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Fusion Pilot Plant Working Group

The TRL approach and the role of different nuclear facilities for the qualification of the BB

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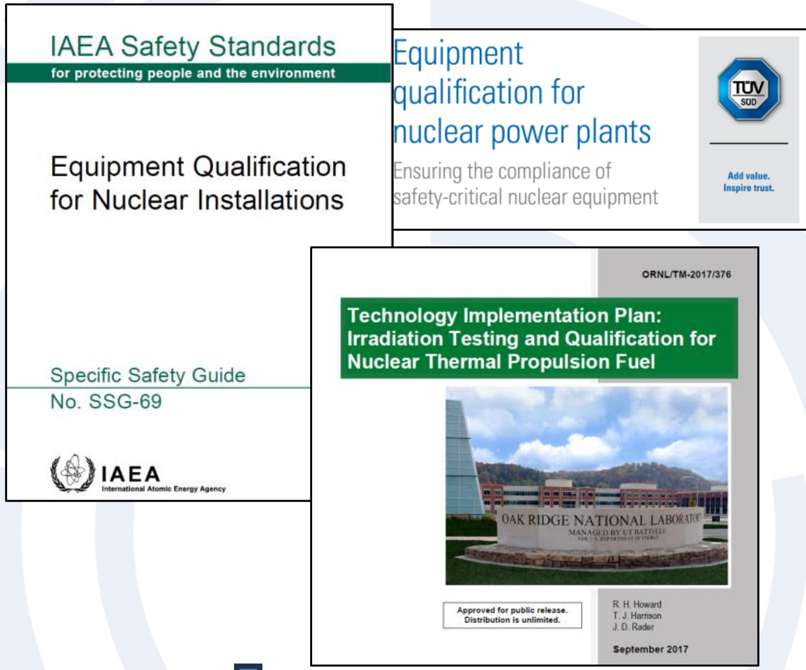
This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

What does it mean to qualify the Breeding Blanket ?

- Component qualification is **an established and codified process in the fission industry**: it involves proving that it performs safely and reliably under all expected conditions.



<u>When this process is applied to the BB, it implies proving:</u>

- **Tritium Breeding Performance**
  Demonstrate TBR ≥ 1 through realistic testing of tritium production, extraction, inventory, and control systems.
- **Irradiation Tolerance**
  Ensure structural and functional materials withstand high-energy neutron exposure without unacceptable degradation (e.g. dpa, swelling, transmutation effects).
- **Thermal & Mechanical Stability**
  Prove heat removal efficiency and structural integrity under thermal cycling, gradients and MHD/electromagnetic loads.
- **System Integration**
  Validate supporting systems: coolant loops, tritium handling, control, diagnostics and related safety functions.
- **Lifetime Performance**
  Demonstrate long-term reliability, supported by failure statistics, ISI and maintenance strategy validation.
- **Safety & Licensing Compliance**
  Ensure safe operation under normal and off-normal conditions;
  Meet all regulatory standards for activation, shielding, and tritium containment.

WE KNOW <u>WHAT</u> TO DO, BUT <u>HOW</u> TO DO IT ?

Which approach for the nuclear qualification of the BB ?

- Fusion and the Breeder Blanket are **first-of-a-kind technologies**: the challenge is not designing or optimizing for known requirements, but dealing with the fundamental uncertainty of "**unknown unknowns**."

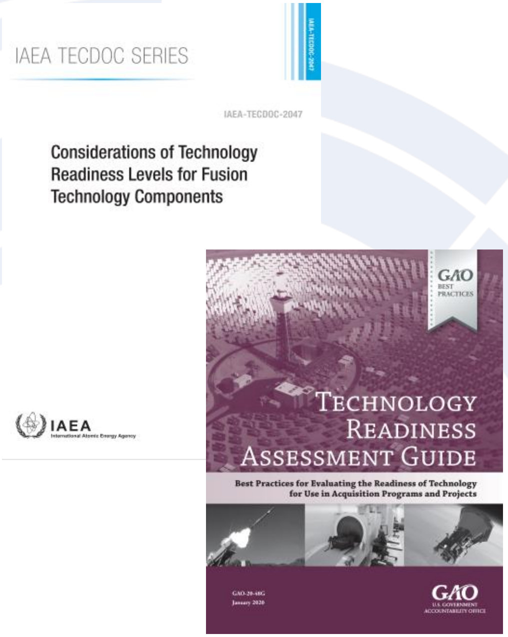
- Unknown unknowns emerge when **technologies are combined, scaled, or subjected to new operational environments** (e.g., high energy neutrons, high temperature thermal cycling, complex integration).

- **A staged, structured approach is the most appropriate** for FOAK technologies in order to:
  - Incrementally detect unexpected phenomena that do not manifest at smaller or partially integrated scales.
  - Validate hypotheses and models under increasingly realistic conditions.
  - Collect data, refine models, and feed lessons learned back into design before scaling up.
  - Gain confidence of regulators (but also investors and stakeholders) by systematically demonstrating the reliability and safety of the technology before full-scale deployment

A staged approach is not only critical for the development of FOAK technologies but also a strategy to systematically expose unforeseen issues at a level where corrective actions can still be managed

The TRL methodology as an established industrial tool

- We adopted **the Technology Readiness Level (TRL) methodology** because:
  - **It defines a structured approach to technology development**
    Provides a clear, stepwise framework to assess technology maturity, revealing technology gaps between current status and readiness required for deployment.
  - **It improves stakeholder communication**
    Facilitates shared understanding and dialogue between scientists, engineers, program managers and regulators.
  - **It allows risk-based planning and infrastructure development**
    Identifies at-risk technologies needing more R&D, align testing needs with suitable facilities to mitigate risks.
  - **It enables strategic roadmapping and investment focus**
    Guides R&D priorities by linking readiness levels to development milestones and supporting justification of resource allocation.



TRL	Definition	Scale of testing	Fidelity	Environment
1	Basic principles observed and reported	-	Paper	-
2	Technology concept and/or application formulated	-	Paper	-
3	Analytical and experimental critical function and/or characteristic proof of concept	Lab	Pieces	Simulated
4	Component and/or breadboard validation in laboratory environment	Lab	Pieces	Simulated
5	Component and/or breadboard validation in relevant environment	Lab/Bench	Similar	Relevant
6	System/subsystem model or prototype demonstration in a relevant environment	Engineering/ Pilot scale	Similar	Relevant
7	System prototype demonstration in an operational environment	Full	Similar	Operational (limited range)
8	Actual system completed and qualified through test and demonstration	Full	Identical	Operational (limited range)
9	Actual system proven through successful mission operations	Full	Identical	Operational (full range)

Present BB TRL level (TRL 4)

The TRL scale defines increasing levels of system integration and environmental relevance, but these terms must be defined for each specific technology.

Increasing the Nuclear TRL towards qualification of the BB

- Qualitative and quantitative estimations on **testing requirements** for the BB have been collected from literature
- They have been consolidated to **associate each type of testing and the related goals to a corresponding (N)TRL level**

NTRL	Type of tests	Testing goals	Required Environmental Conditions	Test-object type & Fluences
4	- Small-scale testing of BB functional materials (T-breeding, n-multipliers) - Tritium production and retention tests. - Neutronic validation of damage, activation and heat production cross sections.	- Estimate expected performances (T-production, T-release rates, n-induced material degradation) - Assess material compatibility with tritium. - Assess initial radiation effects on thermo-physical and mechanical properties of functional materials at Start of Life.	-Single-effect testing, basic phenomenon + one environmental effect - Fusion relevant neutron energies not mandatory - Operational temperature range - Simulated thermal gradients and mechanical loads.	- Material samples (~10s cm^3) or elementary mock-ups (~100s cm^3). - Neutron fluence: 1-50 dpa in fission n-flux 0.1-1 dpa in fast n-flux
5	- Medium scale tests of sub-components under thermo-mechanical loadings. - Tritium permeation and extraction efficiency tests. - Empirical study of heat and mass transfer within realistic BB geometries.	- Confirm expected material performances (tritium extraction efficiency, retention and inventory management). - Assess effects of MHD flows on heat and mass transfer (corrosion, tritium transport). -Assess effect of radiation-induced changes on structural integrity and functional stability of breeder and multiplier materials at beginning of life.	- Multiple-effects testing, two or more concurrent environmental effects. - Fusion relevant n-spectrum. - Realistic temperature gradients and mechanical loads. - Thermal cycling. - Simulated liquid breeder or T-carrier flow. - Surface heat loads. - Stationary magnetic fields (>3 Tesla desirable for MHD characterization).	- Mock-up components (~1000s of cm^3), designed to replicate specific physical effects or operational parameters ("act-alike") - Neutron fluence: 0.1-3 dpa (fusion relevant n-flux).
6	- Partially integrated testing of representative BB mock-ups demonstrating simultaneous thermo-mechanical, nuclear and chemical interactions under fusion-relevant neutron irradiation. - "Proof-of-technology" testing to demonstrate the BB functions with all significant effects simultaneously.	- Confirm full-function tritium extraction and inventory management. - Confirm heat-extraction performance within design margins. - Confirm structural integrity under cyclic loading. - Demonstrate control of corrosion and activation of materials - Demonstrate control of tritium inventories in materials	- Integrated testing, all significant environmental effects for the studied phenomena. - Fusion relevant n-spectrum, representative spectrum shape and intensity. - High-temperature and high-pressure coolant flow. - Replicated liquid breeder or T-carrier flow. - Thermo-mechanical cycling under vacuum and plasma heat loads. - Spatially and time-dependent magnetic fields. - Relevant chemistry for all fluids.	- Prototype modules (~10000 of cm^3), designed to replicate as much as possible the final geometry of the components ("look-alike") - Neutron fluence: 3-5 dpa. (fusion relevant n-flux)
7	- BB module connected to all auxiliary systems in nominal conditions, testing in operational FPP-like environment	- Detect early failures in operational environment at intermediate fluences - Validate tritum self-sufficiency (TBR>1). - Validation of modelling tools used for design - Validate integrated operation of auxiliary systems - Integration and operation of diagnostics. - Validate corrosion laws for ACP calculations	- Operational environment, limited range of loads	- "Test Blanket Modules", fully representative of BB geometries (~m^3). - Neutron fluence: 5-10 dpa
8	- BB Segment integrated into FPP prototype plant.	- Qualification of C&S for DEMO design. - Qualification of Manufacturing and Assembly techniques - Qualification of performances of BB systems under normal and off-normal operation - Qualification of Diagnostics&Control - Qualification of Remote Handling and In-Service Inspection techniques - Qualification of ACP codes and radioactive source terms - Collection of statistical data on failure modes and related frequencies for lifetime evaluation - Qualification of models for extrapolation to end of life conditions	- Prototypical FPP operational conditions, covering a representative range of normal and off-normal operational scenarios.	- Full BB segments (10s of m^3) - Neutron fluence: 10-50 dpa

Screening of Nuclear Fusion Facilities

- The capabilities of existing and planned and proposed Nuclear Fusion Facilities (DONES, ITER, VNS, DEMO) were **collected and matched to each TRL testing requirements.**

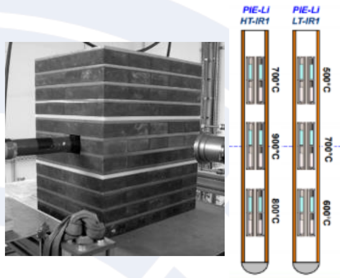
Neutron fluence is not the only factor

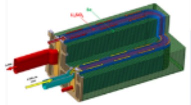
FACILITY	PARAMETER OF INTEREST										
	Max. n-flux @FW ($n.cm^{-2}.s^{-1}$)	Avg. n-flux @FW ($n.cm^{-2}.s^{-1}$)	Max. NWL @FW (MW/m^2)	Max. Availability	Fluence	Test area (XxY cm^2)	Test Volume m^3 (x test objs.)	Heat flux @FW (MW/m^2)	Magnetic field (Tesla)	Integration of aux. systems	Integration of Instrumentation & Control
Fission MTRs	1E+15	(1-5)E+14	N/A	>50%	3-10 dpa/y	8x70	3-5	N/A	N/A	Specific to testing objectives	Specific to testing objectives
DONES MFTM 1-Beam	8.30E+13	3.48E+13	0.3	70%	Max ~3 dpa/fpy	40x40	0.096 (x1)	N/A	N/A	Possible	Possible
ITER DT1	3.21E+14	N/A	0.75	N/A	0.02-0.03 (@EOL)	46x167	0.53 (x2)	0.32	~3.8	Included (not full performance)	Tailored to TBM testing goals
ITER DT2	3.21E+14	N/A	0.75	N/A	2-3 (@ EOL)	46x167	0.53 (x2)	0.32	~3.8	Included (not full performance)	Tailored to TBM testing goals
VNS TBM	1.10E+14	9.80E+13	0.5	40%	~5dpa/fpy	106x111	0.7 (x4)	~0.2	~4.5	Mandatory	Tailored to TBM testing goals
VNS Segment	1.10E+14	9.80E+13	0.5	40%	Max ~5dpa/fpy Avg. ~3dpa/fpy	178x49	0.52 (x12)	~0.2	~4.5	Mandatory	Operational
DEMO Segment	6.10E+14	5.37E+14	1.1	30%	Max. 10.6 dpa/fpy Avg. 8.8 dpa/fpy	1245x160	173 (x80)	~0.3	~3.7	Mandatory	Operational

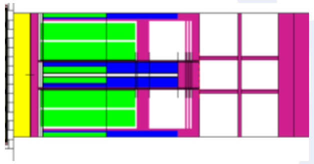
- ***For DONES, we considered the Middle Flux Test Module, located behind the High Flux Test Module where material specimens will be irradiated.***
- ***For the ITER-TBM, we considered separately the DT-1 and DT-2 ITER phases. Feasibility of the DT-2 phase is for the moment assumed but not confirmed.***
- ***For VNS, we considered the present (proposed) VNS design as developed in EUROfusion. The concept of a "Pilot Plant" has recently emerged in EU with similar objectives, but its requirements and design parameters are still under discussion.***

NTRL 4-5: early-stage phenomenological and functional validation

REQUIREMENTS	GOALS	BOUNDARIES
NTRL 4 – single effects experiment ➔Lab scale experiments ➔Pieces or sub-components ➔**Simulated environment** (14MeV-n optional)	Determine tritium production [illegible] for fusion-relevant degradation phenomena MATERIAL PROPERTIES	High fluence in fission spectrum (50-80 dpa) Low fluence in spallation sources (~1 dpa) No Integration of aux. systems
NTRL 5 – multi effects experiment ➔Lab scale/test-bench experiments ➔Elementary mock-ups ➔**Relevant environment** (14MeV-n mandatory)	Study tritium extraction processes and efficiency Assess structural integrity under thermal cycling and neutron irradiation MATERIAL PERFORMANCES	Low fluences to study initial degradation effects (1-3 dpa) Limited integration of auxiliary systems to reproduce gradients







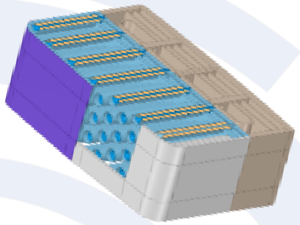
- **MTRs have been and can still be used to achieve TRL 4.** Spallation sources can be used to study effects of high energy neutrons.
- **ITER TBMs can achieve TRL 5, assuming the full scope of the DT2 phase is implemented.**
- **In the absence of DT2, DONES becomes essential to achieve TRL 5.** Its high fluence rates enable rapid irradiation of materials and screening of different BB configurations.
- Due to the lack of full environmental effects (no thermo-mechanical cycling, no MHD effects), **a combination of results from TBM in ITER-DT1 and DONES can be used to achieve the full scope of TRL 5.**

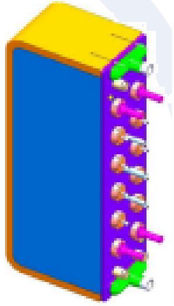
NTRL 6-7: system integration, optimization and lifetime performance

REQUIREMENTS	GOALS	BOUNDARIES
NTRL 6 – technology demonstration ➔Engineering scale ➔Fully functional **mock-ups** ➔Relevant environment (limited environmental factors and loads)	Validate integrated functions under combined loads Identify early failure modes based on environmentally coupled interactions	Low fluence to overcome rapid changes in material properties (3-5 dpa) Integration of specific auxiliary systems mandatory
NTRL 7 – system validation ➔Prototype scale ➔Fully integrated **system** ➔Operational environment (all environmental factors and loads)	Validate the performance of the selected BB concept Compare different design variants in terms of statistical variability and failure probabilities	Moderate fluence to confirm reliability of operation (5-10 dpa) All auxiliary systems connected and in operation

SYSTEM FUNCTIONS

SYSTEM PERFORMANCES





- **A combination of results from DONES and ITER DT-2 phase can achieve the full scope of TRL6.**
- Even with DT-2, ITER-TBMs cannot achieve the full scope of TRL 7 because of the low neutron fluence.
- Only a **VNS-TBM** program could achieve the full qualification goals for TRL 7, enabling prolonged irradiation with reactor-relevant fluences and loads
- A VNS offers greater flexibility, **accommodating up to four larger TBMs** versus ITER's two, enabling more testing volume and evaluation of alternative concepts.

NTRL-8: Final Qualification of Selected BB Concepts

NTRL 8 – system completed and qualified

- The requirement is to test **fully-representative, instrumented BB segments** over extended durations in a **reactor environment**.
- The testing could include tailored **modules designed for specific off-normal conditions** or critical failure modes, along with **integrated diagnostics, non-destructive evaluation, and inspection tools**.
- Neutron fluences should be high enough to **allow extrapolation to end-of-life degradation phenomena** (**10- >20 dpa**)
- The goal is to determine the full **In-service behavior** of materials and systems in an operational FPP environment

- Qualification of **C&S** in irradiated conditions (irradiation creep, creep-fatigue interaction, fatigue crack growth, swelling…).
- Qualification of representative manufacturing and assembly techniques.
- Collection of statistical data on failure modes/frequencies for reliability analyses.
- Effects of n-irradiation on breeder/multiplier materials (irradiation creep, swelling, T burn-up factor, dust formation…).
- Qualification of performances of auxiliary systems (T extraction).
- Check for long-term corrosion effects (IA-SCC, corrosion fatigue, thinning).
- Validation of ACP codes, activation of materials, tritium inventories and radioactive source terms.

- **No current or planned facility - including ITER - can accommodate these requirements.**
- A **VNS-Segment** program is the only feasible platform to achieve TRL 8.
- VNS provides the necessary combination of neutron fluence, test volume, control over test conditions, and capacity to run multiple segments in parallel to collect statistical data.

What are the potential consequences of “skipping” TRLs ?

- **Increased costs and delays**: failure at full-scale tests is vastly more expensive and time-consuming to redesign or modify components than if the issues were detected at smaller scales.
- **“Catastrophic” failures:** large-scale or integrated prototypes are more likely to suffer catastrophic failures because of the many interdependencies between different sub-system.
- **Regulatory and licensing challenges:** regulators require stepwise evidence of reliability, safety, and performance. Gaps in TRLs make it difficult to provide the necessary supporting documentation.
- **Missed “lessons learned” opportunities**: each TRL stage provides structured feedback and lessons learned. Missing stages means losing critical insights that could inform design improvements and risk mitigation strategies.
- **Exponential increase of risk**: risk is usually expressed as the product between the probability (P) and the impact (I) of failure (**R=P x I**). Skipping TRL increases P and the impact at high TRLs is much greater. The overall risk increases therefore non-linearly

The TRL approach is not only a technical framework to increase the likelihood of success but also a critical risk-management strategy, ensuring that "unknown unknowns" are identified and addressed at stages when the costs and consequences of corrections remain manageable.

Conclusions

- By systematically mapping testing requirements with facilities capabilities, we have identified a path to achieve **qualification of BB in a fusion nuclear environment** using the **TRL methodology.**

Facility	NTRL 4	NTRL 5	NTRL 6	NTRL 7	NTRL8
MTRs					
ITER-TBM / DT-1		A			
DONES		A	A		
ITER-TBM / DT-2			A		
VNS(*)-TBM			X		
VNS(*)-Segment					
DEMO – Phase 1					

(*) Or equivalent CTF/Pilot Plant based on a 14MeV VNS-like plasma neutron source.

- **MTR and spallation sources can achieve TRL 4,** providing early material and tritium data but cannot properly address the fusion-specific degradation modes.
- **ITER-TBMs, assuming full execution of the DT-2 phase, can achieve TRL 5.** Alternatively, DONES becomes essential to achieve TRL5 fluences, complemented by results from TBMs in ITER DT-1 phase
- **A combination of DONES and ITER-TBMs in DT-2 phase could be used to reach TRL 6.** DONES is limited by a lack of full fusion-relevant environment, but can provide high-fluence data.
- **A VNS-TBM program could also achieve TRL6 and is required to achieve TRL 7**, extending TBM testing under realistic neutron loads and longer durations, allowing performance **benchmarking across multiple blanket concepts.**
- **A VNS-Segment program is the only option to achieve TRL 8 before DEMO,** enabling full-scale, qualification of the final blanket system under**—essential to de-risk DEMO deployment.**

(Optimal) Facility requirements to achieve TRLs 7-8

- Provide an "operational environment", i.e. all the relevant loads, boundary conditions and operational states of a Fusion Power Plant.
- Reach sufficiently high neutron fluence to enter a phase of operational stability w.r.t. neutron degradation effects (>10, 20 dpa and more if possible)
- Decouple the tritium production function from tritium fueling for operation. Be "fault tolerant" w.r.t. the BB testing.
- Allow for (parallel) testing of different BB concepts for screening and downselection.
- Allow for testing of "fully representative" Blanket segments.
- Allow for integration and testing of instrumentation&control systems, ISI and remote maintenance and repair procedures.

… and a final consideration

- At the very beginning of the **nuclear fission industry**, the deployment of nuclear power plants **was supported by a network of research reactors**, of limited size and power but reproducing operating conditions in a reactor core.

- The development of fusion power has historically suffered from the **lack of facilities allowing for the testing of fusion technologies in a representative nuclear environment.**

- **A VNS offers a controlled, realistic, progressive and flexible path** to develop safe, reliable and efficient fusion reactors, mirroring the role that research reactors had in the development of nuclear fission technology.

With the VNS, we are following the same path that led to the successful deployment of nuclear fission reactors