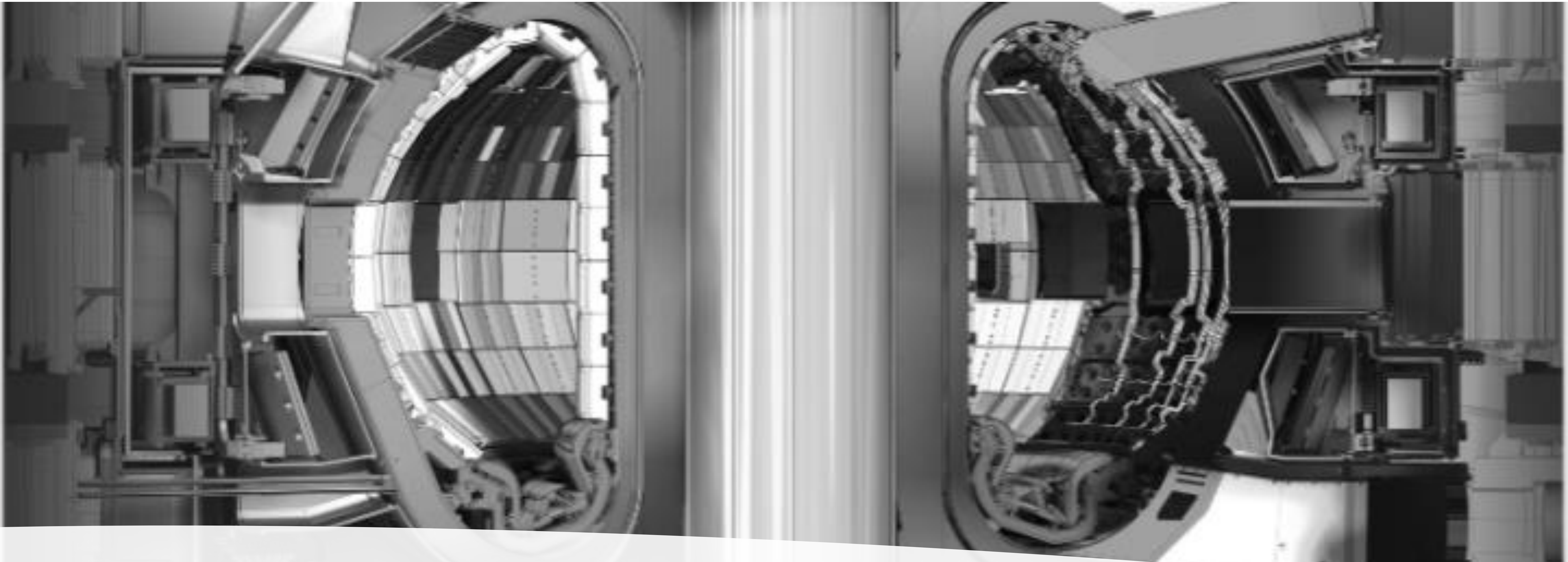


ITER's EXPERIENCE

Codes & Standards for the Engineering of Tokamaks

A. LEE, V. BARABASH, G. KIM, T. SCHIOLER (ITER Org)

Technical Meeting on Experience in Codes and Standards for Fusion Technology

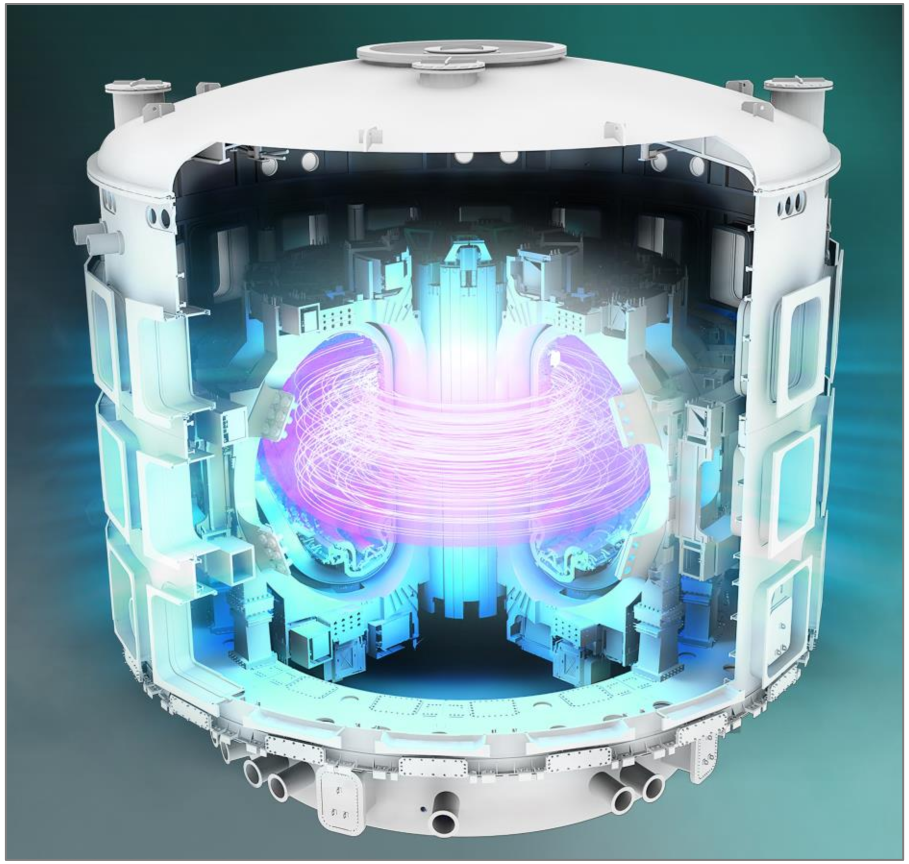
IAEA Headquarters on 18th November 2025

iter

china eu india japan korea russia usa

INTRODUCTION: Scope

Mechanical Engineering of the ITER Tokamak – Fusion Specificities

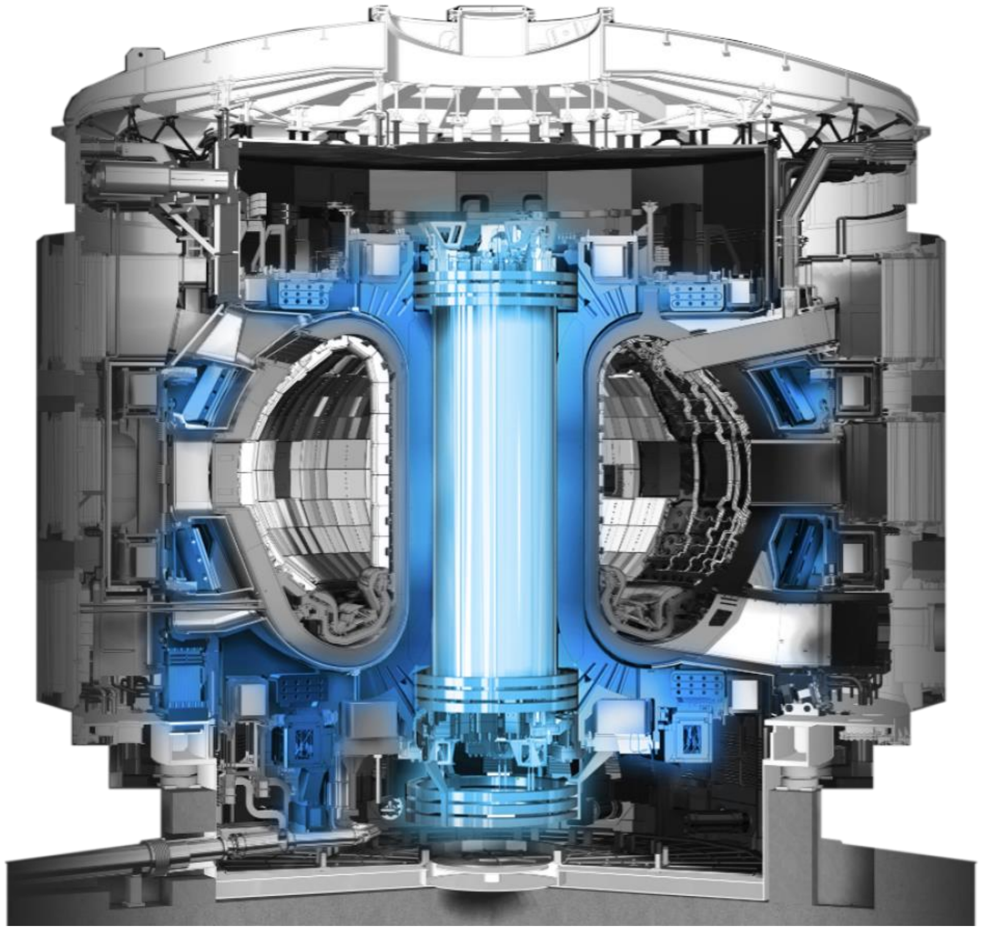


- Mechanical components:
  - Superconducting Magnets
  - In-Vessel Components (incl. diagnostics)
  - Vacuum Vessel
- Loads & environments:
  - Electro-Magnetic loads
  - Cryogenic to warm temperatures
  - Vacuum
  - Neutron-radiation
- Mechanical engineering:
  - Design rules
  - Construction rules
    (material procurement, fabrication, welding, examinations)
  - Tests

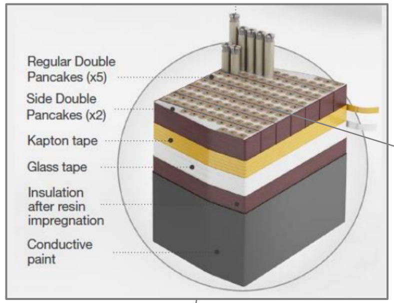
OVERVIEW: Main Mechanical Codes & Standards

Component	Design	Construction	Tests
• Superconducting magnets (incl. bolts, keys, supports & cryogenic piping)	Magnet SDC	Industrial C&S (e.g. ASTM, EN, JSME), Technical Specifications	Technical Specifications
• In-vessel Components: Blankets, divertor, diagnostics, heating systems incl. neutral beam, fuel system, stabilization coils, armour joints	SDC-IC	SDC-IC Appendix A (Material Data), Industrial C&S (EN & ASME), Technical Specifications for armour joints	Plasma-facing components: SDC-IC Annex 1 (Design by Experiment) Pressure: SDC-IC
• Non-metallic windows (diagnostics & heating) • Non-metallic insulating bushing (neutral beam)	Technical specifications (Design by Experiment)		
• Vacuum Vessel (incl. ports & penetrations) • Most other mechanical components forming first confinement barrier • Test Blanket Module • Electron Cyclotron Resonance Heating	AFCEN RCC-MR 2007 & later editions (RCC-MRx)		
• Other components (In-Vessel Coils, Cryostat, Thermal Shields, Cooling Water System, etc.)	Industrial Codes or Standards (e.g. ASME BPVC.VIII.2 & B31.3, EN-13445, etc.)		

MAGNETS: Brief Description

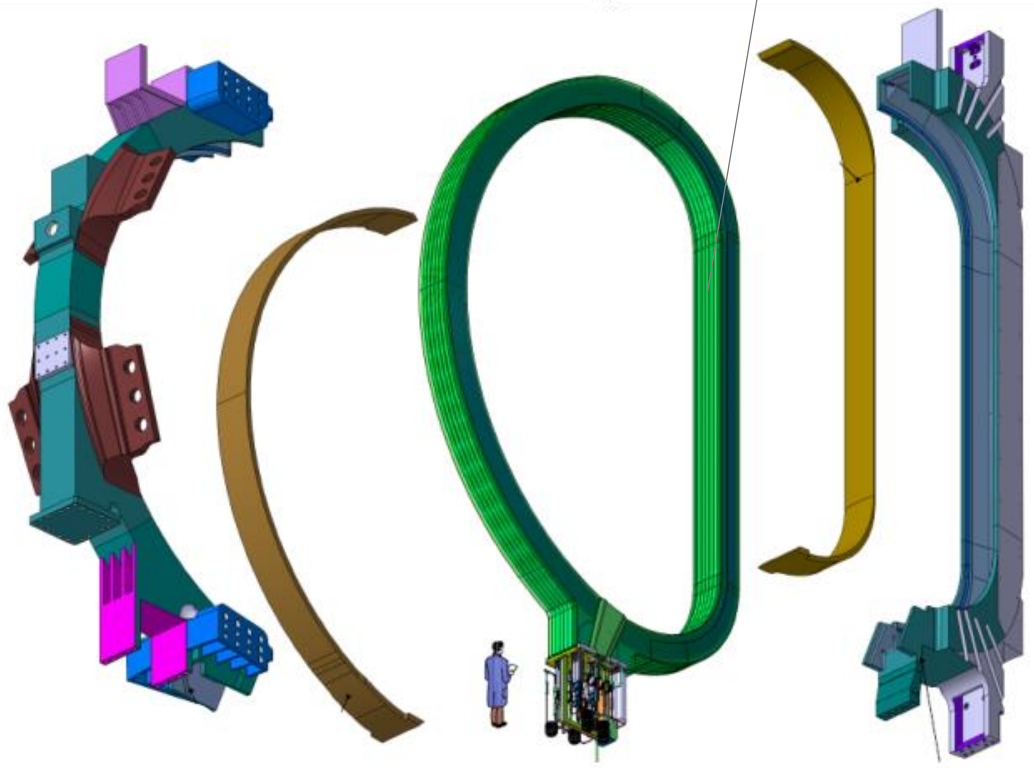


Winding Pack



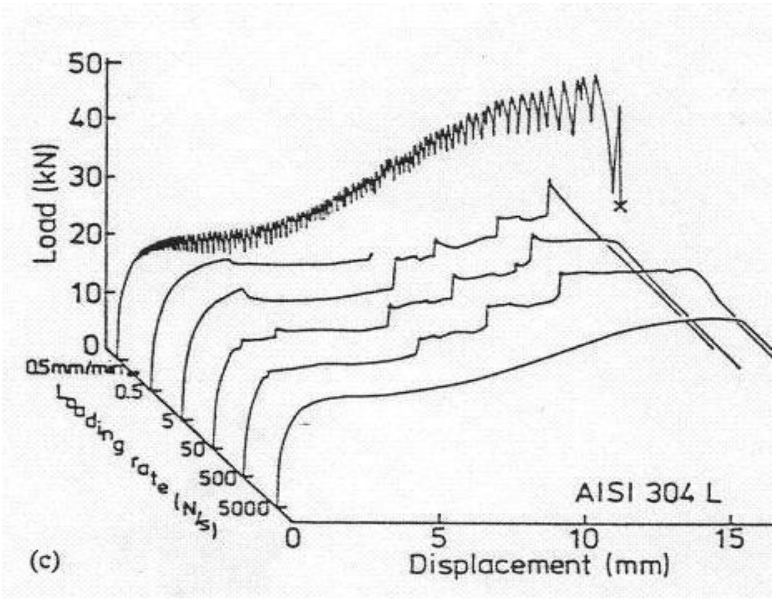
Conductors

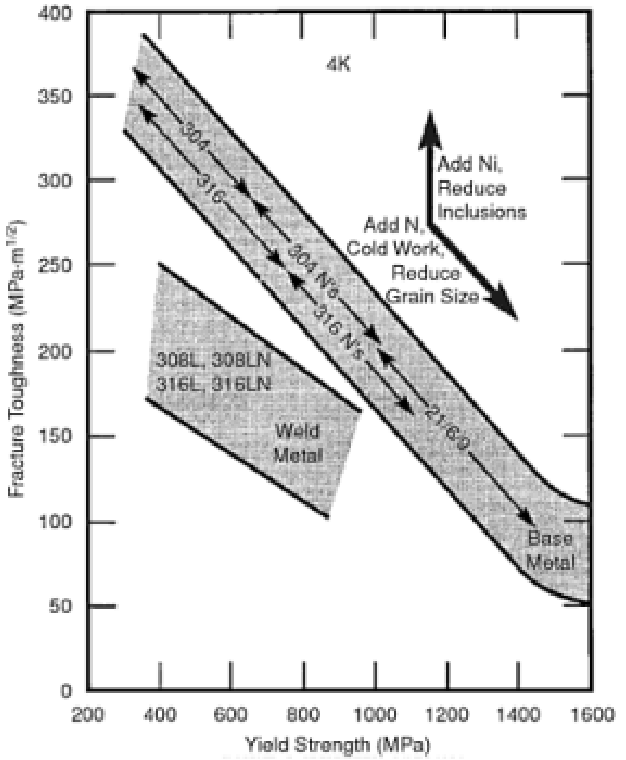
Assembly of One TF Coil:



MAGNETS: Design – Why Specific Magnet SDC?

- Cryogenic temperature (~4K):
  - Serrated yielding and ultimate strength depending on loading rate
  - Decreased fracture toughness
- Main primary loads: Electro-Magnetic
- Geometry:
  - Complicated anisotropic structures
  - Non-metallic material with significant structural role and electrical requirement
- Difficult In-Service Inspection
- First of a Kind





"Loading rate effects on discontinuous deformation" by T. Ogata, K. Ishikawa, R.P. Read and R.P. Walsh

→ **Magnet SDC (S**tructural **D**esign **C**riteria) v2.0 (2012), authored and reviewed by experts from ITER

MAGNETS: Design – Overview of Magnet SDC

- Main Structure:

Part	Title	Pages	Components Concerned
I	Main Structural Components & Welds	73	• Toroidal Field (TF) coil cases • Outer Intercoil Structures (not bolts and keys) • Feeder Ducts
II	Magnet Windings (Radial Plates & Conductors) with High & Low Voltage Insulation and Epoxy Filler	24	• TF winding pack and case-winding filler • Poloidal Field (PF) winding packs • Central Solenoid (CS) coil winding packs • Correction Coils (CC) winding packs
III	Bolts, Keys, Supports & Special Components	31	• CS pre-compression system (top and bottom flanges and vertical tie plates) • CS coil interface plates (between coils) • Inner Poloidal Keys • OIS bolts and keys • Pre-compression rings (PCR) • Supports between PF & TF coils and CS & TF coils • Supports for Correction Coils • TF coil gravity supports
IV	Cryogenic piping	11	• Cryogenic piping

- Commentary sections: Justification of rules
- Appendices: Specific aspects (e.g. calculation procedures for SIF, crack growth, fatigue, …)

MAGNETS: Examples of Specific SDCs

- Allowable stress based only on Yield Strength at operating temperature.
  - Structures: $S_m = 2/3 \cdot S_y$
  - Bolts: $S_{mB} = 1/2 \cdot S_y$
- Prevention of fast-fracture based on defect assessment method of API 579 (incl. crack growth).
  - Initial crack area: 2 x min area detectable
  - Crack growth: Factor of 2 on number of cycles
  - Allowable stress intensity: $2/3 \cdot K_{IC}$
- Buckling
  - Safety factor: 5 (higher uncertainty & potential energy)
  - Magneto-mechanical coupling between Central Solenoid & Poloidal Field Coils
- Non-metallic components
  - High-voltage insulations (> 100 V)
  - Low-voltage insulations (< 2 V)
  - Composite structural components
  - Friction
  - Nuclear radiation

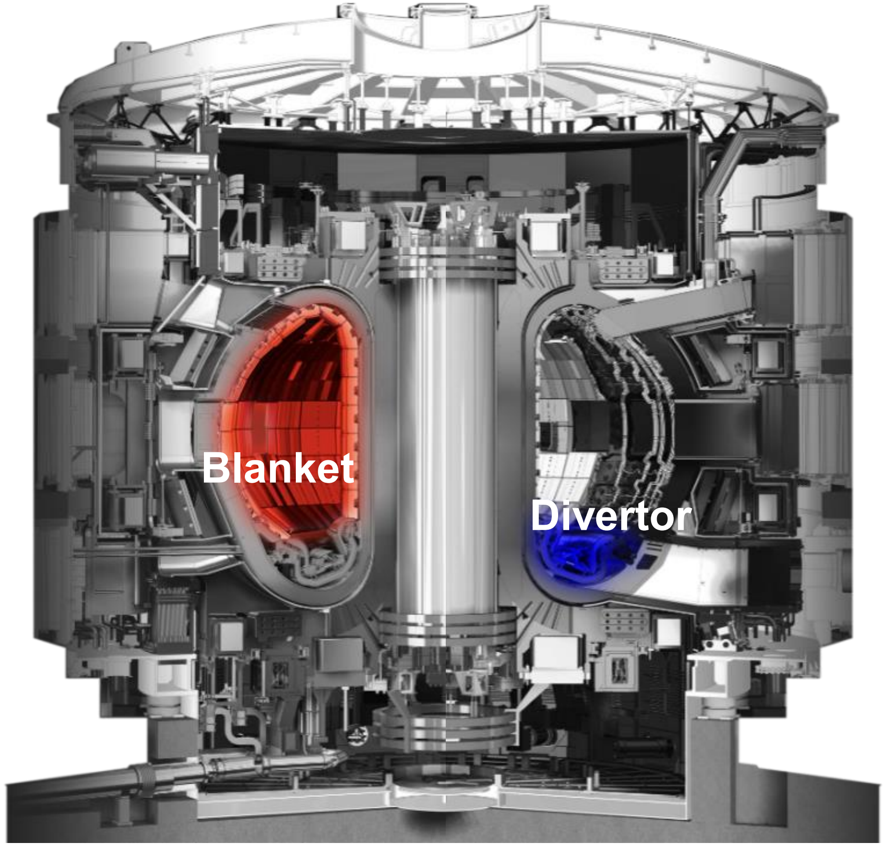
MAGNETS: Construction & Tests

- Material procurement:
    - Stainless Steels: ASTM & EN standards, and other standards from ITER members (e.g. JSME)
    - Superconducting cables (NbTi & Nb3Sn): Technical specifications (procured among ITER collaboration)
- Manufacturing & Examinations: Mostly EN-13445
    - Superconducting cables: Exhaustive performance tests along production
    - Welds: ISO 5817-Level B
- Tests:
    - Pressure tests: PED
    - Leak tests: ITER Vacuum Handbook
    - High Voltage Test (Air & Paschen conditions)
    - Thermal cycling at 80K
    - Some components tested at 4K / high current

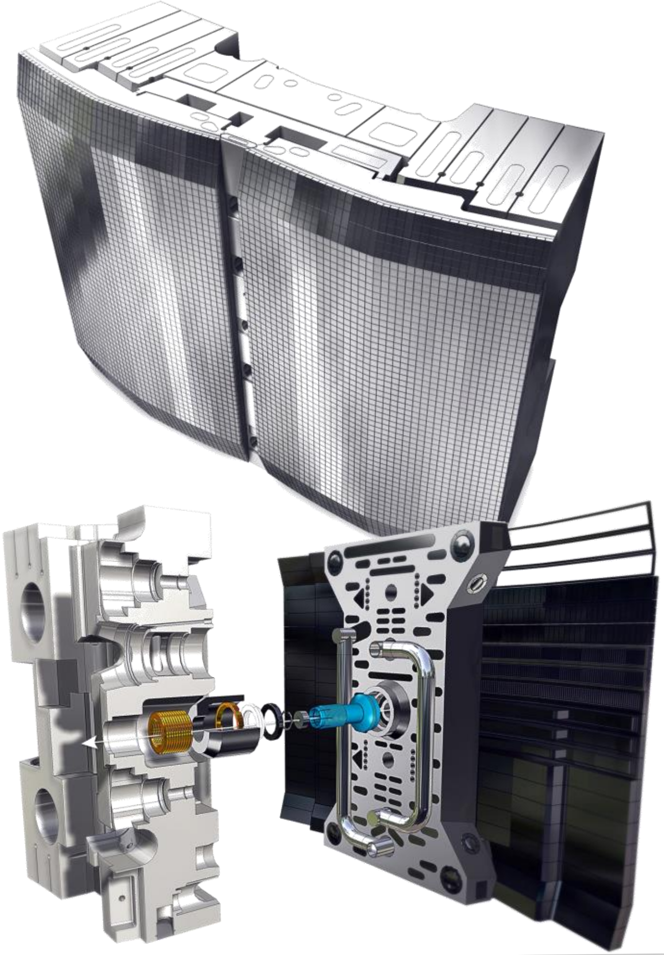
Test of PF Coils at 80K

Cold Test Facility for TF Coils (4K / 68kA)

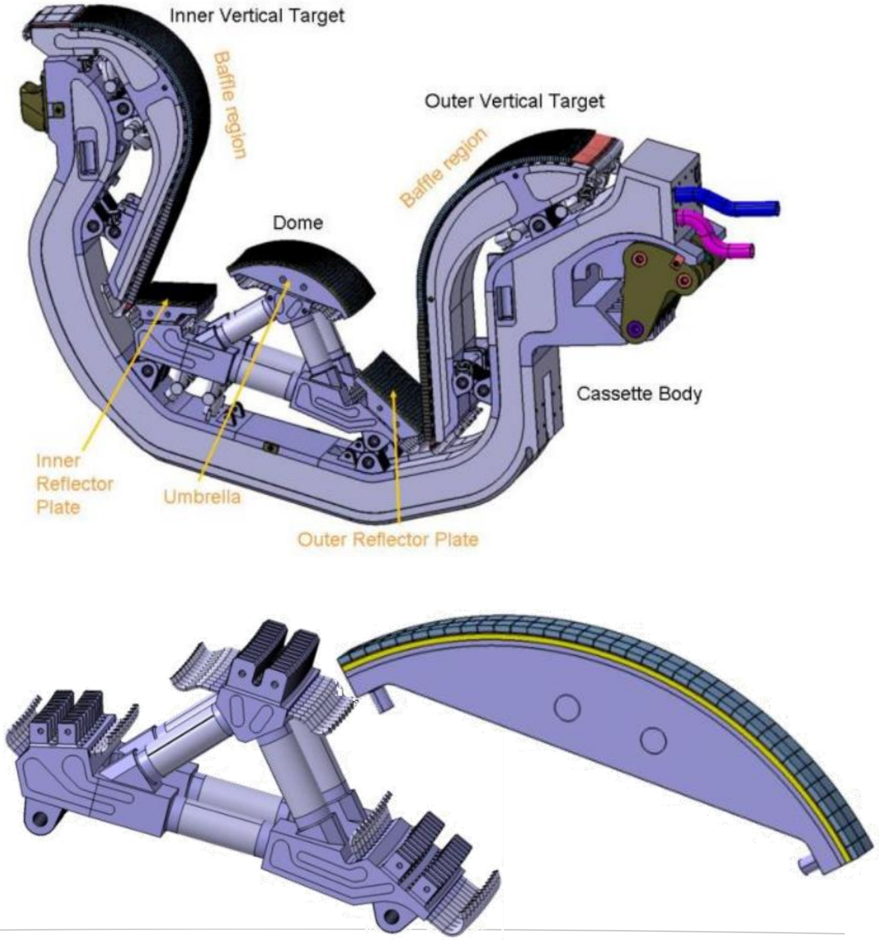
IN-VESSEL COMPONENTS: Brief Description of Blanket & Divertor



One Blanket Module



One Divertor Cassette



IN-VESSEL COMPONENTS: Design – Development of SDC-IC

- Specific nature, not traditional pressure equipment
- Specific environments & loads (neutron radiation, high heat fluxes, electro-magnetic forces, etc.)

→ **SDC-IC**
Structural **D**esign **C**riteria for
In-vessel **C**omponents

- History:

Edition	Contributors	Purpose
2004	Home Teams of the European Union, Japan, the Russian Federation, and the United States, advised by consultants from laboratories and industry	Establish design rules addressing the effects of irradiation, with the RCC-MR as starting point.
2012	ITER Organization, European & Russian Federation Domestic Agencies, and experts from ITER Organization & Domestic Agencies → Presented at “ASME Pressure Vessel & Piping” conference and published in “Fusion Engineering & Design” international journal	• Reflect latest editions of RCC-MR (2007), ASME Code & EN Standards • New material data • New appendices: ○ Consistency with manufacturing rules, ○ Design by experiment, ○ Relationship with PED / ESPN ○ Design of in-vessel coils

- New editions of RCC-MR (MRx): Irradiation covered + Reduced-Activation Ferritic-Martensitic Steels

IN-VESSEL COMPONENTS: Design – SDC-IC 2012 Criteria Levels & Damages

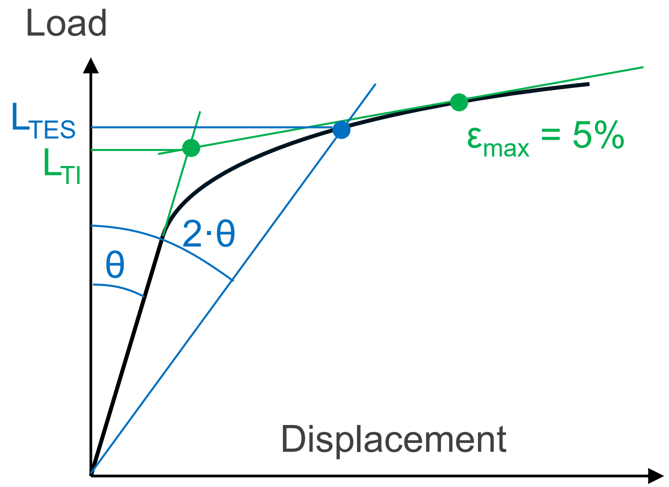
Criteria Level	Damages Prevented

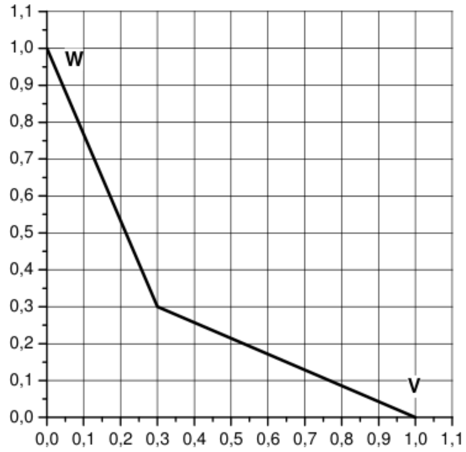
A	• M-type – Ductile Damage Modes:
	    o Immediate plastic collapse & instability
	    o Thermal creep
	• M-type – Non-Ductile Damage Modes:
	    o Immediate plastic flow localization
	    o Local fracture due to exhaustion of ductility
	    o Fast fracture
	• C-Type:
	    o Ratcheting
	    o Fatigue
	• Buckling

C	Same as Level A but with lower safety margins
D	Same as Level C but without C-type damages and lower safety margins
Testing Conditions	• Immediate plastic collapse, • Buckling

IN-VESSEL COMPONENTS: Design – SDC-IC 2012 General Criteria

- Plastic collapse & instability:
  - Elastic: Usual limits on primary stresses (shape factors reduced with irradiation)
  - Elastic-plastic analyses: Two methods for determination of plastic collapse load
- Non-ductile damage modes:
  - Plastic flow localization: Limiting of primary + secondary stress / strain
  - Local fracture due to exhaustion of ductility: Limiting of peak stress / strain
  - Fast fracture: Limiting of Stress Intensity Factors or crack extension force
- Progressive deformation / Ratchetting:
  - Elastic approach: Two methods (efficiency index & $3 \cdot S_m$)
  - Elastic-plastic approach: Limiting of membrane & peak strains
- Fatigue:
  - Low temperature: Strain-life fatigue approach (low-cycle fatigue)
  - High temperature: Creep & fatigue usage factors limited with interaction diagram
  - Guidance for discontinuities, welded / brazed joints & cycle definition
- Buckling (load-controlled): Same load factors than immediate plastic instability





IN-VESSEL COMPONENTS: Design – SDC-IC 2012 Specific Criteria

- Welded / brazed joints:
  - Material property coefficients J_m & J_K or J_J (fast fracture)
  - Joint efficiency coefficients n & fatigue strength reduction factors f
  - Elevated temperatures: Additional coefficient J_t to be obtained experimentally, as well as fatigue strength reduction factor for brazed joints (heterogeneous creep responses)
- Bolts:
  - Rules from RCC-MR 2007 (mainly) but also ASME BPVC.III.1 & .VIII.2, and EN 13445
  - Distinction between leak-tight & structural (non-leak-tight) joints:
    - Leak-tight joints: Rules very similar to ASME BPVC.III.1 & RCC-MR
    - Structural joints: Preload also considered, distinction between high & non-high - strength bolts for structural joints (S_{mB} vs. S_m)
  - SDC-IC Appendix A : Allowable stresses for fastener materials (negligible irradiation)
  - High temperature covered (creep)
  - SDC-IC Appendix B – Guidelines for Analysis: B3800 – Bolted Joints
- Bellows: Design by Analysis – Rules for Homogeneous Structures
- Multilayer heterogeneous structures

IN-VESSEL COMPONENTS: Design – SDC-IC 2012 Materials

Paragraph in SDC-IC Appendix A	Material	Examples of Use
S03	316L(N)-IG	• Blanket Shield Module and the structural part of First Wall • Divertor cassette body and dome / vertical target structures
S01, S02	304L, 316L	• Cooling pipes
S05/B03	XM-19	• Structural material for plasma-facing components • Divertor cassette links & attachments
S04/B02	660	• Fastener components – bolts, washers • Forgings in divertor supports
S11, S10/B01	Inconel 625 & 718	• Connection between Divertor's CuCrZr & 316L cooling pipes • Bolts attaching Blanket Modules to Vacuum Vessel (flexible support)
S31	CuCrZr	• Heat sinks in divertor & blanket • Electrical straps of blanket • Various applications in neutral beam heating system • Conductor of some stabilization coils (ELM)
S33	Al–Ni Bronze	• Pins attaching divertor's plasma facing components to the cassette • Blocks for attachment of divertor to the vacuum vessel
A02	Tungsten	• Armour of plasma-facing components (blankets & divertor)
S30	Copper	• Layer between W armour and CuCrZr heat sink in divertor & blanket • Copper cuffs between diamond windows and stainless-steel housing of ECRH launcher • Wires for diagnostics

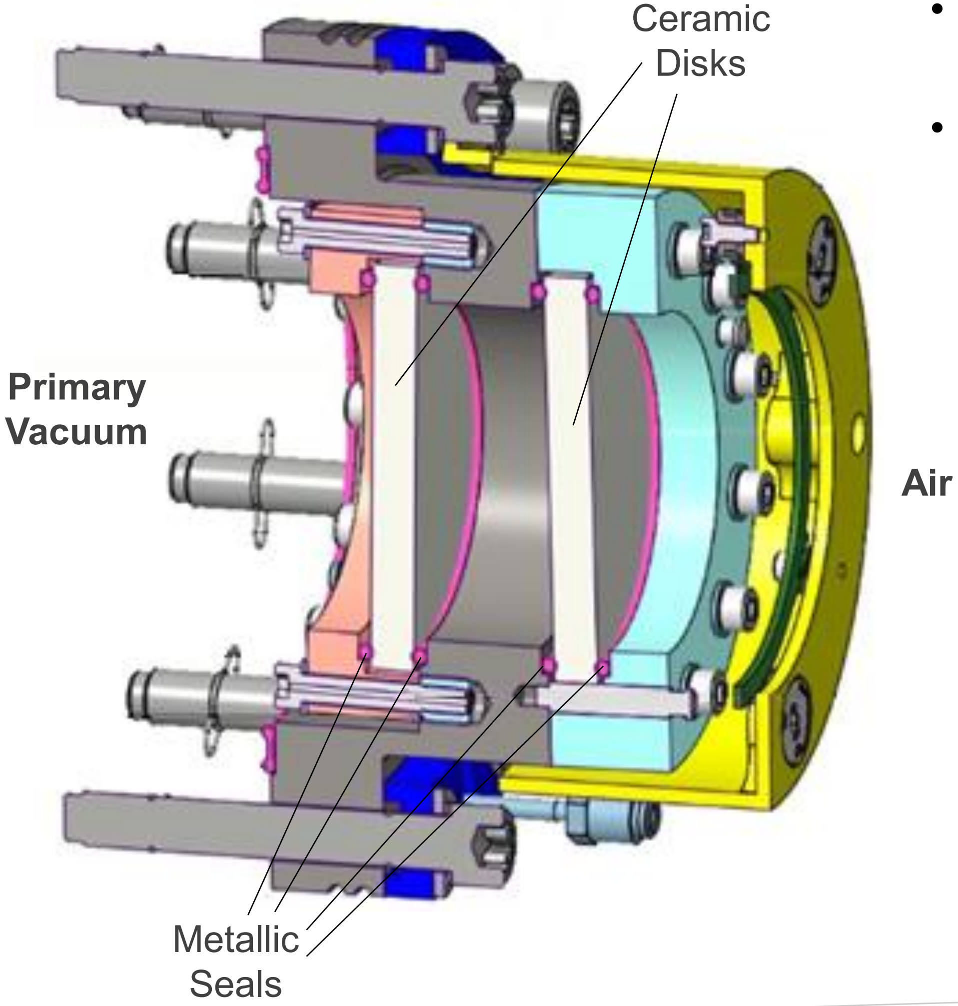
IN-VESSEL COMPONENTS: Construction & Tests

- Material procurement:
  - ASTM & EN standards, and other standards from ITER members
  - Technical specification to reduce material activation (limiting impurities)
- Manufacturing & Examinations: EN-13445 for most components
  - SDC-IC Appendix E1: Consistency with EN-13445 design rules
  - SDC-IC Appendix E2: Consistency with EN-13445 manufacturing rules
- Tests:
  - SDC-IC Pressure tests (compliant with PED)
  - SDC-IC Appendix F1: Design by Experiment – Plasma Facing Components
  - SDC-IC Appendix F2: Design by Experiment – Ceramic Insulation in Pads

Note

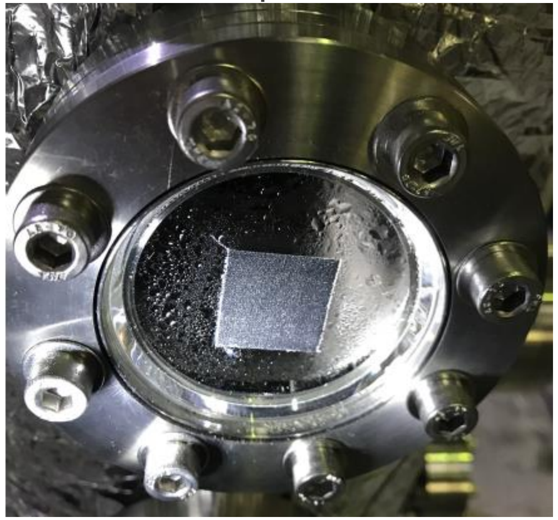
- SDC-IC Appendix G: Relationship with PED/ESPN requirements

WINDOWS: Design, Construction & Tests

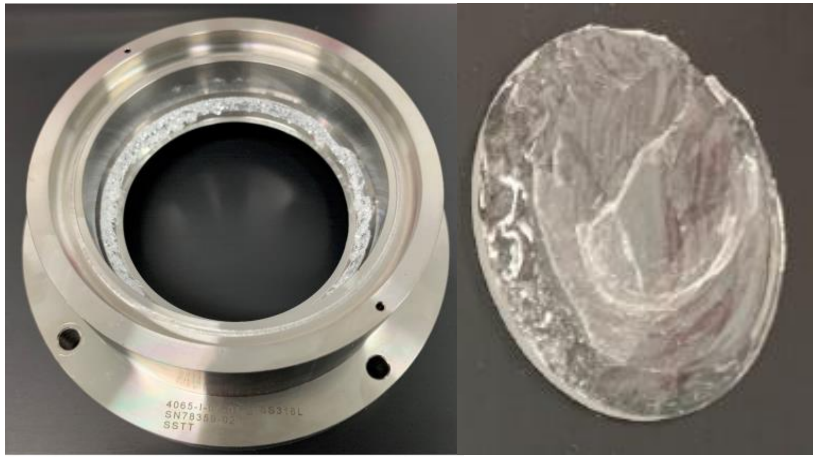


- Metallic parts: RCC-MR 2007, supplier's data for metallic seals
- Ceramic disks (Fused Silica, Saphire, Quartz, ZnSe, Diamond): Technical specifications & design by experiment:
  - Material characterization tests:
    - Optical
    - Flexural strength
    - Fracture toughness
    - Crack growth
  - Qualification tests on window assemblies:
    - Chemical aging
    - Thermal cycling
    - Vibration & impact
    - Max P & T
    - Leak

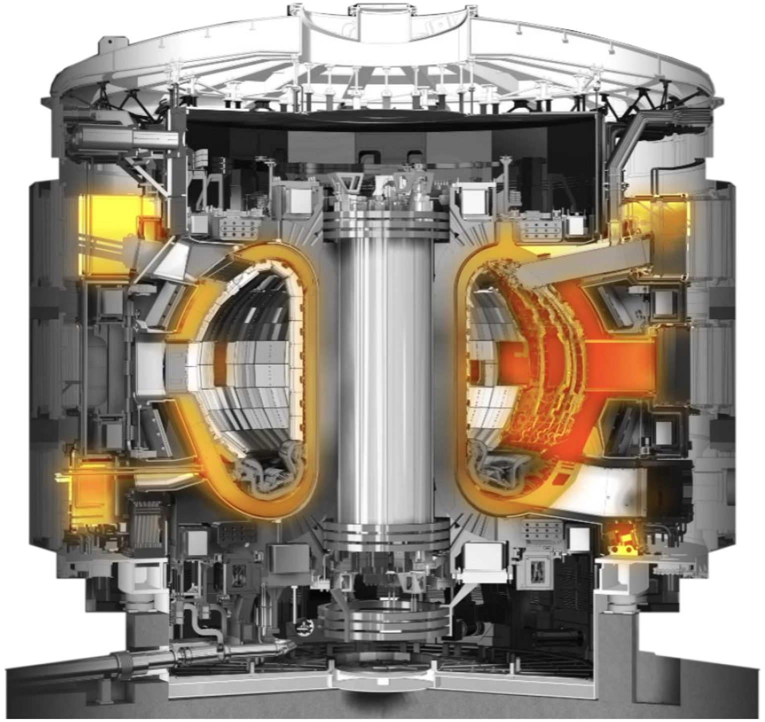
Steam Exposure Test



Broken Specimens after 700-1000kgF

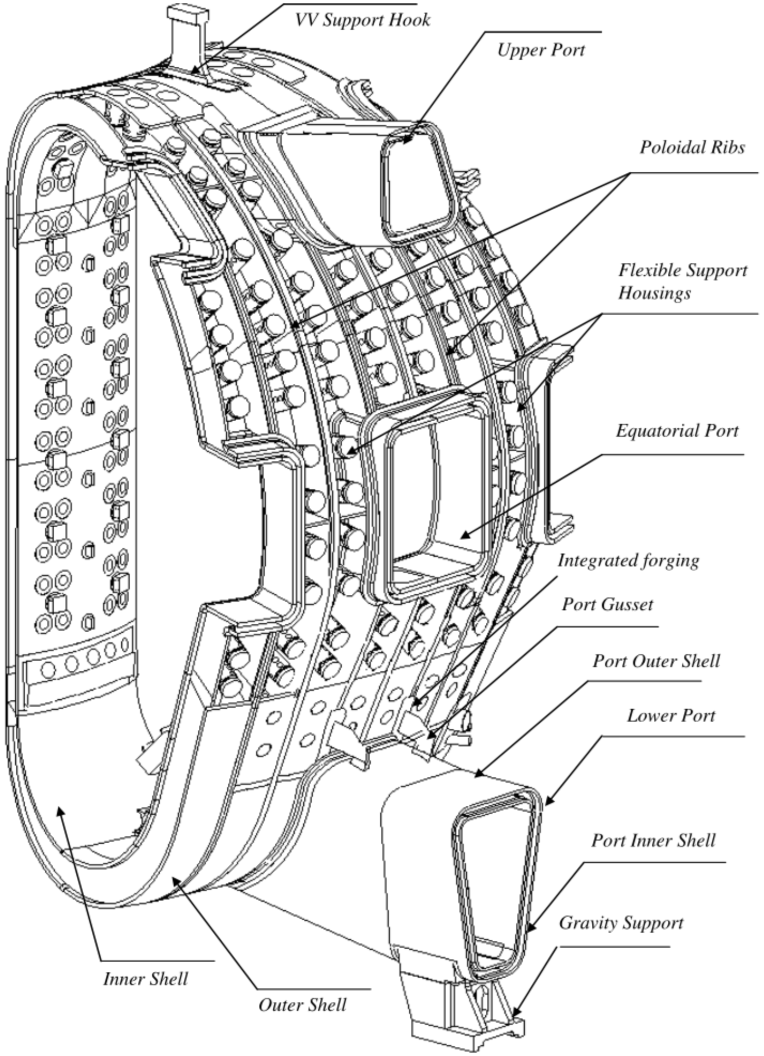


VACUUM VESSEL: Brief Description



One VV Sector
(without Ports)

View from Outside
(Outer Shell Partially Removed)



VACUUM VESSEL: Design, Construction & Tests

- RCC-MR: Comprehensive mechanical code, initially developed for fast neutron reactors
- Edition 2007: Upgrade to cover ITER Vacuum Vessel
  → Appendix 19: ITER Vacuum Vessel Specificities
  - Design rules for box structures (RC 3800), rechecked (elastic/inelastic approaches, cyclic damages)
  - Bolt material data & design rules supplemented
  - Main mechanical data of 316L(N)-IG (Iter Grade) from A3.1S (316L(N))
  - NDE (Non-Destructive Examination) of welds: PAUT (Phased Array Ultrasonic Testing) as alternative to single probe reflexion UT (Ultrasonic Testing)
  - Appendix 16: Detailed rules for fracture mechanics
  - Appendix 18: Additional rules for (Nuclear) Pressure Equipment
- Internal (ITER Org) implementation document, essentially design scope, reference to other C&S (RCC-MR, NF EN, ASME & RCC-MRx).
- RCC-MR 2007 reference for the evaluation of conformity to regulation.

VACUUM VESSEL: Field Joint Welds Between Sectors

- NDT of austenitic high-thickness narrow-bevel weld of ESPN N2
- 100% volumetric examination required:
  - RT (Radiographic Testing): Reference
  - If RT not possible, RCC-MR allows the use of UT under the following condition (RMC 2610):
    "*The Manufacturer shall submit before application the method he intends to adopt to the Contractor along with supporting evidence demonstrating that the method does in fact enable the defects being tested for to be identified and characterised*"
  - **UT Qualification and Demonstration is a Code Requirement whether for UT or PAUT.**
  - **Extensive work has been carried out, especially for VV Sector manufacturing and the upcoming field joint welds between Sectors.**

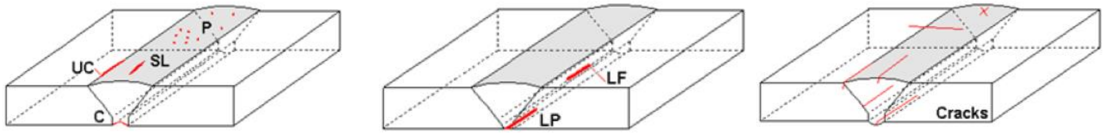
IO Requirements for UT Qualification
(May be updated following experimental campaign)

Definition	Classification in ISO6520-1
Cracks	101-102
Cavities	201-202
Solid inclusions	301-303-304
Lack of fusion or penetration	401-402

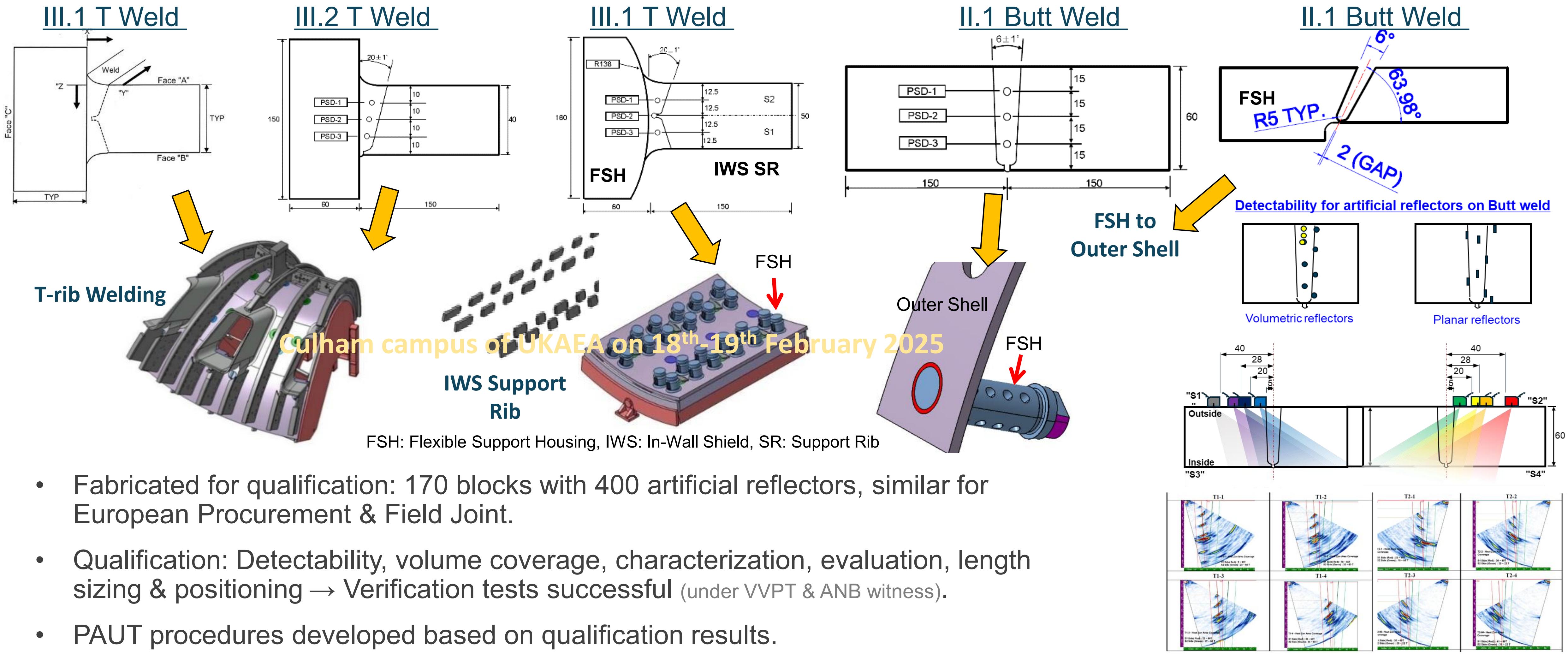
Table 9.1-1: List of the foreseeable defects in production welds[4]

Artificial defects	Real defects simulated	Dimensions
Side Drilled Holes	201-202 301-303-304	Diameter ≤ 2 mm
Surface Breaking Notches	101-102 4013-4021	Wide ≤ 0.25 mm Height ≤ 0.035t
Embedded Notches	101-102 401-402	Wide ≤ 0.25 mm Height ≤ 0.065t

Table 9.3-1: Dimensions of artificial defects



VACUUM VESSEL: UT Qualification for Various Welds of Korean Procurement



FSH: Flexible Support Housing, IWS: In-Wall Shield, SR: Support Rib

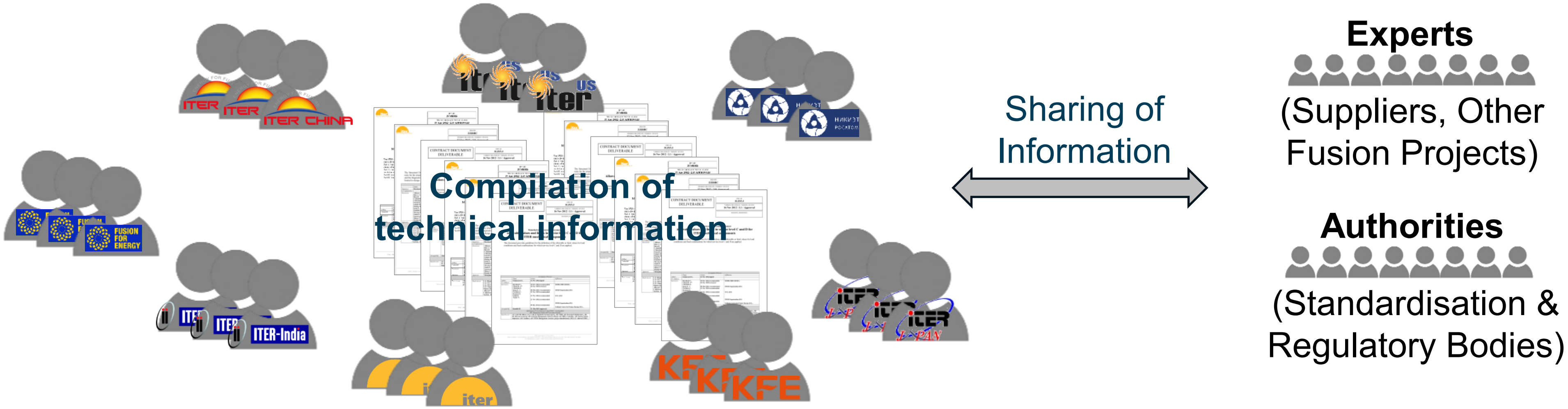
- Fabricated for qualification: 170 blocks with 400 artificial reflectors, similar for European Procurement & Field Joint.
- Qualification: Detectability, volume coverage, characterization, evaluation, length sizing & positioning → Verification tests successful (under VVPT & ANB witness).
- PAUT procedures developed based on qualification results.

FUSION CODES: Suggestions for Development

- EM (Electro-Magnetic) transient loads:
  - Main specific feature of fusion.
  - Complexity of EM Load calculations → Annex with guidelines
- Vacuum Vessel:
  - Parts have different roles (e.g. confinement barrier, mechanical support, field joints) → Criteria could be relaxed where reasonable (e.g. allowing larger defects given good ductility & limited stresses).
  - Reasonably conservative (justified) approaches could be proposed to cover difficulties with In-service Inspections (reconsidering 0.1 fatigue damage).
- Verification / justification by experience very critical: Instrumentation & Tokamak Systems Monitoring, simulator.
- Sharing of ITER's experience on the design & construction of Tokamaks: Start of ITEC activity (see next slide).

INTRODUCTION TO ITEC Activity: Presentation (1/2)

INTERNATIONAL TOKAMAK ENGINEERING CRITERIA



Type of Activity: Collaborative activity to be jointly conducted by the ITER Organization & Domestic Agencies.

Main Objective: Provide a set of technical information or criteria obtained through experience in design & construction of fusion-specific components

→ Could be used for further fusion development, such as construction of fusion power plants in the ITER member countries.

INTRODUCTION TO ITEC Activity: Presentation (2/2)

Scope: Priority on compilation of technical information related to structural integrity of fusion-specific components of Tokamaks.

Components	Technical Information
• Superconducting magnets • Vacuum vessel • Divertor • Blanket • Thermal shields • Cryostat. • Others as needed	• Requirements (e.g. safety, quality, technical) • Design and operating/loading conditions • Design rules and standards • Structural design reports • Manufacturing & inspection reports • Any technical provisions from lessons-learned in ITER experience

Data Management: Technical information initially compiled & structured using ITER Document Management System

Future formulation in the ITER Engineering Database

ITEC Output

Technical Information & Lessons Learned

Example: Some ITER VV Engineering Documents

- Design Description
  - ITER Vacuum Vessel and Ports drawing file (ITER
  - ITER Vacuum Vessel and Ports, General descriptic (ITER_D_2FFSQ4 v2.2)
- Procurement
  - EU DA VV ANNEX B REFERENCE DOCUMENT
  - EU DA VV ANNEXB MANDATORY APPENDICES
  - IWS Annex B (ITER_D_2ET4VL v1.7)
  - KO DA VV ANNEX B MANDATORY APPENDICE
  - Upper Ports Annex B-B1-B2 and Top Documents
- Structural Integrity
  - Structural Integrity Report of the ITER Vacuum \ (ITER_D_2F73RX v5.3)
  - Structural Integrity Report of the ITER Vacuum \ pages summaries (ITER_D_TWZWZ9 v1.1)