OXFORD SIGMA

Advancements in pressure codes & standards for fusion power plants

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UK: Summertown Pavilion, 18-24 Middleway, Oxford, OX2 7LG,UK
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SOFE 2025 Wednesday Parallel 2c - Materials and Materials Systems; Codes/Standards for Fusion, Kresge Little Theater (Building W16, downstairs), June 25, 2025, 2:00 PM - 3:30 PM

About Oxford Sigma in one slide

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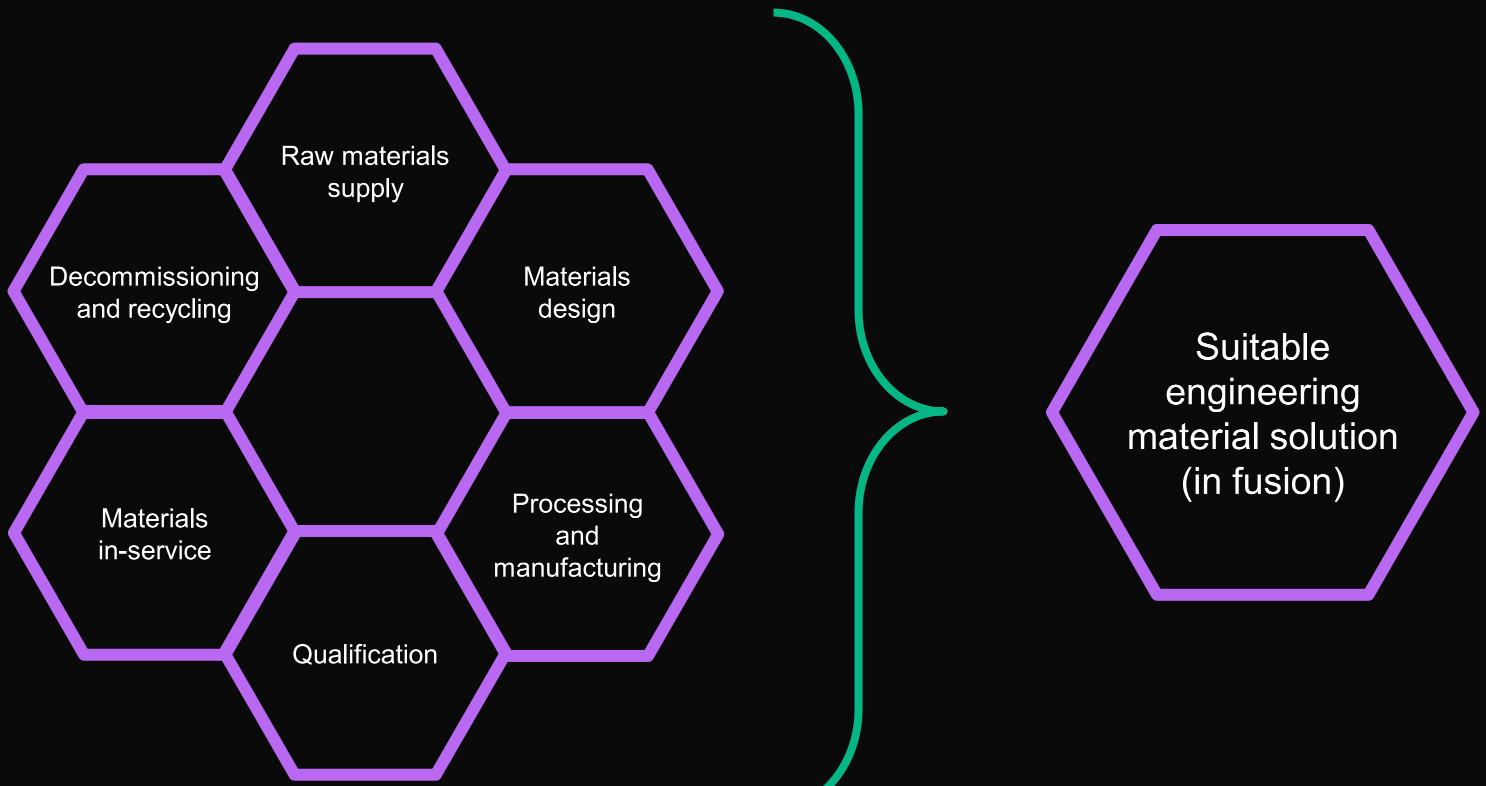

About Oxford Sigma in one slide

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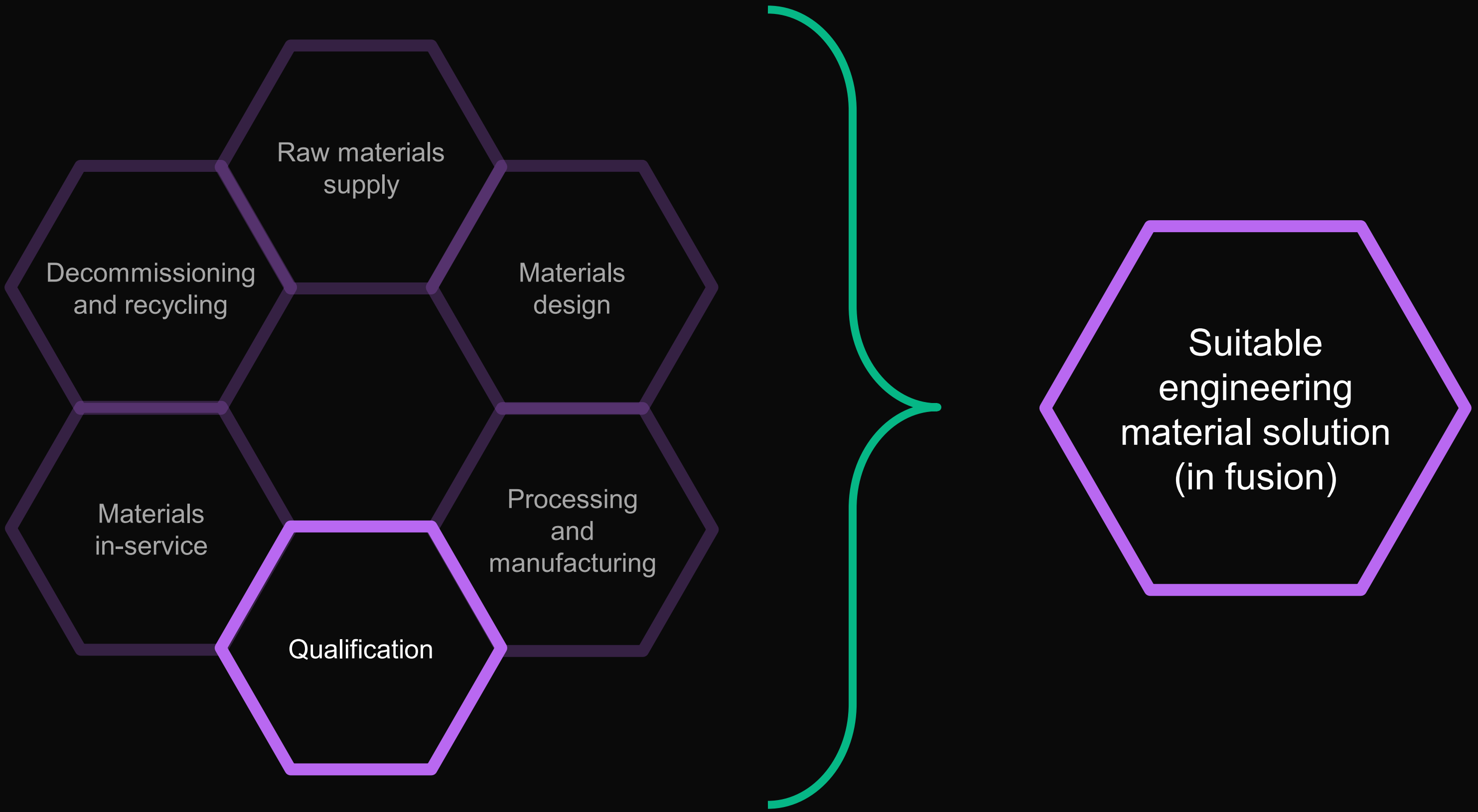

Outline

- Questions on the use of ASME BPV in fusion design and construction
- Component Quality: Importance and challenges in fusion systems
- Existing Codes and Standards for construction of fusion devices
- ASME BPV: Role and relevance in fusion applications
- High level overview of Materials Qualification within ASME framework
- Latest Developments: Updates on ASME BPV Section III, Division 4

Construction Codes and Standards

Ensuring quality through component excellence

Nuclear Fusion: Benefit vs Hazard

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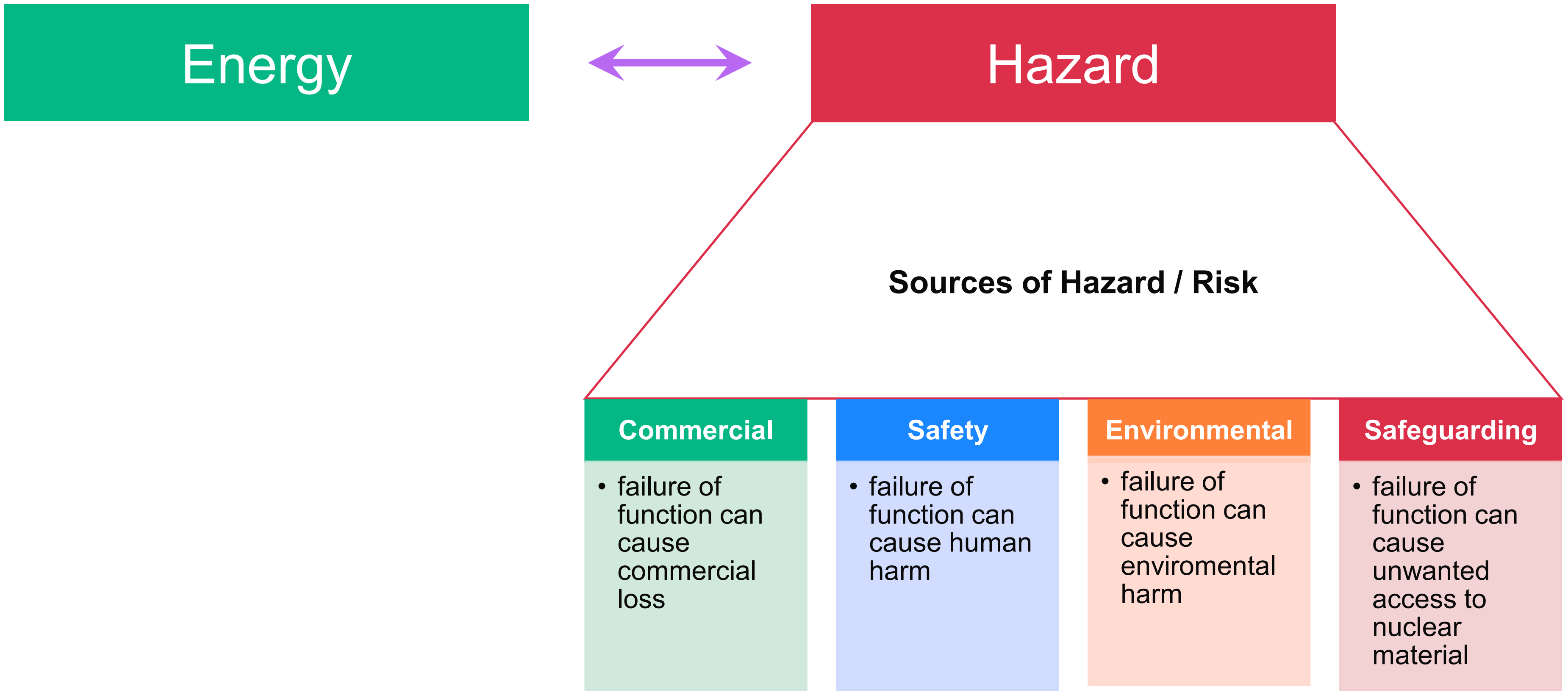
Fusion

Benefit is energy but the cost is hazard creation. **Owner** of the facility is legally required to minimise the hazard; the owner is responsible



Quality of components reduces the hazard

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Components in engineering are expecting to do the following:

- Have **capability** (the components contribution to the structural integrity of the associated system)
- Have **reliability** (is the degree of confidence that a component will perform its intended function over time, consistent with any safety and/or performance analysis claims that have been made against it)
- Have **robustness** (refers to the components resilience against internal or external hazard)

How do we ensure the above is maintained in the supply chain? Hold suppliers and engineers to account through standardisation, certification and verification methods to uphold quality

For what purpose …

1. Ensuring safe fusion component operation (and meet regulator requirements)
2. Ensuring operational fusion component performance (and thus economical output)

Pressure Systems Failures

Why this matters for fusion energy

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What quality assurance and control measures do we need?

Radial Build of a generic fusion reactor

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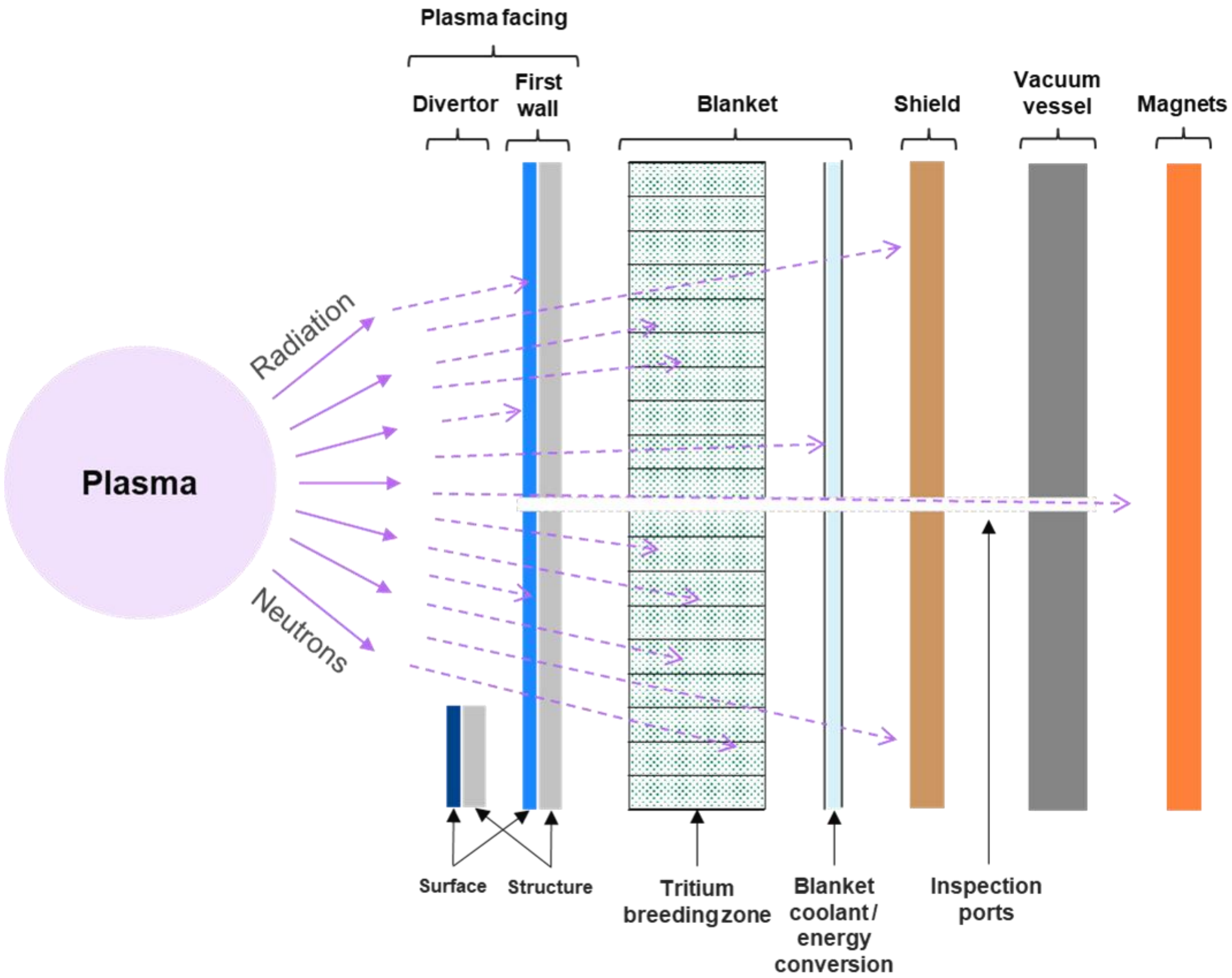

Table: General power plant environmental conditions

	Plasma facing	Breeder blanket	Vacuum vessel	Magnet structure
Neutron irradiation	High	Very high	Low	Very low
Expected life	Shortish	Medium	Forever	Forever
Temperature	High	Medium	Low	Cryo
Pressure	High coolants	High coolants	Medium coolants	Medium coolants
Mechanical loading	Low	High creep / fatigue	High loading	very high loadings
Expected failure modes	Creep, ratchetting etc	Creep, ratchetting, embrittlement	Ductile failure	Fast facture
Tolerability of failure	Maybe some	Maybe fewer or none?	No	No

Strict high demands on quality requirements of components to ensure operational and/or safety requirements

Code and Standards - Definitions

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Structural Integrity: *"Designing and operating products that are safe."*

Code: Tells you what to do and what to assess

Standard: Describes the methodology and minimum requirements

Design Criteria: Provides the "how" to assess your design

Applying Existing Codes and Standards

What can be applied to ensure the quality and operational performance?

Existing Code Base for Fusion Power Plant (FPP)

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Fusion Power Plants (FPP) C&S for Mechanical Components

Industrial Specific (today)

French AFCEN RCC-MRx 2022

AFCEN expanded RCC-MR (2007) to RCC-MRx (2022):
- Vacuum vessel
- Ports
- Port plugs
- Penetrations
- <u>Materials:</u>
  - EUROFER (2012).
  - CuCrZr, (2022).
  - F82H (TBC).

RCC used in ITER selected to meet French regulatory requirements

ASME BPV VIII Div 2, B31.3

- Cryostat
- Cooling water system
- Tritium plant
- Neutral beams
- Hot cells
- Radwaste storage
- Cryoplant (parts)
- Ex-vessel parts:
  - Diagnostics
  - Heating systems
  - Fuel systems
  - etc

EN 13445

- Cryoplant
- Cryopumps
- Liquid and gas distribution
- Manufacturing rules for IVC

ITER Specific (under development)

Magnetic Structural Design Criteria

- Structural components and welds
- Magnet windings
- Bolts, keys, supports
- Cryogenic piping

Structural Design Criteria – In-vessel Components

- Blanket
- Divertor
- In-vessel parts:
  - Diagnostics
  - Heating systems
  - Fuel systems
  - Neutron beams
  - etc

Technical Specifications and Design by Experiments

- Non-metallic windows diagnostics and heating
- Non-metallic insulating bushings
- ELMs and VS Coils
- Armour joints

Gap in ASME/RCC/EN codes mandated the generation of new rules. Experiments are needed to substantiate components

Fusion Power Plant / DEMO Specific (under development)

RCC-MRx 'future'

- Qualification of F82H
- Qualification of RAFM (EUROFER / F82H) weldments
- Aim for power plants (high level of degradation)
- ITER / EU-DEMO focused

ASME BPV Section III Division 4

- Dedicated volume to fusion power plants
- 2023 first edition
- Design recommendations on vacuum vessel today
- No fusion materials qualified for use as a pressure vessel
- Aim for power plants (high level of degradation)

EU-DEMO Design Criteria

- Inelastic Analysis Procedure
- Failure of brittle components (i.e. Tungsten)
- …

Gap in codes (RCC-MRx 'future', and ASME Div 4) drove the development of DEMO Design Criteria. These will likely be included in future C&S once substantiated

ASME BPV Section III
Division 4 “Fusion Energy Devices”

What is ASME BPV? Understanding Code

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Regulates the design and construction of boilers and pressure vessels

- First Edition 1915
- 31 books, 17,000 pages
- Industrial boilers, pressure vessels, nuclear reactor components, transport tanks, etc.
- Bridge between different suppliers, participants, researchers, designers, manufacturers, and regulators
- >1000 volunteer experts
- Balance of interests from industry, Government, Regulators, R&D, manufacturers
- Fully open and transparent consensus-based process
- Volunteers meet every quarter at ASME Code Weeks to vote changes
- Update every two years.

ASME BPV Organisation

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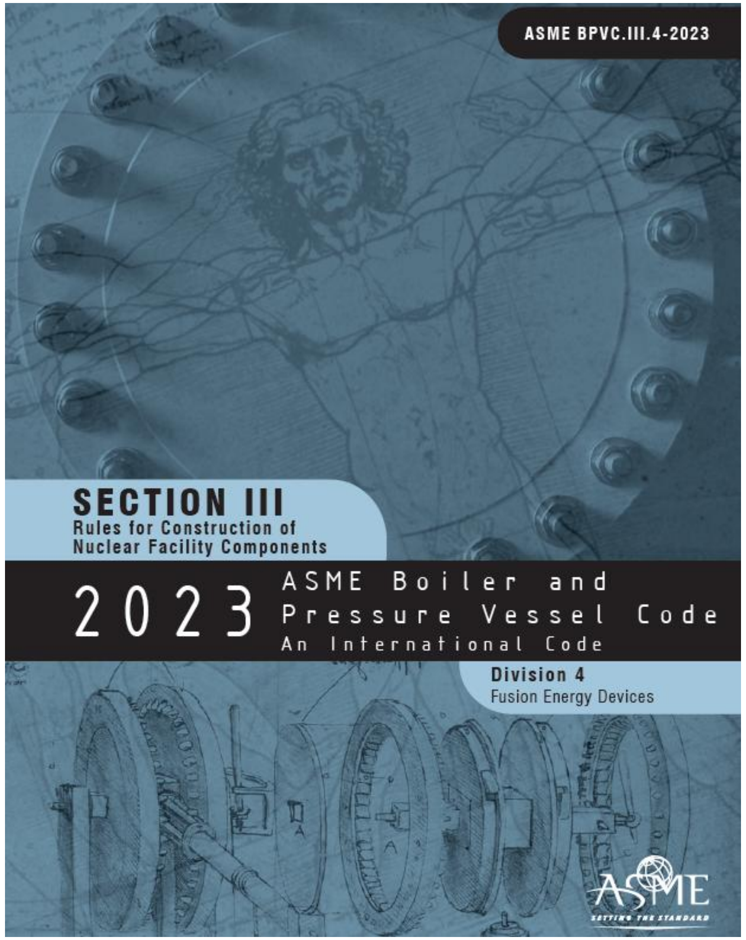
Section I	Power Boilers
Section II	Materials
Section III	Rules for Construction of Nuclear Facility Components
Section IV	Heating Boilers
Section V	Non-destructive Examination
Section VI	Recommended Rules for the Care and Operation of Heating Boilers
Section VII	Recommended Guidelines for the Care of Power Boilers
Section VIII	Pressure Vessels
Section IX	Welding and Brazing Qualifications
Section X	Fiber-Reinforced Plastic Pressure Vessels
Section XI	Rules for Inservice Inspection of Nuclear Power Plant Components
Section XII	Rules for the Construction and Continued Service of Transport Tanks
Section XIII	Over Pressure Protection

Division 1	Metallic vessels, heat exchangers, storage tanks, piping systems, pumps, valves, core support structures, supports, and similar items.
Division 2	Code for Concrete Containments
Division 3	Containment Systems for Transportation and Storage of Spent Nuclear Fuel and High-Level Radioactive Material
Division 4	Fusion Energy Devices
Division 5	High Temperature Reactors
Appendices	Section III Appendices
Section III Code Cases	Collection of Code Cases



ASME BPV Section III Division 4

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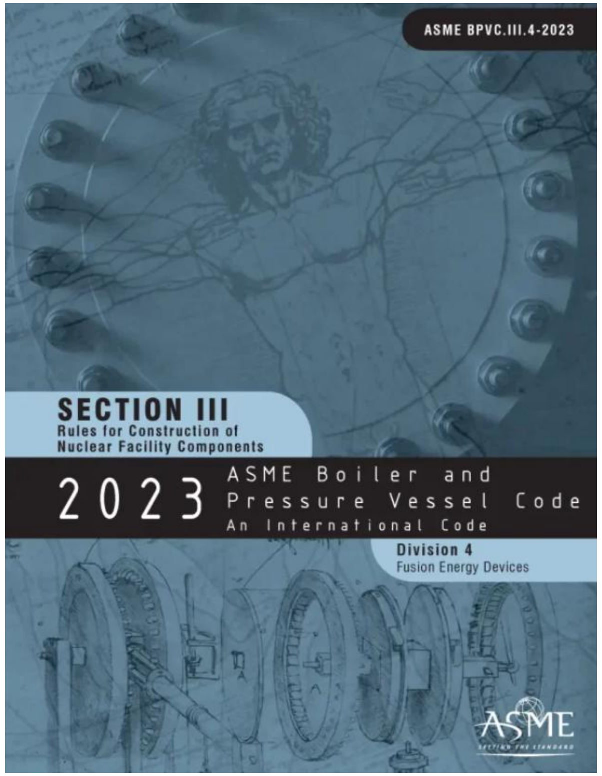
Section III Charter: “To develop, review, and maintain, […] rules governing the construction of […] Division 4 components for fusion devices […]. […]. These rules focus on assuring the pressure boundary integrity and the structural integrity, as applicable, of the component or item being constructed.

Division 4 Charter: “The Subgroup shall develop rules for the construction of fusion-energy-related components such as vacuum vessel (vacuum or target chamber), cryostat and superconductor structures and their interaction with each other. […]. The rules shall contain requirements for materials, design, fabrication, testing, examination, inspection, certification, and stamping.”



ASME BPV Section III Division 4 Phase 1

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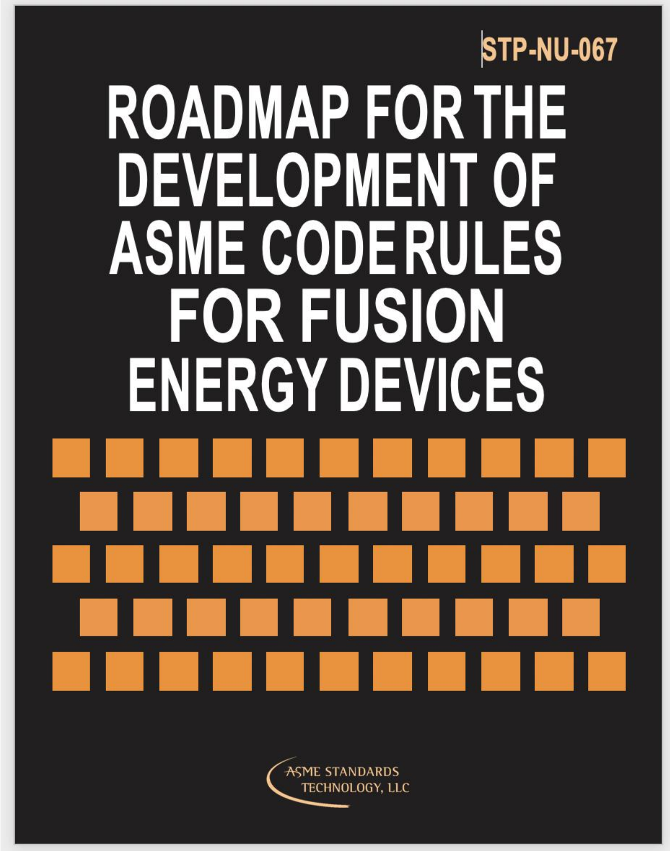
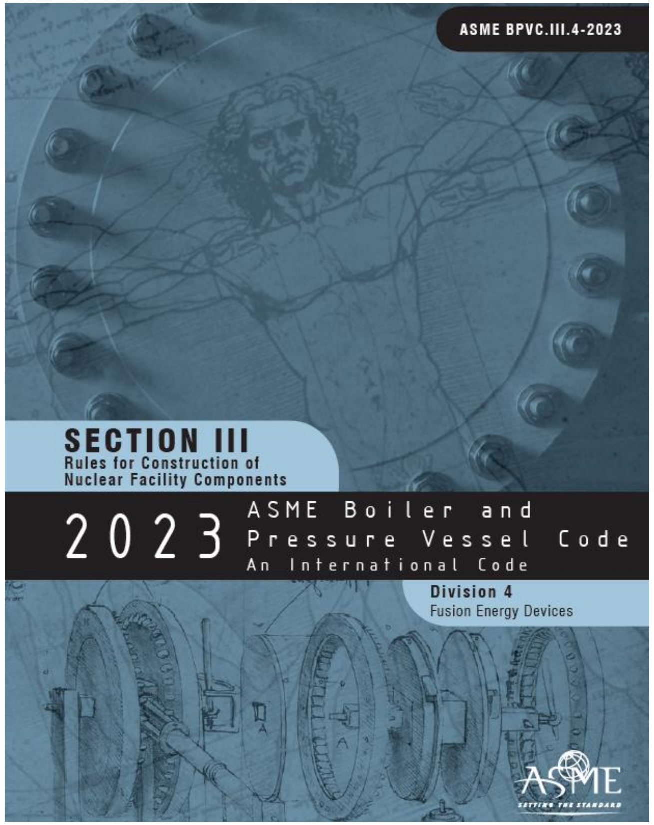
Phase I [2018 – 2024]



First edition Published July 2023

Mission accomplished



ASME BPV Section III Division 4 Phase 2

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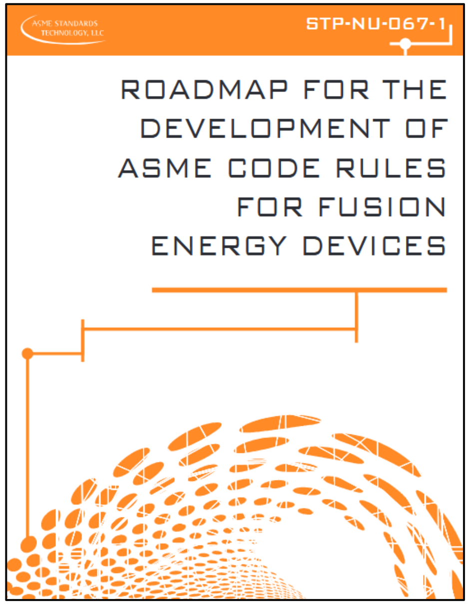
Phase 2 [2024 – 2029]

[Published: STPNU0671-Roadmap for the Development of ASME Code Rules for Fusion Energy Devices | 2024 | PDF | ASME]


STP-NU-067-1

ROADMAP FOR THE DEVELOPMENT OF ASME CODE RULES FOR FUSION ENERGY DEVICES

Identified gaps and future work packages (vacuum vessel design, materials, failure modes, allowable stresses, joining, etc)

2027 edition

2029 edition

Outcome is a usable Code

Questions for the community

Q: US law mandates the use of ASME BPV for unfired pressure systems.
→ *What technical gaps have you identified in BPV Sections (VIII / III) or subparts for fusion prototype plants?*

Q: What quality standards are you requiring for fusion pressure components (such as tight tolerances, low failure tolerance, inspections etc)?

Q: Has your team applied ASME BPV Section VIII Div 1/2 QA programs for prototype vessels?
→ *Did they meet your quality needs, or were there gaps?*

Q: Are there structural or pressure system materials you plan to use that are not listed in ASME Section II?

Q: For materials listed in Section II, what failure modes have you identified that are not addressed in Section VIII?

Q: For all the above, how does the answers change when moving toward components exposed to high neutron irradiation over sustained periods of time (> months)?

Update Brief – May Code Week 2025

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Update 1: Division 4 WG General Requirements

- Ballot 24-2913 for major change in Division 4 structure to be a deterministic component code for fusion energy devices

Update 2: Collaboration with JSME in discussion

- Large input on superconducting structure component code based on ITER experience

Update 3: Drafting underway in WG GR on populating subsection FA

Update 4: WG Materials sitting first time this Code Week

- US DOE funded ($20m) IMPACT FIRE award UT-Knoxville and ORNL to code qualify RAFM steel for BPV Section III Division 4 – started March 2025 for 4 years

- **Subsection FA – General Requirements**
  - Subpart A – Metallic Materials
  - Subpart B – Non-Metallic Materials
  - Subpart C – Magnetic Components
- **Subsection FB – Class A Metallic Pressure Boundary Components**
  - Subpart A – Low Temperature Service
  - Subpart B – Elevated Temperature Service
  - Subpart C – Cryogenic Temperature Service
- **Subsection FC – Class B Metallic Pressure Boundary Components**
  - Subpart A – Low Temperature Service
  - Subpart B – Elevated Temperature Service
  - Subpart C – Cryogenic Temperature Service
- **Subsection FF – Supports**
  - Subpart B – Low Temperature Service
- **Subsection FG – Class CM Core Components**
  - Subpart A – Low Temperature Service
  - Subpart B – Elevated Temperature Service
  - Subpart C – Cryogenic Temperature Service
- **Subsection FH – Class NM Non-Metallic Pressure Boundary Components**
  - Subpart A – Low Temperature Service
  - Subpart B – Elevated Temperature Service
  - Subpart C – Cryogenic Temperature Service
- **Subsection FM – Magnetic Components**
  - Subpart A – Low Temperature Service
  - Subpart B – Elevated Temperature Service
  - Subpart C – Cryogenic Temperature Service

Mandatory Appendices
Mandatory Appendix I – Placeholder

Nonmandatory Appendices
Nonmandatory Appendix A – Vacuum Vessel Design Methodology
Nonmandatory Appendix B – Guidelines for Materials Qualification
Nonmandatory Appendix C – Environmental Damage Considerations

One of the biggest challenges in making fusion energy commercially viable is the lack of nuclear-code-qualified high-temperature structural materials that can be used in fusion reactors. IMPACT aims to create a process and database for the first-ever American Society of Mechanical Engineers Boiler and Pressure Vessel code qualification for a fusion material and to demonstrate how these new materials can more quickly move from code qualification to engineering application.

JSME proposal on superconducting structures in fusion energy

BRIDGE program
“Fusion energy system Standardization”
(BFS)

Program Director：	E. Tada
Project Team Leader:	M. Nakahira
Project Team Subleader:	H. Nakajima

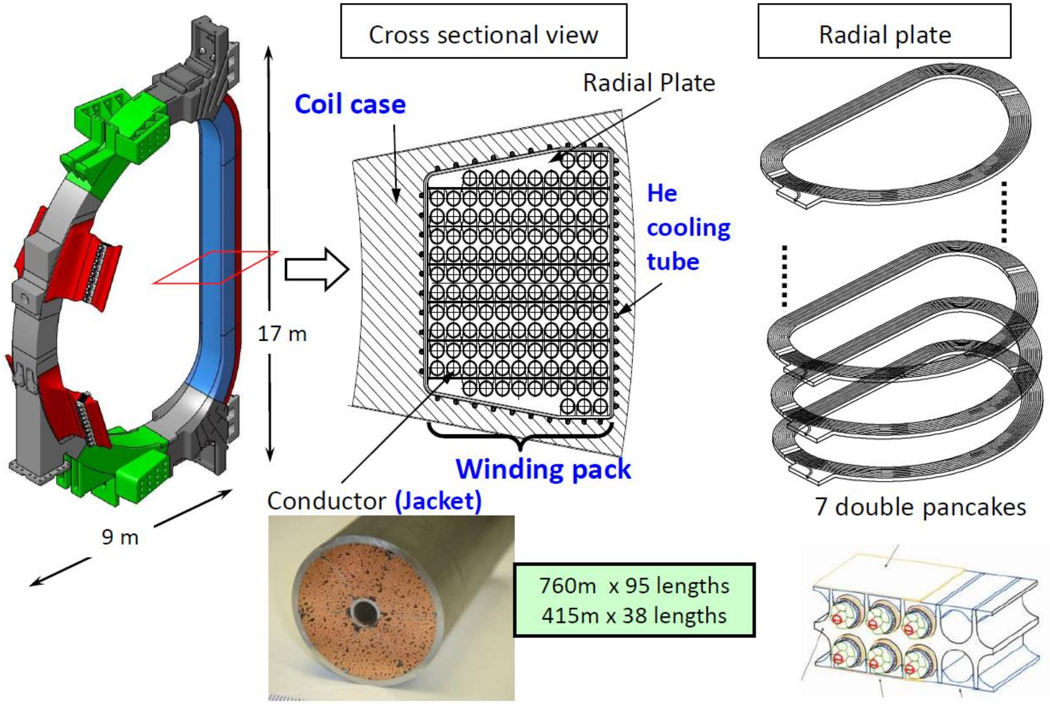
- MAIN TEXT
  - FM-1000 Scope, roles and responsibilities
  - FM-2000 Material
  - FM-3000 Design
  - FM-4000 Fabrication (HIP)
  - FM-5000 Non-destructive examination
  - FM-6000 Pressure and leak testing
  - FM-7000 Glossary
- APPENDICIES（Mandatory)
  - APPENDIX 11 Qualified inspection for superconducting 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

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

Proceedings of PVP2009

10

Provided by JSME and presented at SG FED May Code Week 2025



First Toroidal Field Coil Casing Fitting Completed - December 2017

The radial plates that hold the conductor of the toroidal field coil: D-shaped stainless steel structures with grooves machined on both sides along a spiral trajectory.

Special Working Group for Fusion Stakeholders Meeting Highlights

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- **~30 attendees** spanning a wide range of stakeholders
  - **Fusion technology developers**: Commonwealth Fusion Systems, EX-Fusion, Kyoto Fusioneering, Tokamak Energy, Type One Energy, Zap Energy
  - **Public fusion programmes**: KEA (K-DEMO), QST (JA DEMO), UKAEA (STEP)

- **2 new SWG FS members** (total 18 members) - Commonwealth Fusion Systems, UKAEA

- **2 surveys released** in early-2025, responses received:
  - "*Quality assurance processes and standards*": 9 responses received, survey now closed
  - "*Database for fusion components, materials, conditions, etc.*" 7 responses received, continue to seek responses, feed up to SG FED

Slide provided by Dr R. Holmes, Kyoto Fusioneering, Chair of SWG Fusion Stakeholders

(Fusion) Materials Qualification of Pressure Systems

Vision of Division 4 Materials

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What structural materials are you interested in using under pressure systems / structural integrity that is not in Section II?

ASME BPV Section III Division 5 2021 Class A

Table HBB-I-14.1(a)
Permissible Base Materials for Structures Other Than Bolting

Base Material	Spec. No.	Product Form	Types, Grades, or Classes
Types 304 SS and 316 SS [Note (1)], [Note (2)], [Note (3)]	SA-182	Fittings & Forgings	F 304, F 304H, F 316, F 316H
	SA-213	Smls. Tube	TP 304, TP 304H, TP 316, TP 316H
	SA-240	Plate	304, 316, 304H, 316H
	SA-249	Welded Tube	TP 304, TP 304H, TP 316, TP 316H
	SA-312	Welded & Smls. Pipe	TP 304, TP 304H, TP 316, TP 316H
	SA-358	Welded Pipe	304, 316, 304H, 316H
	SA-376	Smls. Pipe	TP 304, TP 304H, TP 316, TP 316H
	SA-403	Fittings	WP 304, WP 304H, WP 316, WP 316H, WP 304W, WP 304HW, WP 316W, WP 316HW
	SA-479	Bar	304, 304H, 316, 316H
	SA-965	Forgings	F 304, F 304H, F 316, F 316H
	SA-430	Forged & Bored Pipe	FP 304, FP 304H, FP 316, FP 316H
Ni-Fe-Cr (Alloy 800H) [Note (4)]	SB-163	Smls. Tubes	UNS N08810
	SB-407	Smls. Pipe & Tube	UNS N08810
	SB-408	Rod & Bar	UNS N08810
	SB-409	Plate, Sheet, & Strip	UNS N08810
	SB-564	Forgings	UNS N08810
$2^1/_4$Cr-1Mo [Note (5)]	SA-182	Forgings	F 22, Class 1
	SA-213	Smls. Tube	T 22
	SA-234	Piping Fittings	WP 22, WP 22W [Note (6)]
	SA-335	Forg. Pipe	P 22
	SA-336	Fittings, Forgings	F 22a
	SA-369	Forg. Pipe	FP 22
	SA-387	Plate	Gr 22, Class 1
	SA-691	Welded Pipe	Pipe $2^1/_4$ CR (SA-387, Gr. 22, Cl. 1)
9Cr-1Mo-V	SA-182	Forgings	F91
	SA-213	Smls. Tube	T91
	SA-335	Smls. Pipe	P91
	SA-387	Plate	91

+ Alloy 617 (2021)
+ Alloy 709 (~2027)

Table HBB-I-14.1(b)
Permissible Weld Materials

Base Material	Spec. No.	Class
Types 304 SS and 316 SS	SFA-5.4	E 308, E 308L, E 316, E 316L, E 16-8-2
	SFA-5.9	ER 308, ER 308L, ER 316, ER 316L, ER 16-8-2
	SFA-5.22	E 308, E 308T, E 308LT, E 316T, E316LT-1 EXXXT-G (16-8-2 chemistry)
Ni–Fe–Cr (Alloy 800H)	SFA-5.11	ENiCrFe-2
	SFA-5.14	ERNiCr-3
$2^1/_4$Cr–1Mo	SFA-5.5	E 90XX-B3 (>0.05% Carbon)
	SFA-5.23	EB 3, ECB 3
	SFA-5.28	E 90C-B3 (>0.05% Carbon), ER 90S-B3
	SFA-5.29	E 90T-B3 (>0.05% Carbon)
9Cr–1Mo–V	SFA-5.5	E90XX-B91
	SFA-5.23	EB91
	SFA-5.28	ER90S-B91

SPECIFICATION FOR PRESSURE VESSEL PLATES, ALLOY STEEL, CHROMIUM-MOLYBDENUM

SA-387/SA-387M

(Identical with ASTM Specification A387/A387M-17a.)

ASME BPV Section III Division 4 (future vision)

Base Material	Spec No	Product Form	Types / Grades
Austenitic stainless steel	TBD	Same as Div 1/Div 5	316LN-(IG)
Reduced-activation steel	TBD	Plate, pipe?	EUROFER97, F82H-IEA
Vanadium alloys	TBD	TBD	V-4Cr-4Ti, V15Cr-4Ti ?
Copper alloys	TBD	TBD	CuCrZr?
Ceramics	TBD	TBD	SiC_f/SiC?
?			

A recognised standard is required

Infers that the material has a maturity of MTRL 3.5-4

Division 4 Fusion Stakeholders are supporting the collection of interest

Summary

Going forward

Division 4 serves the fusion community.

The (draft) rules evolve over time

To get involved, please join the ASME Code Weeks (free).

If you are interested and want to contribute to the code development, please contact the Chair: Thomas Davis
thomas.davis@oxfordsigma.com

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Special Issue: Fusion Materials with a Focus on Industrial Scale-Up

Prof. Dr. Jan Willem Coenen
Forschungszentrum Julich, Germany
Guest Editor

Dr. Thomas P. Davis
Oxford Sigma and Bangor University, UK
Guest Editor

Special Issue Keywords:

- plasma-facing materials
- structural materials
- breeder materials
- quality control
- upscaling
- production of fusion materials
- advanced manufacturing techniques
- radiation resistance
- structural integrity

Deadline for submissions: 31 October 2025

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