November 18, 2025

Perspectives on US test facilities towards development of a fusion pilot plant

Arnold Lumsdaine[1] & Brian Wirth[1,2]

[1]Oak Ridge National Laboratory
[2]University of Tennessee, Knoxville

ORNL IS MANAGED BY UT-BATTELLE LLC
FOR THE US DEPARTMENT OF ENERGY

Multiple technology facilities are needed to qualify materials and components for use in fusion power plants

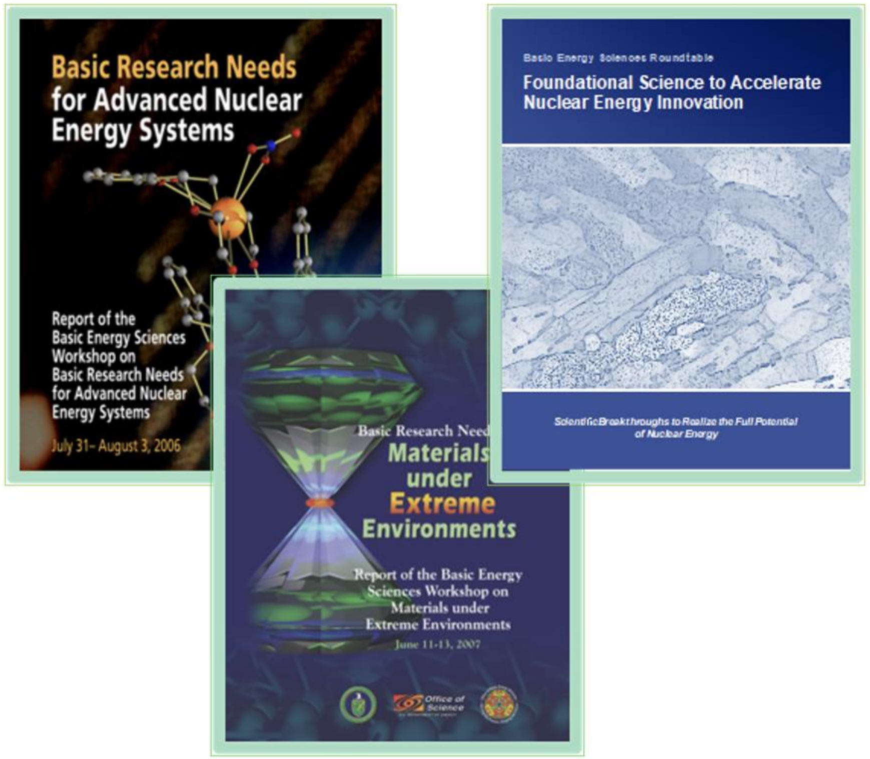
- Material Plasma Exposure eXperiment (MPEX) – Plasma Material Interaction for neutron damaged materials (under construction)
- Blanket Component Test Facility (BCTF) – Testing of blanket components in nuclear and non-nuclear environments
- Fuel Cycle Test Facility (FCTF) – Handling of sufficient amounts of tritium and allow for full scale processing rates that are orders of magnitude higher than state of the art
- Fusion Prototypic Neutron Source (FPNS) – Exploring whether materials retain adequate properties and integrity for damage levels greater than 20–50 displacements per atom (dpa) in a fusion neutron environment
- Volumetric Neutron Source (VNS) – Examine components at scale for performance in the fusion nuclear environment

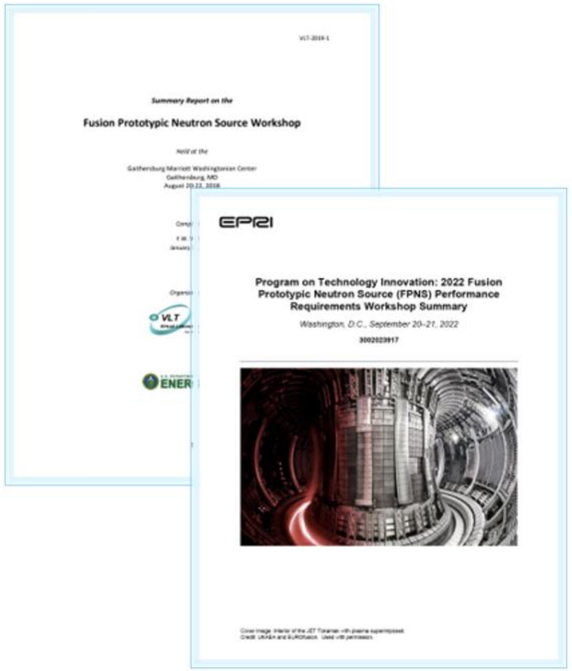
Why don’t these facilities already exist?

- Many of these facilities are under construction internationally (UNITY-1 & 2, CHIMERA, LIBERTI, H3AT, IFMIF-DONES, etc.)
- The facilities are expensive, and many require the development of first-time use critical technologies. All require challenging integration of complex systems.
- The development of a Fusion Pilot Plant (FPP) without verification of materials and components that can survive the integrated fusion environment carries significant risk.
- This verification and qualification will be needed well beyond the development of an FPP.
- It is too expensive and takes to long to develop these facilities. It is too risky and costly to *not* develop these facilities.

Motivation: We have no way to test materials and components in a neutron environment that represents the harsh conditions of a fusion power plant

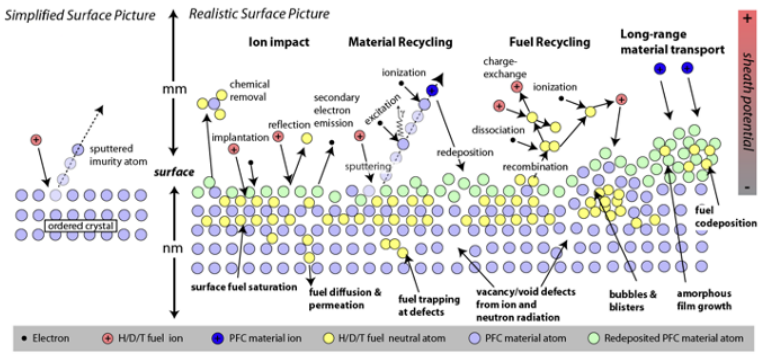
Recent community activities have repeatedly emphasized the U.S. fusion technology community's need for an FPNS. Multiple U.S. reports have identified the relevant **science drivers**, FPNS **performance requirements**, and **community priorities**.





Data for material performance in fusion-relevant conditions is lacking

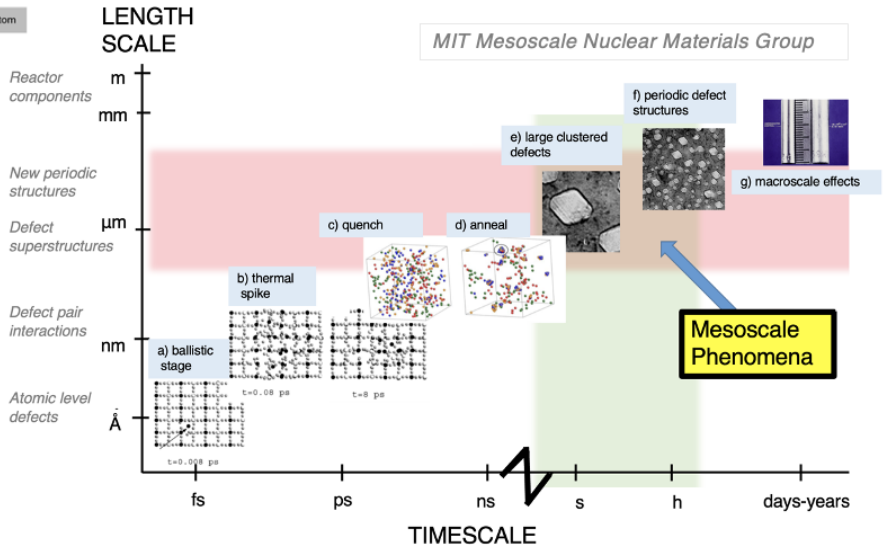
The evolution of PFC armor and structural materials (and thus property changes) in extreme radiation environments is highly complex, dynamic and difficult to predict

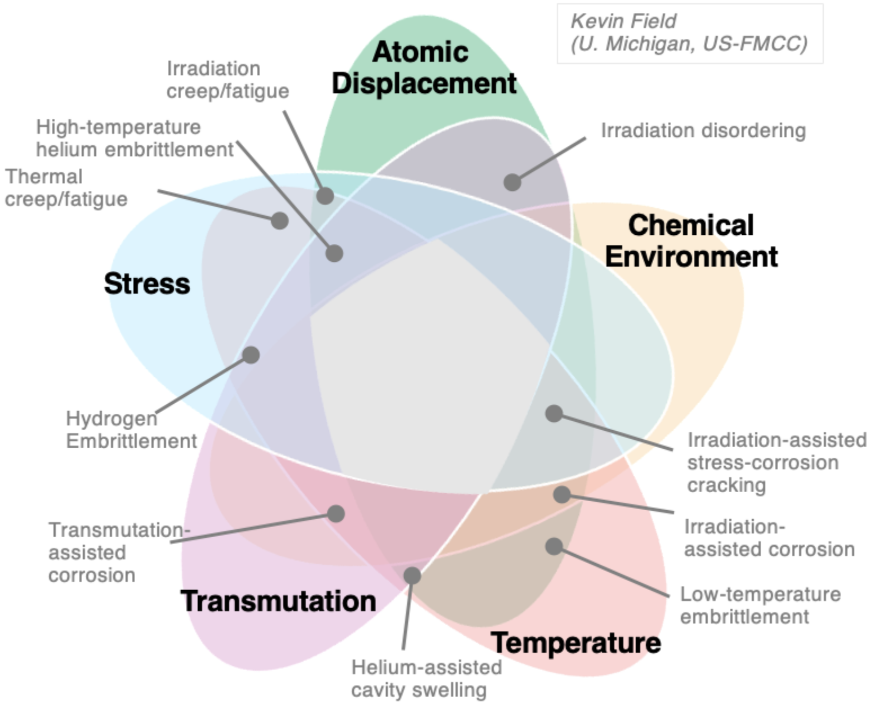


Wirth et al., *MRSB* **363** (2011) 216-222.

Radiation-induced defects migrate, anneal, coalesce, and evolve, resulting in constant change to the material's microstructure and performance. Pictured: the complex phenomena occurring at the surface of a plasma-facing component.

Radiation damage occurs across many orders-of-magnitude in time and size. Advanced simulations can elucidate atomic-scale behavior but understanding mesoscale and macroscale phenomena **via experimental data** is critical to predicting material performance.





US DOE Office of Science requested input on prioritization of facility needs in December 2023

FESAC Facilities Construction Projects Sub-Committee Members

Prof. Brian Wirth, U. of Tennessee - Knoxville (Chair)

Prof. Carlos Paz-Soldan, Columbia University (Vice-Chair)

Dr. Felicie Albert, Lawrence Livermore National Laboratory

Mr. David Babineau, Savannah River National Laboratory

Dr. Kate Bell, Sandia National Laboratories

Dr. Cami Collins, Oak Ridge National Laboratory

Prof. Evdokiya Kostadinova, Auburn University

Dr. Rajesh Maingi, Princeton Plasma Physics Laboratory

Prof. Jaime Marian, U. of California - Los Angeles

Dr. Thomas Sunn Pedersen, Type One Energy

Dr. Erica Salazar, Commonwealth Fusion Systems

Dr. Chase Taylor, Idaho National Laboratory

Dr. Kathreen Thome, General Atomics













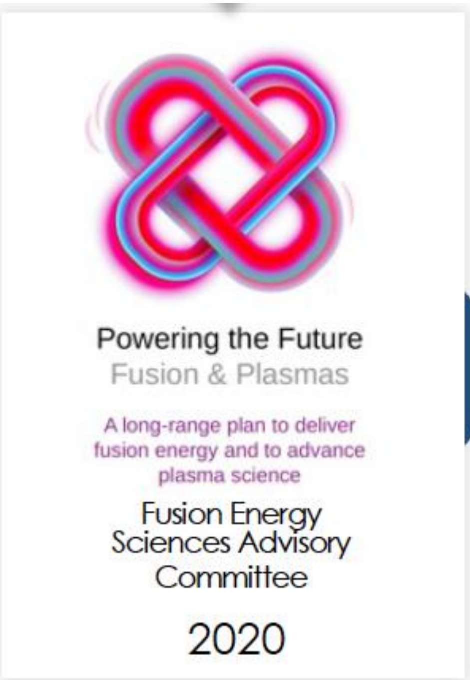


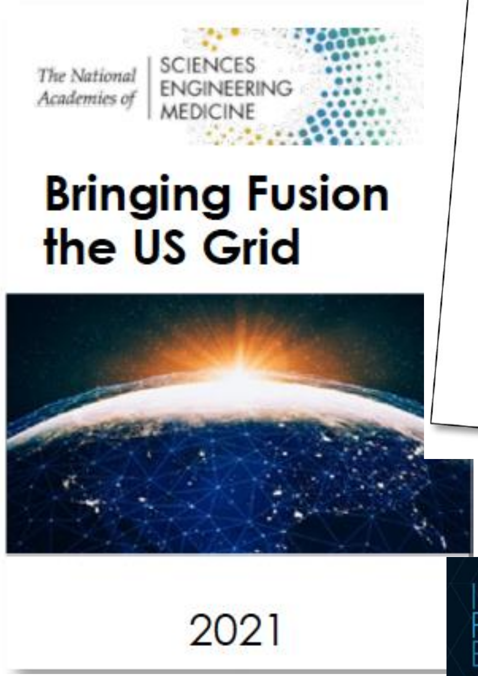
ex officio

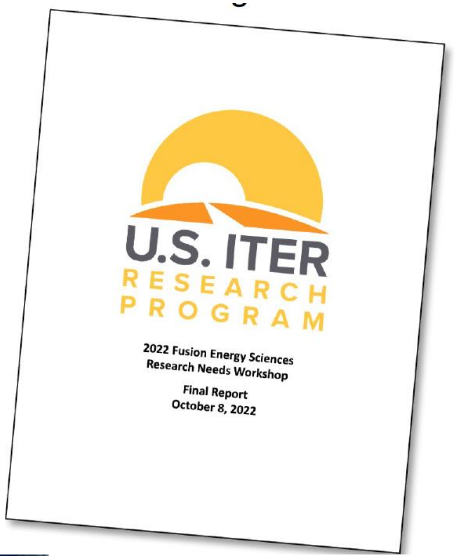
Prof. Troy Carter, U. of California - Los Angeles (ex-officio)

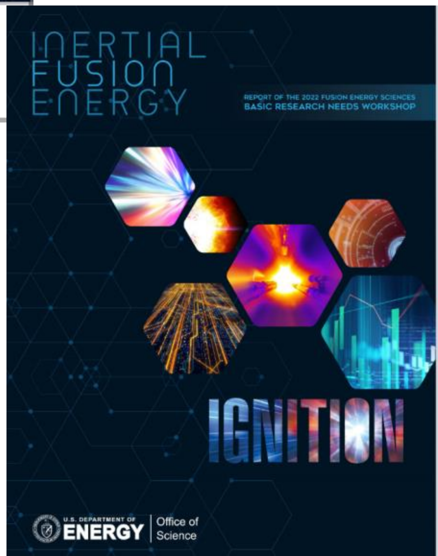
Prof. Anne White, Massachusetts Institute of Technology (ex-officio)

Prior reports & recent events informed our discussions









2022 Whitehouse event to launch ‘Bold Decadal Vision’ and milestone-based public-private partnerships

2022 & 2023 demonstrations of fusion scientific gain from IFE in the US & 69 MJ fusion heating over 6 seconds in the UK

Criteria to Identify Facilities that:

'Best Serve Fusion and the Bold Decadal Vision'

- Urgency of timeline with decadal impact on fusion industry/science;
- Alignment with FESAC LRP and BDV;
- Response to Charge Questions: *"potential to contribute to world-leading science & fusion technology"* and *"readiness for construction"*
- Opportunities for partnerships that could accelerate timeline and/or reduce costs;
- Technology gaps that would be closed by a facility and/or contribution to world-leading fusion science

These criteria were applied holistically to our evaluation and also incorporated a preference for facilities that supported multiple fusion power plant concepts

No predetermined number of facilities in this category

US Consensus on Facilities that Best Serve Fusion

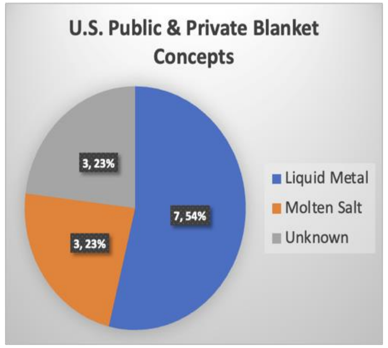
A strong consensus was developed in the Subcommittee that four facilities 'Best Serve Fusion' (in alphabetical order): Blanket Component Test Facility (BCTF), Fuel Cycle Test Facility (FCTF), Fusion Prototypic Neutron Source, and ITER.

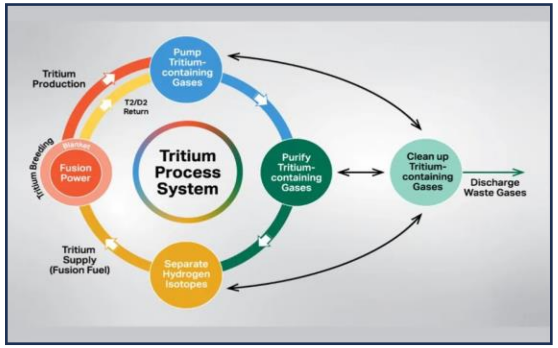
- Each of these facilities support multiple pathways to fusion energy, including ITER which has/will provide knowledge transfer about fusion technology & engineering experience at reactor scale, including system integration, precision engineering and quality control

The other eight facilities were all deemed 'important'. Many of these facilities were associated with single-concept fusion confinement approaches

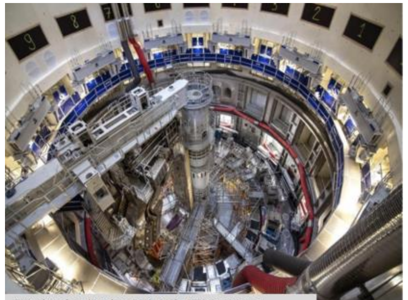
These facilities are highly important and well-deserving of FES support

The readiness for construction varied significantly between all facilities





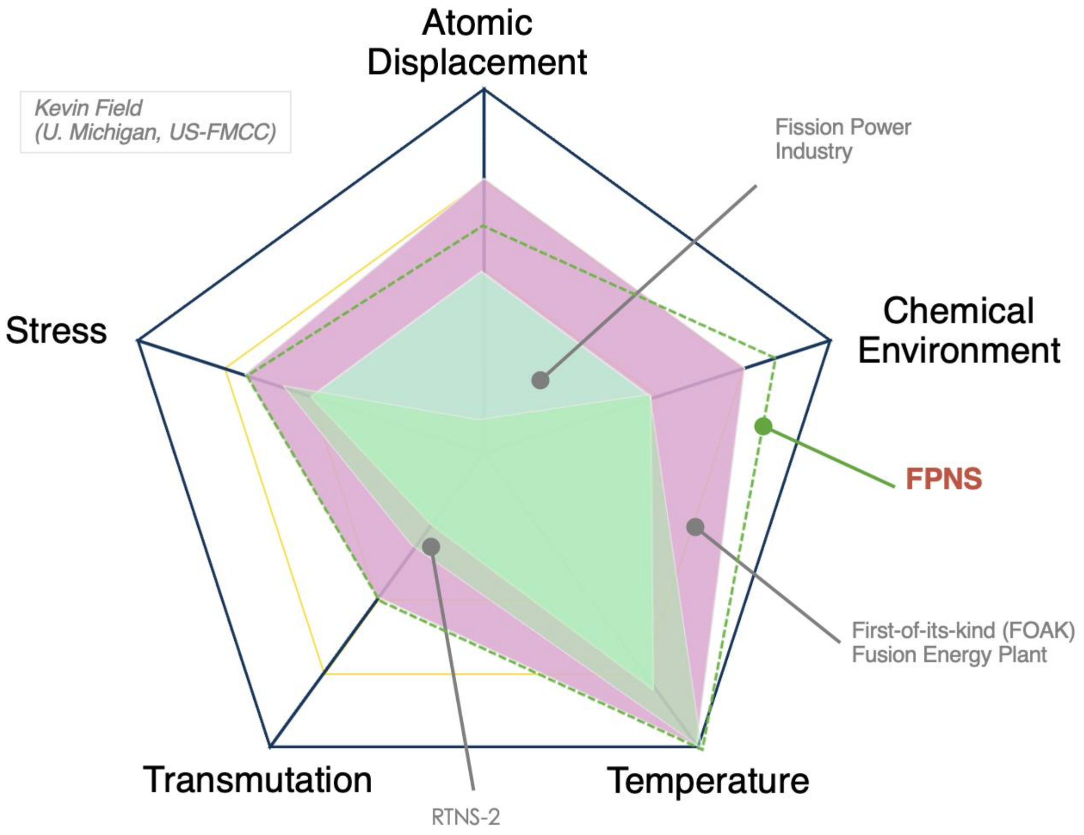
Parameter	Capability by 2028	Capability by 2033
Damage rate	5-10 dpa/yr (Fe eq.)	15 dpa/yr (Fe eq.)
Sample volume	$\geq$50 cm^3	$\geq$300 cm^3
Spectrum	Gaseous & solid trans. consistent with 14 MeV fusion n spectrum	
Temperature range	~300 to 1200 °C	
Temperature control	3 ind. controlled regions	
Flux gradient	$\leq$20%/cm in plane of sample	

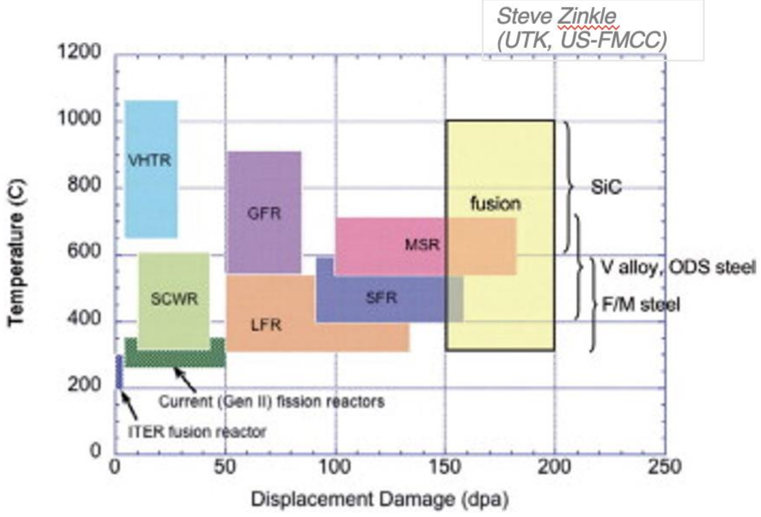


ITER tokamak pit (October 2022). Credit: ITER Organization

Evaluation of options for an FPNS: fusion neutron spectrum considerably harder than fission – introduces substantial gaseous and solid transmutant elements in structural materials closes to fusion engine

Fusion power plants will have higher flux, higher operating temperatures, and harder neutron spectra. Fusion neutrons are **born at 14 MeV, versus 2 MeV for fission**. In addition to much higher dpa rates, there are transmutation reactions that will impact material performance, but which don't appear at fission energies.



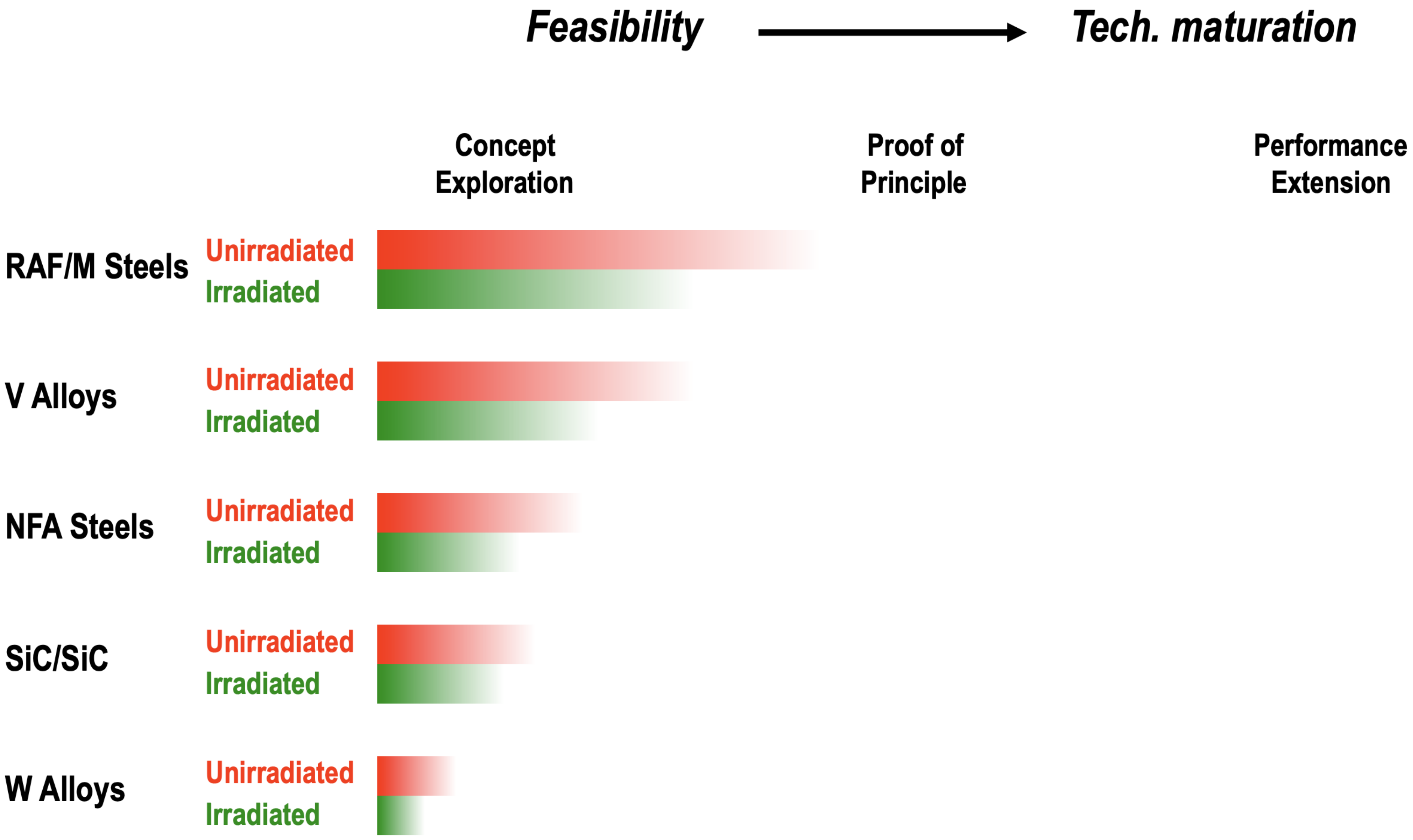


Radiation damage in the existing fission fleet is not representative of the damage expected in fusion power plants. Higher-dpa advanced reactor concepts cannot account for the high-energy reactions that are specific to the fusion environment.

IFMIF-DONES (International Fusion Materials Irradiation Facility – Demo-Oriented Neutron Source) is planned for construction in Granada, Spain, with a target operating date of 2035. IFMIF-DONES is a linac concept (D ions → flowing Li target). The U.S. has no current plan to build a facility with equivalent capabilities.

See: Yiquin Qiu et al., "Overview of recent advancements in IFMIF-DONES neutronics activities," *Fusion Engineering and Design* 201 (2024):114242

Fusion materials current readiness



Fusion materials current readiness: Radiation effects

Data Base Need	0 – 5 years: 10 dpa/100 appm He						5 – 15 years: 50 dpa/500 appm He						>15 years: 150 dpa/1500 appm He					
	RAF/M	NFA	V	W	SiC	Adv Mat	RAF/M	NFA	V	W	SiC	Adv Mat	RAF/M	NFA	V	W	SiC	Adv Mat
Radiation Effects																		
Hardening & Embrittlement																		
Phase Instabilities																		
Irradiation Creep																		
Volumetric Swelling																		
High T Helium Effects																		

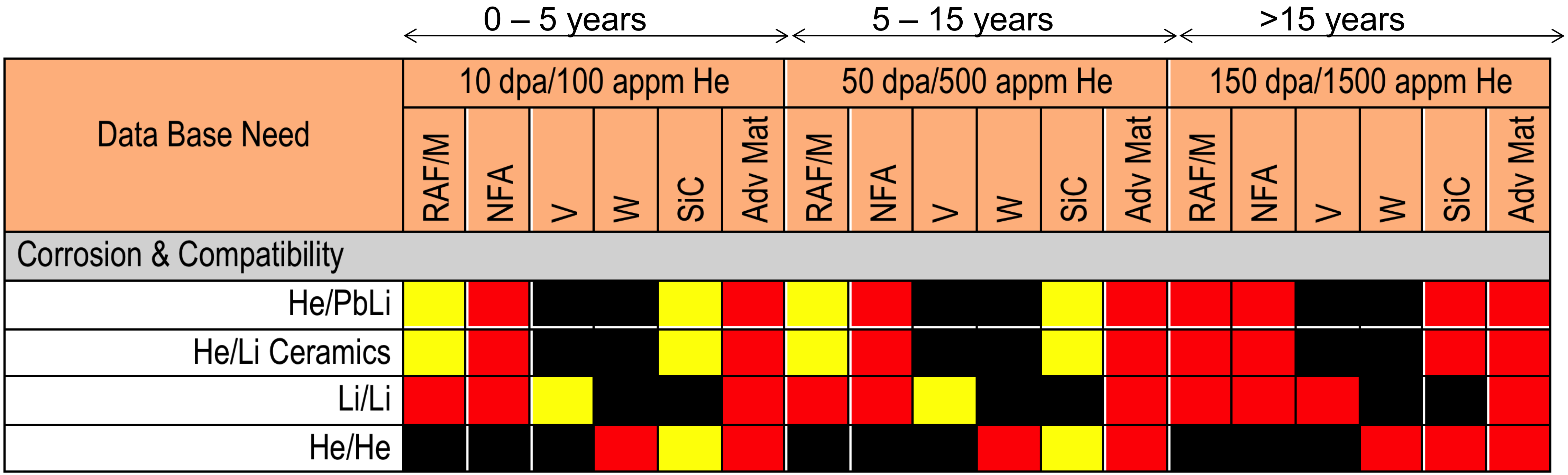
- Table focuses on structural materials for first wall/vacuum vessel, but radiation stability & degradation of magnet (conducting coils & insulators) and on diagnostics (optical/electronic properties) are needed in the near term (< 10 dpa, up to 10^9 Gy)

Note: He levels are for RAF/M, lower and higher values for other materials

Green = Adequate Knowledge Base Exists
Yellow = Partial Knowledge Base Exists
Red = Knowledge Base Does Not Exist of Completely Inadequate

Fusion materials current readiness

- Corrosion/compatibility knowledge to data largely based on isothermal exposures
- Significant need for flowing loop testing + coupled MHD/E-M effects



Green = Adequate Knowledge Base Exists
Yellow = Partial Knowledge Base Exists
Red = Knowledge Base Does Not Exist or Completely Inadequate

Note: He levels are for RAF/M, lower and higher values for other materials

Fusion materials database: Current readiness

0 – 5 years → 5 – 15 years → >15 years

Data Base Need	10 dpa/100 appm He						50 dpa/500 appm He						150 dpa/1500 appm He					
	RAF/M	NFA	V	W	SiC	Adv Mat	RAF/M	NFA	V	W	SiC	Adv Mat	RAF/M	NFA	V	W	SiC	Adv Mat
Fabrication & Joining Technology																		
Basic Fabrication																		
PFM Bonding																		
Investment Casting																		
Self Joints																		

Data Base Need	10 dpa/100 appm He						50 dpa/500 appm He						150 dpa/1500 appm He					
	RAF/M	NFA	V	W	SiC	Adv Mat	RAF/M	NFA	V	W	SiC	Adv Mat	RAF/M	NFA	V	W	SiC	Adv Mat
Structural Design & Licensing																		
Design Data Base																		
Code Qualification Req.																		
Safety Bases																		
Nondestructive Examination Methods																		
Flaw Detection Methods																		
Flaw Evaluation Criteria																		

Note: He levels are for RAF/M, lower and higher values for other materials

Fusion Prototypic Neutron Source (FPNS)

• The need for an irradiation source to test and qualify materials has been recognized since the 1970s.

• Many facilities have been proposed, but in the U.S., only RTNS (I & II) were built and operated at < 0.1 dpa between 1979 and 1987

• IFMIF is being designed and technology prototyped by the Japan/EU (IFMIF EVEDA)
 - IFMIF cost estimated at >$1.25B
 - DONES (essentially half-IFMIF) currently being pursued, estimated at ~$700M

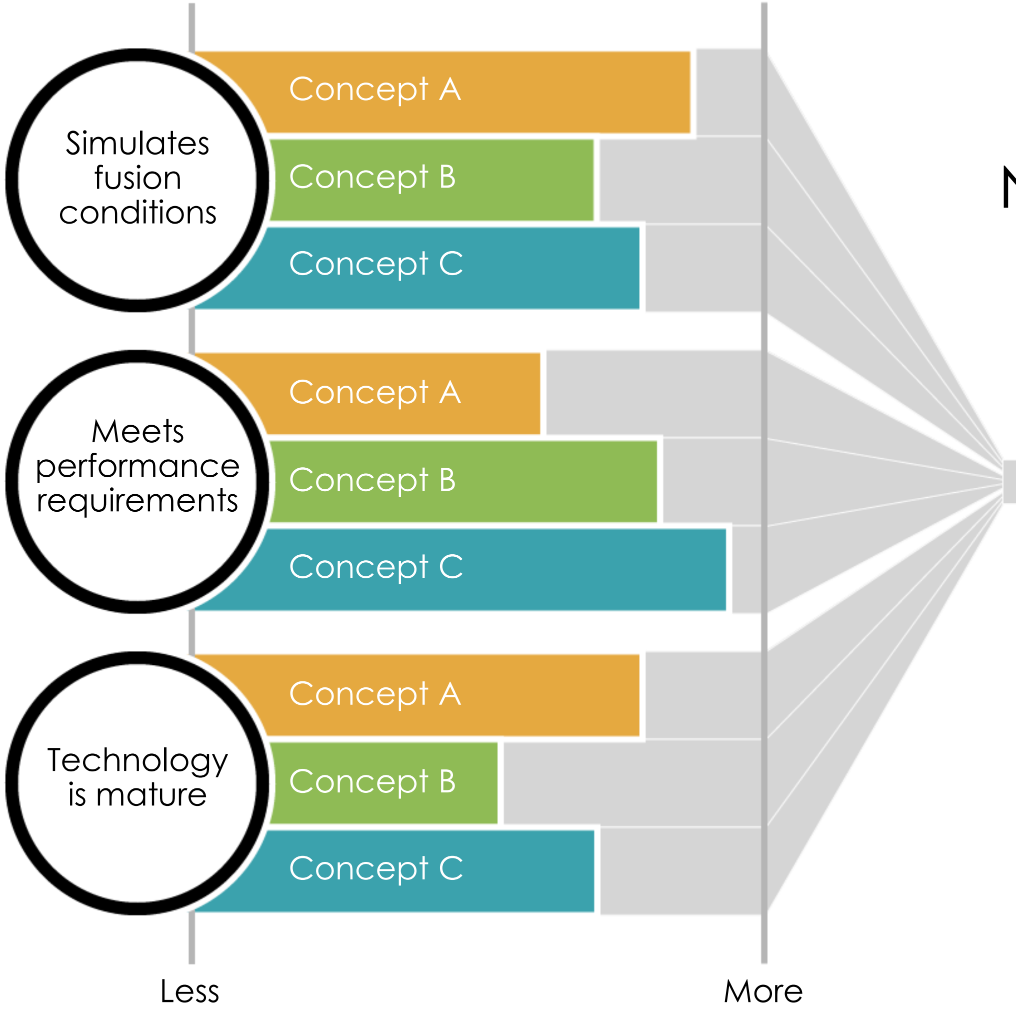
• Multiple FESAC & community reports (e.g., RENEW, Gaps and Priorities, etc.) have promoted material testing in a prototypic fusion neutron spectrum
 - More recently, the US APS-DPP Community Planning Process reiterated that FPNS is needed and assigned a high(est) priority ranking among needed new start facilities
 - In summer/fall 2022, EPRI hosted a 2-part workshop series to further discuss requirements for an FPNS and build consensus on timeline, with the emergence of private fusion companies

Operational performance requirements of FPNS relative to IFMIF (Fe equivalent)

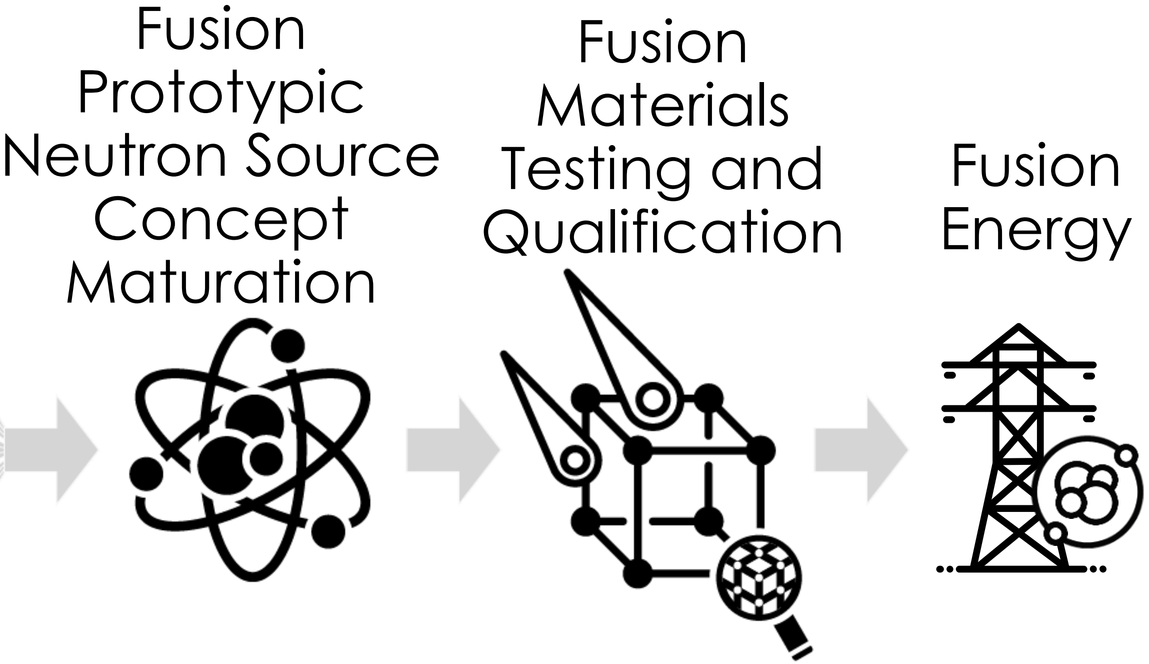
Parameter	Guidelines for minimum FPNS performance by 2032 (*Wirth et al, EPRI/3002023917/2022*)	IFMIF performance requirements (*Garin et al, Fus. Eng. & Des., 2011*)
Damage Rate	10~15 dpa/year (30)	15~30 dpa/year (12~25)
Spectrum	10 appm He/dpa (11)	10 appm He/dpa (13)
Sample Volume	300 cm^3	500 cm^3 (500 cm^3)
Temperature Range	300~1200°C (500~900°C)	300~1100°C (250~550°C)
Temperature Control	3 independently monitored and temperature-controlled regions	12 independently monitored and temperature-controlled regions (4)
Flux Gradient	≤ 20% in the plane of the sample	

DEMO design metrics: Gilbert *et al*, *Fusion Science and Technology* **66** (2014) 9
DONES design metrics: Ibarra *et al*, *Nucl. Fusion* **59** (2019) 065002; Mota *et al*, *Nuclear Fusion* **55** (2015) 123024])

Broad community evaluation of concepts submitted to RFI on FPNS has been completed



16 concepts submitted
(13 other concepts not pictured)



13 university, private industry, and national lab participants are working with every concept proposer to understand the merits.

Final report completed and submitted to DOE in April 2025

FPNS RRA organizational structure

Oversight Team
Phil Ferguson
Arnie Lumsdaine
Brian Wirth
James White

Fusion Conditions (FCC)
Jaime Marian

Yutai Katoh
Ethan Peterson
Lance Snead
Wahyu Setyawan
Jason Trelewicz
Brian Wirth
Ying Yang
Weicheng Zhong

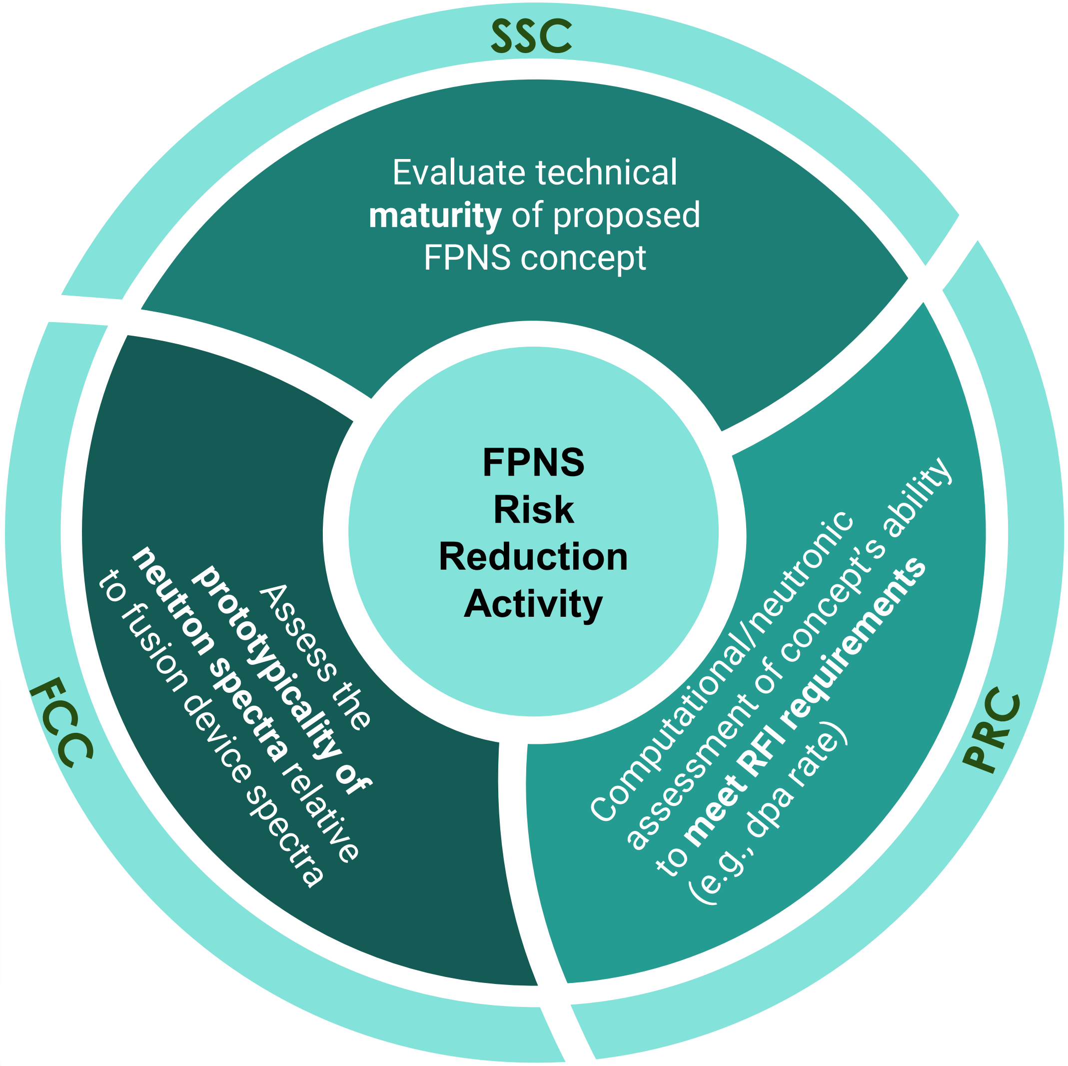
Performance Requirements (PRC)
Eric Pitcher

Tim Bohm
Granz Gallmeier

Systems Studies (SSC)
Sara Ferry
Brian Grierson

Maturity Evaluation
Sehila Gonzalez
Arnie Lumsdaine
Rajesh Maingi
Jacob Schwartz
Jackson Williams

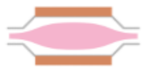
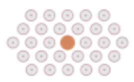
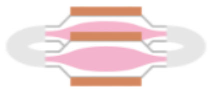
Particle Acceleration
Stuart Henderson
Christian Baumgarten
John Galambos
Cameron Geddes
Peter Ostroumov



In addition to the complete report, each subcommittee wrote a report with significantly more detailed information.

US FPNS Concepts

Submitter	Schematic *created by J. Schwartz*	Concept	Key advantages	Key challenges
Particle accelerator concepts				
SLAC		(1) Conventional rift tube linac with RFQ (2) Novel laser-based ion injector to drift tube linac Both: 35 MeV D → Li	• RFQ technology is high TRL.	• High cost • Low TRL for laser-based ion/neutron sources
MIT/SBU/UTK		Multiple compact 35+ MeV D cyclotrons in a ring impinge on Li target.	• Lower cost than LINAC • Modularity	• First-of-a-kind cyclotron required • Multiple beam integration unproven
NIFS		Staged approach: (1) Low-E, <1 MeV neutron beam (2) 35 MeV D-Li stripping	• Early data quickly with low-E beam • Stage 2 similar to IFMIF-DONES	• Cost • Stage 1 is non-prototypic and adds cost
SAFEnergy/ LBNL		Intense ion beam onto high density target. D-Li or D-T suggested.	• Low cost • Flexible targets	• Low TRL • Spectrum possibly not prototypic
Berkeley/ LBNL		Thick Target Deuteron Breakup with multiple 35 MeV cyclotrons and Be target	• Low cost • Cyclotrons already in production (medical isotopes)	• Dissimilar spectrum • Multiple beam integration unproven
ORNL		Modified IFMIF-DONES design. Accelerate D to 35-50 MeV, impinge on flowing liquid Li target	• Mature design • High damage rate expected	• Very expensive • Will take a long time to build
IFMIF-DONES		40 MeV D linac impinges on Li target; under construction in Spain. Proposal calls for U.S.-funded upgrade (add second accelerator)	• Primary facility already under construction • Lots of R&D done; highly mature design • Extensive international collaboration	• Timeline control • U.S. data priority unclear • Cost of second accelerator still very high for a non-U.S. facility
LANL		Upgrade LANSCE (spallation source with high-power proton linac)	• LANSCE is an operational, mature facility	• Dissimilar neutron spectrum

Submitter	Schematic *created by J. Schwartz*	Concept	Key advantages	Key challenges
D-T and plasma-based steady-state concepts				
Realta		DT plasma in a gas-dynamic-trap mirror configuration	• Large volume • PPP opportunity • Accurate spectrum	• ~Power-plant levels of complexity • Requires breeding blanket (low TRL)
Astral Systems		Many inertial-electrostatic neutron generators developed by Astral are arrayed in a test chamber.	• Factory-style NG production, lower cost • Large test volume • Accurate spectrum	• Need significant NG performance improvements (x100) • NGs would suffer radiation damage • Moderate tritium consumption
Princeton, U. Washington, Marathon Fusion		"Stellarators Linking Axisymmetric Mirrors" combines mirror and stellarator advantages. Neutral beams injected into plasma create VNS.	• Large fusion reaction rate and sample volume • Accurate spectrum • Innovative concept	• Very low-TRL • ~Power plant levels of complexity • Requires tritium breeding blanket and fuel cycle
SHINE		150-200 keV ion beam injected into dense 500 eV plasma target confined in a polywell configuration	• Compact, low-cost • SHINE has operating experience with DT sources	• Moderate tritium burn rate • Low-TRL for driver, target, test fixtures
Laser-based concepts				
Naval Research Laboratory		Laser-irradiated direct drive ICF target	• IFE relevant • Large test volume	• Requires full-demo scale IFE facility
Focused Energy		Laser-driven ions into U-238 spallation target	• Low cost • IFE relevant	• Non-prototypic neutron spectrum • Low-TRL laser drivers
LLNL		Laser-driven ions incident on neutron converter	• IFE relevant • Multiple target options	• Non-prototypic neutron spectrum • Low TRL • Low dpa

Summary of Technology Facilities & Research Needs

- New fusion facilities addressing critical technology and science gaps are urgently needed to meet the timelines of the private industry to provide economically-attractive fusion energy to the U.S. grid
  - FESAC Subcommittee developed a strong consensus that four facilities ‘Best Serve Fusion’ - BCTF, FCTF, FPNS and ITER. *Each of these facilities support multiple pathways to fusion energy, including ITER which has/will provide knowledge transfer about fusion technology*
- FPNS risk reduction activity funded by DOE identified promising approaches and concluded that D-Li^6 stripping source option (e.g., IFMIF, DONES, etc.) provides sufficiently prototypic testing environment for fusion
- Recent community prioritization has emphasized the need, and the urgency, for expanding efforts in fusion technology related to materials development for applications in PMI, blankets, structural components – Note that many aspects of the materials & technology required for IFE shares strong commonality with MFE
- Most significant development needs include: Blanket technology, structural materials development for blankets, including environmental degradation and tritium permeation/retention, and 14 MeV prototypic neutron source

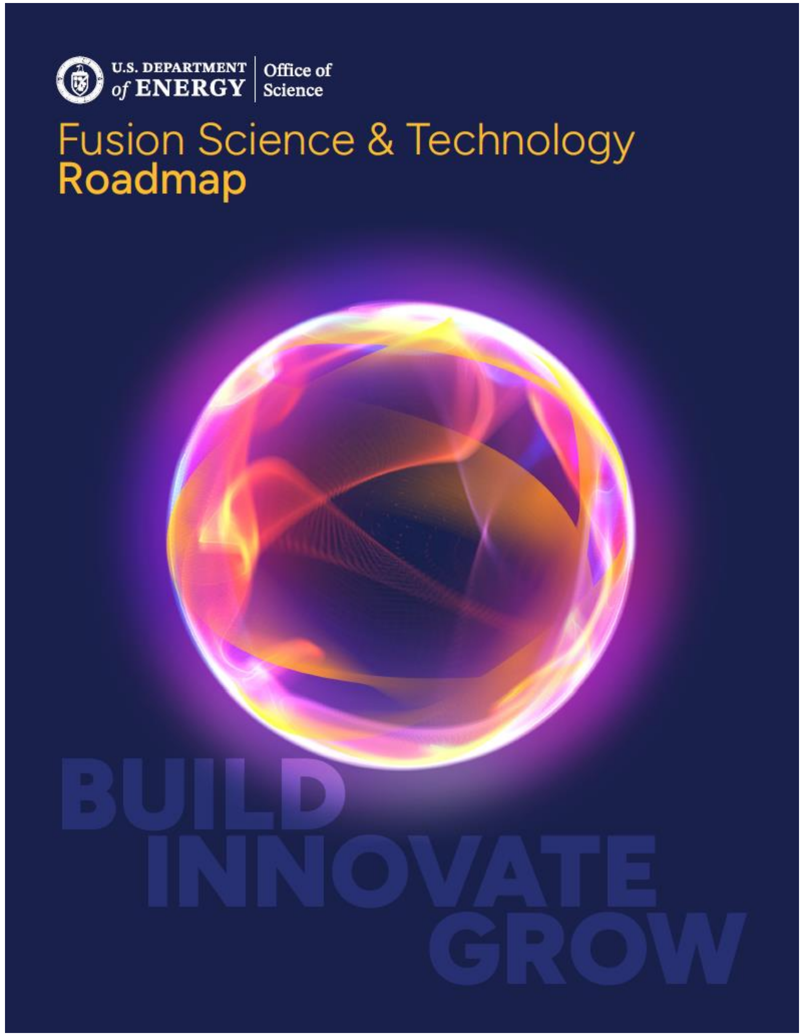
The Special Competitiveness Studies Project (SCSP) recommends substantial investment in fusion

- "Fusion Forward: Powering America's Future" was released in October 2025.
- The SCSP report recommends that the U.S. "make a One-Time Investment of $10 Billion to Enable and Accelerate U.S. Fusion Commercialization."
    - "The DOE fusion program's mission and budget should evolve into one that accelerates fusion R&D and industry-led demonstration activities."
    - "Building on existing FES funding levels, $10 billion in new funding should go towards a multi-pronged approach of . . . [b]uilding commercialization-relevant R&D facilities to close scientific and technological gaps in key fusion components and systems needed to enable the National Fusion Goal and then build reliable power plants thereafter."

The U.S. DOE Fusion Science & Technology Roadmap proposes developments to close key fusion gaps

- “The U.S. will:
  - **Build** key infrastructure to address critical fusion materials and technology (FM&T) gaps;
  - **Innovate** and advance the science and engineering of fusion; and
  - **Grow** the U.S. fusion ecosystem through domestic and international public-private partnerships, fostering new regional consortia, building research FS&T infrastructure and supply chains and fusion manufacturing networks.”

https://www.energy.gov/fusion-energy



The U.S. Fusion Roadmap identifies 6 core challenge areas and 8 infrastructure streams to close technology gaps

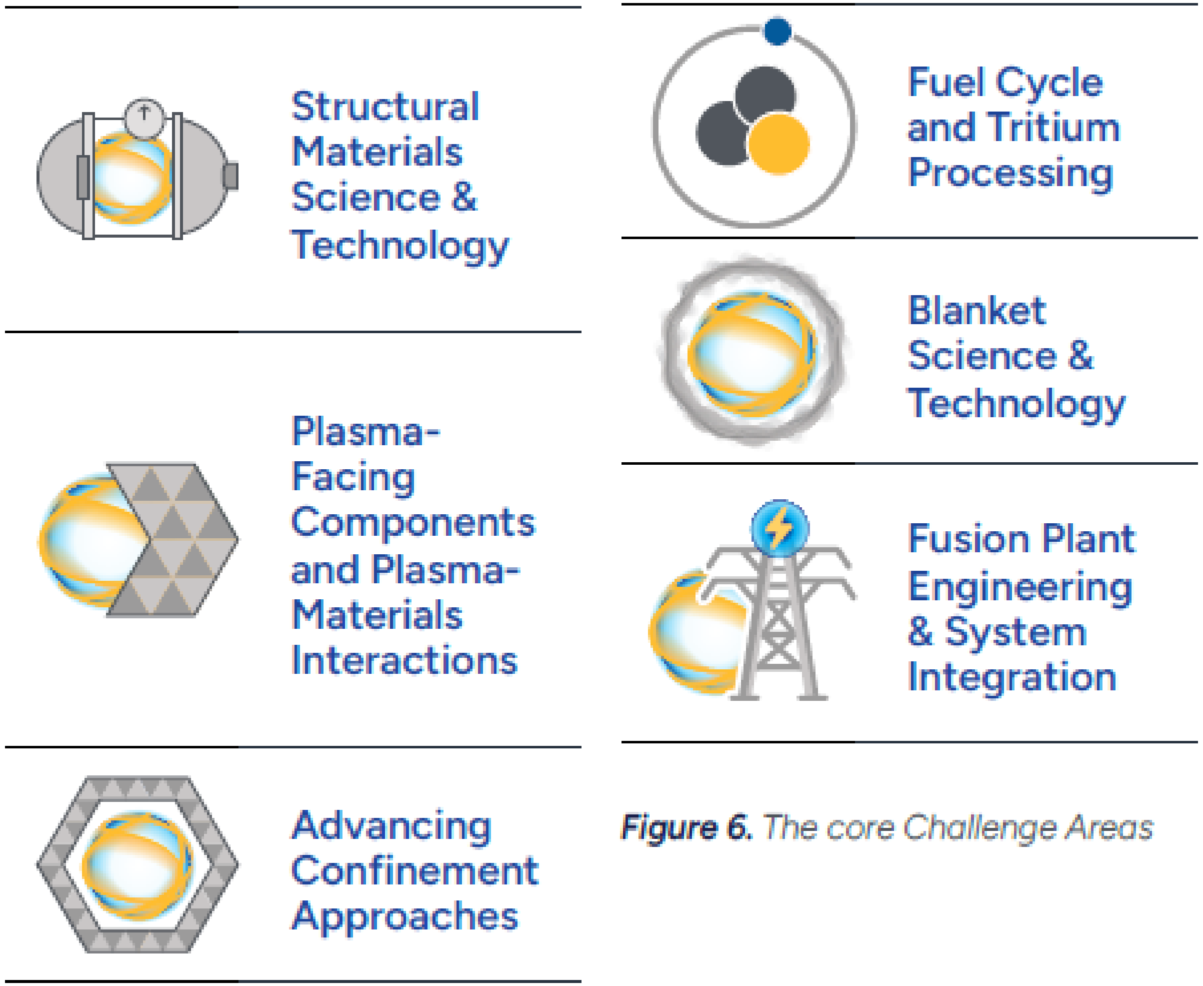


Figure 6. The core Challenge Areas

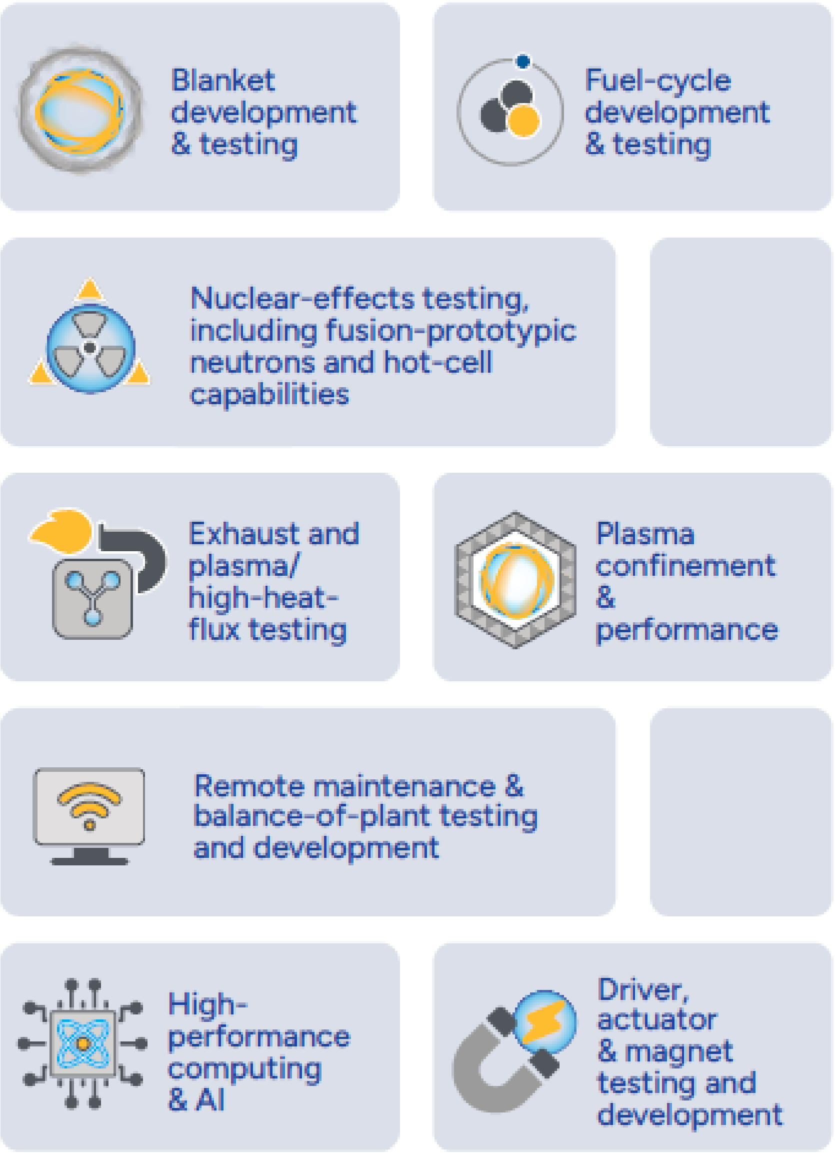


***Figure 4.** Eight distinct infrastructure streams critical for progress towards the development of fusion power plants have been identified.*

The U.S. Fusion Roadmap proposes an aggressive approach to public and private sector facility development

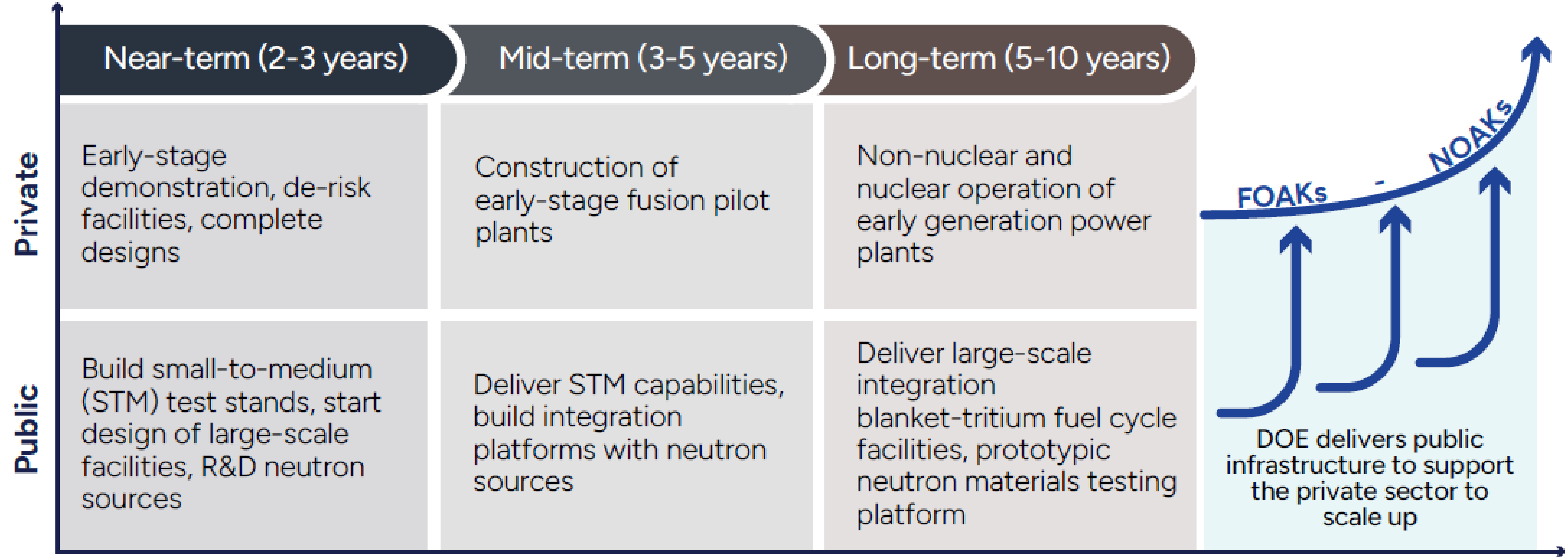


Figure 2. *Roadmap sequence of public and private sector timelines over the near-, mid- and long-term, to support the scaling of private industry as it develops first-of-a-kind (FOAK) and nth-of-a-kind (NOAK) fusion power plants and continue to support innovation.*

Multiple technology facilities are needed to qualify materials and components for use in fusion power plants

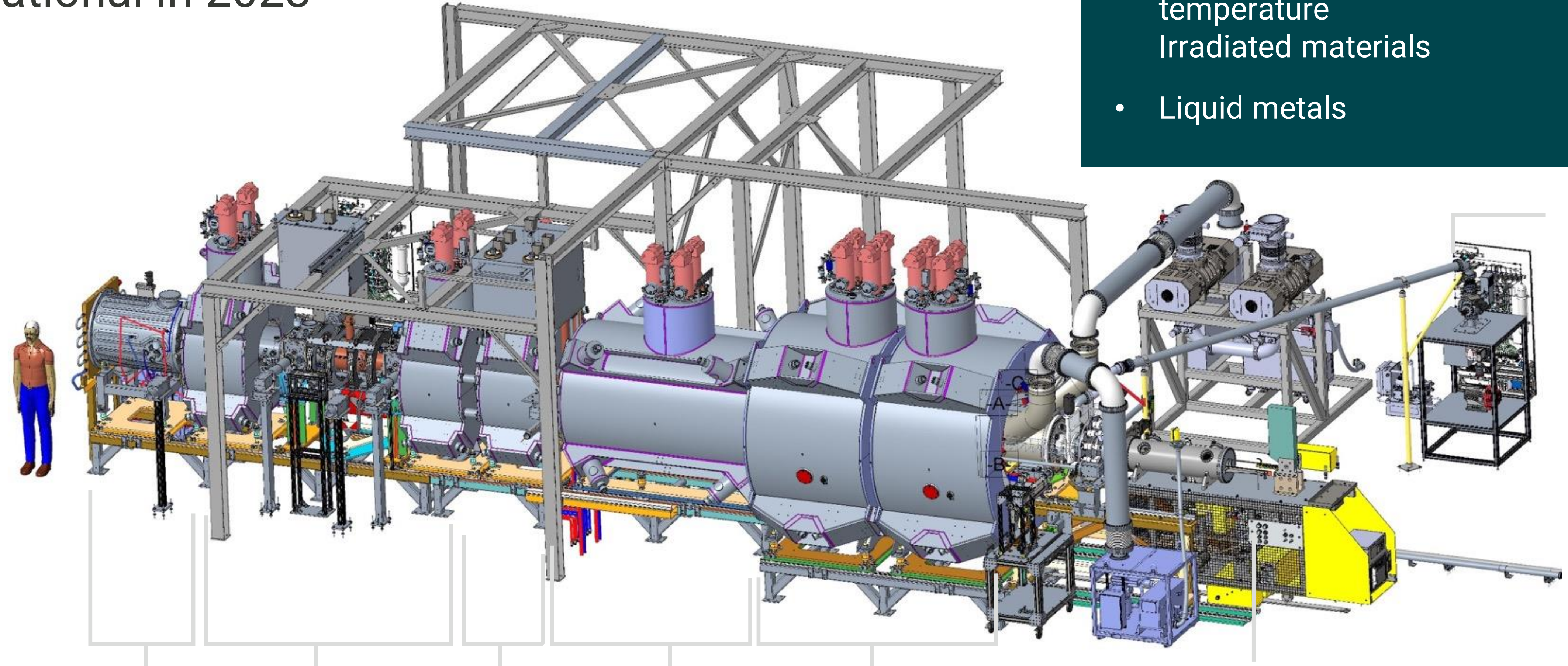
- Material Plasma Exposure eXperiment (MPEX) – Plasma Material Interaction for neutron damaged materials
- Blanket Component Test Facility (BCTF) – Testing of blanket components in nuclear and non-nuclear environments
- Fuel Cycle Test Facility (FCTF) – Handling of sufficient amounts of tritium and allow for full scale processing rates that are orders of magnitude higher than state of the art
- Fusion Prototypic Neutron Source (FPNS) – Exploring whether materials retain adequate properties and integrity for damage levels greater than 20–50 displacements per atom (dpa) in a fusion neutron environment
- Volumetric Neutron Source (VNS) – Examine components at scale for performance in the fusion nuclear environment

MPEX: World-class Plasma-Material-Interaction facility underway

Operational in 2028

Unique Capabilities

- Full-reactor–lifetime exposure in 2 weeks
- Variable plasma density and temperature
  Irradiated materials
- Liquid metals



Upstream dump region

Helicon region
Density control

ECH region
Electron temperature control

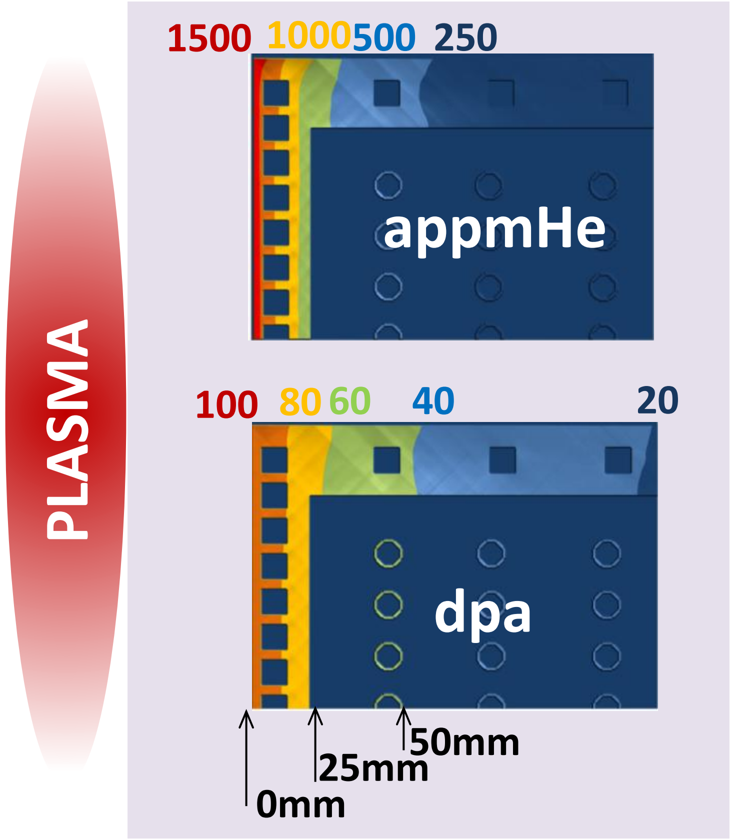
ICH region
Ion temperature control

PMI region
Material exposure

Target Exchange Cart (TEC)
Transports target in-vacuum to analysis station

*However, fusion structural materials have significant synergies with fission neutron damage**

Helium production (appm) for 100 dpa at plasma facing side

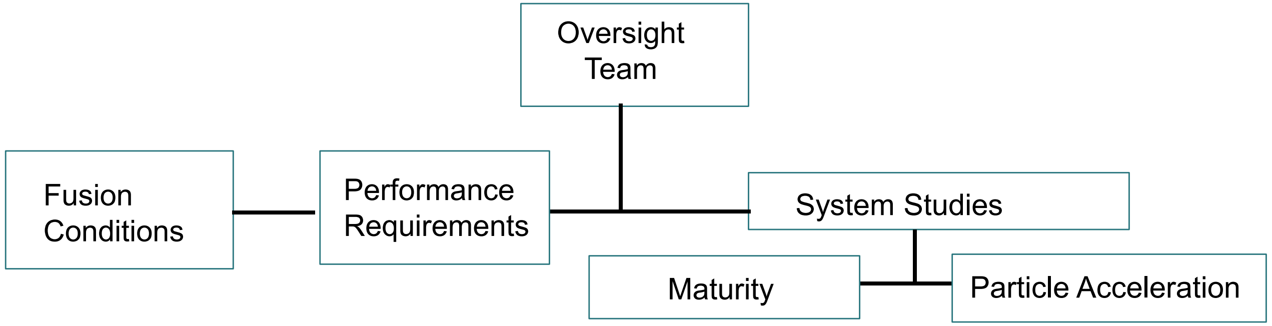


H. Tanigawa, E.Wakai 2012

- ❑ "Only" the first few centimeters have a high He/dpa ratio
- ❑ In addition this part of the blanket carries the highest thermo-mechanical loads
- ❑ Therefore,
  - fission reactor irradiations are still meaningful for a significant fraction of in-vessel components and the fusion blanket
- ❑ Nevertheless, a dedicated fusion neutron source is indispensable, but has to focus on plasma-near materials and loading conditions

** A. Möslang, PFMC (2015)*

FPNS Risk Reduction Evaluation Activity Organization



Address:
Neutron spectrum
Transmutations
Pulse effects

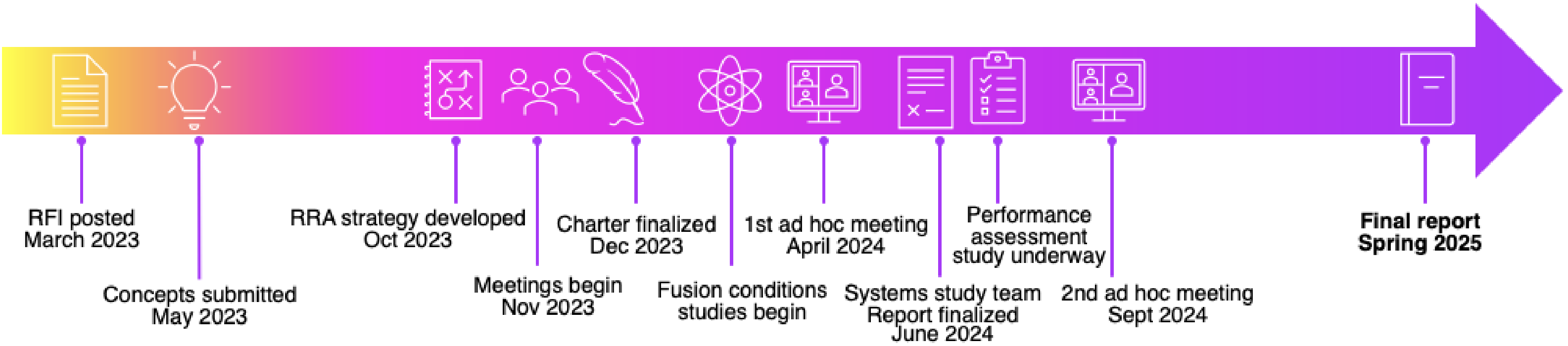
Address:
All systems from a technical standpoint (Fluence, Volume)

Address:
All proposals from a maturity standpoint (TRL)

Address:
Linac vs cyclotron
Different ion sources
Low E acceleration

Risk Reduction Activity process

The risk reduction activity team is comprised of three main committees (fusion conditions, performance requirements, and systems studies) led by an oversight committee. The RRA team systematically reviews the submitted concepts for maturity and ability to meet the performance requirements outlined in the RFI. The goal of the RRA is **not to select a design for a US-FPNS**, but to provide an objective analysis of the possible pathways towards bringing this capability to the U.S. fusion research community.



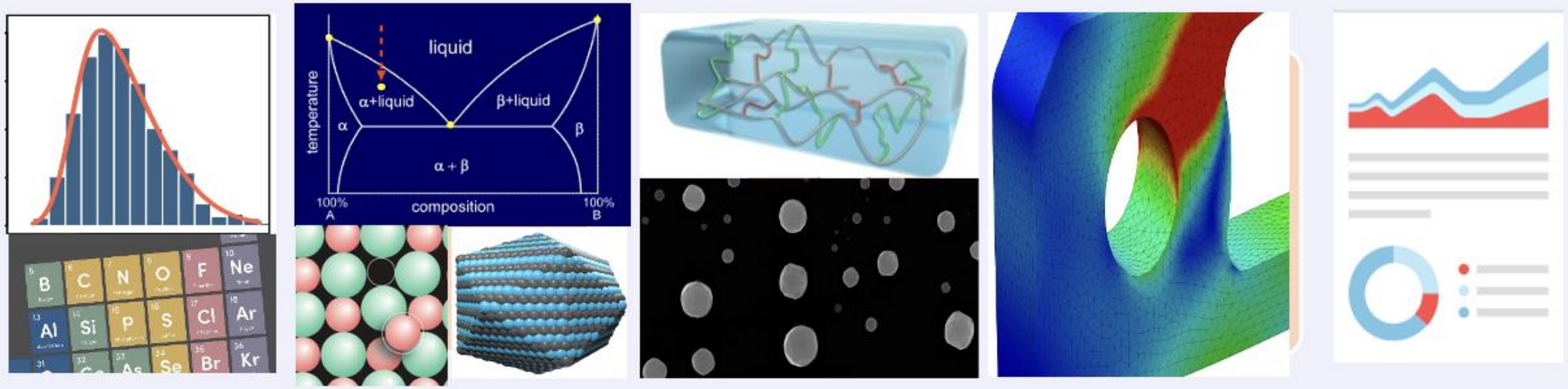
Organizational structure of modeling team

FPNS Concepts:

- DEMO/ITER designs
- D-/Li-stripping source
- Spallation sources
- IFE concepts
- Accelerator concepts

⋮

- Others…



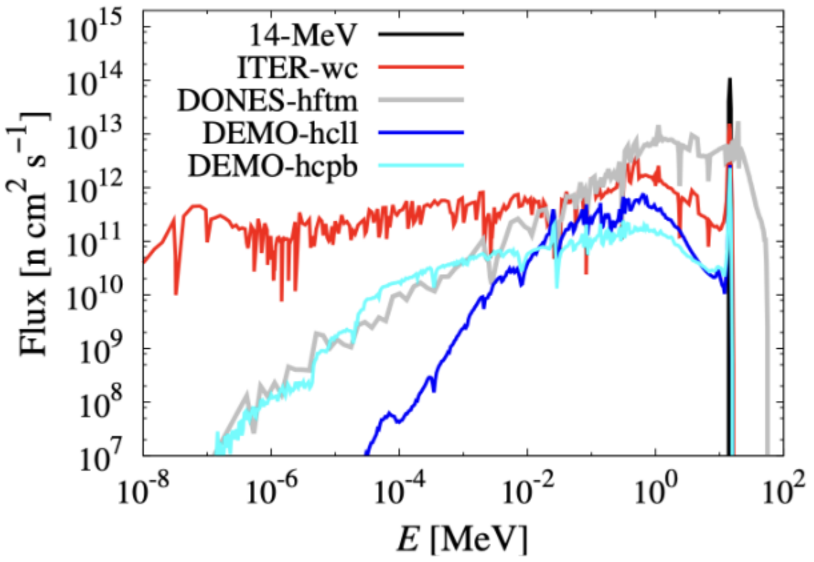
Neutronics/ transmutation	Computational thermodynamics Defect properties	Defect accumulation Irradiation damage Microstructural evolution	Thermal / Mechanical effects and property changes	Final analysis
MIT Stony Brook ORNL	ORNL Stony Brook PNNL	UCLA UT-Knoxville	LANL UCLA UT-Knoxville	UT-Knoxville ORNL UCLA Stony Brook

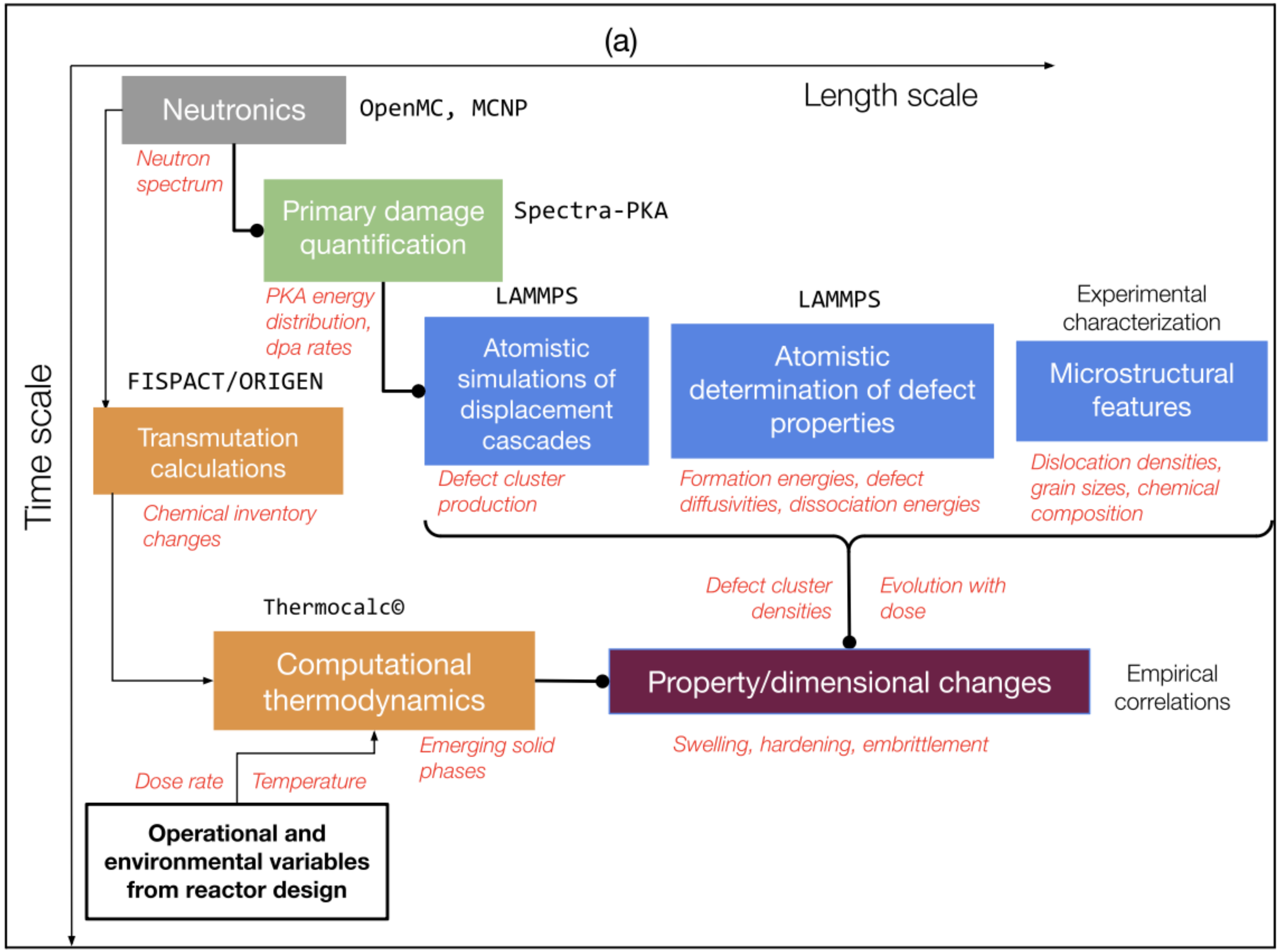
RAFM, W, SiC, V →

Team: Jaime Marian (UCLA), Ying Yang (ORNL), Jason Trelewicz (SBU), Wahyu Setyawan (PNNL), Ethan Peterson (MIT), Lance Snead (SBU/MIT), and B.D. Wirth (UTK)

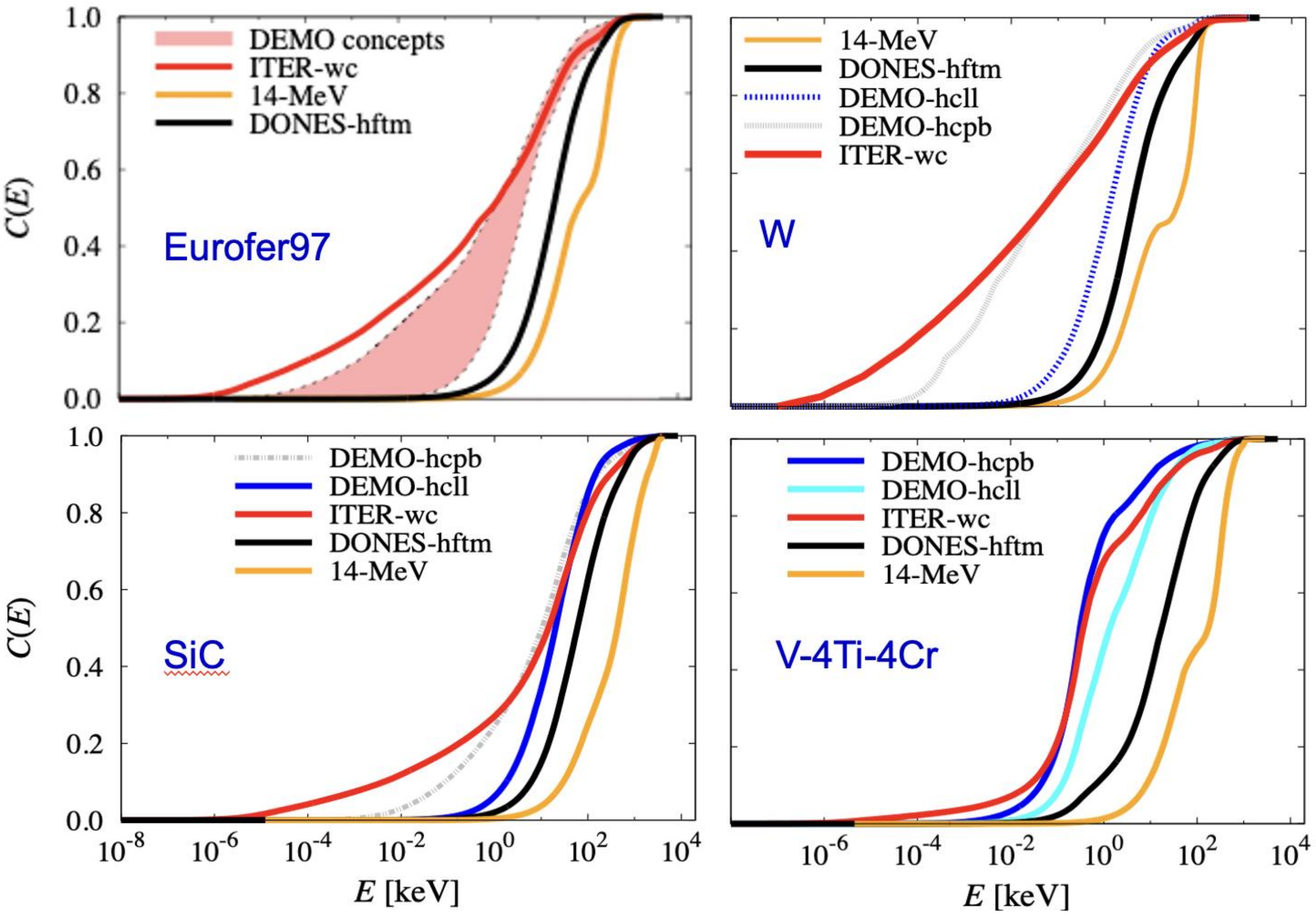
Materials Science Evaluation: from neutronics to thermodynamics

Concepts under consideration:
- ‘**14-MeV**’: ideal single-peaked 14-MeV neutron source
- ‘**ITER-wc**’: water-cooled equatorial plane first wall in ITER
- ’**DEMO-hcll**’: He-cooled Li-Pb blanket DEMO design.
- ’**DEMO-hcpb**’: He-cooled solid ceramic breeder DEMO design.
- ‘**DONES-hftm**’: D/Li-stripping source (high flux test module)

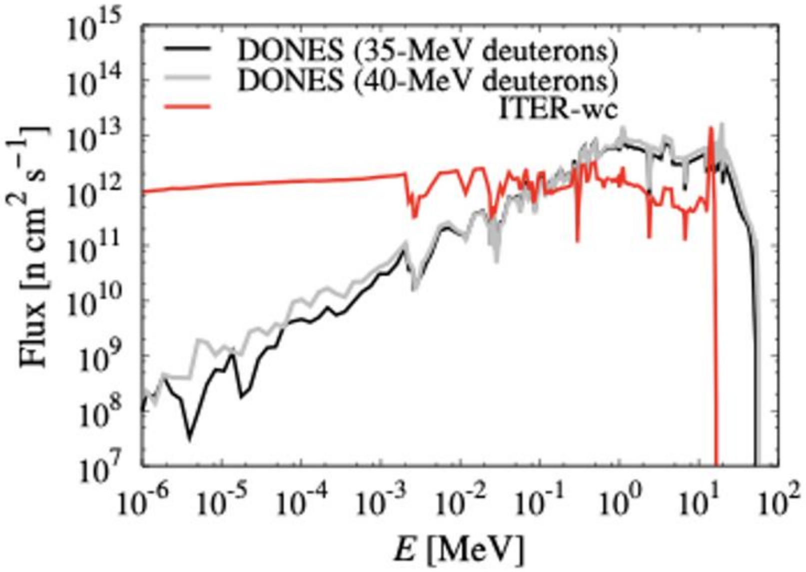




*Damage production**



Analysis performed with SPECTRA-PKA (TENDL-17 nuclear data libraries) [Gilbert et al (2015)]

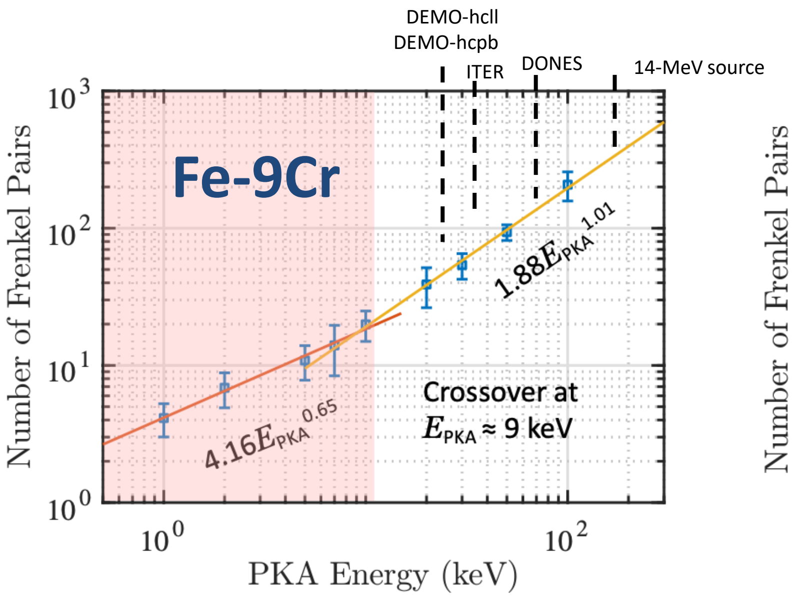


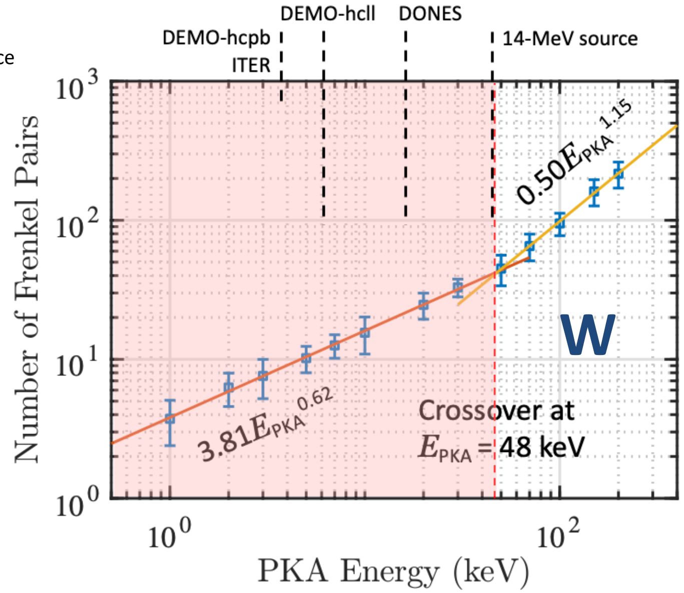
Fluxes for W first wall

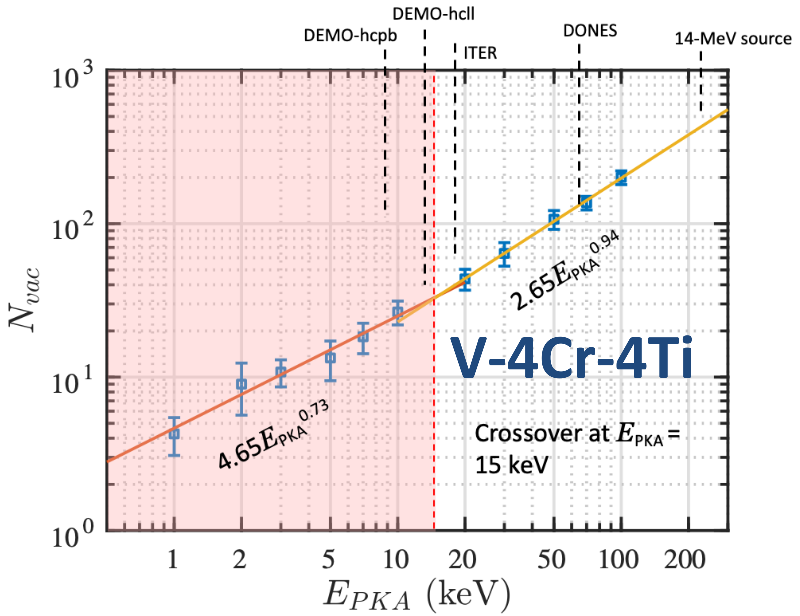
** J. Marian, W. Setyawan, Y. Yang, … and B.D. Wirth, Current Opinion in Solid State Materials Science* **38** *(2025) 101231.*

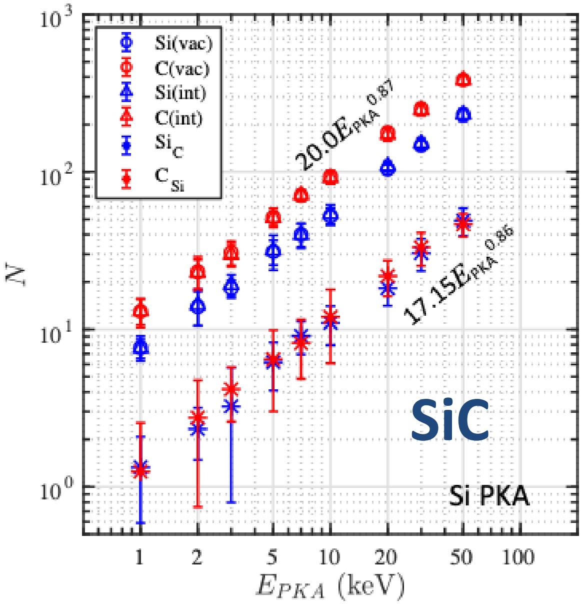
Defect production in high-energy displacement cascades*

Large scale molecular dynamics simulations to quantify defect production as a function of PKA energy









* *J. Marian, W. Setyawan, Y. Yang, … and B.D. Wirth, Current Opinion in Solid State Materials Science* **38** *(2025) 101231.*

Transmutation/Thermodynamic analysis*

Includes calculation of solid transmutants, and thermodynamic phases

Eurofer97

Phase	D/Li-stripping source (40 MeV)	ITER-wc	DEMO-hcpb	DEMO-hcll	14-MeV source
Corundum (Al_2O_3+Cr)	50 dpa (400°C) to 100 dpa (500°C)	50 dpa (400°C) to 150 dpa (550°C)	50 dpa (400°C) to 100 dpa (450°C)	50 dpa (400°C) to 100 dpa (450°C)	50 dpa (<450°C)
TiC	100 dpa (400°C) TO 50 dpa (650°C)	50 dpa (all temperatures)	50 dpa (<450°C)	50 dpa (<450°C)	50 dpa (all temperatures)
C14-Laves phases (dissolution)	No appreciable reduction, except ≈20% at 600°C	≈20% reduction with dose up to 600°C	No appreciable reduction	No appreciable reduction	≈20% reduction with dose up to 600°C
σ phases	0 dpa (400°C) and 100 dpa (450°C)	0 dpa (400°C) and 100 dpa (500°C)	0 dpa (400°C) and 100 dpa (450°C)	0 dpa (400°C) and 100 dpa (450°C)	0 dpa (400°C) and 100 dpa (500°C)
Metal carbides/nitrides (Ta,V)-(C,N)	No appreciable change	Strong decrease at all temperatures	No appreciable change	No appreciable change	Slight decrease at all temperatures

Tungsten

Phase	D/Li-stripping source (40 MeV)	ITER-wc	DEMO-hcpb	DEMO-hcll	14-MeV source
σ phases	> 30 dpa	> 10 dpa	N/A	N/A	> 40 dpa
χ phases	> 10 dpa < 500°C	> 10 dpa < 800°C	> 20 dpa	> 20 dpa	> 10 dpa < 500°C
C14-Laves phase ($HfIr_3$)	> 25 dpa	> 40 dpa < 500°C	> 20 dpa	> 20 dpa	> 15 dpa
Intermetallic phases (IrW, HfIr)	N/A	> 20 dpa	N/A	N/A	N/A
Hydride (HfH_2)	> 10 dpa	N/A	N/A	N/A	N/A

10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} $>10^{-1}$

Molar fraction

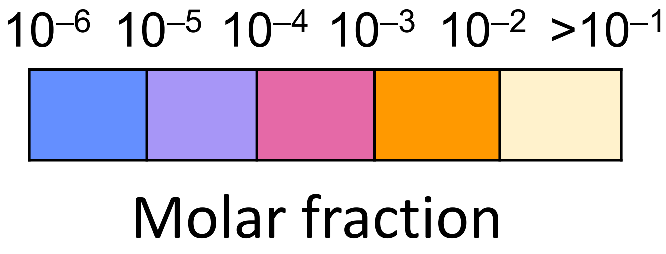
** J. Marian, W. Setyawan, Y. Yang, … and B.D. Wirth, Current Opinion in Solid State Materials Science* **38** *(2025) 101231.*

*Transmutation/Thermodynamic analysis**

Includes calculation of solid transmutants, and thermodynamic phases

SiC

Phase	D/Li-stripping source (40 MeV)	ITER-wc	DEMO-hcpb	DEMO-hcll	14-MeV source
MgH_2	All doses and temps	All doses and temps	All doses and temps	All doses and temps	All doses and temps
Mg_2Si	N/A	All doses, T<600°C	All doses, T<600°C	All doses, T<600°C	All doses, T<600°C
Pure Be (solid)	>20 dpa	All doses and temps	>20 dpa	>20 dpa	All doses and temps
Pure Al (liquid, solid)	>20 dpa	All doses and temps	>20 dpa	All doses and temps	All doses and temps
AlB_2	>20 dpa	N/A	N/A	N/A	N/A
Pure Si (solid)	>20 dpa (>30 dpa at at T<500°C)	All doses and temps, decreases with dose	>20 dpa (>30 dpa at at T<500°C)	>10 dpa (>20 dpa at at T<500°C)	All doses and temps



V-4Cr-4Ti

Phase	D/Li-stripping source (40 MeV)	ITER-wc	DEMO-hcpb	DEMO-hcll	14-MeV source
H_2 (gas)	> 700°C	> 700°C	> 700°C	> 700°C	> 700°C
TiH_2	< 700°C	< 700°C	< 700°C	< 700°C	< 700°C

** J. Marian, W. Setyawan, Y. Yang, … and B.D. Wirth, Current Opinion in Solid State Materials Science* ***38*** *(2025) 101231.*

Materials – tritium issues require additional research

- Identification of a robust, efficient and economic method for extraction of tritium from high temperature coolants
  - Large number of potential tritium blanket systems is both advantageous and a hindrance
- Current materials science strategies to develop radiation-resistant materials may (or may not) lead to dramatically enhanced tritium retention in the fusion blanket
  - Fission power reactors (typical annual T_2 discharges of 100-800 Ci/GW_e; ~10% of production) are drawing increasing scrutiny
  - A 1 GW_e fusion plant will produce ~10^9 Ci/yr; typical assumed releases are ~0.3 to 1×10^5Ci/yr (<0.01% of production)
  - Nanoscale cavity formation may lead to significant trapping of hydrogen isotopes in the blanket structure
  - Tritium trapping efficacy of precipitates and nanoscale solute clusters (blanket & piping) is poorly understood from a fundamental perspective

Status of vanadium alloys in fusion blankets*

Coolant	Compatibility	Effects of magnetic field	Tritium leakage	Tritium recovery	Tritium inventory in V-alloy	Technological challenge
Liquid Li	Minor	Critical (MHD pressure drop)	No	Critical	Minor	MHD coating T recovery
Li–Pb	Critical (oxidation, Pb attack)	Critical (MHD pressure drop)	Moderate to critical	Moderate	Moderate to critical	MHD coating Corrosion protection T permeation barrier
FLiBe	Critical (fluoridation, oxidation)	Moderate (thermofluid)	Critical	Moderate	Critical	Corrosion protection T permeation barrier
He	Critical (oxidation, nitriding)	No	No	Critical	Minor	Corrosion protection T recovery

- Corrosion, MHD and tritium barrier coatings require substantial R&D effort, and lack of stable coating technology led U.S. Fusion Materials Program to de-prioritize V-4Cr-4Ti alloys *(shifted to dual-cooled lead-lithium blanket with SiC flow channel inserts and RAF/M structure)*

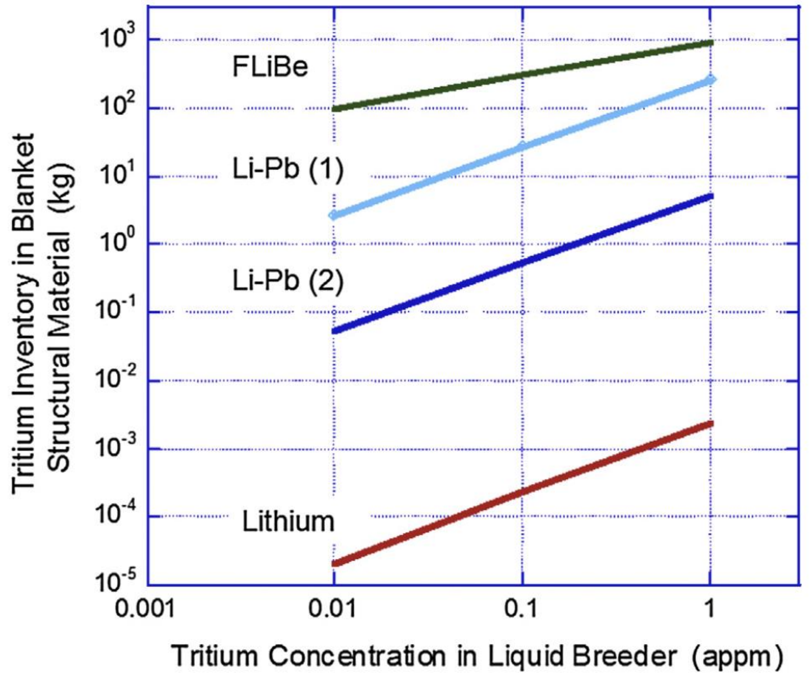


Fig. 1. Equilibrium tritium inventory in V–4Cr–4Ti structural materials at 1000 K for three tritium breeders as a function of tritium level in the breeders assuming self-cooled FFHR reactor [16]. The physical values assumed were shown in the text.

*Ref: T. Muroga, J.M. Chen, V.M. Chernov, R.J. Kurtz, M. Le Flem, *J. Nucl. Mater.* **455** (2014) 263-286.