EUROfusion

Needs and options for qualifying fusion nuclear technologies

G. A. Spagnuolo, G. Federici, S. D’Amico, F. A. Hernandez, and the DEMO Central Team

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Outline

- The context
- Challenges related to the breeding blanket
- Breeding blanket qualification needs
- Current strategy for breeding blanket nuclear qualification
  - MTR
  - IFMIF-DONES
  - TBM
- Additional breeding blanket nuclear qualification options
  - p/d Accelerator-based Neutron Sources
  - VNS
- Conclusion

The context

- <u>DEMO or any other nuclear fusion device after ITER would need to operate from day 1 with a full coverage breeding blanket (BB) able to produce and recover its own fuel.</u>

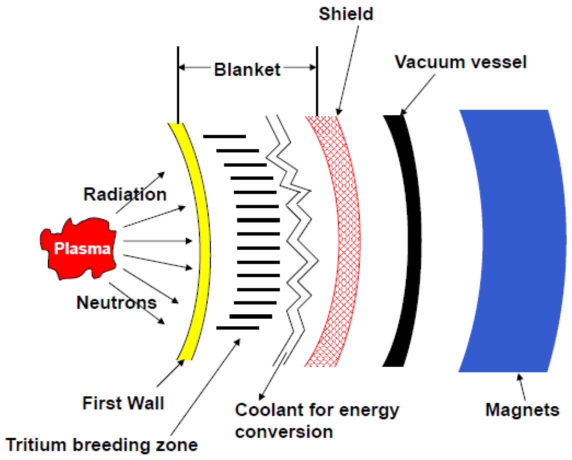
  - ❖ **A 2 GW fusion power DEMO will consume around 111 kg T/fpy, and this clearly underscore the indispensable requirement to achieve T-self-sufficiency.**

- Undisputedly, the BB is one of the most important and novel system of DEMO

- Despite its criticality for the development of fusion power, <u>no breeding blanket has ever been built or tested</u>.

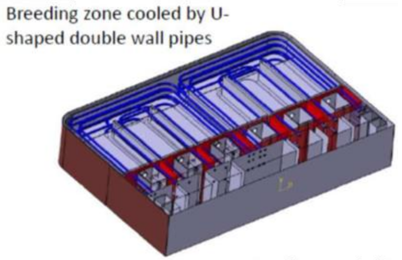
- ITER represents a <u>unique testing opportunity (Test Blanket Module, TBM)</u>.

- Performance and reliability are the main BB design drivers. However, some <u>technical issues still need to be addressed</u>.

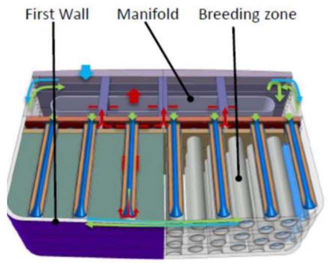


BB coolant: Helium or Water

Water-cooled LiPb (WCLL)



Helium-cooled Pebble Bed (HCPB)



Challenges related to the BB

PL 2: Gianfranco Federici
KN 4: Ambrogio Fasoli

Structure

- ❖ Changes in properties and behaviour of materials
  - ➢ *Effect of heat flux and cycling on fatigue or crack growth-related failure*
  - ➢ ***Premature failure at welds and discontinuities***
  - ➢ ***Effect of swelling, creep and thermal gradients on stresses conc.***
- ❖ Tritium permeation through the structure
  - ➢ ***Effectiveness of tritium permeation barriers***
  - ➢ ***Effect of radiation on tritium permeation***
- ❖ **Structural activation product inventory and volatility**

Solid Breeder / multiplier / structure interactions

- ❖ Solid breeder mechanical and materials interactions
  - ➢ ***Strain accommodation by creep and plastic flow***
  - ➢ ***Stress concentrations at cracks and discontinuities***
- ❖ Neutron multiplier mechanical interactions
  - ➢ ***Beryllium/beryllide swelling (swelling driving force in beryllium)***
  - ➢ ***Strain accommodation by creep in Beryllium/beryllide***
- ❖ Thermal interactions
  - ➢ ***Breeder/multiplier-structure heat transfer (gap conductance)***

Coolant / liquid breeder-multiplier

- ❖ MHD pressure drop and pressure stresses
- ❖ MHD and geometric effects on flow distribution
- ❖ **Helium bubble formation leading to hot spots**
- ❖ **Activation products in PbLi**

Coolant / structure interactions

- ❖ Mechanical and materials interactions
  - ➢ ***Corrosion***
  - ➢ ***Failure of coolant wall due to stress corrosion cracking***
  - ➢ ***Failure of coolant wall due to liquid-metal embrittlement***
- ❖ Thermal interactions
- ❖ **Coolant/coatings/structure interactions**

Breeder and purge

- ❖ **Tritium recovery and inventory in solid breeder**
- ❖ **Liquid breeder tritium extraction**
- ❖ **Thermal conductivity changes under irradiation**
- ❖ **Effect of T mass transfer**
- ❖ **Breeder behaviour at high burn-up/high dpa**

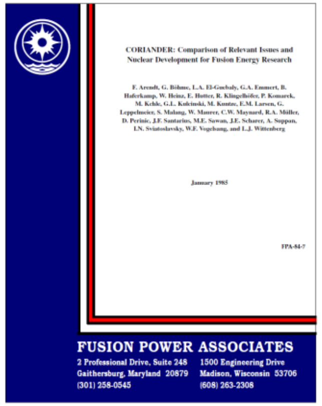
General blanket

- ❖ **Tritium trapping**
- ❖ **Uncertainties in achievable breeding ratio**
- ❖ **Uncertainties in required breeding ratio**
- ❖ **Permeation to blanket coolant**
- ❖ **Failure modes and frequencies**
- ❖ **Nuclear heating rate predictions**
- ❖ **Prediction and control of radioactive effluent**

⬛ **w/o neutrons**

🟧 **w/ neutrons**

🟥 **Fusion environment**



CORIANDER: Comparison of Relevant Issues and Nuclear Development for Fusion Energy Research

F. Arendt, G. Böhme, L.A. El-Guebaly, G.A. Emmert, B. Haferkamp, W. Heinz, E. Hutter, R. Klingelhöfer, P. Komarek, M. Kehle, G.L. Kulcinski, M. Kuntze, E.M. Larsen, G. Leppelmeier, S. Malang, W. Maurer, C.W. Maynard, R.A. Müller, D. Perinic, J.F. Santarius, M.E. Sawan, J.E. Scharer, A. Suppan, I.N. Sviatoslavsky, W.F. Vogelsang, and L.J. Wittenberg

January 1985

FPA-84-7

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Volume I
Summaries
PPG-909
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Volume II
Chapters 3-9
PPG-909
UCLA-ENG-85-39

Technical Issues and Requirements of Experiments and Facilities for Fusion Nuclear Technology

FINESSE Phase I Report

December 1985

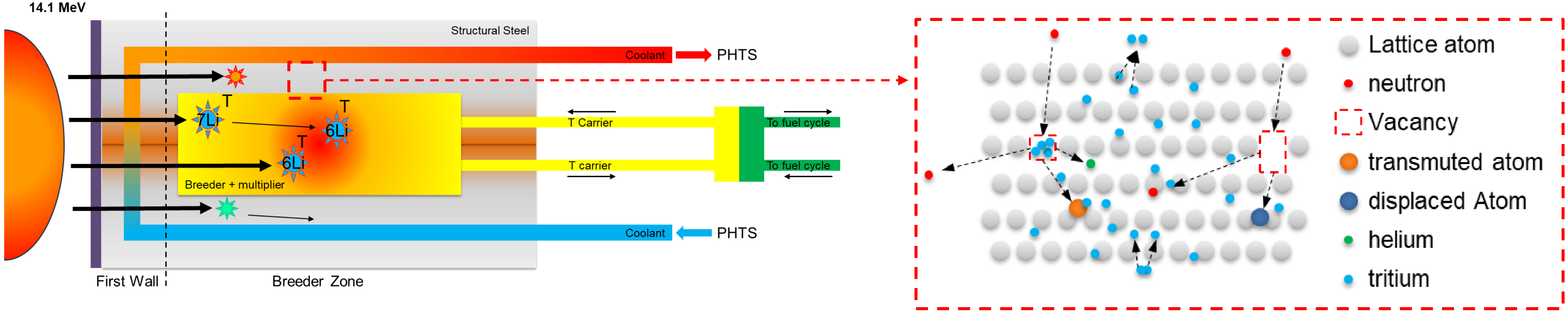
Fusion Engineering
University of California, Los Angeles
Los Angeles, California

M. A. Abdou, et al, (1985) A Study of the Issues and Experiments for Fusion Nuclear Technology, Fusion Technology, 8:3, 2595-2645, DOI: 10.13182/FST85-A24685

Challenges related to the BB

P2A4: Nicola Fonnesu P3A5: James Dark
P3C3: Elisabetta Carella
P6B1: Italo Ricapito
P2D1: Barry Buttler

T management (production, permeation, trapping and extraction)



What are the parameters influencing the T management?

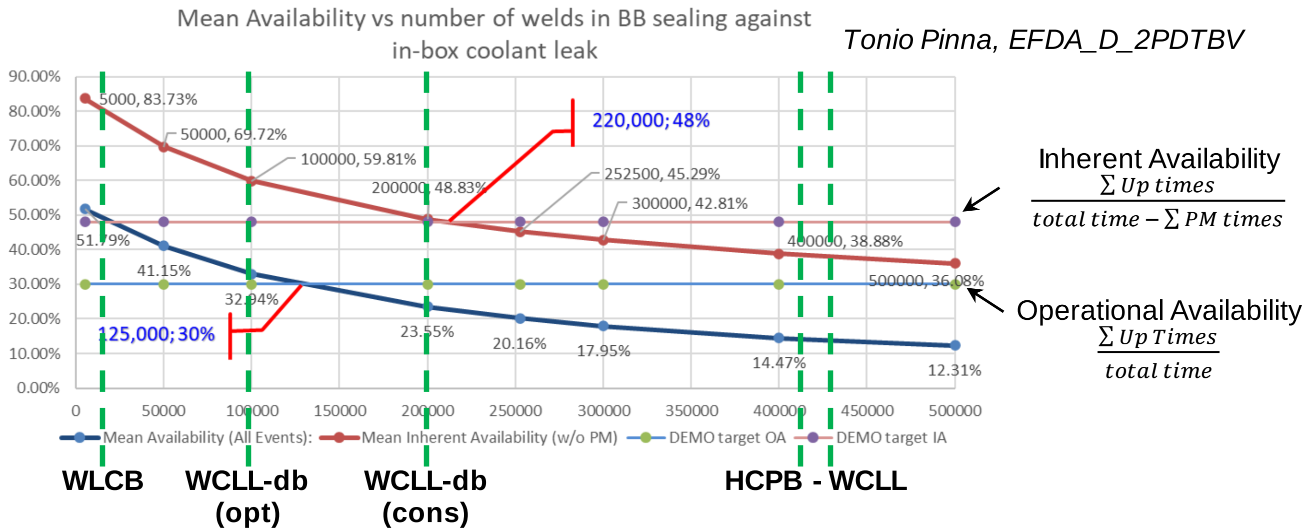
- Uncertainties related to neutronics modelling, nuclear data, and calculational methods → **effect on Tritium Breeding Ratio estimation**
- In solid BB, tritium breeding shifts from high burnup regions to areas with remaining lithium → **changes on temperature & stress gradients (i.e. design challenge in accommodating large variations in heat generation rates)**
- Coolant and T-Carrier physical and thermohydraulic parameters (**G, p, T, chemistry, impurities, etc.**)
- Structural material physical parameters
  - trapping in radiation-induced **bubbles**, **vacancies**, or **dislocations**
  - diffusion mechanisms influenced by **temperature**, **vacancy concentration**, **grain growth rates**, etc.
  - surface conditions (**corrosion, cracks, surface release mechanisms and stresses, etc.**)

Efforts should be planned to test mock-ups and prototypes under relevant conditions to improve the understanding and knowledge of phenomena/processes. Separate effect tests can be foreseen initially. However, integral testing are needed for a full BB qualification.

Challenges related to the BB

P1A1: Guangming Zhou
P3A2: Francisco Hernández
P1A4: Anoop Retheesh
P4A4: Jarir Aktaa

Low reliability & availability



Tonio Pinna, EFDA_D_2PDTBV

Inherent Availability

$$\frac{\sum Up\ times}{total\ time - \sum PM\ times}$$

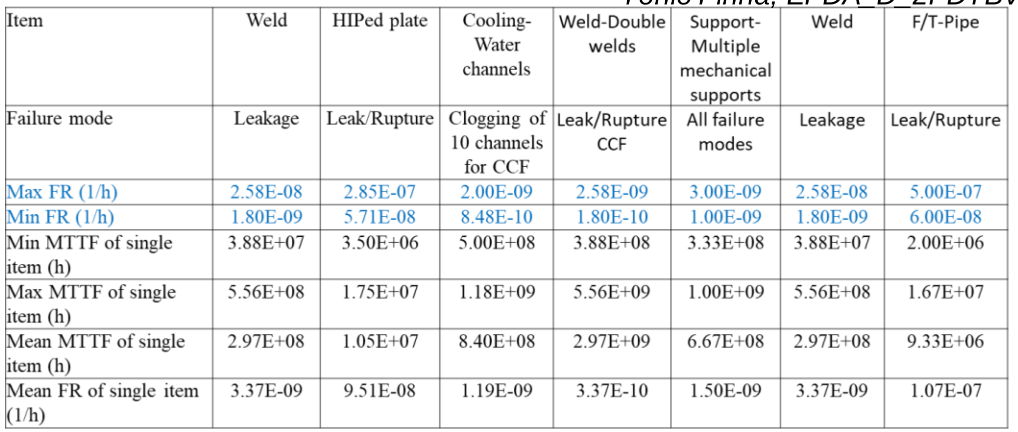
Operational Availability

$$\frac{\sum Up\ Times}{total\ time}$$

- The BB system affect largely the DEMO availability targets → large number of components that can fail.
- Efforts are dedicated to the simplification of the BB design → reduction of welds. However, due to the BB system layout (80 banana-shape segments, 13 m height 0.7-1 m width), the reduction of components and sub-components is limited.
- To reach a BB system availability (A_{BS}) of 30%, the availability associated to each BB segment A_n should be higher than 97% ($A_n = \frac{n}{(n-1)+\frac{1}{A_{BS}}} = \frac{1}{1+\lambda_n MTTR_n}$)

Statistical data used

Tonio Pinna, EFDA_D_2PDTBV



Item	Weld	HIPed plate	Cooling-Water channels	Weld-Double welds	Support-Multiple mechanical supports	Weld	F/T-Pipe
Failure mode	Leakage	Leak/Rupture	Clogging of 10 channels for CCF	Leak/Rupture CCF	All failure modes	Leakage	Leak/Rupture
Max FR (1/h)	2.58E-08	2.85E-07	2.00E-09	2.58E-09	3.00E-09	2.58E-08	5.00E-07
Min FR (1/h)	1.80E-09	5.71E-08	8.48E-10	1.80E-10	1.00E-09	1.80E-09	6.00E-08
Min MTTF of single item (h)	3.88E+07	3.50E+06	5.00E+08	3.88E+08	3.33E+08	3.88E+07	2.00E+06
Max MTTF of single item (h)	5.56E+08	1.75E+07	1.18E+09	5.56E+09	1.00E+09	5.56E+08	1.67E+07
Mean MTTF of single item (h)	2.97E+08	1.05E+07	8.40E+08	2.97E+09	6.67E+08	2.97E+08	9.33E+06
Mean FR of single item (1/h)	3.37E-09	9.51E-08	1.19E-09	3.37E-10	1.50E-09	3.37E-09	1.07E-07

- The data sources [1] have been derived by technological experiences in fission power plants or industrial systems, and existing fusion facilities (JET, TFTR, DIII-D, TLK, etc.) → **not completely relevant!**

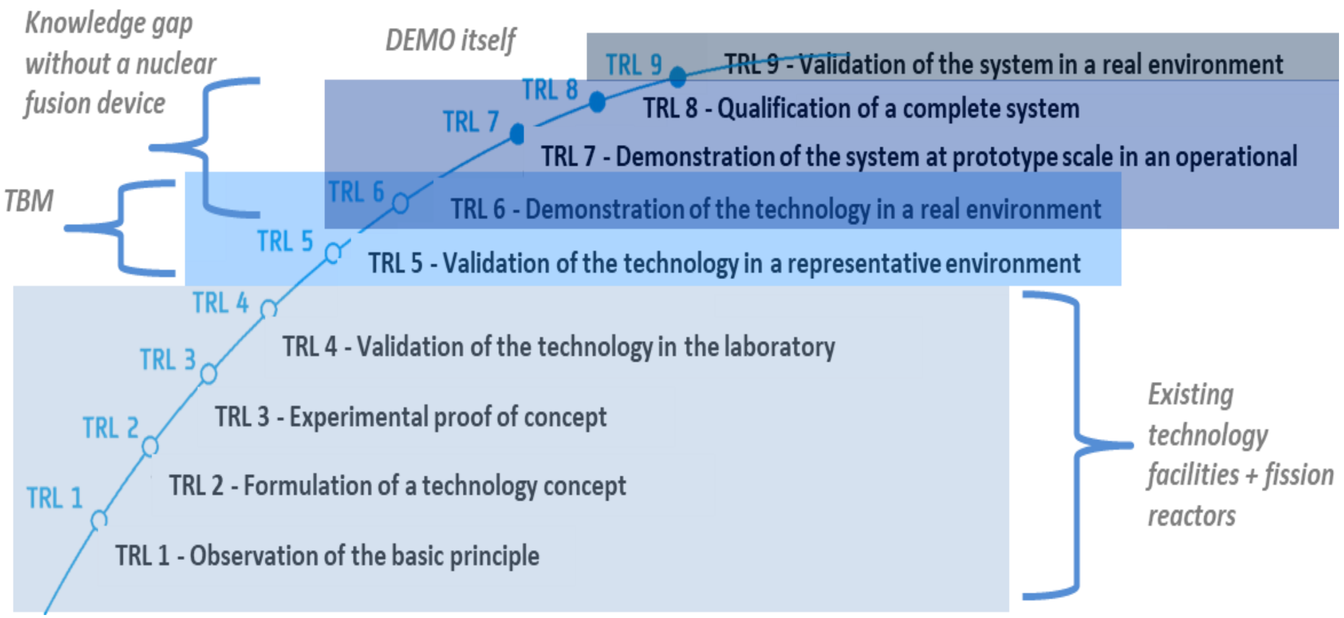
[1] Tonio Pinna, et al., Fusion component failure rate database (FCFR-DB), Fusion Engineering and Design, Volume 81, Issues 8–14, 2006, Pages 1391-1395, doi.org/10.1016/j.fusengdes.2005.05.011.

- New procedures (e.g. HIP welding, additive manufacturing, etc.) extensively assumed for the BB manufacturing are not used in fission therefore these data are based only on engineering judgments.

An extensive R&D effort should be planned to test mock-ups, prototypes, and BB segments under conditions that closely mimic the relevant environmental factors (such as spectra, fluxes, loads, etc.), as well as geometries and manufacturing processes expected for the BB system.

Challenges related to the BB

- Feasibility concerns and performance uncertainties exist in all explored concepts.
- The readiness of EU DEMO breeding blanket concepts is currently low (TRL 3 to 4).
- Achieving TRL 6 would require completing the full TBM program, including extensive nuclear operation.



G. Federici, Testing Needs for the Development and Qualification of a Fusion Breeding Blanket for DEMO, Nuclear Fusion, in press.

- There is still a substantial gap to reach TRL 8 and qualify a breeding blanket for DEMO.
- Urgent action is needed to accelerate the development and testing program.
- Integral testing should be carried out up to the Mid of Life (MoL) and End of Life (EoL) stages to identify the cumulative impacts resulting from (i) neutron exposure as well as other forms of degradation that occur during operation, such as (ii) corrosion, (iii) thermal-cycling fatigue, and (iv) tritium permeation.

Breeding blanket qualification needs

1) Heat Transfer Experiments

Testing goal:

- Empirical study of heat transfer within realistic BB geometries.
- Evaluate the long-term performance of the assembly, considering both MOL and EOL conditions.

Reproduction of Conditions:

- Neutrons for bulk heating and radiation effects on heat transfer.
- Reproduce environmental conditions (temp., pres., vel., etc.).

2) Breeder/Structure Thermo-Mechanical Interactions

Testing goal:

- Measure temperature changes and stress levels at BOL.
- Assess radiation-induced thermal conductivity changes. creep, and swelling, among other effects.

Reproduction of Conditions:

- Neutrons for bulk heating and irradiation effects.
- Replicate BB geometry and temperatures.
- Simulate cycling using submodules.

3) Neutronics Prediction Validation

Testing goal:

- Confirm predictions for tritium breeding, nuclear heating and induced activation.
- Assess tritium inventory.

Reproduction of Conditions:

- Use of fusion spectra in the testing process.
- Replicate similar geometries with mock-ups.
- Emulate the local neutron field.

4) Tritium Permeation

Testing goal:

- Assess tritium permeation rates into the coolant.
- Measure tritium activity within the tritium carrier and analyse the tritium form.
- Evaluate the surface conditions of the clad material.

Reproduction of Conditions:

- Neutrons for the tritium and heat source distribution.
- Replicate breeder, T-carrier and coolant conditions.

5) Tritium behavior in thermal and flow transients

Testing goal:

- Examine the behavior of tritium inventory within breeder unit cells under thermal or flow transient.
- Measure the temperatures of breeder, structure and coolant.
- Monitor activity levels in the coolant and tritium carrier.

Reproduction of Conditions:

- Emulate coolant conditions and T-carrier conditions
- Neutrons for the tritium and heat source distribution and irr. effects.

Increased size of the testing

6) Submodule Thermomechanical Verification

Testing goal:

- Validate the thermomechanical design.
- Assess temperature variations and stress levels.
- Conduct post-test examination for signs of cracks, deformation, any other visible changes.

Reproduction of Conditions:

- Neutrons for heating and to induce specific reactions (i.e. damages).
- Emulate other loads (e.g. press., EM, temp., etc.)

7) Full-Module Thermal and Corrosion Testing

Testing goal:

- Deal with challenges related to the poor modeling of geometry.
- Address uncertainties arising from nuclear and non-nuclear effects during prolonged operation.
- Determine which effects are likely to be life-limiting.

Reproduction of Conditions:

- Fusion relevant environment (i.e. fusion spectrum, EM load, temps, press., etc.).

8) Blanket Response to Coolant Transients

Testing goal:

- Simulate critical incidents to assess the module's response under adverse conditions.
- Measure temperature variations and monitor stress levels
- Post test examination for any signs of deformation or failure.

Reproduction of Conditions:

- Fusion relevant environment (i.e. fusion spectrum, EM load, temp., press., etc.).

9) Tritium Recovery Assessment

Testing goal:

- Conduct in-situ tritium activity measurements in tritium carrier and coolant streams.
- Determine build-up. of tritium inventories

Reproduction of Conditions:

- Fusion relevant environment (i.e. fusion spectrum, EM load, temp., press., etc.).
- Ensure that all other environmental aspects are present (coolant and T-carrier conditions).

10) Module Lifetime Verification

Testing goal:

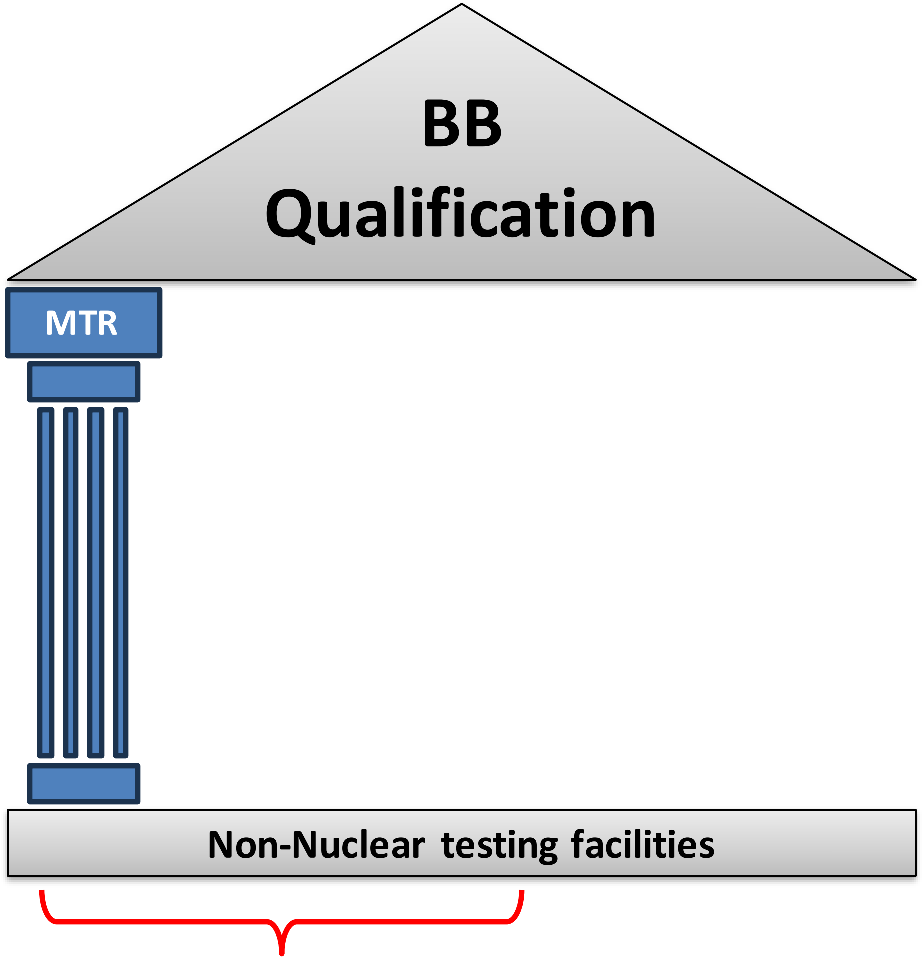
- Conduct comprehensive tests on the full module.
- Focus on identifying structural failure modes.
- Determine the root causes of any observed failures or issues.

Reproduction of Conditions:

- Fusion relevant environment (i.e. fusion spectrum, EM load, temp., press., etc.).

M. A. Abdou, et al, (1984) FINESSE: A Study of the Issues, Experiments and Facilities for Fusion Nuclear Technology Research and Development, UCLA-ENG--84-30-Vol.2, https://doi.org/10.2172/5507921

Current strategy for BB nucl. qual.


BB Qualification

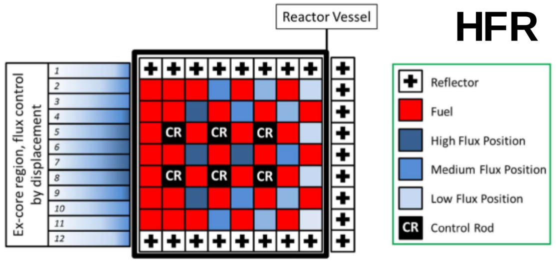
MTR

Non-Nuclear testing facilities

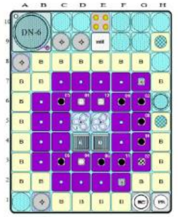
Characterization & codification of structural/functional materials

Material Testing Reactors (MTRs):

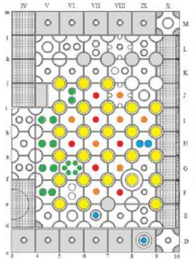
- already available
- material specimen irradiation
- $\Phi_{thermal} < 1E15$ n/cm²/s
- 3-18 dpa/fpy (Ø 25 – 86 mm)



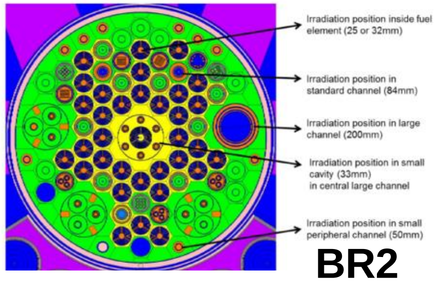
HFR



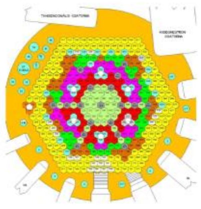
LVR-15



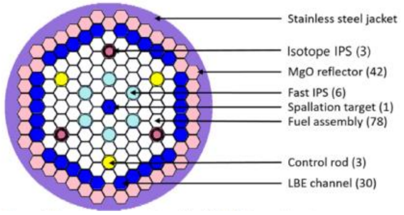
MARIA



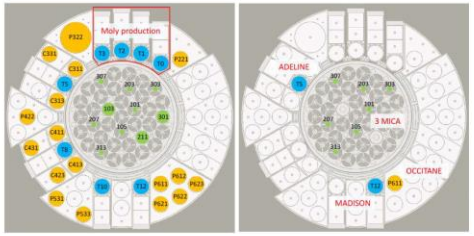
BR2



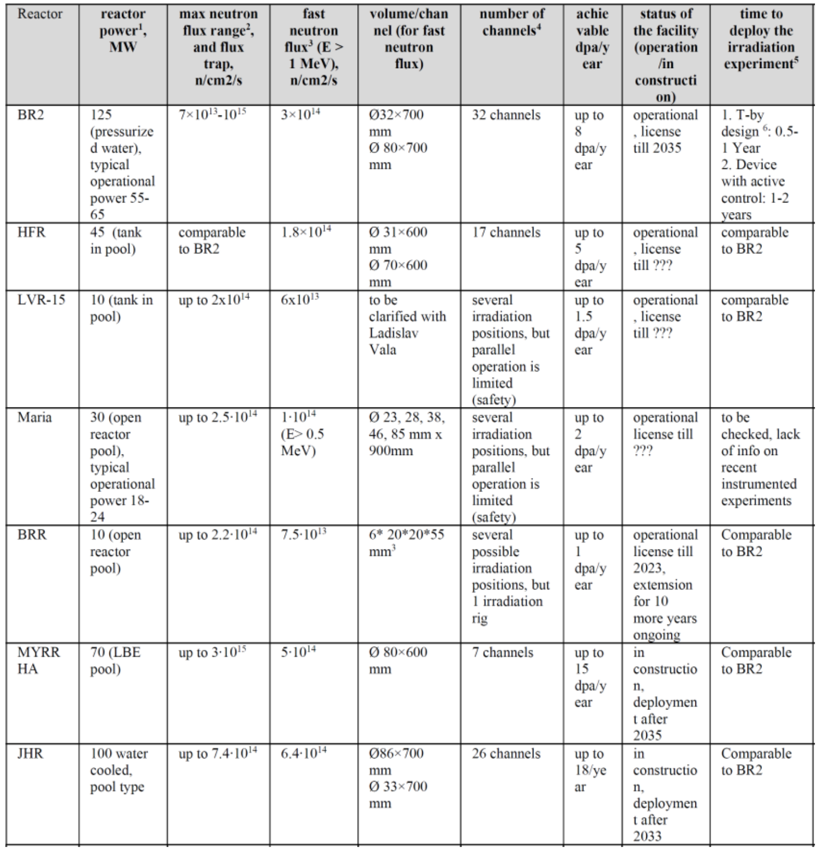
BRR



MYRRHA



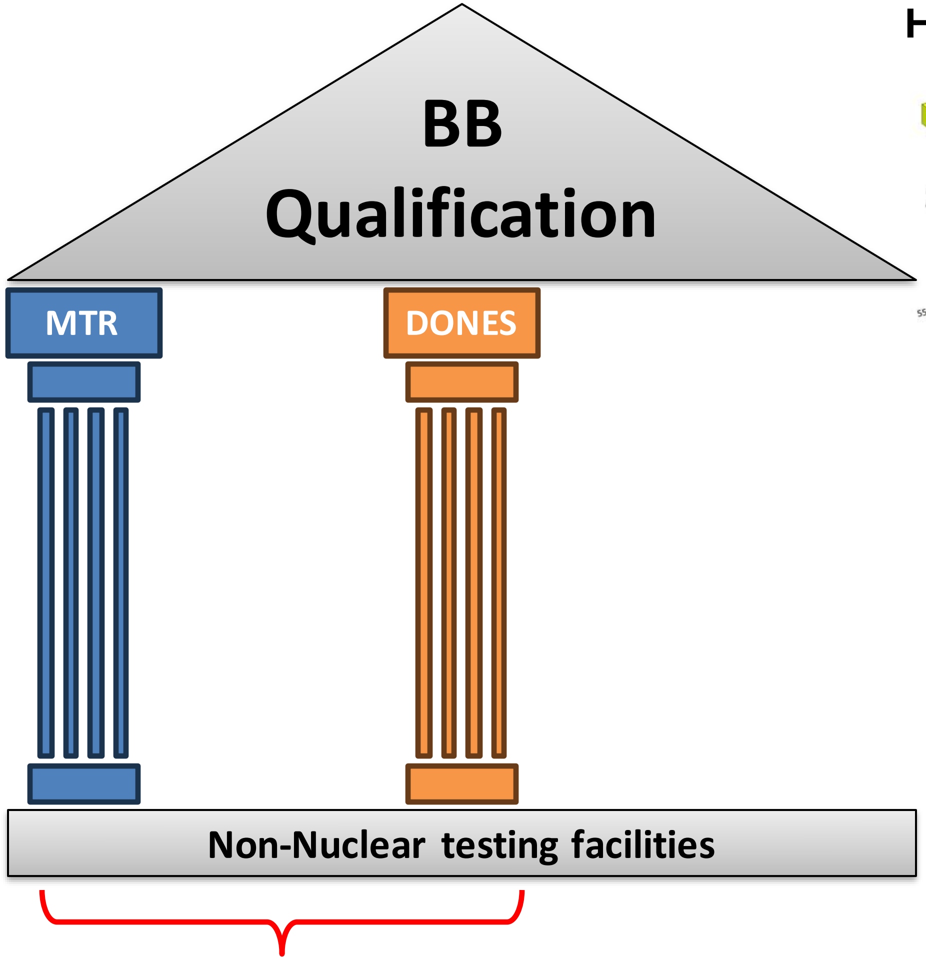
JHR



Reactor	reactor power[1], MW	max neutron flux range[2], and flux trap, n/cm2/s	fast neutron flux[3] (E > 1 MeV), n/cm2/s	volume/channel (for fast neutron flux)	number of channels[4]	achievable dpa/year	status of the facility (operation /in construction)	time to deploy the irradiation experiment[5]
BR2	125 (pressurized water), typical operational power 55-65	7×10^{13}-10^{15}	3×10^{14}	Ø32×700 mm Ø 80×700 mm	32 channels	up to 8 dpa/year	operational, license till 2035	1. T-by design [6]: 0.5-1 Year 2. Device with active control: 1-2 years
HFR	45 (tank in pool)	comparable to BR2	1.8×10^{14}	Ø 31×600 mm Ø 70×600 mm	17 channels	up to 5 dpa/year	operational, license till ???	comparable to BR2
LVR-15	10 (tank in pool)	up to $2x10^{14}$	$6x10^{13}$	to be clarified with Ladislav Vala	several irradiation positions, but parallel operation is limited (safety)	up to 1.5 dpa/year	operational, license till ???	comparable to BR2
Maria	30 (open reactor pool), typical operational power 18-24	up to $2.5\cdot10^{14}$	$1\cdot10^{14}$ (E> 0.5 MeV)	Ø 23, 28, 38, 46, 85 mm x 900mm	several irradiation positions, but parallel operation is limited (safety)	up to 2 dpa/year	operational license till ???	to be checked, lack of info on recent instrumented experiments
BRR	10 (open reactor pool)	up to $2.2\cdot10^{14}$	$7.5\cdot10^{13}$	6* 20*20*55 mm³	several possible irradiation positions, but 1 irradiation rig	up to 1 dpa/year	operational license till 2023, extemsion for 10 more years ongoing	Comparable to BR2
MYRRHA	70 (LBE pool)	up to $3\cdot10^{15}$	$5\cdot10^{14}$	Ø 80×600 mm	7 channels	up to 15 dpa/year	in construction, deployment after 2035	Comparable to BR2
JHR	100 water cooled, pool type	up to $7.4\cdot10^{14}$	$6.4\cdot10^{14}$	Ø86×700 mm Ø 33×700 mm	26 channels	up to 18/year	in construction, deployment after 2033	Comparable to BR2

D. Terentyev, S. Zoletnik, Report Annex 4.1 - Characterization of Materials Test Reactors, 2023 EUROfusion Breeding Blanket Working Group

Current strategy for BB nucl. qual.



BB Qualification

MTR

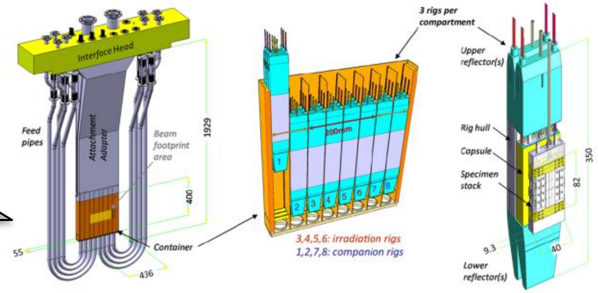
DONES

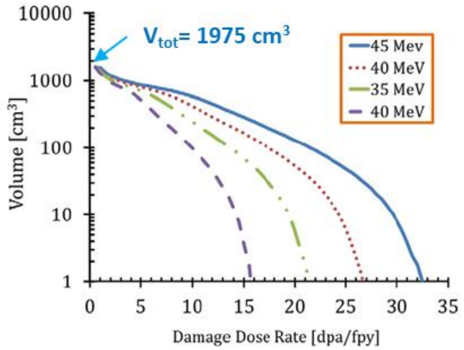
Non-Nuclear testing facilities

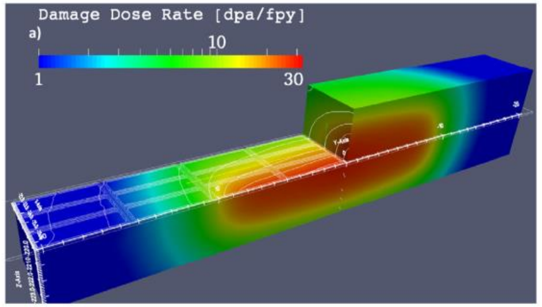
Characterization & codification of structural/functional materials

P3B5: Yuefeng Qiu
PL 10: Ángel Ibarra
P5B4: Beatriz Brañas

High Flux Test Module (HFTM)





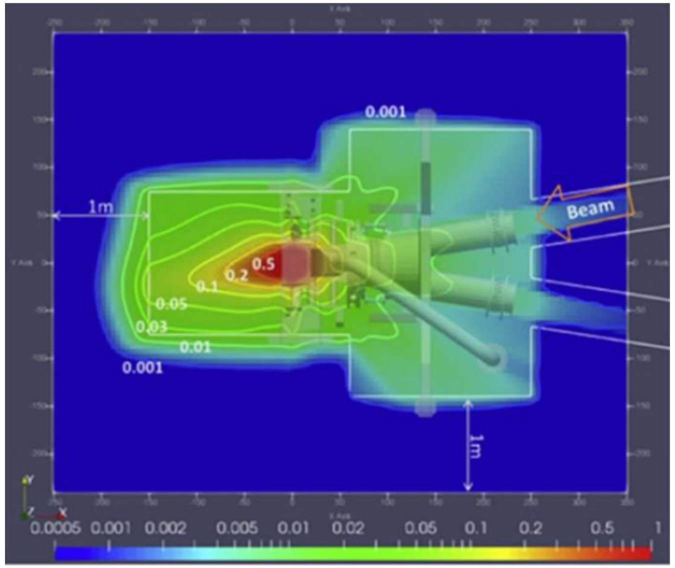


F. Mota et al., Sensitivity of IFMIF-DONES irradiation characteristics to different design parameters, Nuclear Fusion, Volume 55, 2015, 123024, DOI 10.1088/0029-5515/55/12/123024.

Deuteron accelerator with liquid (e.g. Lithium) target (IFMIF-DONES):

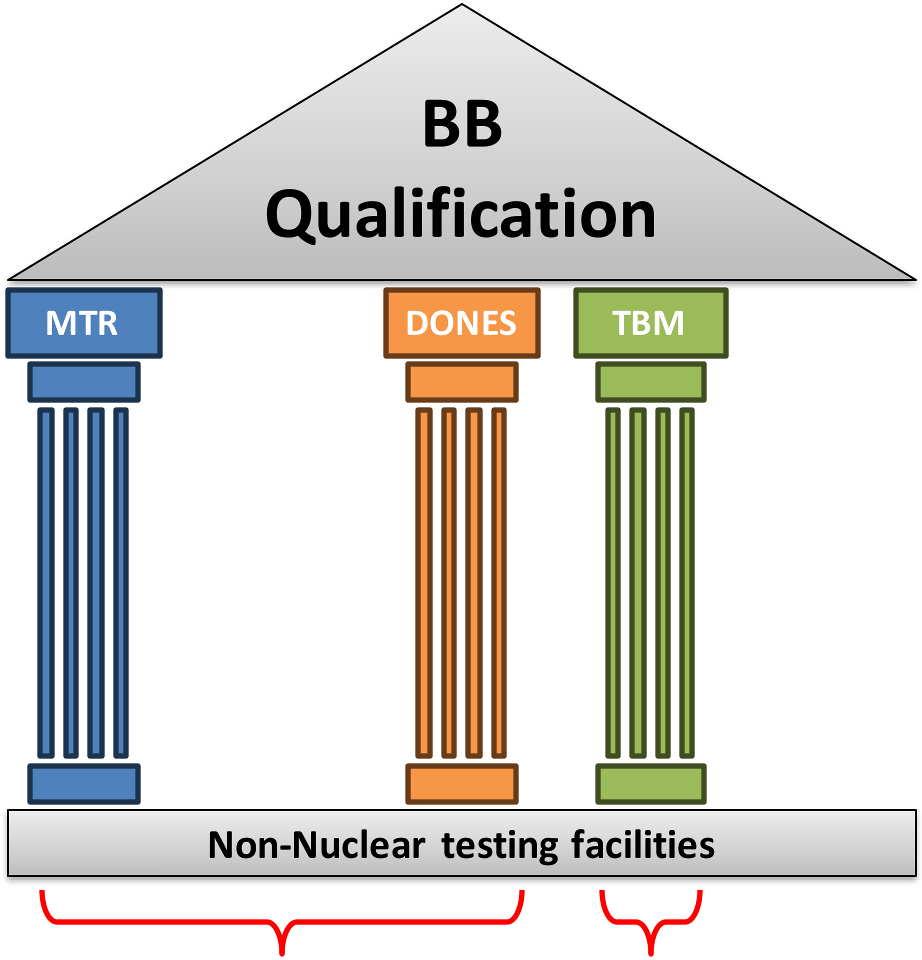
"*Its main goal is to study properties of materials under severe irradiation in a neutron field similar to the one in a fusion reactor first wall*" (W. Królas et al 2021 Nucl. Fusion 61 125002).

- available in 10 years (estimated)
- material specimen irradiation
- $\Phi < 1E15$ n/cm²/s @ High-Flux Test Module (HFTM)
- Up to 35 dpa/fpy (V < 2 l)



D. Rapisarda, Report Annex 4.4 - Characterization of IFMIF-DONES, 2023 EUROfusion Breeding Blanket Working Group

Current strategy for BB nucl. qual.



BB

Qualification

MTR

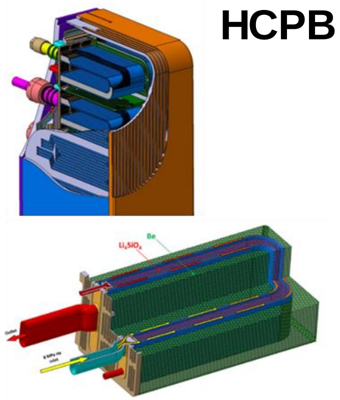
DONES

TBM

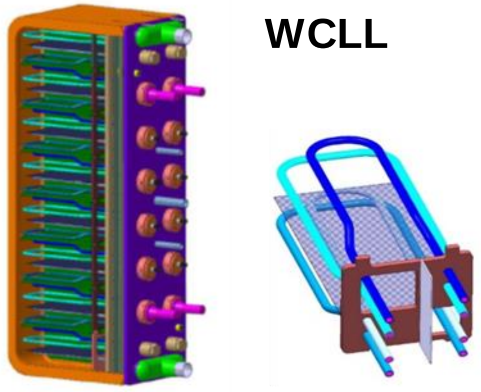
Non-Nuclear testing facilities

Characterization & codification of structural/functional materials

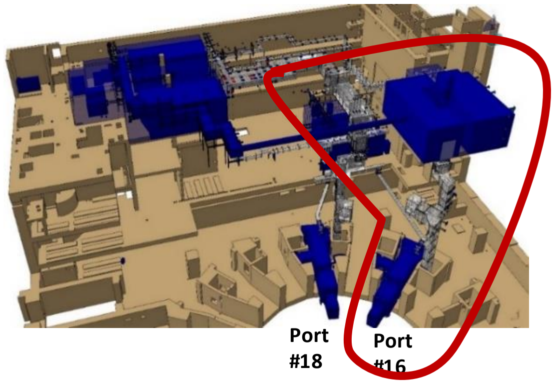
Validation up to 2 dpa of BB concepts in fusion env.



HCPB



WCLL



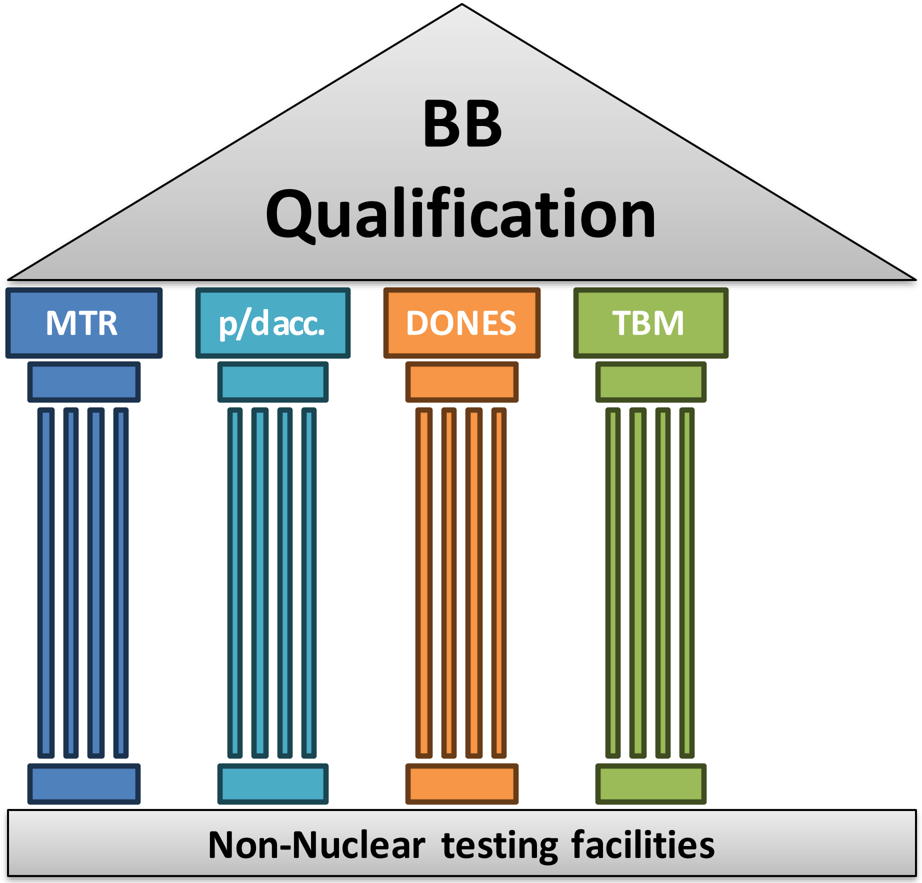
Regulatory & licensing aspects	Project Management	Design – TBM & Ancillary Systems	Safety aspects & Rad-waste	Manufacturing – TBM & Ancillary Systems	Operation at ITER & Maintenance	R&D
First Licensing process on specific issues (materials, technologies and safety provision)	System engineering	ESP(N) equipment	Safety dem. & approach	Non-conv. fusion welding (laser, TIG, EB) & diffusion welding	Integrated, multi-physics testing	EUROFER97 development & qualification
Experience in Risk/hazard analysis on components & material	Requirement management and verification	Just. of code referential (RCC-MRx sections)	Ident. of Protec. Imp. Act. (PIA)	High-precision machining	Oper. verif. of techn. feasibility	Thermo-mechanics of pebble beds
Conformity evaluation procedures (e.g. inspectability, traceability,...)	Integration and interface management	Performance optimization	Det. & Class. of accidental events	Lessons learnt in distortions control	Val. of neutr. and T breeding prediction	Solid/PbLi Breeder development
	QA and QC	Operational domain/optimisation	Accidental analyses	Manufacturing tech. standardization & qualification	Validation of the modelling tools predictions	Be-based neutr. multiplier development
	Procurement strategy	Integration of sensors/instr.	Tritium management	Acceptance tests	In-service inspections	Irradiations for CB and Beryllium
	Cost weighting factors	Nuclear maintenance plan, ORE	Concept of Instr. & Contr. (I&C) for safety func. impl.		Maintenance plans for TBS sub-systems	Tritium extraction from Purge Gas&PbLi
			Radioactive inventory and waste		Validation of maint. strategy	…

P6B1: Italo Ricapito

P6C5: Carlos Ortiz Ferrer

PL 11: Luciano Giancarli **P5D4: Alberto Previti**

Additional BB nucl. qual. options



BB Qualification

MTR | **p/dacc.** | **DONES** | **TBM**

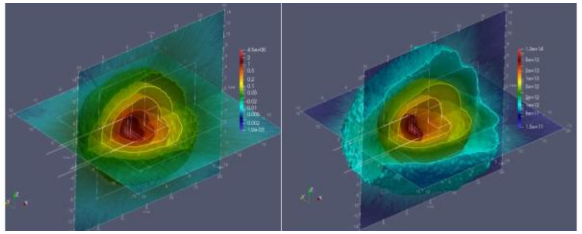
Non-Nuclear testing facilities

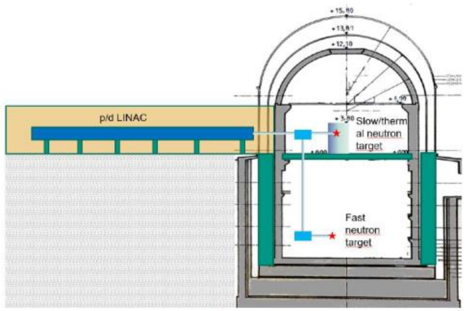
Characterization & codification of structural/functional materials

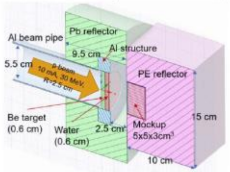
Validation up to 2 dpa of BB concepts in fusion env.

p/d Accelerator-based Neutron Sources:

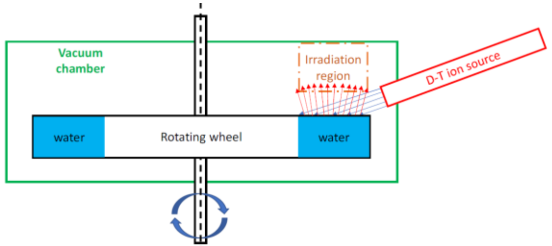
- Available or available in 5 years (estimated)
- Functional material specimen irradiation
- Φ between 1E5 – 1E13 n/cm²/s
- up to 0.1-5 dpa/fpy (V few liters)







p/d-LINAC

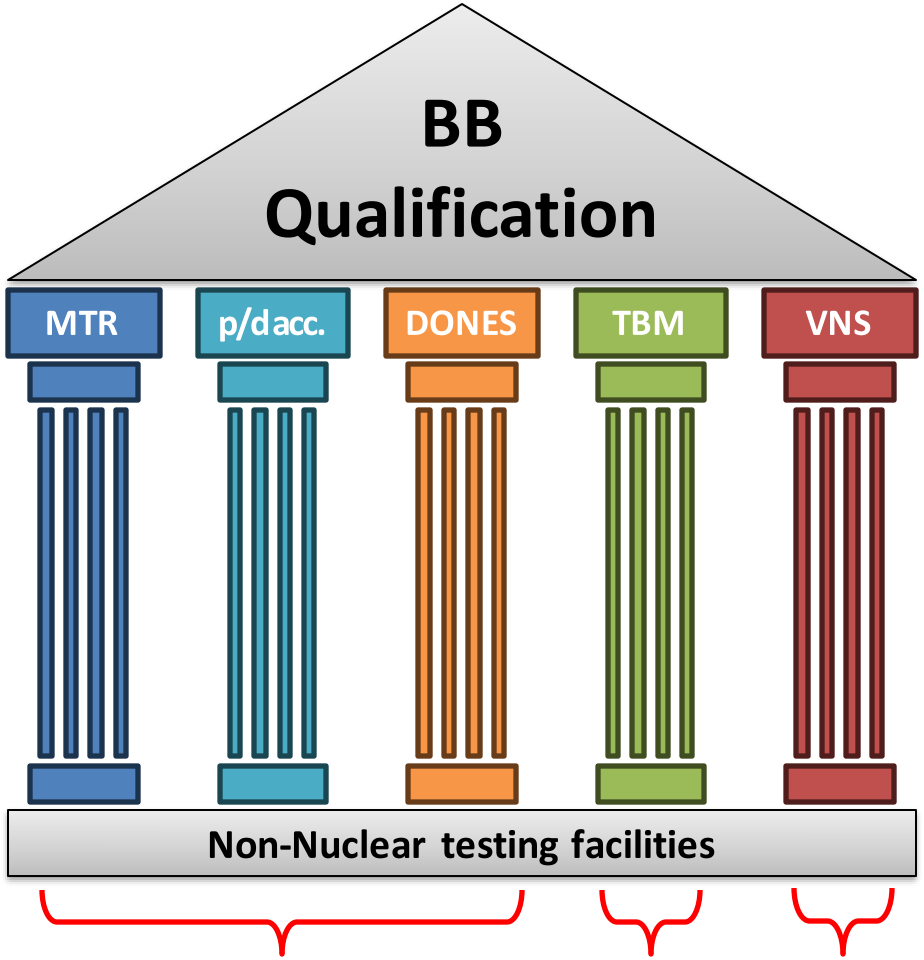


New Sorgentina Fusion Source (NSFS)

CANS	Status	Beam performance	Neutron performance	Applications
CPHS, Bejing	In operation	13 MeV p, 50 mA (peak), 1.25 mA (av.), 2.5 % duty cycle	5×10^{13} n/s	Imaging, SANS, detector R&D
HUNS, Hokkaido	In operation	35 MeV e, 30 μA	1.6×10^{12} n/s	Radiation effects, imaging, SANS, …
KUANA, Kyoto	In operation	3.5 MeV p, 10 mA (peak)	1×10^{11} n/s	
RANS, Riken	In operation	7 MeV p, 10 mA (peak), 100 μA (av.)	1×10^{12} n/s	Imaging, industrial applications
ESS-Bilbao	Projected	50 MeV p, 2.25 mA (av), 115 kW, 3 % duty cycle	1×10^{15} n/s	SANS, moderator testing
LENOS, Legnaro	Projected	5 MeV, 50 mA CW	Up to 1×10^{15} n/s	Nuclear astrophysics, nuclear data etc.
NOVA-ERA, Jülich	Design Study	10 MeV p, 1 mA (peak), 4 % duty cycle, 400 W	3×10^{13} n/s Up to 1×10 n/cm²/s	Multipurpose
HBS, Jülich	Projected	50 MeV p, 100 mA (peak), 100 kW, 4.3 % duty cycle	1×10^{17} n/s (burst), 4.3×10^{15} n/s (av.)	Multipurpose
SONATE, Saclay	Projected	20 MeV, 100 mA (peak), 2-4 % duty cycle	Up to 5×10^{8} n/cm²/s (thermal)	Material science studies
SORGENTINA-RF	In construction	250 keV d/t, 466 mA (per beam)	Up to 7×10^{13} n/s	Medical isotope production
SORGENTINA-BMT	Projected	300 keV d/t, 7 A (per beam)	Ca. 4×10^{15} n/s, ca. 3×10^{13} n/cm²/s	Fusion material research

D. Leichtle, A. Klix, Y. Qiu, Report Annex 4.3 - Characterization of p/d Accelerator-based Neutron Sources

Additional BB nucl. qual. options



Characterization & codification of structural/functional materials

Validation up to 2 dpa of BB concepts in fusion env.

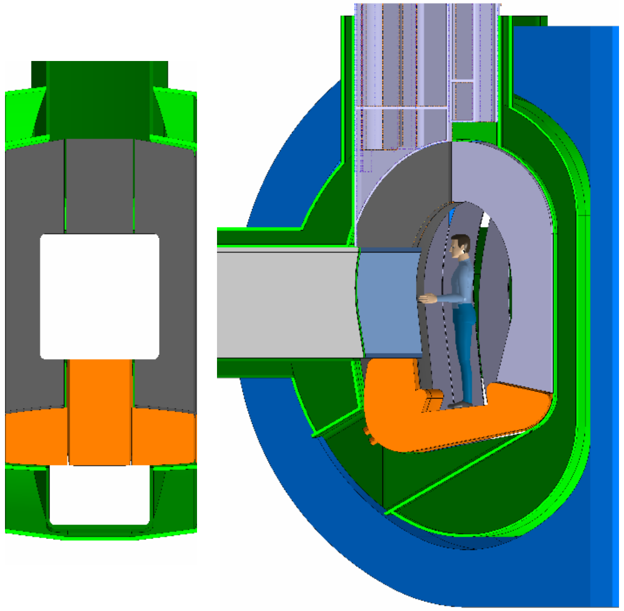
Full validation up to 20 dpa of BB concepts in fusion env.

Volumetric Neutron Source (VNS):

- available in 15 years (estimated)
- suitable for module and sector testing
- $\Phi < 1E15$ n/cm^2/s
- 4-6 dpa/fpy (V from 0.8 m^3 to tens of m^3)

Conduct irradiation tests aiming at:

1. establishing acceptable blanket performance in particular with regard to effectiveness of the tritium breeding and extraction function;
2. exploring coupled phenomena and unexpected synergistic effects in a fusion environment;
3. correcting potential design/ material choice faults;
4. identifying early life failure mode and rates;
5. collecting useful information on safety, licensing and waste management
6. qualifying components whose design and technology shall be relevant for DEMO with moderate extrapolations only.



Conclusion

- The BB and its ancillaries are complicated systems that have never been built and tested in a relevant environment;
- In most cases, the technologies used are the first of a kind;
- A reinforcement of the R&D program to address the BB issues has to be pursued with urgency;
- It is imperative to prioritize the nuclear qualification of the BB;
- Indeed, there is a significant demand for neutron irradiations to make well-informed design decisions;
- The assessment of neutronic responses (e.g., activation and tritium production) can be carried out in currently accessible Materials Test Reactors or, in the future, in p/D accelerators and IFMIF/DONES, although there are limitations due to the different spectra and limited volume available for testing;
- To assess multiple/integrated effects, larger volumes (i.e. prototypes) are needed on short time scales. For the moment, only the TBM might address this point. A VNS may complement and reinforce these assessments;
- With the successful establishment of this nuclear R&D program (e.g. MTR, p/D accelerator, IFMIF-DONES, ITER with TBM RoX, and a VNS), the next fusion device (i.e. DEMO) could potentially serve as a prototype power plant;
- The effective execution of this strategy would mitigate the risks linked to a future power plant, especially concerning blanket availability and performance, but also other crucial matters related to the fuel cycle and safety.

Thank You For Your Attention

Any Questions?

FAIRNESS

Transparency
Collaboration
Loyalty

OPENNESS

Open doors
Open hearts
Open minds
Open ears

COMMITMENT

Ownership
Critical thinking
Determination
Respect

DIVERSITY

Cooperation
Equal opportunities
Inclusion

Suggested talks

P1A1: Guangming Zhou - Overview of the design activities of the EU DEMO Helium Cooled Pebble Bed breeding blanket

P1A3: Thomas R. Barrett - Preparing for the First Integrated Test of a Fusion Breeding Blanket Prototype in the CHIMERA Facility

P1A4: Anoop Retheesh - Structural Integrity Assessment of the Central Outboard Segment of the EU DEMO HCPB Breeding Blanket

PL 2: Gianfranco Federici - DEMO-Related Design Activities in Europe

P2A1: Salvatore D'Amico - Breeding blanket challenges and needs for technology qualification: ongoing R&D efforts and open fields on relevant nuclear testing data

P2A4: Nicola Fonnesu - Measurement of tritium production in the HCPB TBM mock-up at JET during DTE2

P2B1: Alexander V. Müller - Additive manufacturing techniques for the fabrication of tungsten-based plasma-facing components

P2D1: Barry Buttler - Tritium related challenges to be overcome in order to deliver fusion power plants

P3A2: Francisco Hernández - Alternative water-cooled breeding blanket concepts for the EU DEMO: Overview on studies and perspectives

P3A5: James Dark - Multiphysics tritium transport modelling in WCLL breeding blankets: Influence of MHD effects and neutron damage

P3B3: Dieter Leichtle - Radiological protection design considerations for DEMO

P3B5: Yuefeng Qiu - Overview of recent advancements in IFMIF-DONES neutronics activities

P3C3: Elisabetta Carella - Coatings: challenges of Tritium Permeation Barriers in fusion reactors context

P3D1: Oliver Crofts - Overview of progress towards more maintainable architectures for fusion devices

P3D2: Hongtao Pan - Breeding Blanket Remote Handling System for CFETR and EU-DEMO

P4A4: Jarir Aktaa - Embrittlement of WCLL Blanket and Its Fracture Mechanical Assessment

P4D1: Leo Bühler - Liquid metal MHD research at KIT: fundamental phenomena and flows in complex blanket geometries

P4D5: Sara Pérez-Martín - The scaling methodology applied for designing HELOKA-US facility, the EU-DEMO HCPB BOP mock-up

PL 8: Joëlle Elbez-Uzan - Safety approach for future fusion power plant

PL 10: Ángel Ibarra - Overview of IFMIF-DONES: an irradiation facility relevant for fusion materials

P5B4: Beatriz Brañas - TRL analysis of IFMIF-DONES and Overview of the required validation needs

P5B5: Axel Klix - Fusion neutronics experiments utilizing the intense DT neutron generator of Technical University of Dresden

P5C3: María González - Towards the down-selection of ceramic materials for the European High Temperature DCLL BB concept based on Single Module Segments (SMS)

P5D1: Mark Gilbert - Fusion waste requirements for tritium control: perspectives and current research

P5D4: Alberto Previti - Parametric assessment of the Activated Corrosion Products on the ITER Water Cooled Lithium Lead Test Blanket System

P6A4: María Lorena Richiusa - The Integrated Engineering Design Concept of the Upper Limiter within the EU-DEMO LIMITER System

P6B1: Italo Ricapito - Tritium Transport Modelling: Current status, open points and perspectives

P6B5: Jonas Caspar Schwenzer - Tritium inventory evolution modelling for demonstration and future fusion power plants

P6C1: Christian Bachmann - Relevance of a high magnetic field to the design of the EU DEMO

P6C5: Carlos Ortiz Ferrer - The Lead Lithium Loop for the European Water-Cooled Test Blanket System (WCLL-TBS)

KN 4: Ambrogio Fasoli - Recent Progress and Plans in the EUROfusion Program

PL 11: Luciano Giancarli - Status of the ITER TBM Program and overview of its technical objectives

Issues related to the BB

Low reliability & availability

- The DEMO targets are:
  - <u>Operational Availability (OA)</u>, as the proportion of time the system is running with respect to the total system lifetime

    OA = ∑ Up times / Total time = 30% (i.e. 7430 h / 24768 h)

  - <u>Inherent Availability (IA)</u>, as the proportion of time the system is running with respect to the time the system is running plus the time the system is shut down due to failures (time for corrective maintenance)

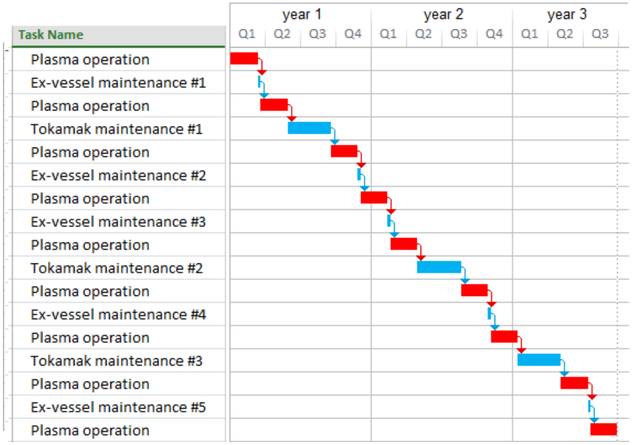
    IA = ∑ Up times / (Total time – PM Time) = 48% (i.e. 7430 h / (24768 h – 9144 h))

- The BB system affect largely the DEMO availability targets → large number of components that can fail.

- The most critical components of the breeding blanket are the welds sealing against in-box coolant leak and the welds sealing against the in-VV coolant leak.

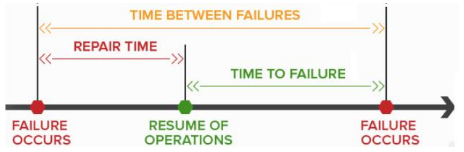
	HCPB	WCLL	WCLL-db (opt)	WCLL-db (cons)	WLCB
Welds in BB sealing against in-box coolant leak	~ 416016	~427712	~99248	~198496	~17312 (Cooling Plate)

Ideal sequence of plasma operation and scheduled maintenance periods during the first DEMO operating phase



In the 3 years of the first operating phase:

Plasma operation	15,624 h
Preventive maintenance	9,144 h
Total	24,768 h



T. Pinna, et al., Approach in improving reliability of DEMO, Fusion Engineering and Design, Volume 161, 2020, 111937, doi.org/10.1016/j.fusengdes.2020.111937.

Breeding blanket qualification needs

1) Heat Transfer Experiments

Testing Scenario:

- Utilize small blanket unit cells as test assemblies to address heat transfer issues.
- Focus on empirically studying heat transfer within realistic breeder blanket (BB) geometries.
- Consider the possibility of multi-cell experiments, especially when conducted alongside tritium recovery experiments.
- Evaluate the long-term performance of the assembly, considering both MOL (Middle of Life) and EOL (End of Life) conditions.

Reproduction of Conditions:

- Neutrons are crucial for bulk heating and radiation effects on heat transfer.
- Replicate the exact geometry, including breeder microstructure and surface roughness.
- Match mechanical boundary stress, coolant and tritium carrier temperature, pressure, velocity, power density, and t carrier chemistry to reproduce required environmental conditions.

2) Breeder/Structure Thermo-Mechanical Interactions

First Set of Tests (BOL - Beginning of Life):

- Measure temperature changes.
- Assess stress levels.
- Conduct post-test examination for gap size analysis, detection of cracks, evaluation of sintering or settling, examination of swelling, other changes).

Second Set of Tests (MOL/EOL - Middle of Life/End of Life):

- Account for radiation-induced thermal conductivity changes.
- Study the impact of radiation on temperature profiles.
- Analyze swelling, radiation-induced creep, and sintering, among other effects.

Reproduction of Conditions:

- Replicate temperature conditions.
- Emulate coolant and purge pressure.
- Neutrons are crucial to recreate bulk heating conditions and irradiation effects.
- Replicate BB geometry.
- Simulate cycling using a BB submodule.

3) Neutronics Prediction Validation

Testing Scenario:

- Confirm predictions for tritium breeding and nuclear heating.
- Verify predictions for induced activation.
- Multiple tests may be required to achieve the necessary accuracy.

Post-Test Examinations:

- Measure activation levels.
- Assess tritium inventory.
- Determine neutron fluence.

Reproduction of Conditions:

- Use of fusion spectra in the testing process.
- Replicate similar geometries with mock-ups.
- Emulate the local neutron field.

4) Tritium Permeation

Testing Scenario:

- Assess tritium permeation rates into the coolant.
- Perform tests under actual geometry and operating conditions.
- Measure tritium activity within the tritium carrier.
- Monitor pressure variations in the system.
- Analyze the tritium form.
- Evaluate the surface conditions of the clad material.
- Utilize Post-Irradiation Examination (PIE) techniques to determine surface conditions.

Reproduction of Conditions:

- Use neutrons to provide the tritium and heat source distribution.
- Replicate breeder temperature conditions.
- Emulate coolant conditions.

5) Tritium behavior in thermal and flow transients

Testing Scenario:

- Examine the behavior of tritium inventory within breeder unit cells.
- Investigate tritium responses under thermal or flow transient conditions.
- Measure the temperatures of both the breeder material and coolant.
- Monitor activity levels in the coolant and tritium carrier.
- Conduct post-test examinations to assess tritium inventory, cracking or other changes.

Reproduction of Conditions:

- Emulate coolant conditions, including flow and temperature.
- Match tritium carrier conditions, including temperature, tritium partial pressure, and impurities.
- Maintain a similar geometry for the testing setup.

Increased size of the testing

M. A. Abdou, et al, (1984) FINESSE: A Study of the Issues, Experiments and Facilities for Fusion Nuclear Technology Research and Development, UCLA-ENG--84-30-Vol.2, https://doi.org/10.2172/5507921

Breeding blanket qualification needs

6) Submodule Thermomechanical Verification

Testing Scenario:

- Validate the thermomechanical design through testing.
- Subject a section of a sub-module to stress conditions similar to those encountered in an operating blanket.
- Measure temperature variations within the module.
- Assess stress levels experienced by the module.
- Conduct post-test examination for signs of cracks, deformation, any other visible changes in the module's structure.

Reproduction of Conditions:

- Employ neutrons as a source of heating and to induce specific reactions within the module (i.e. material damage).
- Replicate temperature gradients.
- Emulate other loads (e.g. pressure, EM, etc.)

7) Full-Module Thermal and Corrosion Testing

- BOL Performance Testing:

- Address uncertainties stemming from unexpected design-specific synergies.
- Deal with challenges related to the poor modeling of precise module geometry.

- MOL Performance Testing:

- Account for the extended operation of the blanket.
- Address uncertainties arising from nuclear and non-nuclear effects during prolonged operation.

- EOL Performance Testing:

- Determine which effects are likely to be life-limiting for the blanket in its end-of-life phase.

Reproduction of Conditions:

- Fusion spectrum is critical to replicate the appropriate conditions.
- Ensure that all other environmental aspects are present during testing.

8) Blanket Response to Coolant Transients

Testing Scenario:

- Simulate critical incidents to assess the module's response under adverse conditions.
- Subject a full or almost full module to scenarios involving loss of flow or loss of coolant.
- Measure temperature variations within the module.
- Monitor stress levels experienced by the module.
- Record coolant pressure and flow rate during the scenario.
- Conduct a thorough examination of the module after the scenario.
- Look for any signs of deformation or failure in the module's structure.

Reproduction of Conditions:

- Neutrons play a crucial role in simulating volumetric heat generation rates in a fusion reactor.
- Implement a magnetic field to accurately simulate system transients during the testing process.
- Ensure that all other environmental aspects are present during testing.

9) Tritium Recovery Assessment

Testing Scenario:

- Conduct in-situ tritium activity measurements in tritium carrier and coolant streams.
- Perform post-test tritium assays to determine the location and magnitude of the tritium inventory.

Reproduction of Conditions:

- Neutrons play a crucial role in producing tritium, inducing damage and swelling in solid breeder materials and structures, generating heat within the blanket module.
- The fusion spectrum is highly important for integrated testing.
- Ensure that all other environmental aspects are present (tritium transport mechanisms, coolant flow, temperatures, etc.).

10) Module Lifetime Verification

Testing Scenario:

- Conduct comprehensive tests on the full module.
- Focus on identifying structural failure modes.
- Measure local temperatures and stresses within the module.
- After testing, perform a thorough post-test examination to determine the root causes of any observed failures or issues.

Reproduction of Conditions:

- Neutrons are vital because they serve as a heating source, induce specific reactions within the module and cause significant damage, affecting structural integrity.
- Reproduce similar temperature gradients and stress fields.
- Ensure the neutron spectrum is accurately tuned.
- Include surface heat flux in testing.
- Reproduce plasma interactions in the testing environment.

Increased size of the testing

M. A. Abdou, et al, (1984) FINESSE: A Study of the Issues, Experiments and Facilities for Fusion Nuclear Technology Research and Development, UCLA-ENG--84-30-Vol.2, https://doi.org/10.2172/5507921