Status of Engineering Effort on ARIES-CS Power Core

A. René Raffray

University of California, San Diego

ARIES Meeting

UCSD

November 17-18, 2005

UCSD

Outline

This presentation:

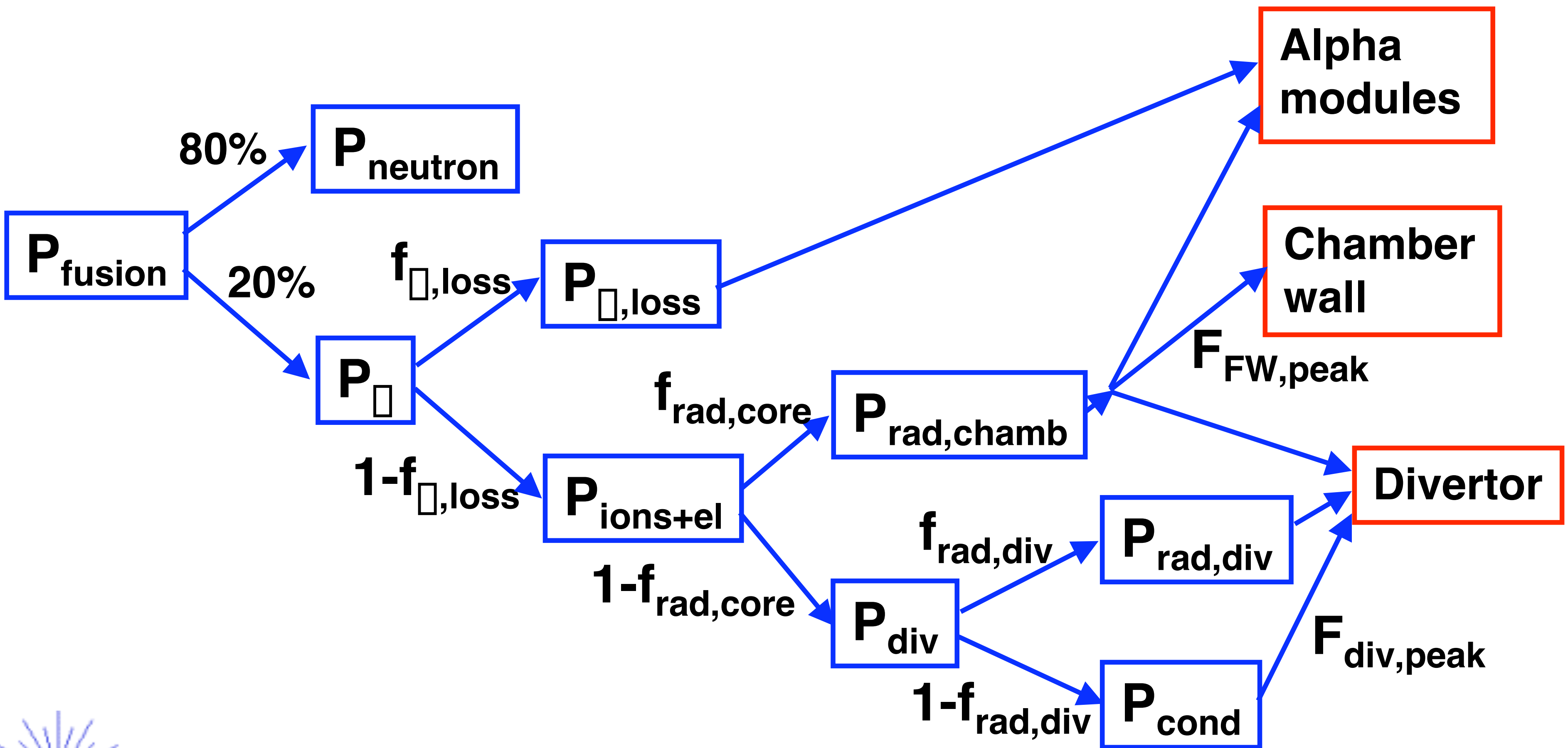
- **Power flows and heat loads on power core components**
- **Alpha particle threat and possible accommodation**
- **Thermal-hydraulic optimization of dual coolant blanket coupled to Brayton cycle for updated heat loads and including friction thermal power and coolant pumping power to estimate net efficiency**
- **Analysis of self-cooled Pb-17Li + SiC_f/SiC blanket coupled with Brayton cycle to provide cycle efficiency data to system code for our higher performance, higher risk alternate blanket option**
- **Choice of maintenance scheme for Phase III**
- **Progress on divertor study**
- **Engineering write-up to keep current and consistent record of parameters**

Other presentations:

- **Neutron streaming design and analysis (Laila, Xueren)**
- **Updated radial builds for breeding and shielding only modules (Laila)**
- **Coil design, analysis and fabrication (Xueren, Dave Williamson, Leslie, Les)**

Power Flow Diagram for Estimating Maximum Heat Fluxes on Divertor and First Wall for ARIES-CS

(based on previous figures from J. Lyon and T. K Mau)



UCSD

Required Fractional Power Radiation from Divertor Region to Maintain Divertor q'' ≤ 10 MW/m^2

- **Parameters consistent with those circulated by Jim Lyon for his example run**

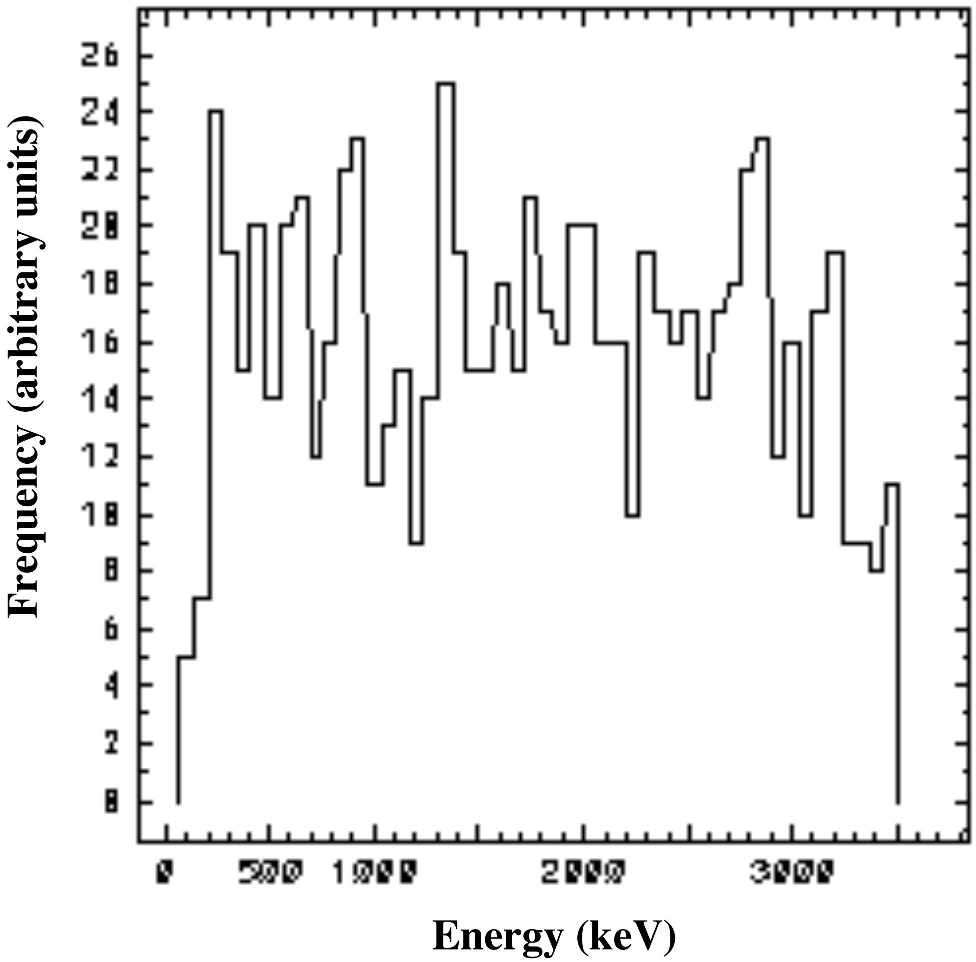
Fusion power (MW)	2350
Neutron power (MW)	1880
Alpha power (MW)	470
Alpha loss fraction	0.1
Alpha power in core (MW)	423
Fraction of core power radiated	0.764
Conducted power to divertor (MW)	100
Energy multiplication factor	1.15
Total thermal power (MW)	2632
Thermal power to blanket (MW)	2279
Thermal power to divertor (MW)	353
Fractional thermal power to blanket (MW)	0.87
Fractional thermal power to divertor (MW)	0.13
Wall load peaking factor	1.52
FW heat flux peaking factor	1.52
Conducted power peaking factor on divertor pl	20
Divertor fractional coverage	0.1
Maximum heat flux on divertor (MW/m2)	10

- **3 possibilities to lower max. heat load on divertor**
  - **Lower peaking factor or increase surface area**
  - **Sweeping**
    - **Can you sweep at high frequency (t_{char}~0.2 s for 1-mm W)?**
  - **Higher radiation in divertor region**
    - **Is up to 77% feasible?**

FW surface area (m2)	1904.7	1428.8	952.5	714.4	571.5
Divertor surface area (m2)	190.47	142.88	95.25	71.44	57.15
Avg wall load (MW/m2)	0.99	1.32	1.97	2.63	3.29
Max wall load (MW/m2)	1.5	2	3	4	5
Average first wall heat flux (MW/m2)	0.17	0.23	0.34	0.45	0.57
Max. first wall heat flux (MW/m2)	0.26	0.34	0.52	0.69	0.86
Fraction of divertor power radiated	0.065	0.32	0.57	0.69	0.77
Conducted power reaching divertor plates (MW)	93.3	68.2	43.2	30.6	23.1
Radiated power to divertor (MW)	6.54	31.6	56.7	69.2	76.7

Alpha Particle Loss

Example Spectrum of Lost Alpha Particles



- **Alpha loss not only represents a loss of heating power in the core, but adds to the heat load on PFC's.**
- **Depending on the magnetic topology, a fraction of these particles are promptly lost from the plasma and hit the PFC's at energies <~3.5 MeV.**
- **Thus, not only must the PFC surface accommodate the heat load of the alpha particle flux but it must also accommodate these high-energy alpha fluxes and provide the required lifetime.**

Accommodating Alpha Particle Heat Flux

- High heat flux could be accommodated by designing special divertor-like modules (allowing for q'' up to ~ 10 MW/m^2).

- e.g. for our example reactor parameters:
  - P_{fusion} = 2350 MW
  - Max. neutron wall load = 5 MW/m^2
  - FW Surface Area = 572 m^2
  - Assumed alpha module coverage = 0.05
  - Ave. q'' on alpha modules = 2.2 MW/m^2
  - Max q'' constrained to <10 MW/m^2
  - Alpha q'' peaking factor < 4.5

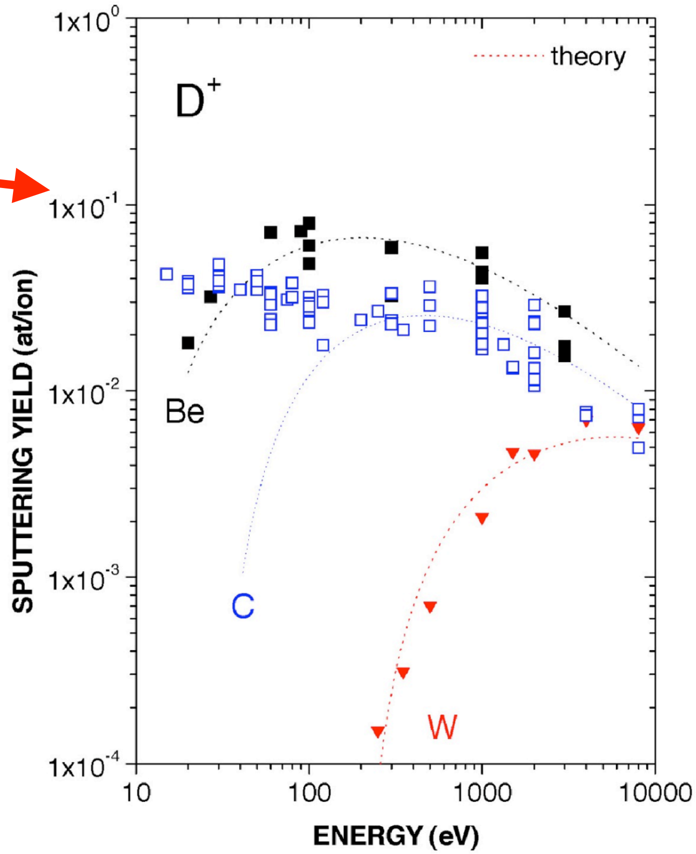
- If the alpha particles end up on the divertor, the combined load will be even more challenging

- Impact of alpha particle flux on armor lifetime (erosion) is more of a concern.

Alpha Particle Flux Impact on Armor Lifetime

- **For these high alpha energies, sputtering is less of a concern and armor lifetime would be governed by some mechanism, such as exfolation, resulting from accumulation of He atoms in the armor.**

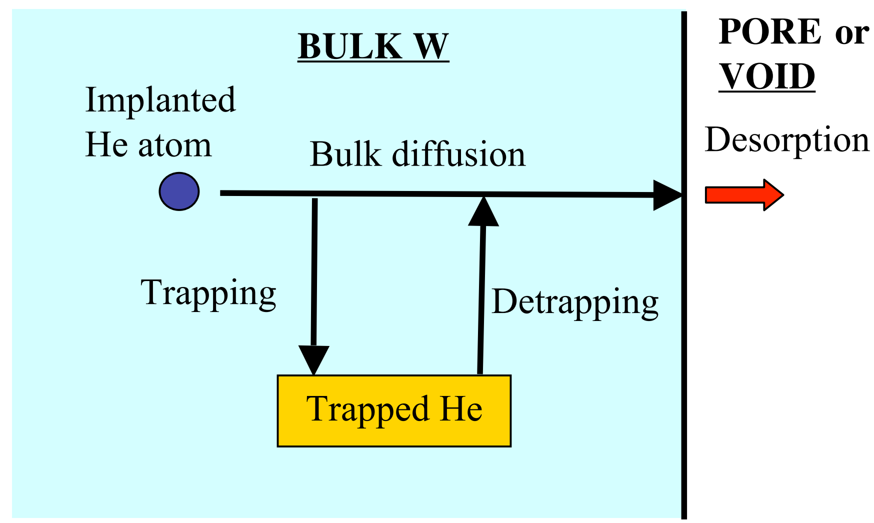
- **As an example, for a W armor, the implantation depth for He at ~ 1 MeV is ~1.5 μm. For an example fusion power of 2350 MW, a 10% alpha loss and assuming a FW surface area of 572 m^2 and an alpha PFC coverage of 5%, the resulting flux on the PFC is ~3 x 10^{18} ions/m^2-s (corresponding to a generation rate of ~2 x 10^{24} ions/m^3-s).**



Sputtering yield at normalized incidence for Be, C and W as a function of ion energy (As illustration assuming a roughly similar He sputtering behavior)

He Implantation and Behavior in W Armor Quite Complex, Consisting of a Number of Mechanisms

- **Due to their high heat of solution, inert-gas atoms are essentially insoluble in most solids.**
- **This can then lead to gas-atom precipitation, bubble formation and ultimately to destruction of the material.**
- **He atoms in a metal may occupy either substitutional or interstitial sites. As interstitials, they are very mobile, but they will be trapped at lattice vacancies, impurities, and vacancy-impurity complexes.**



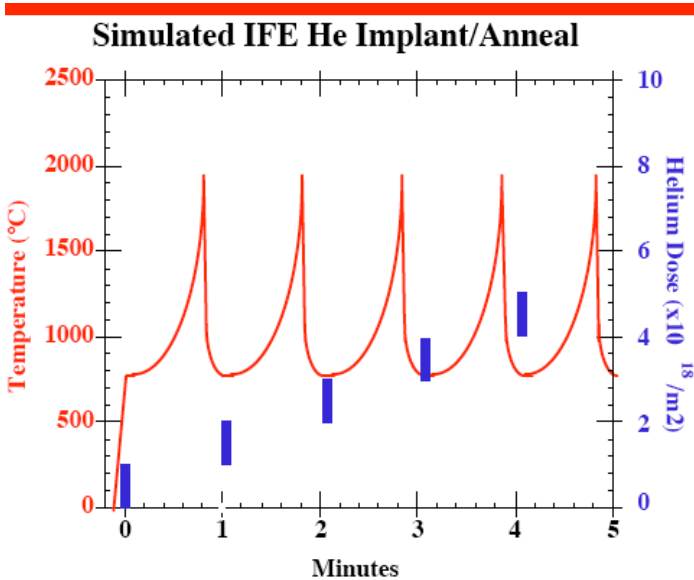
- **Ion and neutron irradiation will generate defects which would enhance He trapping.**
- **Can operation at high temperature can anneal these defects before they trap the He?**
- **The following activation energies were estimated for different He processes in tungsten [1,2]:**
  - Helium formation energy: 5.47 eV
  - Helium migration energy: 0.24 eV
  - He vacancy binding energy: 4.15 eV
  - He vacancy dissociation energy: 4.39 eV

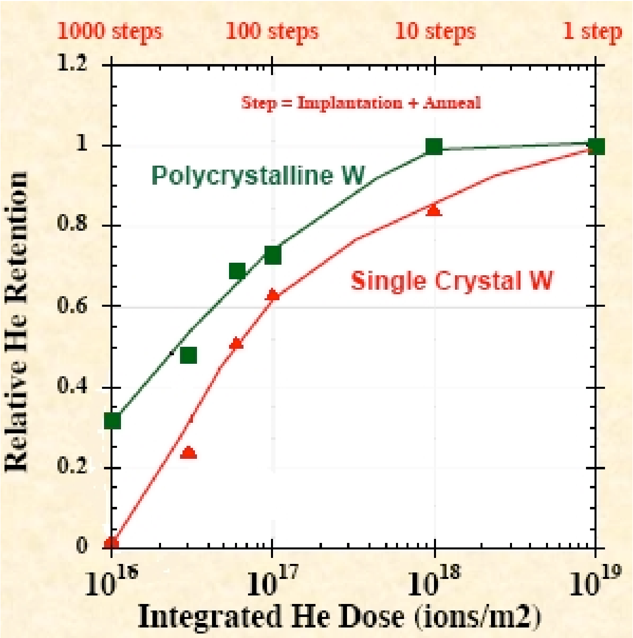
1. M. S. Abd El Keriem, D. P. van der Werf and F. Pleiter, "Helium-vacancy interactions in tungsten," Physical review B, Vol. 47, No. 22, 14771-14777, June 1993.
2. W. D. Wilson and R. A. Johnson, in *Interatomic Potentials and Simulation of Lattice Defects*, edited by P. C. Gehlen, J. R. Beeler and R. I. Jaffee (Plenum New York, 1972), p375.
3. A. Wagner and D. N. Seidman, Phys. Rev. Letter 42, 515 (1979)

  - From [3], $D\ (m^2/s) = D_0 \exp(-E_{Dif}/kT)$; $D_0 = 4.7 \times 10^{-7}\ m^2/s$ and $E_{Dif} = 0.28$ eV

Engineering Analysis of IFE Relevant Experimental Data on He Implantation and Release in W

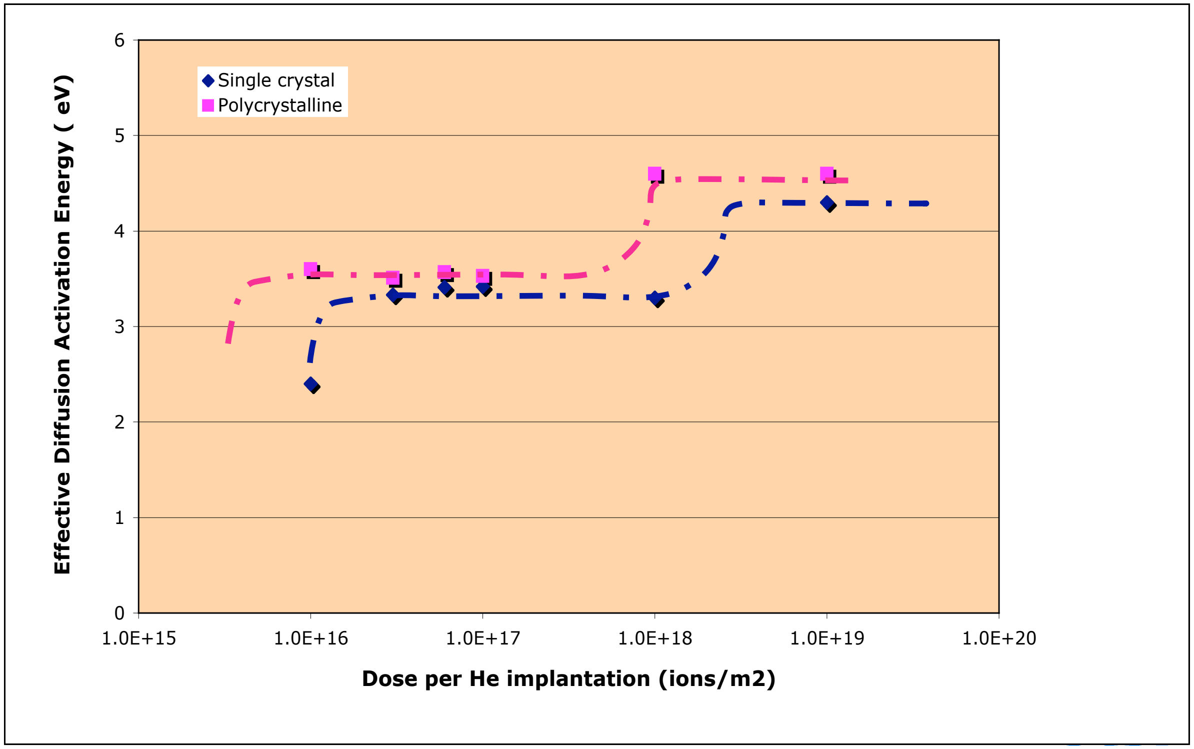
(From UNC/ORNL experimental results presented by L. Snead, et al., March 2005 HAPL meeting or US/Japan Workshop on Laser IFE, General Atomics, San Diego, CA, March 2005)



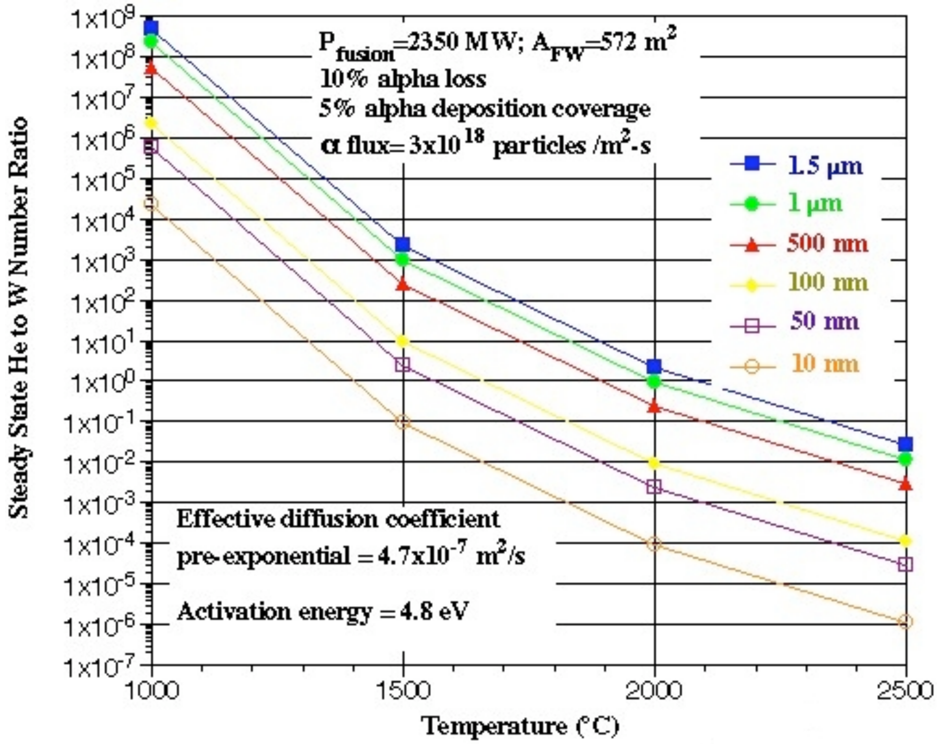


Effective Diffusion Activation Energy ($E_{eff,diff}$) as a Function of Dose per He Implantation

(The curve fit has been drawn to suggest a possible variation of the activation energy with the He dose or concentration)

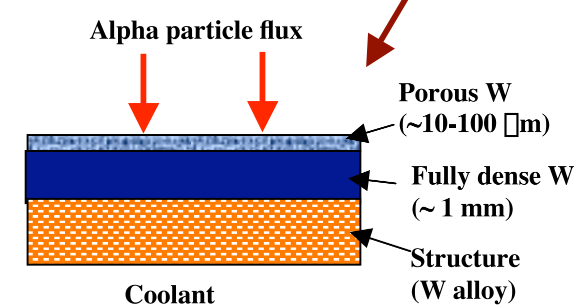


Inventory of He in W Based on Example α-Particle Implantation Case



- Simple effective diffusion analysis for different characteristic diffusion dimensions for an activation energy of 4.8 eV
- Not clear what is the max. He conc. limit in W to avoid exfolation (perhaps ~0.15 at.%)
- High W temperature needed in this case
- Shorter diffusion dimensions help, perhaps a nanostructured porous W (PPI)
- e.g. 50-100 nm at ~1800°C or higher

- An interesting question is whether at a high W operating temperature (>~1400°C), some annealing of the defects might help the tritium release.
- This is a key issue for a CS which needs to be further studied to make sure that a credible solution exists both in terms of the alpha physics, the selection of armor material, and better characterization of the He behavior under prototypic conditions.



UCSD

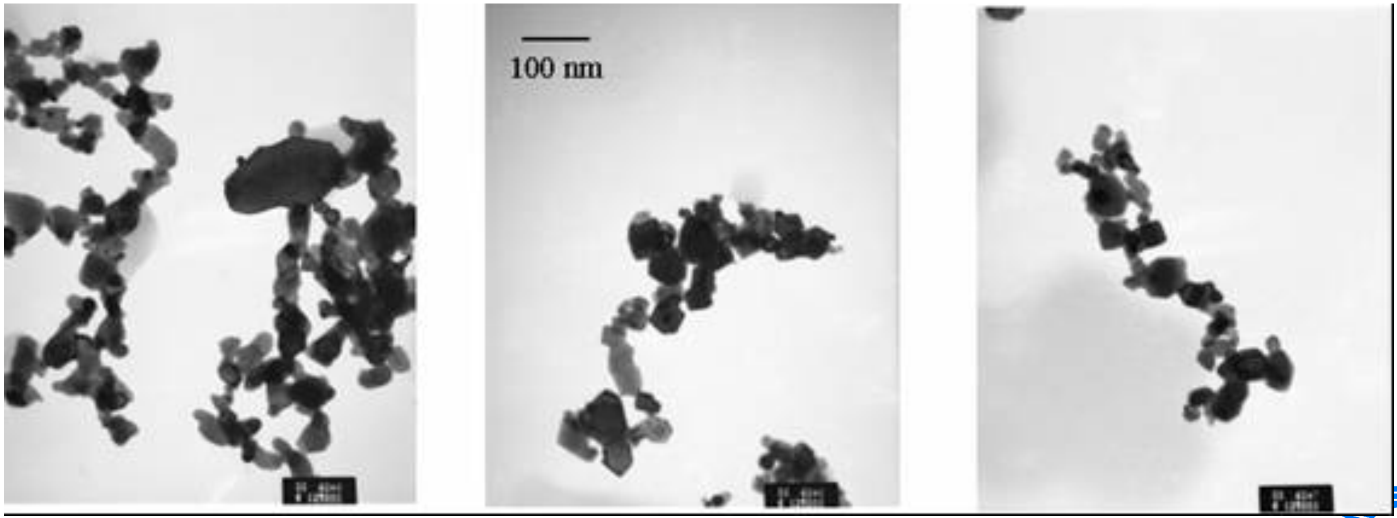
PPI's Progress in Manufacturing Porous W with Nano Microstructure

- **Plasma technology can produce tungsten nanometer powders.**
  - When tungsten precursors are injected into the plasma flame, the materials are heated, melted, vaporized and the chemical reaction is induced in the vapor phase. The vapor phase is quenched rapidly to solid phase yielding the ultra pure nanosized W powder
  - Nano tungsten powders have been successfully produced by plasma technique and the product is ultra pure with an average particle size of 20-30nm. Production rates of > 10 kg/hr are feasible.

- **Process applicable to molybdenum, rhenium, tungsten carbide, molybdenum carbide and other materials.**

- **The next step is to utilize such a powder in the Vacuum Plasma Spray process to manufacture porous W (~10-20% porosity) with characteristic microstructure dimension of ~50 nm .**

TEM images of tungsten nanopowder, p/n# S05-15.

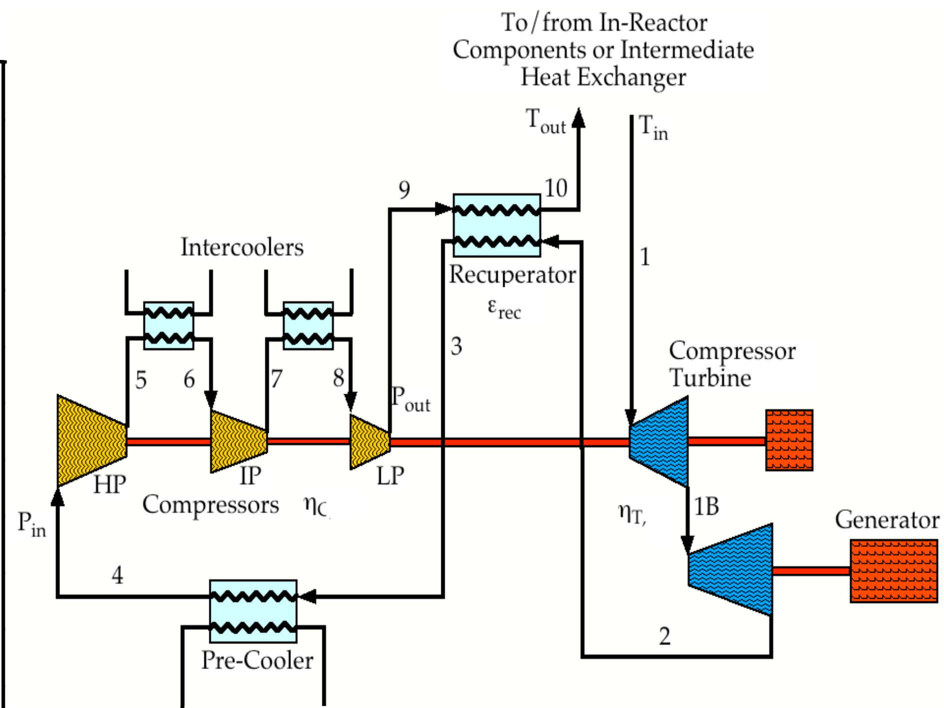


Optimization of DC Blanket Coupled to Brayton Cycle

- **Net efficiency calculated including friction thermal power from He coolant flow and subtracting required pumping power to estimate net electrical power.**

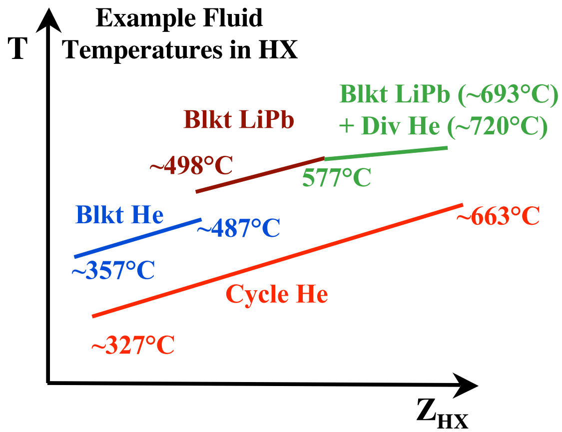
- **Brayton cycle configuration and typical parameters summarized here.**

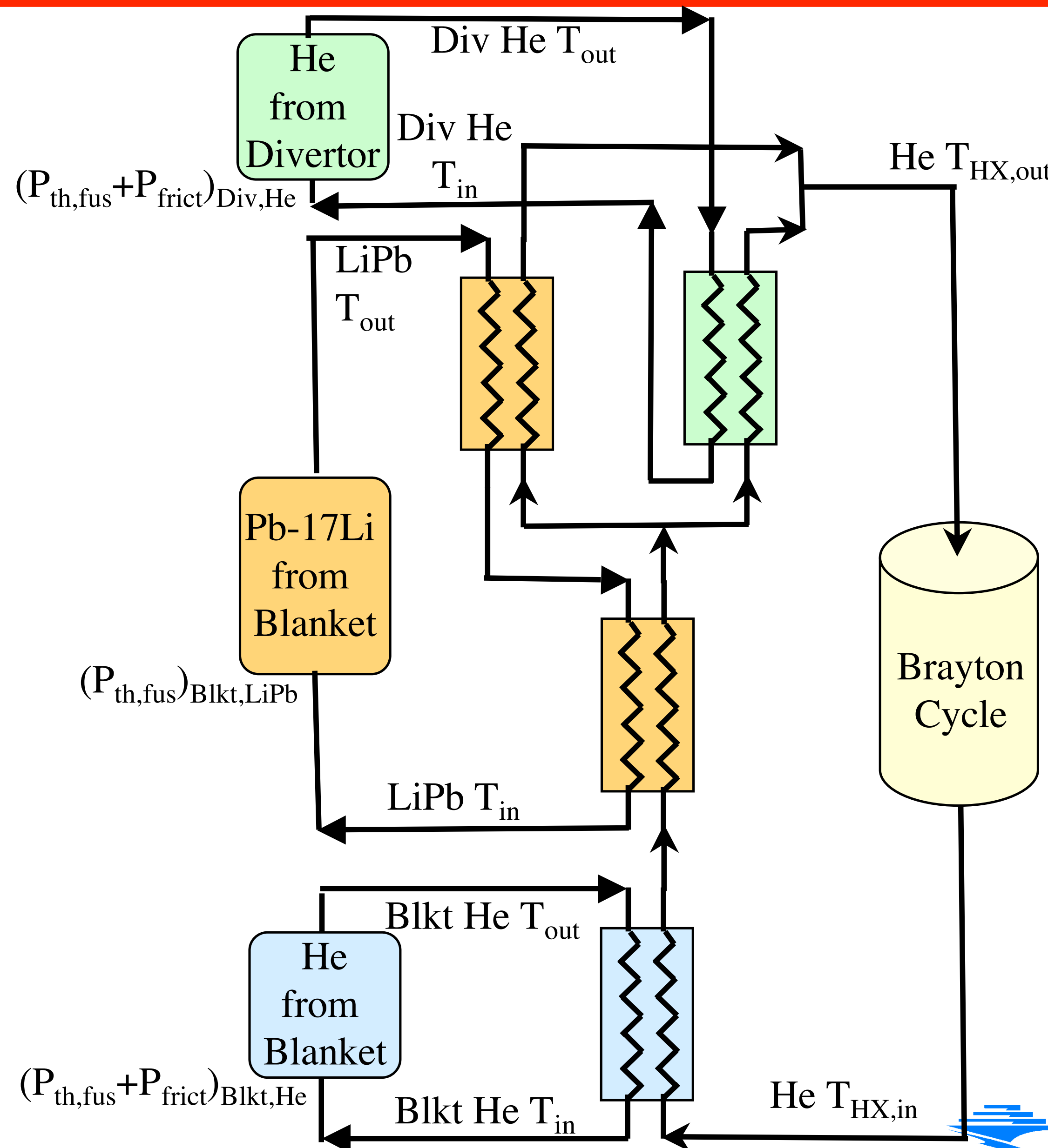
Number of Compression Stages	**3**
Number of Expansion Stages	**1**
HX Min. Temp. Difference between Hot and Cold Legs	**30°C**
Compressor Efficiency	**0.89**
Turbine Efficiency	**0.93**
Recuperator Effectiveness	**0.95**
Total Compression Ratio	**3.5**
Cycle Lowest He Temperature	**35°C**
Fractional Cycle He Pressure Drop	**0.045**
Cycle He Pressure	**15 MPa**
Gross Efficiency	**0.41**
Net Efficiency (+ contribution of blanket & divertor He friction thermal power – pumping power)	**0.38**



Details of Coolant Routing Through HX Coupling Blanket and Divertor to Brayton Cycle

- Div He T_{out} ~ Blkt Pb-17Li T_{out}
- Min. DT_{HX} = 30°C
- $P_{Friction}$ ~ $□_{pump}$ x P_{pump}





Power Parameters for Example Case

Fusion Thermal Power in Reactor Core	2675 MW
Fusion Thermal Power removed by Pb-17Li	1421 MW
Fusion Thermal Power Removed by Blkt He	1029 MW
Friction Thermal Power Removed by Blkt He	91 MW
Fusion Thermal Power Removed by Div He	225 MW
Friction Thermal Power Removed by Div He	26 MW
Fusion + Friction Thermal Power in Reactor Core	2792 MW

Optimization of DC Blanket Coupled to Brayton Cycle Assuming a FS/Pb-17Li Compatibility Limit of 500°C and ODS FS for FW

- $\eta_{Brayton,gross} = P_{elect,gross} / P_{thermal,fusion}$
- $\eta_{Brayton,net} = (P_{elect,gross} - P_{pump}) / P_{thermal,fusion}$

- **Use of an ODS FS layer on FW allows for higher operating temperature and a higher neutron wall load.**

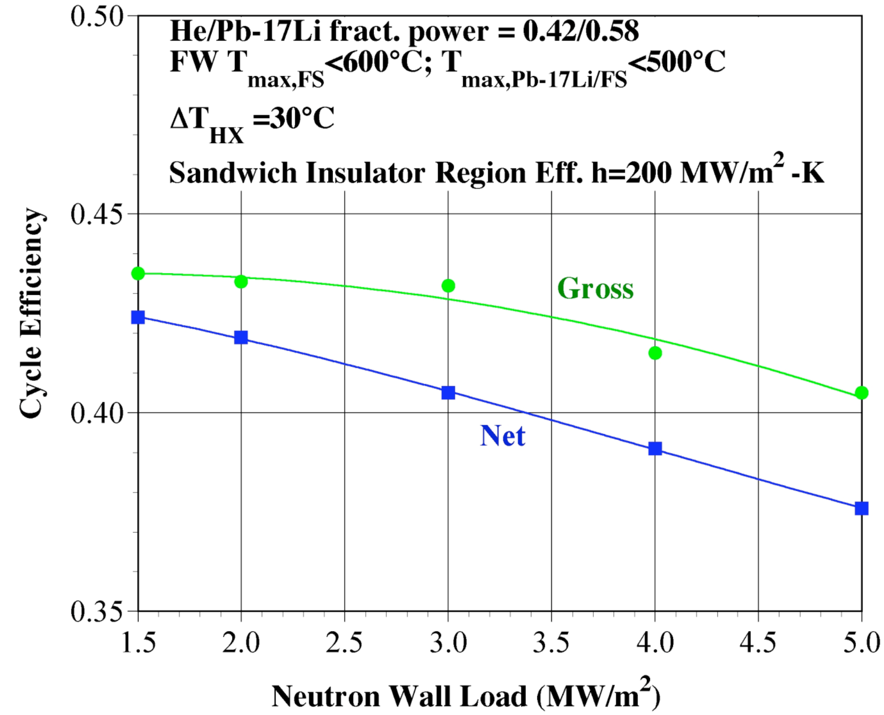
- **For the highly loaded divertor region, He ΔP/P ~0.1**

- **For blanket, He ΔP/P ~0.05.**

- **Calculations based on in-reactor ΔP only (ΔP in outside lines assumed relatively smaller)**

- **The optimization was done by considering the net efficiency of the Brayton cycle for an example 1000 MWe case.**

Efficiency v. neutron wall load data provided as input to system code

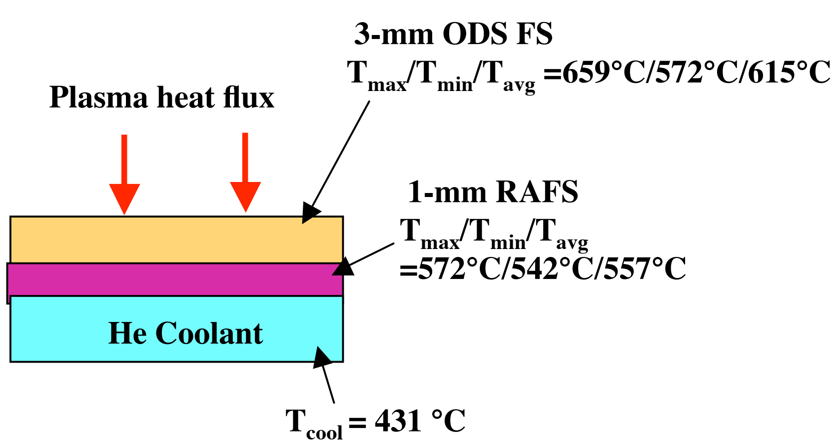


- **The gross efficiency decreases from ~44% to ~41% and the net efficiency decreases from ~43% to ~38% as the maximum wall load is increased from 1.5 to 5 MW/m^2.**

- **The average first wall temperature is <550°C up to a wall load of 3 MW/m^2, and increases to ~600°C for a wall load of 5 MW/m^2.**

- **The corresponding gross thermal efficiency is typically about 2 points higher than the net efficiency.**

Summary of Parameters for Dual Coolant Concept for a Maximum Neutron Wall Load of 5 MW/m²

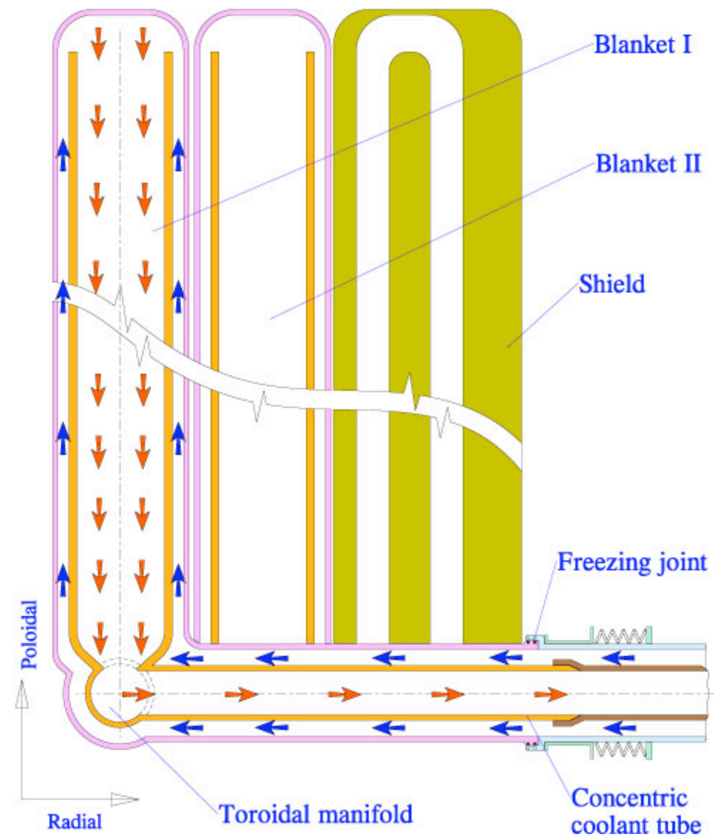


Blanket	
Typical Module Dimensions	2 m x 2 m x 0.62 m
Tritium Breeding Ratio	1.1
Fusion Thermal Power in Blanket	2451 MW
Blanket Pb-17Li Coolant	
Pb-17Li Inlet Temperature	498°C
Pb-17Li Outlet Temperature	693°C
Pb-17Li Inlet Pressure	1 MPa
Typical Inner Channel Dimensions	0.26 m x 0.24 m
Thickness of SiC Insulator in Inner Channel	5 mm
Effective SiC Insulator Region Conductivity	200 W/m²-K
Average Pb-17Li Velocity in Inner Channel	~0.11 m/s
Fusion Thermal Power removed by Pb-17Li	1420 MW
Pb-17Li Total Mass Flow Rate	39,000 kg/s
Pb-17Li Pressure Drop	~1 kPa
Pb-17Li Pumping Power	~ 5.6 kW
Maximum Pb-17Li/FS Temperature	500°C
Blanket He Coolant	
He Inlet Temperature	357°C
He Outlet Temperature	487°C
He Inlet Pressure	8 MPa
Typical FW Channel Dimensions (poloidal x radial)	2 cm x 3 cm
He Velocity in First Wall Channel	64 m/s
Blanket He Pressure Drop	0.31 MPa
Fusion Thermal Power Removed by He	1030 MW
Friction Thermal Power Removed by He	91 MW
Total Mass Flow Rate	1730 kg/s
Pumping Power	101 MW
Maximum Local FS Temperature at FW	659°C
Radially Averaged FS Temperature at T_{max} Location	601°C

Thermal-Hydraulic Study of Alternate Blanket: Self-Cooled Pb-17Li Blanket with SiC_f/SiC

- We decided to keep this high performance higher risk blanket concept as back-up option
- Based on ARIES-AT blanket concept
- High cycle efficiency when coupled to a Brayton Cycle
- Minimal pumping power (<1 MW)
- Power Cycle efficiency as a function of wall load as input to system code
- Some uncertainty as ARIES-AT utilizes Pb-17Li as divertor coolant also but with q_{max}''=5 MW/m^2 (as compared to 10 MW/m^2 for ARIES-CS)

Cross-section Showing Coolant Flow Path and Access Tube



Max. Neutron Wall Load	Cycle Efficiency
2 MW/m^2	0.63
3 MW/m^2	0.61
4 MW/m^2	0.59
5 MW/m^2	0.56

Selection of Maintenance Scheme for Phase III Detailed Design Study

Two Maintenance Schemes Considered

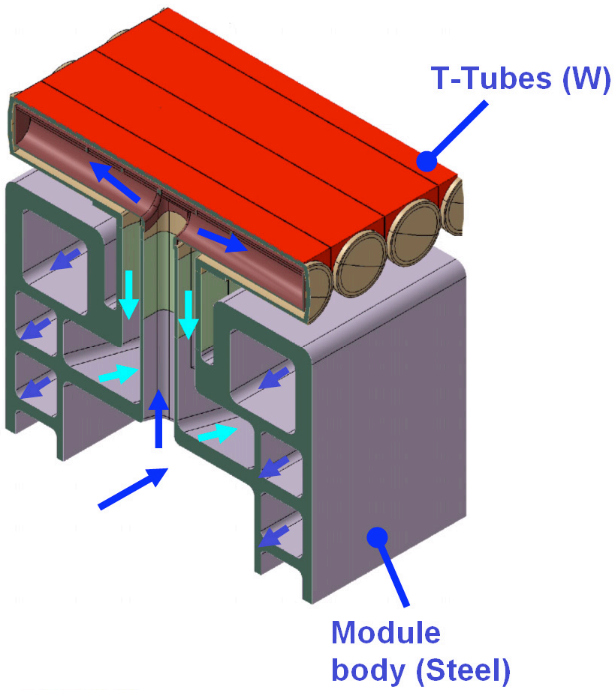
1. Field-period-based maintenance scheme
2. Port-based maintenance scheme

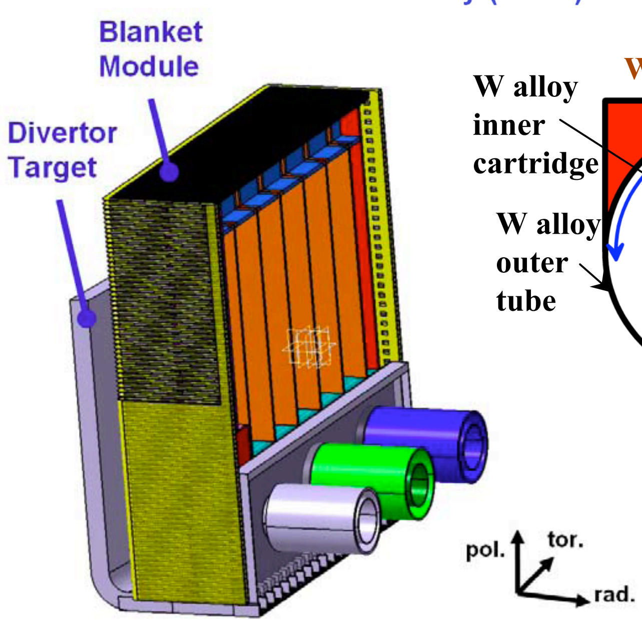
Recommendation

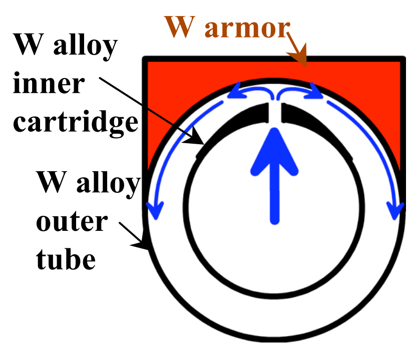
- Advantages and issues for each option have been presented before.
- Comprehensive quantitative comparison study to guide the choice is beyond the scope of our study.
- Two important considerations guiding this recommendation:
  - Keep scheme best suited for both 2-field and 3-field period
  - Avoid too far an extrapolation from what is presently considered for near term (and longer term) MFE reactors (mostly tokamaks)

Port-Based Maintenance Scheme Recommended as Reference Scheme with Field Period-Based Scheme as Back-Up

Divertor Study







- **Good progress on engineering design and analysis (but further progress needed on physics study).**
- **Also integration with blanket needs further study.**

Divertor	
Divertor T-Tube Unit Cell Dimensions	9 cm (tor.) x 1.6 cm (pol.)
He Inlet Temperature	577°C
He Outlet Temperature	720°C
He Inlet Pressure	10 MPa
Typical FW Channel Dimensions	0.5 mm
He Jet Velocity	200 m/s
Average Jet Flow Heat Transfer Coefficient	~ 17,000 W/m^2-K
He Pressure Drop	0.4 MPa
Fusion Thermal Power in Divertor	225 MW
He Friction Thermal Power in Divertor	26 MW
Total Mass Flow Rate	338 kg/s
Pumping Power	29 MW
Maximum W Alloy Temperature	<1300°C
Maximum Primary + Secondary stresses	<370 MPa

UCSD

Important to Document our Work and Maintain a Current and Consistent Record of Various ARIES-CS Power Core and Engineering Parameters

- Engineering write-up on maintenance, dual coolant blanket, divertor and alpha particle threat already circulated
  - Consistent with typical system code results
  - Detailed parameters in tabular form

- Similar write-ups would be very useful for:
  - Neutronics (Laila will provide it shortly)
  - Safety (Brad)
  - Magnet design and material (Leslie)

- Can be regularly updated

- Extracts can provide updated contributions to future paper(s)