An Overview on Development of Codes and Standards for Tokamak Fusion Power Plant in Japan

- Bridge Program “Fusion energy system Standardization” (BFS) -

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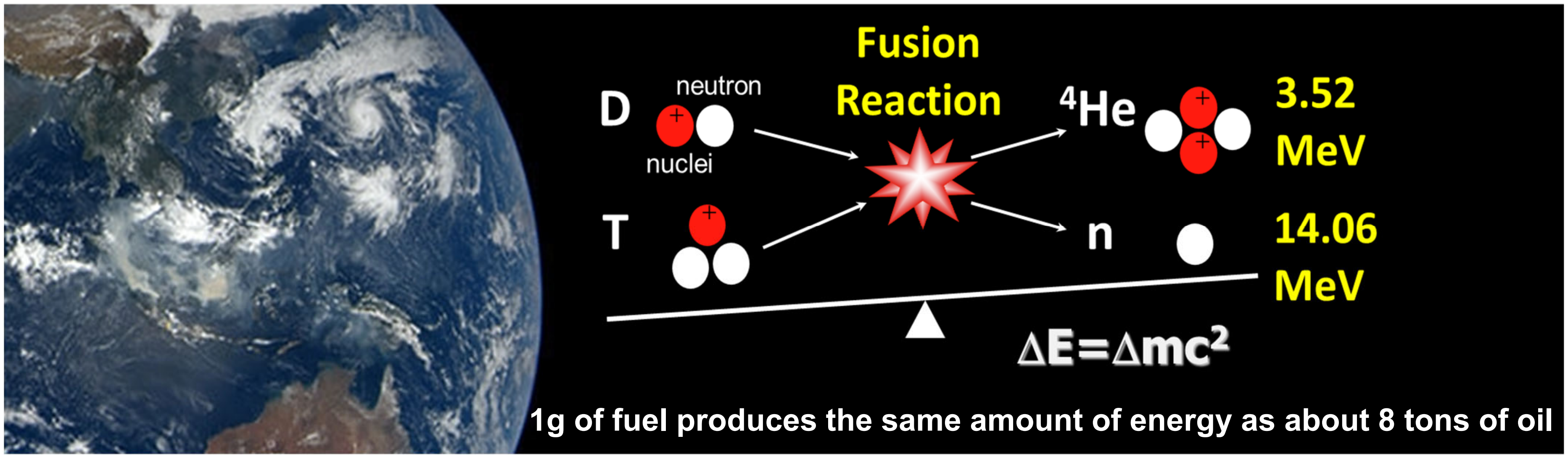
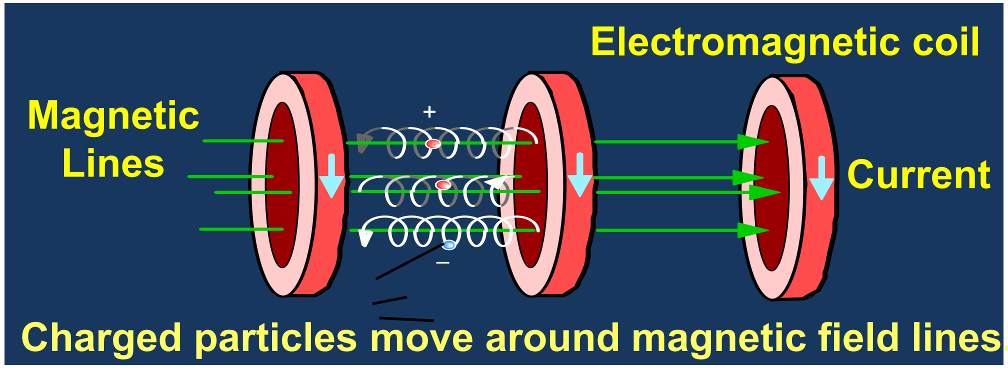
Introduction: Unique Safety Nature in Fusion Reaction

- Heat Deuterium (D) & Tritium (T) to several thousand degrees ⇒ Plasma
- Heat DT Plasma over 100 million degrees, and then nuclei fuse together
- 1g of fuel produces the same amount of energy as about 8 tons of oil
- Single reaction only under limited conditions, no melt-down possible
- Inherent safety：self-shutdown by very small amounts of impurities (LBB utilized) and by temperature and density fluctuations outside operating range
- Low hazard potential： several tenths lower than that of a 1MW fission reactor, safety requirement almost the same as ASME Sec. III ND or Sec. VIII-Div.1.
- Unlimited and non-localized fuel in seawater for millions of years

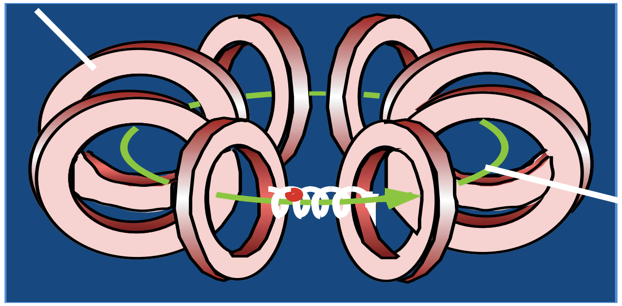


Introduction: Tokamak Fusion Facility

High Temperature Plasma confined by magnetic cage generated by superconducting (SC) coils

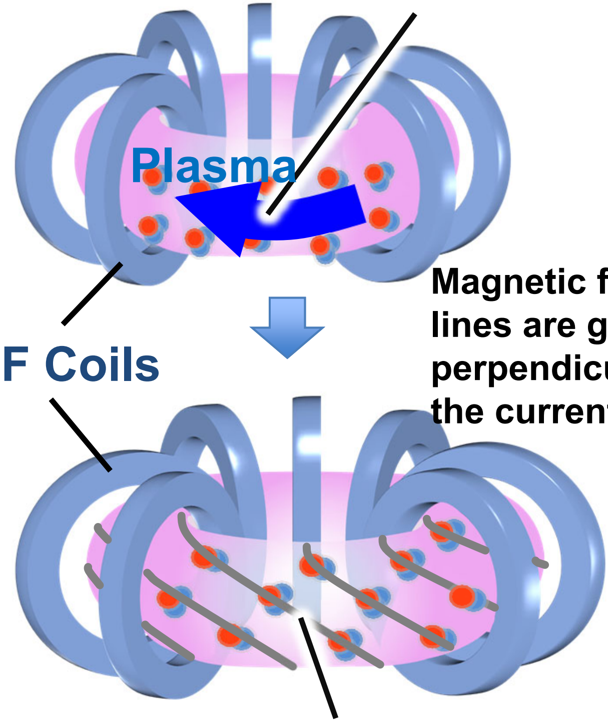


Toroidal Field（TF）Coils



Toroidal Fields

"Tokamak": Russian acronym for "Toroidal Chamber, Magnetic Coils"



Strong magnetic cage with twisted magnetic field lines

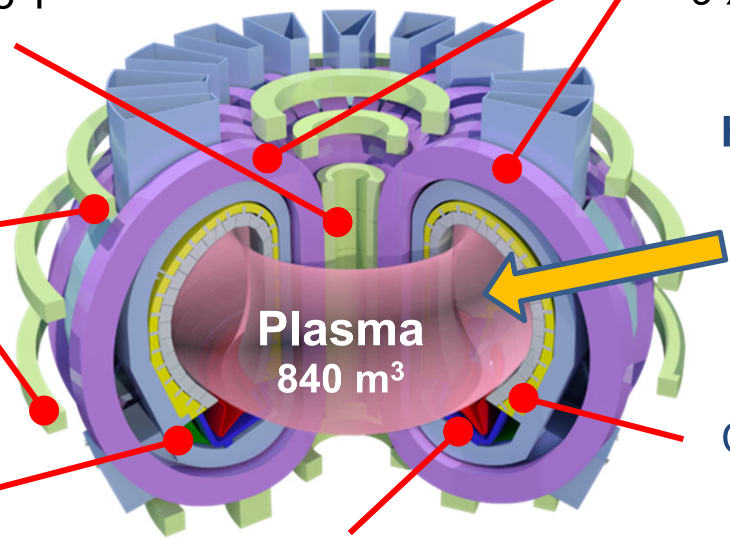
ITER: Tokamak Configuration

Fusion Specific Components and Design Parameters

Center Solenoid (CS)
inducing plasma current
4-m dia.、16-m high, 13 T

Toroidal Field (TF) Coil
confining plasma
9 x 17 m、 18 coils, 12 T

Poloidal Field（PF）Coil
shaping and positioning
8 - 26 m dia.、6 coils
4-6 T、NbTi



Heating & Current Drive
high energy（1 MeV）
beam & high frequency
heating（170 GHz）

Vacuum Vessel (VV)
vacuum for plasma,
shielding for SC coils
D-shaped and double
wall structure
～4,000 ton

Divertor
Exhausting impurities,
shielding for SC coils
54 cassettes, 10-20 MW/m^2

Blanket
Converting from nuclear
heat to thermal energy,
shielding for SC coils
4 ton x 400 modules
(Breeding Tritium in
Demo facility)

SC coils: non-safety, magnetic confinement, electromagnetic (EM) force
VV: safety enclosure (tritium & radioactive materials), shielding, EM force
In-vessel components: non-safety, operational functions, shielding, EM force

Formulation by JSME Code Committee

Superconducting Magnet (SC Coil) Structure Standards

1998	Activity of code development for fusion facilities was started in consideration of siting the ITER in Japan.
2001	A collaboration work between Thermal and Nuclear Power Engineering Society (TENPES), ASME and the Advisory Group (AG), chaired by Mr. R. W. Barnes, was started.
2002.7	Subcommittee on Fusion Power was established in JSME to start code activity for fusion facility. All activities and rights were conferred to JSME from TENPES.
2005	ITER site was determined in France and activities in JSME were suspended.
2006	Activity of code development was resumed with concentrating to the ITER TF coil structures as JA procurement.
2008 Mar	Final version approval at Main committee on Power Generation Facility Codes
Jun - Aug	Public comments
Oct	JSME S KA1-2008 Codes for Fusion Facilities – Rules on Superconducting Magnet Structure – (Japanese)
2010 Sep	JSME S KA1-2008 Codes for Fusion Facilities – Rules on Superconducting Magnet Structure – (English translation)
2014 Jan	JSME S KA1-2013 Codes for Fusion Facilities – Rules on Superconducting Magnet Structure – (Japanese + English translation)
2019 Aug	JSME S KA1-2017 Codes for Fusion Facilities – Rules on Superconducting Magnet Structure – (Japanese + English translation)

Material and Fabrication parts were applied to fabrication of ITER TF Coils procured in Japan

BRiDGE 研究開発とSociety 5.0との橋渡しプログラム programs for Bridging the gap between R&d and the IDeal society (society 5.0) and Generating Economic and social value

Formulation by JSME Code Committee

DEMO DESIGN JOINT SPECIAL TEAM

Basic concepts of the JSME code

(1) A safety requirement is almost the same as ASME Sec.III ND or Sec.VIII-div.1 because the hazard potential of fusion machine is similar to a general structure or general pressure vessel.

(2) Design by analysis, which is used in ASME Sec.III NC or Sec.VIII-div.2 , is adopted to ensure mechanical integrity of the structure having a complex geometry operated under complicated distributions of static and cyclic loadings.

(3) The code is developed from the existing ones taking into account of features of technical consistency between the existing codes, the features of the superconducting coils, manufacture experiences, and a lot of studies performed in these over 30 years on cryogenic structural materials.

(4) Postulation of very rare hypothetical events and evaluation of their consequences are regarded as non-mandatory because they do not have a significant meaning in operation of the fusion magnets.

(5) Over-conservative requirements are avoided as much as possible because the TF coil structured is not a radiological safety component.

(6) Rules of conformity assessment and quality assurance are included as a part of the code.

Formulation by JSME Code Committee

Standardization and Globalization for Tokamak Fusion Demo Reactor

JSME Code Committee Organization

- Main Committee on Power Generation Facility Code
  - Subcommittee on Thermal Power
  - Subcommittee on Nuclear Power
  - Subcommittee on Material
  - Subcommittee on Fusion Reactors
    - Subgroup on metal structure
    - Subgroup on non-metal structure
    - Subgroup on maintenance (planning)

As the initial work plan, focus on fusion specific components such as SC coil, VV, In-vessel components, Tritium facility, and prioritize technical investigation based on ITER experience, latest knowledge and ITER and Demo design.

ITER experience for rationalization

- **Review of System Based Standards**
- **Experience in design, fabrication, etc.**

Practice in nuclear power/existing plants

- **Investigation on the latest knowledge**
- **Advanced structural design, maintenance, etc.**

ITER to Demo design

- **Progressive development of standardization**
- **Risk based maintenance plan (JSM)**

Demo Codes & Standards (JSME)

- **System Based Standards update**
- **Entire lifecycle: design ~ operation**

Formulation by JSME Code Committee

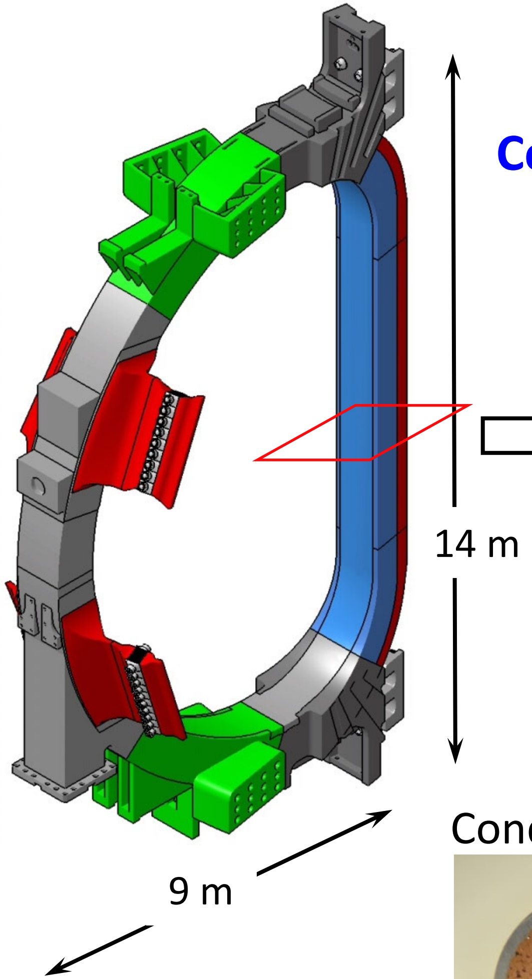
Structure of SC Coil Structure Standards

Red：JSME specific
Blue：partially JSME specific
Black：collaboration with ASME

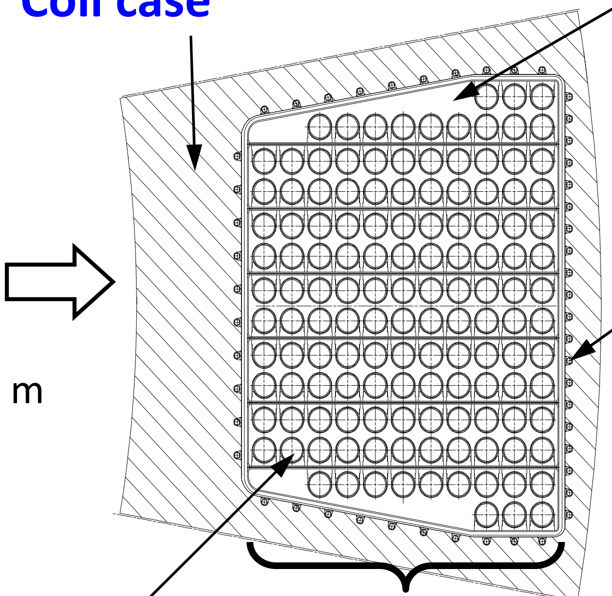
- MAIN TEXT
  - FM-1000 Scope, roles and responsibilities
  - FM-2000 Material
  - FM-3000 Design
  - FM-4000 Fabrication (HIP)
  - FM-5000 Non-destructive examination
  - FM-6000 Pressure and leak testing
  - FM-7000 Glossary
- APPENDICIES（Mandatory)
  - APPENDIX 11 Qualified inspection for superconducting magnet
  - APPENDIX 12 Duties of standard-expert engineers for superconducting magnet
  - APPENDIX 21 Standard for structural material
  - APPENDIX 22 Specification for welding material
  - APPENDIX 23 Guideline for applying new material
  - APPENDIX 31 Design fatigue curve (4K)
  - APPENDIX 41 Welding joints
  - APPENDIX 42 Qualification of HIP diffusion bonding process
  - APPENDIX 51 Ultrasonic examination method
- APPENDICIES（Non-mandatory)
  - APPENDIX 1A Guidelines for quality assurance
  - APPNEDIX 2A Material properties other than yield and tensile strength
  - APPENDIX 3A Rules for evaluation of service condition with limit set which exceeds limit sets 1, 2 and 3
  - APPENDIX 3B Fracture mechanics evaluation
  - APPENDIX 3C Experimental fatigue analysis for cyclic load
  - APPENDIX 4A Characteristic data of HIP diffusion bonded part
  - APPENDIX 4B Technical background of rules for fabrication with hip diffusion bonding

Example of Unique JSME Fusion Magnet Code Contents

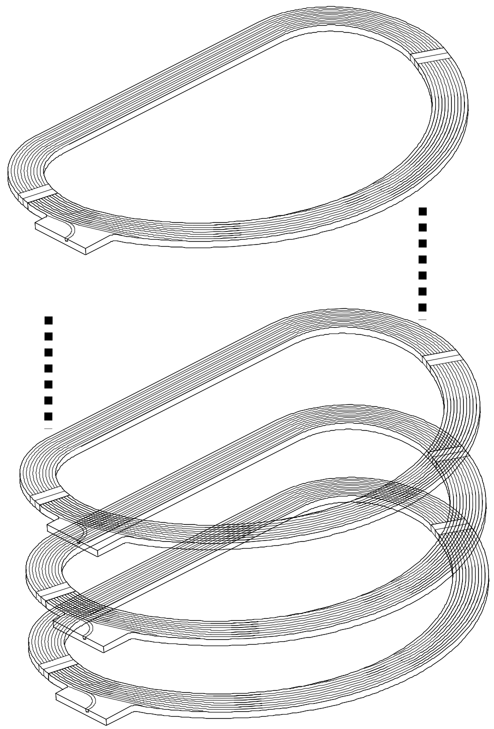
Configuration of TF Coil (Superconducting Magnet)



Cross sectional view



Radial plate

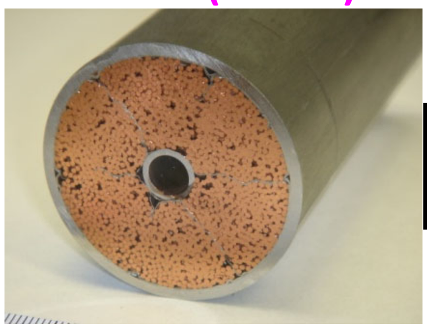


7 double pancakes

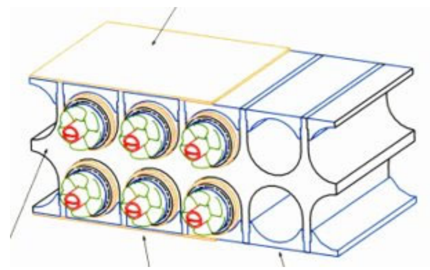
Structural components

Pressure components

Conductor(Jacket)



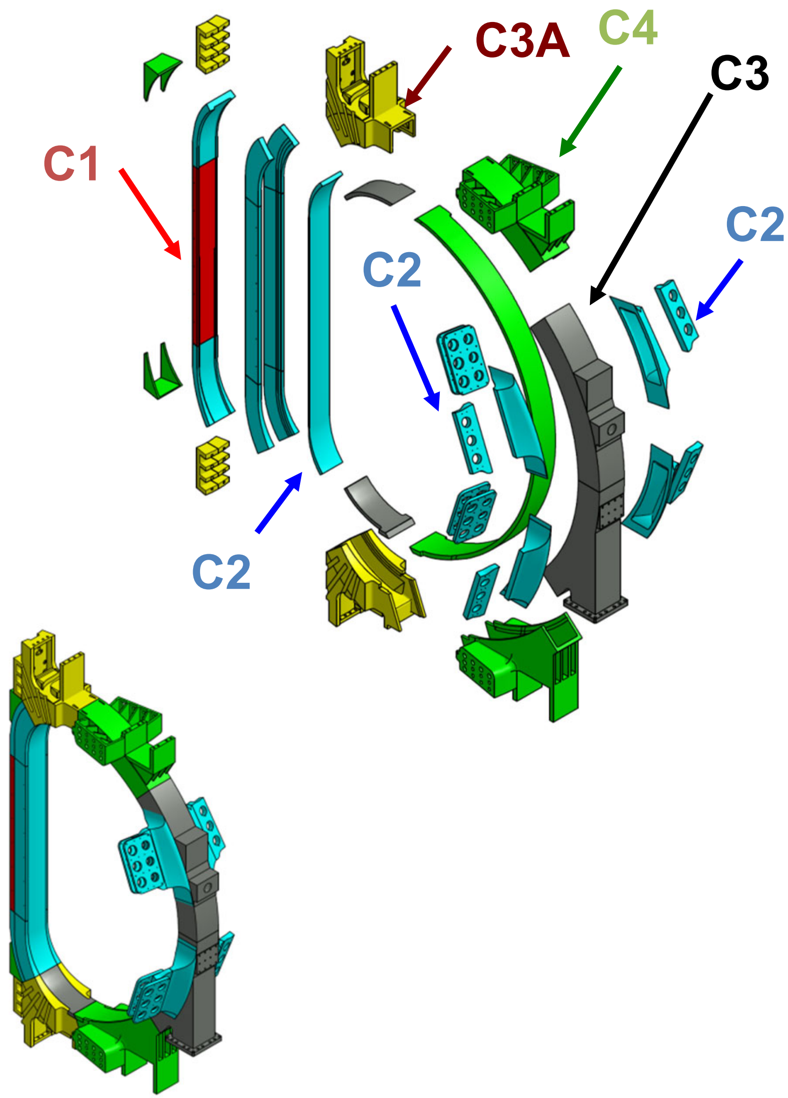
760m x 95 lengths
415m x 38 lengths

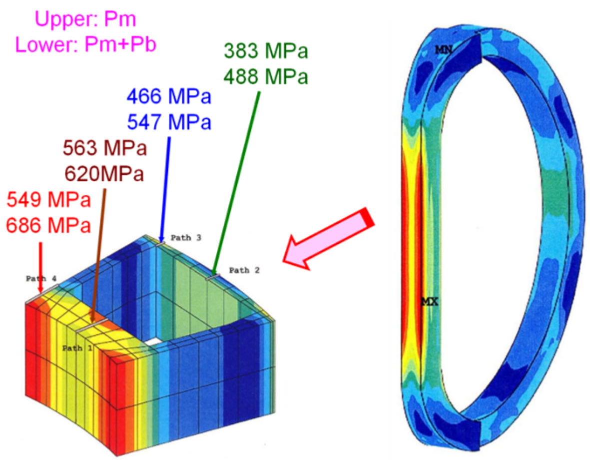


Example of Unique JSME Fusion Magnet Code Contents

Materials used in the TF coil cases

ITER Class	ITER 4K YS Requirements	Material to be used
C1	>1000MPa	JJ1
C2	>900MPa	316LN (C+N≥0.20%)
C3	>700MPa	316LN (C+N≥0.15%)
C3A	and at RT >260MPa	316LN (C+N≥0.15%)
C4	>500MPa	316LN (C+N≥0.08%)





Features of the JSME code: Material (3)

FM-2700 Design Yield Stress & Tensile strength

- Design yield stress and tensile strength of the material of which cryogenic design strength is not specified are those specified in Materials Standard, Table FM-2110-1, except for Y316L, YCu and YNiCr-3.
- Design yield stress and tensile strength of the material of which cryogenic design strength is specified such as FMJJ1, FM316LNL are given by the following equations except for FMYJJ1.

$$S_y = A_1 T^2 + A_2 T + A_3 \qquad \text{(2-1)}$$

$$S_u = B_1 T^2 + B_2 T + B_3 \qquad \text{(2-2)}$$

where, coefficients of A_1-A_3 and B_1-B_3 are given in Table FM-2710-1 and unit of T is Kelvin.

- Design yield stress and design tensile strength in increment of 50 K by obtained from equations (2-1) and (2-2) are shown in Table FM-2710-2 and Table FM-2710-3.

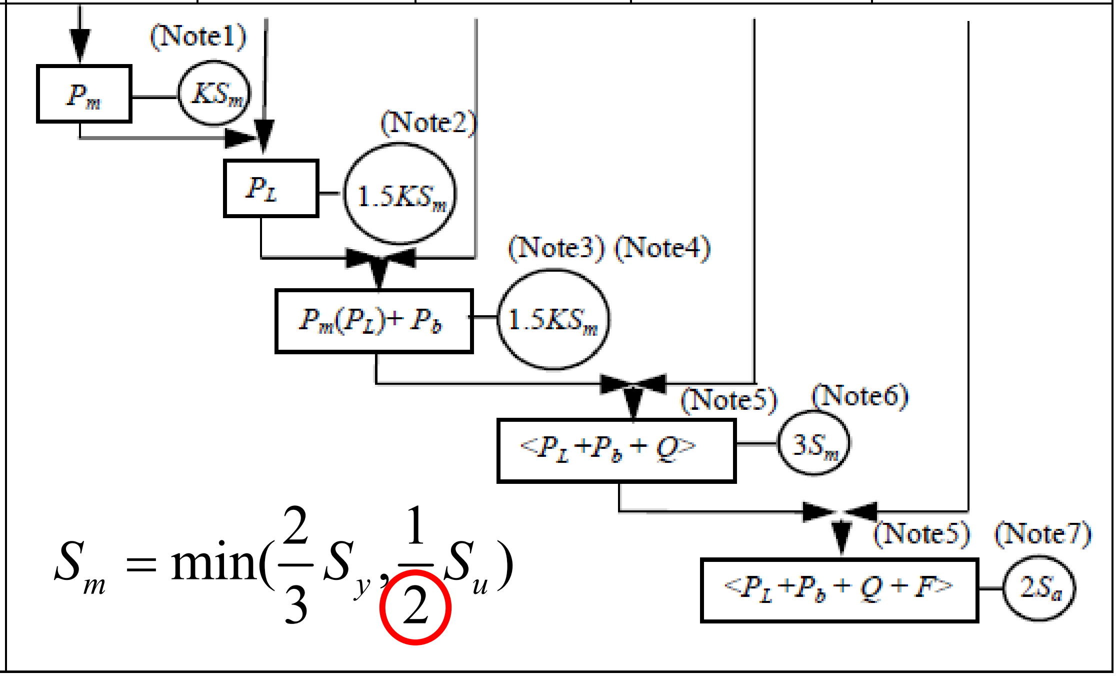
Example of Unique JSME Fusion Magnet Code Contents

Flow of assessment for primary and secondary stress

Classification of Stress	Primary Stress			Secondary Stress	Peak Stress
	General Membrane Stress	Local Membrane Stress	Bending Stress	Membrane Stress and Bending Stress	
Symbol	P_m	P_L	P_b	Q	F

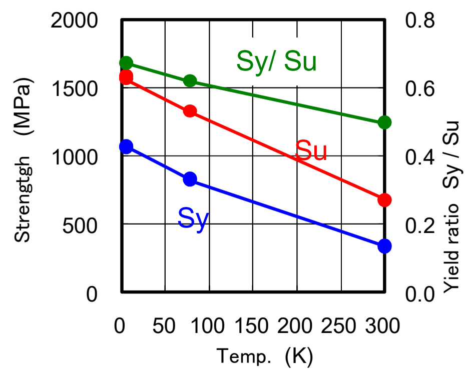
Combination of Stresses and Limit of Stress Intensity

Limit Set 1-3



$$S_m = \min\left(\frac{2}{3}S_y, \frac{1}{2}S_u\right)$$

Limit set	K
I	1.0
II	1.1
III	1.2



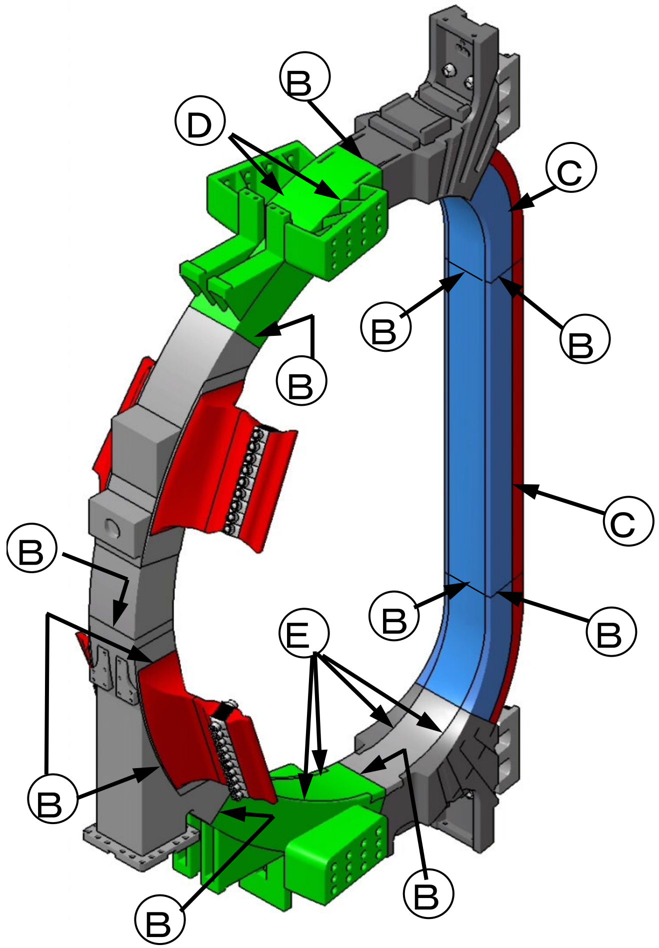
Tensile property of FMJJ1

Allowable stress for determination of wall thickness of jackets and helium piping

$$\sigma_a = \min\left(\frac{2}{3}S_y, \frac{1}{3.5}S_u\right)$$

Example of Unique JSME Fusion Magnet Code Contents

Joint Categorization



Joint categorization(1)
(APPENDIX 41)

Category		NDE, testing requirements	
A	Welded joint requiring high leak tightness	Volume + Surface	RT or UT
			+ (PT or ECT) + VT
			+ Pressure test + Leak test
B	Welded joint not requiring leak tightness and retaining expanding EM loads induced by self-magnetic field	Volume + Surface	RT or UT or PPT
			+ PT + VT

RT : Radiography, UT : Ultrasonic, ECT: Eddy Current
PT : Liquid Penetrant, VT : Visual, PPT : Progressive PT

System Based Standard Overall Structure

General rules

System using conventional standard

Yes

No

Specify group

Baseline and each group's applicable rule are specified for the equipment.

Baseline: Equipment other than those covered by the group rules. Reference standards are SC-III ND or SC-VIII

Group A: Low pressure equipment (e.g. fuel treatment and storage facility equipment)

Group B: Complex shaped equipment used at cryogenic temperatures (superconducting coil structures)

Group C: Complex shaped equipment requiring high leak-tightness (vacuum vessels, except for field weld)

Group D: Equipment requiring high leak-tightness with difficulty of weld inspection (field weld of vacuum vessel)

Group E: Replacing equipment requiring high leak-tightness with new bonding technology (In-vessel components)

Standards Stage:

	Material	Design	Manufacture	Completion inspection	Maintenance Inspection	Repair/ Replacement	Packaging/ Shipping
Baseline	Allowable stress system for Su design margin 3.5	Design by Rule	Conventional welding/joining methods	RT/UT[+PT]	Leak Test	Replacement not assumed.	New formulation
Group A	Same as baseline rule	Same as baseline rule	Same as baseline rule	PT	Same as baseline rule	Same as baseline rule	Same as baseline rule
Group B	2/3Sy	Design by FEM analysis	Same as baseline rule	Same as baseline rule	No leak test required	Same as baseline rule	Same as baseline rule
Group C	Rational allowable stress system	Design by FEM analysis	High quality welding method	UT/RT+PT	Helium leak test for outer shells	Same as baseline rule	Same as baseline rule
Group D	Rational allowable stress system	Design by FEM analysis	Inspection-free automatic welding	Inspection Free	Helium leak test for outer shells	Same as baseline rule	Same as baseline rule
Group E	Rational allowable stress system	Design by FEM analysis	HIP bonding, brazing, etc.	UT/RT+PT	No leak test required	Design life of replacing equipment	Same as baseline rule

Other suggestions

Acceptability proven through experiments, etc.

BRiDGE 研究開発とSociety 5.0との橋渡しプログラム
programs for Bridging the gap between R&d and the iDeal society (society 5.0) and Generating Economic and social value

Collaboration of JSME-ASME for Tokamak Code

DEMO DESIGN JOINT SPECIAL TEAM

JSME Main Committee on Power Generation Facility Code

Working Group on Tokamak Code (TCWG)

- Review of PT draft proposal
- Formulation of Japanese TC
- Update of Japanese TC
- Recommending R&D
- Working with AG & PT
- Coordination with JTG & Div.4 WGs

Subcommittee on Fusion Power
Chair：Nakahira

- Subgroup on Metal Structure
- Subgroup on Non-metal Structure

ASME Sec. III

ASME/JSME Joint Task Group for Tokamak Code (JTG): coordination & harmonization

ASME Sec. III Div.4

- SG Fusion Energy Devices
- SWG for Fusion Stakeholders
- WG General Requirements
- WG Magnets
- WG Vacuum Vessel
- WG Materials
- WG In-Vessel Components
- SWG Division 4 Updates

Advisory Group (AG)

- Review and revise of TCWG/PT TC
- Update of English TC
- Recommending R&D
- Working with TCWG & PT
- Coordination with JTG & Div. 4 WGs

Project Team (PT) / QST Demo Team

① **Draft proposal of Tokamak Code**
- System Based Code update
- Fusion specific components

② **R&D and test facilities**
- R&D plan for Tokamak Code
- Mechanical & engineering data acquisition

③ **Innovative technology & HR development**

Bridge program
“Fusion energy system Standardization”(BFS)
Program Director: Tada
Project Leader: Nakahira
Project Subleader: Nakajima

Industries & Institutions

Academic Society

Conclusion

- JSME SC Magnet Structure Standard prescribes general and technical requirements for construction of superconducting magnet for fusion facility.
- The standard contains rules for structural materials including cryogenic materials, structural design considering magnetic forces, manufacture including welding and installation, nondestructive testing, pressure proof tests and leak tests of TF coil structures.
- The standard covers requirements for structural integrity, deformation control, and leak tightness of all the components of the superconducting magnets and their supports, considering unique safety nature and structural features to avoid over-conservatism.
- JSME and ASME started collaborative work to develop a Tokamak Code.

Reference

SC Coil Structure Standards Published (PVP2009)

Proceedings of PVP2009
2009 ASME Pressure Vessels and Piping Division Conference
July 26-30, 2009, Prague, Czech Republic

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Thank you very much
for your attention