Characterizing the D-T Fusion Environment

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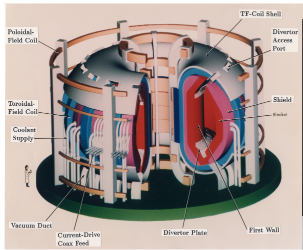
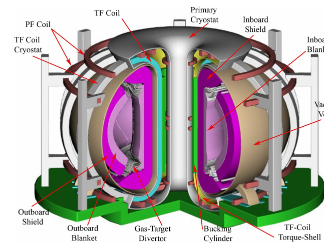
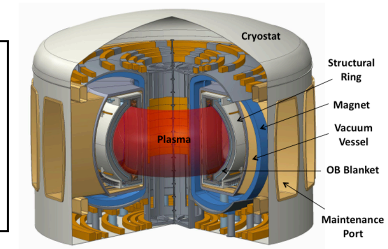
Latitude of Fusion Power Plants Designed Since 1970s Offering Wide Range of Radiation Environment



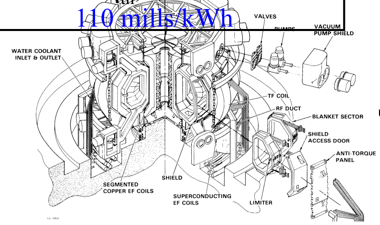
ARIES-I
1000 MW_e, 6.75 m R, 4.5 A
1.9% β_T, 21 T B_c, 16 TFC
SiC/Li_2ZrO_3/He/Be Blanket
49% η_{th}, 76% Avail
87 mills/kWh



ARIES-ACT2
1000 MW_e, 9.75 m R, 4 A
1.5% β_T, 14.4 T B_c, 16 TFC
FS/LiPb/He Blanket
44% η_{th}, 85% Avail
~91 mills/kWh

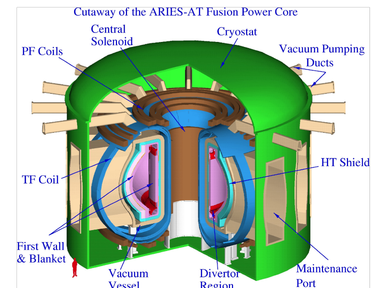


STARFIRE
1st Steady-State Design
1200 MW_e, 7 m R, 3.6 A
6.7% β_T, 11 T B_c, 12 TFC
$PCS/LiAlO_2/H_2O$/Be Blanket
36% η_{th}, 75% Avail
110 mills/kWh

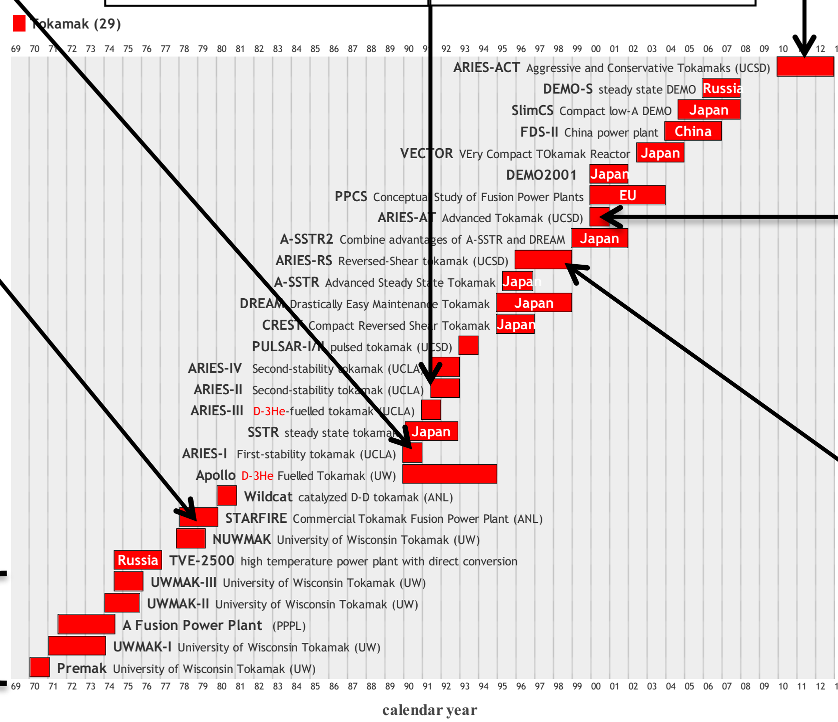


ARIES-II
1000 MW_e, 5.6 m R, 4 A
3.4% β_T, 16 T B_c, 16 TFC
V/Li Blanket
46% η_{th}, 76% Avail
76 mills/kWh

ARIES-IV
1000 MW_e, 6 m R, 4 A
3.4% β_T, 16 T B_c, 16 TFC
SiC/Li_2O/He/Be Blanket
49% η_{th}, 76% Avail
68 mills/kWh



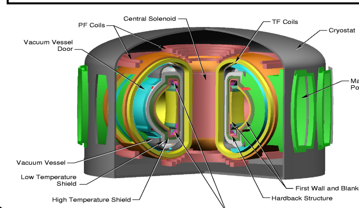
ARIES-AT
1000 MW_e, 5.5 m R, 4 A
9.2% β_T, 11 T B_c, 16 TFC-HT
SiC/LiPb Blanket
59% η_{th}, 85% Avail
48 mills/kWh



1970s **UWMAK series** contributed to basic understanding of fusion power plant design and technology and <u>uncovered undesirable aspects</u> of:

- Pulsed operation
- Low power density machine
- Plasma impurity control problems
- Maintainability issues.

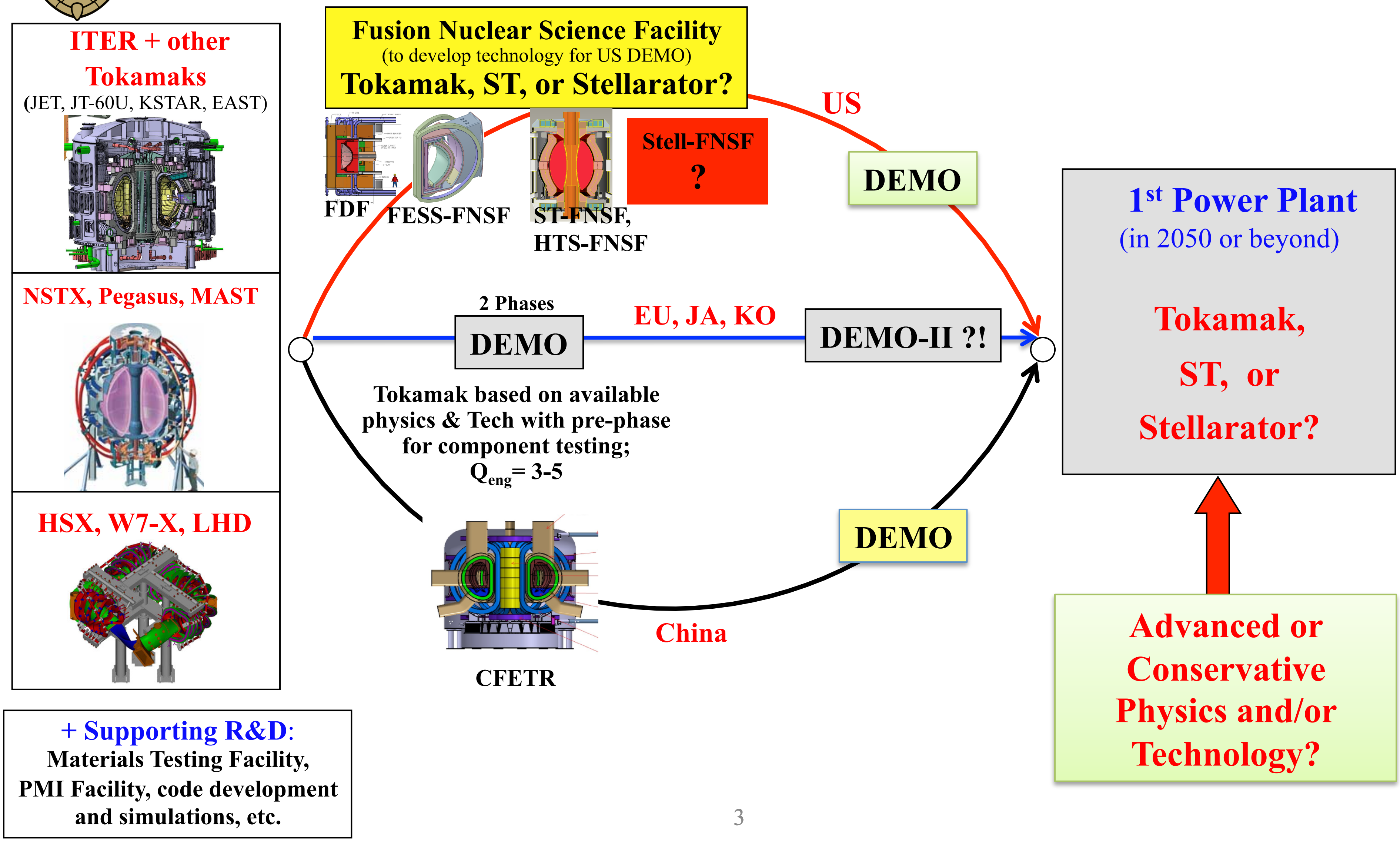
Many proposed technologies are still considered in recent designs: 316-SS, Li and LiPb breeders, solid breeders, Be multiplier, NbTi and Nb_3Sn S/C, solid and liquid Li divertors.



ARIES-RS
1000 MW_e, 5.5 m R, 4 A
5% β_T, 16 T B_c, 16 TFC,V/Li
46% η_{th}, 76% Avail
76 mills/kWh

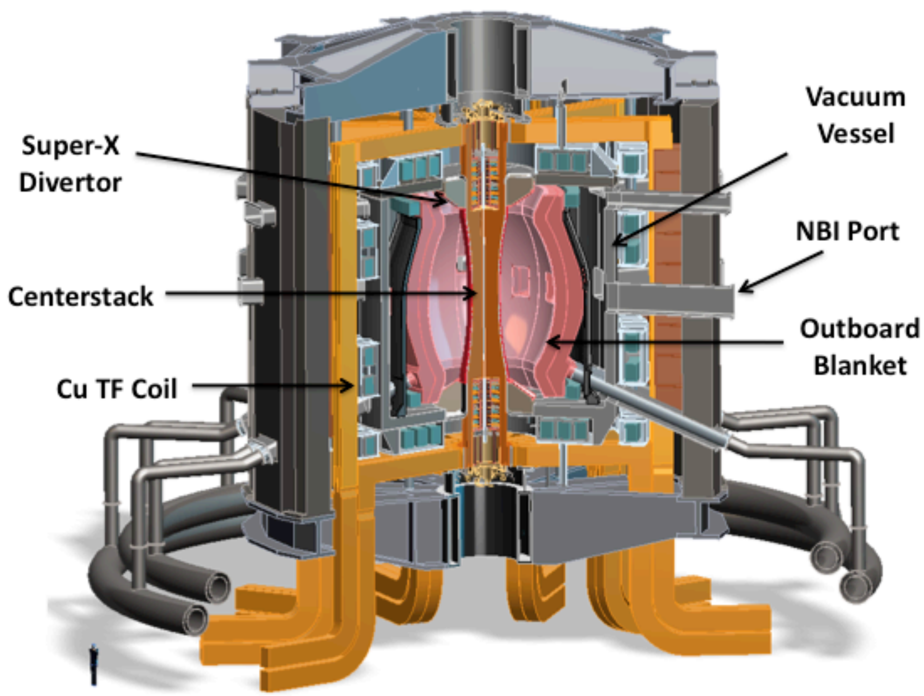
COE in 1992 US $

Transition from Existing Experimental Facilities to First Power Plant Calls for 2-Machines in US Roadmap to Fusion Energy



FNSF Multi-Institution Designs

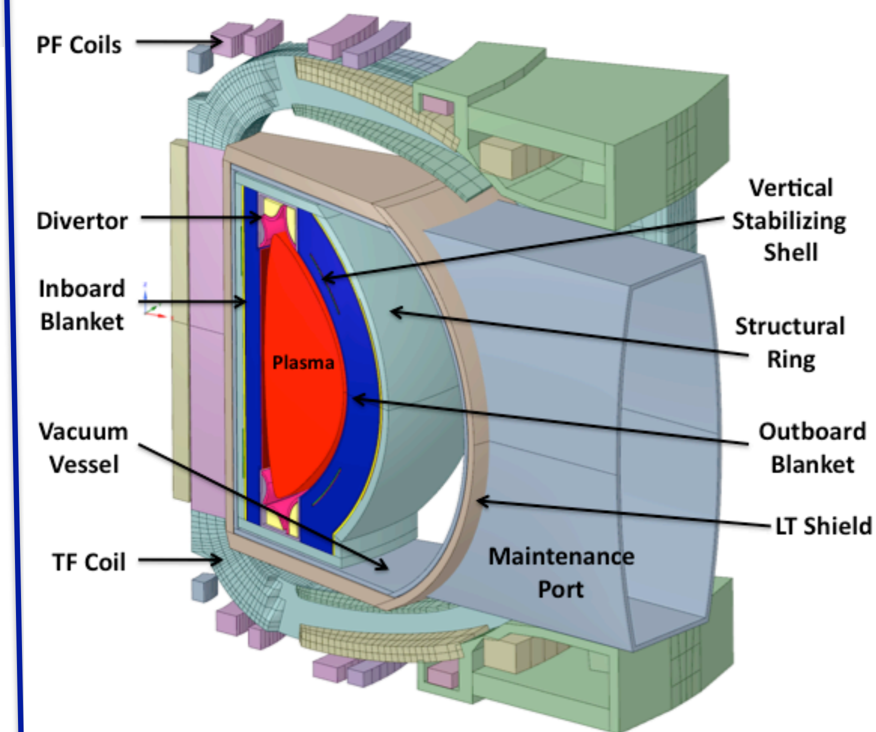
Spherical Tokamak
(PPPL)



ST - FNSF

J. Menard (PPPL)

Tokamak
(DOE Fusion Energy System Study)



FESS - FNSF

C. Kessel (PPPL)

4

Peak Radiation Damage to RAFM Alloy of FW/DCLL Blanket

14.1 MeV neutrons and 1 MW/m^2 NWL result in:

~ 10 dpa/FPY

~ 100 He appm/FPY

~ 400 H appm/FPY

He/dpa ratio ~ 10

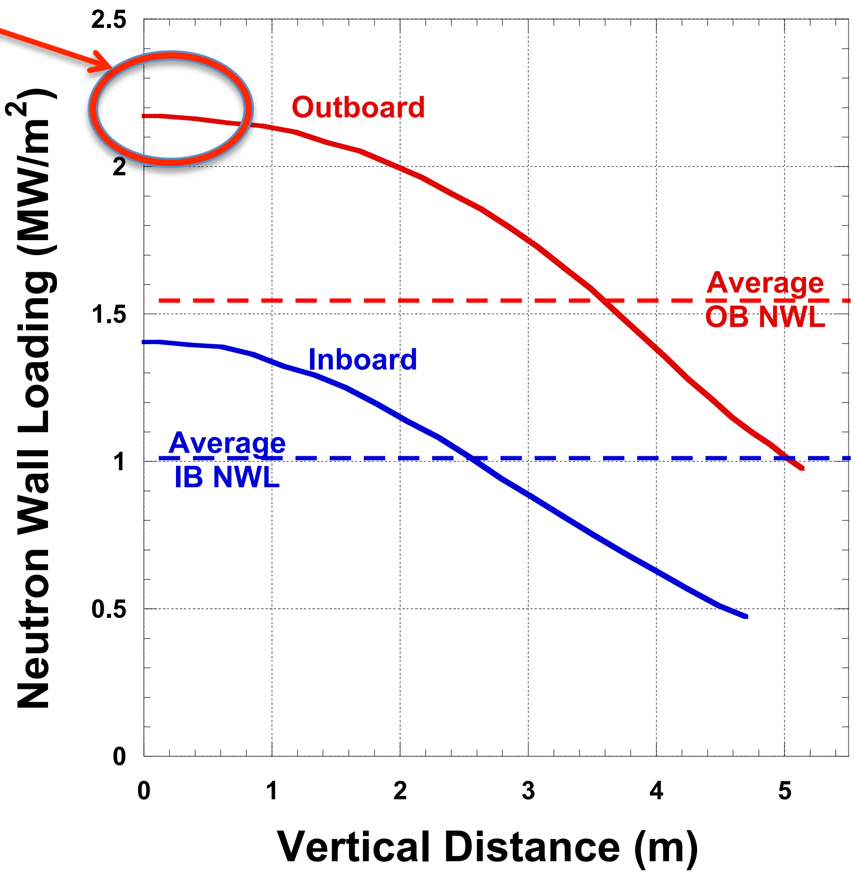
H/dpa ratio ~ 40

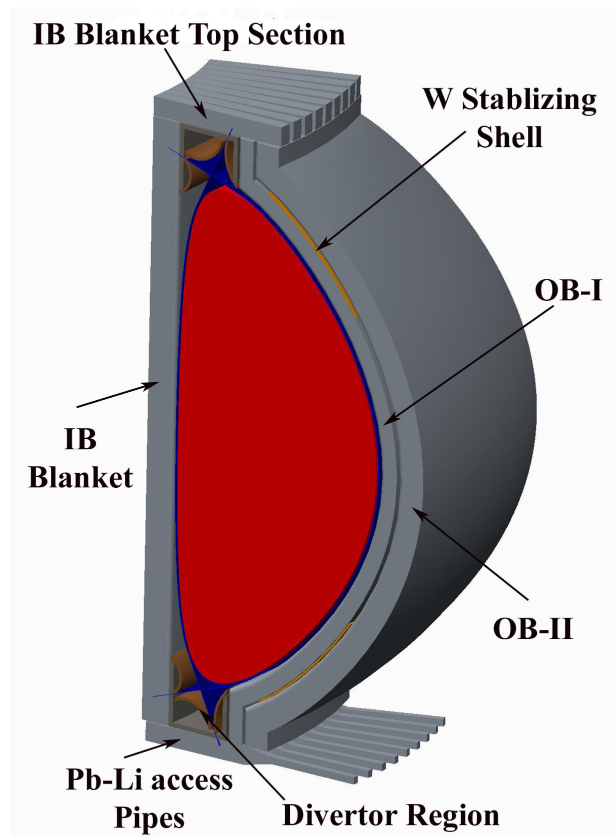
Neutron Wall Loading (NWL) – Indicative of Radiation Level and Replacement Frequency of Fusion Components

NWL is scalable with fusion power and FW area

ARIES-ACT2
(2637.5 MW P_f; $R= 9.75$ m)

NWL always peaks at OB midplane, suggesting potential locations for blanket and materials testing





Ref.: L. El-Guebaly, L. Mynsberge, A. Davis, C. D'Angelo, A. Rowcliffe, B. Pint, "Design and Evaluation of Nuclear System for ARIES-ACT2 Power Plant with DCLL Blanket," Fusion Science and Technology, in press.

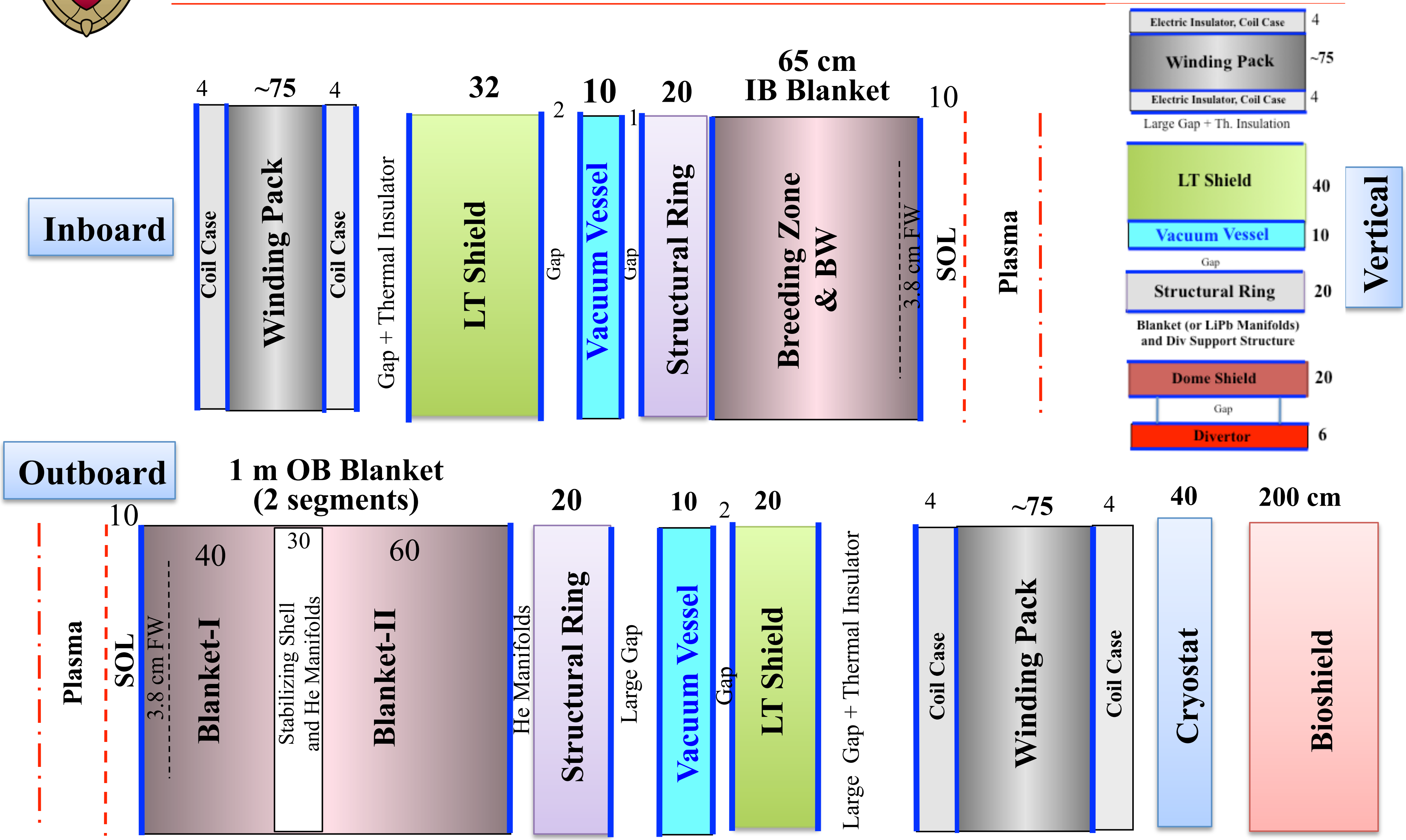
ARIES Design Requirements and Radiation Limits

Overall TBR (for T self-sufficiency)	1.05 with Li-6 enrichment < 90%
Damage to RAFM alloys	200 dpa (goal in 50 y)
Damage to W alloys	? (unknown)
Helium Production (assumed for reweldability of RAFM alloys)	1 He appm (for 316-SS; unknown for RAFM)

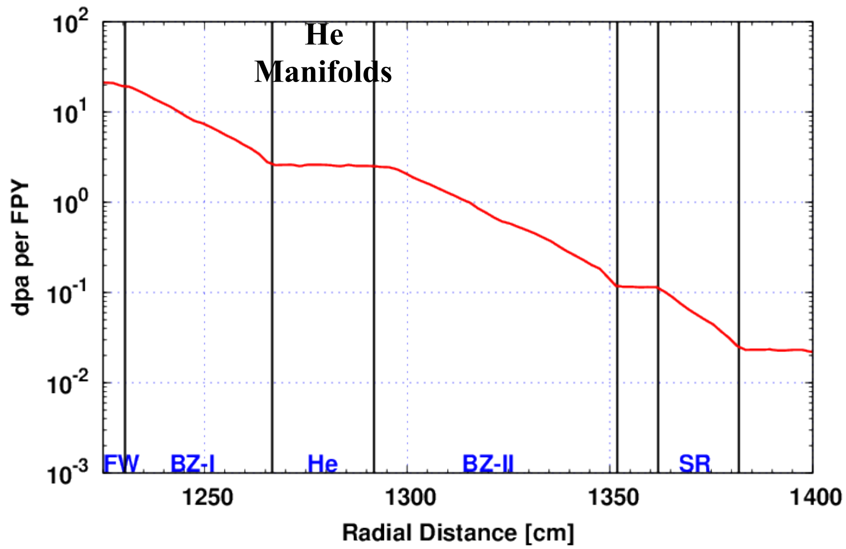
LTS Magnet (@ 4 K):

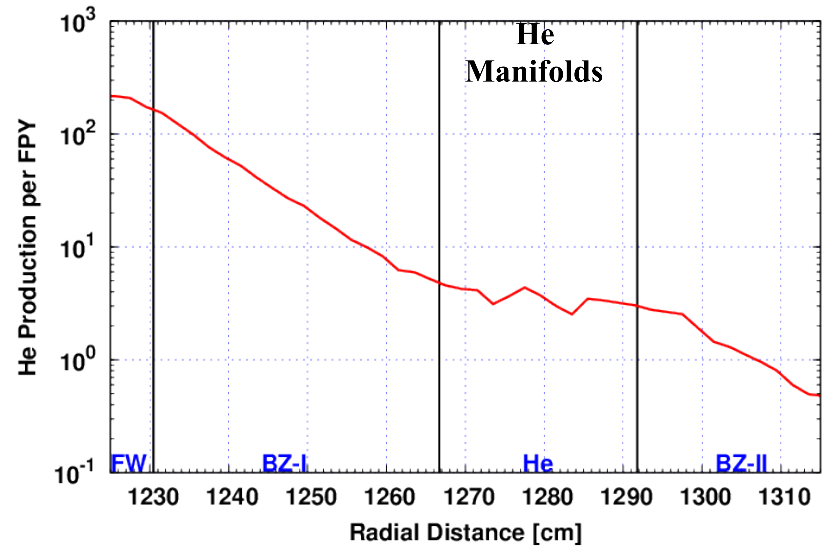
Peak fast n fluence to Nb_3Sn (E_n > 0.1 MeV)	10^{19}	n/cm^2
Peak nuclear heating @ winding pack	2	mW/cm^3
Peak dose to electrical insulator	10^{11}	rads
Peak dpa to Cu stabilizer	6×10^{-3}	dpa

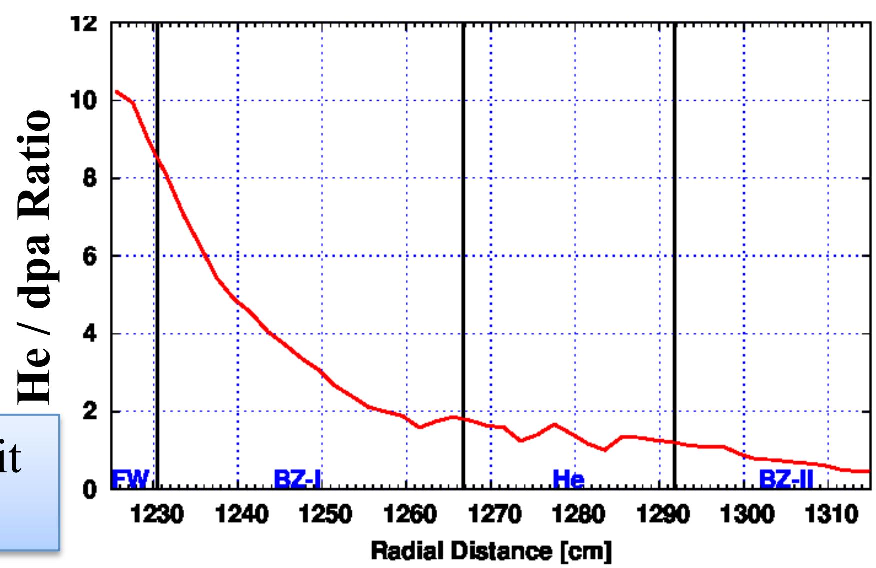
ARIES-ACT2 Radial/Vertical Builds



Radial Variation of Radiation Damage to RAFM Structure
(ARIES-ACT2 Power Plant with DCLL Blanket)



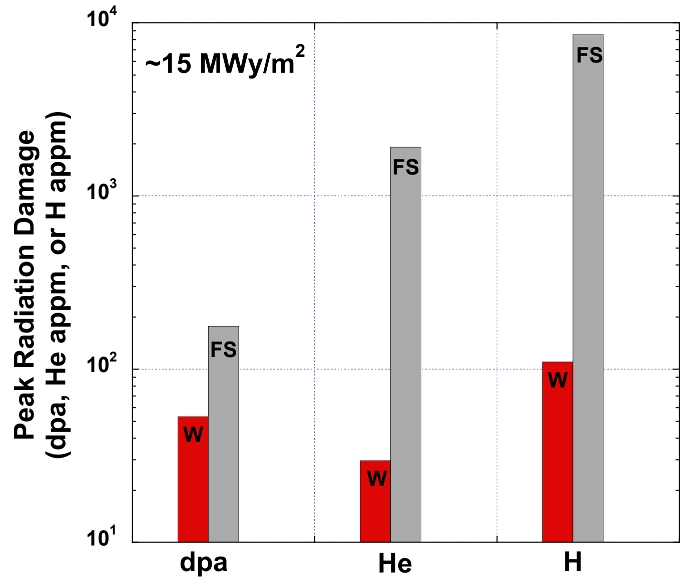


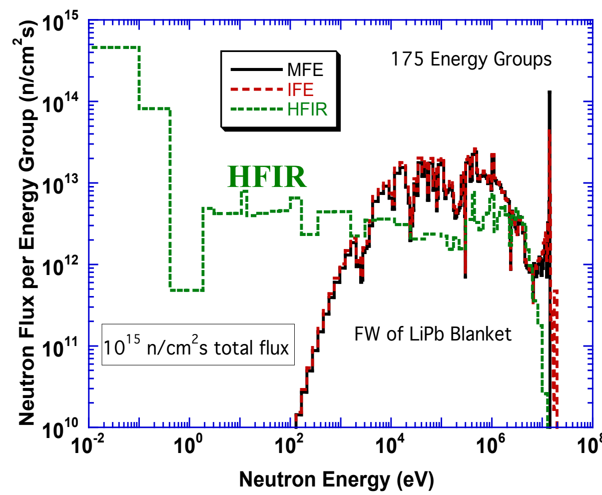


Qs: Reweldability limit for RAFM?

Outboard Components
Peak NWL= 2.2 MW/m^2
(damage level at locations far away from penetrations and assembly gaps)

Radiation Damage to W Armor at FW of DCLL Blanket (ARIES-ACT Power Plant)





	W		RAFM	
	Fusion	**HFIR**	**Fusion**	**HFIR**
He / dpa	**0.6**	**0.0008**	**10**	**0.3**
H / dpa	**2**	**?**	**40**	**?**

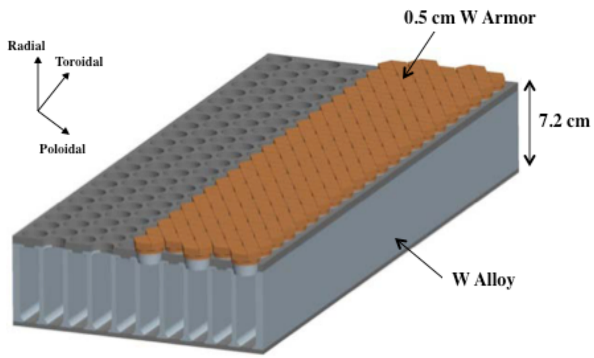
Much softer spectrum in HFIR compared to fusion.
(No neutrons above 10 MeV)

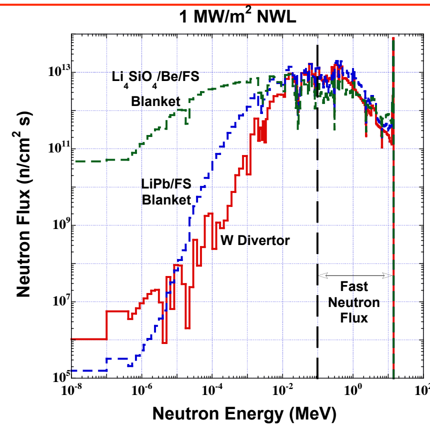
Qs: Life-limiting criteria for W structure?

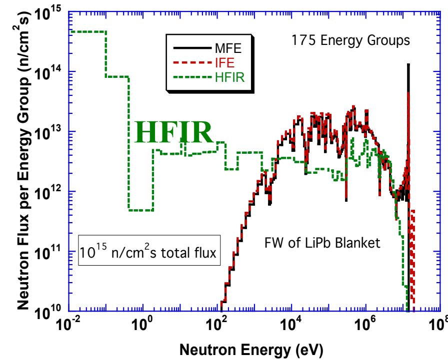
Fission system is inadequate to simulate radiation damage in W of fusion systems

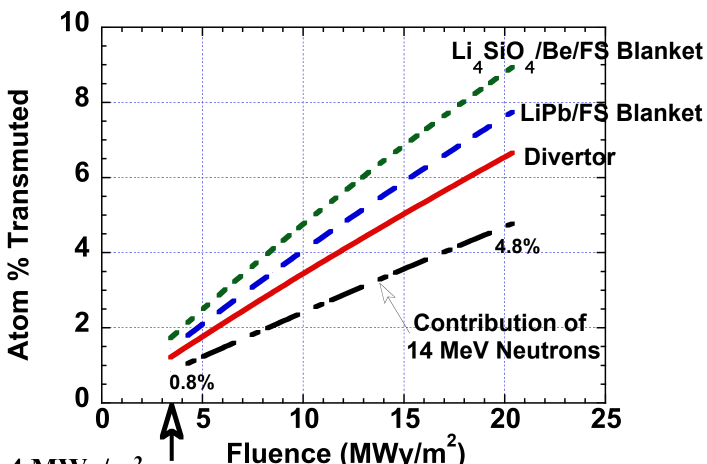
Ref.: L. El-Guebaly, R. Kurtz, M. Rieth, H. Kurishita, A. Robinson, "W-Based Alloys for Advanced Divertor Designs: Options and Environmental Impact of State-of-the-Art Alloys," Fusion Science and Technology 60, (2011) 185-189.

Transmutations in W Structure of Advanced Divertors (ARIES-ACT Power Plant)









3.4 MWy/m²
(ARIES-ACT1
Diveror EOL Fluence)

Hard divertor spectrum transmutes < 1% of W atoms into Re, Ta, and Os

Much softer HFIR spectrum transmutes large fraction (> 10%) of W atoms into Os, Pt, and Re

Fission system is inadequate to simulate amount and mix of transmutants produced in W of fusion divertors

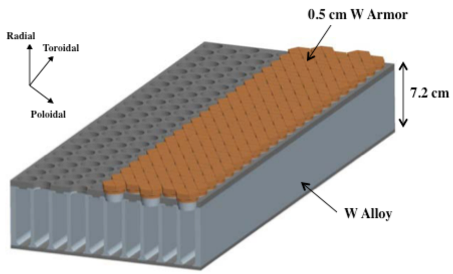
Ref.: A. Robinson, L. El-Guebaly, D. Henderson, "Activation and Radiation Damage Characteristics of W-Based Divertor of ARIES Power Plants," Fusion Science and Technology 60, Number 2 (2011) 715-719.

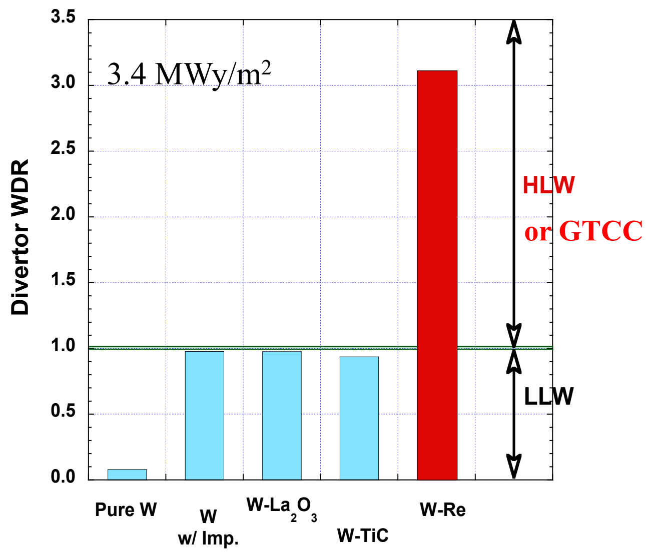
A. Robinson, L. El-Guebaly, and D. Henderson, "W-Based Alloys for Advanced Divertor Designs: Detailed Activation and Radiation Damage Analyses," University of Wisconsin Fusion Technology Institute Report, UWFDM-1378 (October 2010). Available at: http://fti.neep.wisc.edu/pdf/fdm1378.pdf.

M.E. Sawan, "Transmutation of Tungsten in Fusion and Fission Nuclear Environments," Fusion Science and Technology 66, (2014) 272-277.

Waste Classification of W-Based Divertor

(ARIES-ACT Power Plant)





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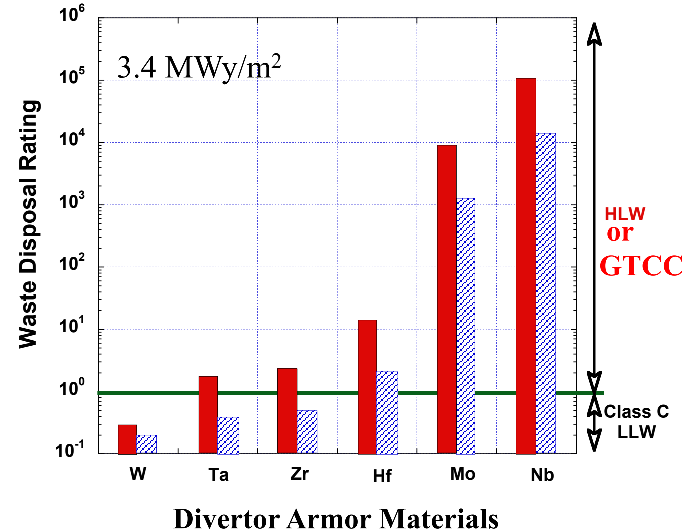
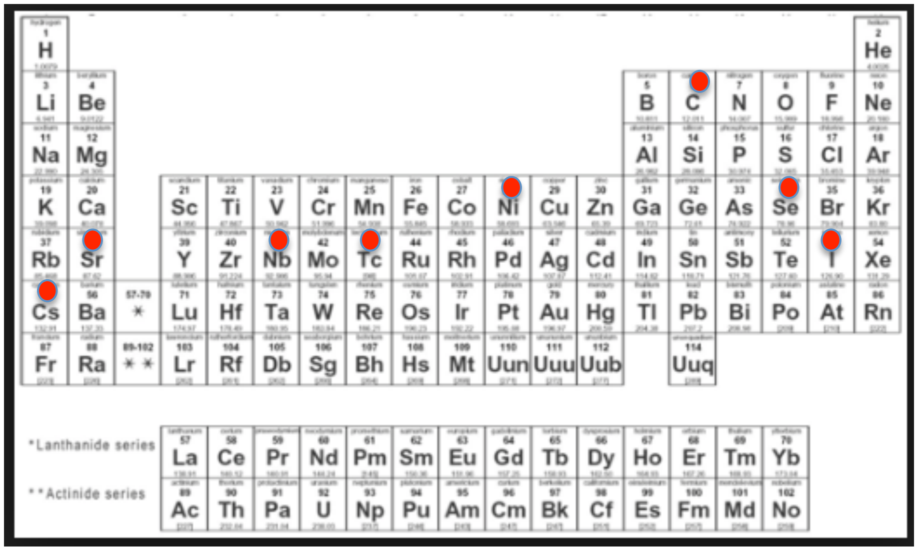


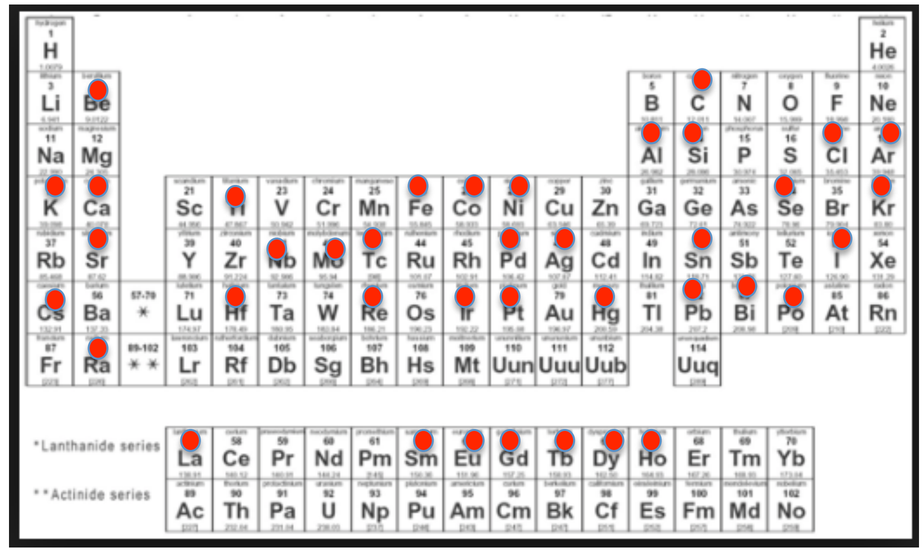
Ref.: J.N. Brooks, L. El-Guebaly, A. Hassanein, T. Sizyuk, "Plasma Facing Material Alternatives to Tungsten," Nuclear Fusion 55 (2015) 043002.

- W-Re alloy and Nb, Hf, and Mo coatings generate Greater Than Class C or High-Level wastes.
- All fusion materials could be recycled* using advanced remote handing equipment that can handle 10,000 Sv/hr.

* L.A. El-Guebaly, "Future Trend Toward the Ultimate Goal of Radwaste-Free Fusion: Feasibility of Recycling/Clearance, Avoiding Geological Disposal." J. Plasma and Fusion Research, 8, 3404041-1-6 (May 2013). Also, University of Wisconsin Fusion Technology Institute Report, UWFDM-1413 (June 2012). Available at: http://fti.neep.wisc.edu/pdf/fdm1413.pdf..

NRC vs. Fetter's Specific Activity Limits for Radionuclides





NRC 10CFR61 developed specific activity limits for only 8 radionuclides (excluding actinides), presenting a weak basis for selecting reduced-activation materials for fusion and qualifying them as LLW for near surface disposal

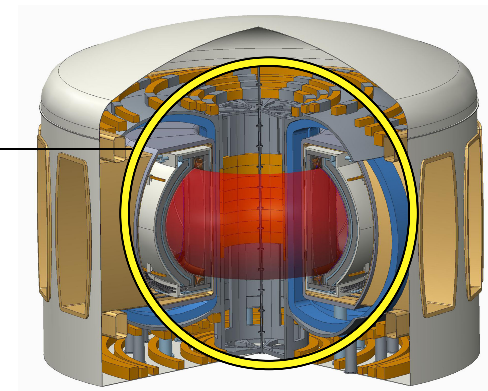
Fetter expanded list of NRC 10CFR61 radionuclides and determined specific activity limits for fusion-relevant isotopes with $5y<t_{1/2}<10^{12}y$, assuming waste form is metal.
NRC did NOT endorse Fetter's limits yet.

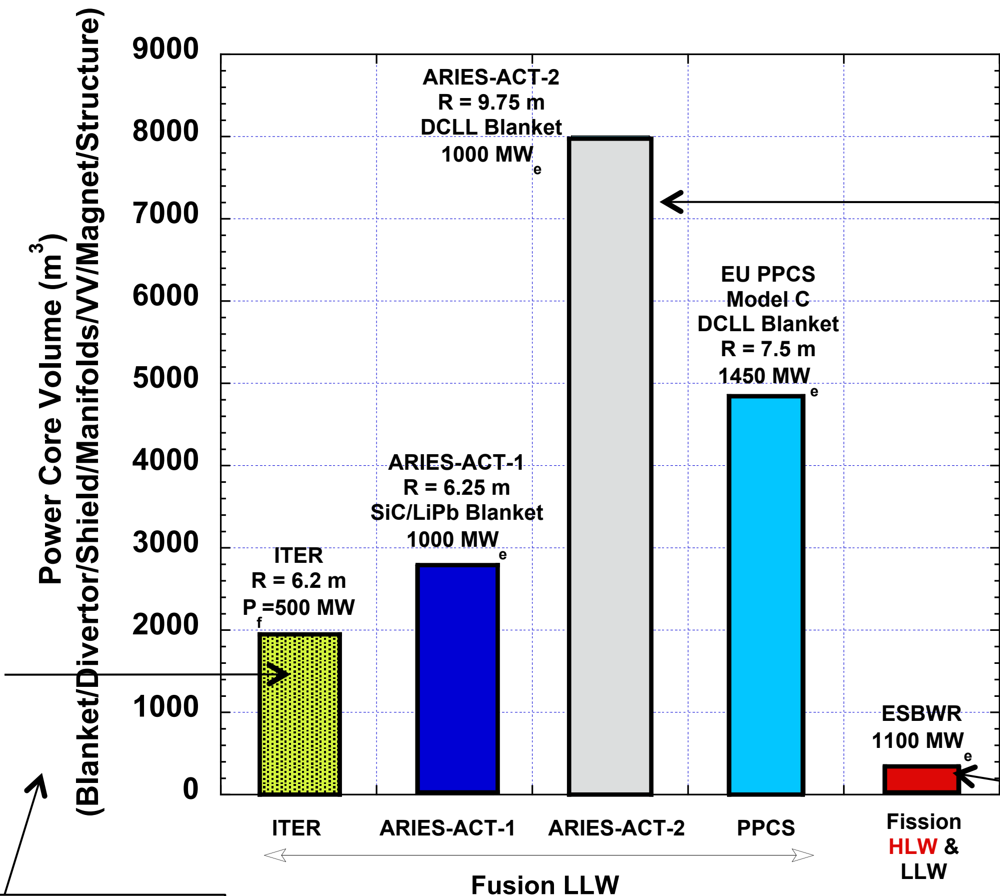
US Code of Federal Regulations, Title 10, Energy, Part 61, Licensing Requirements for Land Disposal of Radioactive Waste, US Government Printing Office, January 2014.

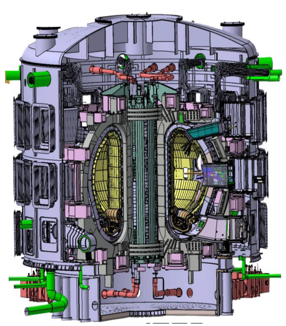
*S. FETTER, E. T. CHENG, and F. M. MANN, "Long Term Radioactive Waste from Fusion Reactors: Part II," Fusion Engineering and Design, **13**, 239 (1990).*

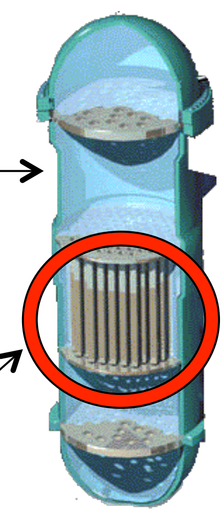
ARIES-ACT2 Generates LLW, but in Large Quantity

ARIES-ACT2









Actual volumes of components; not compacted; no replacement; no plasma chamber; one cycle fuel rods.

Recycle activated materials to enhance environmental attractiveness of fusion

ARIES-ACT2 Generates LLW if Nb Impurity in F82H Structure is < 1 wppm

ARIES-ACT2 Outboard Blanket

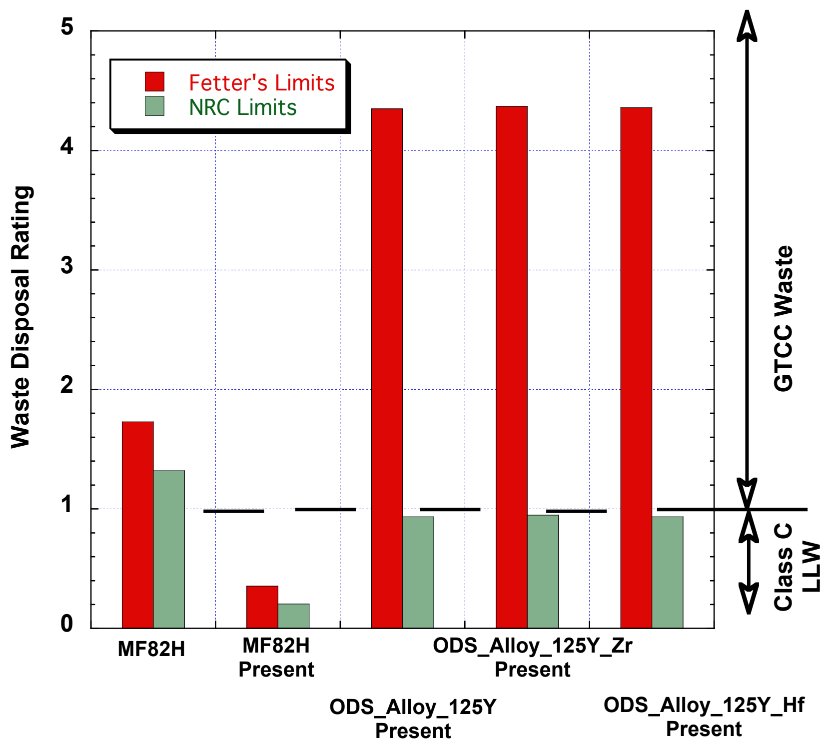
Outboard Blanket (F82H Structure)	WDR (nominal impurities; 3 wppm Nb)	WDR (controlled impurities; 0.5 wppm Nb)
40 cm Inner Blanket Segment (10 y)	1.5 - GTCC	0.3 - LLW
60 cm Outer Blanket Segment (50 y)	2.2 - GTCC	0.4 - LLW

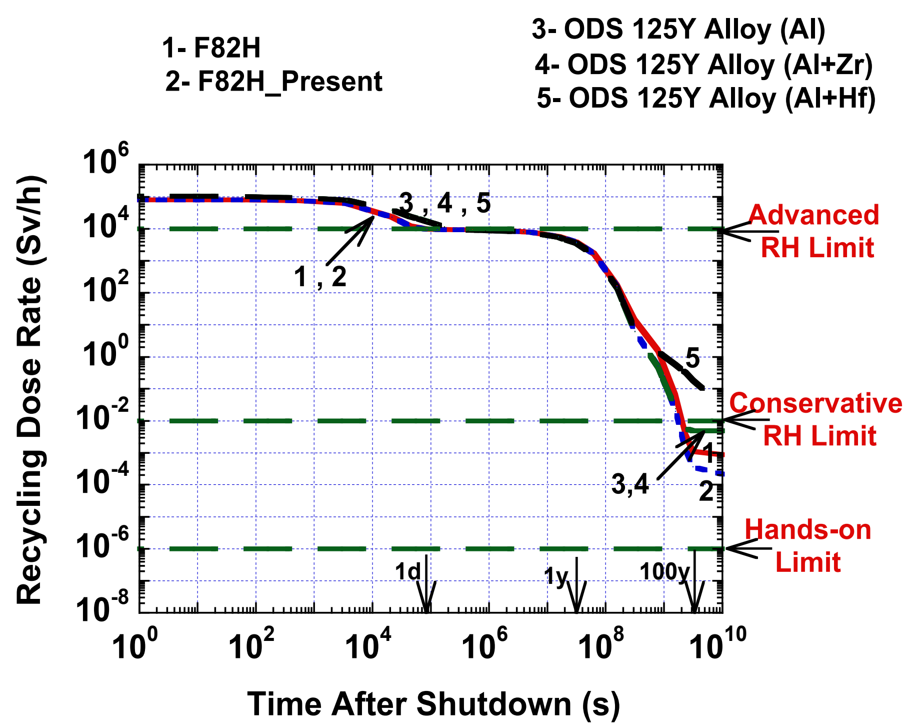
Strict impurity control (0.5 wppm Nb) is a must requirement for fusion to avoid generating GTCC waste.

Cost of impurity control to < 1wppm level !?

Corrosion Resistant ODS Alloys Generate GTCC Waste and are Recyclable

ARIES-ACT2
Inner Segment of OB Blanket
Peak 200 dpa @ FW

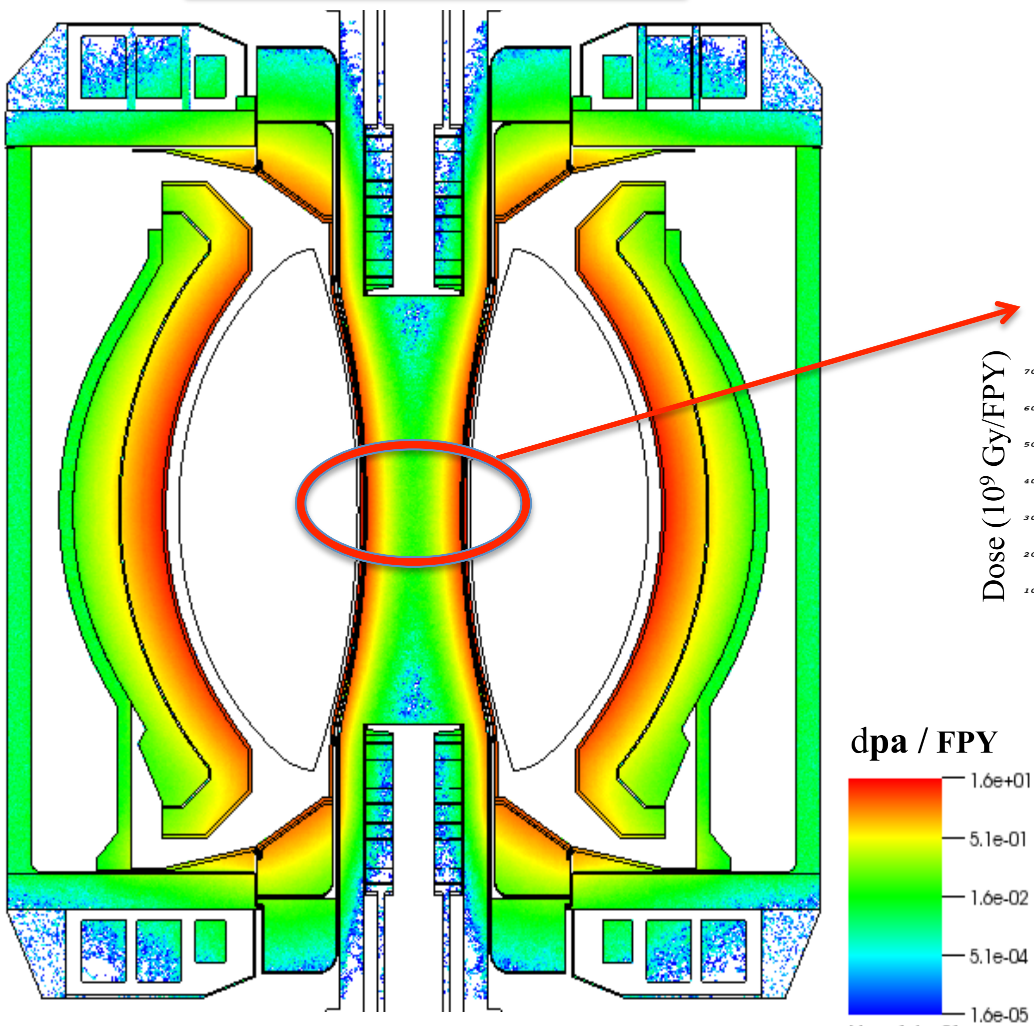


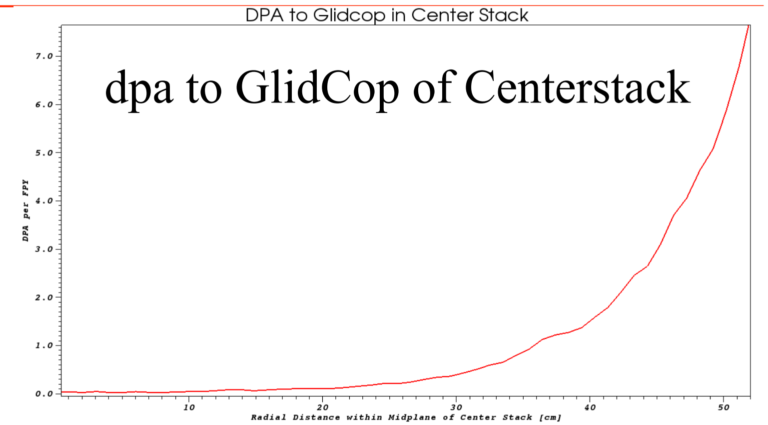


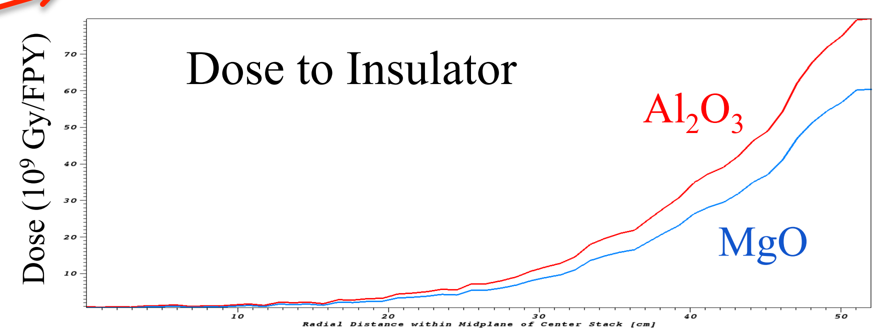
Ref.: L. El-Guebaly, L. Mynsberge, A. Davis, C. D'Angelo, A. Rowcliffe, B. Pint, "Design and Evaluation of Nuclear System for ARIES-ACT2 Power Plant with DCLL Blanket," Fusion Science and Technology, in press.

Atomic Displacement of Cu and Dose to Insulators
(ST-FNSF Design with DCLL Blanket)

R= 1.7 m Configuration
Peak IB NWL = 1 MW/m^2







K Fan (Japan) suggests 10^{11} Gy for MgO.

Qs: Life-limiting criteria for GlidCop and Al_2O_3?

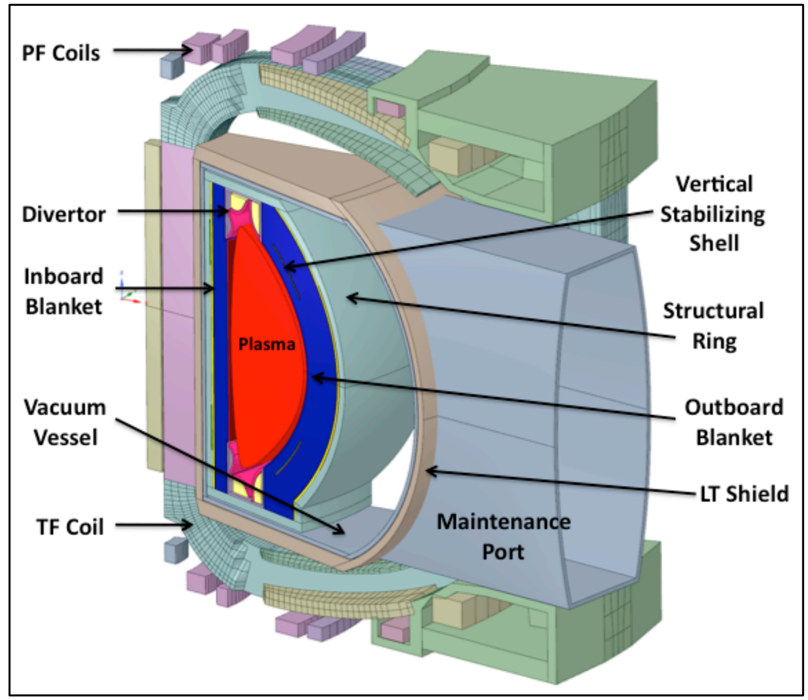
FESS-FNSF Design with DCLL Blanket

- **Key design parameters:**

Major Radius	4.8	m
Minor Radius	1.2	m
Fusion Power	518	MW
Peak OB NWL	1.75	MW/m^2

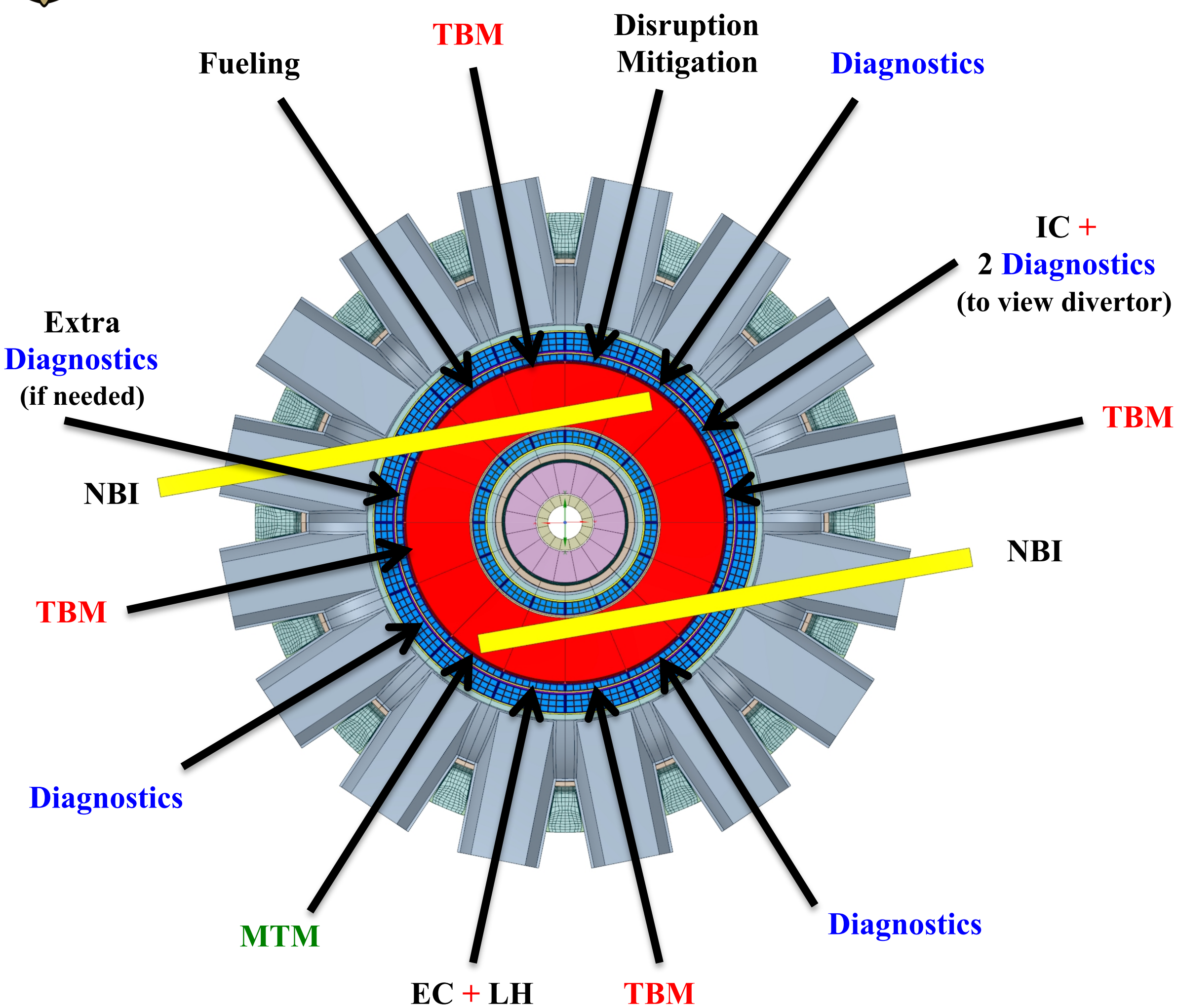
16 TF magnets and maintenance ports.

18 special-use ports on OB side.



- **Peak radiation damage at OB FW:**
  - dpa rate = 15 dpa/FPY
  - He production rate = 157 appm/FPY
  - H production rate = 580 appm/FPY
  - He/dpa ratio = 10.3
  - H/dpa ratio = 39

Layout of 18 Ports in 16 Sectors of FESS-FNSF

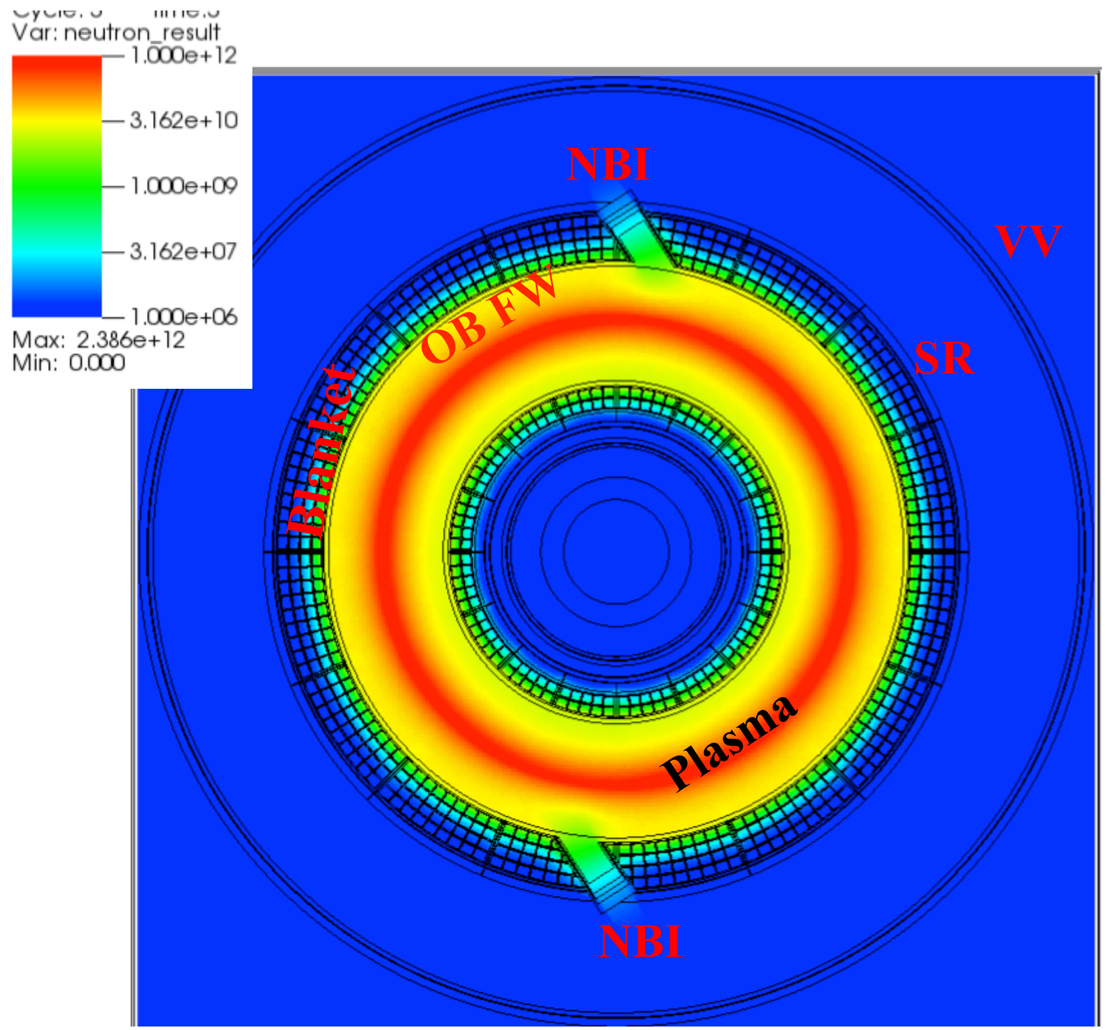


Design with 2 NBIs considered for radiation mapping

Mapping of Neutron Flux

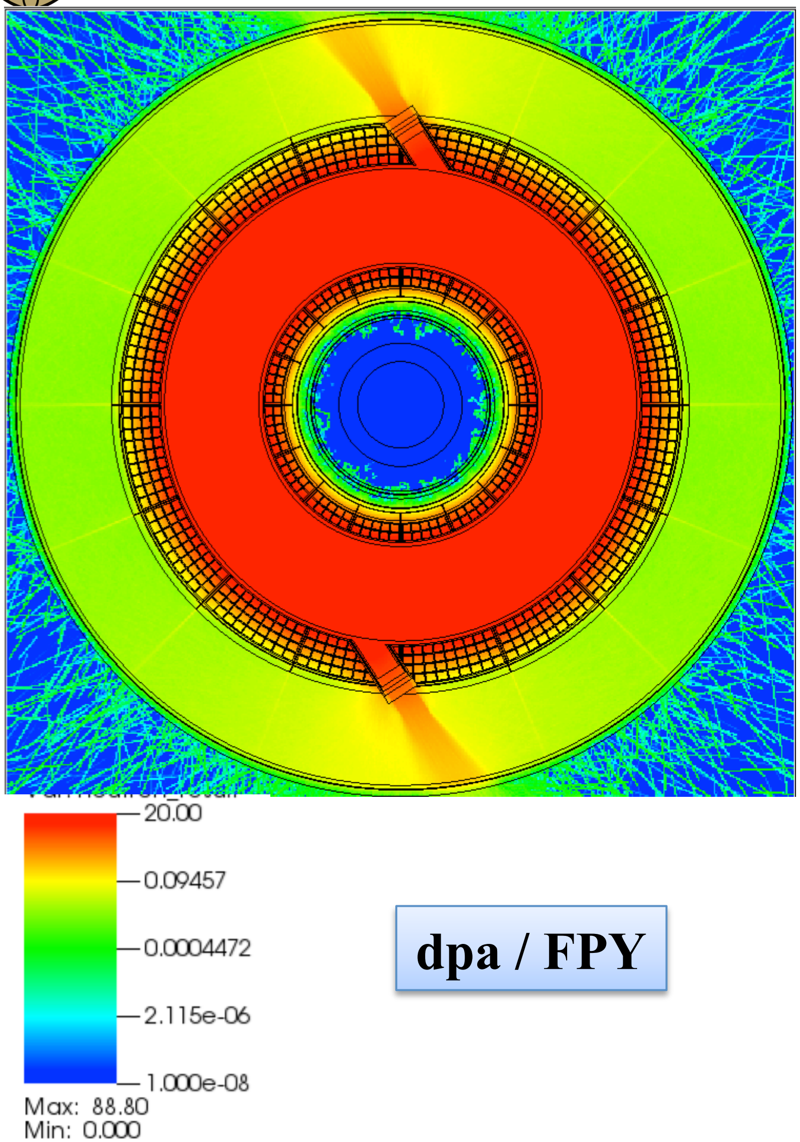
- H/CD ports and assembly gaps degrade the shielding functionality of blanket, structural ring (SR), vacuum vessel (VV), and shield.

- Such penetrations allow neutrons to stream through, raising radiation damage level at all components outside the blanket.

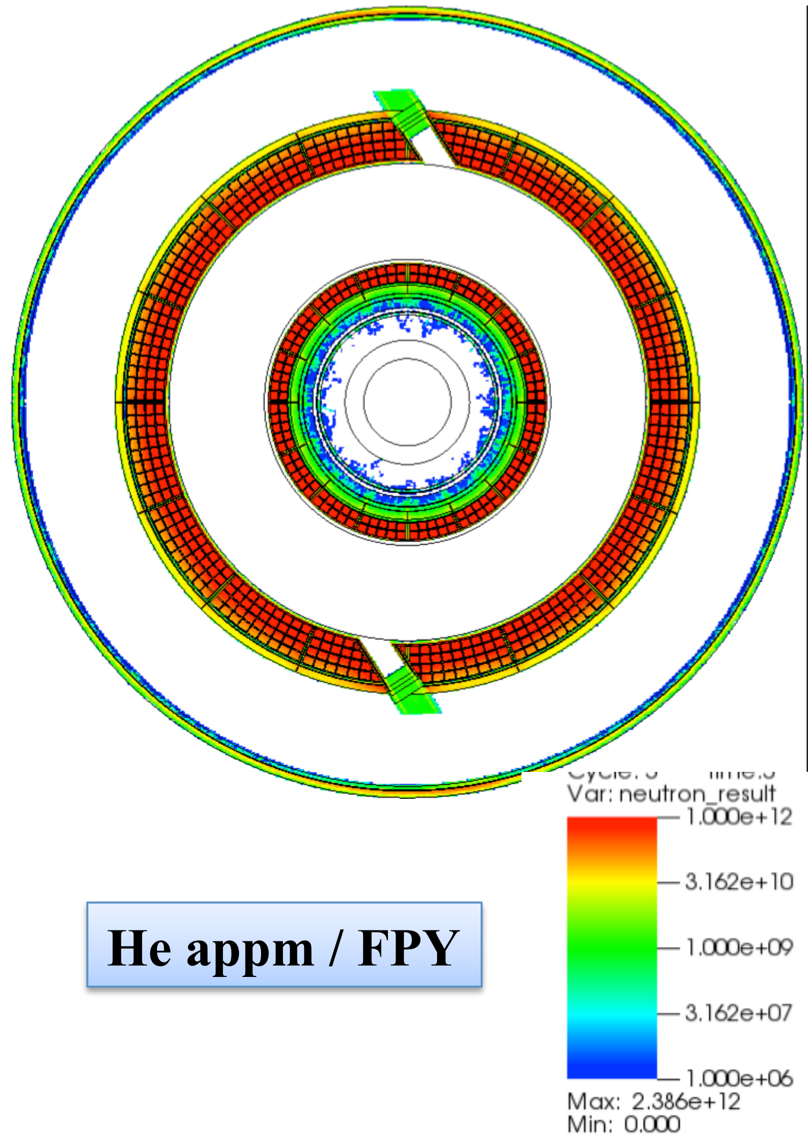


Cross Section at Midplane Showing 2 NBI Ports

Mapping of Radiation Damage in FESS-FNSF

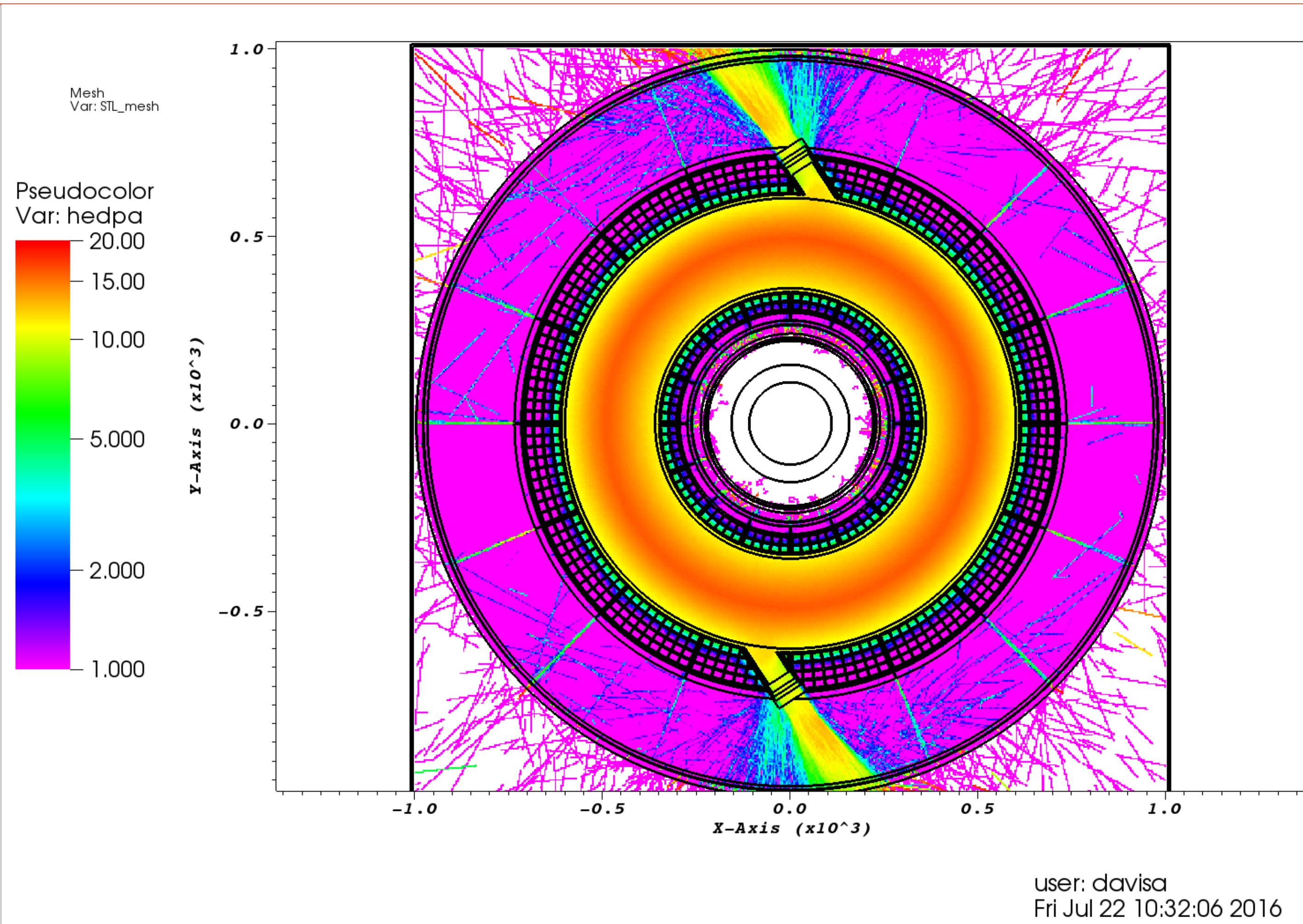


dpa / FPY



He appm / FPY

Mapping of He/dpa Ratio in FESS-FNSF



He/dpa ratio drops below one behind blanket, but remains high along beam line and surrounding components

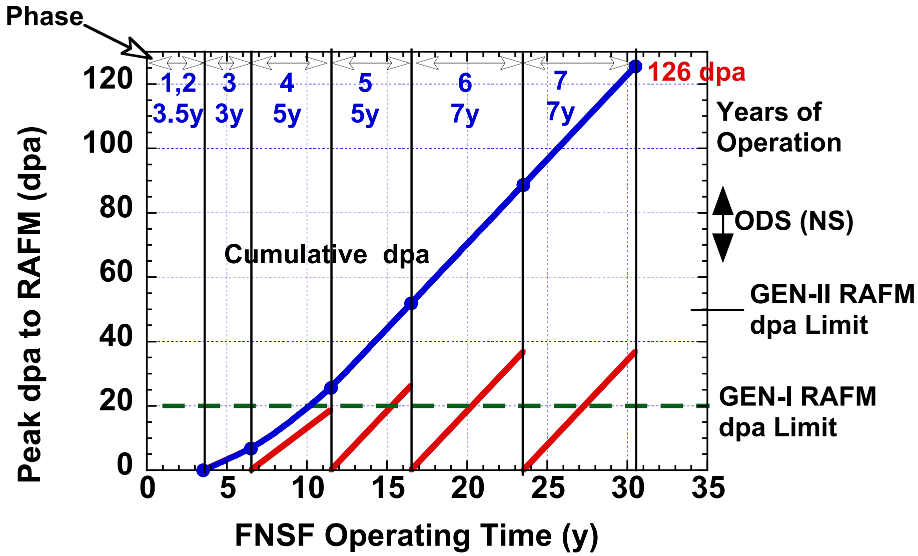
F82H RAFM and Corrosion Resistant ODS-125Y* Alloys Generate LLW

FESS-FNSF

~ 65 dpa

4.7 FPY

Phases 3,4,5, & part of 6



Waste Classification for FNSF OB FW/Blanket	F82H NRC	F82H Fetter	ODS-125Y NRC	ODS-125Y Fetter
28 cm Thick FW and Inner Blanket Segment	0.28	0.4	0.33	1.8 GTCC
72 cm Thick Outer Blanket Segment	0.07	0.1	0.046	0.05
Both Segments (1 m Thick FW/Blanket)	**0.13 Class C**	**0.18 Class C**	**0.13 Class C**	**0.57 Class C**

** B. A. Pint, S. Dryepondt, K. A. Unocic and D. T. Hoelzer, "Development of ODS FeCrAl for Compatibility in Fusion and Fission Applications," JOM 66 (2014) 2458-2466.*

Novel Strategy Developed for Blankets and Materials Testing in FNSF

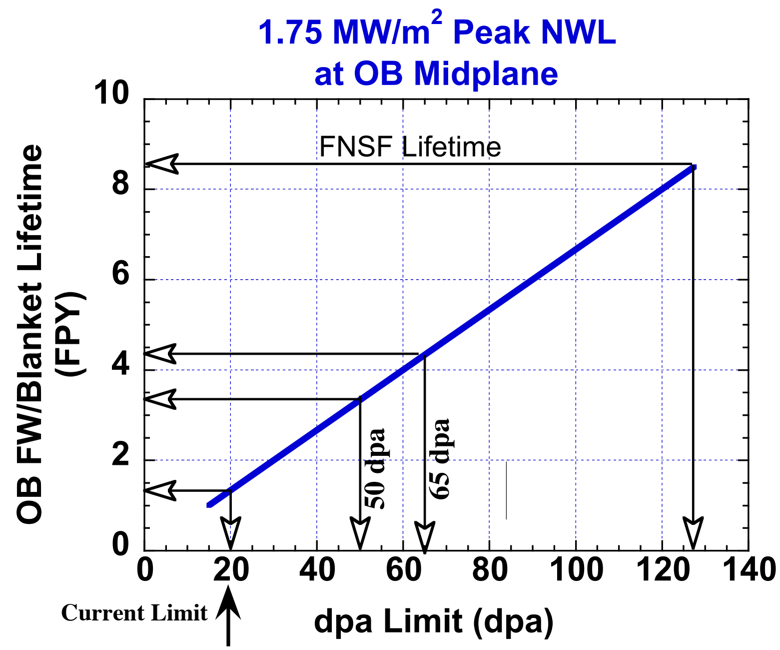
- Test Blanket Modules (TBM) on OB midplane will develop more advanced version of DCLL blanket for US DEMO. A staged blanket testing strategy has been developed to test and enhance the DCLL blanket performance during each phase of FNSF operation.
- TBMs could also test He-cooled PbLi (HCLL) and ceramic breeder blankets.
- Materials Testing Modules (MTM) is critically important to include in FNSF as well to test broad range of specimens of future, more advanced generations of materials in relevant fusion environment.
- This testing strategy suggests the development of more radiation-resistant alloys that expand the operating temperature window (such as GEN-II RAFM and nanostructured ODS) to allow the structure to survive higher fluence without property degradation.

Refs: L. El-Guebaly, S. Malang, A. Rowcliffe, and L. Waganer, "Blanket/Materials Testing Strategy for FNSF and its Breeding Potential," Fusion Science and Technology, Vol. 68, No. 2 (2015) 251-258.

L. El-Guebaly, A. Rowcliffe, J. Menard, T. Brown, "TBM/MTM for HTS-FNSF: An Innovative Testing Strategy to Qualify/Validate Fusion Technologies for US DEMO," Energies online journal. In press.

Development Goals Considered for 3 Classes of Steel-Based Alloys

- **GEN-I RAFMs** (20 dpa/200 appm He).
  ⇒ replace structure after 1.3 FPY of FNSF operation.
- **GEN-II RAFMs** (50 dpa/500 appm He).
  ⇒ replace structure after 3.3 FPY of FNSF operation.
- **Nanostructured ODS** (65 dpa/650 appm He)
  ⇒ replace structure after 4.3 FPY of FNSF operation.
  Such high Cr ODS (NS) alloys have potential for alloying with ~5 wt% aluminum (in addition to Zr or Hf) to improve PbLi corrosion resistance* – an important aspect of DCLL blanket with possible applications at 700-800°C.
- Such alloys for the DCLL blanket will operate at high temperatures > 350°C (above 200-350°C radiation hardening regime for RAFMs – typical of water-cooled blankets).
- Validation of 50-65 dpa goals is entirely dependent on deployment of fusion-relevant neutron facilities, such as IFMIF and DONES.



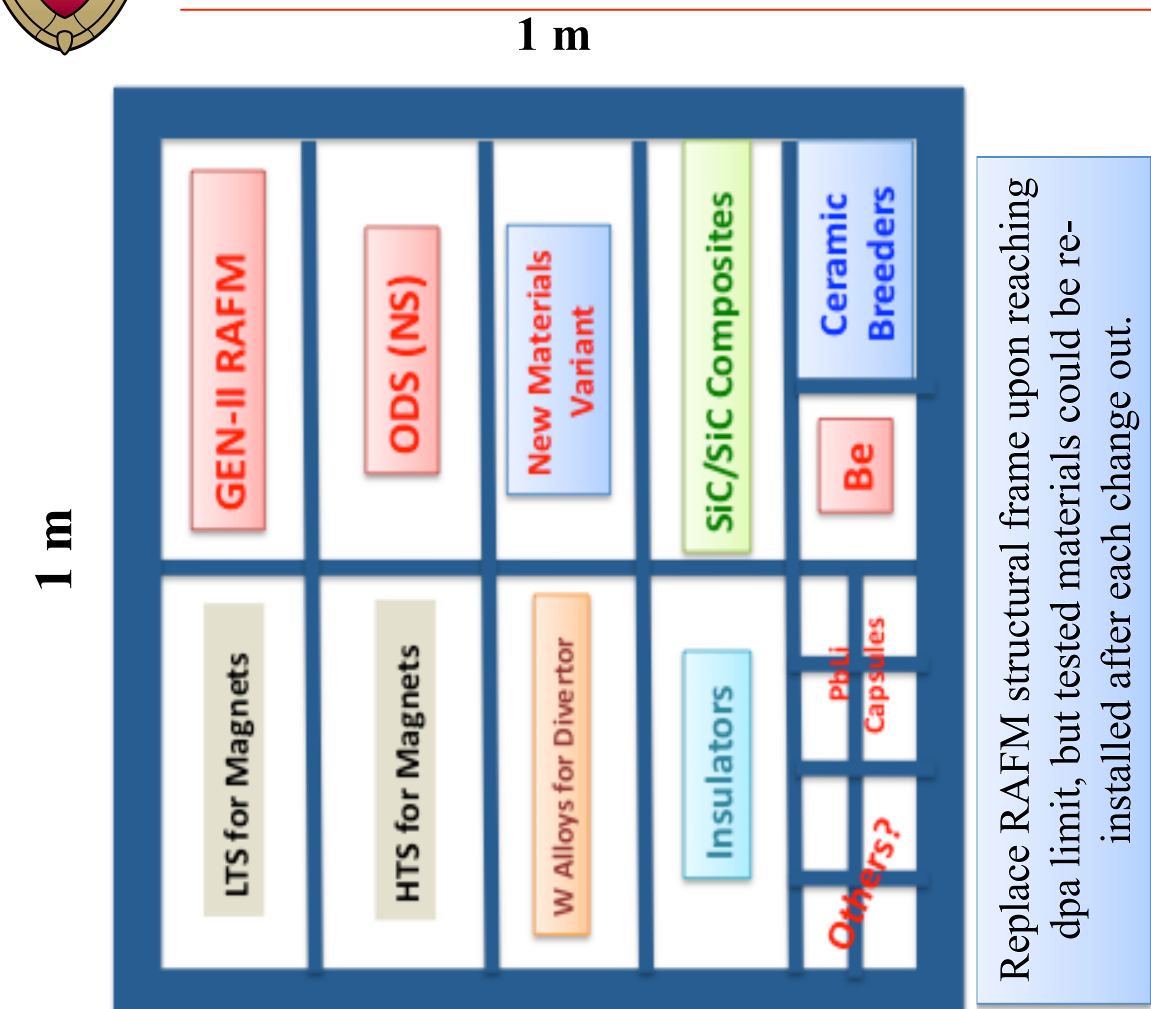
Surviving entire lifetime of FNSF operation (8.5 FPY) requires the development of radiation-resistant alloys that could stand ~130 dpa.

* B. A. Pint, S. Dryepondt, K. A. Unocic and D. T. Hoelzer, "Development of ODS FeCrAl for Compatibility in Fusion and Fission Applications," JOM 66 (2014) 2458-2466.

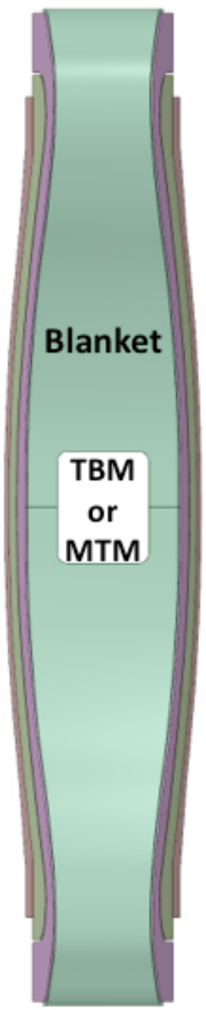
FNSF Itself will Provide Opportunity to Test Materials in Integrated Multi-Effects Fusion Environment

- MTM will be embedded in outboard blanket to contribute to the comprehensive multi-materials database with potential to reach neutron exposures 50-100 dpa.
- Wide variety of materials and test specimens could be accommodated simultaneously. For example:
  - New generations of structural steels, if not tested before the FNSF, including:
    - GEN-II RAFMs designed for operation up to 650ºC
    - Nanostructured ODS steels (12-14% Cr) with enhanced radiation damage tolerance and high temperature capability
    - RAFM variants with reduced susceptibility to radiation-induced DBTT shifts for operating temperatures < 385ºC
  - Multi-material PbLi corrosion capsules
  - SiC/SiC composites for advanced blanket designs
  - W alloys for divertor and stabilizing shells (W-TiC, WL10, W-K, W/W composites, VMW, etc.)
  - Low-temperature and high-temperature magnet materials: superconductors, jackets, insulators, etc.
  - New materials variants arising from:
    - Continuing development of improved compositions/microstructures
    - Application of advances in fabrication technologies (additive manufacturing, precision casting, joining technologies, etc.).

MTM Offers Testing in Relevant Fusion Environment (He/dpa=10)



Layout of material samples within 1x1 m MTM (with varying shapes, sizes, thicknesses, etc.)



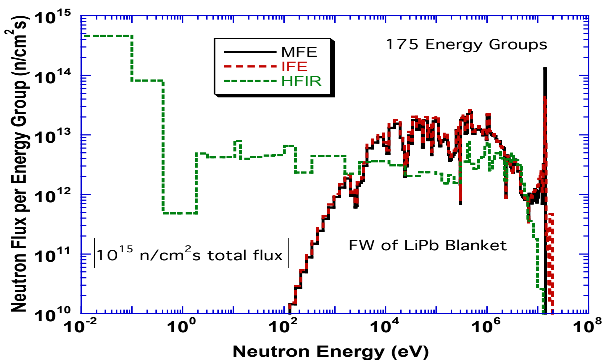
Testing Module at Midplane of OB Blanket

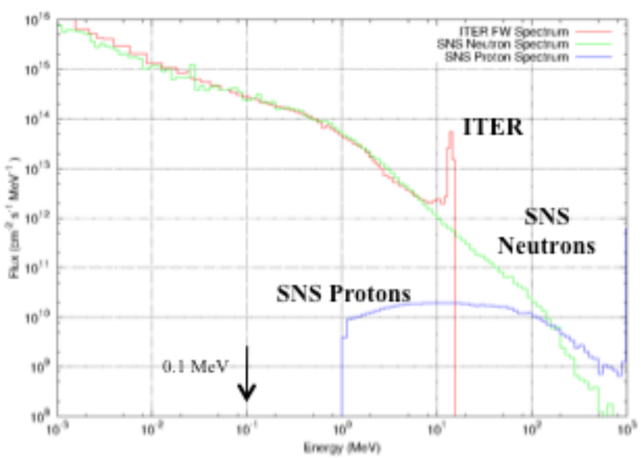
MTM is Critical Resource for Evaluation and Validation of Fusion Materials

- Other data developed with continuous radiation sources (SNS, IFMIF, DONES, HFIR, or other neutron sources in Japan, China, and S. Korea):
  - Forms basis for developing engineering database for designing and licensing FNSF.
  - Is essential for developing science-based understanding of 14 MeV neutron radiation damage phenomena that underpins development of damage-resistant materials.

- **MTM is complementary and necessary resource** with advantages of:
  1. Carrying higher **multiplicity of larger specimens** compared to 10-500 ml range available in the SNS/IFMIF
  2. Providing radiation effects data in pulsed neutron environment with He/dpa ratio of 10
  3. Providing surveillance program to track performance of several materials irradiated in same 14 MeV neutron environment using range of specimen geometries; regulators will require testing of more shapes (tubes, flat and curved plates, etc.) before full admission into design code.
  4. Provide means of testing larger size mechanical property specimens with any shape:
     - Pressurized creep tubes and fracture toughness specimens with range of section thicknesses and crack geometries
     - Validation of data derived from highly miniaturized specimens irradiated in IFMIF/DONES.
  5. Provide means of irradiation testing of new materials variants arising from:
     - Continuing development of improved compositions/microstructures
     - Application of advances in fabrication technologies (additive manufacturing, precision casting, joining technologies, etc.).

Testing in FNSF vs. HFIR*, SNS, and IFMIF#





He / dpa ratio

Irradiation Facility	FNSF	HFIR	SNS (sample @ 3 cm)	SNS (sample @ 5 cm)	IFMIF (high flux test module)
% of neutrons with E > 0.1 MeV	~75%	~24%	~ 65%	~ 65%	96%
F82H or EUROFER	**10**	0.3 (low)	74 (high)	20 (high)	13
W	**0.6**	0.0008 (low)	?	?	4 (high)
SiC	**95**	1.7 (low)	98	37 (low)	150 (high)

Highly energetic neutrons (E_n up to 300 MeV) **and** protons (E_p up to 1000 MeV) in SNS

•M. Sawan, "Damage Parameters of Structural Materials in Fusion Environment Compared to Fission Reactor Irradiation," Fusion Engineering and Design 87 (2012) 551-555.
 # Data provided by J. Knaster (IFMIF project leader), May 2015.

Needed Info for Fusion Materials

RAFM Alloys:

- **New generations of structural steels:**
  - GEN-II RAFMs to extend the max operating temperature into 550-650^{o}C regime
  - Nanostructured ODS steels with enhanced tolerance to radiation damage resistance combined with microstructural stability under temperature excursions during severe accidents.
  - Reusability temperature limit for such an advanced ODS steel?
  - corrosion-resistant ODS alloys that could operate at high temperatures (700-800 oC) to enhance thermal conversion efficiency
  - RAFM variants with less susceptibility to radiation-induced DBTT shifts in the low temperature regime (< 385 oC).
- **dpa limit for RAFM ferritic steels and advanced alloys, such as ODS (NS)**
- **Develop Bainitic ferritic steel (for VV) that does not require PWHT. Need composition (including density and list of ALL impurities)**
- **Reusability temperature limit for advanced steels (such as Nano Structured Ferritic Alloys) after severe LOCA/LOFA accidents. 1000 oC or more?**
- **Reweldability limit for ferritic steel. It is 1 helium appm for austenitic steel. Could ferritic steel be rewardable at higher He content?**
- **Continue developing low-activation materials that decay rapidly to allow recycling all materials after short cooling period**
- **Need compositions (including ALL impurities and alloy density) for: GEN-I RAFM, GEN-II RAFM, ODS (NS)**
- **Cost of controlling impurities in advanced steels (to very low levels, e.g., Nb < 0.5 wppm and Mo < 5 wppm) to avoid generating GTCC waste.**

Needed Info for Fusion Materials (Cont.)

Bainitic steel:

- **Maximum allowable temperature for reusability of bainitic steel-based components after an accident**

W alloys:

- **W alloy for divertor and stabilizing shells: W-1.1TiC, W-La2O3, WVM, or W/W composites?**
- **Lifetime limiting criteria for W structure? dpa limit?**
- **Need to develop design rules and codes for brittle materials (such as W)?**
- **Composition and list of impurities for preferred W alloy.**

SiC/SiC FCI and composite structure:

- **Life limiting criteria for SiC/SiC composite structure and FCI?**
- **Change of FCI electric conductivity and thermal conductivity under fusion neutron irradiation**
- **List of impurities for SiC.**

Needed Info for Fusion Materials (Cont.)

PbLi breeder:

- **Process and cost of adjusting Li-6 enrichment online from natural to 90%**
- **Process and cost of recycling PbLi and filtering out Bi and Po byproducts online**
- **List of impurities for PbLi.**

Superconducting materials

- **Radiation-resistant Ternary Nb3Sn for LTS magnets that can stand > 5e18 n/cm2**
- **Radiation-resistant REBCO for HTS magnets that can stand > 5e18 n/cm2**

Copper:

- **Radiation limit for Cu stabilizer of S/C magnet. Current limit (e-4 dpa) is low**
- **Lifetime limiting criteria for Cu of normal magnets?**
- **Does Cu become brittle at 0.1 dpa?**
- **Should Cu magnet operate at high temperature (200-300 oC) to anneal out damage?**
- **Need to develop design rules and codes for brittle materials (such as Cu)?**

Needed Info for Fusion Materials (Cont.)

Ceramic Insulators (for Cu magnets and ELM coils):

Life limiting criterion for Spinel which is:

- **less susceptible to neutron-induced swelling**
- **more radiation-resistant than Alumina, zirconia, and MgO**
- **capable of handling high fast neutron fluence (> e22 n/cm2 ?!)**

Joining technology:

Alternative joining technologies should be developed (such as friction stir welding, diffusion bonding, cold spray deposition, etc.) since advanced ODS alloys cannot be welded.

Advanced manufacturing techniques:

Develop cost-effective additive manufacturing technique that could build complex fusion components to operate in 14 MeV neutron environment.

Remote handling equipment:

Radiation-resistant tools that can handle high doses > 10,000 Sv/hr .