

Ferritic Steel Lifetime Assessment and Self-Consistent Nuclear Parameters for ARIES-IFE-HIB

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PPPL

Objectives

- **Assess nuclear performance** of structure-free blanket concept using **ARIES design rules**
 - **Breeding** potential of candidate breeders:
 - Flibe
 - Flinabe.
 - **Lifetime** of ODS ferritic steel (FS) protected with liquid blanket
 - **Waste disposal rating and Helium production** for structural components: shield, nozzles, feeding tubes.
- Estimate **reduction in waste** for thick liquid wall concept.



Key Parameters

Target yield	458.7 MJ
Rep rate	4 Hz
# of pulses	126 million/FPY
Average source neutron energy	11.75 MeV
Neutron power	1286 MW
Neutron wall loading @ 0.5 m	410 MW/m ²
Penetrations coverage	3%
Plant lifetime	40 FPY
Availability	85%



ARIES Requirements and Design Limits

Overall TBR	≥ 1.08
dpa* to FS structure	≤ 200 dpa
Helium production for reweldability of FS	≤ 1 He appm
WDR for Class C low level waste	≤ 1

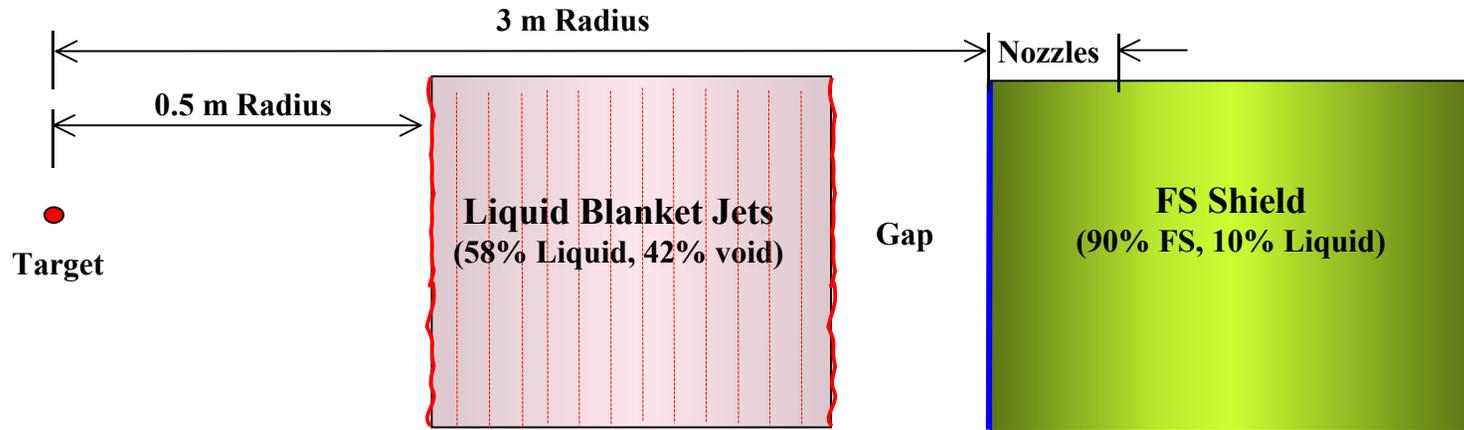
* Thermal creep strength @ EOL is more restrictive than radiation damage, per M. Billone (ANL).

Flibe vs Flinabe

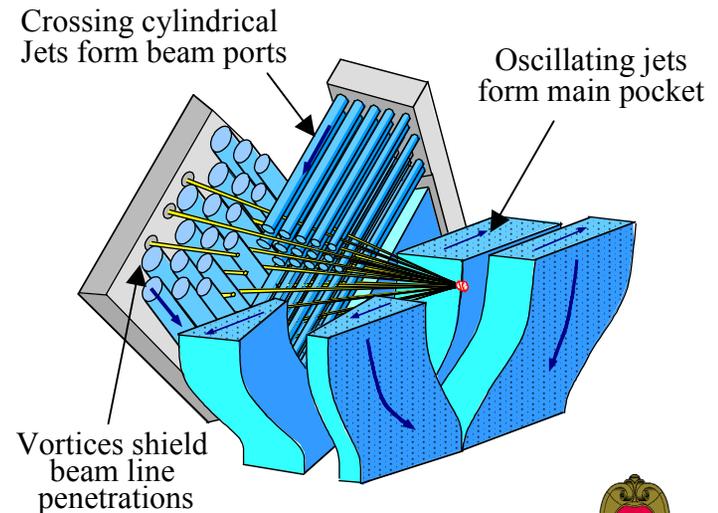
- **Flinabe** has substantially lower melting point (~ 320 °C) compared to **Flibe** (459 °C) , offering low operating temperature and **low vapor pressure**.
- To provide **very low vapor pressure in HIF beam tubes and protect structure** against x-rays and target debris, **Per Peterson (UCB) recommended Flinabe** to create low temperature vortices.
- **It is preferable to have single liquid composition everywhere** (in chamber and beam tubes), if acceptable from perspectives of breeding and safety.



Schematic of Radial Build

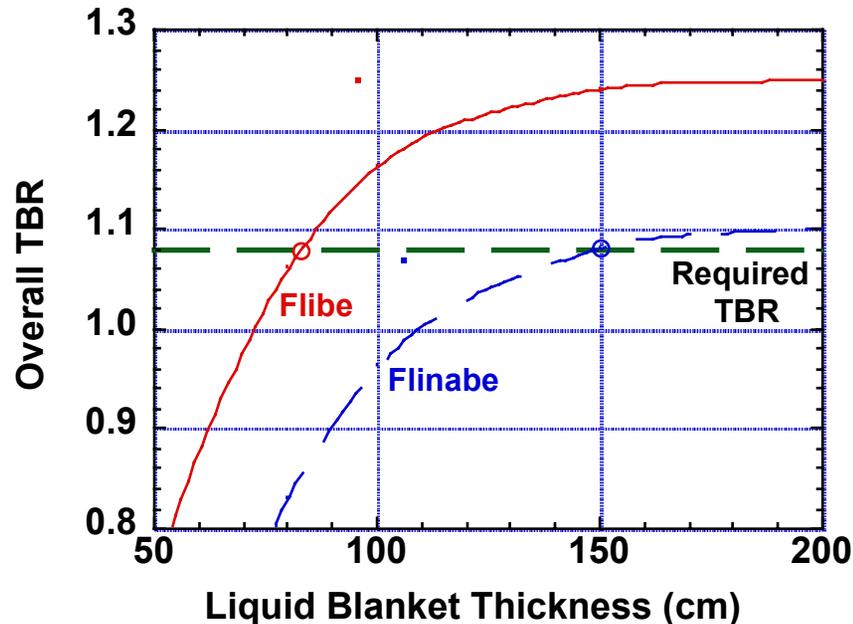


- **Flibe** ($\text{BeF}_2, (\text{LiF})_2$) and **Flinabe** ($\text{NaF}, \text{LiF}, \text{BeF}_2$) with natural Li.
- ODS nanocomposited[#] FS or 304-SS.
- Innermost layer of shield represents nozzles and feeding tubes.
- Point source and 1-D spherical geometry



G.R. Odette and D.T. Hoelzer, "Development of Nanocomposited Ferritic Alloys for High Performance Fusion First Wall and Blanket Structures," article submitted to ANS FED newsletter, <http://fti.neep.wisc.edu/FTI/FED/news0602.pdf> (June 2002).

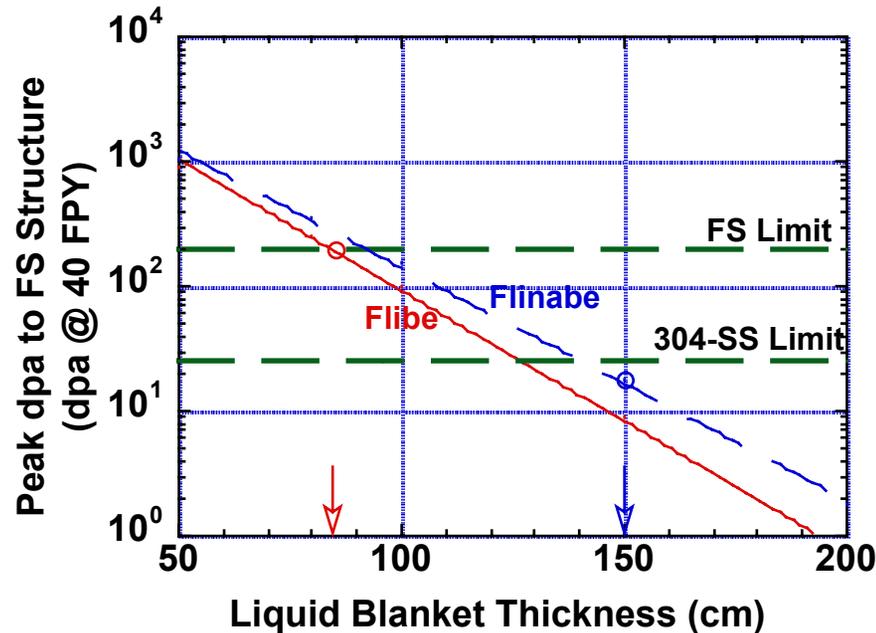
Flibe Breeds more Tritium than Flinabe



- 83 cm thick Flibe and 150 cm thick Flinabe meet ARIES breeding requirement (TBR \geq 1.08).
- Enrichment does not enhance breeding of thick Flinabe.
- Nuclear energy multiplication amounts to \sim 1.25.
- \sim 10% of heating deposited in shield behind Flibe and 1% of heating in shield behind Flinabe.



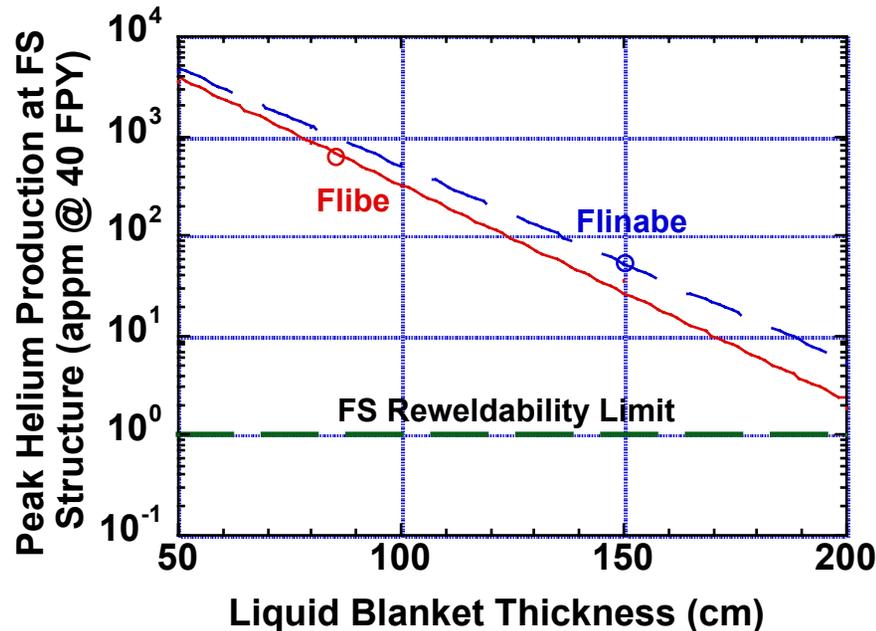
For Same Blanket Thickness, Flibe Provides Better Attenuation than Flinabe



- 85 cm Flibe blanket meets FS 200 dpa limit.
- 1.5 m Flinabe blanket provides better shielding and meets 25 dpa limit for 304-SS.

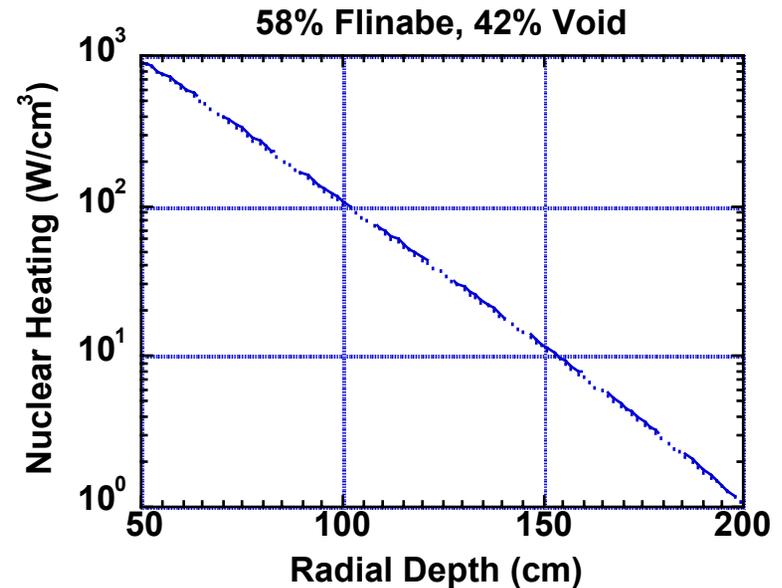
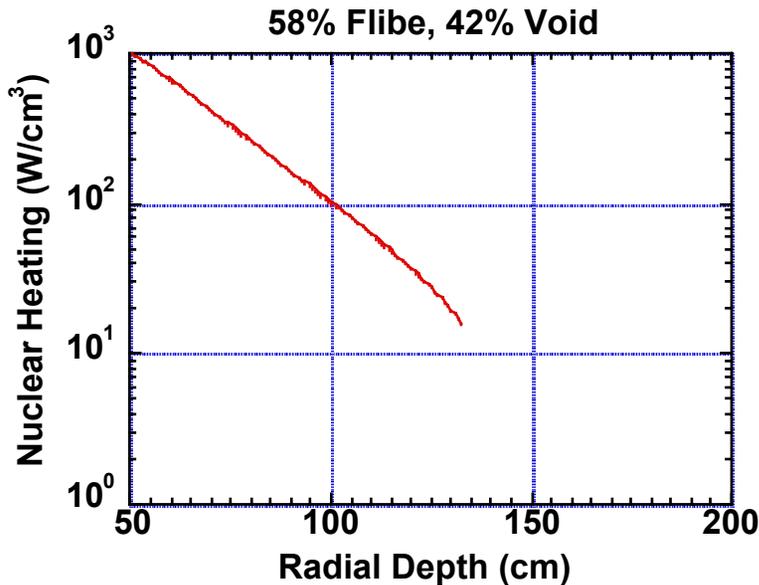


Helium Production is Excessive



Innermost shield layer/nozzles/feeding tubes cannot be re-welded at any time during operation.

Nuclear Source Term for Aerosol Calculations



- Heating evaluated at midplane per unit volume of actual blanket composition.
- For isochoric heating analysis, detailed **heating in fine meshes** and **time-dependent nuclear heating** will be computed upon request.



Steel Composition (in wt%)

	<u>ODS-12YWT-FS*</u> (Experimental Alloy)	<u>ODS M-F82H-FS**</u>	<u>304-SS#</u>
Fe	83.818	87.891	70.578
C	0.052	0.04	0.046
N	0.014	0.005	0.038
O	0.16	0.13	—
Si	0.1	0.24	0.47
P	—	0.005	0.026
S	0.001	0.002	0.012
Ti	0.35	0.09	0.03
V	0.01	0.29	—
Cr	12.58	8.7	17.7
Mn	0.05	0.45	1.17
Co	—	0.0028	0.1
Ni	0.27	0.0474	9.3
Cu	0.02	0.01	0.2
Nb	0.01	0.00033	—
Mo	0.02	0.0021	0.33
Ta	—	0.08	—
W	2.44	2	—
Y	0.16	0.7	—

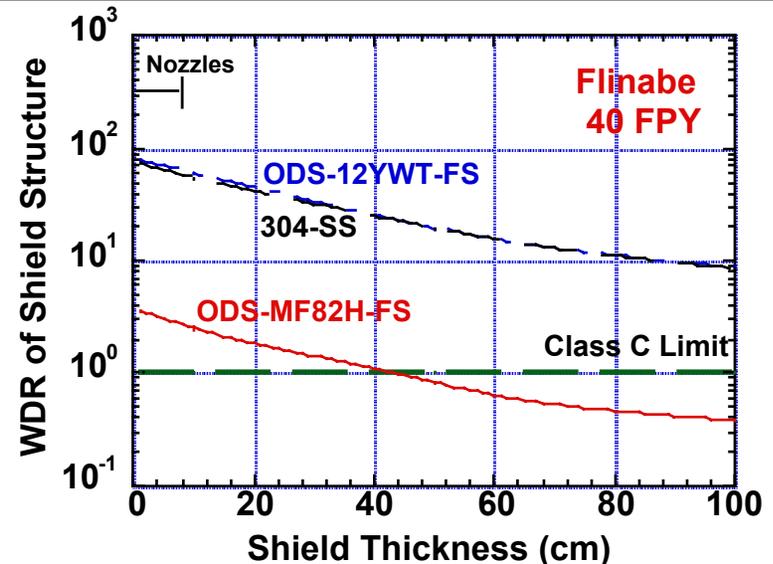
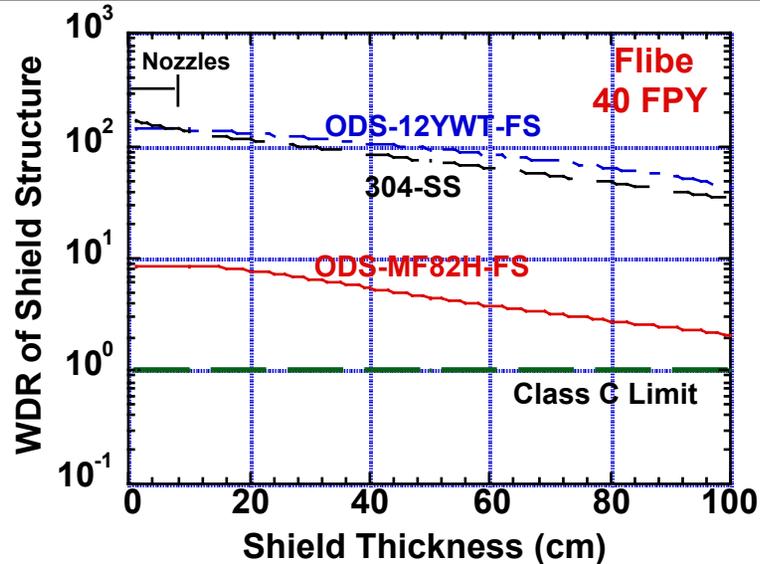
* R. Klueh et al., "Microstructure and Mechanical Properties of Oxide Dispersion-Strengthened Steels" fusion materials semiannual progress report for the period ending June 30, 2000 (DOE/ER-0313/28), pp. 123-130. Fe-12Cr-3W-0.4Ti-0.25Y₂O₃ (12YWT) experimental alloy.

** IEA Modified F82H FS + 0.25wt% Y₂O₃, per M. Billone (ANL).
include: B, Al, As, Pd, Ag, Cd, Sn, Sb, Os, Ir, Bi, Eu, Tb, Dy, Ho, Er, U.

Other elements

Starfire report: C. Baker et. al, "Starfire-A Commercial Tokamak Fusion Power Plant Study," Argonne National Laboratory Report, ANL/FPP-80-1 (1980).

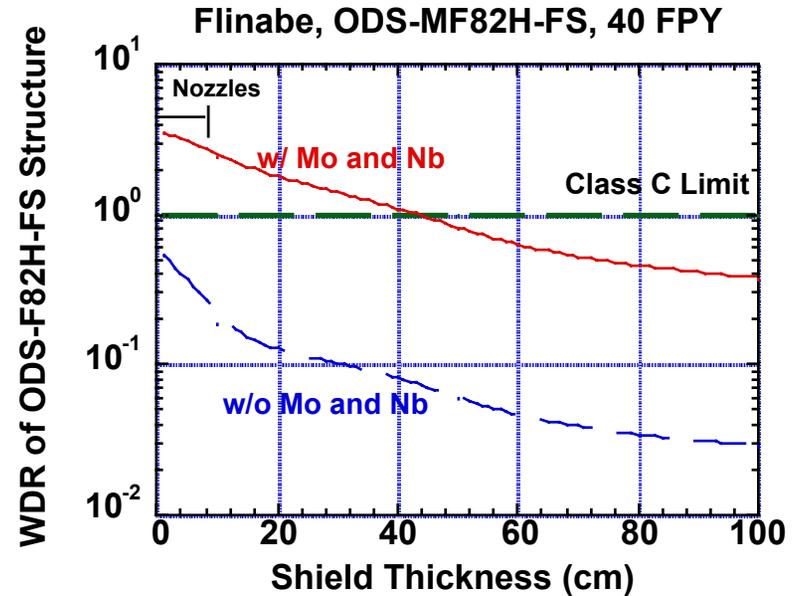
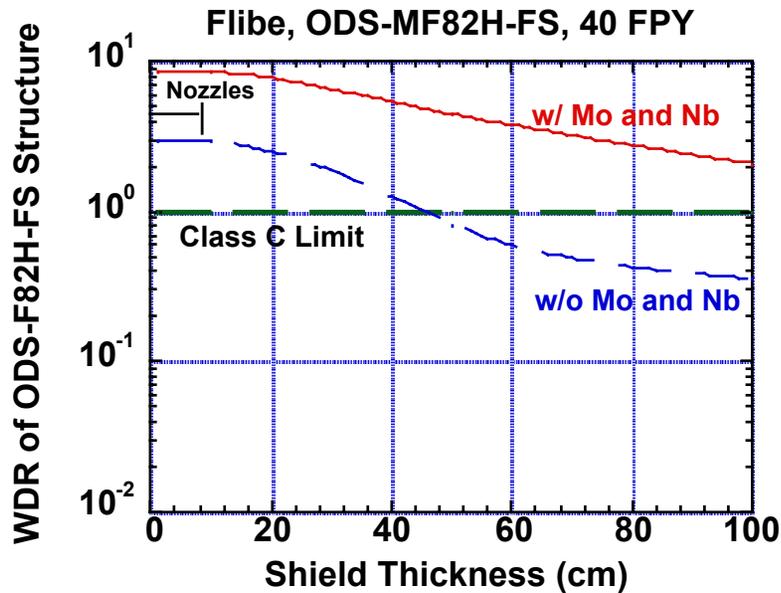
All Alloys Generate High Level Waste



- ODS-MF82H-FS offers lowest WDR.
- Thicker Flinabe blanket results in lower WDR.
- Main contributors to WDR: ⁹⁴Nb (from Nb), ⁹⁹Tc (from Mo), and ^{192m}Ir (from W).
- Potential solutions to meet waste requirement (WDR < 1):
 - Control Mo and Nb,
 - Thicken blanket.



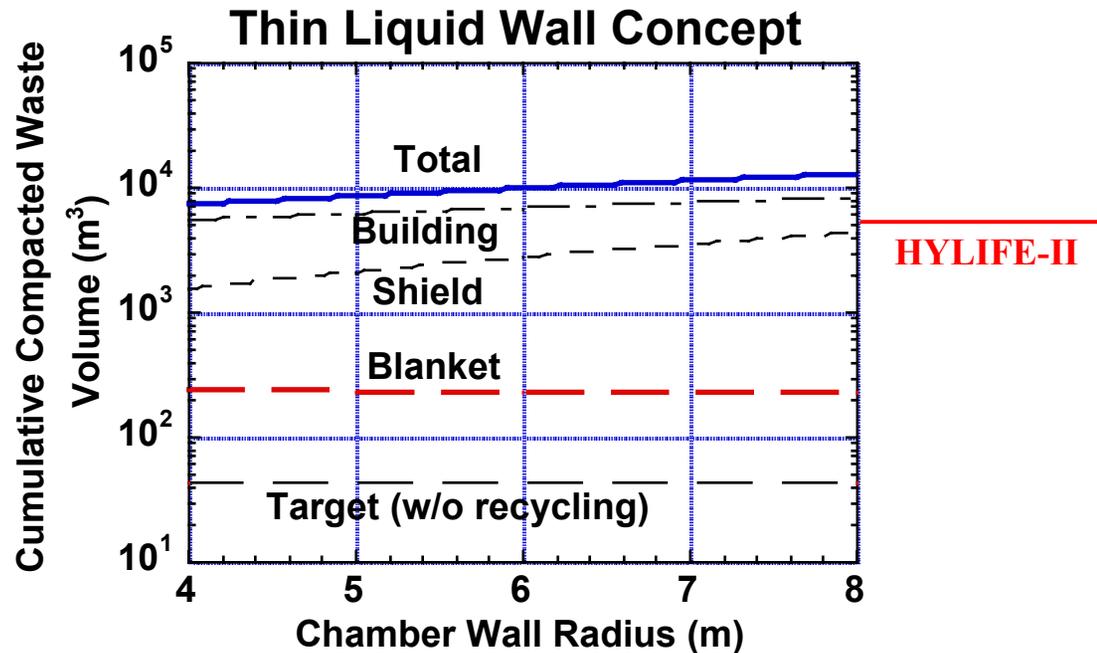
Effect of Mo and Nb on WDR



- In practice, Mo and Nb impurities cannot be zeroed out. Actual level depends on \$/kg to keep Mo and Nb < 1 wppm.
- Flibe shield with Mo/Nb control should be > 50 cm thick to qualify as LLW.
- Flinabe shield without Mo/Nb control meets waste requirement if ≥ 45 cm thick.
- Nozzles/feeding tubes generate high level waste unless protected by thicker blanket or mixed with shield and disposed as single unit at EOL.



Revisiting Logic Behind Thick Liquid Wall Concept



- Thick liquid wall concept developed to eliminate blanket replacement, **reduce waste**, and increase availability by 10% \Rightarrow 20% lower COE, per R. Moir (UCRL-JC-115748, April 1994).
- In IFE solid wall designs, **blanket generates only 2-4% of total waste**
 \Rightarrow **Thick liquid wall concept offers small waste reduction.**
(same conclusion made for MFE - APEX project)



Conclusions

- **Class C LLW requirement is more restrictive** than breeding and dpa requirements.
- **No breeding problem identified for Flibe and Flinabe.**
- 85/150 cm thick Flibe/Flinabe blankets provide TBR of 1.08 and meet FS dpa limit.
- **Helium production in FS is excessive and precludes FS reweldability during operation.**
- **All steels produce high level waste (WDR \gg 1).**
- **ODS-MF82H-FS and Flinabe system offer lower WDR for FS structure.**
- **Low level waste can be achieved with combination of Mo/Nb control and blanket/shield adjustment.**
- **Nozzles/Feeding tubes need additional protection to qualify as LLW unless combined with shield.**



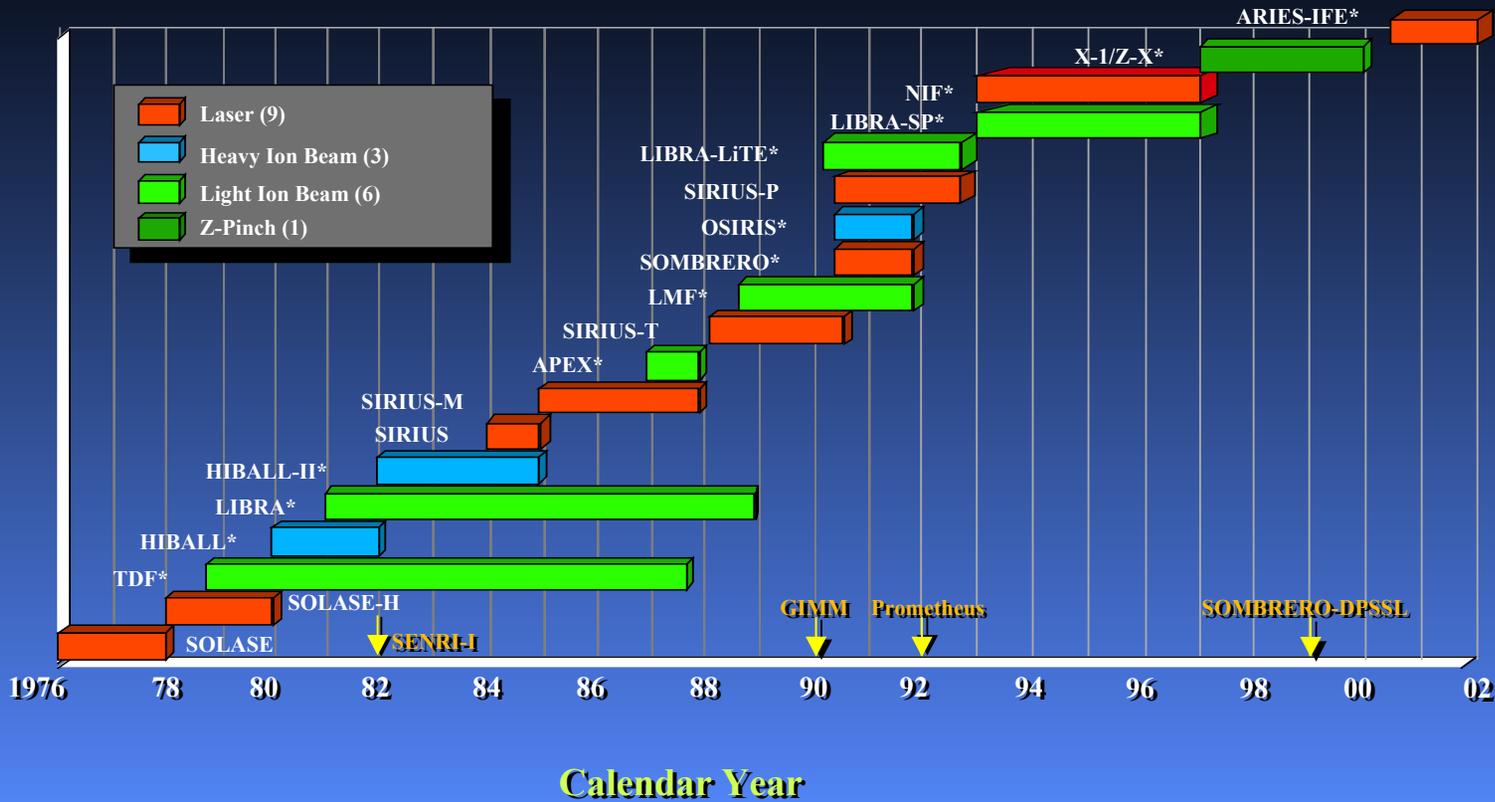
Importance of Results and What needs to be done

- **Nuclear assessment is important to feasibility of thick liquid wall concept.**
Results show impact of thick liquid wall on:
 - FS lifetime
 - Waste level
 - Reduction in waste volume.
- **Design-specific analysis needed** to meet LLW requirement for nozzles and shield using:
 - Nb and Mo impurity control
 - Thicker blanket (adjust TBR)
 - Thicker shield.
- **Need feedback from materials community** on acceptable Nb and Mo impurity level **and** impact on FS unit cost.



UW IFE Designs

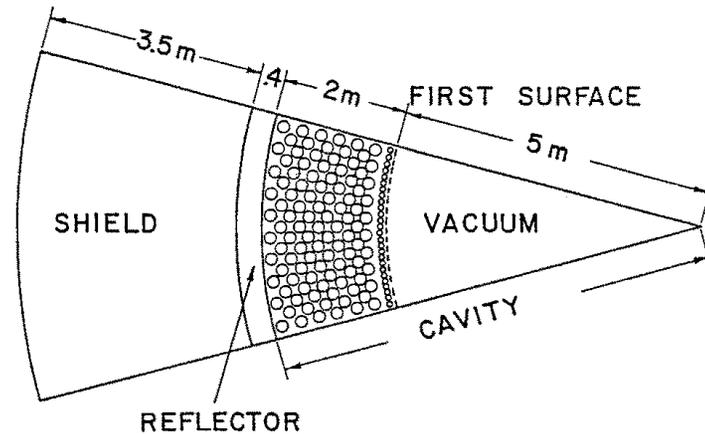
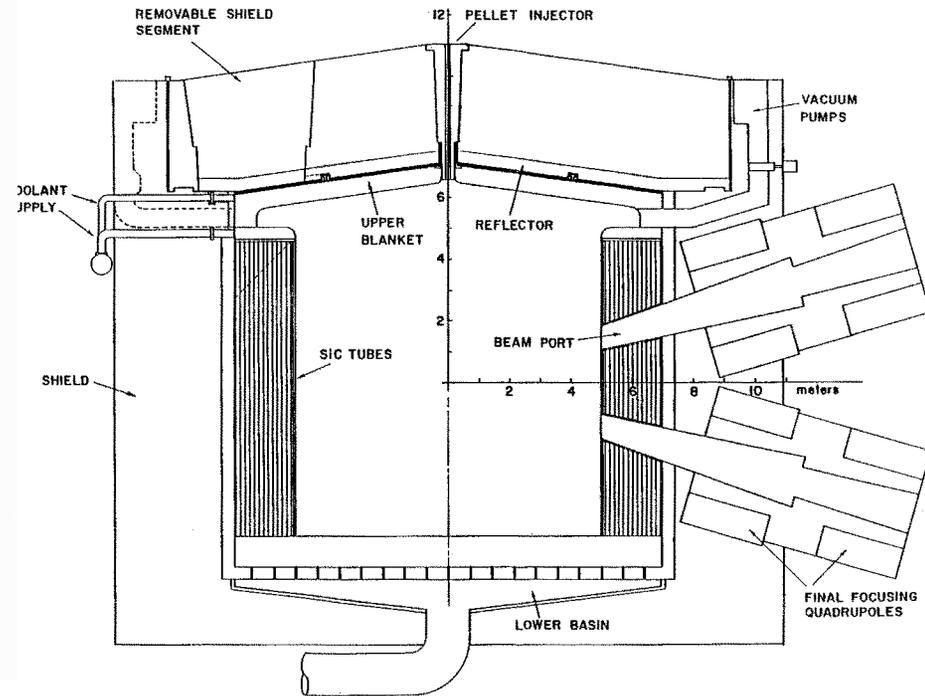
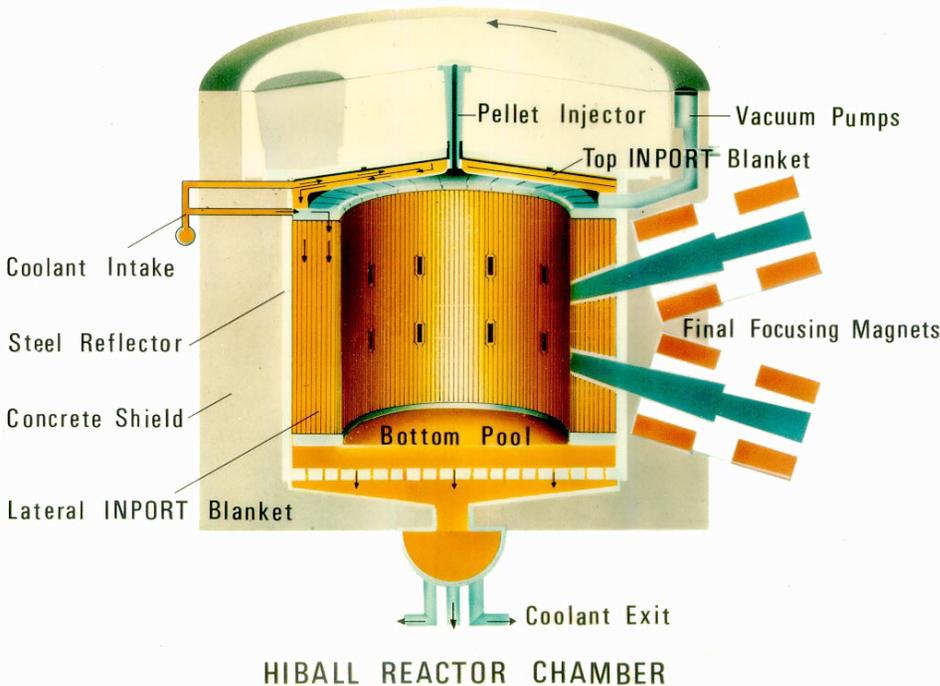
Fusion Technology Institute IFE/ICF Reactor Studies



**in conjunction with other universities, national and international labs*



UW IFE Design - HIBALL (1981)



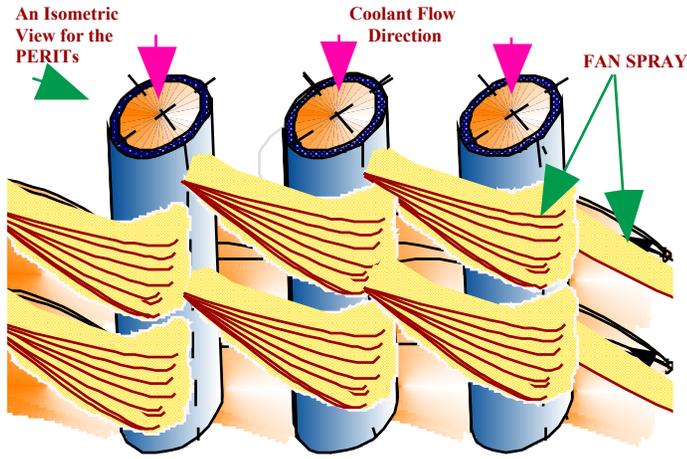
- Many **INPORT*** units \Rightarrow high surface area for condensation.
- **LiPb** seeps through woven, porous **SiC flexible** tubes.
- **Axial tension** applied on tubes to limit motion.
- **Concerns:** vaporized LiPb exerts high impulse load on tubes, uncertainties in applied tension, possible change in SiC porosity, possible deviation from circular tube shape.

* **Inhibited flow Porous Tubes**



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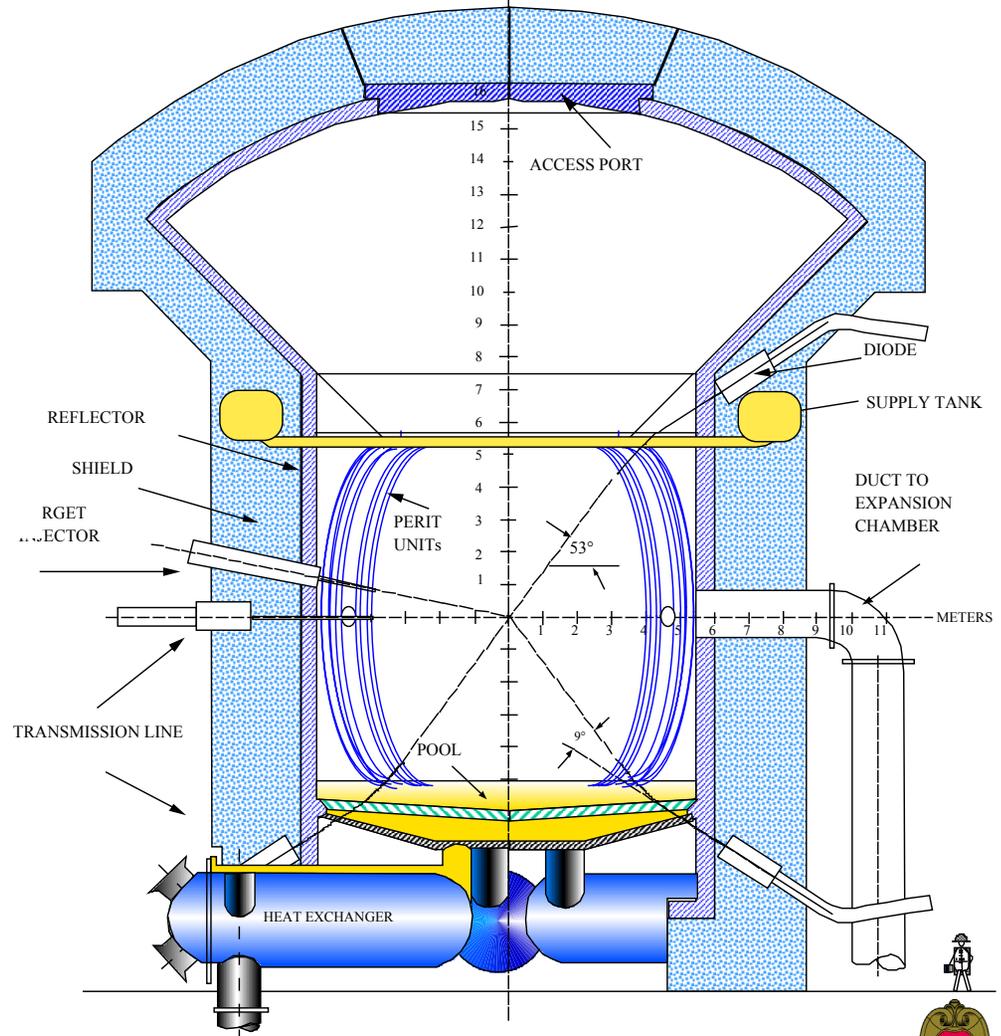
UW IFE Design - LIBRA-SP (1995)



PERIT Unit

- **Two rows of PERIT* unit:**
 - **Perforated** to maintain wetted surface through jet fan spray
 - **Rigid** to withstand shock waves.
- **LiPb coolant/breeder and FS tubes.**

* Perforated Rigid Tube



Cross-Section of the LIBRA-SP Target Chamber

