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EUROfusion

Challenges in Adapting Existing Nuclear Codes & Standards for Fusion Breeding Blanket Design & Manufacturing

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Breeding Blanket Project in EUROfusion

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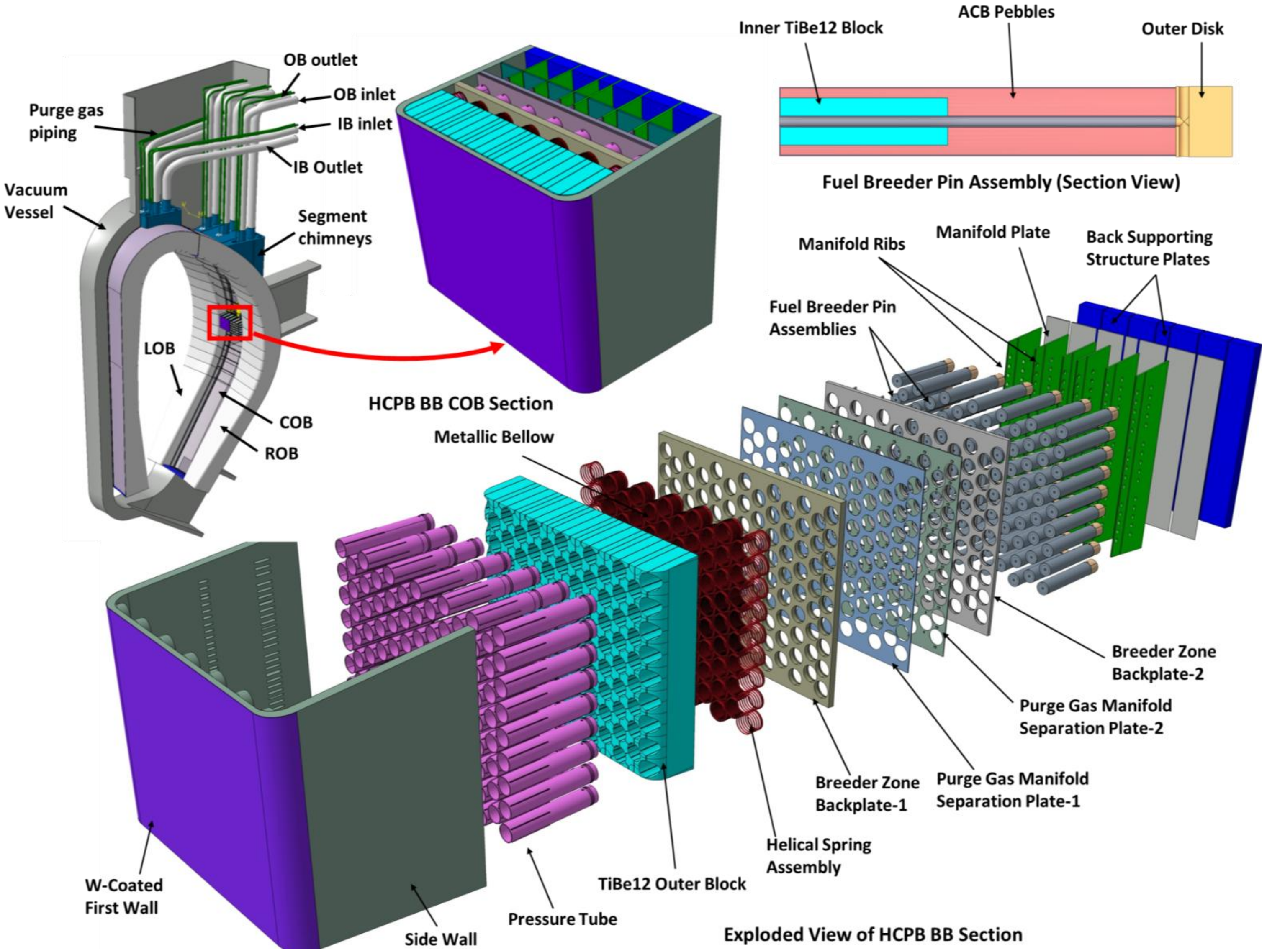
VI. Considerations for Existing C&S: Insights from BB

VII. Summary

Design Description of Helium-Cooled Pebble Bed (HCPB) Breeding Blanket (BB)



- **Coolant: He @80 bar, 300-520°C**
- **Structural steel: Eurofer97**
- **Fuel-breeder pins - Advanced Ceramic Breeder (ACB) pebbles**
- **Beryllide neutron multiplier of triangular prism with lateral edges filleted**
- **T-extraction: He + 100 Pa H_2 @80 bar; He + 100 Pa H_2O @80 bar (backup)**
- **FW and critical structure thicker + cooler by fresh coolant**
- **Inner beryllide block inside ACB pebble**

(Ref:- G Zhou et al 2023 EFDA_D_2S39EB)

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Safety and Design Classification of HCPB BB

- Safety classification methodology for EU DEMO Structures, Systems & Components (SSCs) based on an evolving nuclear fusion facility approach;
- SSCs that are not safety important are identified as **Safety Related (SR)**, if they have some relevance to nuclear safety;
- A SSC providing prevention, detection or mitigation against a risk, or as part of **Defence-in-Depth (DiD)** would be classified as **SR**;
- These SSCs can be credited in any safety analysis if designed to operate in conditions induced by an initiating event or hazard;
- Failure of an SR SSC should not impact any safety function.

Safety and Design Classification of HCPB BB

- The BB inside Vacuum Vessel (VV) is not itself a confinement barrier;
- BB segments outside of VV constitute VV extension; and VV with its extensions make up the **first confinement barrier**;
- BB First Wall (FW) provides some radiation shielding for VV and some thermal and radiation shielding for ex-vessel components;
- This function can be treated as a Safety Related (SR) function to both the **confinement function** and the **shielding function**;
- BB SSCs are classified as **Design Class-2 (Quality Class-2); RCC-MRx: N2RX** is followed for its qualification.

OVERVIEW

Status of HCPB BB Design: Unit Slice Analysis

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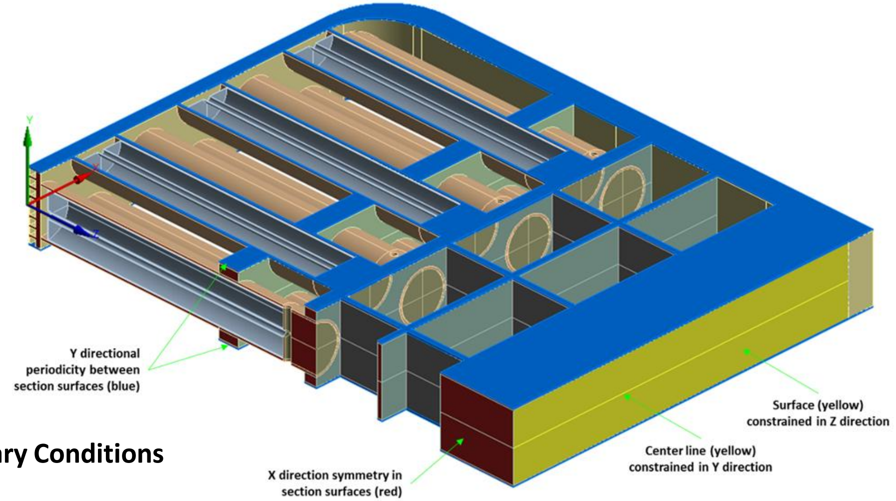
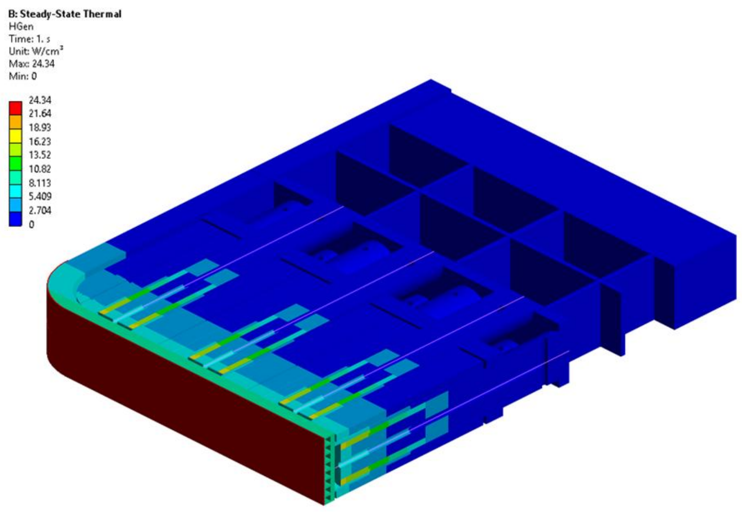
- Assumed generalized plane strain conditions (Poloidal periodic BCs)
- Thermo-hydraulics simulation followed by Thermo-structural simulation
- Primary Loads: Pressure & EM Loads (NO: Ferromagnetic only)
- Secondary Load: Fusion flux and Nuclear power density as thermal loads
- Coolant flow approximated using 1D fluid lines
  - ✓ HTC as per Gnielinski correlations
- Structural Assessments according to RCC-MRx & SDC-IC
  - ✓ Elastic assessments for Monotonic and Cyclic Damage modes
  - ✓ Inelastic assessments to evaluate *Immediate Plastic Flow Localization*

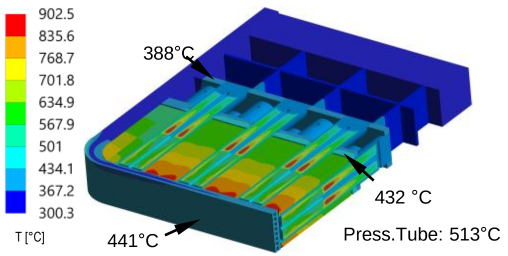


Structural Boundary Conditions

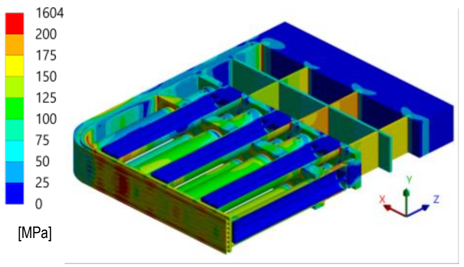


Nuclear power density as body heat generation

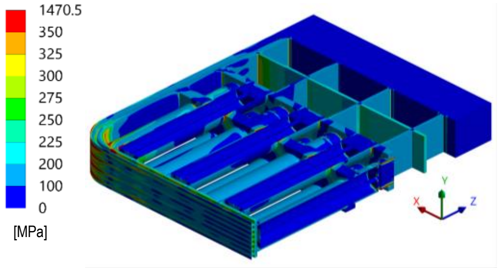
(Ref:- G Zhou et al 2023 EFDA_D_2S39EB)



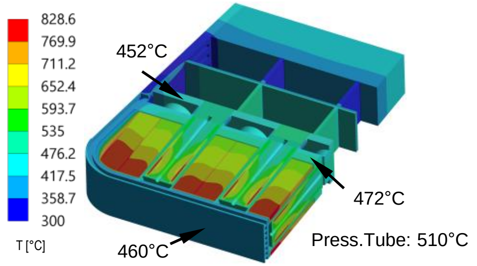
COB half unit-slice: Temperature Field



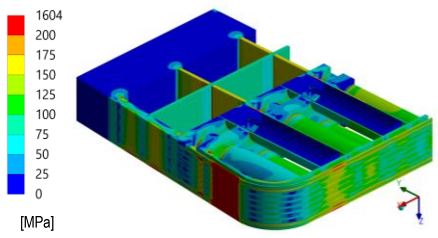
COB half unit-slice: Primary Stress



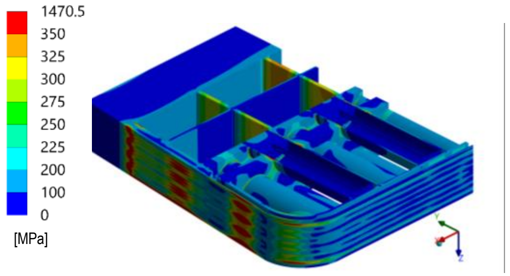
COB half unit-slice: Primary + Secondary Stress



LIB half unit-slice: Temperature Field



LIB half unit-slice: Primary Stress

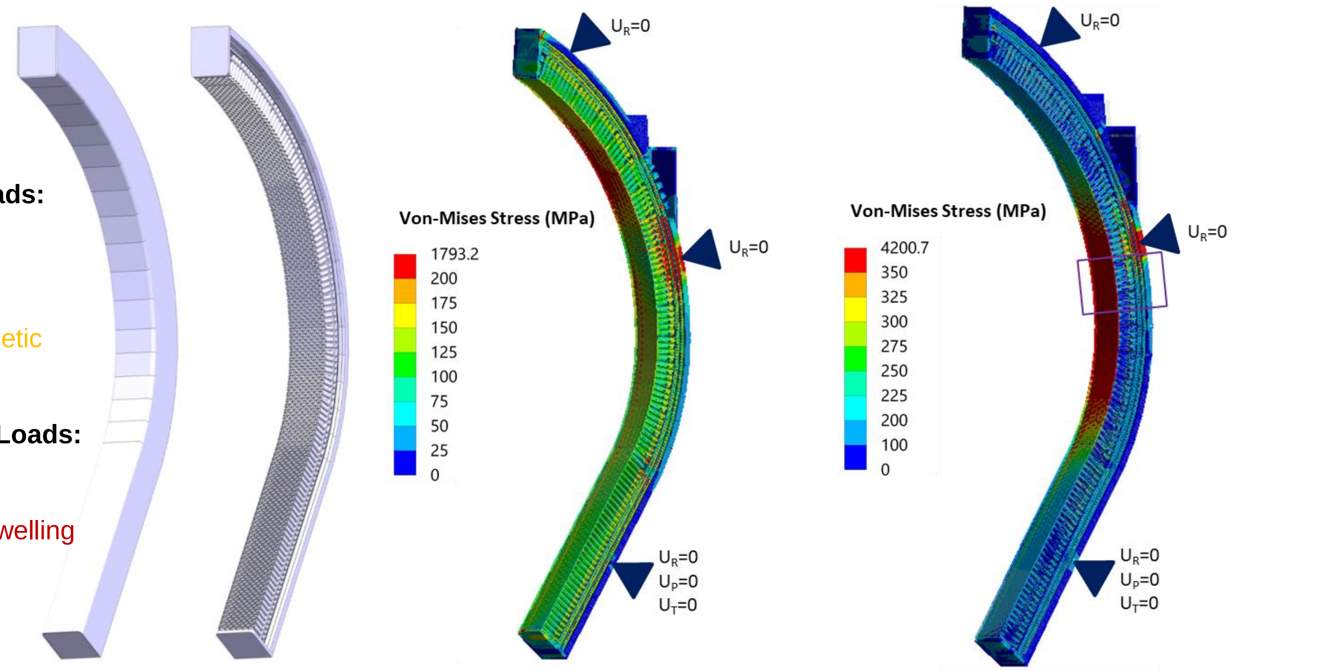


LIB half unit-slice: Primary + Secondary Stress

Status of HCPB BB Design: Global Segment Analysis

- **Reduced DOF model**
  - ✓ **COB Shell element based model (2 Million Nodes)**
  - ✓ **LIB Solid element model (4 Million Nodes)**
  - ✓ **Benchmarking carried out using unit slice model**
- **First wall channels represented by equivalent orthotropic material**
  - ✓ **Verification studies using I-beam bending analytical solution**
  - ✓ **Equivalent properties estimated using Representative Volume Element (RVE) approach**
- **Temperature distribution on the segment interpolated from unit slice results**
- **Sub-model results showed considerable variation from unit slice GPS solution**
- **Electro-magnetic loads mapping**
  - ✓ **Normal Operation: Uniformly distributing the ferromagnetic loads**
  - ✓ **Off-normal (VD): Lorentz force spatial distribution needs to be mapped at different time points**

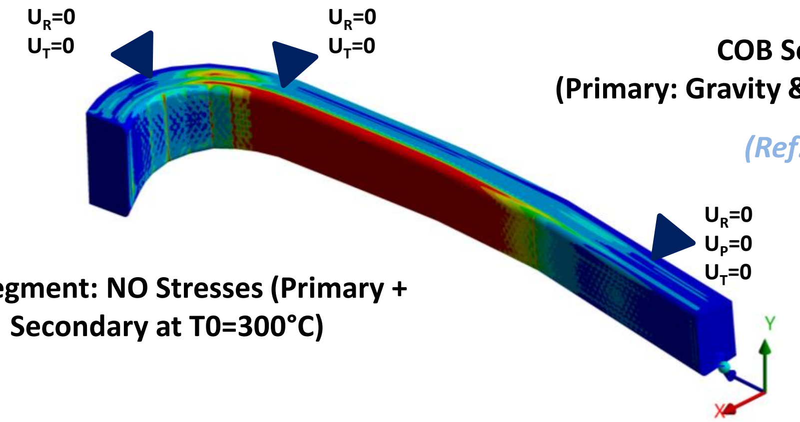
Primary Loads:
Gravity
Pressure
Electromagnetic
Seismic
Secondary Loads:
Thermal
Irradiation Swelling



Primary (P) Loading **Primary + Secondary (P+Q) Loading**

COB Segment: Stress Contours (Primary: Gravity & Pressure, Secondary: Temperature)

(Ref:- G Zhou et al 2023 EFDA_D_2S39EB)



LIB Segment: NO Stresses (Primary + Secondary at T0=300°C)

Status of HCPB BB Manufacturing

Adherence to Nuclear Design C&S for Manufacturing [7]

- Preliminary manufacturing & assembly sequence for BB segment conceptualized as per **RCC-MRx:N2RX** (& compared ASME BPVC Sec. III Div.1 Sub. NC);
- For each joint/connection, appropriate joining techniques have been identified based on design specifications and material properties;
- Most Joining techniques are code compliant. Certain techniques which are not explicitly mentioned in codes, **intent of the code being adhered**;
- NDE techniques enlisted in **Component Connection Chart (CCC)** will be performed to verify joint integrity & quality during manufacturing.

Status of HCPB BB Manufacturing: Preliminary Assembly Sequence

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Step 0: Develop Component Connection Chart as per RCC-MRx & ASME Sec-III Sub NB

Step 1: Manufacturing of Tungsten-coated U-shaped FW (using HIP/ machining & bending)

Step 2: In-Bore Laser welding of cylindrical PT to FW

Step 3: Section welding (stacking) of U-shaped FW to form a complete segment (12 Slices)

Step 4: Insertion of TiBe12 Blocks along longitudinal guides of PT OD

Step 5: Drill holes in Back Plate-1 section and welding of bellows to it by aligning the centers

Step 6: Welding of Helical Spring Assemblies (HSA) to Back Plate-1 by aligning the centers

Step 7: Aligning and welding Back Plate-1 to PT and to SW in sections, for all sections

Step 8: Welding all the Back Plates-1 sections along the poloidal direction to each other

Step 9: Insertion and sequential welding of PGM Separation Plate-1 to PT and SW

Step 10: Welding all the PGM Separation Plate-1 sections along the poloidal direction to each other

Step 11: Welding of Purge Gas Inlet Tubes to PGM Separation Plate-2 section

Step 12: Insertion and sequential welding of PGM Separation Plate-2 to PT and SW

Step 13: Welding of PG Outlet Tubes to BZ Back Plate-2 section

Step 14: Insertion and welding of Back Plate-2 to SW

Step 15: Joining PT to Back Plate-2 with Expansion Joint

Step 16: Welding Purge Gas inlet pipe section to Back Plate-2 section

Step 17: Poloidal welding of BZ Back Plate-2 sections to each other

Step 18: Assembly of Fuel-Breeder Pin Components to form Assemblies

Step 19: Insertion & welding of Fuel Breeder Pin Assemblies to PT

Step 20: Welding of Manifold Rib section to Back Plate-2

Step 21: Welding all the Manifold Rib sections to each other along poloidal direction

Step 22: Welding of He coolant outlet pipe sections to specific Manifold Plate Section

Step 23: Welding the Manifold Plate to Manifold Ribs in a section

Step 24: Welding of Purge Gas inlet/outlet pipe sections to Manifold Plate Section

Step 25: Welding all the Manifold Plate strip sections to each other poloidally

Step 26: Welding of Back Supporting plate sections to Manifold Ribs and SW

Step 27: Welding of He coolant pipe to specific Back Supporting Plate section

Step 28: Welding of Purge Gas inlet/ outlet pipe to specific Back Supporting Plate section

Step 29: Welding of Top End Cap to FW

Step 30: Welding Top Cap to BZ Back plates, Purge Gas plates, Manifold Ribs & Manifold Plate strip

Step 31: Welding of Bottom End Cap to FW

Step 32: Welding Bottom Cap to BZ Back plates, Purge Gas plates, Manifold Ribs & Manifold plate strip

Step 33: Welding of Back Supporting plate sections poloidally to each other

Step 34: Welding of Back Supporting plate sections to the Top and Bottom End Caps

Step 35: Welding of He coolant and Purge Gas piping sections to sections in the blanket

Step 36: Welding of Chimney Region Plates to BSS sections to form an enclosure

Step 37: Welding of Chimney Enclosure Plates to He coolant Piping

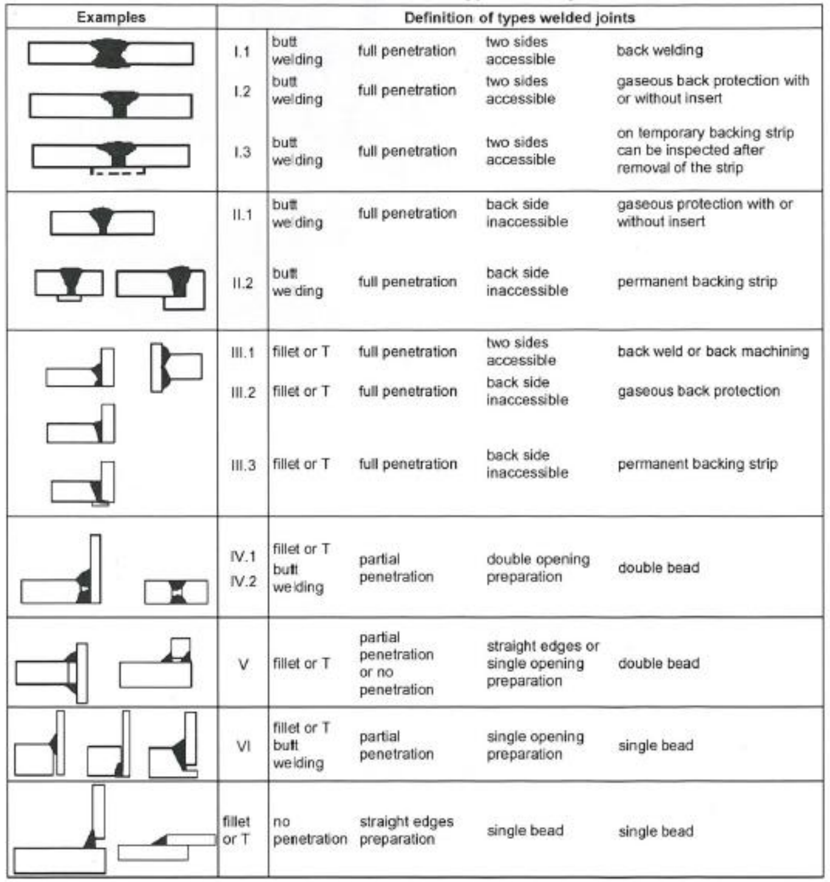
Step 38: Welding of Chimney Enclosure Plates to Purge Gas Piping

(Ref:- G Verma et al 2024 EFDA_D_2SHB7M)

Status of HCPB BB Manufacturing: Component Connection Chart (CCC)

A detailed CCC has been prepared with reference to relevant sections of the design codes RCC-MRx: N2RX (& compared to ASME BPVC Section III Div.1 Subsection NC)

Sr.	Component	MOC	Joining Technique	Types of Welds		ND Examination	
				RCC-MRx: $N2_{Rx}$	*ASME Sec III Class NC*	*RCC-MRx: $N2_{Rx}$*	*ASME Sec III Class NC*
1.0	**First Wall and Side Wall** (Eurofer97)						
1.1	Pressure Tube[1]	Eurofer97	In-Bore Laser Welding/WEBAM	RC 3834.3b Cat. b (II.1)	NC 4242 Cat. B Joints	RS 7720b1-b3 (Pipes)	NC 5220
1.2	BZ Back Plate-1	Eurofer97	TIG /EB Welding	RC 3834.3b Cat. d (III.2)	NC 4244(b) Cat. D Joints	RS 7720c1-c3 (Box)	NC 5240
1.3	PGM Separation Plate-1	Eurofer97	TIG /EB Welding	RC 3834.3b Cat. d (III.2)	NC 4244(b) Cat. D Joints	RS 7720c1-c3 (Box)	NC 5240
1.4	PGM Separation Plate-2	Eurofer97	TIG /EB Welding	RC 3834.3b Cat. d (III.2)	NC 4244(b) Cat. D Joints	RS 7720c1-c3 (Box)	NC 5240
1.5	BZ Back Plate-2	Eurofer97	TIG /EB Welding	RC 3834.3b Cat. d (III.2)	NC 4244(b) Cat. D Joints	RS 7720c1-c3 (Box)	NC 5240
1.6	HeC Manifold Plate	Eurofer97	TIG /EB Welding	RC 3834.3b Cat. d (III.2)	NC 4244(b) Cat. D Joints	RS 7720c1-c3 (Box)	NC 5240
1.7	BSS Back Plate	Eurofer97	TIG / EB Welding	RC 3834.3b Cat. d (III.2)	NC 4244(b) Cat. D Joints	RS 7720c1-c3 (Box)	NC 5240



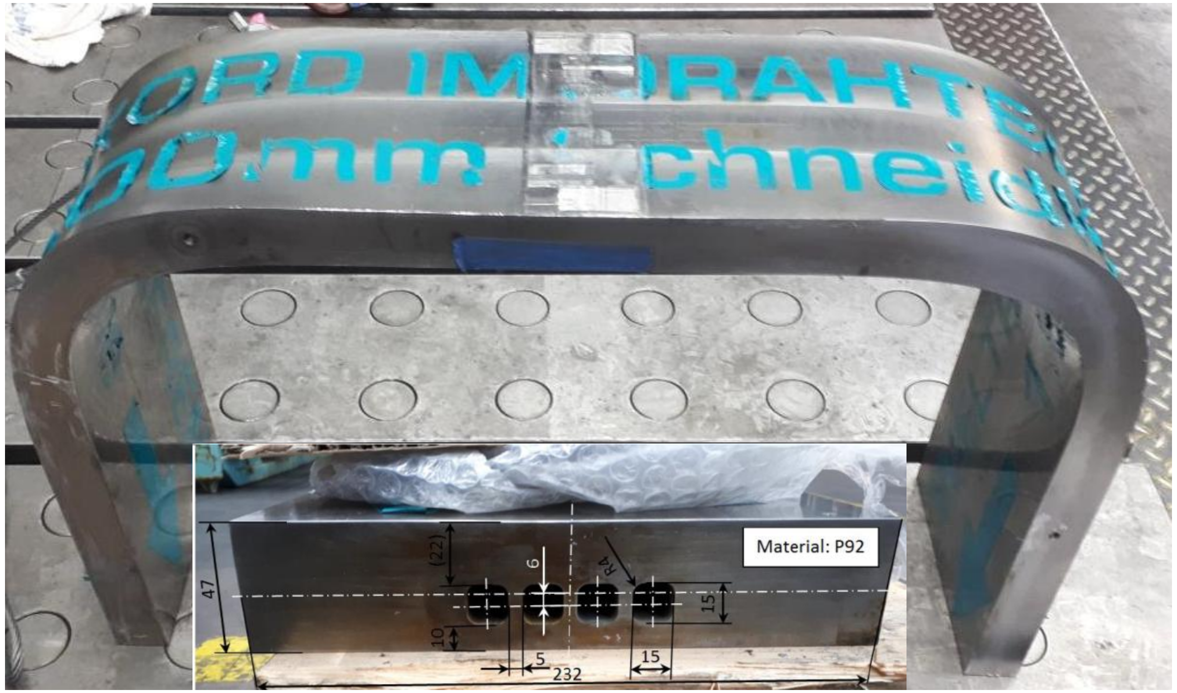
Examples	Definition of types welded joints				
	I.1	butt welding	full penetration	two sides accessible	back welding
	I.2	butt welding	full penetration	two sides accessible	gaseous back protection with or without insert
	I.3	butt welding	full penetration	two sides accessible	on temporary backing strip can be inspected after removal of the strip
	II.1	butt welding	full penetration	back side inaccessible	gaseous protection with or without insert
	II.2	butt welding	full penetration	back side inaccessible	permanent backing strip
	III.1	fillet or T	full penetration	two sides accessible	back weld or back machining
	III.2	fillet or T	full penetration	back side inaccessible	gaseous back protection
	III.3	fillet or T	full penetration	back side inaccessible	permanent backing strip
	IV.1 IV.2	fillet or T butt welding	partial penetration	double opening preparation	double bead
	V	fillet or T	partial penetration or no penetration	straight edges or single opening preparation	double bead
	VI	fillet or T butt welding	partial penetration	single opening preparation	single bead
	fillet or T	no penetration	straight edges preparation	single bead	single bead

(Ref:- G Verma et al 2024 EFDA_D_2SHB7M)

Status of HCPB BB Manufacturing: Different Manufacturing Techniques for First Wall (FW)

2.5 m FW Demonstrator 8-Ch full length with Wire-EDM

EDM Machined + Cold Formed (Manf-TRL: 4)



1.6m U-shape FW 4-Ch Wire-EDM Machined and Cold Formed

(Ref:- J Rey et al 2024 EFDA_D_2ST6QV)

Status of HCPB BB Manufacturing: Different Manufacturing Techniques for First Wall (FW)

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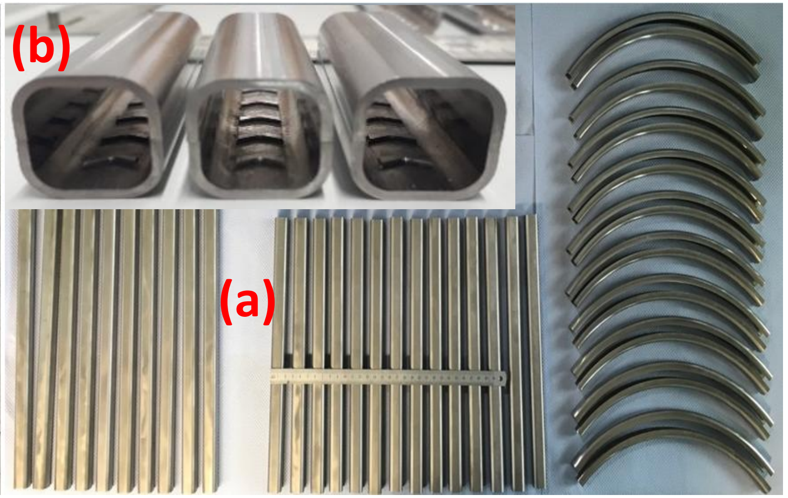
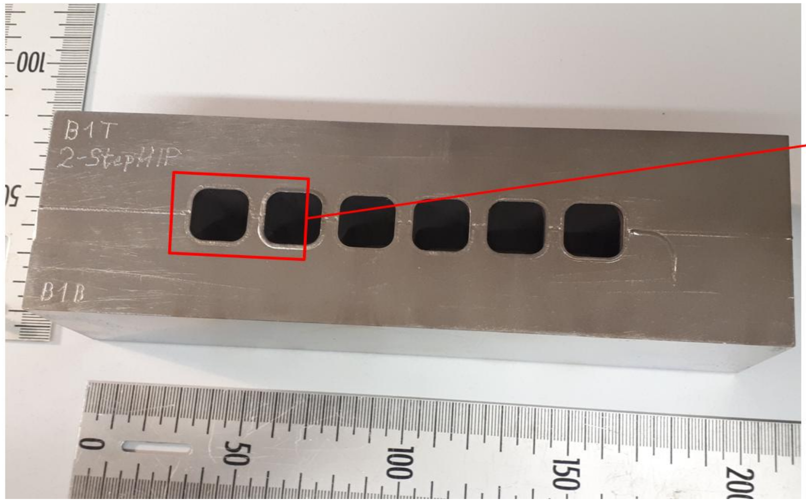
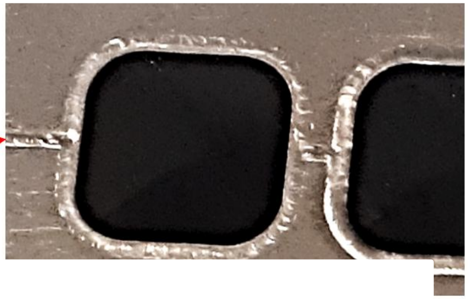
U-shaped FW plates for HIPing



(a) Channel inserts (b) EB welding of channel inserts with V-ribs



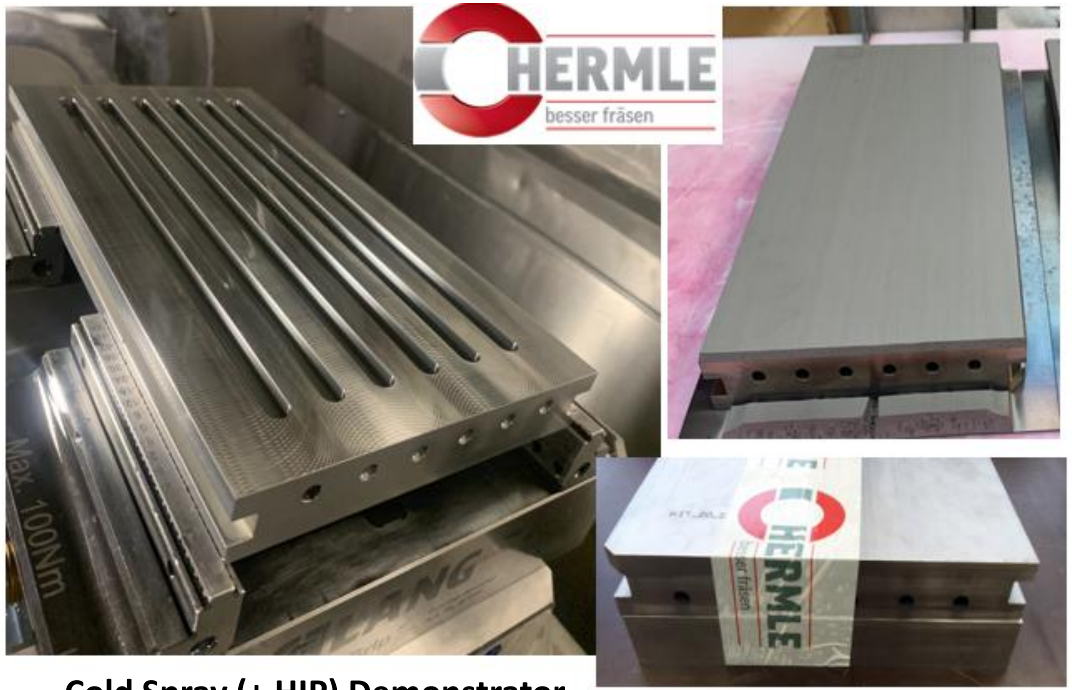


Result: No seal defects as with the 3 ch. MU.

6 channel FW mock-up after EB-seal welding & successful HIPing

HIP (Manf-TRL: 3)

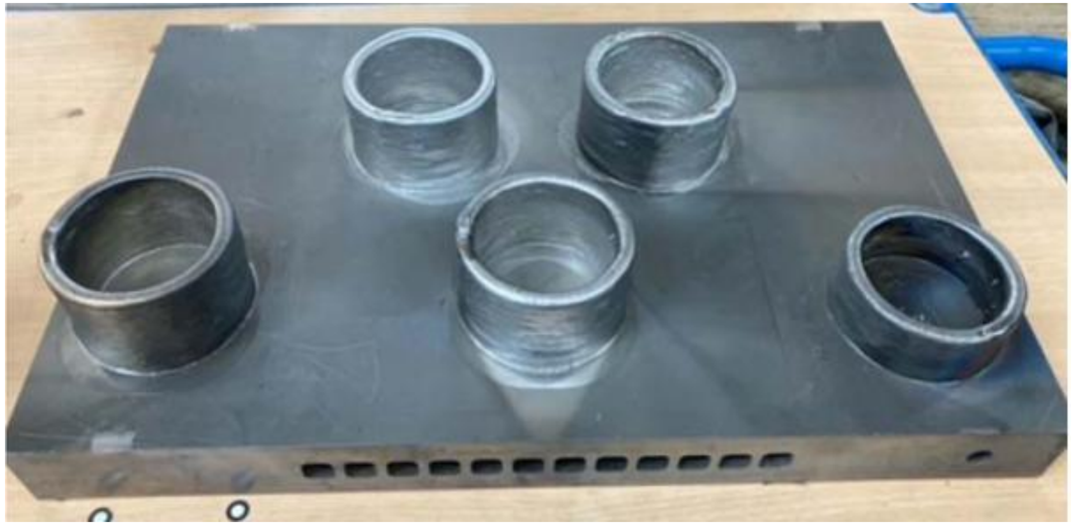
Cold Spray + HIP (Manf-TRL: 3)



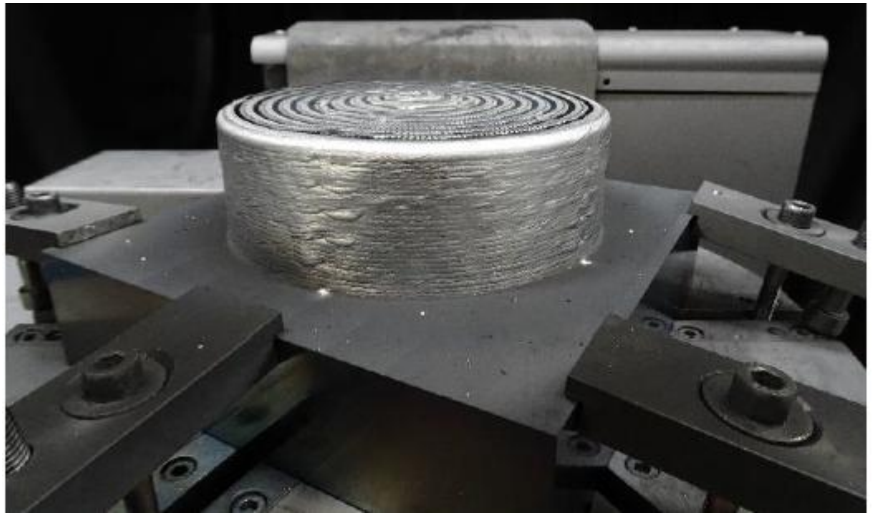
Cold Spray (+ HIP) Demonstrator

(Ref:- H Neuberger et al 2023 EFDA_D_2S5AT4)

Status of HCPB BB Manufacturing: Different Manufacturing Techniques for BB Components



Pressure Tube projection on FW Mock-up with WEBAM



Cylinder deposited via WEBAM on P92 Plate

Pressure Tubes via WEBAM on U-shaped FW Mock-up

Wire-Electron Beam Additive Manufacturing (Manf-TRL: 3)

(Ref:- H Neuberger et al 2023 EFDA_D_2S5AT4)

(Ref:- J Rey et al 2024 EFDA_D_2ST6QV)

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Gap Areas in Existing C&S: BB Perspective

- **Loads unique to fusion lack codified treatment:** Existing codes do not address plasma-induced loads, off-normal thermal transients, disruption EM loads, etc in addition to mechanical, thermal and neutronic loadings.

- **Material data gaps (and qualification routes) at fusion conditions:** especially under 14 MeV neutron spectra, high heat flux, and irradiation-assisted creep/fatigue/embrittlement;

- **IAEA TECDOC-1851-** integrates methods to identify safety & supporting functions, categorize them by safety significance, assign safety classes to SSCs; needs revision based on current developments and know-how as it is more magnetic confinement centric;

  - ✓ Eg: **QC-1** is recommended for **SIC-1** components (like ITER VV), but RCC-MRx Sec. III Tome 1 A19 classifies ITER VV as Class N2RX welded box structure

- Existing **Fusion-relevant C&S space is fragmented**; Need of more coherent framework for multi-code approach;

- **Evolving regulatory landscape;** regulators are actively shaping fusion-specific frameworks.

Gap Areas in Existing C&S: BB Perspective

<table>
<tr><th>Materials</th><th>ASME BPVC</th><th>RCC-MRx</th><th>SDC-IC</th></tr>
<tr><td>Eurofer</td><td>Not Addressed</td><td>Addressed</td><td>Not Addressed</td></tr>
<tr><td>ODS steels</td><td colspan="3">Not Addressed</td></tr>
<tr><td>W and W-Alloys</td><td colspan="2">Not Addressed</td><td>Addressed</td></tr>
<tr><td>W-Cu composites</td><td colspan="3">Not Addressed</td></tr>
<tr><td>Be</td><td>Not Addressed</td><td colspan="2">Addressed</td></tr>
</table>

<table>
<tr><th>Modifying Effects</th><th>ASME BPVC</th><th>RCC-MRx</th><th>SDC-IC</th></tr>
<tr><td>Irradiation Effects</td><td>Not Addressed</td><td>Addressed</td><td>Partially Addressed</td></tr>
<tr><td>Environmental Effects (Corrosion, etc)</td><td colspan="3">Recommendations for Corrosion</td></tr>
<tr><td>Impure He on Fatigue and Creep-Fatigue</td><td colspan="3">Not Addressed</td></tr>
<tr><td>Stress Corrosion Cracking</td><td colspan="2">Recommendations</td><td>Not Addressed</td></tr>
</table>

<table>
<tr><th>Joining Tech.</th><th>ASME BPVC</th><th>RCC-MRx</th><th>SDC-IC</th></tr>
<tr><td>Welding (EB, TIG, laser)</td><td colspan="3">Addressed</td></tr>
<tr><td>Friction Stir Welding</td><td colspan="2">Addressed</td><td>Not Addressed</td></tr>
<tr><td>Brazing</td><td colspan="3">Addressed</td></tr>
<tr><td>PM-HIP</td><td>Addressed (CC N-834)</td><td>Not Addressed</td><td rowspan="2">Not Addressed</td></tr>
<tr><td>Diffusion Welding</td><td colspan="2">Addressed</td></tr>
<tr><td>Plasma spraying</td><td colspan="3">Not Addressed</td></tr>
<tr><td>Metal Casting</td><td colspan="2">Addressed (only for Pump casings)</td><td>Not Addressed</td></tr>
<tr><td>AM (DED, MPA)</td><td>Addressed (wire additive welding, GMAAM using CC 3020)</td><td colspan="2">Not Addressed</td></tr>
</table>

(Ref: IAEA-TECDOC-TE1851 revised)

Gap Areas in Existing C&S: BB Perspective

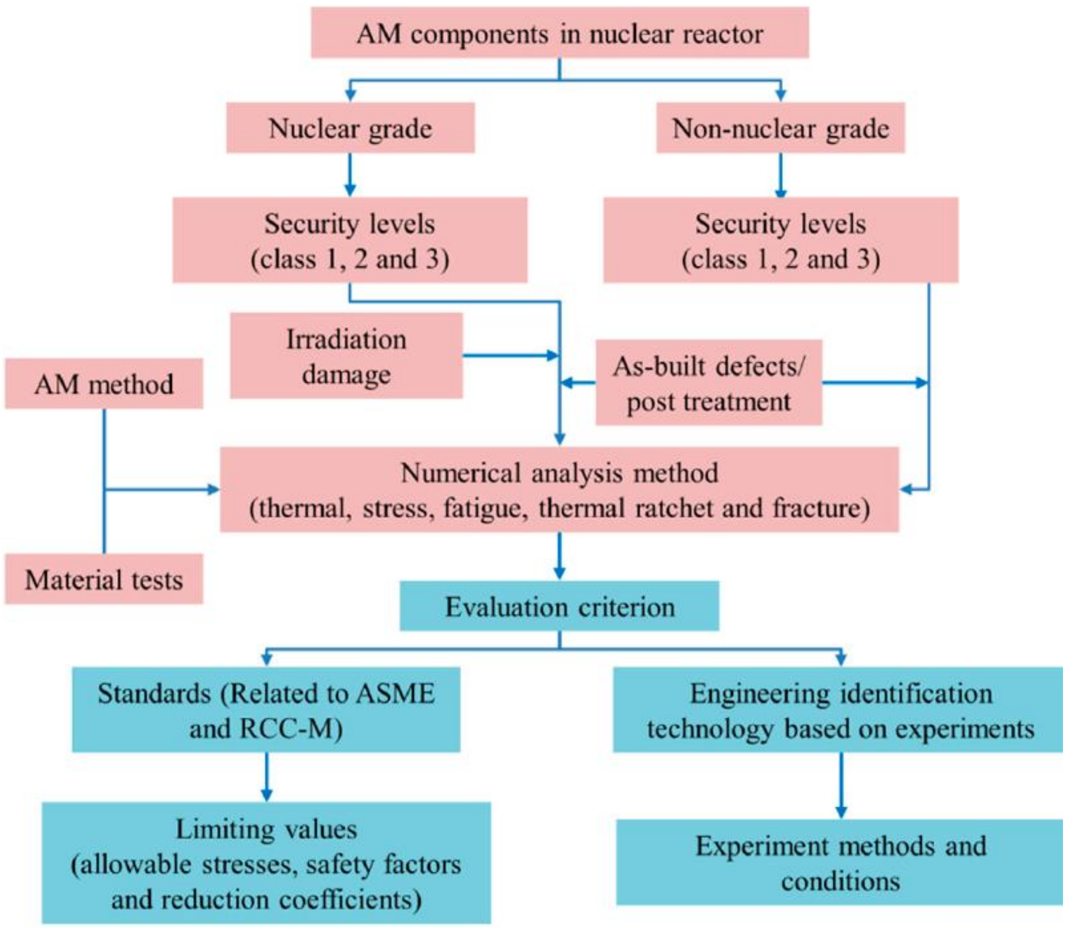
- **ASME BPVC Sec-III Div. 1** not adequate for Innovative Reactor Designs; **Div. 5** appropriate for Advanced Fission Reactors (Gen IV);
- Fusion Energy Devices specific **Div. 4** still in early stages of development;
- Structural Design Criteria for In-vessel Components **(SDC-IC)** - developed for **ITER**. Only design criteria covered; rules for manufacturing, quality assurance & examination not covered;
- Presently, **RCC-MRx** is relatively more mature C&S for BB; still consists many shortcomings;
- Building on SDC-IC, DEMO Design Criteria for In-vessel Components **(DDC-IC)** which is expected to fill in for some of these shortcomings is in development phase;
- For rapid deployment of fusion installations – key role of private fusion industry is imminent – a **dedicated**, **versatile** & **highly mature C&S** solely for design & construction of components for fusion power plants - needs to be envisaged.

OVERVIEW

Considerations for Existing C&S: Insights from BB

C1: Inclusion of Additive Manufacturing (AM) Techniques (for Manufacturing & Joining) for IVCs

- Considerable effort being made towards standardization of AM techniques for Nuclear Industry;
- Preliminary applications in nuclear reactors for classical parts - RPV for small reactor (508-III steel), fuel assembly inlet nozzles (SS 304L), fuel cladding (Zircaloy), etc;
- Ongoing initiatives by **EPRI (USA)** for inclusion of **wire-fed DED** (SS316L) through **code case** in **ASME;**
- **ASTM F42 technical committee** & **ASME BPTCS/BNCS** special committee working on AM for pressure equipment, **KIWG TG** on AM for Valves;
- **ASME BPVC Sec IX Code Case 3020** approved in 2021 for Gas Metal Arc Additive Manufacturing **(GMAAM)** or **GMA-DED**;



Evaluation flow chart for use of AM components in nuclear reactors

(Ref:- H Li et al 2022 Crystals 12 918)

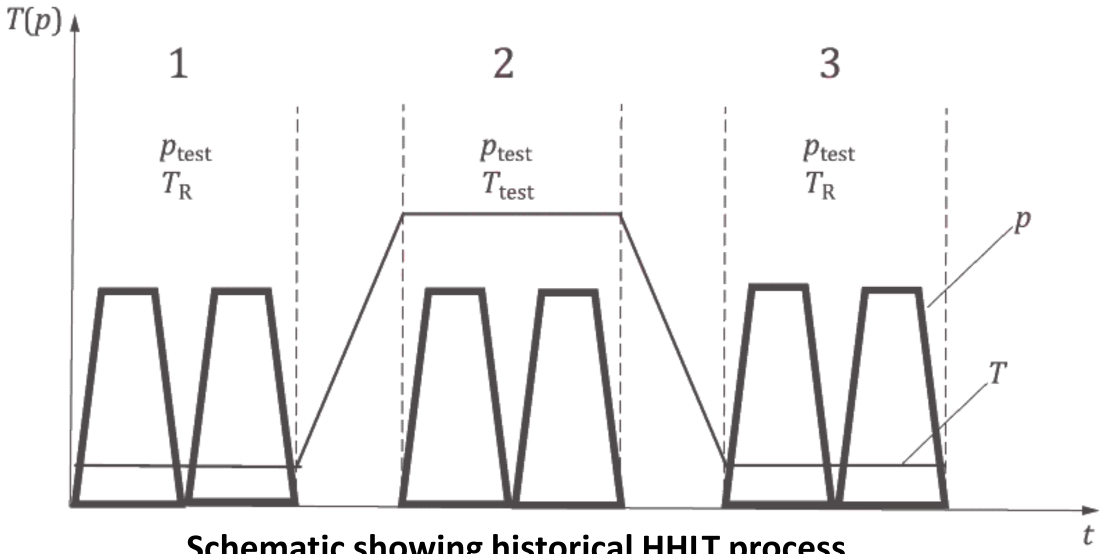
Considerations for Existing C&S: Insights from BB

- **Powder Bed Fusion** work published in **ASME PTB-13:2021** “Criteria for Pressure Retaining Metallic components using Additive Manufacturing;
- **EU funded NUCOBAM** project (2020-24) consolidated key elements for nuclear standardization of AM focused on **Laser Powder Bed Fusion (L-PBF)** of SS 316L;
- Numerous standards exist – **ISO/ASTM 52904:2024** (Metal Powder Bed Fusion Process-critical applications); **ASTM F3187-16** (Standard Guide for Directed Energy Deposition of Metals), etc;
- Multiple accepted **Weld Metal Buildup** Code Cases accepted by US NRC in RG-1.147 with no added restrictions e.g.- **N-853**, **N-740**, **N-653**, etc;
- Recent **F4E AM Workshop 2025** – a promising step towards fusion related AM;
- Initial implementation to **non-SIC** components and subsequently to **SR** components with component specific manufacturing after rigorous testing & qualification.

Considerations for Existing C&S: Insights from BB

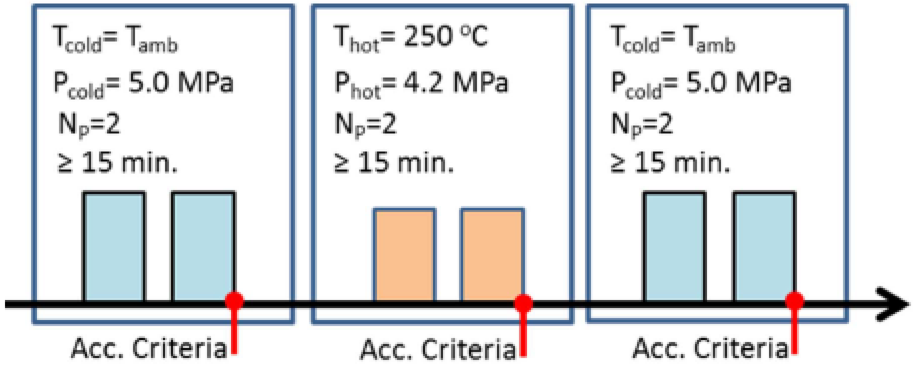
C2: Inclusion of Hot Helium Leak Test (HHLT) as an NDE technique for IVCs

- HHLT realizes more reliable leak tightness assessment than conventional cold helium leak testing for components that run at elevated temperatures;
- HHLT already used for **ITER-blanket shield block modules** demonstrating vacuum performance;
- HHLT was also adopted for various components in **Tore Supra**, **Wendelstein 7X** and **EAST**;
- T_{test} is maximum working temperature of a component in operation, T_R is ambient temperature, ① is initial helium leak testing ② is the helium leak testing at elevated temperature & ③ is final cold helium leak testing;



Schematic showing historical HHLT process

(Ref:- ISO 4233:2023)



HHLT process for ITER internal components

(Ref:- T Hirai et al 2017 Phys. Scr. 014045)

Considerations for Existing C&S: Insights from BB

- **ISO 4233:2023** (Reactor technology - Nuclear fusion reactors - Hot helium leak testing method for high temperature pressure-bearing components in nuclear fusion reactors);
- HHLT is carried out with cyclic operating pressure & temperature process;
- Minimum detectable leakage rate - **as low as 10^{-10} Pa·m^3/s**, depending on dimension, external configuration complexity and materials of component;
- It is also applicable to the overall leak tightness test of welds in other metallic components and equipment that could be evacuated and pressurized;
- Presently, **RCC-MRx (refers EN 13185)** & **ASME** do not specify or require leak testing at elevated temperature or temperature-dependent acceptance criteria or test sequences under operational temperature.

Summary

- BBs in EU DEMO are classified as SR SSC and is classified as Design Class-2 (QC-2); RCC-MRx: N2RX is followed for its qualification;
- Design Assessments of HCPB BB segment being performed using unit slice model and reduced DOF global segment according to RCC-MRx & SDC-IC;
- Preliminary manufacturing assembly sequence for BB segment devised as per RCC-MRx:N2RX with code compliant joining and inspection techniques;
- Gap areas in existing C&S space is addressed from BB perspective;
- Two considerations for inclusion in existing C&S: Additive Manufacturing (for Manufacturing and Joining) & Hot Helium Leak Testing (HHLT).

Thank You for Your Attention !

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