STEP

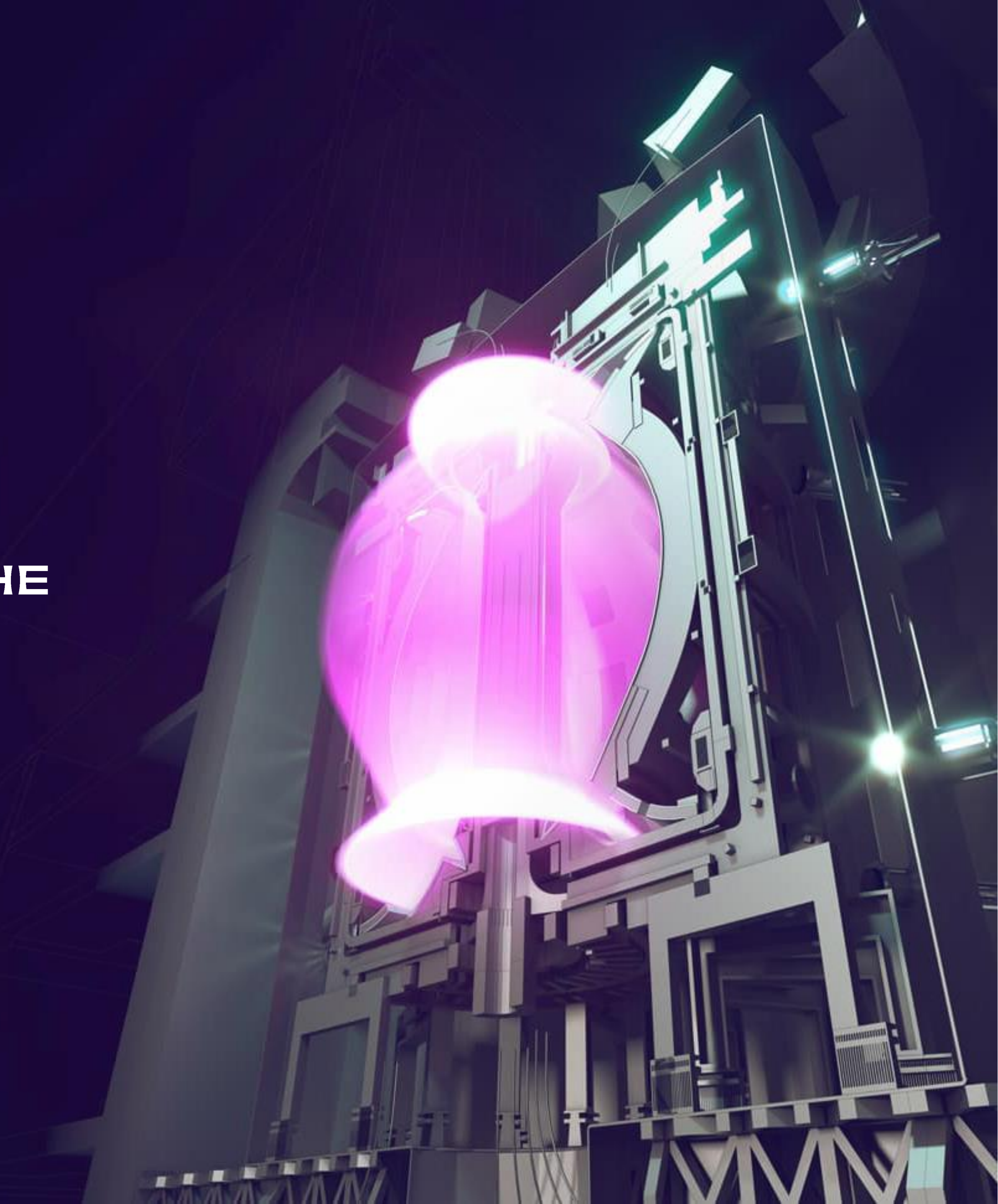
DESIGN EXPLORATION AND TECHNOLOGY DEVELOPMENT OF THE STEP LI2O CERAMIC BREEDER BLANKET

CHRIS HARRINGTON, ADITYA PIDAPARTHY,
& THE STEP BLANKETS TEAM

OUTBOARD FIRST WALL AND BREEDER BLANKET
SYSTEM LEAD

IAEA Technical Meeting on Tritium Breeding Blankets and Associated Neutronics

IAEA Headquarters, Vienna, Austria, 2nd – 5th September 2025



"DELIVER A UK PROTOTYPE FUSION ENERGY PLANT, TARGETING 2040, AND A PATH TO COMMERCIAL VIABILITY OF FUSION"

STEP MISSION

OUTLINE

Context:
STEP Prototype Powerplant (SPP) breeding challenges

Background:
Breeder and structural material re-selections

Design Exploration:
Performance window and design constraints

Technology Challenges:
Known risks and potential mitigations

Future Roadmap:
Testing and technology demonstration needs

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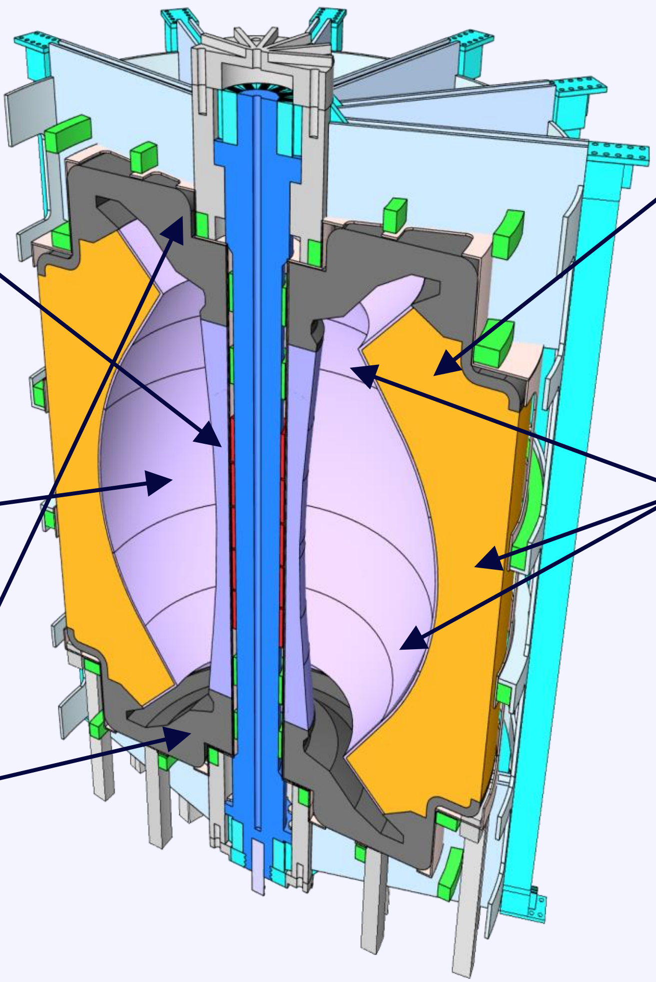
FUNCTIONAL REQUIREMENTS

Key Functional Requirements

Breeder Blanket

- Extract Thermal Power
- Breed Tritium for Fuel Self Sufficiency
- Provide Radiation Shielding

STEP Prototype Powerplant (SPP) Specific Challenges



No inboard breeding for compact spherical tokamak design

Aspect ratio = 1.8

Double null divertor configuration for heat load management

600 °C outlet temperature for net power confidence

Upper, lower, and midplane limiter coverage for plasma uncertainty

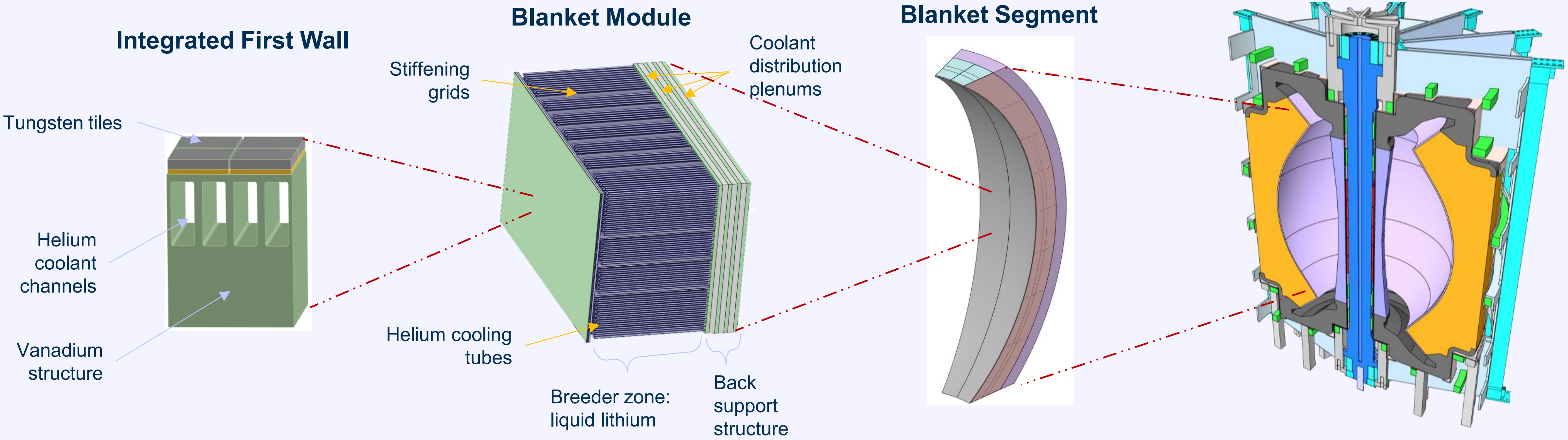
Release to manufacture **mid-2030s**

SEPTEMBER 2023: LIQUID LI AND ASSOCIATED CHALLENGES

Design Rationale
• Liquid lithium blanket provides **greatest breeding** within spherical tokamak constraints
• Helium cooling to reduce MHD issues
• Vanadium structure for Li compatibility

Blanket Specification
Type: Helium-Cooled Lithium
Coolant: Helium ~460 ^{o}C in, 600 ^{o}C out
Structural material: Vanadium
Breeder: Pure liquid Lithium (35–45%) Li6 enrichment
Multiplier: None

Development Challenges
Vanadium supply chain
Tritium extraction from lithium
Lithium safety and reliability
Helium leakage and pipe integration
Vanadium-lithium irradiation data



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BREEDER OPTIONS: COMPARISON SUMMARY

Breeder	TBR	Tritium Transport/FC	Thermal Mgmt./Performance	Material Compatibility	Safety/Stability	Power	Composite Risk
Li	++	-	++	-	--	++	--
Li_2O	**+**	**++**	**O**	**O**	**+**	**++**	**+**
Li_7Pb_2	++	--	--	O	--	++	O
Li_4SiO_4	O	++	-	+	O	+	O
Li_4SiO_4-Li_2TiO_3	-	++	-	+	O	+	O
Li_8PbO_6	O	-	--	???	+	+	-
$Li_{17}Pb_{83}$	--	-	++	+	O	--	--
$Li_{50}Pb_{50}$	++	???	++	???	???	--	--
FLiBe	--	+	+	--	O	-	--

LEGEND	
++	Looks very promising, Almost no issues found or very minor concerns.
+	Looks promising. Some issues found. But generally, looks manageable.
O	Middling performance or Some important concerns, or marginal properties. Needs further study.
-	Poor performance. Some major concerns, would require massive effort.
--	Very Poor Performance. Mostly improbable for SPP timelines.
???	Significant unknowns/uncertainty constituting major risk for SPP timelines.

STRUCTURAL MATERIALS: COMPARISON SUMMARY

Requirements	Target performance	Grade 92	Ti-modified Austenitic Stainless Steel
Resistance to irradiation swelling	Swelling at 10 dpa < 1%	< 1% up to 100s dpa (ion irradiation)	< 1% up to 50 dpa
High temperature strength (irradiated & unirradiated)	Yield strength > 300 MPa	> 150 MPa at 650°C	YS of ~500MPa at 650°C
Creep rupture strength (unirradiated)	At 650°C for 5200h > 100MPa	~100MPa at 650°C (unirradiated)	~200 MPa at 650C
Resistance to irradiation induced embrittlement	DBTT < 350°C	249°C after n irradiation to 2.5dpa at 300°C	No DBTT
Low temperature hardening embrittlement after 10 dpa	Change in YS < 50%	Possible – YS increases 60% following irradiation to 6.5dpa at ~295°C.	YS increases 17% up to 51 dpa
Strain at rupture	(after 10 dpa) > 5%	Unlikely – total elongation 2.7% after at 6.5dpa	~9% up to 54dpa (at 510C) Creep rupture elongation ~2-3% after 5000hrs life (700C)
Fracture toughness at minimum operating temperature (10dpa)	> 70 MPa.$\sqrt{m}$	Likley - KJq ~145MPa.m0.5 at 650°C	~60MPa.m0.5 at 400°C, irradiated at 410 °C
Time to LLW (~3FPY)	< 200 years	Yes (~30years)	No (~400years)
Supply chain readiness	TRL > 4	Yes (5-6)	Yes (DIN1.4970)
ΔTBR	>= 0	0	-0.03
Coatings compatibility	Good compatibility	CTE mismatch 44%	CTE mismatch 33%
Compatibility with CO2	Good compatibility	Formation of dual-layered oxide	High-Cr alloy.
H/He embrittlement	No concern	Unknown at relevant fusion conditions	Unknown effect of He generation at high energy n

SOLID BREEDER DESIGN SPACE

- **Breeder Material:** Lithium Oxide (Li_2O)
- **Coolant:** Carbon Dioxide (CO_2)
- **Multiplier:** Titanium Beryllide ($Be_{12}Ti$)
- **Structural Material:** Ti-modified Austenitic Stainless Steel
- **Tritium Carrier (Purge) Gas:** Helium
- **Coating:** Yes (Yttria/Erbia/Alumina)
- ***Blanket Architecture:** Work in Progress…*

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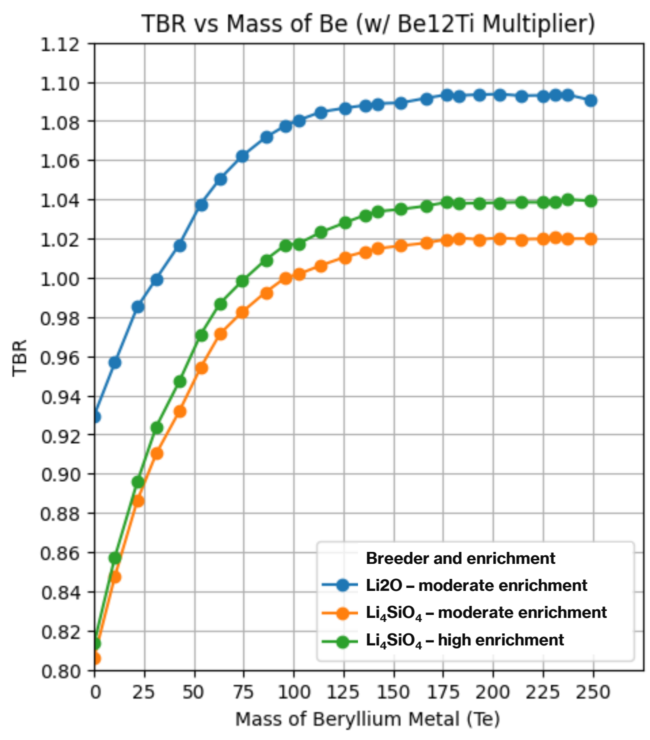
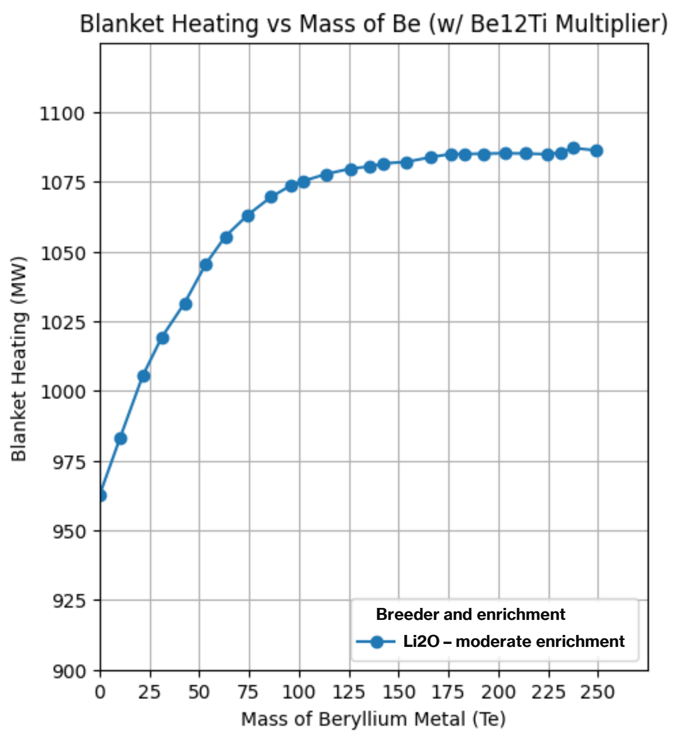
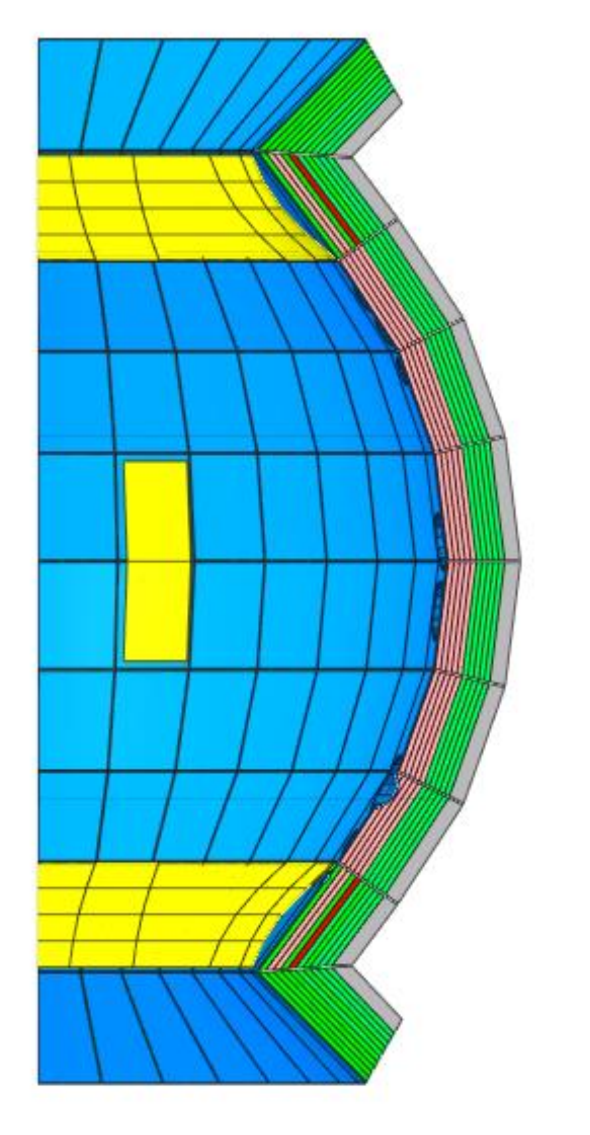
TRITIUM BREEDING PERFORMANCE

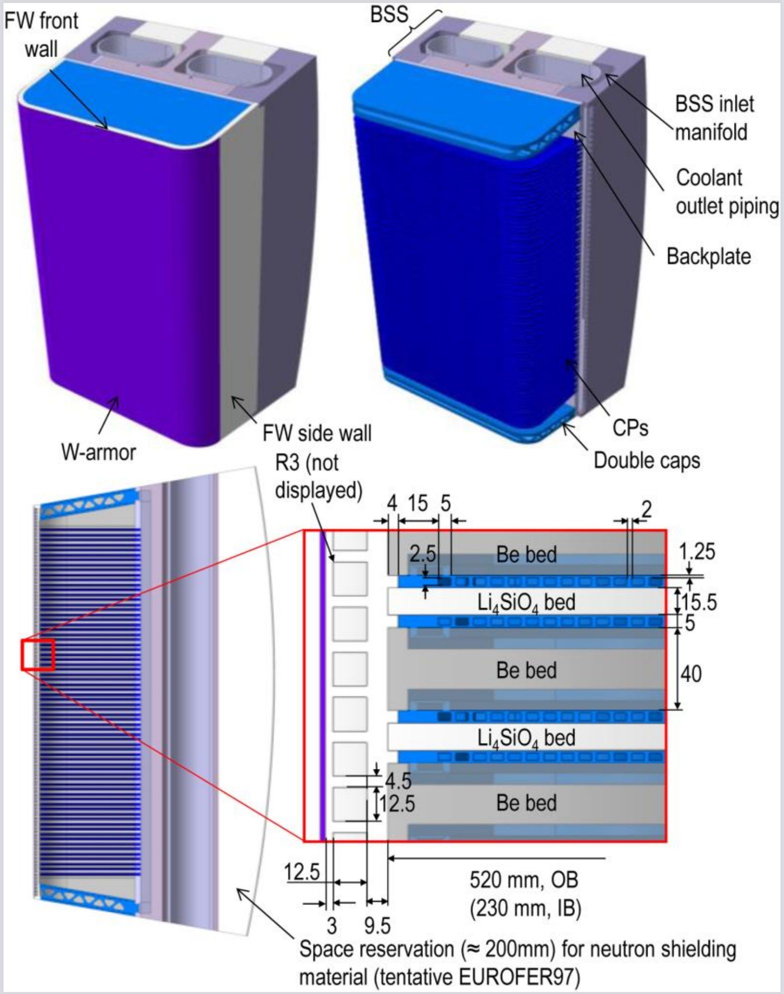
- OpenMC model with radially and poloidally varying volume fractions of breeder, multiplier, structure, and coolant
- Placement of Be12Ti placed strategically to give maximal TBR increase per additional mass (most efficient near first wall at the equatorial plane)
- TBR plateaus with around 125 Te of BeTi





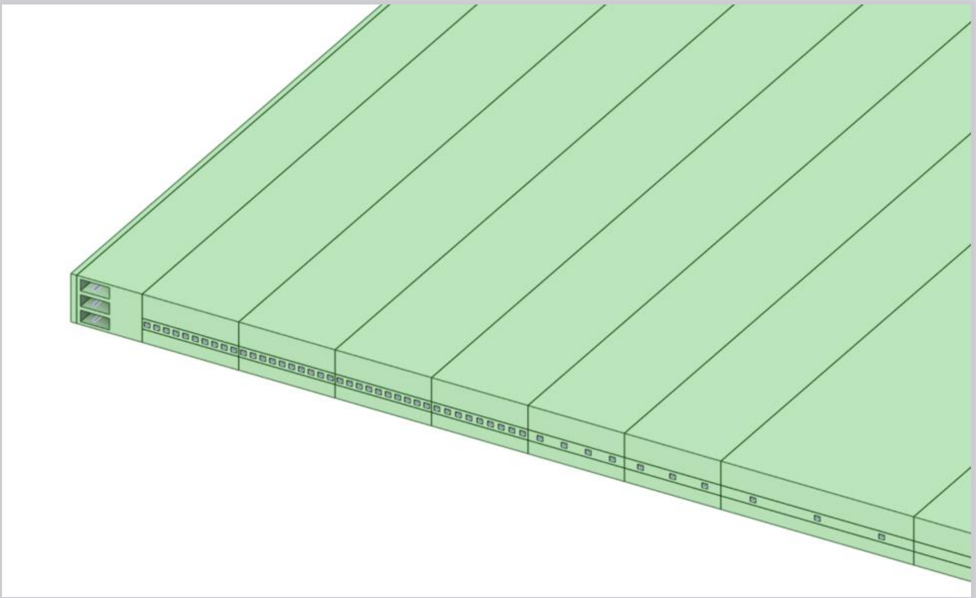


THERMAL PERFORMANCE ASSESSMENT



F. Hernandez et al., Fus. Eng. Des., 124 (2017) 882-886

- Assume a layout similar to DEMO HCPB design 2016
- Apply volumetric heating from OpenMC calculation
- Run Ansys steady state thermal analysis (simple thermal conduction problem)
- Coolant flow rates and HTCs calculated from energy balance and number of coolant channels



$v_{coolant}$	18 m/s
T_{in}	440 °C
Peak q'''	27.1 MW/m^3
Li_2O layer height	14 mm
$Be_{12}Ti$ layer height	25 mm
Plate height	5.5 mm

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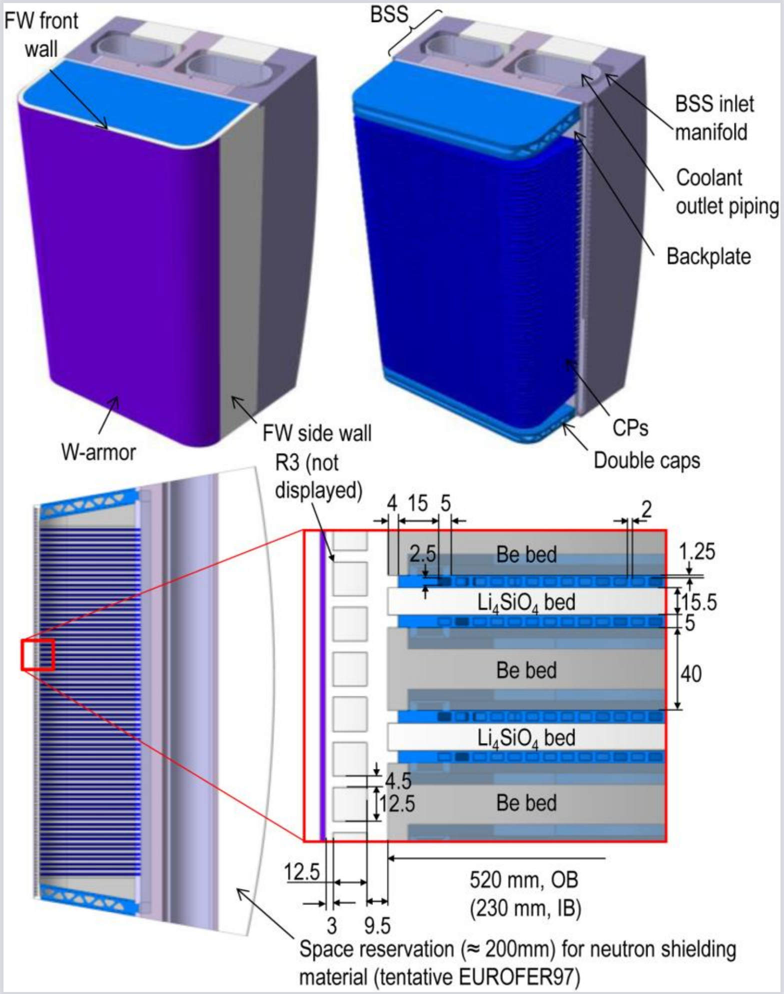

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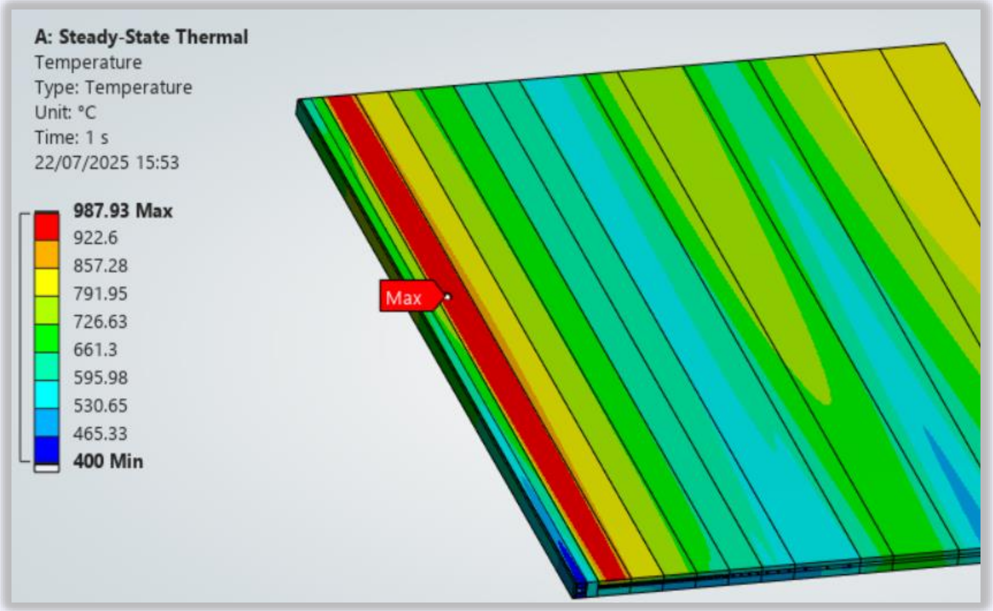

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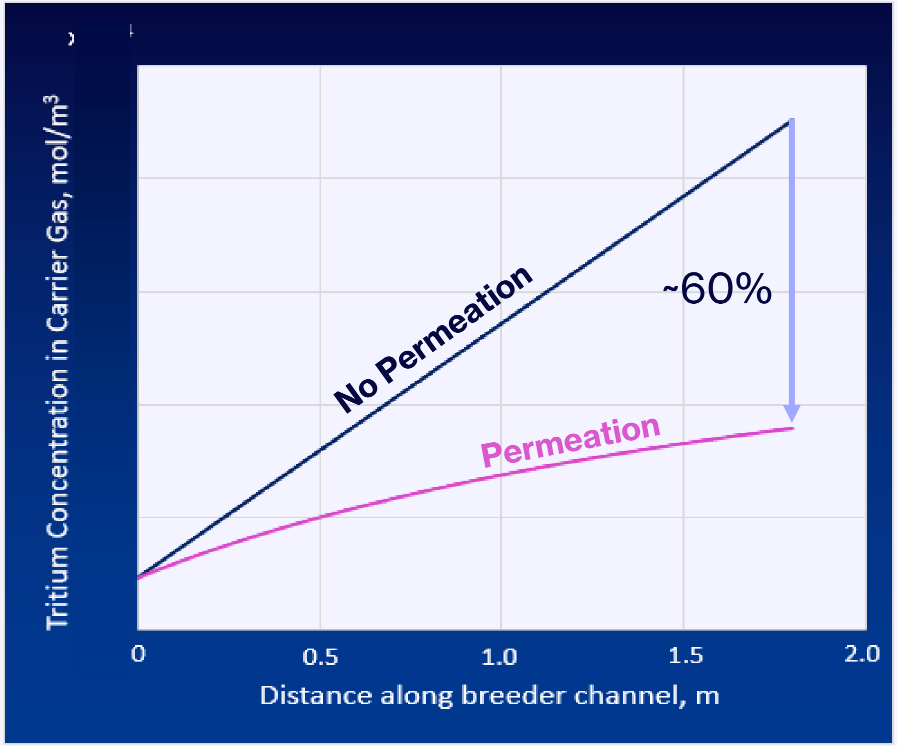
TRITIUM PERMEATION ASSESSMENT

- COMSOL model of unit cell to model tritium permeation into coolant
- Worst-Case Scenario:
  - Significant amount of bred tritium permeates into the coolant
  - Tritium Extraction System (TES) only recovers smaller amount of bred tritium
- Sensitive to temperature, but reduction not possible without significant decrease from 600 °C outlet temp
- Higher purge gas flow helps but quickly leads to high pumping powers

Importance of permeation reduction coatings and/or coolant detritiation



Breeding rate	2.5 x10^{-6} mol/s/m3
Gas velocity	2 cm/s
TES efficiency	90%
Present species	HT (not HTO)
Trapping effects	None

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HISTORICAL ISSUES REPORTED WITH LI2O

Stability, reactivity, and chemical degradation	Corrosion and influence on structural material	Mechanical degradation	Tritium diffusivity
• LiOH generation and equilibrium concentration • Free oxygen equilibrium concentration • Reactivity with CO_2	• Contact corrosion rates • LiOH corrosion rates • Free oxygen corrosion rates • (Dependency of structural material choice)	• Sintering – rates and temperature/ irradiation dependence • Swelling rates under irradiation • Creep deformation rates • Mechanical strength • Fracture / pulverisation under irradiation	• Dependency on oxide layer formation • Dependency on grain growth, bubble or porosity formation • Impact of manufacturing process • Impact of redeposited corrosion products

HISTORICAL DATA: AN 800 °C TEMPERATURE LIMIT?

As we have seen (Section 2.1.2), a major concern with solid breeding materials is preventing them from experiencing temperatures outside their operating range. For Li_2O (see Table 5-3), this range is 410 to 800°C.

Jackson et al., A Review of Fusion Breeder Blanket Technology, CFFTP-G-84033, 1985

	PROPERTIES			RECOMMENDED TEMPERATURE LIMITS	
	MP, °C	ρLi, g/cm^3	K^b, W/mK	T_{min}, °C	T_{max}, °C
Li_2O	1433	0.93	3.4	410[d]	800[c,h]
γ-$LiAlO_2$	1610	0.28	2.2	300[d]	1200[f]
Li_5AlO_4	1047	0.61	2.3	350[d]	780[g]
Li_2SiO_3	1200	0.36	1.5	410[d]	1000[f]
Li_4SiO_4	1250	0.54	1.5	320[d]	950[f]
Li_2ZrO_3	1616	0.33	1.3	400[e]	1400[f]
Li_8ZrO_6	1295	0.68	1.5	350[e]	980[g]
Li_2TiO_3	1550	0.33	2.0	400[e]	1185[g]

Blanket comparison and Selection Study, ANL/FPP-83-1, Volume II, 1983

has a T_2O pressure of ~ 10^{-5} atm. Substitution of these pressures into eq. (3) indicates that the Li_2O temperature should not exceed 800°C. The effect of 10 vppm

Tetenbaum and Johnson, Journal of Nucl. Mat. 120 (1984) 213-216

LIOH–H2O EQUILIBRIUM HISTORICAL ASSESSMENT

$$Li_2O(s) + H_2O(l) \rightleftharpoons 2\,LiOH(aq)$$

- The peak temperature limit allowable for the Li2O is based on equilibrium concentrations of H2O and LiOH expected to be in the system
- The equation used is from *Tetenbaum, J. Nucl. Mater. 120 (1984) 213–216:*

$$\log P_{(LiOH,g)}/atm = -8635/T + 1/2 \log P_{(H_20,g)} + 4.57 \qquad (19)$$

- This gives equilibrium partial pressures of LiOH and H2O at a given temperature

Temps in °C		Achievable H2O concentration (ppm)					
		100	**10**	**1**	**0.1**	**0.01**	**0.001**
Allowable LiOH concentration (ppm)	**100**	1041	1150	1277	1430	1616	1849
	10	868	948	1041	1150	1277	1430
	1	735	**797**	868	948	1041	1150
	0.1	629	679	735	797	868	948
	0.01	544	584	629	679	735	797
	0.001	473	507	544	584	629	679

- The **800 °C** limit is chosen based on assumptions for:
  - The *allowable* LiOH concentration to limit loss of lithium from the breeder volume = 1 ppm
  - The *achievable* H2O/HTO concentration in the purge gas = 10 ppm
- Different assumptions in ppm will lead to different interpretations of the peak temperature limit

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$$\log p_{\mathrm{LiOH}} = 4.5013 - 9297.9/T + 0.5 \log P_{\mathrm{H_2O}} \quad (22)$$

C.E. Johnson et al., International Workshop on Ceramic Breeder Blanket Interactions, University of Tokyo, 1992

- This gives equilibrium partial pressures of LiOH and H2O at a given temperature

Temps in °C		Achievable H2O concentration (ppm)					
		100	<u>10</u>	1	0.1	0.01	0.001
Allowable LiOH concentration (ppm)	100	1157	1276	1417	1586	1793	2051
	10	967	1055	1157	1276	1417	1586
	<u>1</u>	821	**<u>889</u>**	967	1055	1157	1276
	0.1	706	760	821	889	967	1055
	0.01	612	657	706	760	821	889
	0.001	535	572	612	657	706	760

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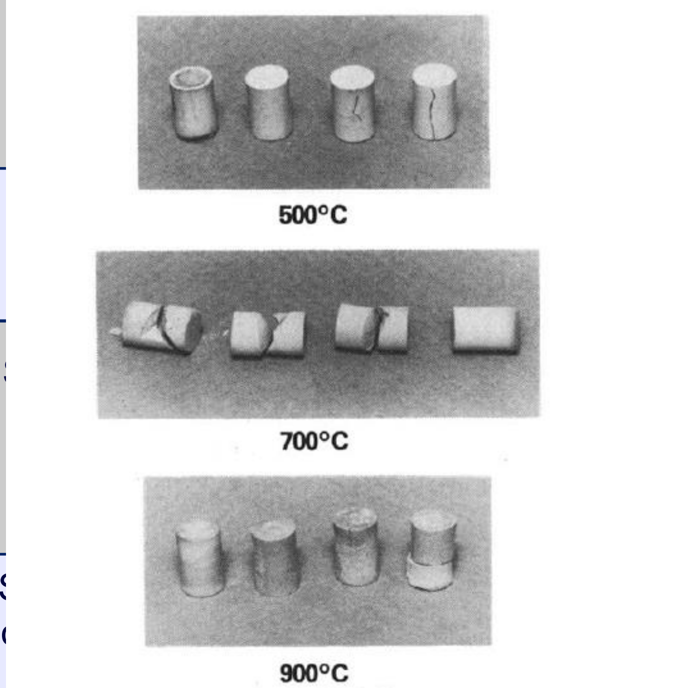
- Different assumptions in ppm will lead to different interpretations of the peak temperature limit
- *Later data suggests an 889 °C limit for the same assumptions!*

Li_2O IRRADIATION SWELLING

Programme	Reactor	Start	Li Burnup	Effective full power days	Reported Volumetric Swelling	Comments
FUBR-1A	EBR-II	1982	~0.5-3%		**6 – 12%**	Shrinkage @ 500 °C, attributed to poor moisture control and LiOH generation.
FUBR-1B	EBR-II	1985	2.5-7%		**-8.5 – 4.4%**	
BEATRIX-I	EBR-II	1986	7-11%*			
BEATRIX-II: Phase I	FFTF	1990	4.8%	300	**~4 – 7%**	
BEATRIX-II: Phase II	FFTF	1991	4.6%	203	***~20%**	
CRITIC-1	NRU	1986	1%		Not reported	



Li_2O IRRADIATION SWELLING CONCLUSIONS

- Despite multiple irradiations, the data, reporting, and understanding of swelling of Li_2O is patchy. Swelling appears to be in the range of 5 – 8% but may be as high as 20%
- Influencing factors include:
  - Bulk temp / temp gradient
  - H_2O/T_2O concentration
  - Geometry/Particle dimensions
  - ^{6}Li enrichment / burnup rate
  - Stress loading and creep rate
  - Initial density / porosity
  - Initial grain size
  - He retention & defect concentration

→ Further irradiation campaigns and post-irradiation characterisation are required to fully quantify and understand swelling susceptibility

- **A mitigating factor for the SPP *may* be lower burnup, burnup rate and availability. However, limitations for commercial plant would still be present.**

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Reported risks with LiOH generation and swelling but must be considered in context of SPP

Future Roadmap: Testing and technology demonstration needs

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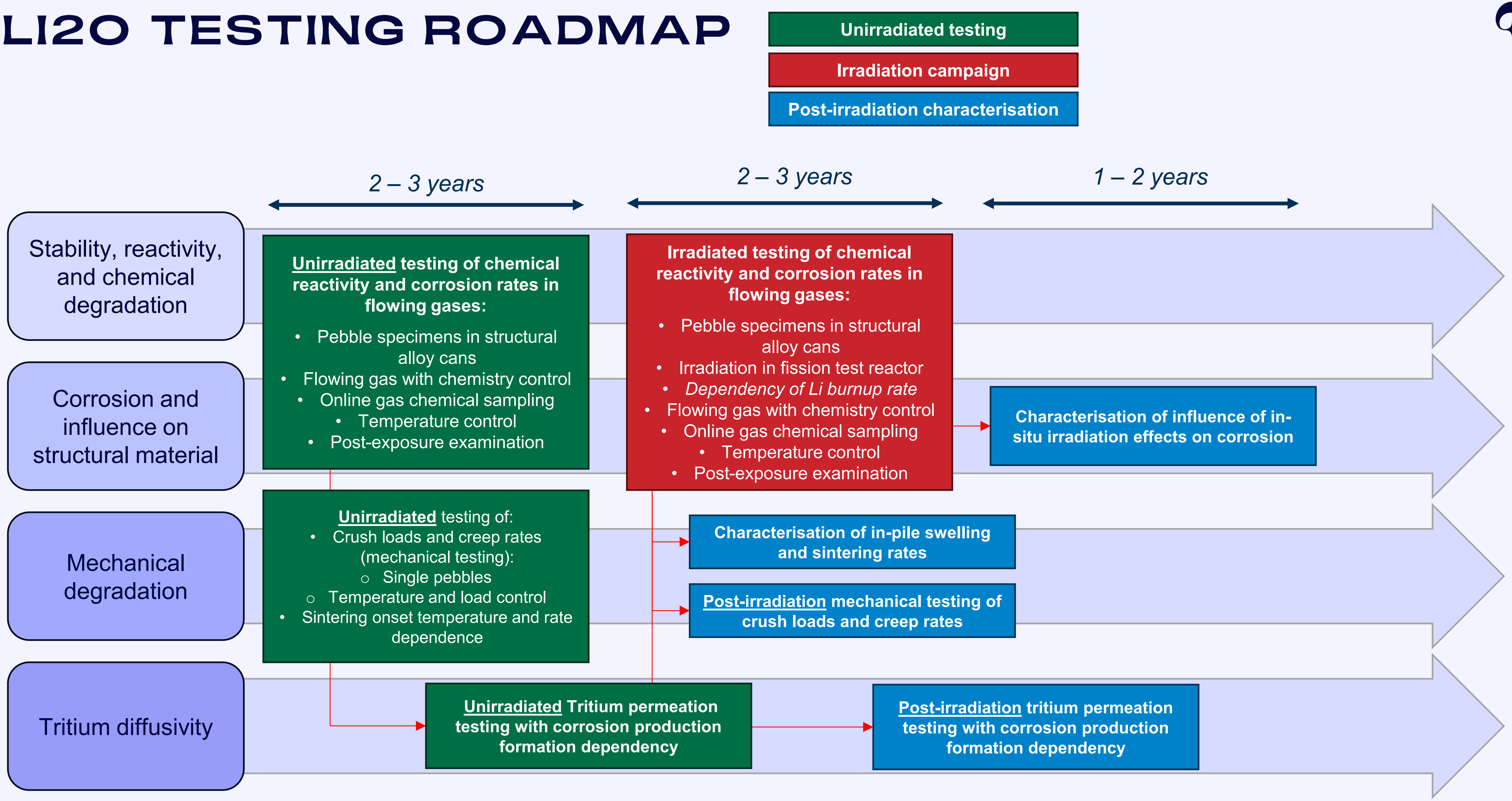
LI2O TESTING ROADMAP



5–YEAR BLANKET DEVELOPMENT ROADMAP

	2025	2026	2027	2028	2029

Milestones

Design Development

- **Multi-physics** modelling development: integrated workflow applied to module design
- **Module Concept Design** Development
- Plant-scale segmented **component design** development and **integration** with all Outboard systems
- **Design iteration:** increasing fidelity, feedback from testing & validation, design for manufacture

Material Testing

- **Unirradiated testing:** breeder, structure, & coating compatibility
- **Fission neutron irradiation** materials testing for > 10 dpa in breeder/structure
- **Proxy irradiation testing** outputs e.g. ion irradiation
- **Design by Fundamentals** development & validation

Manufacturing Trials

- **Manufacturing trials:** fundamental processes for materials and quality control
- Manufacturing prototype **process trials** e.g. coatings, joining
- **Module-scale prototype** manufacture demonstration
- **Unit cell prototype** manufacture demonstration

Tritium Breeding & Transport Performance

- **Tritium permeation testing:** unirradiated and irradiated base material samples
- **Module-scale tritium breeding and transport testing** with D-T neutron source e.g. LIBRTI

Heat Transfer & Mechanical Loads Performance

- **FW Unit cell High Heat Flux testing** (Non-irradiated, elec. heating) e.g. HIVE / HHF-TVF
- **Module-scale thermal-mechanical-EM load testing** at high temperature and B-field e.g. CHIMERA

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Near term testing priorities for known breeder risks; rapid progression to component scale required

STEP

THANK YOU
ANY QUESTIONS?