Z-Pinch Chamber Assessment and Design

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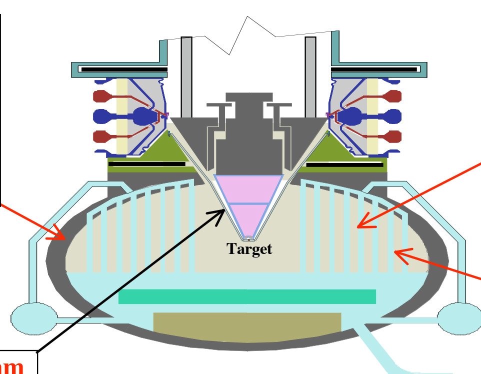
Z-Chamber & Areas of Research

Chamber wall parameters for A-286 & F82H steels :
- Thickness
- Radiation damage profile
- Service lifetime
- Activation

Breeder parameters for Flibe & LiPb:
- Thickness
- TBR
- Enrichment
- Energy multiplication
- Heat loads



Jet design and flow routing

RTL activation & waste stream
(Tuesday Poster Session)

Objectives

- Perform engineering scoping assessment for two candidate breeders: Flibe and LiPb.
- Develop list of engineering design requirements and radiation limits to guide design process.
- Explore design space using 1-D parametric study.
- Identify self-consistent parameters for candidate breeders and chamber wall materials based on 3-D nuclear assessment:
  - Breeder and wall dimensions
  - Overall TBR and Li enrichment
  - Damage profile @ chamber wall
  - Wall lifetime
  - Isochoric heat load
  - Overall energy multiplication
  - Thermal, gross and net electric powers
  - Breeder volume and cost.
- Assess activation and waste classification of chamber wall for two candidate steels: A-286 and F82H.
- Compare Flibe and LiPb systems.

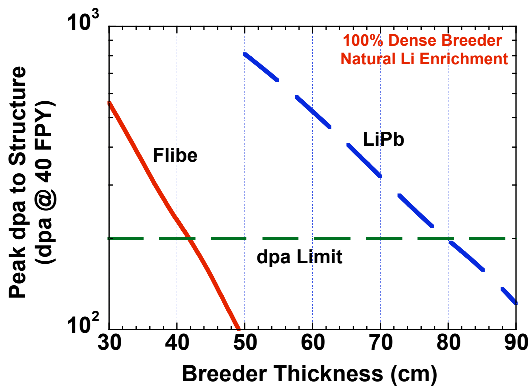
Design Requirements and Radiation Limits

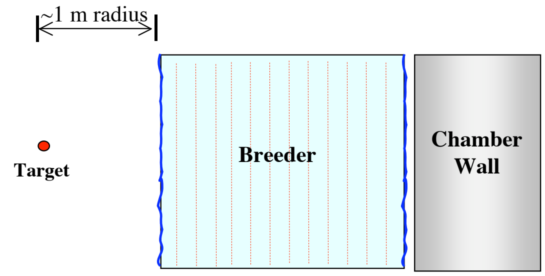
Overall TBR (for T self-sufficiency)	**1.1**	
Nuclear Heat Leakage from Chamber Wall (to enhance power balance)	**1%**	
dpa to Structure* (for structural integrity and service lifetime)	**200**	**dpa**
Reweldability Limit	**1**	**He appm**
Low-Level Waste - Class A or C WDR	**≤ 1**	
Plant Lifetime	**40**	**FPY**
Projected Plant Availability	**85%**	

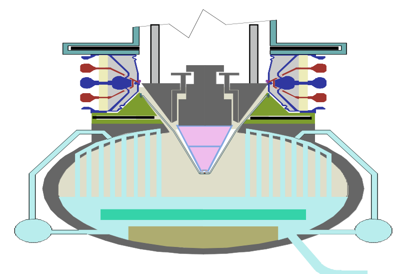
* Thermal creep and stresses may limit structure lifetime.

Thicker LiPb Needed to Protect Chamber Wall

(1-D Analysis)





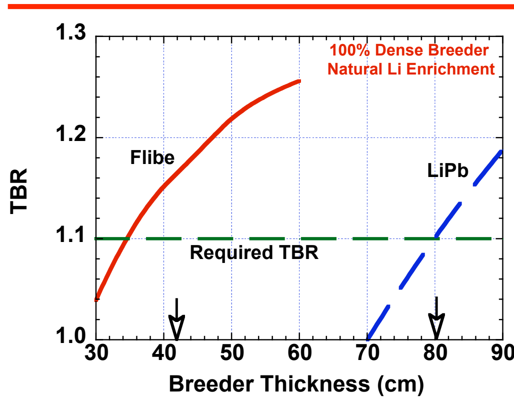


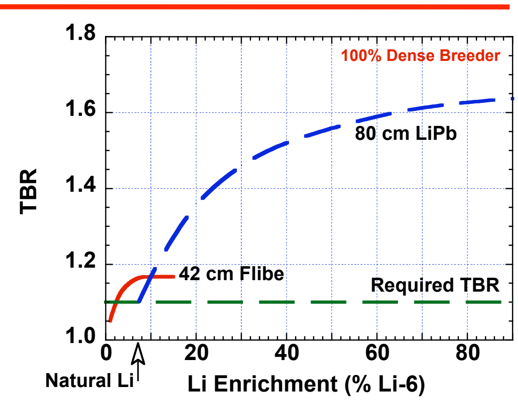
To protect wall, need:

- 42 cm Flibe (100% dense)
- 80 cm LiPb (100% dense)

Both Breeders Provide Adequate Breeding

(1-D Analysis)

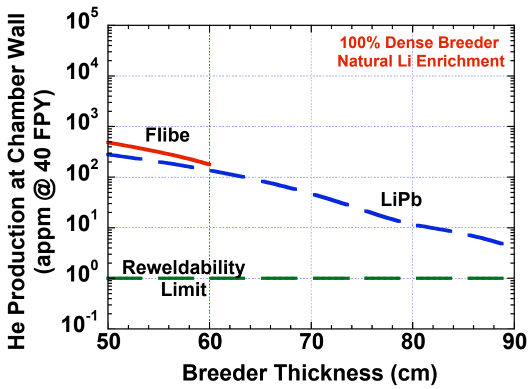


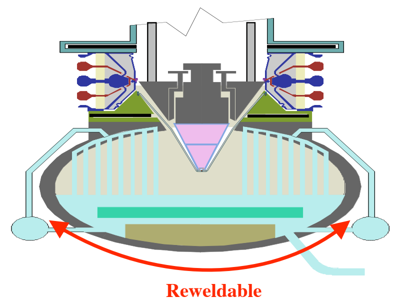


- No significant change to breeding with Flibe enrichment.
- LiPb enrichment increases breeding significantly.
- 3-D analysis will determine reference breeder thickness and enrichment.

Most of Chamber Wall Cannot be Rewelded During Operation

(1-D Analysis)

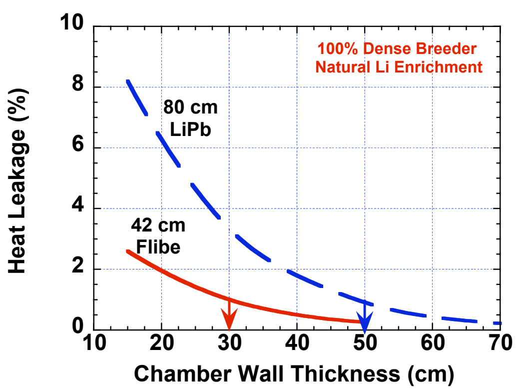


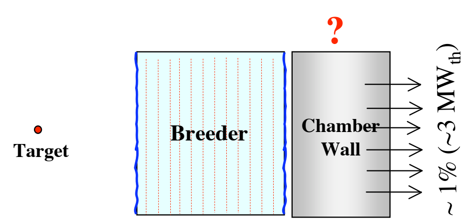


Mechanical attachments or other means for wall assembly should be considered for chamber top and behind jets

Size of Chamber Wall Controls Nuclear Heat Leakage

(1-D Analysis)

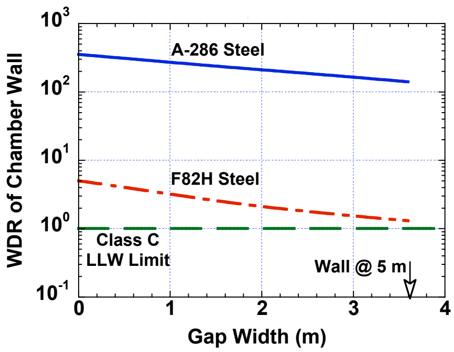


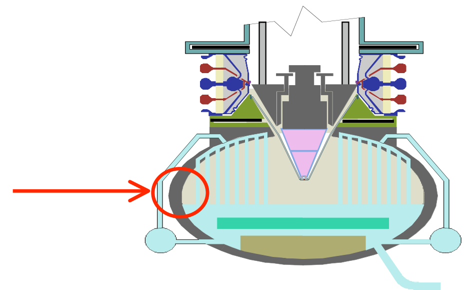


Recommended wall thickness:
- 30 cm thick wall for Flibe.
- 50 cm thick wall for LiPb.

Chamber Wall Activation

(1-D Analysis)





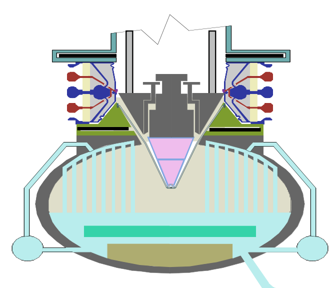
	Dominant Radionuclides
A-286 steel	99% Tc-99 (from Mo **alloying element**)
F82H steel	91% Nb-94 (from Nb **impurity**)
	8% Tc-99 (from Mo **impurity**)

- A-286 steel generates high-level waste (WDR > 100).
- F82H steel could qualify as LLW if Nb and Mo **impurities** are controlled.
- **F82H is preferred** steel based on activation consideration.

Impact of Breeders on Selected Parameters

(3-D Nuclear Parameters*)

	Flibe	**LiPb**
Thickness of jet zone*	1.1 m	1.7 m
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**



Total breeder volume and overall cost are comparable

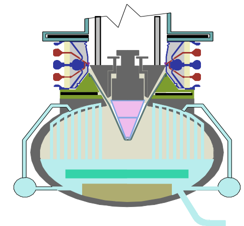
* M. SAWAN, L. EL-GUEBALY, and P. WILSON, "Three-dimensional Nuclear Assessment for the Chamber of Z-Pinch Power Plant," Nuclear Analysis and Experiment Session, Wednesday at 1 PM.

@ 100% dense breeder; 10 units. Pool dominates volume.

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

Chamber Wall Parameters

(3-D Nuclear Parameters*)



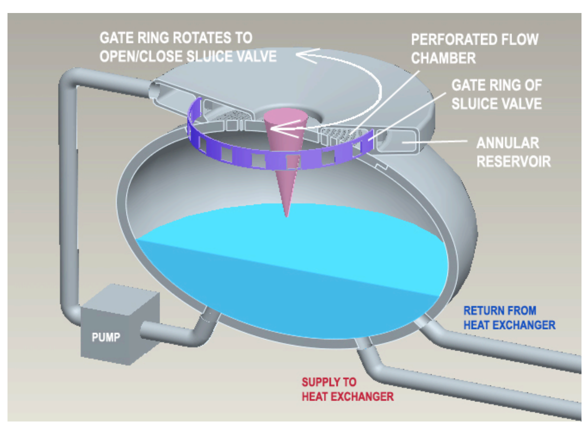
	Flibe	LiPb
Wall thickness (cm)	30	50
Peak dpa @ EOL	200	200
Lifetime* (FPY)	10 – 40	6 – 40
Top reweldable?	No	No
Waste classification	HLW - A286 steel LLW - F82H steel (with impurity control)	
Waste volume (m^3) - 10 units:		
Replaceable components (6-20 FPY)	150	480
Permanent components (40 FPY)	630	1060
Total	780	1540
Building volume (m^3)	~2 x 10^5	~2 x 10^5

- LiPb chamber generates more radwaste.
- 10 chamber walls represent only 1% of building volume.

* M. SAWAN, L. EL-GUEBALY, and P. WILSON, "Three-dimensional Nuclear Assessment for the Chamber of Z-Pinch Power Plant," Nuclear Analysis and Experiment Session, Wednesday at 1 PM.

Establishing Jet Flow

- Design reservoir on top of chamber with amount of fluid adequate to supply jets for single shot.
- Mechanism such as sluice valve can release fluid in 1-2 s.
- Valve is rotated several degrees of revolution, releasing fluid to jet holes, initiating jet flow.
- As valve closes, new fluid from pool is pumped into reservoir behind valve in preparation for next shot.



Thermal Parameters

	Flibe	LiPb
Starting temperature in pool (C)	**530**	**275**
Energy dissipated in jets (GJ)	**2.685**	**2.692**
Energy dissipated in pool (GJ)	**0.661**	**0.868**
Temperature rise in jets per shot (C)	**38.5**	**54.3**
Temperature rise in pool per shot (C)	**2.9**	**6.86**
Equilibrated temperature rise per shot (C)	**8.65**	**20.22**
Power cycle	**Brayton**	**Rankine**
Liquid temperature to heat exchanger (C)	**680**	**450**
Thermal power supplied by each chamber (MW_{th})	**334.6**	**356.0**
Power cycle efficiency (%)	**43.5**	**41.9**
Electric power less pump power (MW_e) for each chamber	**144.2**	**139.3**

Breeder Comparison

	Flibe		LiPb	
Steel type	**F82H**	**ODS[#*]**	**F82H**	**ODS[#*&]**
Steel T_{max}	**700°C**	**800°C**	**550°C**	**800°C**
Breeder/steel interface T_{max}	**~700°C**	**< 800°C**	**500-550°C**	**< 800°C**
Breeder T_{out}	680°C[+]	750-800°C[+]	< 550°C[@]	750-800°C[+]
η_{th}	40-45%	~50%	40-45%	~50%
P_{th} (MW_{th}/chamber)	335	335	356	356
Gross P_e (MW_e/chamber)	134-151	~168	142-160	~178
Pumping power (MW_e/cham.)	2	2	12	12
P_e (MW_e/chamber)	132-149	~166	130-148	~166
P_G (10 units)	1320-1490	~1660	1300-1480	~1660
P_e ** **(10 units)**	**900-1070**	**~1240**	**880-1060**	**~1240**

Need cleanup system?

Flibe: yes (for REDOX chemistry control and separation of RTL/target debris)

LiPb: yes (to limit Bi and Po concentrations and separate RTL/target debris)

\# Advanced oxide dispersion strengthening (ODS) steel with nano-sized TiO_2 and Y_2O_3 particles, offering high operating temp and strength. Assuming 200 dpa limit @ 800°C.
* If plated with 1 mm W (or Ta) or coated with 10 microns alumina; W nozzles.
@ Rankine power conversion cycle (for T < 600°C).
\+ Brayton power conversion cycle (for T > 650°C).
** Assuming 170 MW_e driver power, 200 MW_e for RTL fabrication plant, 50 MW_e miscellaneous power, totaling 420 MW_e.
& Oxygen in LiPb should be excluded or minimized.

Cleanup Systems Needed for Flibe and LiPb

Flibe:

- **Flibe dissociates under irradiation** and has a compatibility problem with FS if radiolysis byproducts cannot be controlled by chemical means.
- Neutrons interact with Flibe and produce extremely **corrosive free fluorine** and the less corrosive **tritiated hydrofluoric acid** (TF).
- A reduction and oxidation (**REDOX**) agent, such as beryllium, is essential for the viability of Flibe to control free fluorine and TF and minimize corrosion.
- Experimental work on REDOX to limit corrosive effects of F and TF is being performed at Idaho National Laboratory as part of US-Japan Jupiter-II program.

LiPb:

- Neutrons interact with Pb and Bi, producing **^{210}Po and ^{203}Hg**.
- **Controlling Bi impurity** can limit ^{210}Po inventory.
- Online purification system is necessary to remove ^{210}Po and/or ^{209}Bi.

Pros & Cons of Flibe

Advantages	Disadvantages
- **Good shielding performance** - Light weight - **Low pumping power** (2 MW_e per chamber) - Low-pressure operating system - Very low tritium solubility; low tritium inventory - Relatively inert with air and water.	- Higher unit cost than LiPb - High melting temperature (460^{o}C); small temperature window with F82H steel - High viscosity - **Tritium permeation and control is a serious issue** - Low thermal conductivity - Limited heat transfer capability - **Very corrosive** in radiation environment - REDOX chemistry control is needed - Very steep radial power profile and large temperature gradient - **Pool shoots up at high speed (> 750 m/s),** hitting remaining RTL - **Limited database.**

Pros & Cons of LiPb

Advantages

- Lower T partial pressure than Flibe
- Low tritium solubility; low tritium inventory
- **Generate more thermal power than Flibe**
- React mildly with water
- Higher heat conductivity than Flibe
- Less steep radial power profile and temperature gradient than Flibe
- **Suppress shock wave; pool may hardly move**
- Lower melting temperature (234°C); **large temperature window**
- Lower unit cost than Flibe
- **Large database** from ITER and Gen-IV

Disadvantages

- **Lower shielding performance** compared to Flibe
- **Heavy weight**
- **12 MW_e pumping power per chamber**
- Tritium permeation and control is an issue
- Need online Po and/or Bi removal system
- Corrosive

Conclusions

- Engineering requirements and constraints have been developed for Z-chamber.
- Nuclear performance has been assessed using combination of 1-D and 3-D analyses.
- A mechanism called a sluice valve is proposed for quickly initiating and terminating jet flow in chamber.
- Both Flibe and LiPb breeders are technically feasible for Z-pinch concept, breeding sufficient tritium and protecting chamber wall.
- Net electric power and breeder cost (that influence COE) are comparable.
- The chemistry control by REDOX tops the list of critical issues for Flibe. Its dissociation under Z-pinch operating conditions needs further evaluation.
- Bi and/or Po control system is required for the LiPb option.
- Flibe moves violently after target implosion. LiPb offers unique advantage as pool may hardly move.
- A-286 steel generates high-level waste ⇒ employ F82H or ODS steel (with controlled Nb/Mo impurities) for more environmentally attractive design.