Three-dimensional Nuclear Assessment for the Chamber of Z-Pinch Power Plant

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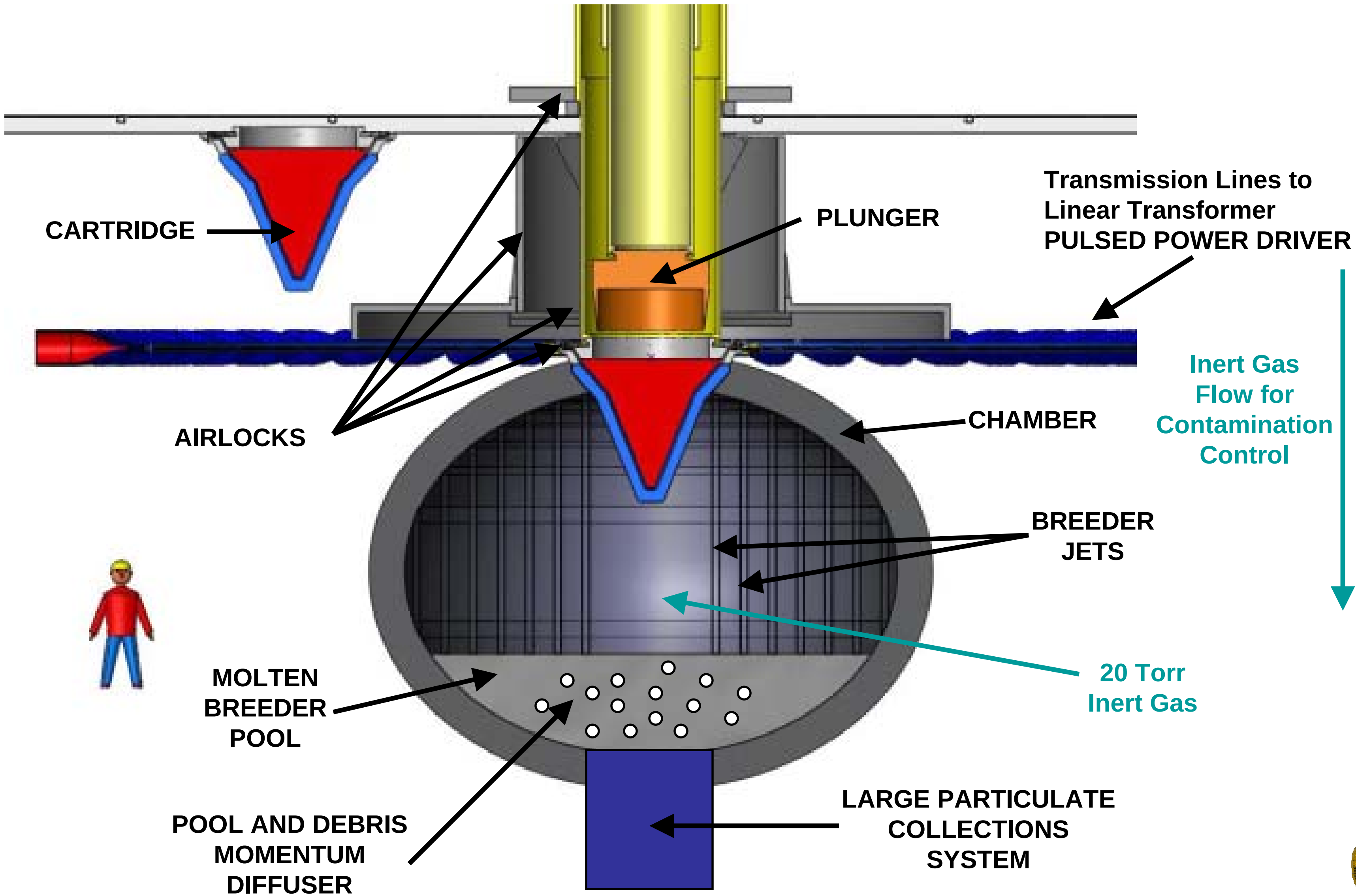
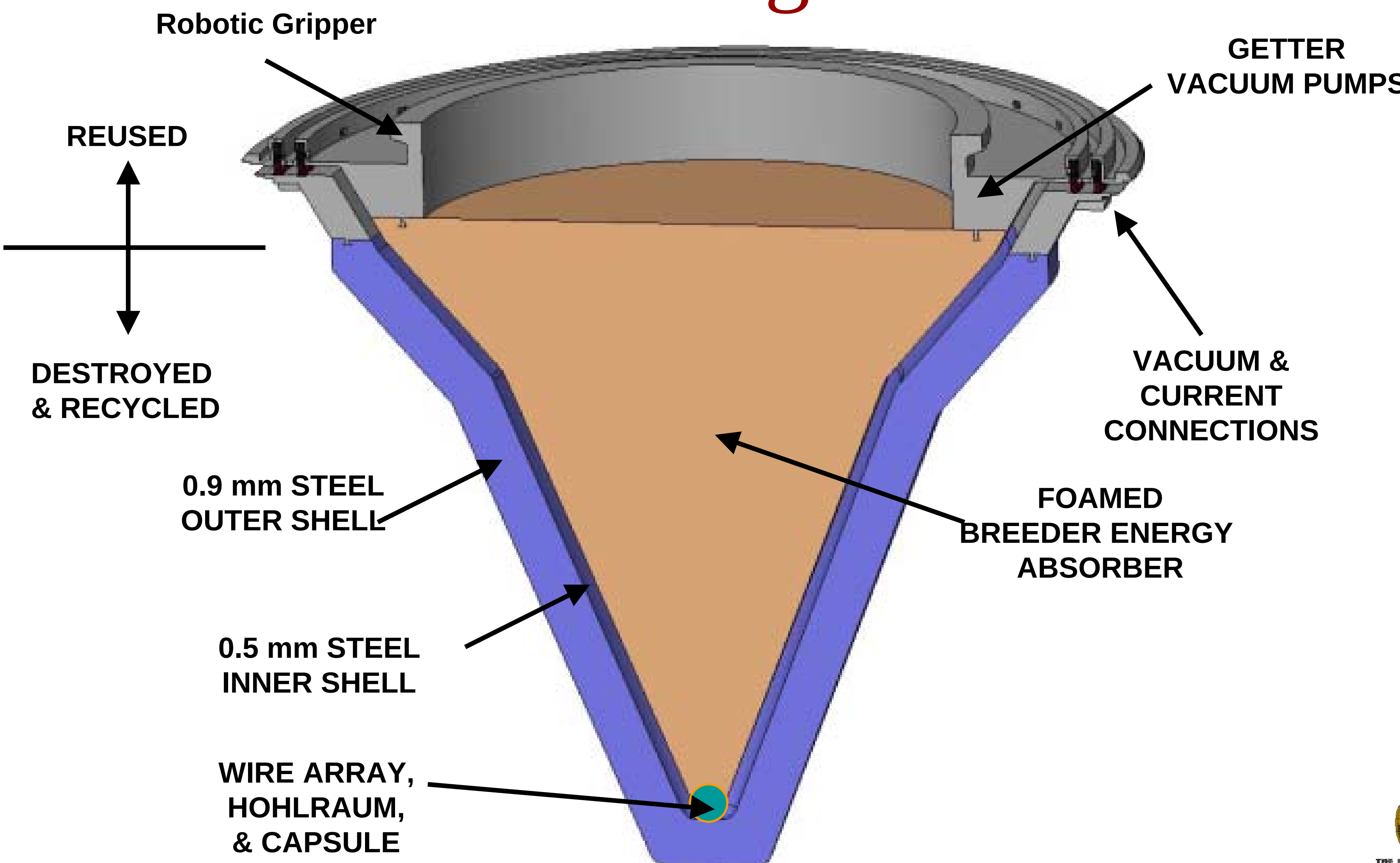
BASE Z-IFE UNIT

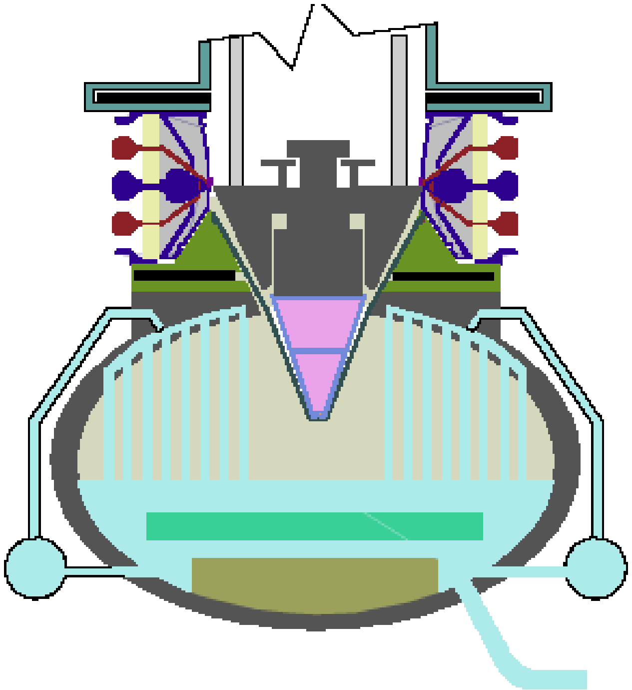


Not to Scale

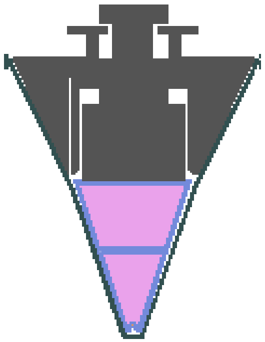
RTL Configuration

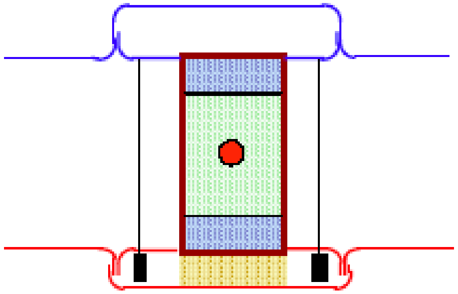


Base Z-IFE Unit



Cartridges containing fusion capsules are repetitively inserted, ignited and burned in a dynamic hohlraum driven by a shaped 150 ns rise time 60-100 MA pulse connected through a recyclable transmission line.



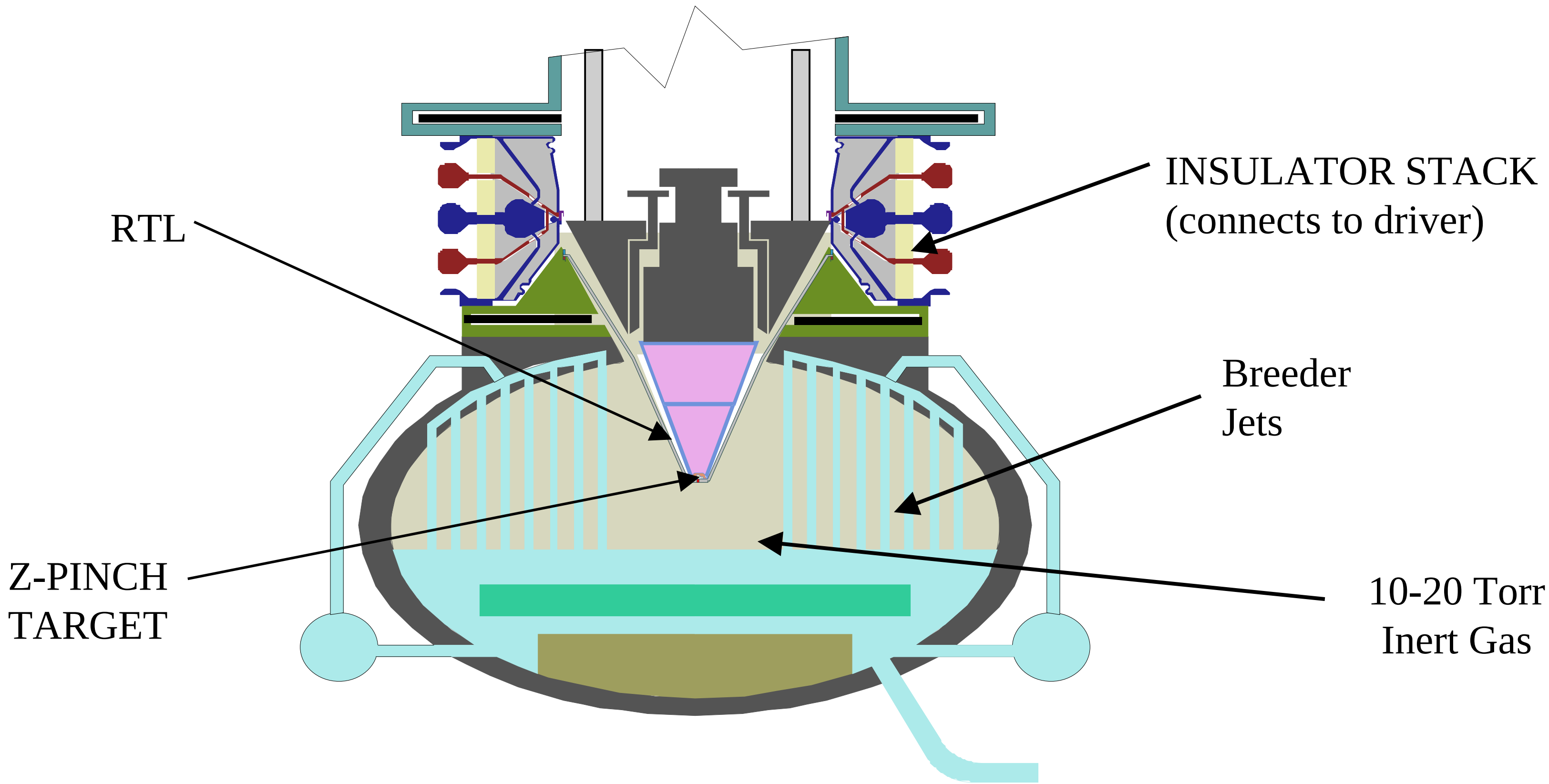


Target Yield 3 GJ

Rep Rate 0.1 Hz

10 Chambers

Elliptical Z-pinch IFE Chamber Concept



- Liquid breeder jets and pool required for tritium breeding, recovering fusion energy, and shielding structural chamber wall

- Two breeder options considered: ***Flibe (F_4Li_2Be)***, ***LiPb ($Li_{17}Pb_{83}$)***

Objectives

- Explore design space using 1-D parametric study
- Identify chamber self-consistent parameters for candidate breeders based on 3-D nuclear assessment:
    - Breeder and wall dimensions
    - Overall TBR and Li enrichment
    - Nuclear heating
    - Overall energy multiplication
    - Isochoric heat load
    - Damage profile @ chamber wall
    - Wall lifetime
- Compare Flibe and LiPb systems

Design Requirements

Overall TBR (for T self-sufficiency)	**1.1**
Heat Leakage from Chamber Wall (to enhance power balance)	**1%**
dpa to Structure* (for structural integrity and service lifetime)	**200 dpa**
Reweldability Limit	**1 appm**
Fluence to Ceramic Insulator	**$4x10^{22}$ n/cm^2**
Plant Lifetime	**40 FPY**

* Thermal creep and stresses may limit structure lifetime

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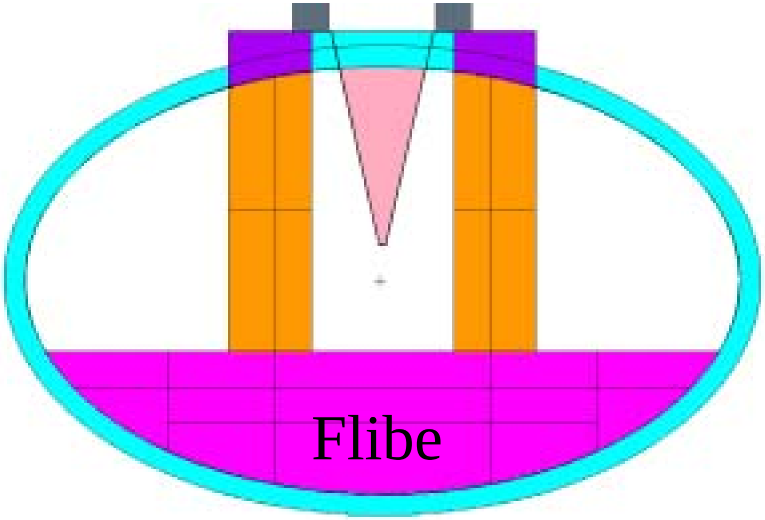
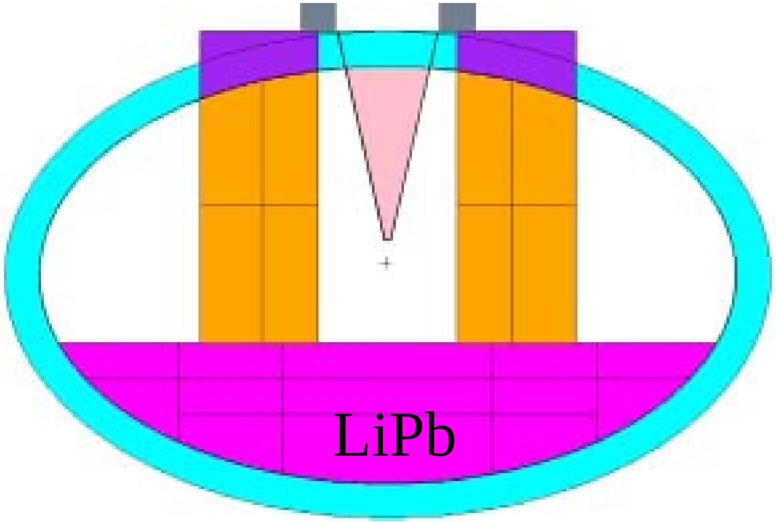
Three-Dimensional Neutronics Analysis

- Calculations performed using latest versions of MCNP code (MCNP5) and FENDL nuclear data (FENDL-2.1)
- Ellipsoidal chamber with inner diameter of 10 m and height of 6 m
- Target at 0.5 m above chamber center
- Imploded target radial build and composition with ρR of 3
- Double-layered RTL truncated cones made of carbon steel
- Pool depth is 2 m with gas bubbling for chock mitigation (0.8 d.f.)
- Jet zone p.f. is 37%. Inner surface of 1st row of jets at 1 m radius
- Two options for breeder (Flibe and LiPb) assessed
- Insulator stack simulated at top of chamber

Three-Dimensional Neutronics Model of Chamber



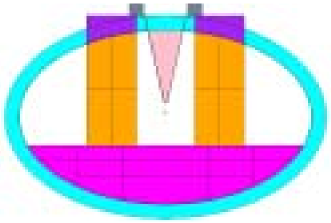


- Natural Li used in Flibe
- Outer surface of last (8th) row of jets at 2.1 m radius
- Chamber wall made of LAFS alloy F82H and is 0.3 m thick
- Flibe foam at 0.1 density factor used to fill the RTL cone

- ***20% ^{6}Li*** enrichment used in LiPb
- Outer surface of last (12th) row of jets at ***2.7 m*** radius
- Chamber wall made of LAFS alloy F82H and is ***0.5 m*** thick
- LiPb foam at 0.1 density factor used in the RTL cone

100,000 source particles sampled. <2% local. <0.5% integral

Tritium Breeding



	Tritium Production per Fusion	
	Flibe Breeder	LiPb Breeder
Jets	0.840	0.711
Nozzle Zone	0.019	0.053
Pool	0.246	0.362
RTL Foam	0.011	0.005
Overall TBR	**1.116**	**1.131**

- Most of tritium breeding occurs in the jet zone (jets exposed to 88% of source neutrons compared to only 9% for pool)
- Tritium self-sufficiency can be ensured with both breeder options

Nuclear Heating in Target

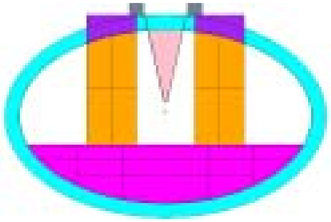
	MeV/fusion	MJ per 3GJ DT yield shot
DT core	1.476	251.59
Be shell	9.62×10^{-3}	1.64
CH shell	2.95×10^{-4}	0.05
Au shell	4.13×10^{-4}	0.07
TOTAL	***1.487***	***253.35***

Target nuclear heating 1.487 MeV per fusion ⇒ x-rays and ion debris energy 4.987 MeV per fusion

↓

Of the 3 GJ target yield 2.15 GJ is carried by neutrons and 0.85 GJ is carried by x-rays and ion debris

Nuclear Heating for Flibe Design



	Nuclear Heating (GJ/shot)	X&D Heating (GJ/shot)	Thermal Energy (GJ/shot)
Jets	1.798	0.748	2.546
Pool	0.402	0.072	0.474
Chamber Wall	0.139	0.000	0.139
Nozzle Zone	0.062	0.000	0.062
RTL Support Structure	0.054	0.020	0.074
RTL	0.008	0.010	0.018
RTL Foam	0.033	0.000	0.033
Total	**2.496**	**0.850**	**3.346**

Overall Energy Multiplication = 1.115

Nuclear Heating for LiPb Design

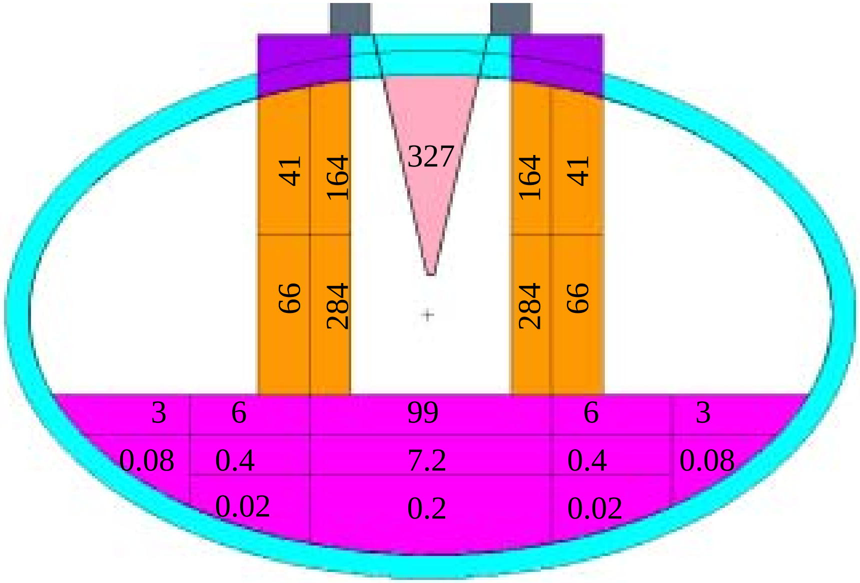
	Nuclear Heating (GJ/shot)	X&D Heating (GJ/shot)	Thermal Energy (GJ/shot)
Jets	1.624	0.748	2.372
Pool	0.494	0.072	0.566
Chamber Wall	0.320	0.000	0.320
Nozzle Zone	0.158	0.000	0.158
RTL Support Structure	0.084	0.020	0.104
RTL	0.007	0.010	0.017
RTL Foam	0.023	0.000	0.023
Total	**2.710**	**0.850**	**3.560**

Overall Energy Multiplication = 1.187

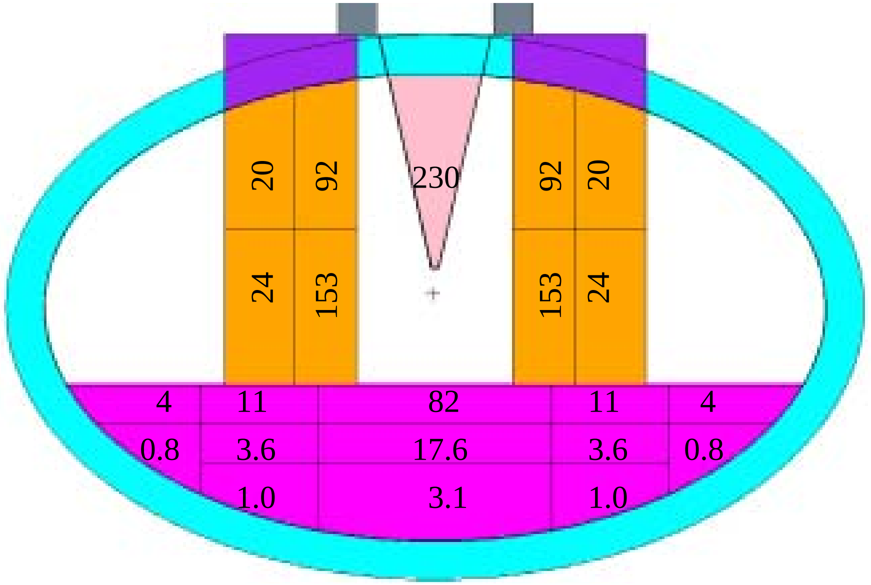
(~6.5% higher than with Flibe)

Isochoric Heating

- Pulsed nature leads to sudden energy deposition in liquid resulting in instant pressurization and disassembly with possible high speed acceleration of fluid masses inside chamber



Chamber with Flibe



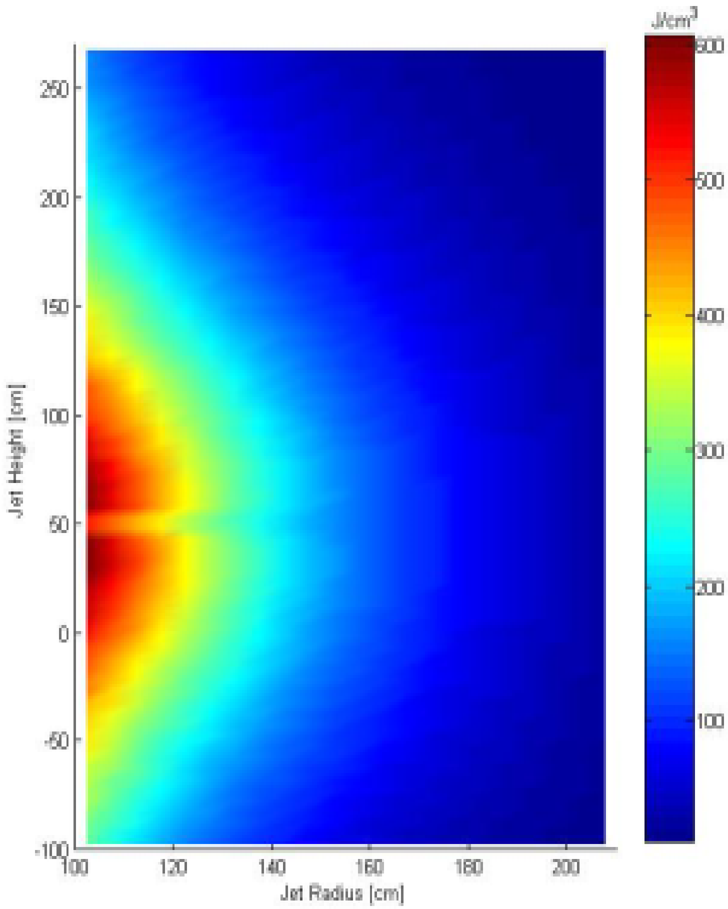
Chamber with LiPb

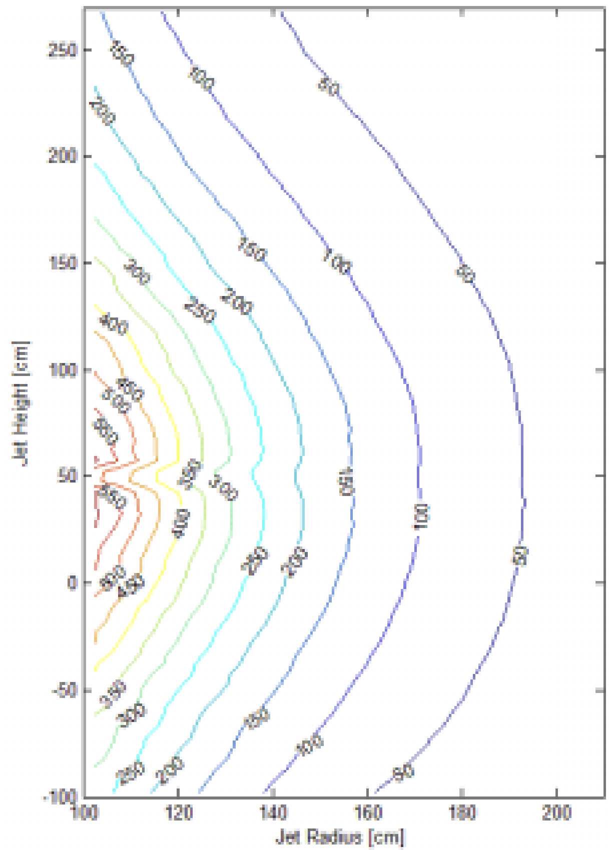
Nuclear energy per shot per unit volume of fluid (J/cm^3)

- Flibe has higher nuclear heating per unit volume at front zones but lower values at back zones compared to LiPb

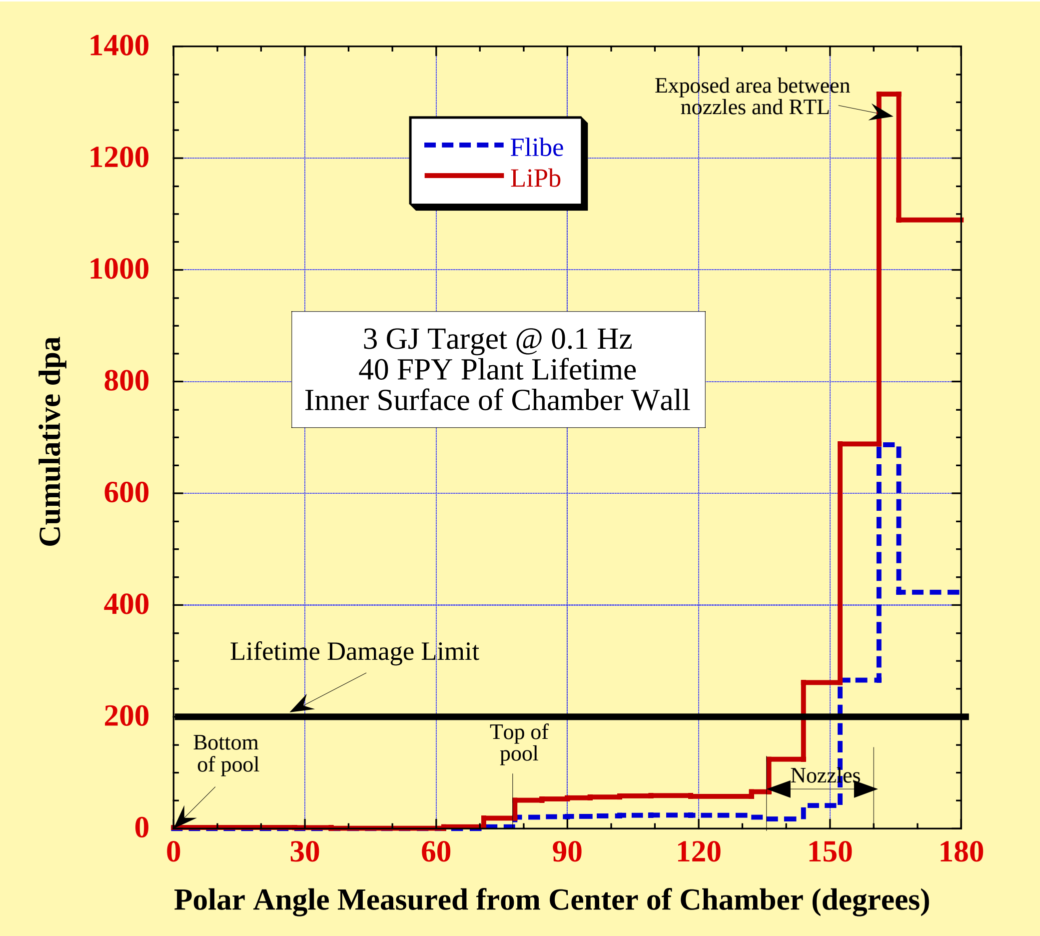
Isochoric Heating

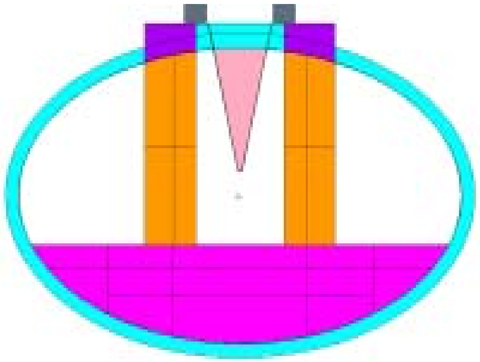
The mesh tally capability of MCNP5 used to calculate detailed distribution (5 cm x 5 cm mesh) of isochoric heating in Flibe jets



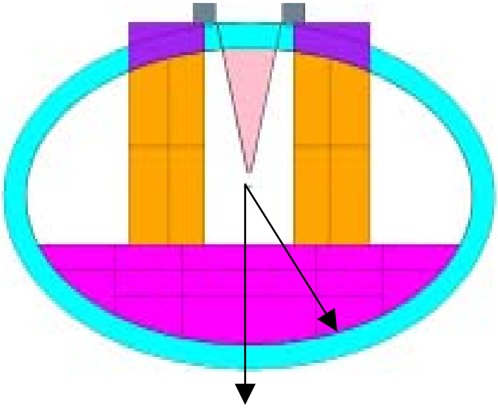


Radiation Damage in Chamber Wall





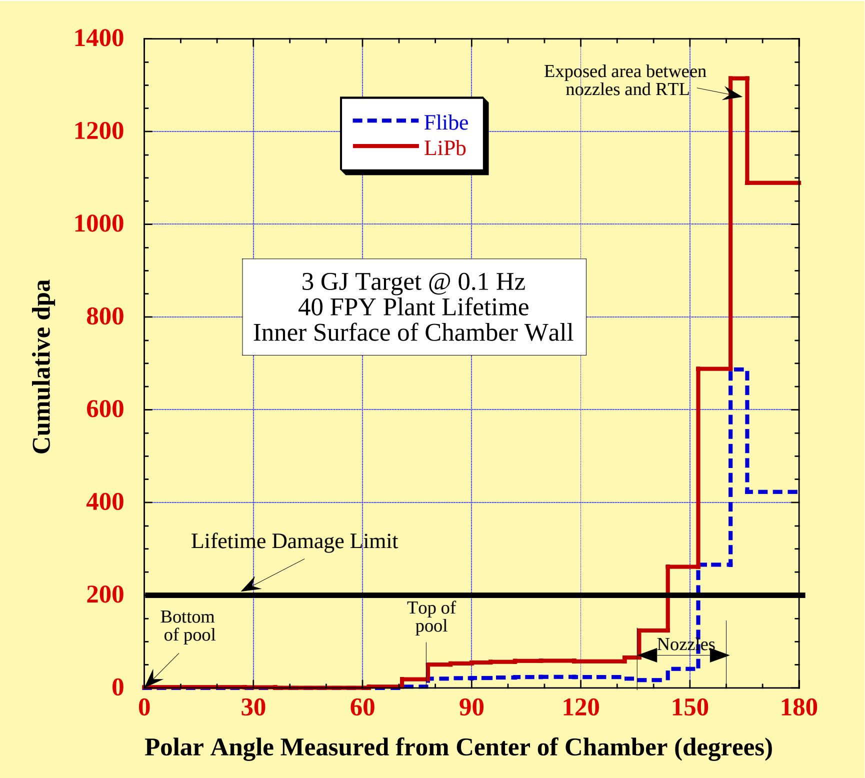
Chamber with Flibe

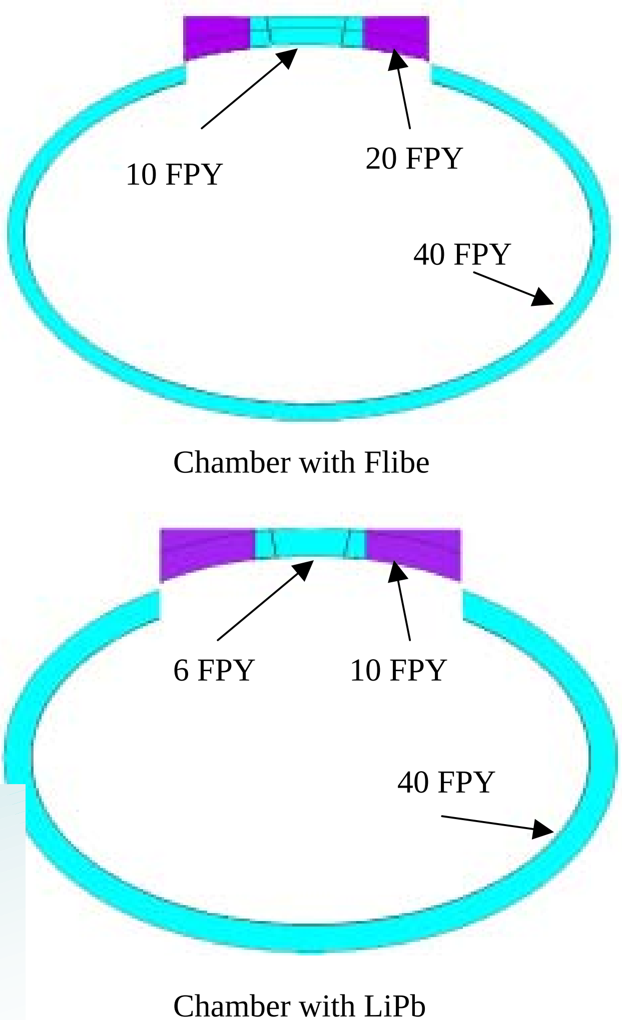


Chamber with LiPb

- Radiation damage in chamber wall is about a factor of 2 higher with LiPb
- Chamber wall is lifetime component except for top part starting in nozzle zone

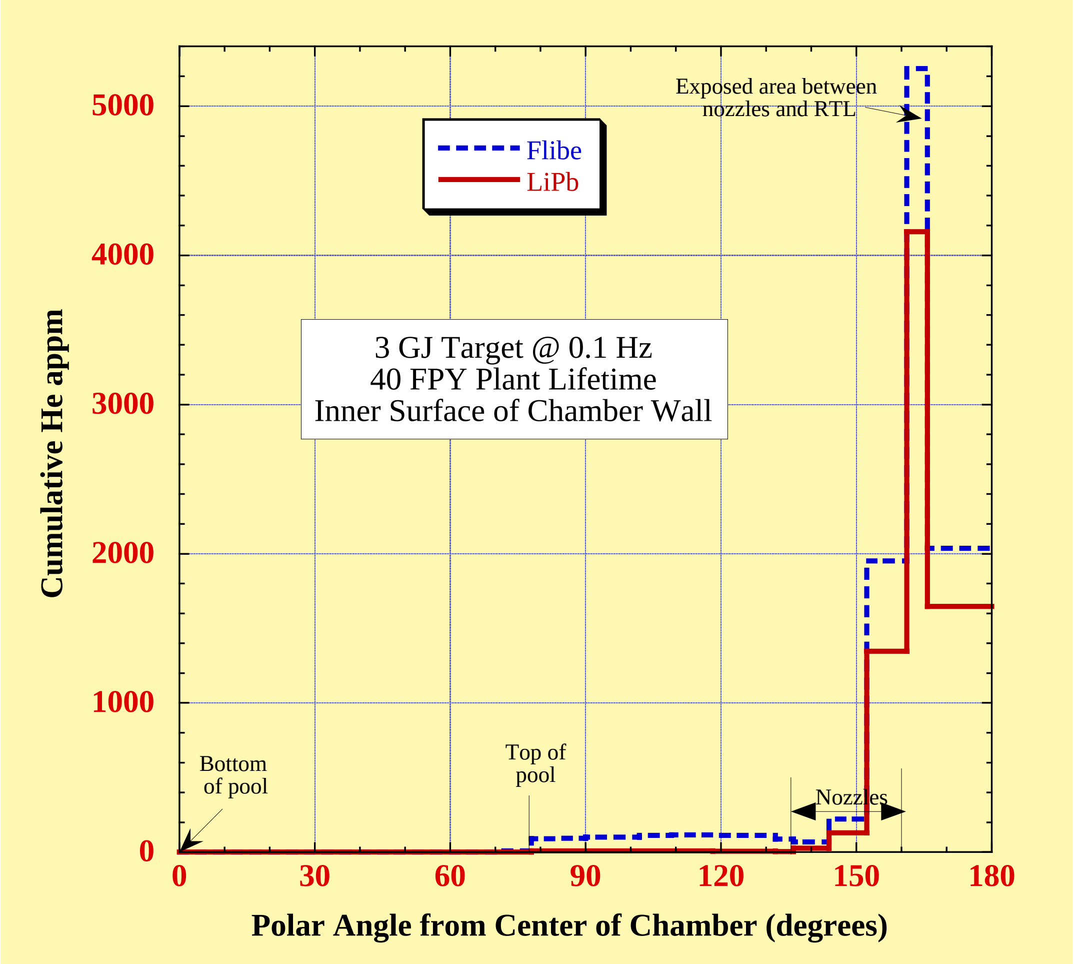
Lifetime of Chamber Wall

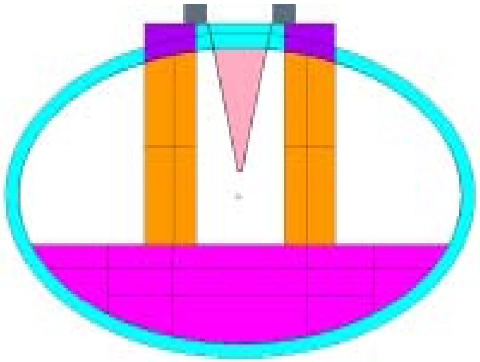




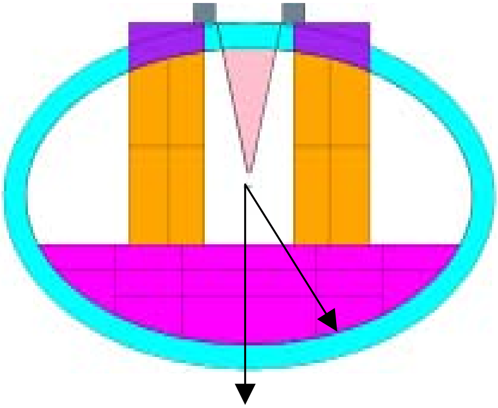
- Nozzle zone of chamber wall should be replaced once (Flibe) or three times (LiPb) with RTL support structure replaced a factor of 2 more frequent
- Rest of chamber wall is lifetime component

Helium Production in Chamber Wall





Chamber with Flibe

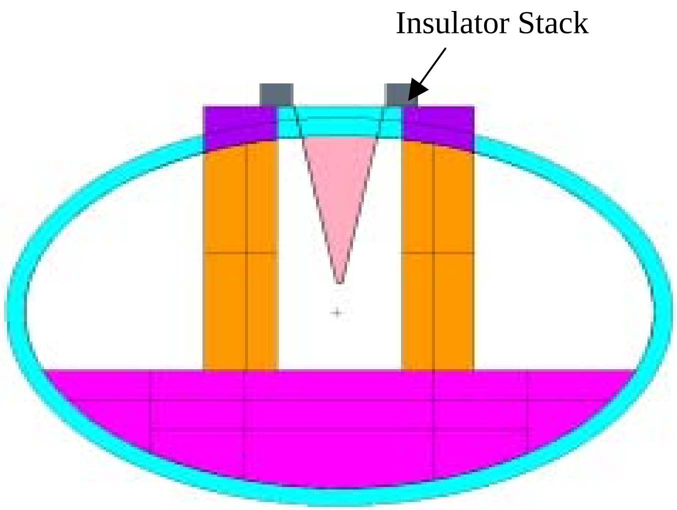


Chamber with LiPb

- Helium production in chamber wall is lower with LiPb
- He production is < 1 appm (rewelding limit) in part of wall below the LiPb pool. With Flibe only the part of wall ~20 cm below pool surface satisfy rewelding limit

Insulator Shielding

- Absorbed dose and fast neutron (E>0.1 MeV) fluence calculated in insulator stack located above chamber with both Flibe and liPb breeders
- Ceramic insulators are 2-3 orders of magnitude more radiation resistant than organic insulators
- Candidate materials include Al_2O_3, MgO, and spinel ($MgAl_2O_4$)
- Spinel offers lowest mechanical and structural degradation in nuclear environment
- Fast neutron fluence limited to $4x10^{22}$ n/cm^2 based on 3% swelling swelling tolerance in magnets



	Flibe	LiPb	Limit
End-of-life (40 FPY) organic insulator dose (Rads)	$4.4x10^{12}$	$2.0x10^{13}$	10^{9}-10^{10}
End-of-life (40 FPY) fast neutron fluence (n/cm^2)	$1.4x10^{21}$	$6.4x10^{21}$	$4x10^{22}$

- ➢ About a factor of 5 higher insulator radiation level results with LiPb
- ➢ Organic insulators cannot be used and ceramic insulators will survive for the whole plant lifetime

Breeder Parameters

	Flibe	***LiPb***
Thickness	**1.1 m Jets**	**1.7 m Jets**
Overall TBR	**1.1**	**1.1**
Li Enrichment	**Natural**	**20%**
Overall energy multiplication	**1.1**	**1.2**
In-chamber volume* (m^3)	**800**	**900**
Total volume# (m^3)	**1600**	**1800**
Unit cost ($/kg)	**43**	**10**
Total cost (M$)	**140**	**170**

* 100% dense breeder; 10 units

Inside and outside the chambers. Assuming outer loop contains same breeder volume as in all 10 chambers

Chamber wall Parameters

	Flibe	*LiPb*
Wall thickness (cm)	**30**	**50**
Peak dpa @ EOL	**200**	**200**
Lifetime (FPY)	**10, 20, 40**	**6, 10, 40**
Top reweldable?	**No**	**No**

Waste volume (m^3) - 10 units:		
Replaceable components (6-20 FPY)	**150**	**480**
Permanent components (40 FPY)	**630**	**1060**
Total	**780**	**1540**

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Comparison of Nuclear Related Issues

	Flibe	***LiPb***
Thermal Power	Lower	Higher
Isochoric Heating	Higher	Lower
Jet Zone	Thinner	Thicker
Tritium Self-Sufficiency	OK	OK
Chamber Wall	Thinner	Thicker
Wall Damage	Lower	Higher
Wall He Production	Higher	Lower
Insulator Damage	Lower	Higher
Breeder Cost	Lower	Higher
Waste Volume	Less	Larger

Other issues (safety, chemistry control, thermal hydraulics, thermomechanical, compatibility, etc) should be factored in breeder choice

Summary and Conclusions

- ***Both Flibe and LiPb* breeders are technically feasible, *breeding sufficient tritium* and *protecting chamber wall* with *comparable thermal power***
  - Thermal power 6.5% higher with LiPb
  - 55% thicker jet zone required with LiPb
  - Radiation damage in chamber wall factor of 2 higher with LiPb
  - In both cases chamber wall does not need replacement except for top
  - He production in chamber wall much lower with LiPb
  - Rewelding possible only in lower part of chamber wall below pool
  - Factor of 5 higher insulator radiation level with LiPb
  - Ceramic insulators will survive for whole plant lifetime
- ***Other issues* (safety, chemistry control, thermal hydraulics, compatibility, etc) *should be factored in breeder choice***