DONES Users Workshop

EUROfusion material development and qualification roadmap for baseline and advanced materials for fusion in-vessel components

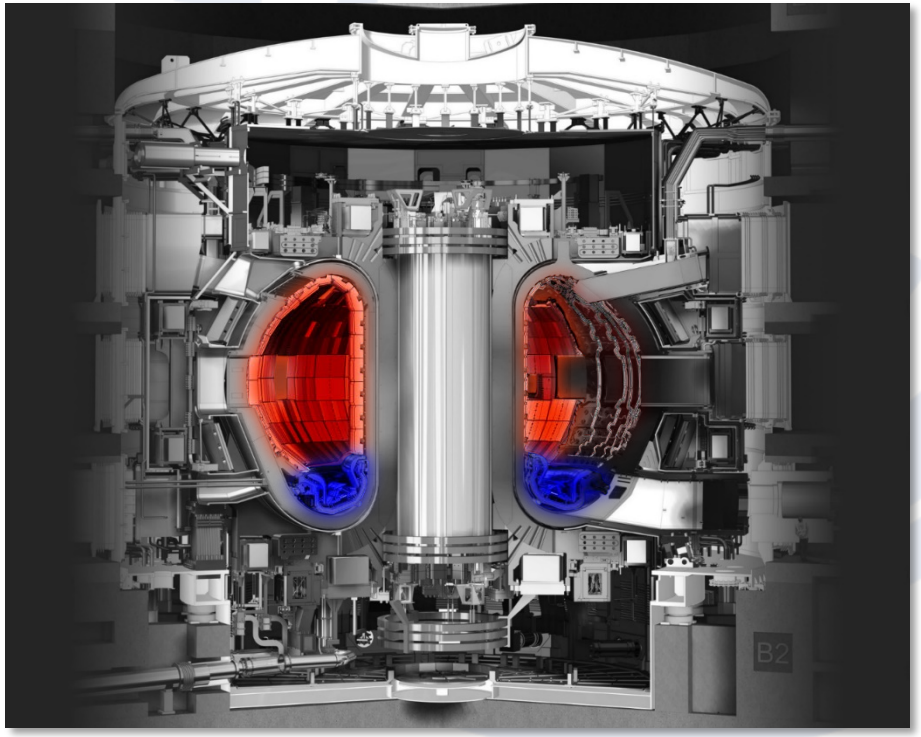
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European Fusion Roadmap: Mission 3, Neutron Tolerant Materials

- Characterization and qualification of the in-vessel **baseline materials EUROFER97, CuCrZr and tungsten**
- Development, characterization and qualification of **advanced structural and high heat flux materials for risk mitigation and enhanced performance**
- Characterization and qualification of **optical and dielectric functional materials** for application in diagnostics, heat and current drive systems and as insulators
- Qualified data for **material property handbook**, **design criteria for in-vessel components** and **material design limits** for fusion relevant operational conditions
- Material properties / system integrated material performance under fusion neutron irradiation / operational conditions in a Fusion Neutron Source (e.g. **IFMIF-DONES, VNS**)
- **Simulation of (fusion) neutron effects** on material microstructure and properties → **risk mitigation**
- System integrated **assessment of the materials readiness**



Material Technology Readiness Level (MTRL)

MTRL	Horizon 2020 definition
1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in **laboratory**
5	Technology validated in **relevant environment**
6	Technology demonstrated in **relevant environment**
7	System prototype demonstration in **operational environment**
8	System complete and qualified
9	Actual system proven in **operational environment**

EUROFER97: **4.9**
Tungsten & CuCrZr: **4.7**

Level 4 is the maximum that can be achieved without defining the related system and the operational conditions

→ ‘Fully integrated’ material testing

→ IFMIF/DONES + ITER + ...

→ Licensing & regulation

→ DEMO/FOAK FPP

More details see M. Richardson et al, J. Nucl. Mater. 550 (2021) 152906 (https://doi.org/10.1016/j.jnucmat.2021.152906)

Key challenge(s) in the roadmap for materials

- **Industrial upscaling and material manufacturing** → alternative production routes for large quantities, reproducibility and homogeneity of physical and mechanical properties
- **Generation and exploitation of material data** → limited availability of MTRs, waiting time for 14 MeV neutron source, systems' design and operating conditions still evolving, safety/licensing approach tbd

Main challenge: How to achieve MTRL 7- Qualification of materials in operational environment

- Facilities for the evaluation of **synergistic effects via sequential loading**
  - Mechanical and physical properties, corrosion effects, high heat flux performance and particle loads, ...
- **Lack of facilities** for the qualification of materials (incl. welds and components) **via simultaneous loading**
  - Combination of temperature / stress gradients and high neutron dose & neutron dose gradients on materials and components

On the road to MRTL 7

Database and MPH – EUROFER97 introduction to RCC-MRx

Non-irradiated/Base Metal	Test types	2020	2021	2022	2023	2024	2025	2026	Completion (%)
Immediate Plastic Flow Localization	Plain/Notched Tensile								100
	Plain/Notched 4 Points Bending								100
Ratcheting	Tension/Torsion Cyclic								40
Uniaxial Ratcheting	Stress-controlled Cyclic Uniaxial								100
Creep-Fatigue Interaction	Creep-Fatigue Cyclic Uniaxial								95
	Fatigue-Relaxation Cyclic Uniaxial								70
Sm after Cyclic Softening	Cyclic + Tensile Tests								100
Sigma d	CCT								15
Fatigue	Strain-controlled Cyclic Uniaxial								97
Fracture Toughness	Compact Tension (CT)								90
Creep	Tensile Creep								90
Fatigue Crack Growth	Cyclic CT								40

Irradiated/Base Metal	Test types	2020	2021	2022	2023	2024	2025	2026	Completion (%)
Immediate Plastic Flow Localization	Plain/Notched Tension								100
	Plain/Notched 4 Points Bending								100
Tensile Properties	Cylindrical Tensile								60
Irradiation Creep	Creep pipes								100
Fracture Toughness	CT and Disk CT								60

Investigation of TIG-welds just started 2026

- Non-irradiated: tensile, LCF, fracture toughness, creep
- Irradiated: tensile, fracture toughness

Database and MPH – EUROFER97

Material qualification issues

- Definition of manufacturing acceptance criteria to guarantee **homogeneity**, **reproducibility** and **impurity content**
  - → Can this be obtained at large scale (>100 t) or only smaller heat production?
- **Neutron irradiation data** & **H/He transmutation effects** (IFMIF/DONES)

Campaign	Irradiation facility	Materials & parameters
PIE of EUROFER97	HFIR, ORNL	EUROFER97/2 20 dpa @ 220 / 250 / 300 / 350 °C
High-dose irradiation in BOR60 and PIE	BOR-60, RIAR	EUROFER97/3 and welds, F82H, adv. steels 8-10 (welds) / 20 / 40 dpa @ 330 / 550 °C
Irradiation and PIE of isotopic tailored EUROFER	HFIR, ORNL	^{54}Fe and $^{58/60}$Ni doped EUROFER97 12-15 / 25-35 dpa @ 300 / 400 / 500 °C

- Development of fusion-specific material test standards → **Small Specimen Test Techniques (SSTT)**
- Material data (non-irradiated and irradiated) on **welds** → strongly related to design (**system TRL**)
- Neutron irradiation effects in a temperature and stress field → **Modelling & Component Test Facility** (VNS)

Database and MPH – CuCrZr

Qualification needs & issues

- Definition of **baseline** depending on manufacturing route
  - → Europe: **SAcwA + HRP-process** (2 h @ 580°C); semi-finished product: **plate** & tube
- **Qualification campaign** (started in 2023) based on gap analyses and defined test program including irradiation
  - → **Thermo-physical properties** after irradiation
- **Neutron irradiation data** (10-15 dpa, 150-350/450°C for DEMO) & **H/He transmutation effects** (IFMIF/DONES)
- Further topics: SSTT, **dissimilar material joints, corrosion**

CuCrZr Properties	Non-irradiated	Irradiated
Tensile properties	H	H
Fracture toughness	H	H
Fatigue strain controlled	H	M
Fatigue crack growth	H	L
Creep fatigue	M	
Creep	M	M (post)
		M (in-situ)
Charpy impact	L	L
Ratchetting	L	L
Creep crack growth	L	L

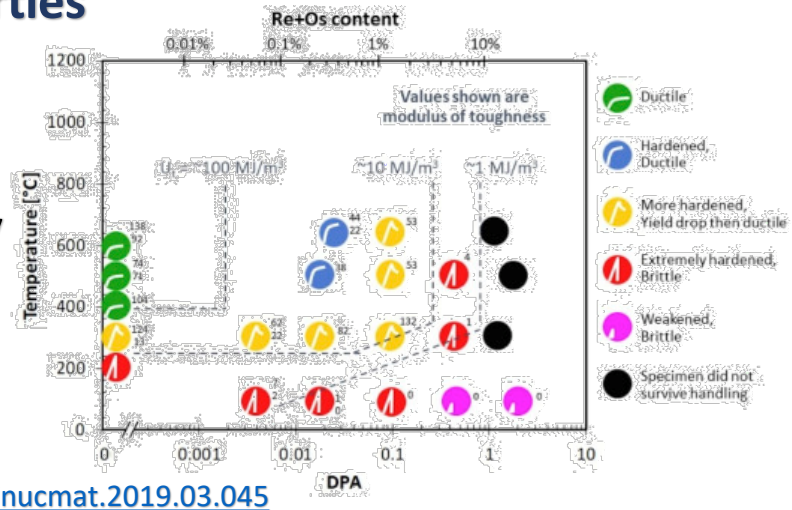
Priority: High (H), Medium (M), Low (L)

Task title	Irradiation facility	Materials & parameters
PIE of CuCrZr	LVR-15, Rez PIE: VTT	CuCrZr 0.7-1.3 dpa, 150 / 250 °C
Low temperature irradiation of divertor materials	BR-2, SCK.CEN	**CuCrZr**, **OFHC-Cu**, EUROFER97 1 / 3 / 6-9 dpa @ 50 / 150 / 250 / 350 / 450 °C

Database and MPH – Tungsten

Qualification needs & issues

- Definition of baseline
  - → 12 mm tungsten plate (A.L.M.T., ITER grade)
- No standardized manufacturing technology - **homogeneity and reproducible properties**
- **Qualification campaign** (main start in 2025)
- **Re+Os-transmutation** by thermal neutrons



Y. Katoh et al., JNM 2019
https://doi.org/10.1016/j.jnucmat.2019.03.045

Tungsten Properties	Non-irradiated	Irradiated
Tensile properties	H	H
Fatigue strain controlled	H	H
Bending	M	M
Fracture toughness	M	M
Fatigue crack growth	M	M
Creep	L	L (post) L (in-situ)
Charpy impact	L	L

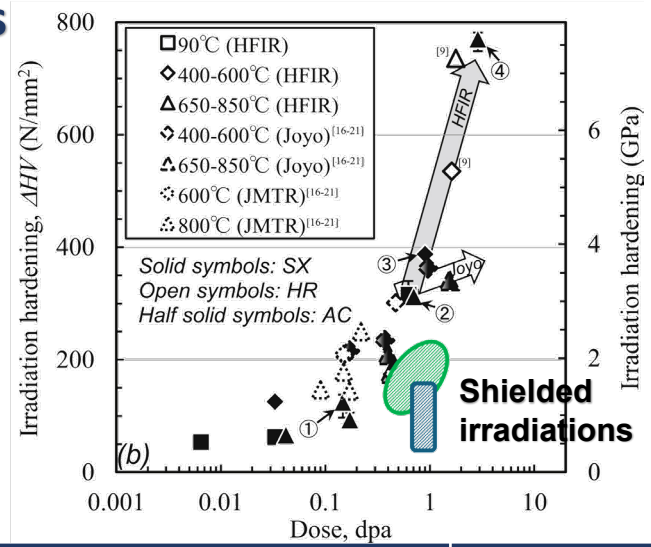
Priority: High (H), Medium (M), Low (L)

Task title	Irradiation facility	Materials & parameters
Irradiation of PFMs with thermal neutron shielding	BR-2, SCK.CEN	Commercial W, Tohoku-W & K-doped W, self-passivating W, W-ZrC 1 dpa @ 400 / 800 / 1100 °C

Database and MPH – Tungsten

Qualification needs & issues

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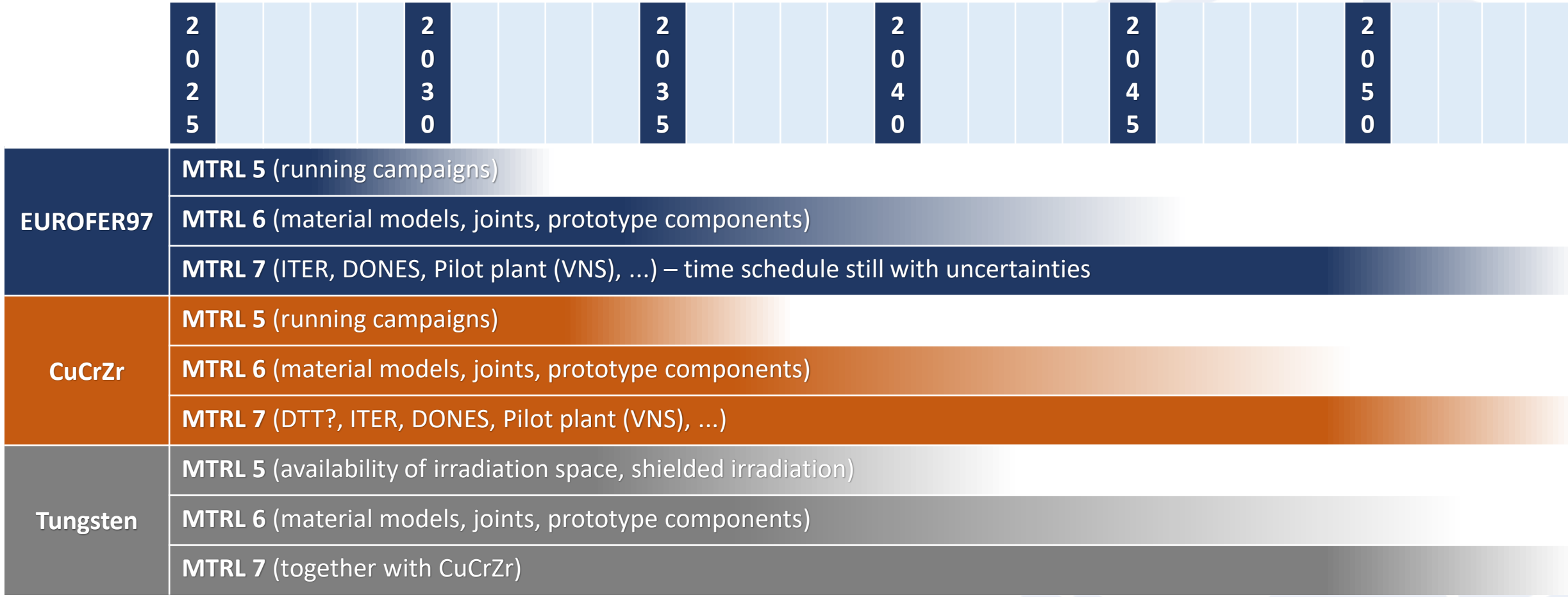


Tungsten Properties	Non-irradiated	Irradiated
Tensile properties	H	H
Fatigue strain controlled	H	H
Bending	M	M
Fracture toughness	M	M
Fatigue crack growth	M	M
Creep	L	L (post)
		L (in-situ)
Charpy impact	L	L

Priority: High (H), Medium (M), Low (L)

Task title	Irradiation facility	Materials & parameters
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Conclusion on baseline materials towards TRL 7



- Maturation of **advanced materials** (e.g. HT-steels, ODS-steels, SMART-W, K-doped W, W-reinforced CuCrZr, ODS-Cu) ongoing but MTRL evolution clearly behind baseline materials and still existing uncertainties

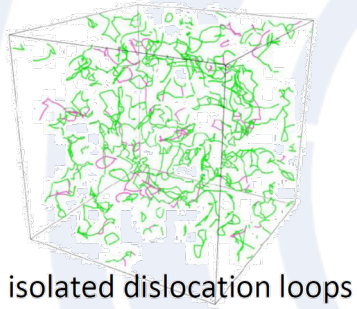
Irradiation modelling – from microscopic to macroscopic

Status and issues to be clarified

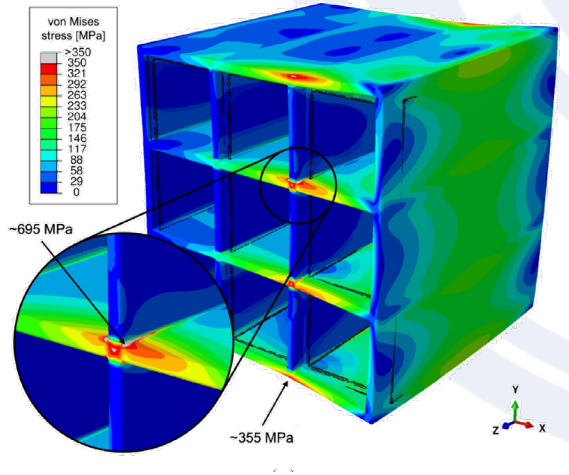
- Stepwise assessment of **singular effects** (e.g. hydrogen & screw dislocations, effect of C15 clusters in FeCr-alloys) towards **ML-approaches** for microstructure and property predictions
- **Multiple open topics**, e.g. complex microstructures, high temperature relaxation, influence of **stress & strain fields**, **experimental validation** (e.g. vacancies)

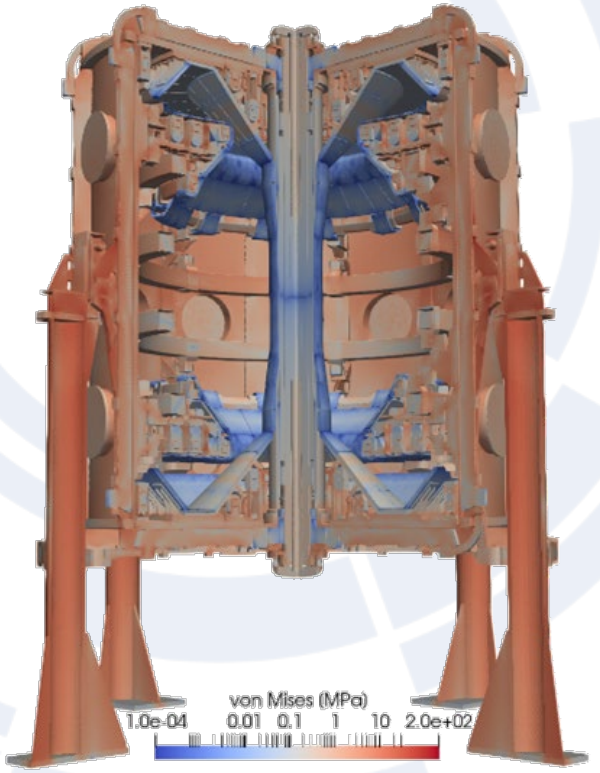
Strain and stress generated by irradiation: *eigenstrain*

- Critically significant **concept linking microscopic radiation effects to engineering models**
- Source of swelling, which can be anisotropic and **can relax thermally or athermally to accommodate applied loads**
- Work ongoing towards implementation of a **Virtual Reactor**



isolated dislocation loops and dislocation network





W.M.E. Ellis et al, App.Phys (2024)
https://doi.org/10.48550/arXiv.2409.13554

DEMO Design Criteria (DDC-IC)

Part A: General Provisions
Part B: Design criteria and analysis procedures
Part CA: Analysis examples
Part CB: Justification of design criteria



DDC Roadmap

❖ First official draft version issued in 2020, **update in 2023**

→ **Design rules drafted** for *immediate plastic flow localization (IPFL), multi-axial fatigue*, *ratcheting*, *creep-fatigue interaction*, *brittle fracture* and *FCG*

❖ On-going work towards the issue of the first formal edition by end of 2027

→ **Validation of design rules** for DEMO-relevant materials and loading conditions (**irradiation data!**) → **availability of experimental facilities and material for non-standard tests critical**

→ **Benchmarking with other C&S**, assessment of conservatism, definition of margins → performed by specific FEM simulations: interaction with designers and **availability of codification experts critical**

→ **Harmonization with other C&S**, definition of an integrated design methodology → yearly code review and audit by C&S experts from AFCEN: also steers the 2 previous points

Underlying issue: Lack of an established safety framework and requirements for IVCs

Obstacles and time constraints

Obstacles and time constraints

- Material maturation **correlated to system maturity** (e.g. welds, material interaction) – continuous change of design points not helpful as holistic characterization approach needs to be adapted instead of focusing
- **Industrial interest** on and **upscalability** of advanced materials **not guaranteed**
- **Usability of fusion neutron data** depending on
  - standardization of SSTT
  - combination of specimens and irradiation parameters, e.g. strong dose gradients in DONES even for small specimens → to be alleviated by more sophisticated irradiation programs, which may (slightly) delay results
- **Performance/lifetime limits** (for baseline and advanced materials) as result of fusion neutron data → assessment of economic viability of a fusion reactor (component replacement, storage capabilities)
- **Expectations** due to (unrealistic?) time schedule of private companies – DONES, Pilot Plant and ITER come, according to this schedule, “late”
- **National interests and political decision process**

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