromagnetic forces due to sufficient surface contact and there are no large forces transmitted to the vacuum vessel and to the hydraulic driving system during disruption.

3) This system provides better nuclear shield because of no streaming effect in comparison with welded bolt and mechanical bolting connectors. In addition, this system ensures the cooling of nuclear heating by means of the same pressurized water which drives the system, that means, no additional cooling circuit is required.

4) The wedge surfaces are coated with an oxide layer or anodized to provide electrical insulation break between the adjacent blanket segments.

5) This can be a remotely operated system, located behind the blanket, that does nor required any access to the vacuum vessel or any hole or gaps in the first wall for remote tools to reach the locking system.
The driving mechanism is the key of this system and two different types of driving systems, as schematically shown in Fig. III.7-1 were proposed and discussed. Their key features are described below.

1) Flexible tube type: This is based on use of thin wall pipes with non-circular cross-section and can be capable of providing elastic displacement in both directions (expansion and compression) by changing the internal pressure of cooling water. This system provides a good locking effect by pushing wedges in wide surface area to fix the segments. However, stroke of wedges is limited in a range of 10-20 mm and the reliability of thin tube should be demonstrated.

2) Jack type: This is based on use of hydraulic piston with bellows and the piston can be moved in both direction by adjusting the pressure difference of both sides of the piston. This system can provide a sufficiently long stroke, but the fixing forces are limited by the number of these systems installed in the blanket segment. The main concern refers to the reliability of the bellows.

Flexible tube type: Figs III.7-2 and III.7-3 shows a typical example of hydraulic locking system with flexible tube for the outboard blanket segments and its location. Movable wedges driven by cooling water are installed in the center segment. Three blanket segments (center and 2 lateral segments) are attached to the vacuum vessel by support rails and their relative position can be fixed. For normal operation, the wedges of the locking system are extended to push the center segment in radial direction and the adjacent lateral segments in toroidal direction, so that three segments can be tightly connected due to combination between the driving forces produced by wedges and the reacting forces at the support rails. In addition, the driving forces eliminate clearance between adjacent segments due to radial movement of the center segment, resulting in good surface contact against the electromagnetic loads. In case of maintenance, the wedges are moved in the opposite direction in order to provide unlocking and clearance between the adjacent blanket segments. If a longer stroke is needed, the hydraulic jack system described below can be applied for a driving mechanism instead of the flexible tube.

Hydraulic jack type: Fig. III.7-4 shows the proposed solution with hydraulic jack for locking the inboard blanket segments. The blanket
segment is attached to the vacuum vessel through a hook located in the upper part of the blanket. The main function of this hook is to support the weight of the blanket and seismic and electromagnetic vertical forces. The hook, which is part of the back plate of the blanket, fits in a slot machined in the protruding part of poloidal ribs of the vacuum vessel. Once the blanket is installed on its support, two pins actuated by the water hydraulic jacks engage in hole machined laterally on the support of the vacuum vessel. The bellows must be long enough to get 70-100 mm of stroke, therefore, to gain length, it is necessary to locate two bellows one inside to the other separated by a pipe which divides the two chambers of the double-acting cylinder. In this solution, the blanket segment is constrained also in toroidal direction. That means that at least the supporting points must follow the movements of the vacuum vessel; therefore, any change in the toroidal dimension of the segment (differential thermal expansion) is kept by the gap between blankets. The lower stop which is located in the middle of the width of the segment allows vertical and lateral expansion of the segment keeping always the centered position. Figs III.7-5 and III.7-6 shows the typical hydraulic jack system which was fabricated as a first step of the hydraulic locking system development and whose basic performances were measured. It was demonstrated that this hydraulic jack can produce fixing force in proportion to the internal water pressure and the maximum force of 17.5 ton with a stroke of 25 mm appears at 100 bar. The life time of bellows was about 200 cycles under the cyclic pressure loading from 0 to 100 bar with a stroke of 25 mm. These results shown in Table III.7-1 seem to be sufficient for the pressure design condition from thermomechanical point of view, since the fixing force of a few ton per hydraulic jack is large enough to sustain the electromagnetic load and number of locking/unlocking operation is limited only for assembly/disassembly of the blanket segments. If more stroke is required, bellows can be connected in series.

(2) Concept evaluation

The hydraulic connectors meet the primary requirements for the blanket locking system. A comparisons with other locking systems are shown in Table III.7-2. An evaluation of the concept with respect to the main requirements are as follows:
Function: The hydraulic connectors structurally attach the blanket/shield segments to each other. Only vertical loads (gravity and residual electromagnetic loads) are transmitted to the vacuum vessel.

Mechanical loads: The electromagnetic loads from a plasma disruption are reacted directly between adjacent blanket/shield segments through the contracted surface of the segment and wedges of the locking system. Therefore, lower number of wedges than the welded bolt concept should be enough to sustain the electromagnetic loads. There are no direct electromagnetic loads applied to the hydraulic driving system (flexible tube and bellows) during disruption and only internal pressure should be supported by itself. The induced loads from relative thermal expansion of adjacent blanket/shield segments can be adjusted in case of hydraulic jack concept but these loads should not be considered as a normal operation as mentioned in the welded bolt concept.

Thermal loads: This system can be cooled by the same pressurized water which drives the system without any additional cooling supply.

Fault loads: The blanket/shield segments are tightly connected each other independently from the vacuum vessel. Therefore, a major fault should not cause a breach of the tritium barrier even in the worst case.

Fatigue life and reliability: This system includes mechanically movable part such as flexible tube and bellows, which should have high reliability including fatigue characteristic required for the ITER operation. In this concept, fortunately, electromagnetic loads do not directly apply to the movable part, resulting in a less critical issue. The maximum loads are from the internal pressure during locking/unlocking procedure for the blanket assembly/disassembly. The frequency of maintenance of the blanket/shield segment is low enough, probably once a lifetime, according to the present design requirement. Therefore, it can be concluded that the fatigue life of this locking system can be manageable but should be demonstrated.

As for reliability, there are a number of connectors installed in the blanket/shield segments, so that a reasonable number of redundant connectors and water circuits can be provided if a poor or failed connection occurs.
Radiation damage: The radiation damage in this system is not critical because hydraulic locking system is fully metallic structure and no rewelding is necessary for assembly/disassembly of the blanket/shield segments.

Compatibility with high vacuum: The connector system can be cleaned and baked to the same temperature as the blanket/shield segments. In addition, no outgassing from the connectors can be expected. In case of flexible tube concept, however, no gap between the adjacent segments is available, which is inconsistent with the vacuum conductance requirements.

Compatibility with remote handling: This connector is a fully remote-operated system and special tools for locking/unlocking of the connectors are not required.

Blanket/shield segments positioning: The positioning and geometric tolerance of the blanket/shield segments are a critical issue and the connectors should allow at least misalignment of around 10 mm.

Minimum gaps between blanket/shield segments: The gaps between the adjacent blanket/shield segments are not necessary for locking/unlocking the connectors and sufficient nuclear shield for TF coil can be provided because of no streaming effect.

(3) Primary concerns

Four primary problems exist with the hydraulic connector and should be qualified with some modification and R&D results in the next design phase:

1) Allowable geometric tolerance and alignment for the connector should be clarified by scalable model testing.

2) Reliability including fatigue limits of the movable parts such as flexible tube and bellows should be investigated under the certain design condition; it is possible to increase the reliability with double seal structure for the movable part.

3) In case of failure of the connector, possible back-up scheme should be qualified; it may be possible to cut the wedges by cutter ac-
cessing from the enlarged gaps between the adjacent segments.

4) There are a large number of cooling/pressure lines and connectors. Four connectors are required for each hydraulic jack.

Table III.7-1 Performance test results for hydraulic jack

<table>
<thead>
<tr>
<th>Material</th>
<th>Leakage (cc/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
</tr>
<tr>
<td>Graphite</td>
<td>4000</td>
</tr>
<tr>
<td>Mn Bronze</td>
<td>680</td>
</tr>
<tr>
<td>Ni Based SA</td>
<td>800</td>
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</tbody>
</table>

Table III.7-2 Comparison of the locking systems

<table>
<thead>
<tr>
<th></th>
<th>weld connection</th>
<th>liquid metal</th>
<th>hydraulic system</th>
</tr>
</thead>
<tbody>
<tr>
<td>connector approach</td>
<td>blanket-to-blanket</td>
<td>blanket-to-VV</td>
<td>both</td>
</tr>
<tr>
<td>uncertainty</td>
<td>edge preparation/inspection</td>
<td>material/heating</td>
<td>little</td>
</tr>
<tr>
<td>reliability</td>
<td>low for welds</td>
<td>low for heater</td>
<td>low for driving mechanism</td>
</tr>
<tr>
<td>nuclear heating</td>
<td>problem</td>
<td>removable</td>
<td>removable</td>
</tr>
<tr>
<td>locking unlocking</td>
<td>difficult</td>
<td>easy</td>
<td>easy</td>
</tr>
<tr>
<td>back-up scheme for system accident</td>
<td>essentially not required</td>
<td>required</td>
<td>required</td>
</tr>
</tbody>
</table>
Basic Concept: Cotter + Hydraulic Driving Mechanism

<table>
<thead>
<tr>
<th>Hydraulic Driving Mechanism (Feature)</th>
<th>Flexible Tube Type</th>
<th>Bellows Type</th>
<th>Jack Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1. Strong Driving Force</td>
<td>Intermediate</td>
<td>Long Stroke</td>
</tr>
<tr>
<td></td>
<td>2. Simple Mechanism</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. III.7-1 Hydraulic locking approach
Fig. III.7-2 Hydraulic cotter in outboard blanket
Fig. III.7-3 Hydraulic cotter layout
Support Rail

Hydraulic Cotter

INBOARD BLANKET

Fig. III.7-4 Hydraulic cotter in inboard blanket
**Major Dimensions of The Jack**

1. total length : 260 mm  
2. outer dia. : 170 mm  
3. piston stroke : 25 mm  

**Bellows Spec.**

1. double walled welding bellows  
2. outer dia./inner dia. : 93mm/66mm  
3. thickness : 0.3mm/each  
4. convolution : 30  
5. material : Ni based superalloy  

**Piston Ring Spec.**

1. material : graphite, Mn bronze, Ni based superalloy

---

*Fig. III.7-5 Developed hydraulic jack*
Fig. III.7-6 Appearance of hydraulic jack developed
III.8 Cooling pipe & coil services[2]

Basic layout of the divertor and blanket cooling pipe is described below together with the magnet services, cryogenic pipe and current feeder between magnet and current lead.

III.8-1 General layout (see Fig. III.8-1)
a. The cryogenic pipe and current feeder of magnet are led to the valve box and current lead located in the bottom area of reactor hall.
b. The cooling pipes of the lower divertor and blanket center module are located in the bottom area of the machine.

III.8.2 Magnet services
Magnet service systems are shown in Figs III.8-2 to III.8-14.
(1) Cryogenic pipe (see Fig. III.8-15)
a. The cryogenic pipe has to be designed to be a vacuum insulated one with thermal shield to avoid excessive heat to 4-K region by thermal radiation.
b. A common vacuum pipe, in which cryogenic pipes of magnets are inserted, is led from the cryostat to the valve box: this means the cryostat vacuum boundary is extended to the valve box.
c. For magnet maintenance (ex. lower divertor coil), the piping should be cut and partially removed to keep a space for traveling magnet. Accordingly, the bottom plate of the cryostat should give a biological shield.

(2) Current feeder (see Figs III.8-15 to III.8-19)
a. The current feeder is a superconductor cooled by 4-K helium and has to be insulated to avoid excessive heat to 4-K region by thermal radiation.
b. A common vacuum pipe, in which current feeders are inserted with thermal and electric insulation, is led from the cryostat to the current leads: this means the cryostat vacuum boundary is extended to the current leads.
c. For magnet maintenance (ex. lower divertor coil), the current feeder should be cut and partially removed to keep a space for travelling the magnet.
d. The bottom plate of the cryostat should be biological shield because the connection of the superconductor can be only done by personal access.

III.8-3 Cooling pipe

(1) Lower divertor (see Fig. III.8-20)
   a. Typical layout of the lower divertor cooling pipe is described.
   b. Key features are as follows:
      o Cutting/welding the pipe from the inside should be done for the remote maintenance of the divertor plate.
      o A shielding plug should be inserted to give biological shield in the cryostat bottom area.

(2) Lower blanket center module (see Figs III.8-21 to III.8-24)
   a. Typical layout of the lower blanket center module cooling pipe is shown but the double wall may be not required from safety point of view.
   b. Key features are as follows:
      o Cutting/welding the pipe from the inside should be done for the remote maintenance of the blanket center module.
      o A shielding plug should be inserted to give biological shield in the cryostat bottom area.

(3) Vertical port (see Fig. III.8-25)
   The piping layout in a vertical port is shown and the key features are as follows;
   a. The vertical port is widely extended in the upper position of TF magnet in order to keep a space for piping arrangement.
   b. The upper divertor cooling pipe is located in the highest position for easy access of remote maintenance equipment.
   c. The shield plug cooling pipe is arranged to be able to replace the plug independently.

[Issues]
   From maintenance point of view, the present configuration of the vertical port is not preferable because personal access for cutting pipes is not allowed.
   A large vertical port penetrated the cryostat can give more feasible scenario for the maintenance.
Fig. III.8-1 General layout of service lines
Fig. III.8-2 Magnet cryogenic system
Cross-section A-A

Partial Structure

Thermal Shield

1. Winding Supply (40, 48.6)
2. Winding Return (50, 60.5)
3. Case Supply (15, 21.7)
4. Case Return (20, 27.2)
5. Shield Supply (15, 21.7)
6. Shield Return (15, 21.7)
7. Current Feeder (50*)
8. Current Feeder (50*)

Fig. III.8-4 Cross-section A-A
Cross-section B-B

Partial Structure

Thermal Shield

9 Structure Supply (15A, 21.7)
10 Structure Return (20A, 27.2)
11 Shield Supply (15A, 21.7)
12 Shield Return (15A, 21.7)

Thermal Shield

Spacer/Support

Partial Structure

Fig. III.8-5 Cross-section B-B
Fig. III.8-6 Penetration for TF (4/16 sector)
Fig. III.8-7 Central flow scheme of TF magnet (4/16)
Fig. III.8-8 Basic flow scheme of center solenoid (4/8)
Partial Structure
Thermal Shield

©PF-1 Winding Supply (40A 48.6)
©PF-2 Winding Supply (40A 48.6)
©PF-3 Winding Supply (40A 48.6)
©PF-4 Winding Supply (40A 48.6)
©Structure Supply (15A 21.7)
©Structure Return (20A 27.2)
©Shield Supply (15A 21.7)
©Shield Return (15A 21.7)

Cross-Section A-A
Center Solenoid (4/8)

Fig. III.8-9 Cross-section of center solenoid
Fig. III.8-10  Penetration of center solenoid (4/8)
Fig. III.8-11 Basic flow scheme of outer PF magnet
Fig. III.8-12 Cross-section of outer PF magnet
Fig. III.8-13 Penetration for outer PF magnet
Current Lead Flow Scheme of a magnet

Fig. III.8-14 Current lead flow scheme of a magnet
CRYOCENIC PIPING BASIC LAYOUT (PART-A)  CURRENT FEEDER BASIC LAYOUT (PART-B)

Fig. III.8-15 Cryogenic piping and current feeder basic layout
Fig. III.8-16  Schematic drawing of the concepts for the current lead and the current supply
Fig. III.8-17  He piping and the current supply in the building (a) Elevation view
Fig. III.8-18  He piping and the current supply in the building 
(b) Plan view
Fig. III.8-19  Overview of the He piping and the current supply
Fig. III.8-20 Divertor piping basic layout (part-C)
Fig. III.8-21 Center blanket cooling pipe basic layout (part-D)
Fig. III.8-22 Manifold and coolant flow concept (outboard central module)
Fig. III.8-23 Poloidal segmentation of outboard central blanket
Fig. III.8-24 Coolant pipe location for outboard modules on the bottom
Fig. III.8-25 Upper port pipe layout
III.9 Cryostat Design Description

(1) General design description

The cryostat vessel consists from a large cylinder (26m diameter, 27m high) with at least 64 large penetrations and flat removable roof. The bottom part of the cryostat is fixed to be concrete floor. The cylinder and bottom are permanent parts.

During the conceptual design phase, two basic options were proposed and discussed for the CV, which are the metallic cryostat and concrete cryostat which is proposed by Japan. The key features of the concrete cryostat option is as follows.

(2) Concrete cryostat

- This cryostat is composed of prestressed concrete with thin lining made of stainless steel (see Fig. III.9-1)
- This is commercial base technology for pressure vessel of nuclear fission reactor but some modifications are required to use for the vacuum vessel.
- This cryostat provides biological shield and no additional shielding for big penetrations between VV port flanges and cryostat contour is required. However, concrete cryostat is much heavier than all-metal option.
- This cryostat can also be used as a part of building structure.

In the conceptual design phase, the nuclear analysis for biological shielding was available and, based on this analysis, the thickness of the outboard blanket was sufficient to provide the required biological shielding (personal access outside the cryostat 24 hr after shutdown). Since it is not necessary for the cryostat to have the function of the biological shield, the decision was made to use the metallic cryostat. It is clear that additional nuclear shielding around all penetrations in the region between the VV port flanges and cryostat cylindrical wall is a feature that differentiates the metallic from the concrete cryostat. The mass of this additional material is relatively small (a few hundred tons) compared to the extra mass in the cylindrical section of the all-concrete cryostat (a few thousand tons). But if the cryostat will be needed as a part of building structure, the concrete cryostat may be chosen. The final decision will be made in the next design phase based
on the detailed nuclear analysis and taking into account the present basic machine configuration.

Comparisons of various cryostat concepts are described in Tables III.9-1 and III.9-2.

### Table III.9-1 Biological shielding impact to cryostat

<table>
<thead>
<tr>
<th>cryostat type positions</th>
<th>concrete (1m thick)</th>
<th>double SS wall (3.5cm thick)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside cryostat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>point A</td>
<td>$5.4 \times 10^5$</td>
<td>$6.8 \times 10^5$</td>
</tr>
<tr>
<td>point B</td>
<td>$1.0 \times 10^6$</td>
<td>$1.5 \times 10^6$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outside cryostat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>point A'</td>
<td>$7.9 \times 10^2$</td>
<td>$7.8 \times 10^4$</td>
</tr>
<tr>
<td>point B'</td>
<td>$1.8 \times 10^3$</td>
<td>$1.7 \times 10^5$</td>
</tr>
</tbody>
</table>

- Biological dose rate criteria of 25 $\mu$Sv/h (2.5 mrem/h).

### [2] Cryostat options

Thicknesses of cryostat and duct walls in various cryostat options

<table>
<thead>
<tr>
<th>cryostat options</th>
<th>Cryostat wall thickness</th>
<th>duct wall thickness (SS:H\textsubscript{2}O=0.8:0.2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Double SS wall</td>
<td>SS 3.5cm x 2</td>
<td>~120cm*</td>
</tr>
<tr>
<td>(2) Single SS wall</td>
<td>70-80 cm</td>
<td>50cm</td>
</tr>
<tr>
<td>(3) Double SS wall with water</td>
<td>SS 3.5cm x 2 water ~160cm</td>
<td>50cm</td>
</tr>
<tr>
<td>(4) Concrete wall</td>
<td>~160cm</td>
<td>50cm</td>
</tr>
</tbody>
</table>

* Defending against streaming from gap between duct wall and SCM is the problem.
Table III.9-2 Description of comparison of cryostat concepts

[Requirements]
  a. Vacuum boundary for superconducting magnets.
  b. Biological shield for personal access.
  c. Building structure to minimize radial built up if requested.

[Vacuum boundary]
There are two concepts which are a metal cryostat and a concrete cryostat with stainless lining plate, but no difference is expected for providing the vacuum boundary.

[Biological shield]
Five types of configurations are compared as shown in an attached table. As a conclusion, it is recommended that the concrete cryostat is preferable from point of the biological shielding capability.

[Building structure]
In case of the metal cryostat concept, additional building structure is required around the cryostat, so that longer horizontal port is needed. In addition, the layout of basic devices such as heating/current drive and vacuum pump is extremely restricted.
Fig. III.9-1 Typical concept of concrete cryostat
III.10 Horizontal port penetration (see Fig. III.10-1)[2]

[Requirements]
   a. Double containment for tritium boundary
   b. Flexibility to move in radial direction for replacement of the outer poloidal magnets.
   c. Biological shield
   d. Flexible for thermal expansion

[Key features]
In order to meet these requirements, the separated structure into a shield structure with sliding part (bolt with loosed hole) and a thin vacuum vessel as secondary boundary is proposed. The typical configuration is shown below.
   a. The V/V extension structure is movable structure in radial direction for the outer PF magnet maintenance. (see Figs III.10-2 to III.10-4)
   b. The remountable structure can be vertically removed for the outer PF magnet maintenance. (see Fig. III.10-5)
   c. The thin wall vacuum vessel is the secondary tritium container and is assembled around the shield structure.
Fig. III.10-1 Concept of horizontal port
PORT SEPARATION (Horizontal Access Port) (Set Up)

Fig. III.10-2 Port separation (horizontal access port)(1)

Fig. III.10-3 Port separation (horizontal access port)(2)
Fig. III.10-4 Port separation (horizontal access port)(3)

Fig. III.10-5 Port separation (horizontal access port)(4)
III.11 Long-term R&D Plan Short Description[1]

(1) Vacuum Vessel Feasibility

[COS-1.1] Partial model manufacturing
Thick & thin wall vessel manufacturing

- Mechanical loading test
  . Cooling pressure : 2.5 MPa
  . Electromagnetic load : 1 MPa (pressure)
      : 5 MPa (shear)
- Thermal load : 0.1 MW/m\(^3\)
- Non-destructive test : UT, ET,...
- Destructive test : macro/micro structure

- Fabrication
  . Vacuum vessel sector (L:1-3m, W:1.8m, T:0.3m)
  . Vacuum vessel sector (L:1m, W:1m, T:0.3m)
  . Port/duct parts (L:3m, W:1.8m, T:0.5m)
- Test and conditions
  . Cooling system pressure : 2.5 MPa
  . Electromagnetic load : 1 MPa (pressure)
      : 5 MPa (shear)
  . Bending and shear test : \(10^4\) cycles
  . Non-destructive & destructive test

STEP-3: Full scale torus sector mock-up
Redundant approach: Thick and thin concepts

Resources required[M$]
\[
\begin{array}{cccccc}
1.0 & 2.0 & 2.5 & 0.3 & 0.2 & 6.0 \\
\end{array}
\]

[COS-1.2] Structural assembly joint
On site thick welding/cutting/rewelding
- Short straight test pieces
  . Welding qualification
  . Non-destructive/destructive examination
- Full scale short straight pieces (L:2m, W:0.5m)
  . Welding/cutting/rewelding qualification
  . Mechanical test : 10 MN/m
  . Destructive test : micro/macro structure
  . Non-destructive test
  . Leak test : $10^{-6}$ Acc/sec

- Fabrication
  . D-shape full scale long piece (L:15m, W:0.5m)
- Test and conditions
  . Automatic welding/cutting/rewelding procedure
  . Non-destructive test
  . Destructive test : micro/macro structure
  . Leak test : $10^{-6}$ Acc/sec

STEP-3: Full scale torus sector mock-up
Redundant approach: Not required
Resources required [M$\$]:

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[COS-1.3] Large flange connections and secondary seals
Large flange connections with secondary seal

- Fabrication
  . 1 m$^2$ port opening with real thickness
- Test and conditions
  . Bolting/welding/cutting procedure
  . Preloading of bolt
  . Mechanical load : 5 MPa (local)
  . Thermal load : $0.1 \text{ MW/m}^3$ (nuclear heat)
- Fabrication
  - Full scale partial pieces for horizontal port
- Test and conditions
  - Bolting/welding/cutting procedure
  - Mechanical load: 5 MPa (local)
  - Thermal load: 0.1 MW/m³ (nuclear heat)

STEP-3: Full scale torus sector mock-up
Redundant approach: Not required
Resources required [M$]:

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[COS-1.4] Electroinsulating connectors
Surface insulation, insulated bolt and shear keys

STEP-1: Manufacturing procedure development (1991-1992)
- Fabrication
  - Small test pieces (~20 cm²)
- Test and conditions
  - Break down voltage >2 kV
  - Resistivity >0.01 Vm²
  - Compression load >500 MPa (10⁴ cycles)
  - Shear/bonding loads TBD
  - Temperature range: 0-500 °C (2 cycles) 0-200 °C (1000 cycles)
  - Radiation dose wide range for different applications
  - Thermal nuclear load: 0.1 MW/m³
  - Vacuum: 10⁻⁵ mbar

- Fabrication
  - Full scale short straight pieces (0.2 x 0.6 x 1.5 m)
- Tests and conditions
  - Same as STEP-1
STEP-3: Full scale torus sector mock-up
    Redundant approach: Not required
    Resources required[M$]:
    \[
    \begin{array}{cccccc}
    0.2 & 0.4 & 0.5 & 0.3 & 0.1 & 1.5 \\
    \end{array}
    \]

[COS-1.5] Resistive elements
    Toroidal one-turn resistive elements

STEP-1: Manufacturing procedure study (1991-1992)
    - Select candidate manufacturing procedures including joint and
      attaching methods of cooling tubes

    - Fabrication
      \[0.26 \text{ m width} \times 7 \text{ m poloidal length including straight and}
      \text{curved sections}\]
    - Tests and conditions
      - Mechanical load : up to 1 MPa ($10^4$ cycles)
      - Steady state heat load : up to 0.1 mW/m$^3$
      - Joule/disruption heat : up to 15 MJ/m

STEP-3: Full scale torus sector mock-up
    Redundant approach: Not required
    Resources required[M$]:
    \[
    \begin{array}{cccccc}
    0.2 & 0.4 & 0.3 & - & - & 0.9 \\
    \end{array}
    \]

[COS-1.6] Feasibility of casting
    Welding/forming of large cross-section casting with cooling channels

STEP-1: Manufacturing procedure study
    - Select candidate casting procedures embedded cooling channels
      and surface treatments

STEP-2: Short sample test
    - Fabrication
Casting model of around 2 ton mass

- Test and conditions
  - Outgassing test: comparable to rolled plate
    \(10^{-9}\) mbar and up to 180°C
  - Mechanical test: comparable to rolled plate
  - Corrosion tests
  - Irradiation tests

STEP-3: Full scale torus sector mock-up

If the feasibility is demonstrated through STEP-1 & 2, full scale prototype will be fabricated.

Redundant approach: Not required

Resources required [M$]:

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(2) Attaching Locks and Supports

[COS-2.1] Blanket attaching locks

Attaching locks to fix blanket structure

STEP-1: Basic mechanism development (1991-1992)

- Fabrication
  - Critical parts of the following candidate
  - Welded bolt
  - Water hydraulic jack & cotter
  - Mechanical bolts
  - Liquid metal

- Test and conditions
  - Locking procedures
  - Mechanical load: up to 10 MN/m
  - Fatigue test: up to 1000 cycles
  - Thermal load: up to 1 MW/m³
  - Outgassing test: comparable to solid plate
  - Insulation voltage: up to 2 kV


- Fabrication
A complete set of the attaching lock system
- Test and conditions
  - Same as STEP-1

STEP-3: Full scale torus sector mock-up
Redundant approach: welded bolt, hydraulic locking, mechanical bolts and liquid metal

Resources required[$M$]:

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[COS-2.2] Machine flexible supports
Flexible tension/compression gravity support

- Fabrication
  - Full scale supports for magnet and vacuum vessel (VV):
    - $2m(R) \times 1m(W) \times 3-4m(H)$
- Test and conditions
  - Load:
    - Magnet up to 100 MN
    - VV up to 100 MN
  - Displacement:
    - Magnet 15-20 mm
    - VV 20-30 mm
  - Temperature:
    - Magnet 4-80-300'K
    - VV 300-450'K

STEP-3: Full scale torus sector mock-up
Redundant approach: Flexible tension and compression supports

Resources required[$M$]:

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(3) Plasma Stabilizing Elements

[COS-3.1] Passive loops
Passive loops attached to the blanket structure

- Fabrication
  
  . Full scale partial pieces
    Cu and Al: 1-2 m² x 5-10 mm thick

- Test and conditions
  
  . Process sequences: bending before/after bonding
  . Bonding processes: welding/brazing/explosive welding/bolting
  . Thermal cycles: 20-500°C (2 cycles)
    20-200°C (1000 cycles)
  . Bending test: 10⁶ cycles
  . Outgassing test

STEP-3: Full scale torus sector mock-up

Relevant approach: Not required

Resources required [M$]:

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</table>

[COS-3.2] Active coils

50-kA turn (DC) and 300-kA turn (pulse) active coil with cooling channel


- Fabrication
  
  . Cable: 50 mm dia. x 25 m (multi-turn)
    100 mm dia. x 10 m (single-turn)
  . Joint: comparable to remote handling tools

- Test and conditions
  
  . Cable: Bending test: minimum radius 3-5 m
    Electroinsulation: up to 3 kV/turn
    Current flow test
      peak current: 300 kAT
      average current: 50 kAT
  . Thermal test
    Electromagnetic load: 3 x 10⁶ cycles
    Irradiation test
  . Joint: Same as cable plus remote handling procedure
STEP-3: Full scale torus sector mock-up
Redundant approach: Not required
Resources required[M$]:

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<td>1.0</td>
<td>0.3</td>
<td>0.2</td>
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</tr>
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</table>

(4) Cryostat Elements

[COS-4.1] Large bellows
Large bellow to allow the mechanical/thermal movements

- Fabrication
  . One full-scale rectangular bellow : 4.6m(H)x2.6(W)x2m(L)
  . One full-scale trapezoidal bellows : 0.5m(H)x5m(L)x1m(W)
- Test and conditions
  . Accidental pressure : 0.2 MPa
  . Movements vertical : 36 mm
    axial : 36 mm
    lateral : 30 mm
torsion TBD
  . Leak test (see cryostat requirements)
  . Heating/cooling : up to 180°C

STEP-3: Full scale torus sector mock-up
Redundant approach: Not required
Resources required[M$]:

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</table>

[COS-4.2] Penetration and lip seals
Port/duct penetration structure with lip seals

- Fabrication
  . Full scale port penetrations including shielding structure and bellows
- Test and conditions
Flexibility test: mechanical/thermal movement (30-40 mm)
Mechanical test: loads simulating in-vessel manipulator, antenna etc.
Leak test: seal characteristics in various loads
RH procedures: remote maintenance procedures

STEP-3: Full scale torus sector mock-up
Redundant approach: Not required
Resources required [M$]:

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</table>

[COS-4.3] Thermal shield/superinsulator
Thin thermal shield with thickness of less than 50 mm

STEP-1&2: Full scale partial model tests
- Fabrication
  . Thin test pieces: $1 \text{ m}^2 \times 50 \text{ mm} \text{ thick}$
Test and conditions
  . Thermal radiation test: 4-80-300/450 K
  . Mechanical load: 1.5 ton/m$^2$
  . Electroinsulation test: up to 1 kV

STEP-3: Full scale torus sector mock-up
Redundant approach: Not required
Resources required [M$]$

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</table>

(5) Full Scale Mock-up Manufacturing

There are three torus mock-ups in STEP-3, which are the VV 1st sector, in-vessel components and VV 2nd sector mock-ups. The key features of these mock-ups are as follows.

**VV 1st sector mock-up (COS-5.1)**

The VV 1st sector mock-up is composed of 2 parallel and 1 wedged segment without resistive elements, insulation break, real cooling
channels and fabricated by real material with real structure in the segment welding region, but simplest structure in bulk for simulating mass and shape. Main purpose of the VV 1st sector is to demonstrate the feasibility of welding/cutting/rewelding of the VV segment joint including remote handling tools/procedures.

Resources required[M$]:

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**In-vessel components mock-up (COS-5.2)**

The in-vessel component is composed of 1/16 sector of inboard blanket, outboard blanket, divertor plate and shield plug and fabricated with real structure in the attaching lock region and simplest structure in bulk for simulating mass, shape and cooling channels. Main purpose of the in-vessel component is to demonstrate the feasibility of attaching lock system installed in the blanket and divertor.

Resources required[M$]:

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**VV 2nd sector mock-up (COS-5.3)**

The VV 2nd sector is finally composed of 2 parallel and 1 wedged sectors (1/16 sector) with resistive elements, insulation break, cooling channels manufactured by real materials and structure, and the first 1/32 sector (1 parallel and 1/2 wedged segment) is fabricated before 1995 in order to obtain a minimum technological information for the construction basis with the minimum resources. Another 1/32 sector will be fabricated after 1995 and the total cost of VV 2nd sector is divided into two equal amounts before and after 1995. The both sectors will be tested together under the similar operating conditions to the real one in the Full Integration Mock-up Test during 1997-1998 to finalize the construction design specifications before the actual manufacturing processes.

Resources required[M$]:

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(6) Full Scale Mock-up Test

The full scale mock-up test consists of the simplified mock-up test in the existing test facility before 1995 and the full integrated mock-up test in the upgraded test facility after 1995. In the simplified mock-up test, on site welding/cutting/rewelding and replacement of VV 1st sector mock-up are simulated in 1994 by using VV remote handling prototype equipment and thereafter, assembly/disassembly of in-vessel component is tested by using the in-vessel component remote handling equipment. After 1995, the test facility is upgraded and the full integrated mock-up test is conducted. The whole structural feasibility including remote handling tools/procedures of all components except vacuum pump and heating/current drive devices are demonstrated under the similar operating condition to real one.

1) Simplified Mock-up Test: 1994
   a. On site welding/cutting/rewelding and replacement of VV 1st sector mock-up by using VV handling prototype equipment developed in AMA-9.
   b. VV 1st sector mock-up (4.0 MS) is
      - composed of 2 parallel and 1 wedged segments without resistive elements, insulation break, real cooling channels,
      - fabricated by real material with real structure in the segment welding region by simplest structure in bulk for simulating mass and shape.
   c. VV handling prototype equipment is
      - composed of welding/cutting/rewelding tools and assembling/disassembling tools.
   d. For this simplified mock-up test, AMA-12 prepares
      - Cryostat (1/16 sector): 1.0 MS
      - Port and cooling tube (1/16 sector): 1.5 MS
      - Bellows for penetration (1/16 sector): 1.0 MS
      - Casks for upper/horizontal/lower ports: 2.5 MS
      - Supporting structures: 1.0 MS
      - Instrumentations: 1.0 MS
   e. Test facility involves
      - 200-ton Gate crane: 2 MS
      - Building modification: 2 MS
2) Simplified Mock-up Test: 1995
   a. Assembly/disassembly of cooling tubes and in-vessel components by
      using the blanket handling prototype equipment, in-vessel component
      handling prototype equipment and port assembling prototype equip­
      ment developed in AMA-5, -1, -2, -3, -4, -6, and -8.
   b. The cooling tubes of in-vessel components are prepared by the task
      AMA-12.
   c. The in-vessel components are
      - prepared by CSDU as a mock-up manufacturing
        - composed of In-board blanket (1/16 sector): 2.0 M$
        - Out-board blanket (1/16 sector): 3.4 M$
        - Divertor plate (1/16 sector): 0.4 M$
        - Shield plug (1/16 sector): 0.2 M$
      - fabricated with real structure in the attaching lock region
        and simplest structure in bulk for simulating mass, shape
        and cooling channels.
   d. The blanket handling prototype equipment is for assembly/disassem­
      bly of shield plug, in- and out-board blankets.
   e. The in-vessel component handling prototype equipments are rail-
      mounted vehicle, articulated boom and vertical robot: these feasi­
      bilities are demonstrated by using full-scale partial torus model
      before this mock-up test.
   f. The port assembling prototype equipment are to make the
      cryostat/vacuum vessel open and close and to weld/cut/reweld cool­
      ing tubes of the upper, horizontal and lower ports: these feasibil­
      ities are demonstrated by using full-scale partial torus model
      before this mock-up test.

3) Simplified Mock-up Test Upgrades: 1996-1997
   a. For Full Integrated Mock-up Test (1998), the simplified Mock-up and
      Test facility are upgraded as follows:
   b. AMA-12 will prepare
      - Cooling tubes for all components including connecting tubes
        between components and cooling system: 1.0 M$
      - Port extension including Gate valves, double seal doors and
        shield structure outside the cryostat: 6.5 M$
- Main vacuum pump structure: 0.5 M$
- TF & PF structure including thermal shield: 1.0 M$
- Standard connectors: 3.0 M$
- Supporting structures: 2.0 M$
- Ex-vessel transporter: 3.0 M$
- Ex-vessel RH equipment for outer PF handling: 3.0 M$
- Pipings and cables including coil services: 0.5 M$

c. The test facility upgrading involves
  - Building extension for full extraction of blanket: 4.0 M$
  - Mechanical load test device: 2.0 M$
  - Thermal load test device: TBD
  - Vacuum and water systems: 3.0 M$
  - Data acquisition system: 1.0 M$
  - Piping and Cables: 3.0 M$
  - Operation fee: 2.0 M$

4) Full Integrated Mock-up Test: 1998
a. Remote handling demonstration except vacuum pump and heating/current drive basic devices are performed as well as structural feasibility test of torus structure prepared by CSDU.
b. CSDU will organize the complete fabrication of VV 2nd sector as well as the upgrade of the Mock-up as follows:
   - Upgrade VV 2nd sector to 1/16 sector with real resistive elements insulation break, cooling channels and port seal structure: 6.0 M$
   - Cryostat for vacuum chamber: 4.8 M$
   - Structural supports: 0.6 M$
   - Port extension (bellows, lip seals, flange): 4.0 M$
   - Active control coil: 1.0 M$
c. AMDU will prepare
   - Standards components developed in AMA-11
   - Viewing system prototype developed in AMA-10
   - TF & PF handling prototype developed in AMA-9 and the VV handling, blanket handling, in-vessel component handling and port assembling prototypes are continuously used after the Simplified Mock-up Test.
d. As for the vacuum pump handling and heating/current drive basic device handling system, the actual fabrication will be initiated
after individual feasibility test by using full-scale partial torus model.

5) Key items to be tested in the Full Integrated Mock-up Test
The following items are tentatively proposed but it will be finalized during EDA.

1 Remote handling demonstration
All procedures are remotely and sequentially demonstrated in the both conditions: initial assembly and after operation simulated temperature profile and mechanical loading.

2 Hydraulic test
a. Cooling and pressure drop characteristics of all components including the cooling manifold layout.
b. Pressure propagation and flow rate behaviour in the LOCA/LOFA simulation experiments.
c. Drain out and purging experiments to simulate real procedures for baking and maintenance.
d. Flow instability simulation test then a cooling channel in several parallel passes is highly heated.

3 Thermal tests
a. Baking characteristics measurements by supplying warm gas into the cooling channels of components with the fixed boundary temperature.
b. Thermal movement measurements due to normal operating temperature profile with different mechanical boundary conditions.

4 Mechanical tests
Mechanical stiffness measurement under the scalable mechanical loading with approximate profile and different mechanical boundary conditions.

7 Electromagnetics Sub-size Model (COS-5.4)

Design criteria and optimized locking system for dynamic loads due to disruption.

Subsized model:
A partial subsized model of vacuum vessel and blanket structure

Test and conditions:
Electromagnetic mechanical test: Dynamic behaviour should
be investigated by simulating loading due to disruption.

Milestone:
Test and analysis : 1991-1993

Resources required[M$]:

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Redundant approach: Not required
III.12 Conclusions and Future Needs

(1) Vacuum vessel

Alternative thin-wall VV options were analysed during the CDA phase as attractive, simplified design solutions. The analysis and corresponding R&D studies of these concepts should be continued during the EDA phase. If the feasibility questions relating to the total structural integration, such as compatibility with passive/active elements and blanket attaching locks, can be successfully answered, then the thin-wall VV concept has a good chance to be adopted on ITER. The final VV design solution may be a combination of the reference and thin-wall options, using the best features of each concept.

(2) Attaching Locks

A common understanding was reached by the ITER team that only results of the earliest planned technology R&D efforts can give a reliable basis for the locks design choice. From the point of view of successful machine design integration during the EDA phase, these results (positive or negative) should be received as early as possible, not later than in 1992-93 years. This means that extensive R&D studies of all five proposed attaching locks options should be started as early as possible and ongoing activity in this area should continue without interruption.

(3) Cryostat

As a possible alternative approach, the thick prestressed concrete cryostat with thin inner metallic liner has also been proposed, which combines the cryostat, biological shielding, and building wall functions. It was shown during the CDA phase, however, that biological shielding 24 hours after shutdown can be provided by the reactor itself (blanket and VV) with extra shielding around all penetrations, so there are no nuclear shielding requirements for the cryostat cylindrical wall.

The concrete cryostat will be the best solution if, in the future, the detailed nuclear shielding analysis, taking into account all penetrations, will require that the biological shield be provided by the cryostat, or, if it will be necessary to combine the cryostat and building structure.
(4) Critical design issues

The most critical design issues which need design development and
detailing for the near future can be listed as follows:
- Blanket attaching locks:
  Feasibility analysis, stress analysis, structural drawings, ther-
momechanical and transient process analysis, compatibility with remote
handling tools, etc.
- Vacuum vessel assembly joints both for reference and alternative
  concepts:
  Design detail analysis and improvements, stress analysis, reliabil-
  ity estimates, compatibility with remote handling tools, etc.
- Passive loops/active coils:
  More detail design integration into the reference VV design.
  Passive loops compatibility study with alternative VV design. Proposed
design details and feasibility study of active coils.
- Recent results of electromagnetic analysis for plasma disruption,
  including 5 msec current quench, 28 MA operation regime effects and
  halo current.
- Some results of more detail machine design integration provided by
  home teams also can be presented; for example:
  - Interface design and drawings for all port penetrations in refer-
    ence and alternative (concrete) cryostat concepts
  - Integration design and drawings of all service (piping, current
    feeders etc.) inside the cryostat.

References
[1] S. Sadakov et al, ITER Containment Structures, IAEA ITER Documen-
tation Series, No.28, Vienna, 1990.
[2] E. Tada et al, Japanese Contribution to ITER Containment Struc-
ture, July 1990.
IV. Assembly and Maintenance

VI.1 Introduction

The design of the ITER tokamak device and auxiliary systems are specified with maintainability and repairability as a fundamental requirement. These fundamental requirements are reflected in the basic layout and configuration of the tokamak device.

Once operation with DT fuel commence, the entire tokamak device, and to a lesser extent the auxiliary system, will become activated, and remote maintenance procedures become indispensable.

Within the torus vessel, the maintenance will be done with in-vessel manipulator (articulated boom and/or In-vessel vehicle). These booms and vehicles, equipped with specialized handling fixtures and remotely operable tools, will be used to remove and re-install in-vessel components such as first wall tiles and divertor plates. These maintenance operation can be carried out relatively quickly, and are planned as routine in ITER operation (see Fig. IV.1-1).

This concept is preferred to minimize the radioactive waste, to simplify the building/reactor interface, to ease the contamination control problems during divertor change-out, and to allow for a simpler design for the top access port. In parallel with the conceptual design, the R&D on in-vessel vehicle was carried out and the feasibility of the deployment of rail and moving vehicle were demonstrated by fabricating 1/5 scale model by JAERI. Remote handling devices are also provided for semi-permanent components such as blanket/shield which is planned as an unfrequent and unscheduled maintenance. The maintenance will be done using specialized end-effector/manipulator and ex-vessel removing system and remote heavy crane.

A system of double door and container-transporter device is provided for avoiding the spread of activated materials during transporting them to the decontamination and repair or disposal facilities.

Other ex-vessel subsystem equips also similar remote-handling crane, manipulator and transporter devices.

The permanent tokamak device system, such as vacuum vessel and TF/PF magnet which are expected to last the life of ITER (except enter solenoid which needs replacement during reactor life time) are designed to make disassembly and replacement feasible by remote-handling means,
although major maintenance operation are not anticipated.

This technical report is a Japanese contributions[1] to remote handling equipment designs based on the maintenance data and requirements which are discussed during Conceptual Design Activity and finally described in Chapter III of ITER Assembly and Maintenance technical report[2].

IV.2 Articulated boom

The articulated boom is composed of multiple articulations which rotate in the horizontal plane. One end of the boom is equipped with an end-effector/manipulator, the other end is supported on the floor with sliding system. The end-effector/manipulator penetrates into the vacuum vessel through the horizontal access port using snake like movement of the articulated boom. This end-effector grips, lifts and transports the divertor plate to the material transfer ports located 90 degree from the boom access port. A transporter will receive the divertor plate at this area and transfer it to the outside of the vacuum vessel.

At the maximum deployment of the boom, to reduce the deflection from the cantilever load, the boom will be supported from the access port floor.

(1) Structure of the articulated boom (Figs IV.2-1(a) and IV.2-1(b))

- Size and number of articulations

  Total length: 25m (including straight section of 12m)

  Cross section: Extreme part: 1400x400mm,
  Other part: 2000x500mm

  Thickness of the wall: 50mm

  Number of articulation: 7

  Length of articulation: Extreme section: 1000mm
  Other sections: 2000mm

- Driving system

  Two extreme parts: Motor with deceleration system connected directly to the articulation axe.

  Other parts: Rod driving system with a pair of piston cylinder (piston cylinder is driven by motors and ballgear) (Fig. IV.2-2)

- Load: (at the extremity of the boom) 2000kg
- Material:
  Boom: Aluminium alloy
  Axes, Driving rod: Stainless steel

(2) Structure analysis
- FEM was used for static and dynamic analysis for studying stress, deflection and eigen frequency of the articulated boom (Fig.IV.2-3)
- Static analysis (Fig. IV.2-4)
  Stress distribution and deflection calculations were performed with the boom deployed to the maximum reach to grip the divertor plate located at-/+90 degree.
  (1) Stress: Stress is lower than 5 Kg/mm²
  (2) Deflection at the extremity of the boom:
    (total of the result of torsion and bending)
    - With end-effector but without divertor: 42.8mm
    - With end-effector and divertor: 57.8mm
- Dynamic analysis/deflection (Fig.IV.2-5)
  - Impact loading of 1 ton divertor plate: -17mm
  - Impact unloading of 1 ton divertor plate: +/-15mm
- Eigenfrequency analysis (Fig.IV.2-6)

(3) End effector
End effector attached to the end of the boom is used to grip the divertor plate. End-effector is composed of gripper and lifting device.
- Lifting device
  (1) Composition: 3 staged pantagraphe
  (2) Lifting stroke: 4m
  (3) Driving system: 8 motors and direct drive by chain for back-up
- Gripper
  (1) Composition: gripper and base plate supported at 3 points
  (2) Degree of freedom: base plate: 3, gripper: 3(gripping, rotation, translation)
- Static analysis (Fig. IV.2-7)
- Eigenfrequency analysis (Fig. IV.2-8)

(4) Support structure (Fig. IV.2-9)
Support structure has a sliding system with rollers, and guide
rail.
- Guide rail.
- Roller
- Location: Access port surface at the level of vacuum chamber

(5) Sensor, actuator
- Sensor: tachogenerator, encoder, potentiometer, limit sensor, load sensor, acceleration sensor, TV camera
- Actuators: Motor with reduction gear,
  Capacity: min 10 W, max 1 kW

(6) Maintenance operation time
All divertor plate(64) replacement by two articulated boom:
- Movement of articulated boom from 0 degree to 90 degree: 40 min
- Divertor gripping/positioning: 10 min
- Pantagraph flexion (lifting and down): 45 min
  Sum total of above 3 items
  \[(40 + 10 + 45) \times 2 \times 64 = 12160 \text{ min} = 203 \text{ hr} = 8.5 \text{ days}\]

(7) Control system
Control system is consist of operation planning computer and controller.
- Operation planning computer carries out movement simulation and analysis control data generation and operation command.
- Controller drives the articulated boom according to the command of operation planning computer.

(8) Conclusion/future needs
The important items to be develop are sensors and actuators which should be sufficiently resistive to gamma irradiation. Development of the viewing sensor is also a most important item. The system of flexible structure supporting a heavy load will generate oscillations and make positioning operation difficult; therefore the establishment of the oscillation control technique is indispensable. Prototype development is essential to demonstrate the feasibility of the articulated boom and end-effector.
IV.3 In-vessel vehicle

A rail-mounted vehicle system consists of six-linked rails, rail deploying device, rail supports from 90 degree ports and rail-mounted vehicle system that covers 180 degree (Fig. IV.3-1). The features of this system are as follows.

a) mechanical stability of the rail is very high by multi-points supports from every 90 degree,
b) the rail is light and simple structure,
c) the rail structure has no sensitive equipments such as actuators and sensors,
d) the locking of the rail joints is carried out by a locking mechanism included in the vehicle,
e) the deployment of the rail is carried out by the combination of the vehicle and the deploying system, (Fig. IV.3-2)
f) additional mechanism to the vehicle is only a looking mechanism for the rail (Fig. IV.3-3) and

g) the rail deploying is carried out by simple sequential control.

(1) Structure of the vehicle

1) Composition
   - vehicle
   - rail
   - rail deploying device
   - rail supports

2) Vehicle manipulator
   - degree of freedom: 5
   - stroke of telescopic mast: 4m
   - number of grippers for divertor plate: 4

3) Size and number of articulations
   - total length: 23 m
   - cross section: 540mm deep x 270mm wide (wall thickness: 20mm)
   - number of joints: 6 per set (cover 180 degree)
   - material: aluminum alloy
   - locations of rail supports: 0, 90, 180, 270 degree
(2) Structural analysis of the vehicle rail

Static analysis was carried out by FEM in order to study the stress and the deflection of the rail system. The deflection of the rail is very important for the sensitive operations in the divertor plate maintenance.

1) Analysis conditions

FEM analyses were carried out for two cases; case 1 is the rail supported at 180 degree opposite positions (that is, two supporting points concept), case 2 is the rail supported every 90 degrees (that is, four supporting points concept).

2) Structural dimension (Fig. IV.3-4)

- Rail
  - rail size: 540mm x 270mm wall thickness 20mm
  - radius of the rail: 5640 mm
  - material of the rail: aluminum alloy

- Support
  - Support size: for 0 and 180 degree supports
    715mm x 470mm x 4200mm (thickness 30 mm)
  for 90 and 270 degree supports
    540mm x 270mm x 4200mm (thickness 20 mm)
  - material of the support: stainless steel

3) Load

- Weight
  - divertor: 1 ton
  - vehicle: 2 ton

- Location of load
  - 90 degree position for case 1 (0 and 180 degree supports)
  - 45 degree position for case 2 (0, 90, 180 and 270 degree supports)

4) Analysis Results (Fig. IV.3-5)

**case 1**

The deflection, the torsion angles x, y, and z are 27.6 mm, 0, 0.28 and 0.18 degrees, respectively.

**case 2**

The deflection, the torsion angles around x, y, and z are 3.4 mm, -0.0014, 0.0018, 0.035 degrees, respectively.
(3) 1/5 size scale model demonstration

A 1/5 scale model of this system has been fabricated and tested by JAERI as one of the activities of ITER related short term R&D (see Figs IV.3-6 to IV.3-7(b)). The following test operations were performed:

1) Deploying the rail into the torus and extracting it
2) Moving the vehicle along the rail
3) Swinging and telescoping the manipulator
4) Feeding a cable simultaneously with the vehicle’s movements
5) Measurement of the deflection of the rail (the maximum deflection of the rail was 1.3 mm when the weight of the vehicle (30 kg) was loaded on the supported semicircular rail).

The results were successful and it was demonstrated that the rail is stable, simple and reliable.

In this model, a winding mechanism for rail storage and a two-step slide arm were adopted (see Fig. IV.3-7). This concept is used also for the ITER design in order to minimize the impact to the reactor building of the length of a maintenance cask. The length is reduced from 25 m for a linear storage concept to 13 m for the wound storage concept.

Also, by using the deflection data from this model, minimum clearance during maintenance between divertor plate and surrounding components were estimated and used to determine and inboard and outboard profile (protrusion) of the blanket (see Fig. IV.3-8)

IV.4 Divertor jacking/locking system

Figures IV.4-1 to IV.4-5 show a proposal for the divertor plate jacking/locking system. Divertor plate is locked by cotter using hydraulic jack. Hydraulic jack is also used to lift a divertor plate for replacement.

A divertor plate is installed on three lifting jacks by an in-vessel maintenance equipment. Then four support legs of a divertor plate are set into four guide holes of a divertor shield, where a divertor plate is arranged automatically, and a divertor plate is locked to a divertor shield by hydraulic cotters (see Fig. IV.4-6).

The proposed concept is basically able to agree with the requirements mentioned in III.1.1 of Technical Report[2]. Nuclear heating of the cotter can be removed by coolant. Contacting surfaces are coated by ceramics to prevent the diffusion bonding. The most favorable feature
of this concept is an ability of easy full remote maintenance. The major concern of the concept is the reliability, especially for bellows. In the concept, the bellows are not subjected to the hydraulic pressure due to plasma disruption.

IV.5 Divertor gripping system

The divertor plate grip requirements are as follows:
- Gripping of the gravity center to avoid the torque during tilting motion.
- Gripping of the support flame of the divertor plate to avoid the deformation
- Gripping the divertor support flame from its side after jacking (pushing) up the divertor plate.

Figures IV.5-1 and IV.5-2 show a concept of end-effector and the gripped side and gripper of the divertor plate.

IV.6 Divertor pipe cutter/welder

The requirements to the connection/disconnection of the cooling pipes for the divertor plate are shown as follows.

a) access space for connecting/disconnecting of the pipes for the divertor plate is limited in order to minimize neutron streaming to the surrounding of the reactor and to keep the sufficient shielding thickness to the toroidal coils.

b) connecting/disconnecting position of the divertor plate is as close as possible to the divertor in order to minimize the moving space of the divertor plate in the vacuum vessel.

As a candidate method satisfied the requirements, a concept of in-pipe laser welding/cutting is the most available (Figs IV.6-1 to IV.6-4). This concept is the method which has access from the inside of the pipe. Therefore, the excessive space around the pipe is not necessary for the pipe welding/cutting, whereby the structure around the pipe and the maintenance procedures become simple. Moreover, this system can carry out both works of welding/cutting of the pipe by means of one system.
(1) Composition
- laser welding/cutting head
- rotating mechanism of head
- telescopic tube (stroke: 5m)
- flexible beam guide
- vehicle

The beam guides for laser beam, which are connected to the laser beam source, are initially installed near the positions of the cooling pipes to be welded and cut. At welding/cutting of the pipes, the initially installed beam guides are connected to the vehicle by the flexible beam guide. The vehicle installs a telescopic tube with welding/cutting head at the tip. (see Fig. IV.6-5).

IV.7 Poloidal segmentation versus Toroidal segmentation
(two segmentation each between TF coils)

The following items are considered for comparison of toroidal segmentation and poloidal segmentation. (see Table IV.7-1)

(1) Kinematics
1) Toroidal segmentation (See Fig. IV.7-1)
   Size of divertor plate, width: 1.2m, length: 3.4m
   - Lower divertor plate
     Simple lifting with slight tilting motion
   - Upper divertor plate
     Moving down with tilting motion, and turning.

   Above toroidal schemes are considered for vehicle with telescopic mast. However the scheme of the above divertor plate can be applied for support divertor (symmetrically) and lower divertor plate kinematics in the case for boom with pantagraphe.

   Above toroidal scheme are considered without lateral support of rail at 90 degree, however, this scheme can be applied also for with lateral support of rail at 90 degree. The lateral support has no interaction with above kinematics.

2) Poloidal segmentation (See Fig. IV.7-2)
   Size of divertor plate (including pipe length):
   - lower and upper outboard divertor, width: 2.4m, length: 1.5m
   - lower inboard divertor, width: 2.4m, length: 2.9m
upper inboard divertor, width: 2.4m, length: 3.4m

- Lower outboard divertor plate
  Lifting with tilting motion and rotation around horizontal axe
- Lower inboard divertor plate
  Lifting with tilting motion and rotation around vertical axe
- Upper outboard divertor plate
  Moving down with tilting motion, and rotation around horizontal axe.
- Upper inboard divertor plate
  Moving down with tilting and turning, and rotation around horizontal axe.

Above poloidal schemes are considered for vehicle with telescopic mast. However the scheme of the above divertor plate can be applied for upper divertor (symmetrically) and lower divertor plate kinematics in the case for boom with pantagraphe.

Above poloidal kinematics are considered for vehicle with telescopic mast without lateral support of rail at 90 degree. If the lateral support is provided to the rail at 90 degree, the interaction of the divertor plate occurs during rotation of the divertor plate. Because the rotation should be performed at the port at 90 degree by the transfer device located at this port.

(2) Divertor pipe layout

Poloidal segmentation is beneficial only for lower inboard divertor piping layout. For lower inboard divertor layout, the shorter divertor piping on the divertor shield will be possible. On the other hand, the upper inboard divertor plate has longer piping on the divertor shield because inboard side of upper access port has a inboard blanket piping.

(3) Divertor gripping concept

For toroidal segmentation, after divertor plate will be jacked up, the side wall of divertor plate emerges. The divertor plate can be gripped by using this side wall without violating the divertor surface area. Conceptual design exists.

For poloidal segmentation, gripper may have access from the splitted area of divertor plate. Conceptual design does not exist for the moment.
(4) Clearance between divertor plate and surrounding structures

Required clearance between divertor plate and surrounding structures should be considered from the deflection and certain safety factor of it.

- Deflection of transporter

**Boo**: Deployment area: +/-90 degree, Supported on entry part of access port

Static deflection (not including divertor weight): 42.8mm
Static deflection (including divertor weight 1 ton): 57.8mm
Dynamic deflection (impact loading): -17mm

\[(42.8\text{mm}+17\text{mm}=59.8\text{mm})\]

Dynamic deflection (impact unloading): +/-10mm

\[(42.8\text{mm}+/-10\text{mm}=52.8/32.8\text{mm})\]

**Vehicle(a)**: Supported at 0,90,180 degree at the entry part of access port.
Static deflection (not including end-effector and divertor weight): 1.13mm
Static deflection (including end-effector and divertor weight): 1.4mm

**Vehicle(b)**: Supported at 0,180 degree at the entry part of access port.
Static deflection (not including end-effector and divertor weight): 89.7mm
Static deflection (including end-effector and divertor weight): 185.1mm

According to the above results, 90 degree support of the vehicle or boom is essential for deflection.

The vehicle rail has a very low deflection when supported from 90 degree ports.

For estimation of required clearance, uncontrollable end-effector displacement should be also considered. It is difficult for the moment to conclude by clear-cut statement on it. However, at the end of the end-effector, +/-1 degree of displacement should be considered, which leads to +/-70mm.

So, if we take the boom as example, required clearance will be \((70+59.8=) 130\text{mm}\).
(5) Replacement scenario

For poloidal segmentation, inboard divertor plate should be removed after removal of the outboard divertor plate because of pipe interaction. If the outboard divertor plate is much more frequently damaged/replaced, this disadvantage will be reduced.

(6) Conclusion

The following table shows comparison between toroidal segmentation and poloidal segmentation.

Toroidal segmentation was recommended and decided as reference.

IV.8 Armor tile handling equipment (Figs IV.8-1 to IV.8-5)

It is necessary to exchange a number of armor tiles by in-situ maintenance. The maintenance of the armor tiles is a scheduled one. The armor tile handling equipment is required to have manipulators, which are installed on both sides of the vehicle. Features of this equipment are shown as follows:

a) armor tile exchange is carried out by twin manipulators installed on the vehicle,
b) each manipulator has access to every where of the first wall,

1) Pay load: 10 kg
2) Size: slide arm: 3250x150x100mm
   last arm: 1800x120x120mm
   2nd arm: 1450x60 dia
3) Degree of freedom: 8
4) Location of installation: both side of the vehicle
5) Number of manipulator: 2 (per vehicle)

Especially, the exchange time of armor tiles will be reduced, if the manipulator can carry the carrying case filled with armor tiles. This concept is very useful to minimize the number of maintenance equipment.

Moreover, the vehicle with twin manipulators can pass through the equatorial port by bending the arms in parallel.
IV.9 ITER viewing/inspection system

Comparison between horizontal access and vertical access

1) System explanation: Horizontal access (Fig. IV.9-1)

The viewing equipment and the transporter are designed for different atmosphere; the viewing equipment, for vacuum; and the transporter, for inert gas. As a result, a complex double cask must be designed to separate the two components.

A shield plug must be removed from the maintenance port in order to gain access. This plug must be actively cooled both when installed and while in temporary storage within the cask. Connection/disconnecting of the pipes required delays the introduction of the in-vessel manipulator into the vessel and consequently the start of the maintenance operations.

As the viewing system has a limited life time and rather frequently replaced, so the rapid replacement of the viewing system is indispensable. Replacement in the maintenance cask is an obligation for horizontal access case in common port with in-vessel transporter cask.

2) System explanation: Vertical access (Fig. IV.9-2)

The upper maintenance ports are available for viewing/inspection system. Viewing system can have independent ports from maintenance port. The main characteristics are small movable shielding plug connected by flexible cooling tube, and container of the viewing system is located on the upper cryostat. Container and cryostat can be separated for replacement of the viewing system.

During reactor operation, small movable shielding plug is closed nd upper valves are closed. The viewing system is storaged in the container.

After reactor shut down, the small movable shield is removed without cutting the cooling tube, two valve are open, and viewing system with telescopic mast will be inserted in the vacuum vessel.

For maintenance or remplacement of viewing system, two valves are closed and flange between two valves is disconnected, the container including viewing system will be transferred to other area.

 Intervention of the viewing system into the vessel can be rapid without cutting/connecting the cooling pipe.
IV.10 Blanket handling equipment

The blankets are installed inside the ITER vacuum vessel as an assembly of inboard and outboard modules. Each of the 16 machine sectors contains four outboard breeding modules and two inboard modules as shown in Fig. IV.10-1. Four additional pieces with only a shielding function, i.e. no breeding are required to complete the assembly. Each module must be sequentially lower into and positioned in the vacuum vessel by equipment working through to top vertical ports.

The overall scheme for blanket handling calls for extensive use of an special blanket handling equipment. For removal of a module, the special equipment must be first outfitted with a manipulator and special purpose tools to gain access to the vacuum vessel port through the cryostat vessel, to cut the blanket/shield service piping, and dismantle the primary vacuum seal welds. Before they can be lifted the blankets must also be freed from their structural supports. In order to react the high electromagnetic loads associated with a plasma disruption, each module is structurally tied to the adjacent module as well as to the vacuum vessel which must react the net vertical load. A long term R&D program is planned to develop the blanket locking concept. Once all interfaces to the blanket/shield modules are free, the modules can be lifted by the special blanket handling equipment through the top vacuum vessel and cryostat vessel port.

The following sections describe the equipment required to perform these steps.

IV.10.1 Blanket transporter

The function of this system is to provide the weight support, lowering/lifting and translations required to position the modules within the vacuum vessel. This is accomplished by providing a hoisting mechanisms within a container (Fig. IV.10-2). The concept requires a collapsible shroud or had container that permits the hoist to lower the gripper into position for attaching to the module. The hoist mechanism must have the ability to move the gripper with the attached module through a these dimensional path to remove the modules through the vertical port.

Studies of date have looked at tools required for the maneuvering
the modules within the vessel. Due to the size and shape of the components, a conceptual design was developed of a moment carrying attachment as well as a load centering device. A design of a mechanism for sliding and tilting the modules about each axis is shown as Fig. IV.10-3.

The main body of blanket transporter installs mechanisms for sliding and tilting to each axis. Especially, the tilting mechanisms use for the adjustment of final setting of the blankets. As a lifting mechanisms of the blankets, a telescopic mast and a winch system with guide rods for stable lifting are used. The role of telescopic mast is mainly to install the blankets to the vacuum vessel and that of winch system is mainly to stow the blankets into the container. This transporter can handle only one module.

1) Sliding mechanism
   Linear guide system

2) Tilting mechanism
   Load surface: spherical surface
   Driving mechanism: jack up/down

IV.10.2 Gripping equipment

The detail design of the required gripping equipment has not been yet addressed, and is dependent on the segmentation scheme chosen. The design must take into account the irregular shapes of the several modules, their weight and centre-of-gravity, and the surface available for gripping. In general the shield plug and outboard centre modules must be gripped from the top, the lateral outboard blankets from the side, and the inboard modules from the top.

IV.10.3 Pipe handling

Approximately forty pipes are required in each machine sector to supply the fluid services to the blanket modules. A plan view of a typical routing is shown in Figs IV.10.4 and IV.10.5. The top port is arranged so that access to the pipes can be obtained from above without breaking of the seals to the plasma vacuum zone; thus pipe cutting, welding, and pressure testing after welding can be accomplished without danger of contamination of this region. The layout shown was developed to allow sufficient spacing between the pipes for the use of remote pipe
cutters/welders as shown in Fig. IV.10-6. Laser welding from inside the pipe as well as external automatic welding is being studied. Since the pipe joints are isolated from the plasma by independent welded seals, the use of mechanically sealed joints for the pipes can also be considered. Conventional auto welders/cutters for pipe and port lip-seal are shown in Figs IV.10-7 and IV.10-8.

IV.10.4 Container/shroud

When removed from the reactor assembly, the individual blanket modules must be contained in a sealed enclosure for transportation to the hot cell. A flexible covering concept has been developed for providing this function. In addition to providing the required containment, the enclosure must provide removal of the after-heat present in the blankets, contain tools for the pipe and vacuum seal cutting/welding, provide a method of transferring the weight of the contained components to the external building crane, and provide a double door seal to the vacuum vessel port. In order to simplify the design requirements and minimize handled weight, the containers would be sized for individual blanket modules. The overall concept is summarized in Fig. IV.10-9. Studies are presently being conducted to identify the optimum shroud material, both metals and non-metals are being investigated.

IV.10.5 Double seal door

A separate double sealing door arrangement must be used with the transfer of the modules between the vacuum vessel and the transfer unit. The door provides four seals in order to contain tritium and activated dust and keep the surface clean which are exposed to the atmosphere when the container is separated. Considering the limited space available on the upper port, a hinged type double door arrangement has been proposed. Examples are shown in Fig. IV.10-10.
### IV.10.6 Impact of newly proposed blanket segmentation:

- Separated upper divertor shield from inboard blanket  
  (Figs IV.10-11 and IV.10-12)

Comparisons between integrated upper divertor shield and separated upper divertor shield to/from inboard blanket are as follows.

<table>
<thead>
<tr>
<th>Items</th>
<th>Integrated upper divertor shield</th>
<th>Separated upper divertor shield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of segmentation</td>
<td>Inboard blanket: 2</td>
<td>Inboard blanket: 2</td>
</tr>
<tr>
<td></td>
<td>Lower divertor shield: 2</td>
<td>Upper divertor shield: 2</td>
</tr>
<tr>
<td></td>
<td>Shield plug: 3</td>
<td>Lower divertor shield: 2</td>
</tr>
<tr>
<td></td>
<td>Outboard blanket</td>
<td>Shield plug: 1</td>
</tr>
<tr>
<td></td>
<td>Side: 2</td>
<td>Outboard blanket</td>
</tr>
<tr>
<td></td>
<td>Central: 2</td>
<td>Side: 2</td>
</tr>
<tr>
<td></td>
<td>Total: 11</td>
<td>Central: 2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of pipes in upper port</th>
<th>Pipe number of shield plug is tripled</th>
<th>Pipe number of inboard is doubled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Larger</td>
<td>Smaller</td>
<td>Inboard is very tight</td>
</tr>
</tbody>
</table>
Maintenability | Additional motion is required | Simpler

Locking of upper divertor shield | Locking of inboard blanket | No proposal of locking concept

Space for divertor locking & jacking system | Space available | Limited space available

Divertor back-up removal | Divertor plate can be removed with inboard blanket (see Fig.IV.10-13) | Divertor plate cannot be removed with divertor shield if permanent

Conclusions

Problem of the newly proposed blanket segmentation are difficulty of divertor back-up concept and of locking concept of the upper divertor shield.

Advantages are simpler motion for replacement and reduction of the number of the pipe of upper port.

Comparing the above items in taking into consideration that the blanket is considered as semi-permanent components which are expected to have a same life time as reactor basic machine, and blanket will be replaced only the case of unexpected accident, so it seems that the difficulty of divertor back-up and difficulty of locking concept are critical.

The following is horizontal maintenance port versus vertical port comparison. (see Table IV.10-1)
IV.11 Maintenance of LHWH and ICWH systems

1) Maintenance of LHWH system

Within the installed module, an array of waveguide extends from the vacuum windows, around shielding, and into the vacuum vessel port. Since the windows are protected by the shielding, there is no requirement for in-situ change-out. In order to track the movement of the plasma edge, especially during start-up, the waveguide array must be translated radially within the vacuum vessel/port by a linear actuator.

For complete LHWH module change-out, the vacuum pumping system and cooling pipes must first be decoupled. The inner containment bellows are then cut allowing the module, and the first inner bellows and linear actuator, to be removed to the hot cell using sealed casks.

The plasma facing end of the waveguide array (LH front surface) is subject to high duty and corresponding high wear. Consequently in-vessel methods to replace it without moving of the entire module have been investigated (See Fig. IV.11-1). A laser beam can be introduced for cutting the pipes from the inside of pipes. Once cut the in-vessel manipulator is used to remove the grill mouths and transport them to the material transfer casks installed on the maintenance port.

2) Maintenance of ICWH system

ICRH antennas for NBI supplement are arrayed in center-line horizontal ports and integrated into the adjacent outboard blanket module. ICRH antennas for NBI alternative are integrated into the outboard blanket side modules. For maintenance planning the system can be divided into two line replaceable units; the Faraday shield and antenna assembly including the power/cooling supply module. For maintenance, the two units are disconnected from outside the vacuum vessel and the Faraday shield module withdrawn from in-vessel (see Figs IV.11-2 and IV.11-3) and antenna assembly including the power/cooling module decoupled with ex-vessel techniques, i.e. manipulators, casks, etc. Lapped, spring pressure joints (i.e. mechanical plugs) are provided at the antenna to power connection for easy decoupling and internal pipe welding/cutting will be required in the cooling pipes. The in-vessel manipulator will also be required to make/break the structural connection of the Faraday shield to antenna module.
IV.12 Maintenance of diagnostics of magnetics system (see Figs IV.12-1 to IV.12-3)

1. Diagnostics system of magnetics maintenance data
a) Components to be replaced
   - Flux loop (integrated in vacuum vessel)
   - Diamagnetic loop (integrated in vacuum vessel)
   - Pick-up coil (Bp/Bn) (integrated in outboard blanket side module and inboard blanket)

b) Maintenance status and frequency
   - Flux loop
     Unscheduled (Permanent) 0/10 years
   - Diamagnetic loop
     Unscheduled (Permanent) 0/10 years
   - Pick-up coil (Bp/Bn)
     Unscheduled (Semi-permanent) 1-0/10 years

c) Components configuration, size and weight
   - Flux loop
     (Toroidal loop located inboard and outboard inside of vacuum vessel).
     Cross section: 8mm diameter (TBD)
     Number: inboard, 10 loops (TBD)
     Outboard, 10 loops (TBD)
     Weight: (TBD)
   - Diamagnetic loop
     (Poloidal loop located inside of vacuum vessel at the shadow of TF coils).
     Cross section: 20 mm x 50 mm (TBD)
     Number: 16 (TBD)
     Weight: TBD
   - Pick-up coil (Bp/Bn)
     (Integrated in outboard blanket side module and inboard blanket)
     Number: TBD
     Weight: 80 ton (outboard blanket side module)

d) Environment condition during maintenance
   - Atmosphere Inert gas/air
   - Pressure TBD
   - Temperature TBD (20 degree)
- Radiation (one day after shut down dose rate)  
  TBD
- Contamination  
  Dust and tritium
- Magnetic field  
  TBD
- Humidity  
  TBD

2. Maintenance requirements
- No removal/installation for the flux loop, several redundant flux loops should be provided from the beginning.
- No removal/installation for the diamagnetic loop, several redundant diamagnetic loops should be provided from the beginning.
- Remote removal/installation of the pick-up coils integrated in outboard blanket side modules and inboard blanket.
- Remote transfer of the components without spread of contamination into the hot cell through the transfer hatch.
- When the vacuum vessel is open, consideration should be given to the use of an inert gas.
- A double door system is necessary when local containment is required for maintenance/transfer of components.

3. Maintenance scheme
a) Pick-up coil (Bp/Bn) integrated in outboard blanket side module and inboard blanket.

Disassembly
- After shut down, warm up SC coil system, start baking and the cooling of decay heat.
- Fill the vacuum chamber with air or inert gas
- Disconnect the bolts on the access door of cryostat
- Cut the vacuum seal on the access door of vacuum vessel
- Remote the access door of vacuum vessel
- Cut the cooling pipe
- Remove the pipes
- Disconnect the shield plug, remove the shield plug
- Release locking system, remove the outboard center module
- Release locking system, remove the outboard side module

Assembly
- Install the new outboard blanket side module, drive locking system
- Install the shield plug, connect then shield plug
- Weld the cooling pipe
- Install the access door of vacuum vessel
- Weld the vacuum vessel on the access door of vacuum vessel
- Connect the bolts on the access door of vacuum vessel
- Bake, evacuate and perform NDT
- Remove the container for blanket replacement
- Install the access door of cryostat
- Weld the vacuum seal on the access door of cryostat
- Connect the bolts on the access door of cryostat
- Evacuate and perform NDT

6. Required remote handling equipment
- Crane
- Blanket handling device with container
- Viewing and inspection system
- Pipe cutting/welding equipment
- Gripper of blanket

IV.13 Maintenance of neutron diagnostics system (see Figs IV.13-1 and IV.13-2)

1. Neutron diagnostics system maintenance data
a) Components to be replaced
- Neutron diagnostics large module
  (including Front shield, 13 Collimators and jacket).
- Neutron diagnostics small module-A
  (including 13 polyethylene radiators, 13x10 sensors (Si-SSD), 13 neutron dumpers)
- Neutron diagnostics small module-B
  (including 13 polyethylene radiators, 13 scintillators, 13 neutron dumpers)

b) Maintenance status and frequency
- Neutron diagnostics large module
  Unscheduled (Semi-permanent) 1-0/10 years
- Neutron diagnostics small module-A
  Scheduled 1-2/10 years
- Neutron diagnostics small module-B
  Scheduled 1-2/10 years
c) Components configuration, size and weight

- Neutron diagnostics large module
  3.4m x 4.5m x 0.6m, 30 ton
- Neutron diagnostics small module-A
  3.4m x 1.0m x 0.2m, 5 ton
- Neutron diagnostics small module-B
  3.4m x 1.0m x 0.2m, 5 ton

d) Environmental condition during maintenance

- Atmosphere Inert gas/air
- Pressure TBD
- Temperature TBD (20 degree)
- Radiation (1 day after shut down dose rate) TBD
- Contamination Dust and tritium
- Magnetic field TBD (none)
- Humidity TBD

2. Maintenance requirements

- Remote removal/installation of neutron diagnostics large module
- Remote removal/installation of neutron diagnostics small module-A
- Remote removal/installation of neutron diagnostics small module-B
- Remote transfer of the components without spread of contamination into the hot cell through the transfer hatch.
- Remote inspection, leak detection, welding/cutting and flange connection/disconnection.
- When the vacuum vessel is open, consideration should be given to the use of an inert gas.
- A double door system is necessary when local containment is required for maintenance/transfer of components.

3. Maintenance scheme

a) Neutron diagnostics large module

  Disassembly
  - Bake out the components in the vacuum vessel and remove the decay heart
  - Attach the large module container to the access port
  - Open the double seal door
  - Disengage the bolts
- Drain the cooling pipes, disconnect the cooling pipe and set the cooler to the pipe if required.
- Remove the large module, close the double door and transfer it with container to the hot cell.

Reassembly
- Install the new large module
- Connect the bolts
- Connect the cooling pipes and perform the leak test
- Close the double seal door
- Bake and evacuate

b) Neutron diagnostics small module-A and -B

Disassembly
- Bake out the components in the vacuum vessel and remove the decay heat.
- Attach the small module container to the access port
- Open the double seal door
- Disengage the bolts
- Drain the cooling pipe, disconnect the cooling pipes.
- Remove the small module
- Close the double seal door

Assembly
- Open the double seal door
- Install the new small module
- Connect the cooling pipes perform leak test.
- Connect the bolts
- Close the double seal door
- Bake and evacuate

4. Equipment requirements
- The location and storage of remote handling equipment should be such that activation due to neutron scattering is prevented during normal operation of reactor. (A diagnostics port section may have a sufficient shielding capacity to have a personnel access after one day reactor shut down, the remote handling equipment can be stored in diagnostics room just behind the diagnostics port).
- The area where the maintenance of remote-handling equipment will be carried out should allow personnel access.
5. Equipment function and description
- Crane:
  which transports the large and small module container.
- Large module container:
  which equips some handling equipments for pipe connection/disconnection and for connecting/disconnecting of the bolts.
- Small module container:
  which equips some handling equipment for pipe connection/disconnection and for connecting/disconnecting of the bolts.
- End effector/tool:
  - Transport rig of large module container
  - Transport rig of small module container

IV.14 Maintenance procedure and equipment of neutral beam injector

1. Maintenance Procedure

The procedures given below are for a concept where the beamline module and ion source module are cylindrical vessels of the same diameter and connected via a double door assembly.

a) Ion source unit replacement

Disassembly
(C0.-C4: common to upper, middle, and lower ion source subassemblies)

C0. Tokamak and neutral beam injector shut down.
C1. Stop the operation of cryopumps and warm them up. Evacuate deuterium and tritium gases desorbed from the cryopanels, by roughing pumps (turbo-molecular pumps, mechanical booster pumps, and rotary pumps).
          Transfer the gases to the isotope separation section of the fuel cycling system.
          Then, close the valves of the roughing pumps.
C2. Introduce inert gas (ex. N₂ gas) into the ion source unit and the beamline module up to 1 atm.
C3. Close the source maintenance valves installed in between the ion source unit and the beamline unit.
C4. Disconnect electric service lines, water cooling lines, and gas service lines connected to the ion source unit (see Figs IV.14-1(a) and IV.14-1(b)), making use of remote handling devices, end effecters, and special tools, etc.

(In case of upper ion source subassembly)

5. Lift up one block of the radiation shield ceiling above the ion source unit by the overhead crane.
   Store the one block of the ceiling, temporarily at other space.

6. Hold the weight of the upper ion source unit by the crane with a weight balancing tool.

7. Separate the ion source unit from the beamline unit, by disconnecting the source maintenance valves (double door system, see Fig. IV.14-2).

8. Slightly move the ion source unit backwards in horizontal direction and lift it up by the crane.

(In case of middle or lower ion source unit)

5. Separate the ion source unit from the beamline unit, by disconnecting the source maintenance valves (see Fig. IV.14-2).

6. Move the ion source unit backwards in the beam axis direction on the rail, using an auto-mobile type truck installed below the ion source unit.
   Stop the truck when it reaches the stoppre position.

7. Push down four wheels for side motion from the truck by motors, until the wheels hold the whole weight of the ion source unit and the truck. (Change of the wheels for beam axial motion to those for side motion).

8. Move the ion source unit sidewards on the side-ways rail, using the same truck.
   Stop the truck when it reaches the stopper position.

9. Lift up one block of the radiation shield ceiling above the ion source unit, and lay it down at other space by the overhead crane.

10. Lift up the ion source unit by the crane.
(C5.-C7.: common to upper, middle, and lower ion source units)

C5. Transfer the ion source unit in horizontal direction and lay it down in a cask prepared on the ceiling in advance by the crane.

C6. Lift up the cask and transport it of the hot cell through the hatch, by the crane.

C7. Open the cask and repair the ion source unit in the hot cell.

Assembly

(C1.-4.: common to upper, middle, and lower ion source subassemblies)

C1. Close the source maintenance valve of the repaired ion source unit, in the hot cell.

C2. Introduce inert gas into the repaired ion source unit, in the hot cell.

C3. Lay down the ion source unit in the cask, in the hot cell.

C4. Transport the cask from the hot cell to on the ceiling of the NBI room, through the hatch.

(In case of upper ion source unit)

5. Lift up one block of radiation shield ceiling above the position where the repaired ion source unit is to be attached, by the crane.

6. Open the cask and lift up the repaired ion source unit on the ceiling, by the crane.

7. Transfer the ion source unit horizontally to the opened position of the ceiling, get it down and lay it down on the truck.

8. Fix on the ion source unit to the truck, and release the crane from the ion source unit.

9. Lift up the one block of the ceiling and return it to the original position.

10. Move the repaired ion source unit sideways on the side-ways rail, using the truck.

   Stop the truck when it reaches the stopper position.

11. Withdraw the four wheels for side motion into the truck by motors, until the whole weight is held by the four wheels for beam axial
motion.

12. Move the truck forwards in the direction of the beam axis on the rail.
Stop the truck at the appropriate position close to the beamline unit.

13. Connect the repaired ion source unit to the beamline unit by connecting the source maintenance valves (see Fig.IV.14-2).
(C5.-C.7.: Common to upper, middle, and lower ion source units)

C5. Connect electric service lines, water cooling lines, and gas service lines to the ion source unit (see Figs IV.14-1(a) and IV.14-1(b)).

C6. Open the source maintenance valves.

C7. Open the valves of roughing pumps and start to evacuate the inert gas by the roughing pumps.

b) Beamline module replacement

We describe the replacement procedure of lower beamline unit which is the most time consuming and troublesome, as the typical case.

Disassembly

0. Tokamak and neutral beam injector shut down.

1. Close the double vacuum gate valves installed in between the beamline units and the drift tubes of the vertically stacked three modules.

2. Stop the operation of all cryopumps in the three modules, and warm them up.
Evacuate deuterium and tritium gases desorped from the cryopanels, by roughing pumps.
Transfer the gases to the isotope separation section of the fuel cycling system.
Then, close the valves of the roughing pumps.

3. Introduce inert gas into all the three modules up to 1 atom.

4. Close the source maintenance valves of all the three modules.

5. Disconnect electric service lines, water cooling lines, liquid helium service lines, and gas service lines connected to all the
three beamline units.

6. Lift up a few blocks of the radiation shield ceiling above the modules by the overhead crane. Store the blocks, temporarily at other space.

7. Hold the weight of the upper beamline unit by the crane with a weight balancing tool.

8. Separate the upper beamline unit from the upper ion source unit, by disconnecting the source maintenance valves (see Fig. IV.14-2).

9. Separate the upper beamline unit from the upper drift tube, by disconnecting the double vacuum gate valves (see Fig. IV.14-2). After this, the bellows attached in the middle of the double vacuum gate valves should be shrunk to keep sufficient clearance between the drift tube and the beamline unit.

10. Lift up the upper beamline unit and then transport it to other space. Store it there temporarily.

11. Disconnect and remove two concrete bridges which have supported the weight of the upper beamline unit, with remote handling devices and the crane. Store the two concrete bridges, temporarily at other space.

12.-16. Similar to procedures 7.-11. except that the term "upper" should be changed to "middle"

17.-19. Similar to procedures 7.-9. except that the term "upper" should be changed to "lower".

20. Lift up the lower beamline unit by the crane.

21. Lay down the lower beamline unit in the cask prepared in advance on the floor of the NBI room.

22. Lift up the cask and transport it to the hot cell through the hatch by the crane.

23. Open the cask and repair the lower beamline unit in the hot cell.

During the repairment of the lower beamline unit in the hot cell, the following procedures are necessary to return the middle and the upper modules as they were.

24. Lift up the two concrete bridges for supporting the weight of the middle beamline unit, which was temporarily stored, and
transport them to the original positions by the crane.
Fix the two bridges to the support columns.

25. Lift up the middle beamline unit temporarily stored and transport it to the original position by the crane.
Hold the weight of the middle beamline unit by the crane.

26. Connect the middle beamline unit with the middle drift tube, by connecting the double vacuum gate valves (see Fig. IV.14-2).

27. Connect the middle beamline unit with the middle ion source unit, by connecting the source maintenance valves (see Fig. IV.14-2).

28. Release the crane from the middle beamline unit.

29.-33. Similar to procedures 24.-28. except that the term "middle" should be changed to "upper".

34. Lift up the few blocks of the radiation shield ceiling temporarily stored, and return them to the original positions.

35. Connect electric service lines, water cooling lines, liquid helium service lines, and gas service lines to the middle and the upper beamline units.

36. Open the source maintenance valves of the middle and the upper modules.

37. Evacuate inert gas by roughing pumps.

Assembly

0.-16. Similar to procedures 0.-16. in disassembly case except that the term "three modules" should be changed to "upper and middle modules".

17. Close the source maintenance valve and the double vacuum gate valve of the repaired lower beamline unit in the hot cell.

18. Introduce inert gas into the lower beamline unit in the hot cell.

19. Lay down the lower beamline unit in the cask in the hot cell.

20. Transport the cask from the hot cell to the NBI room, through the hatch, by the crane.

21. Open the cask and lift up the lower beamline unit over the radiation shield ceiling, by the crane.

22. Transfer the lower beamline unit horizontally to another opended position of the ceiling, and get it down to the original posi-
tion, by the crane.
Hold the weight of the lower beamline unit by the crane.

23. Connect the repaired lower beamline unit with the lower drift tube, by connecting the double vacuum gate valves (see Fig. IV.14-2).

24. Connect the lower beamline unit with the lower ion source unit, by connecting the source maintenance valves (see Fig. IV.14-2)

25. Release the crane from the lower beamline unit.

26.-36. Similar to procedures 24.-34. of disassembly case.

37. Connect electric service lines, water cooling lines, liquid helium services lines, and gas service lines to all the three beamline units.

38. Open the source maintenance valves of all the three modules.

39. Evacuate inert gas by roughing pumps.

2. Concepts of connection/disconnection of standard components and equipment

a) Electricity

For low current feed, SMA (Shape Memory Alloy) can be used for connection/disconnection of electric cables.
- Sleeve type SMA (Ni-Ti alloy)

Figure IV.14-3 shows Sleeve type SMA cable connection and disconnection. The SMA sleeve shrinks (Austenite phase) at temperature above 45°C (connection), and enlarge (Martensite phase) at temperature below 25°C (disconnection). Thus, connection/disconnection of the electric cables can be done by only cooling/heating SMA sleeve.

R&D activities on the sleeve type SMA of up to 20 to 30 mm in diameter is in progress.

- SMA bolt

Figure IV.14-4 shows concept of the SMA bolt. One metal plate is sandwiched between other two metal plates which are connected with each other by SMA bolts. When the SMA bolts are heated up, the length of the SMA bolts decreases at a certain temperature and the sandwiched metal plate is fastened by other two plates (connection). On the contrary, if the SMA bolts are cooled down below a certain temperature, the length of the SMA bolts increases. Then, the sandwiched metal plate is released.
from other two plates (disconnection).
- Quick couplers
  Quick couplers such as Solton couplers are commercially available
  for relatively low current and low voltage. Resistance against neutrons
  and gamma rays should be checked.

b) Water

- Flange connection/disconnection
  Figure IV.14-5 show the concept of flange connection/disconnection
  for water service line. Double valve system is necessary to minimize
  leak of contaminated water during disconnection of the line.
- Quick couplers
  Various quick couplers are commercially available for relatively
  small water flow rate. Resistance against neutrons and gamma rays
  should be checked.
- Laser welding/cutting
  Figure IV.14-6 shows the concept of laser welding/cutting of water
  pipe. This technique can be applicable to relatively large diameter
  pipe (about 200 mm in diameter).

c) Gas

- Flange connection/disconnection
  Similar to water service lines.
- Wilson seal
  Usually, Wilson seal uses viton O-ring. Thus, Wilson seal can be
  used only at the place where radiation dose rate is very low.
- Swedgelock
  Swedgelock is commercially available gas connectors. This connec-
  tor is metal seal type and seems to be resistive against radiations.
  Improvement to fit remote handling is necessary.

d) Vacuum

- Flange connection/disconnection
  Similar to water service lines.
e) Liquid helium

To keep thermal insulation, coaxial pipe structure is necessary for liquid helium service line. The concept of connection and disconnection of the coaxial structures suitable for remote handling should be developed.

3. Description of remote handling equipments

a) General requirement to remote handling equipments

- The location and storage of remote handling equipment should be such that the activation due to neutron scattering is prevented during normal operation of NBI system.
- The area where the maintenance of remote handling equipment will be carried out should allow personnel access.
- Some form of gaitering or flexible diaphragm should be incorporated when feasible over the remote handling equipment to prevent the ingress of contamination and facilitate cleaning.

b) Equipment function and description

- Overhead crane (200 ton): which transports the ion source unit, the beamline unit, the weight supporting bridge, the blocks of radiation shield ceiling, the cask, etc.
- Atuo-mobile type truck: which supports the weight of the middle or the lower ion source unit, during operation of NBI system. If any failure occurs in the ion source unit, the truck moves on the rail, in the direction of the beam axis as well as in the direction perpendicular to the beam axis, to the position where the overhead crane is accessible. This truck has two seats of wheels: one for movement in beam axis direction, another for side-ways motion. The latter can be pushed down and retracted by a motor drive jack system (see Figs IV.14-7 and IV.14-8).
- Bridge mounted overheat telescopic mast: which has a master-slave manipulator or pwrp manipulator at the end
of an arm for inspection, leak detection, welding/cutting machine setting, and flange connection/disconnection.

- End effector/tool:
- transport rig of ion source unit
- transport rig of beamline unit
- end effector/tool for electrical connection, pipe connection etc.

4. Hot cell requirements

- An inner space about 5 m wide, 5 m high, and 20 m long is necessary to contain and repair a beamline unit (4 m in outer diameter, 12 m long) or an ion source unit (4 m in outer diameter, 5 m long).
- A trolley and trolley tracks are necessary to move a beamline unit (about 70 ton) in one direction.
- Inner cranes (about 10 ton) are necessary to extract and transport various components (ion source body, neutralizer, beam dump, calorimeter, etc.).
- Surrounding walls and windows with sufficient thickness to shield gamma rays from beamline unit or ion source unit are necessary.
- The hot cell is tightly closed and pumped to keep inner pressure slightly lower than atmosphere.
- Master-slave type manipulators, power manipulators, and various end effectors/tools are necessary to repair the components in the beamline unit, and the ion source unit.
- Welders, cutters, inspecting devices, etc. are also necessary in the hot cell.

IV.15 Assembly of alternate vacuum vessel concept

Alternate concepts for the design and assembly of the vacuum vessel has been studied. The design have double thin waists to simultaneously obtain in the required toroidal resistance and the double all welded vacuum/tritium boundary. This concept split the vacuum vessel toroidal-ly into only 16 equal sectors, versus the 16 parallel and 16 wedge sectors of the reference concept. In this segmentation scheme the required field joint is in the midplane between the TF Coils, and toroid-ally bisects the ports. Each vacuum vessel sector is installed into the bore of a TF Coils and assembled into its installed position with
the TF Coil. From an Assembly and Maintenance perspective, this concept differ only of shield installed with the vacuum vessel by introducing additional sections to form a separate structural shell (to support the blankets) within the vessel.

In addition to the configuration/structural advantages discussed in the Containment Structures section, this concept has features which can be beneficial to Assembly and Maintenance.

- Fewer, lighter pieces must be handled
- Fewer field joints
- Fit up tolerances at assembly are less severe since sections are welded (i.e. no bolts or shear keys)
- The interspace between walls, usually used for cooling passages, can be evacuated and used for leak checking of the two walls independently while still in the workshop. Since the field joints used to connect adjacent sectors contains independent inner and outer splice plates, a similar void area is formed that can be also be used for leak checking. This means that individual vacuum vessel sectors can be leak checked without having a complete toroidal assembly.

IV.15.1 Installation of alternate VV concept

The overall ITER assembly operations are as described in Section III.5. The steps required to assemble the vacuum vessel are shown in Figures IV.15-1 and IV.15-2.

1) The assembly unit of a TF coil, 1/16 of the vacuum vessel, and a 15.5 degree sector of permanent shield is preassembled.
2) The units are sequentially installed onto the machine support structure.
3) The vacuum vessel sectors are aligned and welded together, inner and outer walls, in the gaps of the shield sectors.
4) The 7 degree sectors are installed to complete the torus and welded in place.
5) The cooling pipes connecting the 7 degree sectors to the 15.5 degree sectors are installed.
6) Continue the machine assembly as in the reference case.
IV.15.2 On-site testing of SC and VV

The on-site TF and PF coil testing under cryogenic temperature should be performed to fined out the initial failure of the magnet and replace the module because some troubles in the magnet are possibly foreseen. The replacement of the magnet, however suffers from many drawbacks if the connection of the vacuum vessel and ports has been completed as example of reference VV concept.

Here proposed are an assembly procedure to have priority on purging the magnet system of the initial failure and making replacement of the magnet module easy for the case of alternative VV concept.

The coil test is carried out by evacuating cryostat vessel and cooling down the magnet system to the cryogenic temperature. The penetrations of the cryostat vessel are covered by the temporary caps to plug them. After the coil test, the VV sectors and ports are connected together. Then the final leak test is performed to check the total outgassing characteristics of the vessel (see Fig. IV.15-3).

IV.16 Disassembly/reassembly of center solenoid

1. Maintenance requirements
   
   - Only mechanical attachment of the Center Solenoid to the torus structure is recommended as a maintenance operation in cryostat.
   - Complicated maintenance operation such as electrical leads connection/disconnection in side of the cryostat should be limited.
   - Connection of electrical leads at the bottom cryostat port is recommended to be performed outside of biological shield because of the wider maintenance space and possibility of hands-on access.

2. Center solenoid replacement procedure (Fig. IV.16-1)

Disassembly
   
   - After reactor shut down, warm up SC coil system and start the cooling of the decay head of reactor in vessel components.
   - Disconnect the electrical leads of center solenoid from outside of the biological shield at the bottom of cryostat.
   - Disconnect the vacuum seal between cryostat and electrical lead cover.

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Cut the upper cryostat port vacuum seal
- Disconnect the bolts on the upper port of cryostat
- (Thermal shield removal)
- Remove the upper port of cryostat
- Disconnect the bolts connecting the center solenoid to the adjacent structure.
- Gripp the center solenoid
- Remove the center solenoid
Assembly is reverse procedure of disassembly

3. Required remote handling equipment

- Crane and rig: lifting and transporting of the center solenoid.
- Large telescopic mast with manipulator/end-effector at the end.
- Welder/cutter of seal, electrical leads
- etc.

IV.17 Cooling pipe & Coil services maintenance

1) Cooling pipes

Table IV.17-1 lists all the cooling pipes connected to the in-vessel components that must be remotely maintained. The in-vessel components can be disassembled only after these pipes are remotely cut. Many of them are located in the top vertical port as shown in Fig. IV.17-1. During maintenance, the manipulator will access the port after opening of the cryostat and the pipes will be cut/welded by the cutter/welder. It may be necessary to work from inside the pipe if sufficient space is not available on the outside. In any case the divertor piping must be cut/welded from the inside near to the divertor.

In the outboard region the cooling pipes for the lower divertor plate and center/bottom blanket module will be installed in the vertical lower port, as shown in Fig. IV.17-2. In this case, the pipe/cutter/welder will be accessed from the bottom of the machine. Cutting/welding from inside of the pipes will be required for the divertors. The possibility of putting the pipes for the center/bottom blanket module into the horizontal ports has also been discussed. The final decision will be based on the detailed structural design taking
into account the shielding requirements, especially for the NBI port region.

2) Coil services

Table IV.17-2 shows the coils services including the superconducting current feeder connecting the magnet and current lead: Figures IV.17-3 and IV.17-4 show the typical layout of the coil services with key features as follows:

- The cryogenic piping should be surrounded by an intermediate thermal shield somewhere in the vacuum space in order to decrease the thermal radiation heat.
- The current feeder inside the cryostat is superconducting (cooled by 4-K helium) and has to be thermally insulated the same as the cryogenic pipe.
- For the lower divertor magnet (PF-5L), the piping and current feeders must be cut and partially removed to minimize the space for moving the magnet.

High reliability is necessary for the current feeder joints because of high current and voltage operation of the superconducting magnet system. Therefore, hands-on maintenance of all joints of the current feeder and cryogenic pipe is preferrable to remote maintenance. In this case, however, it will be required to have sufficient space for personal access inside the cryostat. Based on the preliminary nuclear shield analysis, it may be possible to keep the personal access area in lower region of the cryostat by installing local shielding.

In parallel with this personal maintenance scheme, the detailed pipe layout and structural design drawings for remote handling scheme has been prepared and discussed. The final decision will be based on the detailed nuclear analysis in future design work. The R&D effort for the reliable joint technique is significant in order to support the feasibility and availability of the ITER machine.
IV.18 Main crane concept

The followings are the basic device components list and weight.

Cryostat

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segmentaton: TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>TF coils (1/16)</td>
<td>470 ton</td>
</tr>
<tr>
<td>Vacuum vessel (VV)</td>
<td></td>
</tr>
<tr>
<td>Wedged segment</td>
<td>80 ton</td>
</tr>
<tr>
<td>Parallel segment</td>
<td>180 ton</td>
</tr>
<tr>
<td>TF coil+Parallel segment of VV</td>
<td>550 ton</td>
</tr>
<tr>
<td>Inter coil structure (1/32)</td>
<td>45 ton</td>
</tr>
<tr>
<td>Center solenoid</td>
<td>720 ton</td>
</tr>
</tbody>
</table>

PF coils

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF5 (1/2)</td>
<td>140 ton</td>
</tr>
<tr>
<td>PF6 (1/2)</td>
<td>380 ton</td>
</tr>
<tr>
<td>PF7 (1/2)</td>
<td>230 ton</td>
</tr>
<tr>
<td>PF5+PF7</td>
<td>610 ton</td>
</tr>
</tbody>
</table>

PF magnet supports (1/16)

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inboard blanket/shield (1/32)</td>
<td>40 ton</td>
</tr>
<tr>
<td>Outboard side blanket (1/32)</td>
<td>80 ton</td>
</tr>
<tr>
<td>Outboard center top/bottom (1/32)</td>
<td>64/35 ton</td>
</tr>
</tbody>
</table>

The followings are heavy components to be lifted by crane for assembly and for replacement.

- TF coil+Vacuum Vessel parallel segment:
  470 ton+80 ton=550 ton
  For initial assembly and replacement (unscheduled)
- Center solenoid:
  720 ton
  For initial assembly and replacement (scheduled)
- PF6+PF7:
  610 ton
For initial assembly and replacement (unscheduled)

To fulfill the above requirements, the maximum required capacity of crane will be about 800 ton.

However, for transport of other components such as container of blanket, etc. which will happen more frequently, the use of 800 ton is not convenient. Lower capacity crane like 100 ton crane will be more convenient. Therefore, the first option will be to have 800 ton crane and 100 ton crane at different level.

A proposal for using two 400 ton cranes instead of one 800 ton crane was proposed. For the transport of the blanket, 400 ton crane is planned to be used.

The following is an comparison of two options.

<table>
<thead>
<tr>
<th></th>
<th>800 ton +100 ton</th>
<th>400 ton x 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact to building</td>
<td>building height</td>
<td></td>
</tr>
<tr>
<td>Failure of crane</td>
<td>800 ton crane can rescue 100 ton crane</td>
<td>400 ton crane can rescue each other</td>
</tr>
<tr>
<td>Use of crane for usual maintenance</td>
<td>100 ton crane</td>
<td>400 ton crane</td>
</tr>
<tr>
<td>Use of crane for assembly and accidental replacement</td>
<td>800 ton crane with assistance of 100 ton crane</td>
<td>two 400 ton cranes</td>
</tr>
<tr>
<td>Transport rig</td>
<td>Smaller</td>
<td>Larger</td>
</tr>
</tbody>
</table>

Conclusions:

Use of 800 ton crane and 100 ton crane is more flexible compared to the use of two 400 ton cranes from the view point of maintenance. If the impact on building height/structure is negligible, the first option will be recommended.
IV.19 Carbon dust cleaner for ITER

One of the serious problems for ITER is a large amount of carbon dust (a few kg) generated by heat loads to the first wall when a plasma is disrupted. The usual cleaning system by air cannot be applied in the vacuum vessel (V.V). Therefore it is difficult to remove the carbon dust. Here, the electrostatic method for cleaning carbon dust is proposed as a candidate option.

Figure IV.19-1 shows the illustration of the carbon dust cleaner. The carbon dust cleaner is installed at the end effector of a vehicle and put into V.V through the horizontal port. The system can be operated during F/W and/or divertor maintenance. The schematic drawing of the carbon dust cleaner is shown in Fig. IV.19-2. The principle of the carbon dust cleaner is simple. The belt conveyor is charged up by the electrode and carbon dust is collected owing to the electrostatic force $F$. The belt conveyor is rotated by the rotator and is discharged by the other electrode, then the carbon dust falls on the trash.

The required voltage of the electrode is determined by the shape and size of the carbon dust and the design of the cleaner. Typical voltage of the electrode is estimated as follows. The electrostatic force $F$ for a small carbon sphere is represented by

$$F = 2\pi a^3 \varepsilon_0 \text{grad} \mathbf{E}^2$$

where $a$ is a radius of the carbon sphere, and $\varepsilon_0$ is dielectric constant of vacuum, and $E$ is the electric field. The gravity of the carbon sphere is represented by

$$F_g = \frac{4}{3}\pi a^3 \zeta g$$

where $\zeta$ is the density of carbon, and $g$ is the gravity constant. If $F = F_g$, then $\text{grad} \mathbf{E}^2$ is $2\zeta g/3\varepsilon_0 (\sim 1.5 \times 10^{15})$. The effective length of the carbon dust cleaner may be about 0.01~0.1 m. Therefore, the voltage is about $10^4$~$10^6$ V for the small carbon sphere.

If the cleaner is adjusted precisely by end effector and/or vehicle, the effective length of the cleaner may be about 0.01 m. Then the required voltage is about $10^4$ V. The high voltage circuit can be
used to charge up the belt conveyor. However, if the cleaner is not adjustable precisely, the required voltage is about $10^6$ V. Then the charge up of belt conveyor must be owing to the friction with the electrode and the belt conveyor.

IV.20 Conclusions and future needs

Conceptual design activities on ITER have resulted in the definition of a maintenance approach designed to match the different levels of requirements on the various reactor systems. In order to maximize on-line availability, in-vessel manipulators are being designed and developed for replacement of short lived components located within the vacuum vessel, and back-up maintenance procedures are required. For the longer life components, the basic machine configuration has been developed to allow for their replacement by use of overheat cranes outfitted with special remote handling tools. Preliminary design for maintenance of ex-vessel systems is being carried out in parallel with their definition and design.

Though the following more detail comparative studies between options are required for;
- Viewing system access port options (vertical port, horizontal maintenance port or other horizontal port)
- Maintenance port shield plug location (at the level of blanket or outside of cryostat),
- Impact of double containment of vacuum vessel on the maintenance
- Main crane options (single heavy crane or double cranes),
- Back-up options for divertor replacement,
- Inert gas options during maintenance operations,

the basic design concepts presented have been developed during the Conceptual Design Phase. They are based on present technology and are intended to establish a reference concept to be updated as required by future progress. Their feasibility will be investigated and new technology introduced and incorporated through a R&D program. A two stage R&D program is planned; prototype equipment functional tests using full scale mock-ups and a full scale integration demonstration test facility with real components, i.e. vacuum vessel with ports, blanket modules, divertor modules, armor tiles, etc. Crucial in-vessel and ex-vessel operations and the associated RH equipment,
including handling of divertor plates and blanket modules will be demonstrated in the first phase. These tasks will provide the data base required to proceed with the engineering design of the device. Finally, the second phase will demonstrate the ability of the overall system to execute the required maintenance procedures as well as evaluate the performance of the prototype equipment; manipulators, viewing system, transporters, etc. before finalizing the fabrication design.

References

Table IV.7-1 Toroidal segmentation versus poloidal segmentation

<table>
<thead>
<tr>
<th></th>
<th>Poloidal Segmentation</th>
<th>Toroidal Segmentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematics</td>
<td>more complex</td>
<td>simpler</td>
</tr>
<tr>
<td></td>
<td>(addition rotation)</td>
<td></td>
</tr>
<tr>
<td>Pipe length on divertor</td>
<td>same as toroidal</td>
<td>----------</td>
</tr>
<tr>
<td>on shield</td>
<td>segmentation for upper inboard divertor</td>
<td></td>
</tr>
<tr>
<td>Divertor plate gripping</td>
<td>only schematic</td>
<td>conceptual design</td>
</tr>
<tr>
<td>scenario</td>
<td>no conceptual design</td>
<td>exists</td>
</tr>
<tr>
<td>Clearance between divertor plate and surrounding components</td>
<td>large clearance +/-150mm with support</td>
<td></td>
</tr>
<tr>
<td>Replacement scenario</td>
<td>Removal of inboard divertor after removal of outboard divertor</td>
<td>----------</td>
</tr>
<tr>
<td>Sacrification of divertor plate</td>
<td>Toroidal cut &amp; Large poloidal cut</td>
<td>Toroidal cut</td>
</tr>
<tr>
<td>Lateral support at entry part of port at 90 degree</td>
<td>Difficult for vehicle</td>
<td>Easy for vehicle</td>
</tr>
</tbody>
</table>
Table IV.10-1  Horizontal port vs vertical port

<table>
<thead>
<tr>
<th>Interaction with maintenance port</th>
<th>Horizontal maintenance port</th>
<th>Vertical port</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location of viewing system</td>
<td>Inside of viewing cask located inside of maintenance cask</td>
<td>Inside of viewing cask located outside of cryostat</td>
</tr>
<tr>
<td>Maintainability of viewing system</td>
<td>Removal of viewing cask from inside of maintenance cask after cutting of cooling pipe</td>
<td>Removal of viewing cask outside of cryostat without cutting cooling pipe</td>
</tr>
<tr>
<td>Intervention of in-vessel manipulator</td>
<td>After removal of viewing cask with shield plug after cutting of cooling pipe of shield plug</td>
<td>Rapid intervention</td>
</tr>
</tbody>
</table>
### Table IV.17-1 Estimate of heat load distribution/coolant flow rate/
pipe diameter

<table>
<thead>
<tr>
<th>Region</th>
<th>Heat Load [MW]</th>
<th>Coolant Temp. [°C]</th>
<th>Number of Modules</th>
<th>Flow Rate [t/h]</th>
<th>Flow Rate [m³/s]</th>
<th>Water Supply/Return Pipe Diameter*1 [mm]</th>
<th>Velocity [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface Nuclear</td>
<td>Total</td>
<td>In-Out</td>
<td>T</td>
<td>Total per Module</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inboard</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First wall</td>
<td>26</td>
<td>92</td>
<td>60-100</td>
<td>40</td>
<td>32</td>
<td>1972</td>
<td>0.0176</td>
</tr>
<tr>
<td>Blanket</td>
<td>-</td>
<td>183</td>
<td>60-100</td>
<td>40</td>
<td>32</td>
<td>3920</td>
<td>0.0351</td>
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<tr>
<td>Shield</td>
<td>-</td>
<td>110</td>
<td>60-100</td>
<td>40</td>
<td>32</td>
<td>2350</td>
<td>0.0211</td>
</tr>
<tr>
<td>Shield Plug*2</td>
<td>-</td>
<td>110</td>
<td>60-100</td>
<td>40</td>
<td>32</td>
<td>2350</td>
<td>0.0211</td>
</tr>
<tr>
<td>Inboard Total</td>
<td>26</td>
<td>430</td>
<td>60-100</td>
<td>40</td>
<td>32</td>
<td>962</td>
<td>0.00863</td>
</tr>
<tr>
<td>Outboard</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side Module</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First Wall</td>
<td>52</td>
<td>221</td>
<td>60-100</td>
<td>40</td>
<td>32</td>
<td>4740</td>
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<tr>
<td>Blanket</td>
<td>-</td>
<td>468</td>
<td>60-100</td>
<td>40</td>
<td>32</td>
<td>10000</td>
<td>0.0887</td>
</tr>
<tr>
<td>Shield</td>
<td>-</td>
<td>13</td>
<td>60-100</td>
<td>40</td>
<td>32</td>
<td>279</td>
<td>0.00249</td>
</tr>
<tr>
<td>Centor/Top</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First wall</td>
<td>8</td>
<td>33</td>
<td>60-100</td>
<td>40</td>
<td>16</td>
<td>708</td>
<td>0.0127</td>
</tr>
<tr>
<td>Blanket</td>
<td>-</td>
<td>75</td>
<td>60-100</td>
<td>40</td>
<td>16</td>
<td>1610</td>
<td>0.0288</td>
</tr>
<tr>
<td>Shield</td>
<td>-</td>
<td>3</td>
<td>60-100</td>
<td>40</td>
<td>16</td>
<td>64.3</td>
<td>0.00115</td>
</tr>
<tr>
<td>Centor/Bottom</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>First wall</td>
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<td>1610</td>
<td>0.0288</td>
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<tr>
<td>Shield</td>
<td>-</td>
<td>3</td>
<td>60-100</td>
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<td>64.3</td>
<td>0.00115</td>
</tr>
<tr>
<td>Port</td>
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</tr>
<tr>
<td>First Wall</td>
<td>10</td>
<td>35</td>
<td>60-100</td>
<td>40</td>
<td>16</td>
<td>750</td>
<td>0.0134</td>
</tr>
<tr>
<td>Shield Plug*3</td>
<td>-</td>
<td>65</td>
<td>60-100</td>
<td>40</td>
<td>16</td>
<td>1390</td>
<td>0.0249</td>
</tr>
<tr>
<td>Outboard Total</td>
<td>78</td>
<td>1024</td>
<td>60-100</td>
<td>40</td>
<td>16</td>
<td>1390</td>
<td>0.0249</td>
</tr>
<tr>
<td>Divertor Plate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper</td>
<td>78</td>
<td>110</td>
<td>50-65</td>
<td>15</td>
<td>32</td>
<td>6320</td>
<td>0.0565</td>
</tr>
<tr>
<td>Lower</td>
<td>78</td>
<td>110</td>
<td>50-65</td>
<td>15</td>
<td>32</td>
<td>6320</td>
<td>0.0565</td>
</tr>
<tr>
<td>Divertor Total</td>
<td>156</td>
<td>22</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vacuum Vessel</td>
<td>-</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>260</td>
<td>1700</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*1: 50 mm of minimum inner diameter to be cut and welded from inside according to the maintenance requirements

*2: including top shielding region behind divertor

*3: behind lower divertor plate

*4: TBD for detail specification of each port (test modules, heating/current drive devices etc.)
### Table IV.17-2 Coil services layout

<table>
<thead>
<tr>
<th>REGION</th>
<th>PIPE SIZE</th>
<th>NO. OF PIPE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TF magnet</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winding supply</td>
<td>40 A</td>
<td>16</td>
</tr>
<tr>
<td>Winding return</td>
<td>50 A</td>
<td>16</td>
</tr>
<tr>
<td>Case supply</td>
<td>15 A</td>
<td>16</td>
</tr>
<tr>
<td>Case return</td>
<td>20 A</td>
<td>16</td>
</tr>
<tr>
<td>Thermal shield supply</td>
<td>15 A</td>
<td>16</td>
</tr>
<tr>
<td>Thermal shield return</td>
<td>15 A</td>
<td>16</td>
</tr>
<tr>
<td>Current feeder</td>
<td>O.D. 60 mm</td>
<td>16x2</td>
</tr>
<tr>
<td><strong>Center solenoid</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winding supply</td>
<td>40 A</td>
<td>8</td>
</tr>
<tr>
<td>Winding return</td>
<td>50 A</td>
<td>8</td>
</tr>
<tr>
<td>Structure supply</td>
<td>15 A</td>
<td>2</td>
</tr>
<tr>
<td>Structure return</td>
<td>20 A</td>
<td>2</td>
</tr>
<tr>
<td>Current feeder</td>
<td>O.D. 60 mm</td>
<td>16x2</td>
</tr>
<tr>
<td><strong>Outer PF magnet</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winding supply</td>
<td>15 A</td>
<td>6</td>
</tr>
<tr>
<td>Winding return</td>
<td>50 A</td>
<td>6</td>
</tr>
<tr>
<td>Current feeder</td>
<td>O.D. 60 mm</td>
<td>6x2</td>
</tr>
<tr>
<td><strong>TF and PF structure</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structure supply</td>
<td>15 A</td>
<td>16</td>
</tr>
<tr>
<td>Structure return</td>
<td>20 A</td>
<td>16</td>
</tr>
<tr>
<td><strong>Thermal shield</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shield supply</td>
<td>15 A</td>
<td>18</td>
</tr>
<tr>
<td>Shield return</td>
<td>15 A</td>
<td>18</td>
</tr>
<tr>
<td>Shield plug</td>
<td>80/90</td>
<td>16x2</td>
</tr>
<tr>
<td><strong>Total number of pipe</strong></td>
<td></td>
<td>256</td>
</tr>
</tbody>
</table>

* The size of pipe is tentatively specified and more detailed analysis is needed.
Fig. IV.1 ITER assembly and maintenance
Fig. IV.2-1(a) Layout of in-vessel boom
Fig. IV.2-1(b) Boom design
Fig. IV.2-2  Actuator of articulated boom
2ton Load

(End Effector : 1 ton)
(Divertor : 1 ton)

gravity support (Option 1)

gravity support (Option 2)

Fig. IV.2-3 FEM-model
Cross Section (a)

Cross Section (b)

Detailed Model for Stress Calculation

Calculation Results

<table>
<thead>
<tr>
<th>Location of Support</th>
<th>Deflection</th>
<th>Torsion Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>on V.V.</td>
<td>186 mm</td>
<td>$\theta_x = 0.72^\circ$, $\theta_y = 0.56^\circ$</td>
</tr>
<tr>
<td>on Cask</td>
<td>58 mm</td>
<td>$\theta_x = 0.51^\circ$, $\theta_y = 0.18^\circ$</td>
</tr>
</tbody>
</table>

Deflection

<table>
<thead>
<tr>
<th>Thickness of Wall</th>
<th>Deflection</th>
<th>Torsion Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 mm</td>
<td>58 mm</td>
<td>$\theta_x = 0.51^\circ$, $\theta_y = 0.18^\circ$</td>
</tr>
<tr>
<td>30 mm</td>
<td>84 mm</td>
<td>$\theta_x = 0.80^\circ$, $\theta_y = 0.22^\circ$</td>
</tr>
</tbody>
</table>

Detailed stress Analysis

<table>
<thead>
<tr>
<th>Thickness of Wall</th>
<th>Joint Pin</th>
<th>Boom Body</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 mm</td>
<td>4.3 kg/mm$^2$</td>
<td>3.2 kg/mm$^2$</td>
</tr>
<tr>
<td>30 mm</td>
<td>5.44 kg/mm$^2$</td>
<td>3.8 kg/mm$^2$</td>
</tr>
</tbody>
</table>

Fig. IV.2-4 Detailed model for stress calculation and results
Dynamic Deflection under Quick Load

Dynamic Deflection under Quick Unload

Fig. IV.2-5 Dynamic analysis of boom
Fig. IV.2-6  Oscillation mode patterns and dynamic deflection
Deflection of Pantograph Structure

Max. Deflection : 2.6 mm (Z)

Max. Stress : 148 kg/mm²

(at the axis jointed pantograph elements)

Fig. IV.2-7 Deflection of pantagraphe structure
a) 1st Mode (1.86Hz)

Patterns of Eigen Frequency

2nd Mode (10.3Hz)

c) 3rd Mode (19.6Hz)

Fig. IV.2-8 Patterns of Eigen frequency of pantagraph structure
Fig. IV.2-9  Intermediate support structure of articulated boom
Fig. IV.3-1 Layout of in-vessel vehicle
(1) INITIAL POSITION

(2) INSERT RAIL INTO EQUATORIAL PORT

(3) INSERT FIRST RAIL LINK INTO TORUS

(4) SWING FIRST RAIL LINK ALONG TORUS

Fig. IV.3-2(a) Insertion of vehicle/rail system(1)-(4)
Fig. IV.3-2(b) Insertion of vehicle/rail system(5)-(8)
Fig. IV.3-2(c) Insertion of vehicle/rail system(9)-(10)
Fig. IV.3-3 Locking system for rail
Static Analysis of Vehicle Rail

- Case 1: Without ± 90° Supports
  Load Point : 90°

- Case 2: With ± 90° Supports
  Load Point : 45°

Load 1.5 ton (3 ton/2)

Static Analysis of Vehicle Rail
- Rail Material : Alluminium Alloy
  Weight : 3 ton (180° part)

- Support Material : Stainless Steel

Case 1

Support (Sus)

Rail (Al Alloy)

Case 2

Symmetric Surface

Load 3 ton

Fig. IV.3-4 Static analysis for rail
Calculation Results

<table>
<thead>
<tr>
<th>Deflection</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-direction</td>
<td>0</td>
<td>0.27</td>
</tr>
<tr>
<td>Y-</td>
<td>-1.8 mm</td>
<td>-0.30 mm</td>
</tr>
<tr>
<td>Z-</td>
<td>-27.5 mm</td>
<td>-3.4 mm</td>
</tr>
<tr>
<td>θz-angle</td>
<td>-0.21°</td>
<td>0.0026°</td>
</tr>
<tr>
<td>θy-</td>
<td>0.11°</td>
<td>0.0089°</td>
</tr>
<tr>
<td>θz-</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Fig. IV.3-5 Static deflection of rail
Fig. IV.3-6 1/5 scale size model of vehicle/rail system

Fig. IV.3-7(a) Photograph of storage mechanism of rail
Fig. IV.3-7(b) Scheme of storage mechanism of rail
Fig. IV.3-8 Divertor gripper concept
Fig. IV.4-1 Divertor locking system

Fig. IV.4-2 Divertor lifting jack system
Fig. IV.4-3 Jacked up lower divertor

Fig. IV.4-4 Upper divertor jacking system
Fig. IV.4-5 Jacked up upper divertor

Fig. IV.4-6 Divertor support (shield) structure
Fig. IV.5-1 Gripper/end-effector for divertor
Fig. IV.5-2 Isometric view of gripper/divertor frame

Fig. IV.6-1 Welding/cutting concept using laser beam
Fig. IV.6-2  Welding/cutting concept using laser beam

Fig. IV.6-3  Access of cutter/welder for upper divertor pipe
Fig. IV.6-4 Access of cutter/welder for lower divertor pipe
Fig. IV.6-5 Concept of in-pipe laser welding/cutting system
Fig. IV.7-1 Divertor plate kinematics during replacement (Toroidally segmented divertor plate)
(a) Lower outboard divertor plate
(b) Lower inboard divertor plate
(c) Upper outboard divertor plate
(d) Upper inboard divertor plate

Fig. IV.7-2 Divertor plate kinematics during replacement (Poloidally segmented divertor plate)
Fig. IV.8-1 Armor tile handling system

Fig. IV.8-2 Function of armor tile handling manipulator
Fig. IV.8-3  Manipulator for armor tile replacement

Fig. IV.8-4  Rotation mechanism
Fig. IV.8-5 Armor tile handling manipulator kinematics

Fig. IV.9-1 Horizontal access viewing system
Fig. IV.9-2 Vertical access viewing system
Fig. IV.10-1 Revised reference segmentation scheme
Fig. IV.10-2 Concept for blanket lowering equipment
Fig. IV.10-3 Concept for blanket handling device with tilt capability
Fig. IV.10-4 Penetration configuration
Fig. IV.10-5 Lower cooling pipes layout
Fig. IV.10-6 Remote piping cutting/welding access
Fig. IV.10-7 Remote piping welder and cutting

Fig. IV.10-8 Remote welder/cutter for access port lip seal
Fig. IV.10-9 Blanket module handling system
Fig. IV.10-11 Blanket segmentation - Alternate 1

Fig. IV.10-12 Blanket segmentation - Alternate 2
Fig. IV.10-13 Divertor removal with inboard blanket and divertor shield

Fig. IV.11-1 LH front surface maintenance procedure
Fig. IV.11-2 Faraday shield maintenance procedure

Fig. IV.11-3 Faraday shield maintenance procedure
Fig. IV.12-1 Flux loop layout

(a) Full flux loops located on vacuum vessel
(b) Flux loops at outer blanket

Central blanket module
Stir blanket module
Full flux loops

271
Fig. IV.12-2 Diamagnetic loop layout

Fig. IV.12-3 Location of Mirnov coils and alternative proposal of flux loop location.

- **a)** Location of Mirnov Coils
- **b)** Alternative Proposal of Flux Loop Location
Fig. IV.13-1 Neutron diagnostic maintenance concept (Large module replacement)

Fig. IV.13-2 Neutron diagnostic maintenance concept (Small module maintenance concept)
Fig. IV.14-1(a) Concept of connection/disconnection of electric power cable and water pipes in large diameter SF6 gas duct connected to the ion source unit

Fig. IV.14-1(b) Cross-sectional view of connection terminals
Fig. IV.14-2 Concept of connection/disconnection of the source maintenance valve and the double gate valve
Fig. IV.14-3  Concept of sleeve type shape memory alloy for cable connection and disconnection

Fig. IV.14-4  Concept of shape memory alloy bolt for cable connection and disconnection
Fig. IV.14-5 Concept of flange connection/disconnection of water service

Fig. IV.14-6 Concept of laser cutting/welding of water pipe
Fig. IV.14-7 Concept of auto-mobile type truck for maintenance of ion source

Fig. IV.14-8 Layout of rail for auto-mobile type truck
Before Assembling

Temporary center column for reference

Gravity support for TF coil
Gravity support for torus structure

Set up of 16 assembling units

TF coil
Vacuum Vessel
15.5 degree Permanent Shield

Fig. IV.15-1 VV alternative concept assembly-vertical view
Fig. IV.15-2 VV alternative concept assembly—horizontal view

Fig. IV.15-3 Testing of SC and VV

- (a) Testing of SC
- (b) Installation of Ports and others
- (c) Testing of VV
- (d) Installation of In-vessel component and completion of assembly
Fig. IV.16-1  CS coil maintenance scenario
Fig. IV.17-1 Penetration configuration

Fig. IV.17-2 Lower cooling layout
Fig. IV.17-3 Coil services layout

Fig. IV.17-4 Coil service layout (elevation view)
The electrostatic force for carbon sphere is represented by

\[ F = 2\pi a^3 \epsilon_0 \text{grad } E^2 \]

where \( a \) is the radius of the carbon sphere.

Fig. IV.19-2 Schematic drawing of the carbon dust cleaner
V. Reactor building layout

V.1 Introduction

This report describes the results of the conceptual design and the process of design evolution on ITER reactor building.

The evolution of the reactor building is reflected in a series of report and papers mostly presented by Japan team during ITER plant design workshop (Feb. and July 1990).

Planning of the reactor building design has been conducted to realize effective arrangement of inclusions considering the requirements from reactor configuration and procedures for its assembly and maintenance. The major consideration has been paid on the followings;

1) Torus configuration and peripheral equipments arrangements

The Special Group developed a reference configuration and arrangements of peripheral equipments. They are torus, NBIs, LH device, EC device, transporter cask and articulated boom/vehicle house for maintenance and vacuum pumps. Figures V.1-1 to V.1-3 show their configuration and arrangements.

2) Requirements from maintenance scenario

The special group also developed a reference scenario for replacing the torus components and peripherals. Our plan is based on this scenario. The reference scheme of replacing equipments are shown in Figs V.1-4 to V.1-6. Replacing scheme for NBIs has two options.

3) Structural requirements

Structural requirements are discussed later in the section 4.

4) Zoning satisfying safety requirements

Requirements to Building planning as shown below are 2 items.
* Zoning planning (Building block planning) should be defined.
* Containment block (Building block planning) should be defined.

V.2 The points of ITER reactor building design

The major design points of ITER reactor building are shown followings.

- Planning Strategy
  a. Feasible design should be considered
     * according to the existing nuclear plants
- expecting near future licensing process
b. Total performance should be appraised
* not only building but also whole equipments
which are included in reactor building

- Key points of planning
  a. Whole reactor structure and peripheral equipments should
     be considered and maintenance considered.
  b. Flexible design to cope with variation of equipments
design should be considered.
  c. Available building design for floor mobiles operation
     should be considered.
  d. Maintenance space for frequent replacement should be
     considered as precedence space.

- Important Points for ITER reactor building design in this phase
  a. Equipments layout
* Basic layout has been developed after the last
  winter session
  b. Tritium containment
  c. Basic structural design
* Supporting configuration for vertical load condition
* Volume estimate of major structural element
* Detail study of structural design can not be done in this
  phase. Basic approach and issue, however, should be
  clarified.

- Design Approach
  a. Conventional design approach
* Equipment design → Building design →
  b. ITER Building design approach
* Equipments design

Two types of design approach are compared as shown Fig. V.2-1
V.3 Planning of horizontal arrangements

V.3.1 General strategy

a. Block separation should be defined.
   * Safety zoning
   * Building structural arrangements
   * Service supply

b. The reactor building including structural members should be designed.
   * Checking clashes to equipments arrangements.

c. Shorter flow line should be considered.
   * Equipments / Persons / Service

V.3.2 Planning

Blocks which the central part of building consists of

In order to make planning, four blocks are defined in sequence from the central part of building. Figure V.3-1 shows these blocks schematically.

Block 1 which includes cryostat -- circular
Block 2 which includes reactor hall and torus peripheral equipment
Block 3 which includes space for replacing and transporting failed components
Block 4 which includes whole reactor building

Since shape of cryostat is cylindrical the Block 1 should be circular. Outer part of reactor building will be rectangular because of effective use of space for containing auxiliary systems. Two options as shown below are studied.

<table>
<thead>
<tr>
<th>Block</th>
<th>Option 1</th>
<th>Option 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block 1 Cryostat</td>
<td>circular</td>
<td>circular</td>
</tr>
<tr>
<td>Block 2 Reactor hall</td>
<td>circular</td>
<td>rectangular</td>
</tr>
<tr>
<td>Block 3 Transfer space for</td>
<td>circular</td>
<td>rectangular</td>
</tr>
<tr>
<td>maintenance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Block 4 Whole reactor</td>
<td>rectangular</td>
<td>rectangular</td>
</tr>
</tbody>
</table>
These options have advantages and disadvantages. The most important consideration in comparing those options are the followings:

1) Dead space will be expected just outside the circular building.
2) Building will be the one of the most important element for confining radioactivities.

<table>
<thead>
<tr>
<th>Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Option 1</strong></td>
</tr>
<tr>
<td>1) Being able to avoid having dead space in the critical region which includes many reactor peripherals such as vacuum pumps, heating devices, fueling equipments and inside torus remote handling equipments</td>
</tr>
<tr>
<td>2) Shorter path ways of failed components for replacements</td>
</tr>
<tr>
<td><strong>Option 2</strong></td>
</tr>
<tr>
<td>1) Shorter span main crane</td>
</tr>
</tbody>
</table>

Plan view of the central part of building for the option 1 is shown in Figs V.3-2 to V.3-4. The horizontal movement option for NBI neutralizer make the size of Block 3 larger leading to have larger dead space. Then the vertical movement option for the NBI neutralizer is employed. Although this option gives more complex replacing scheme for the neutralizer it can be accepted because of infrequent occurrence. Ion sources of NBI should be replaced still in horizontal way since its replacement is expected to be frequent.

Figure V.3-5 shows appropriate direction of the access of power supply line, new and failed components transfer and cooling water line. Figure V.3-6 shows general arrangement of auxiliary systems in the Block 4.

V.4 Planning of vertical arrangements

V.4.1 General strategy

a. Crane space
   * Working/Maintenance
b. Service space
   * Ducting/Piping/Wiring

c. Building Structure
   * Checking clashes to equipments arrangement.
   * Floor height will be adjusted when balance of equipments scaling will be made clear.
V.4.2 Planning
Elevation of floors are determined as shown in Fig. V.4-1 taking into account of heights of equipments included, required space for maintenance of those equipments and ducting for HVAC system and structural constraints. A draft of reactor building plan and vertical views are shown in Figs V.4-1 to V.4-11.

V.5 Structural consideration

V.5.1 General strategy
Structural design should be based on the existing practice in nuclear plant expecting future licensing process. The design should be as simple as possible since exotic building configuration will have difficulty in proving its soundness. The nuclear plant practice in selecting spans of columns are shown below which support floors of building.

<table>
<thead>
<tr>
<th>SPAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>40 (M)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>STRUCTURAL SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC</td>
</tr>
<tr>
<td>PC</td>
</tr>
<tr>
<td>SRC</td>
</tr>
<tr>
<td>S</td>
</tr>
</tbody>
</table>

- RC: Reinforced concrete construction
- PC: Prestressed concrete construction
- SRC: Steel-flame and reinforced-concrete composite construction
- S: Steel-flame construction

the commonest range in used for nuclear facilities

Applicable range

Feasible range
According to this figure around 15m of span will be appropriate. Though slight scattering of spans can be acceptable, significant deference in spans makes structural problems.

In designing reactor building the following loads are taken into account.

- Vertical load (gravity)
- Seismic load
- Soil load
- Inner pressure in case of accidents

V.5.2 Example of Structural analysis for national project

1) Design conditions

FER Reactor building for analysis model are shown in Figs V.5-1 to V.5-11. Floor loads for FER are shown in Table V.5-1(1)~(6) which are roughly similar to those in the ITER. Static seismic load is assumed to be TBD. The following three analysis have been done.

a) FEM analysis with NASTRAN for the cylindrical reactor hall wall including its roof.

- Inputs: Physical properties of reinforced concrete
  - Wall dimensions
  - Loads, such as vertical loads including crane load, seismic load,
  - Inner pressure in case of accidents.

- Outputs: Horizontal and vertical stresses for each elements
  - (bending moment, out of plane shear stress, axial stress, in-plane shear stress)

b) Eigen value analysis with the DYNA2E

- Inputs: Mass of each element
  - Shear stiffness of vertical elements
  - Flexing stiffness of vertical elements
  - Rocking spring constants
  - Sway spring constants

- Outputs: Eigen modes
  - Eigen values

c) Stress analysis of each elements

- Floor slab

- Inputs: Vertical loads
  - Static seismic load
Soil load
Thickness required for vibration protection

Outputs: Bending moment due to vertical load
Out-of-plane shear stress due to vertical load
In-plane shear stress due to seismic load
In-plane stress due to soil load

Beam
Inputs: Vertical load
Soil load

Outputs: Bending moments due to vertical load
Shear stress due to vertical load

Column
Inputs: Vertical load

Outputs: Axial stress due to vertical load
Bending moment due to vertical load
Shear stress due to vertical load

Wall
Inputs: Seismic load
Soil load

Outputs: In-plane shear stress due to seismic load
Out-of-plane shear stress due to soil load
Bending moment due to soil load

2) Results

Structural Drawing of FER Reactor building are shown in Figs V.5-12 to V.5-48 which according to calculational results.

3) Implications to the ITER building design

Considering results for the FER building structural analysis, stresses are appropriate range and ITER building should not far different.

The Table showing below importance in determining dimensions of structural members in each Block.

Configuration of effective loads to structural block as shown below are considered.
V.5.3 Structural issues for constructing ITER buildings

1) Site dependent issues
   - Selection of level of building base
   - Effect of under ground water for building structure
   - Effect of soil characteristics for building concrete
   - Thermal stress by temperature gradient depending on meteorological condition

2) Joint part structures of circular and rectangular buildings considering safety requirements such as leak tightness.

3) Construction process
   Significant overlapping of schedules for building construction and reactor of the building

4) Openings of the building
   - structural issues
   - design and development of large size door which satisfies radiation shielding and leak tightness.

V.6 Whole ITER reactor building schematic planning

V.6.1 Planning conditions

Planning conditions according to agreement in plant system workshop are shown followings.

a. Upper part (Reactor hall) Figs V.6-1 and V.6.2
   RECTANGULAR Plan

b. Lower part
   CIRCULAR Plan
V.6.2 Planning

(1) Structural consideration of upper part (side wall of reactor hall)

Condition of structural consideration in asides wall of reactor hall has been paid on as follows.

Major loads:

1. Over head crane 800 t & 100 t
2. Top Roof
   • Required thickness of concrete is 1.6 m for reducing skyshine dose during blanket maintenance to allowable level.

Supporting configuration:

1. Top roof: Flat type with supporting beam
   Total height: 3.5 m
2. Wall-Beam: Necessary thickness
   2 point support 3 m
   3 point support 2 m
3. Column
   2 point support
   End 6.0x6.0 m
   3 point support
   End 4.0x4.0 m
   Intermediate 2.5x6.0 m

Three types of structural systems are compared as shown in Table V.6-1 and Fig.V.6-3.

(2) Structural consideration of lower port

Condition of structural consideration for lower part has been paid on as follows

Major load:
1. Live load (equipment weight)
2. Dead load

Supporting Configuration:

1. Slab-Beam
2. Cylindrical wall
Volume estimation of Slab-Beam:

Case A
Necessary slab thickness  4.0 - 5.0 mm

Case B
Necessary slab thickness  -1.5 mm

Schematic drawings of structural system are shown in Figs V.6-4 to V.6-8.

V.7 Conclusions

1. Although current building planning has many issues from structural point of view they seem to be solved in future detail engineering design.
2. Since structural members are added around the cryostat the following design should be reviewed to confirm consistency with building.
   (1) Cryostat design
   (2) Horizontal access port design
   (3) Heating / Current drive design
   (4) Vacuum pumping design
   (5) Assembly and Maintenance design
3. Slab thickness of floors could be insufficient to support vertical loads.
4. Zone boundary should be determined in this phase.
5. The following information is necessary to develop whole building configuration.
   Design Requirements (Space & Weight)
   (1) Primary cooling system
   (2) HVAC & Detritiation system
   (3) Baking & Conditioning system
   (4) Tritium Building
   (5) Cryogenic System
V.8 Additional figures for reactor building

Fig.V.8-1 Sectional View of ITER Reactor Structural System
Fig.V.8-2 Comparison of Cryostat Structural System
Fig.V.8-3 Birds Eye View of FER Reactor Building
Fig.V.8-4 Interior Elevation of Reactor Hall
Fig.V.8-5 Interior Elevation of Cryostat (concrete)
Fig.V.8-6 Schematic Drawing of Structural Planning
   (Horizontal consideration)
Fig.V.8-7 Scheme of Structural Planning (Rectangular Type)
Fig.V.8-8 Scheme of Prestressed Concrete
   Containment Vessel
Fig.V.8-9 Scheme of Prestressed Concrete
   Containment Vessel (Horizontal Sectional View)
Table V.5-1 Design conditions of FER Reactor Building (1)

<table>
<thead>
<tr>
<th>Roomname</th>
<th>Equip. load T/OM/12</th>
<th>Liming</th>
<th>Clamber com. t+600 LBC</th>
<th>Area m²</th>
<th>Volume m³</th>
<th>CE m</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Emergency Generator Rm.</td>
<td>0.6</td>
<td>○</td>
<td>2.916</td>
<td>26.110</td>
<td>10.0</td>
<td>CE is above room height</td>
<td></td>
</tr>
<tr>
<td>2. Primary Cooling sys. (D/T)</td>
<td>7.0</td>
<td>○</td>
<td>5.320</td>
<td>61.900</td>
<td>10.0</td>
<td>pool</td>
<td></td>
</tr>
<tr>
<td>3. Fueling System 1</td>
<td>0.1</td>
<td></td>
<td>0.970</td>
<td>10.0</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Fueling/Cryo System</td>
<td>1.6</td>
<td></td>
<td>1.200</td>
<td>30.000</td>
<td>10.0</td>
<td>in cylinder wall assume the following weight cryo sys.</td>
<td></td>
</tr>
<tr>
<td>5. Transferer 1</td>
<td>←</td>
<td>○</td>
<td>214</td>
<td>1.540</td>
<td>10.0</td>
<td>to Hot Cell Transporting weight: 80 x 1.8 = 144ton</td>
<td></td>
</tr>
<tr>
<td>6. Transferer 2</td>
<td>←</td>
<td>○</td>
<td>60</td>
<td>910</td>
<td>10.0</td>
<td>for diverter cell 1.20ton</td>
<td></td>
</tr>
<tr>
<td>7. Delivery area</td>
<td>←</td>
<td></td>
<td>512</td>
<td>5.120</td>
<td>10.0</td>
<td>Transporting weight: 1.20ton</td>
<td></td>
</tr>
<tr>
<td>8. Piping shaft 1</td>
<td>1.0</td>
<td></td>
<td>145</td>
<td>1.450</td>
<td>10.0</td>
<td>under the Reactor</td>
<td></td>
</tr>
<tr>
<td>9. Piping Circuit</td>
<td>1.6</td>
<td></td>
<td>1.600</td>
<td>16.600</td>
<td>10.0</td>
<td>in cryostat</td>
<td></td>
</tr>
<tr>
<td>10. Piping shaft 2</td>
<td>1.0</td>
<td></td>
<td>480</td>
<td>4.800</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11. Horizontal d. l 1</td>
<td>1.0</td>
<td></td>
<td>256</td>
<td>2.560</td>
<td>10.0</td>
<td>Power Supply</td>
<td></td>
</tr>
<tr>
<td>12. Horizontal d. l 2</td>
<td>1.0</td>
<td></td>
<td>512</td>
<td>5.120</td>
<td>10.0</td>
<td>Cooling Water</td>
<td></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Roomname</th>
<th>Equip. load T/OM/12</th>
<th>Liming</th>
<th>Clamber com. t+600 LBC</th>
<th>Area m²</th>
<th>Volume m³</th>
<th>CE m</th>
<th>Note</th>
</tr>
</thead>
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<tr>
<td>13. Electrical Equip.</td>
<td>0.6</td>
<td></td>
<td>2.916</td>
<td>26.110</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14. Primary Cooling sys. (D/T)</td>
<td>7.0</td>
<td></td>
<td>5.320</td>
<td>61.900</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15. Fueling System</td>
<td>0.1</td>
<td></td>
<td>0.970</td>
<td>10.0</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16. Vacuum Pumps System 0</td>
<td>←</td>
<td>○</td>
<td>1.600</td>
<td>16.300</td>
<td>10.0</td>
<td>T/L: Divertor N/O + Transferer = 10 ton</td>
<td></td>
</tr>
<tr>
<td>17. Transferer 3</td>
<td>←</td>
<td>○</td>
<td>214</td>
<td>1.540</td>
<td>10.0</td>
<td>Transferer T/L: 30 ton</td>
<td></td>
</tr>
<tr>
<td>18. Transferer 4</td>
<td>←</td>
<td>○</td>
<td>600</td>
<td>910</td>
<td>10.0</td>
<td>in cylinder wall assuming a Div 5/N T/L: 30 ton</td>
<td></td>
</tr>
<tr>
<td>19. Delivery area</td>
<td>←</td>
<td></td>
<td>512</td>
<td>5.120</td>
<td>10.0</td>
<td>T/L: assume the following 4 pumps units = 5 ton</td>
<td></td>
</tr>
<tr>
<td>20. Piping Shaft 1</td>
<td>1.0</td>
<td></td>
<td>145</td>
<td>1.450</td>
<td>5.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21. Piping Shaft 2</td>
<td>1.0</td>
<td></td>
<td>480</td>
<td>4.800</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22. Horizontal d. l 1</td>
<td>1.0</td>
<td></td>
<td>256</td>
<td>2.560</td>
<td>10.0</td>
<td>Power Supply</td>
<td></td>
</tr>
<tr>
<td>23. Horizontal d. l 2</td>
<td>1.0</td>
<td></td>
<td>512</td>
<td>5.120</td>
<td>10.0</td>
<td>Cooling Water</td>
<td></td>
</tr>
</tbody>
</table>
Table V.5-1 Design conditions of FER Reactor Building (3)

<table>
<thead>
<tr>
<th>Room No.</th>
<th>Equip. load</th>
<th>Lining</th>
<th>Colder conn. 1+600 LND</th>
<th>Area m²</th>
<th>Volume m³</th>
<th>CH cm</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>RF Amplifier System</td>
<td>0.2</td>
<td>0</td>
<td>2.816</td>
<td>29.140</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Primary Cooling sys.</td>
<td>1.0</td>
<td>5.320</td>
<td>63.200</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Hbl System (ION Source 1)</td>
<td>1.2</td>
<td>1.177</td>
<td>14.110</td>
<td>20.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Hbl System (ION Source 2)</td>
<td>0.6</td>
<td>5.6</td>
<td>61.780</td>
<td>20.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Hbl System (Beam dump)</td>
<td>0.6</td>
<td>0</td>
<td>44.0</td>
<td>4.400</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>Hbl Auxiliary sys.</td>
<td>1.0</td>
<td>0</td>
<td>256</td>
<td>2.560</td>
<td>10.0</td>
<td>FL-4000 Hbl T/L : 50 ton</td>
</tr>
<tr>
<td>32</td>
<td>Hbl Auxiliary sys. 2</td>
<td>1.0</td>
<td>0</td>
<td>300</td>
<td>3.000</td>
<td>10.0</td>
<td>FL-4000 Ion source room to Bot Cell T/L : 50 ton</td>
</tr>
<tr>
<td>33</td>
<td>Hbl Auxiliary sys. 3</td>
<td>1.0</td>
<td>0</td>
<td>300</td>
<td>3.000</td>
<td>10.0</td>
<td>FL-4000 Ion source room to Bot Cell T/L : 50 ton</td>
</tr>
<tr>
<td>34</td>
<td>Horizontal Port Area</td>
<td>0.6</td>
<td>0</td>
<td>1.630</td>
<td>16.300</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>Transfer 1</td>
<td>1.0</td>
<td>0</td>
<td>256</td>
<td>2.560</td>
<td>10.0</td>
<td>to Bot Cell T/L: assume the following LMF 350 ton</td>
</tr>
<tr>
<td>36</td>
<td>Transfer 2</td>
<td>1.0</td>
<td>0</td>
<td>256</td>
<td>2.560</td>
<td>10.0</td>
<td>in cryostat TRANSFER CIRCUIT T/L : 350 ton</td>
</tr>
<tr>
<td>37</td>
<td>Delivery area</td>
<td>1.0</td>
<td>0</td>
<td>512</td>
<td>5.120</td>
<td>10.0</td>
<td>T/L : assume the following LMF 350 ton</td>
</tr>
<tr>
<td>38</td>
<td>Piping shaft</td>
<td>1.0</td>
<td>0</td>
<td>440</td>
<td>4.400</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>Horizontal duct 1</td>
<td>1.0</td>
<td>0</td>
<td>256</td>
<td>2.560</td>
<td>10.0</td>
<td>Power Supply</td>
</tr>
<tr>
<td>40</td>
<td>Horizontal duct 2</td>
<td>1.0</td>
<td>0</td>
<td>512</td>
<td>5.120</td>
<td>10.0</td>
<td>Cooling Water</td>
</tr>
</tbody>
</table>

Table V.5-1 Design conditions of FER Reactor Building (4)

<table>
<thead>
<tr>
<th>Room No.</th>
<th>Equip. load</th>
<th>Lining</th>
<th>Colder conn. 1+600 LND</th>
<th>Area m²</th>
<th>Volume m³</th>
<th>CH cm</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>RF Amplifier System</td>
<td>0.2</td>
<td>0</td>
<td>2.816</td>
<td>29.140</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>Primary Cooling sys.</td>
<td>1.0</td>
<td>5.320</td>
<td>63.200</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>Fueling System</td>
<td>0.1</td>
<td>0</td>
<td>2.410</td>
<td>24.100</td>
<td>10.0</td>
<td>In cryostat TCS</td>
</tr>
<tr>
<td>44</td>
<td>Hbl Auxiliary System 4</td>
<td>0.6</td>
<td>0</td>
<td>788</td>
<td>7.880</td>
<td>10.0</td>
<td>FL-4000 assume the following Electrical equipments</td>
</tr>
<tr>
<td>45</td>
<td>Hbl Auxiliary System 5</td>
<td>0.6</td>
<td>0</td>
<td>550</td>
<td>5.500</td>
<td>10.0</td>
<td>FL-4000 assume the following Electrical equipments</td>
</tr>
<tr>
<td>46</td>
<td>Hbl Auxiliary System 6</td>
<td>0.6</td>
<td>0</td>
<td>550</td>
<td>5.500</td>
<td>10.0</td>
<td>FL-4000 assume the following Electrical equipments</td>
</tr>
<tr>
<td>47</td>
<td>Hbl Auxiliary System 7</td>
<td>1.0</td>
<td>0</td>
<td>420</td>
<td>4.200</td>
<td>10.0</td>
<td>FL-20 above the beam dump</td>
</tr>
<tr>
<td>48</td>
<td>Transfer 1</td>
<td>1.0</td>
<td>0</td>
<td>236</td>
<td>2.360</td>
<td>10.0</td>
<td>to Bot Cell T/L: piping unit 5 ton</td>
</tr>
<tr>
<td>49</td>
<td>Delivery area</td>
<td>1.0</td>
<td>0</td>
<td>512</td>
<td>5.120</td>
<td>10.0</td>
<td>T/L : 4 ton</td>
</tr>
<tr>
<td>50</td>
<td>Piping Circuit</td>
<td>1.0</td>
<td>0</td>
<td>1.430</td>
<td>14.300</td>
<td>10.0</td>
<td>Piping for primary cooling</td>
</tr>
<tr>
<td>51</td>
<td>Piping Shaft</td>
<td>1.0</td>
<td>0</td>
<td>450</td>
<td>4.500</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>Horizontal duct 1</td>
<td>1.0</td>
<td>0</td>
<td>236</td>
<td>2.360</td>
<td>10.0</td>
<td>Power Supply</td>
</tr>
<tr>
<td>53</td>
<td>Horizontal duct 2</td>
<td>1.0</td>
<td>0</td>
<td>512</td>
<td>5.120</td>
<td>10.0</td>
<td>Cooling Water</td>
</tr>
</tbody>
</table>
### Table V.5-1 Design conditions of FER Reactor Building (5)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Equip load</th>
<th>Lossing</th>
<th>Cinder con. 1/400 LEC</th>
<th>Area m²</th>
<th>Volume m³</th>
<th>CE m</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 DF Amplifier System</td>
<td>0.2</td>
<td>○</td>
<td>2,816</td>
<td>28.140</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17 HVAC</td>
<td>1.5</td>
<td>○</td>
<td>2,840</td>
<td>28.400</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18 HVAC</td>
<td>1.5</td>
<td>○</td>
<td>2,840</td>
<td>28.400</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19 HRI Auxiliary System 4</td>
<td>0.6</td>
<td>○</td>
<td>740</td>
<td>7.440</td>
<td>10.0</td>
<td></td>
<td>FL-6000 Electrical Equipments</td>
</tr>
<tr>
<td>20 HRI Auxiliary System 5</td>
<td>0.6</td>
<td>○</td>
<td>300</td>
<td>3.000</td>
<td>10.0</td>
<td></td>
<td>FL-6000 Electrical Equipments</td>
</tr>
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<td>21 HRI Auxiliary System 16</td>
<td>0.6</td>
<td>○</td>
<td>300</td>
<td>3.000</td>
<td>10.0</td>
<td></td>
<td>FL-6000 Electrical Equipments</td>
</tr>
<tr>
<td>22 Entrance for HRI</td>
<td>0.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23 Reactor Hall</td>
<td>2.5</td>
<td>○</td>
<td>2,200</td>
<td>22.000</td>
<td>10.0</td>
<td></td>
<td>MAX Equipment load: Toroidal coil 350 ton</td>
</tr>
<tr>
<td>24 Transferway</td>
<td>--</td>
<td>○</td>
<td>250</td>
<td>2.500</td>
<td>10.0</td>
<td></td>
<td>to hot cell T/L: Toroidal coil 350 ton</td>
</tr>
<tr>
<td>25 Delivery area</td>
<td>--</td>
<td>○</td>
<td>510</td>
<td>5.120</td>
<td>10.0</td>
<td></td>
<td>Ceiling height: 10.0 / 30.0 M T/L: 550 ton</td>
</tr>
<tr>
<td>26 Piping Circuit</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27 Piping Shaft</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28 Horizontal duct</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>29 Horizontal duct</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
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### Table V.5-1 Design conditions of FER Reactor Building (6)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Equip load</th>
<th>Lossing</th>
<th>Cinder con. 1/400 LEC</th>
<th>Area m²</th>
<th>Volume m³</th>
<th>CE m</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>66 HVAC</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>67 Delivery area</td>
<td>--</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>T/L: 30 ton</td>
</tr>
<tr>
<td>68 Transferway</td>
<td>--</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>T/L: Conditioning 30 ton</td>
</tr>
<tr>
<td>69 Piping Circuit</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70 Piping Shaft</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>71 Horizontal duct</td>
<td>1.0</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>72 Horizontal duct</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>73 Delivery area</td>
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<td>Inspection of polar crane</td>
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Table V.6-1 Comparison of ITER Reactor Building Structure models

<table>
<thead>
<tr>
<th>Structural Model</th>
<th>A. Half-Circle</th>
<th>B. Half-Circle Roof + Tension Member</th>
<th>C. Flat Roof</th>
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<tr>
<td></td>
<td>A-1</td>
<td>A-2</td>
<td>B-1</td>
</tr>
<tr>
<td>Roof Thickness (m)</td>
<td>3.0</td>
<td>1:6</td>
<td>1.6</td>
</tr>
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<td>Wall Thickness (Bending) (m)</td>
<td>3.0-3.5</td>
<td>3.0</td>
<td>2.0-3.0</td>
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<td>Column</td>
<td>6.0x6.0</td>
<td>5.0x5.0</td>
<td>6.0x6.0</td>
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<td>Intermediate Support</td>
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<td>2.5x6.0</td>
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<td>3.0</td>
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<tr>
<td>Judgment</td>
<td>X</td>
<td>△</td>
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</table>

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2. 3 Point Support
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(PRELIMINARY DRAWING)

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FER REACTOR BUILDING C-C SECTION
(PRELIMINARY DRAWING)

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Normal Operation Assembly and Disassembly Set up Reactor components

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VI. Conclusion

The central purpose of the International thermonuclear Experimental Reactor (ITER) is to develop an experimental fusion reactor through the united efforts of many technologically advanced countries. As a result of the Conceptual Design Activity, a concept with a consistent set of technical characteristics was well developed and the basic feasibility was preliminary evaluated by the design analysis. In addition, technical issues, whose feasibility should be demonstrated by further engineering R&D and detail analysis, were pointed out and the engineering R&D plan was fully developed. Accordingly, the CDA has produced significant technical base to the Engineering Design Activity (EDA) in which the detailed design and R&D will be carried out.

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