

Recent advancements in pressure codes & standards for fusion power plants

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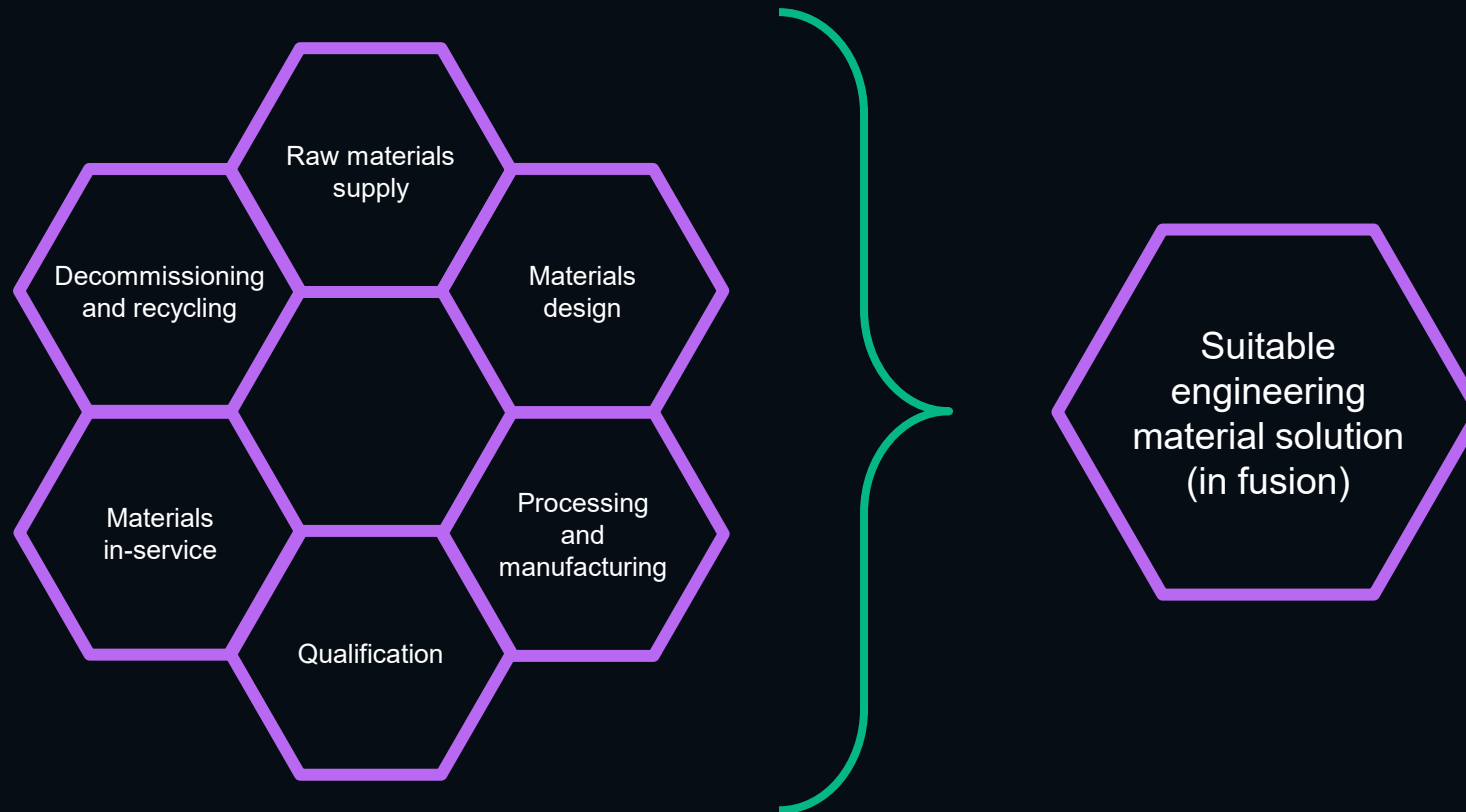
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Summertown Pavilion, 18-24 Middleway, Oxford, OX2 7LG, UK

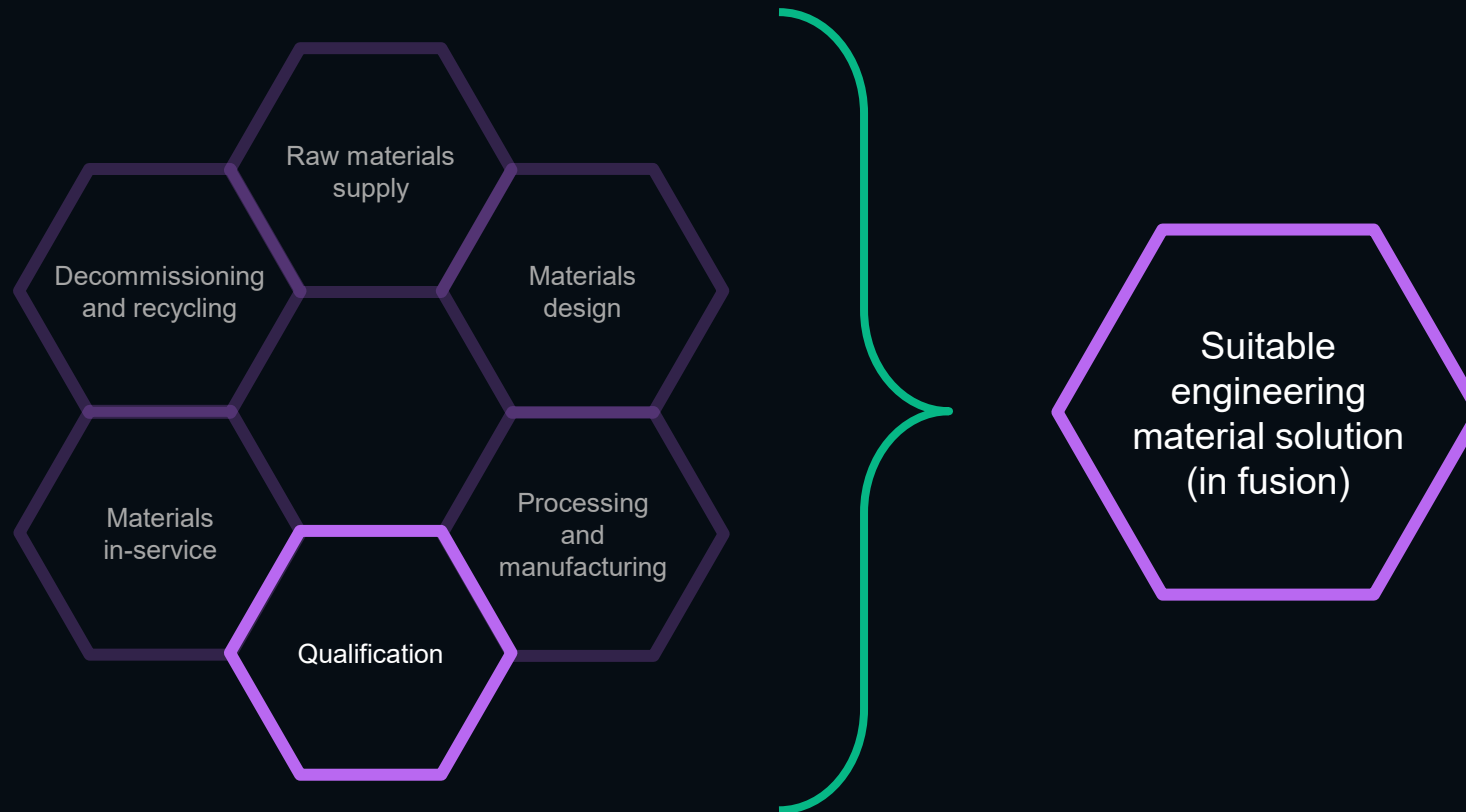
About Oxford Sigma in one slide

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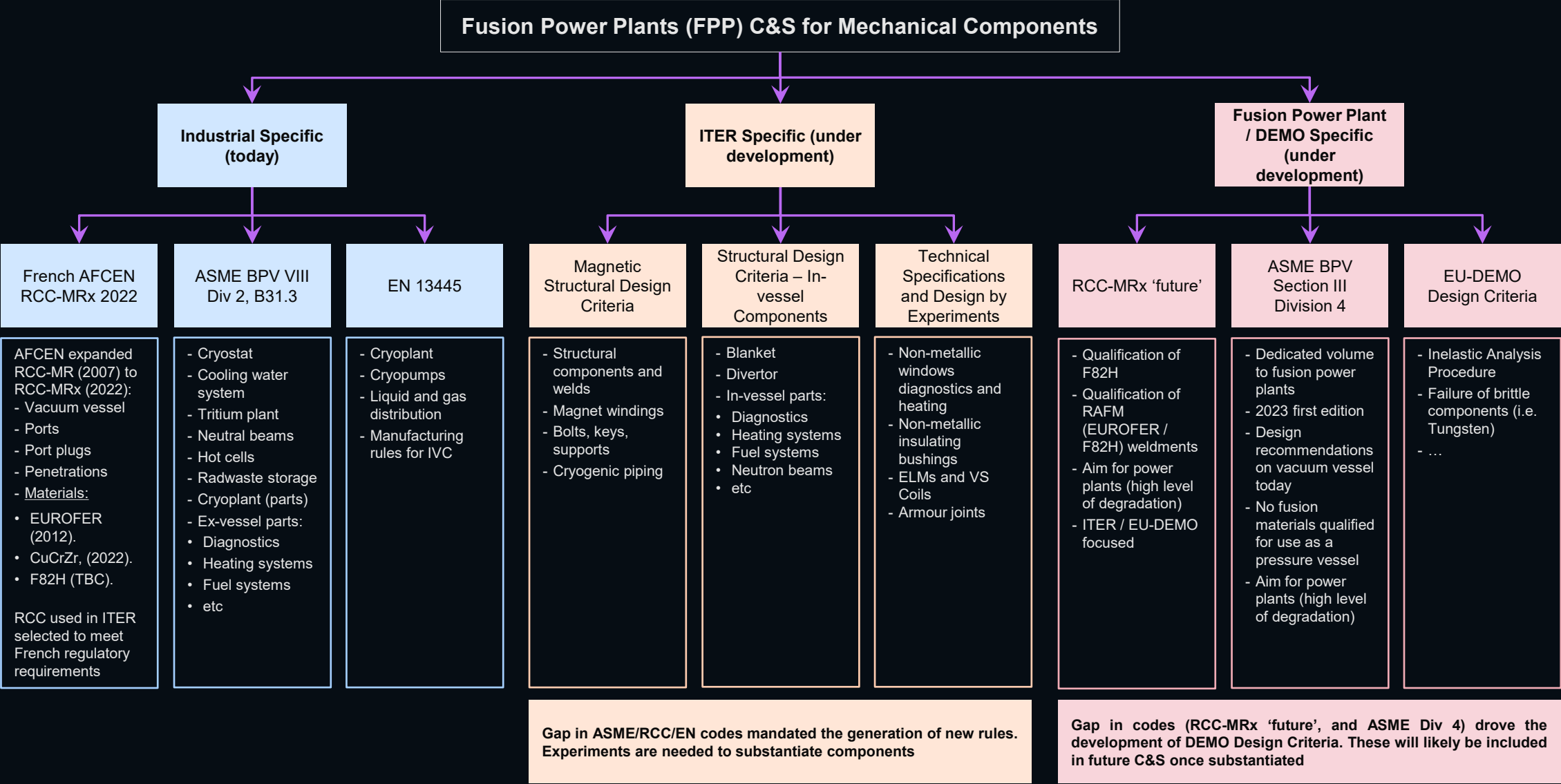


Objectives

- 1) Provide an update on the development of the codes and standards for fusion power plants
- 2) Outline a proposal for the materials qualification route for Division 4 which outlines the testing requirements, standards, assessment methodologies, environmental effects such as corrosion and irradiation, and
- 3) Update the fusion community on the work undertaken by Oxford Sigma in developing C&S.

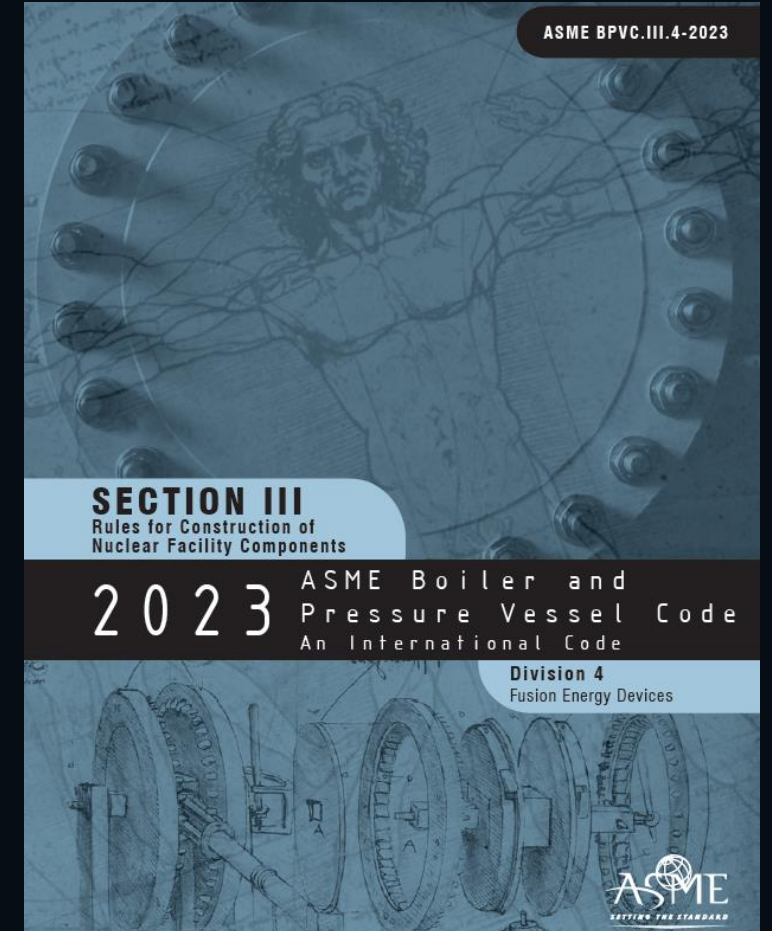
Applying Existing Codes and Standards

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

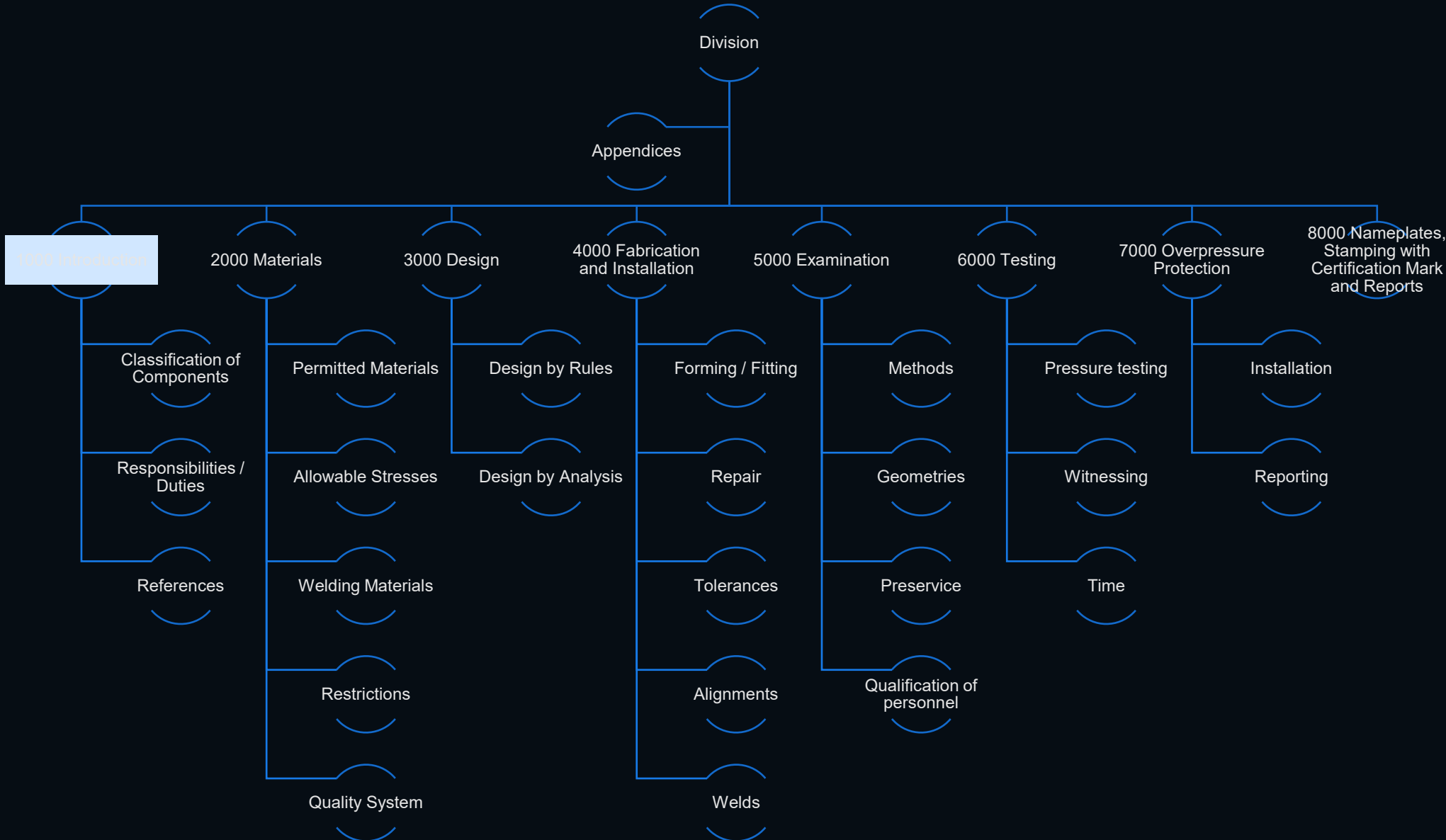


Section I	Power Boilers
Section II	Materials
Section III	Rules for Construction of Nuclear Facility Components
Section IV	Heating Boilers
Section V	Non-destructive Examination
Section VI	Recommended Rules for the Care and Operation of Heating Boilers
Section VII	Recommended Guidelines for the Care of 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

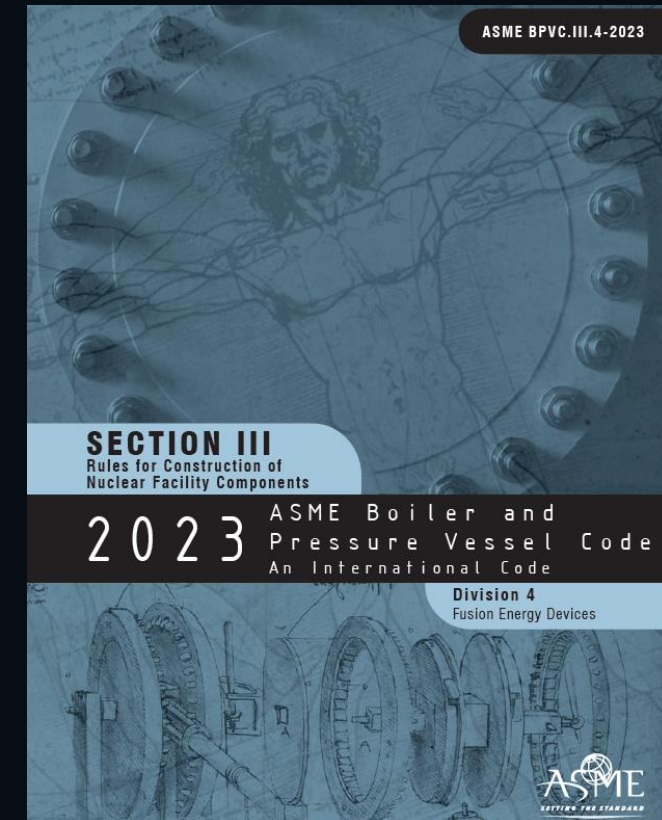
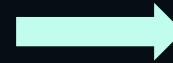
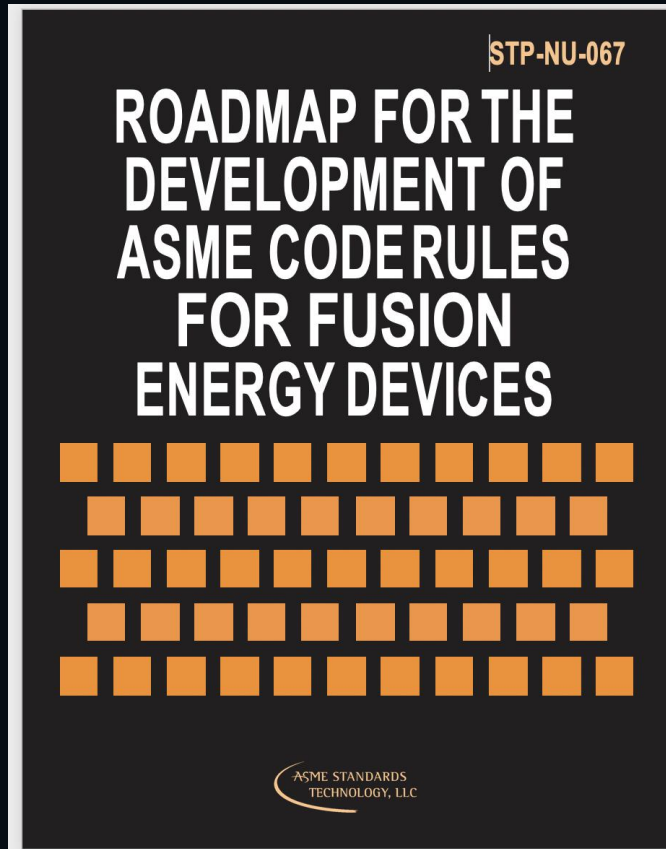
Division 1	Metallic vessels, heat exchangers, storage tanks, piping systems, pumps, valves, core support structures, supports, and similar items.
Division 2	Code for Concrete Containments
Division 3	Containment Systems for Transportation and Storage of Spent Nuclear Fuel and High-Level Radioactive Material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



Example General Layout of a Section III Division

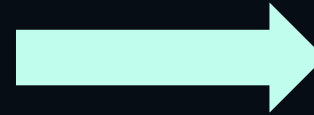
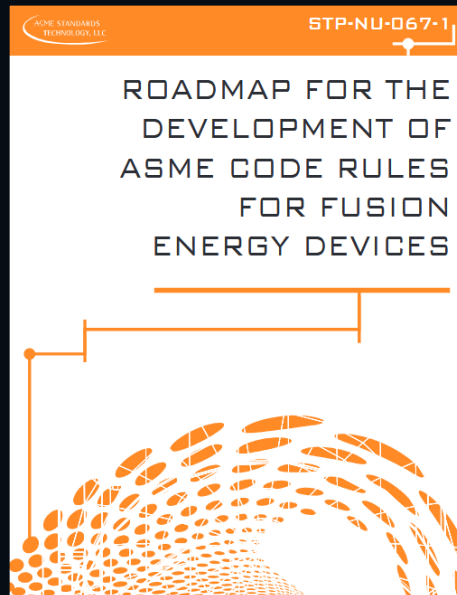


Phase I [2018 – 2024]



Phase 2 [2024 – 2029]

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



2027 edition



2029 edition



Outcome is a
usable Code

Update ASME BPVC Sec. III, Div. 4

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 sat for the first time in May 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**
 - o Subpart A – Metallic Materials
 - o Subpart B – Non-Metallic Materials
 - o Subpart C – Magnetic Components
- **Subsection FB – Class A Metallic Pressure Boundary Components**
 - o Subpart A – Low Temperature Service
 - o Subpart B – Elevated Temperature Service
 - o Subpart C – Cryogenic Temperature Service
- **Subsection FC – Class B Metallic Pressure Boundary Components**
 - o Subpart A – Low Temperature Service
 - o Subpart B – Elevated Temperature Service
 - o Subpart C – Cryogenic Temperature Service
- **Subsection FF – Supports**
 - o Subpart B – Low Temperature Service
- **Subsection FG – Class CM Core Components**
 - o Subpart A – Low Temperature Service
 - o Subpart B – Elevated Temperature Service
 - o Subpart C – Cryogenic Temperature Service
- **Subsection FH – Class NM Non-Metallic Pressure Boundary Components**
 - o Subpart A – Low Temperature Service
 - o Subpart B – Elevated Temperature Service
 - o Subpart C – Cryogenic Temperature Service
- **Subsection FM – Magnetic Components**
 - o Subpart A – Low Temperature Service
 - o Subpart B – Elevated Temperature Service
 - o 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.

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

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

Proceedings of PVP2009

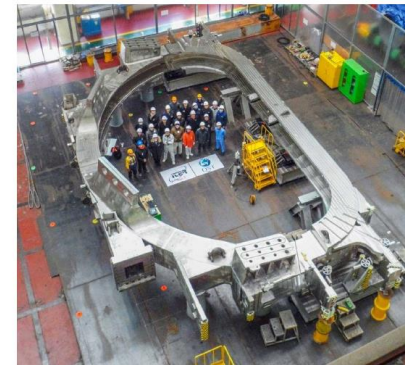
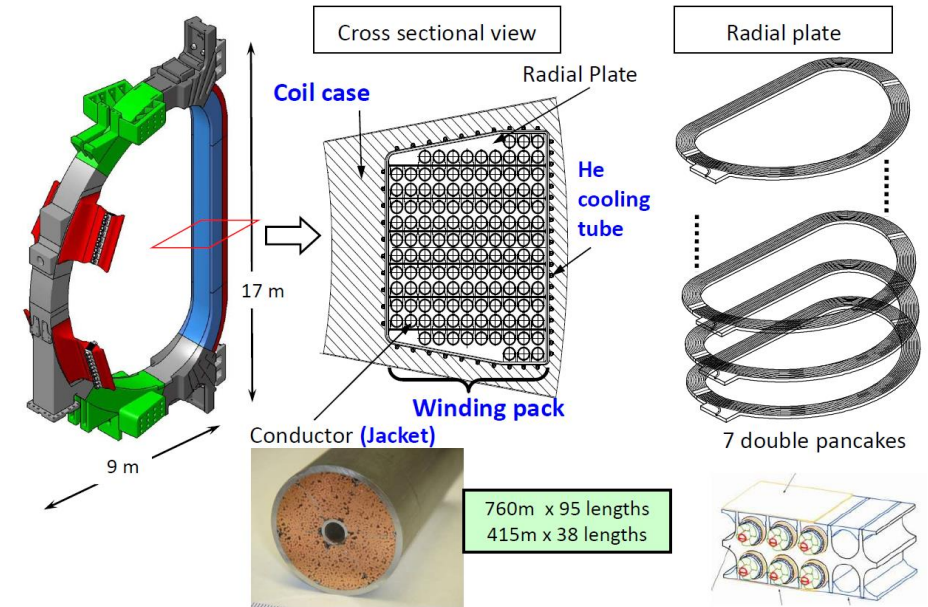
• APPENDICIES (Mandatory)

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
APPENDIX 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

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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.

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

Project Overview & Contributions

- **Goal:** Finalise rewrite of Division 4 and deliver a complete draft for review and balloting.
- **Drivers:**
 - Strategic Initiative SI-2027-07 (ASME)
 - Fusion Roadmap ST LLC Report STP-NU-067-1
 - Global urgency for harmonised standards.
- JSME brings decades of expertise in superconducting magnet design for fusion.
- Their existing rules form the backbone for Division 4's magnetic component standards.



Magnetic Components

- Integrate JSME rules into Division 4, Subsection FM.
- Reconcile JSME text into FM 1000–9000 articles.
- Ensure technology-agnostic mandatory rules, with optional tokamak-specific guidance.

Tokamak Design Principles

- JSME input will inform non-mandatory appendix for tokamak design.
- Harmonisation with JSME's Tokamak Code work anticipated.

Collaboration Activities

- Dedicated technical meetings between ASME, JSME, and ITER.
- Recognition of JSME contributions in Division 4 draft.
- Alignment with AFCEN RCC-MRx for global interoperability.

Impact

- Accelerates development of internationally harmonised fusion standards.
- Positions ASME–JSME partnership as a global leader in fusion safety and design.

Fusion Materials Qualification of Pressure Systems

Vision of Division 4 Materials

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
Ni-Fe-Cr (Alloy 800H) [Note (4)]	SA-430	Forged & Bored Pipe	FP 304, FP 304H, FP 316, FP 316H
	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
2 ¹ / ₄ Cr-1Mo [Note (5)]	SB-564	Forgings	UNS N08810
	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
9Cr-1Mo-V	SA-691	Welded Pipe	Pipe 2 ¹ / ₄ CR (SA-387, Gr. 22, Cl. 1)
	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	E 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

For 2000 Materials articles in Class A and B Metallic Pressure Boundary Materials

Mandatory

All materials must comply to ASME BPV Section II Part D Mandatory Appendices 1 – 10
- Appendix 5 – Guidelines on the Approval of New Materials

Materials specification and form must be in a recognised standard

Weldments must be considered

Allowable stresses will be generated and ASME BPV Section II Part D Mandatory Appendix 1 will apply

Requested party who wants a new material qualified must understand the environment

- Only qualify up to your intended environment
- For example: blanket life is 4 fpy and a failure mode could be creep-related, then only qualify the material up to 4 fpy (35,064 hours).
- Quashes the “myth” that materials qualification takes decades – this based on a user need in Generation IV reactors to have RPVs operating for 40 years or more.

Radiation damage and environmental data not required for ASME BPV qualification. The onus will be on the owner to ensure detrimental effects from the environment are considered → design dependent

If the material undergoes time-dependent properties (creep), a minimum creep data of 30,000 hours is required (3.4 years).

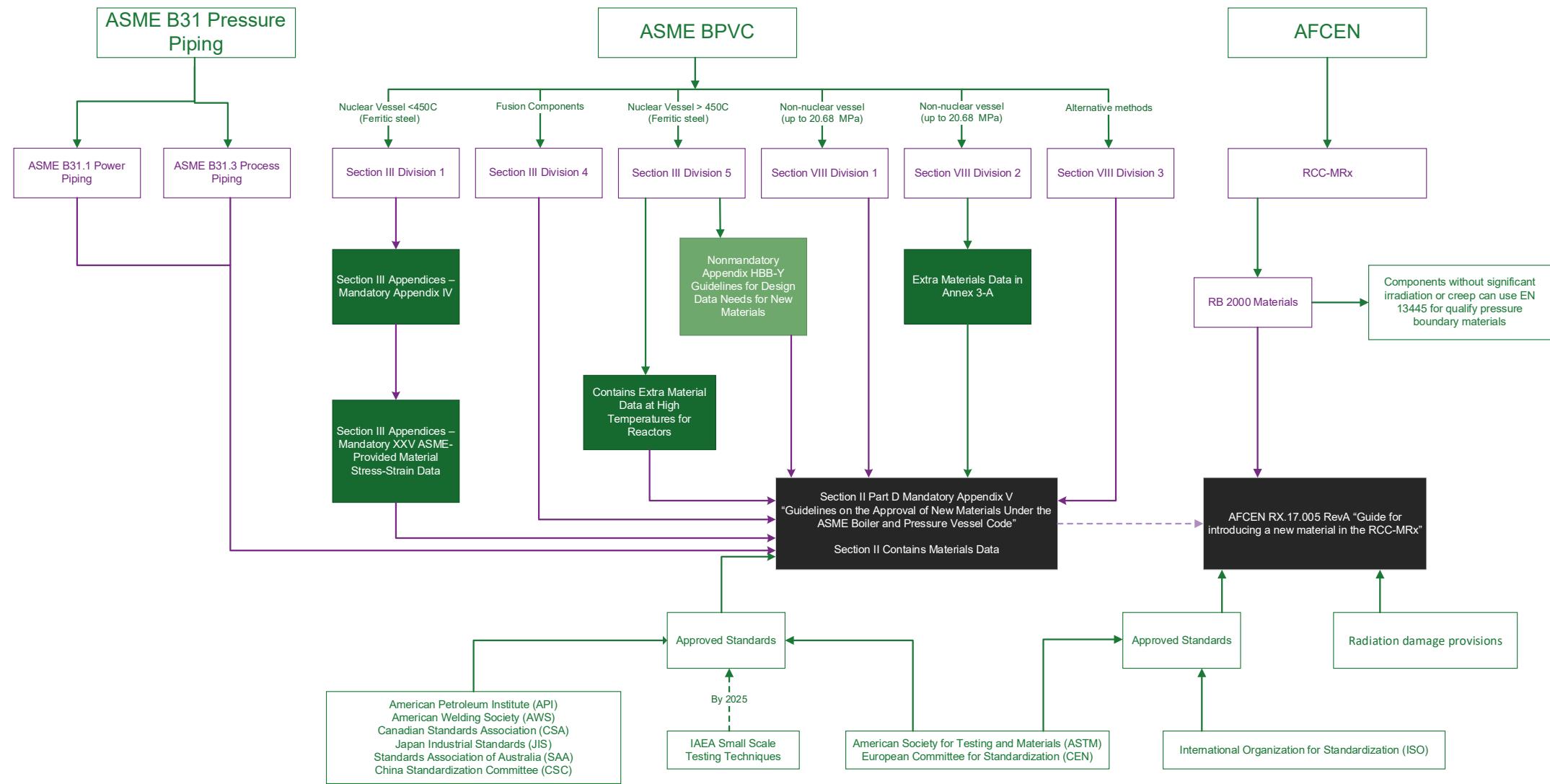
Non-Mandatory (optional / advice)

Division 4 Non-Mandatory Appendix B – guidance on materials qualification

- Expectation on data required
- Guidelines on surveillance programs
 - Location of specimens within the neutron field
 - Temperature
 - Synergetic effects
- Guidelines on fusion specific activation challenges (reduction of Co, Ni etc)
- Guidelines on staged approach to qualification

Non-Mandatory Appendix C – Environment effects

- Inherits Section III Appendix W
 - Erosion and Corrosion (inc Stress corrosion cracking, pitting, intergranular)
 - Environmental effect on fatigue life
 - Embrittlement by radiation (IASCC)
 - Thermal ageing embrittlement
 - Irradiation embrittlement
 - Hydrogen damage embrittlement
 - Creep
- Guidelines on helium embrittlement
- Guidelines on liquid metal embrittlement
- Guidelines on tritium embrittlement
- Guidelines on radiation embrittlement for fusion
- Guidelines on testing requirements
 - Include future provisions for IAEA SSTT-II CRP



Oxford Sigma development activity in codes and standards

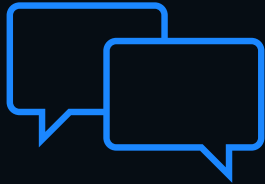
Applying justification for client designs using the codes



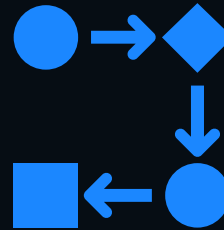
- The term "nuclear grade" materials is a misconception propagated by sources outside the code
- Specifically, the Section III classifies Class 1, 2, 3, A, and B components with the following criteria:
 - List of permitted materials
 - Specification accepted (these are standard materials defined in ASTM)
 - Manufacturing controls and quality program
 - Inspection of the materials
- Physical material does not differ between the classes.
- Each class requires differing inspection to meet the standard

What quality / inspection on materials specifications is required for pressure-retaining and structural integrity of fusion components (such as VV BB FW)?

- Any new material needs to pass Section II Part D Appendix V qualification.
- Experience with blankets, vacuum vessels, and first wall fusion components, the quality requirements are stringent.
 - Undergo extensive testing, including impact testing, fatigue, and creep tests, given the conditions they operate under.
 - Specifications must meet high impurity limits.
- Developers can inform code of the quality requirements for their blankets, first walls, and vacuum vessels.
- Currently, ASME BPVC Sec. III, Div. 4 stakeholder group is attempting to gather this information – but too high level



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

Recent advancements in pressure codes & standards for fusion power plants

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Q: US state laws mandate 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)?