Z-Pinch Chamber Assessment and Design

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The 3 GJ target with low repetition rate and thick liquid wall chamber presents the mainline choice for the Z-Pinch power plant. An engineering scoping assessment has been developed for two candidate breeders (Flibe (F_4Li_2Be) molten salt and $Li_{17}Pb_{83}$ liquid metal) to identify the design requirements and optimize the components' dimensions. Several important engineering features have been incorporated to improve the Z-Pinch performance. For instance, an advanced high-temperature steel-based structure could operate near 800^{o}C, an advanced power cycle could achieve high thermal conversion efficiency approaching 50%, a low-activation F82H-based steel with controlled impurities will generate only low-level waste, and an innovative idea has been developed to establish jet flow using a sluice valve. This paper identifies self-consistent reference parameters and documents an interesting comparison between the candidate breeders, highlighting the fundamental differences in performance and the benefits and drawbacks of each breeder.

I. INTRODUCTION

The Z-Pinch project,[1,2] initiated by Sandia National Laboratories (SNL), investigates the scientific principle of a power generation system using the Z accelerator in a 1000 MW_e power plant application. The study integrates the liquid-protected chamber, shown in Fig. 1, with the recyclable transmission lines (RTL), and the cartridge replacement mechanism. The present strategy is to use high yield (3 GJ per shot), low rep rate per chamber (0.1 Hz), and RTL that is manufactured on-site. Every 10 seconds, the RTL connects the repetitive pulsed power driver to the target, driving 50-100 MA in 150 nanoseconds. Each pulse destroys the in-chamber portion of the cartridge. Remote operation using robots to pick up the ignited cartridge and insert a new one into the chamber seems feasible.

The 2005 Z-Pinch design[2] is built on the previous 2004 study,[1] focusing on more detailed analysis and advanced technology. Identifying the design requirements, optimizing the components' dimensions, establishing the jet flow, determining the thermal and power cycle parameters, characterizing the radiation environment, and meeting the Z-Pinch specific design needs were given considerable attention.[3] Reference 2 covers in detail other aspects of the chamber design such as the target injection, survivability, and blast effects.

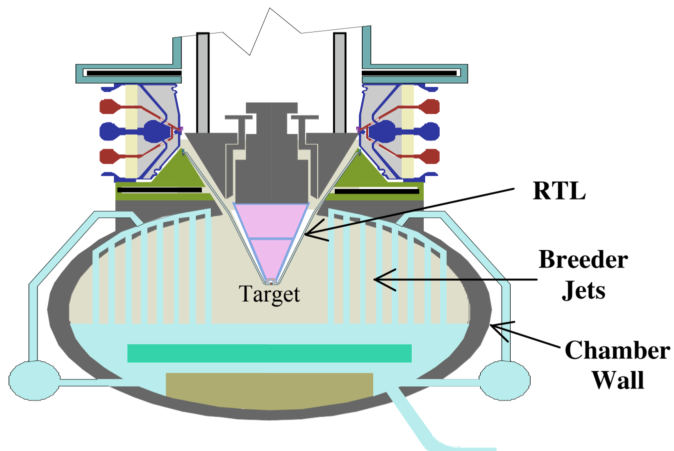

Fig. 1. Z-Pinch chamber.

II. DESIGN REQUIREMENTS AND LIMITS

The chamber assessment is maintained by identifying a set of nuclear objectives. These are summarized below:

Design Requirements	Impact and limits*
Closed tritium fuel cycle	Calculated TBR ≥ 1.1
Structural integrity	200 dpa to steel-based structure at end-of-life
Thermal conversion efficiency	> 40% to enhance net electric power
Minimal heat leakage	< 1% nuclear heat leakage from chamber wall
Reweldability limit	1 helium appm for steel-based structure
Only low-level waste	Class A or C LLW with careful material choice
Plant lifetime	40 FPY
Plant availability	85%

* Acronyms: TBR for tritium breeding ratio, dpa for displacement per atom, appm for atom part per million, LLW for low-level waste, FPY for full power year.

A tritium-breeding ratio (TBR) of 1.1 assures tritium self-sufficiency.[4] A flexible blanket design could adjust the net TBR after operation in case of over-breeding or under-breeding. The ability to identify the life-limiting criteria for the steel structure is a key factor to determine accurately the service lifetime of the chamber wall. We adopted the high 200 dpa limit in concert with similar ground rules being considered for advanced fusion designs, such as ARIES. A key engineering aspect of the Z-Pinch machine is the potential for high thermal conversion efficiency (40-50%) with advanced steel-based structure that is capable of operating at high temperature (550-800^{o}C). The nuclear heat leakage from the chamber wall to the surroundings must remain below 1% (~ 3 MW_{th}) to enhance the thermal power. If there is a need to cut and reweld the chamber wall during plant operation, the helium production level should not exceed 1 appm at the chamber wall. No high-level waste should be produced to avoid the deep geological burial.

III. CHAMBER NUCLEAR ASSESSMENT

Addressing the nuclear issues, it is prudent to routinely check if the design requirements are met when the design choices are made. We performed 1-D scoping and detailed 3-D analyses[4] to examine the breeding capacity of the Flibe and LiPb candidate breeders and roughly estimate the jet parameters (thickness and Li enrichment) that protect the chamber wall for the plant life (40 FPY). The chamber wall size was determined to essentially limit the nuclear heat leakage to less than 1%. Because of the strict low-level waste (LLW) requirement, we included the activation assessment at an early stage during the design process and an important decision was made regarding the selection of the chamber wall material. Finally, we determined the reference parameters with a detailed 3-D computational model of the chamber jets, pool, and wall. The deliverables, summarized in Table I, are the jet size, Li enrichment, overall TBR, total thermal power, nuclear heat load to all components, radiation damage profile at wall segments and their service lifetimes.[4] The entire nuclear assessment proceeded interactively with guidance from the thermal analysis.

TABLE I. Impact of Breeders on Selected Engineering 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
Chamber wall thickness (cm)	30	50
Peak dpa @ EOL	200	200
Lifetime (FPY)	10–40	6–40
Top of chamber wall reweldable?	No	No

IV. ESTABLISHING JET FLOW AND THERMAL PARAMETERS

Figure 2 is a cutaway of the chamber showing details of the upper section. The chamber is elliptical, 10 m in diameter and 6 m high. It consists of a conical RTL structure in the center, which holds the target at the apex of the cone, surrounded by the nozzle plate spanning a radial distance determined by the mass flow rate as prescribed by nuclear analysis. This is followed by a mechanism that allows the nozzle area to be flooded with fluid in a short time. This mechanism is called a sluice valve. It is surrounded by an annular reservoir which holds the fluid inventory needed to supply the jets for a single chamber shot.

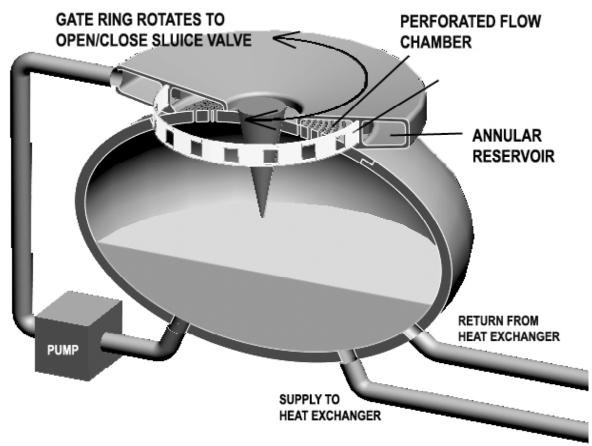

Fig. 2. Cutaway of the chamber showing details of the upper section.

The jet flow is initiated by rotating the sluice valve several degrees of rotation. The rush of the fluid into the nozzle enclosure starts the jets flowing. A pump, which supplies the annular reservoir from the chamber pool, runs continuously, insuring that the fluid keeps flowing into the reservoir until the valve is closed and the reservoir is filled in preparation for the next shot.

Table II gives the preliminary thermal parameters of the chamber, needed to calculate fluid temperatures. The low viscosity formulation of Flibe [$(LiF)_2(BeF_2)$] has a melting temperature of 460^{o}C and its corrosion limit is ~700^{o}C. LiPb, on the other hand, has a melting temperature of 234^{o}C and a corrosion limit of 460^{o}C. For these reasons, the starting temperature for Flibe is 530^{o}C and the temperature at which the Flibe is taken to the heat exchanger is 680^{o}C. For LiPb, these temperatures are 275^{o}C and 450^{o}C, respectively. The energy released in the Z-Pinch is 3 GJ, but because of energy multiplication in the fluid, the total energy is somewhat higher. This can be seen in the sum of the energies dissipated in the jets and the pool, which are 3.346 GJ in the Flibe and 3.56 GJ in the LiPb. A Brayton cycle is used for Flibe because the temperature is high enough to justify its use. In this cycle, the Flibe exchanges heat with He gas, which is then used to drive a turbine. For Flibe, using the Brayton cycle at 953^{o}K and 2 reheat stages, the estimated efficiency is 43.5%. On the other hand, for LiPb, a steam (Rankine) cycle is used at 700^{o}K, also with two reheat stages, an efficiency of 41.9% is estimated. These efficiencies result in electrical power outputs of 145.6 MW_e for Flibe, and 149.2 MW_e for LiPb.

Table II. Preliminary Thermal Parameters of Z-Pinch Chamber

	Flibe	LiPb
Depth of fluid in the pool (m)	2.0	2.0
Fraction of gas in the form of bubbles in the pool (%)	20	20
Volume of fluid in the pool (m^3)	66.6	66.6
Starting temperature in the pool (^{o}C)	530	275
Energy dissipated in jets (GJ)	2.685	2.692
Energy dissipated in the pool (GJ)	0.66	0.87
Temperature rise in jets per shot (^{o}C)	30.4	49.3
Temperature rise in the pool per shot (^{o}C)	2.1	6.9
Equilibrated temperature rise per shot (^{o}C)	8.3	19.7
Number of shots to reach operating temperature	18	9

V. ACTIVATION AND RADWASTE CLASSIFICATION

The candidate steels for the chamber wall are A-286[5] and F82H.[6] The ALARA pulsed activation code[7] was used to check the radwaste level of both steels. The yield of 1.1 x 10^{21} n/pulse and the 2.68 million pulses per year combined with the projected 85% system availability formed the basis for the irradiation history for ALARA. The overall WDR of the chamber wall was estimated using the 3-D analysis where the spectral neutron flux for each chamber wall segment was coupled with the ALARA activation code. Use is made of the recommended service lifetimes[4] to specify the irradiation time for each segment.

The chamber wall generates high-level waste (WDR > 100) if made of A-286 steel, even if placed at a fairly large distance (>> 5 m) away from the jets. The dominant radionuclide is ^{99}Tc ($T_{1/2}$= 2.1x10^5 y) from the Mo alloying element. Reducing the Mo content to enhance the WDR may jeopardize the mechanical properties of the A-286 steel. On the other hand, the F82H steel looks promising as its WDR exceeds the Class-C LLW limit by a factor of ~2. The dominant radionuclides are ^{94}Nb ($T_{1/2}$= 2x10^4 y) and ^{99}Tc from Nb and Mo impurities, respectively. Controlling these impurities would easily qualify the F82H steel as Class C LLW. This activation assessment has ruled out the A-286 steel from further consideration. A chamber wall made of F82H steel can qualify as Class C LLW (WDR < 1) with Nb and Mo impurity control. If feasible at a reasonable cost, the LLW design requirement will be met within a wide margin.

VI. FLIBE / LiPb SYSTEM COMPARISON

The selection criteria for the preferred breeder should include several elements that play an essential role in the acceptability of the breeder. These are the compatibility with the FS structure, nuclear performance, stability under irradiation, operating temperature window, power conversion efficiency and net power output, safety characteristics, and impact on the overall cost of electricity (COE). It would be relatively simple to achieve attractiveness for a few elements, but it will be a challenge to achieve attractiveness for all elements. Each of the candidate breeders ($Li_{17}Pb_{83}$ liquid metal and F_4Li_2Be molten salt) has its own benefits and design challenges. Historically, the Flibe breeder has been employed by the IFE OSIRIS and HYLIFE-II type studies as well as the MFE Japanese stellarator project, while numerous IFE and MFE designs utilized the LiPb breeder.

From its very inception, the Z-Pinch project selected steel as the main structure for the chamber wall. Advanced steels can withstand a relatively high temperature (> 550°C), a property of high payoff. The steel temperature limits are set by the mechanical properties, breeder's corrosion and compatibility issues, irradiation effects, etc. The higher the steel temperature, the higher the breeder output temperature, and thus the higher the power conversion efficiency. The desire for high-temperature steels inspired the materials community and steel industries to develop advanced steels suitable for service at 800–1000^{o}C.[8,9] At present, establishing more definitive temperature limits is difficult as such advanced steels are currently under development for nuclear applications. It seems likely that the advanced steel database will be established over the next 10-20 years and, hopefully, become available before the next Z-machine is built.

The following tables summarize the key features, benefits, and issues for each breeder. Table III compares the breeders on the basis of the engineering and economic parameters. A 55% thicker LiPb jet zone is required to protect the chamber wall. Despite the thicker jets, the LiPb volume differs by only 10% as the pool dominates the in-chamber volume. The effect of the more expensive Flibe counterbalanced the effect of the more massive LiPb and the total breeder cost is $140M for Flibe and $170M for LiPb, only a 20% difference. A thicker chamber wall is required with LiPb to reduce nuclear heat leakage to < 1%. The LiPb option generates almost twice the life-cycle steel wall radwaste. However, the entire 10 chamber walls represent only ~1% of the building waste.

TABLE III. Impact of Breeders on Selected Chamber Parameters, Cost, and Radwaste Stream

	Flibe	LiPb
Thickness of jet zone	1.1 m	1.7 m
In-chamber breeder volume* (m^3)	800	900
Total breeder volume# (m^3)	1600	1800
Unit breeder cost ($/kg)	43	10
Total breeder cost (M$)	140	170
Wall thickness (cm)	30	50
Waste volume (m^3) - 10 units:		
Replaceable components (6-20 FPY)	150	480
Permanent components (40 FPY)	630	1060
Total over plant life	780	1540
Building volume (m^3)	$\sim 2 \times 10^5$	$\sim 2 \times 10^5$

* 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.

Table IV compares the two breeders and the conventional and advanced steels on the basis of the anticipated impact on the operating temperature and net electric power output. The assumptions made are included in the footnotes. Both Flibe and LiPb breeders have a compatibility problem that controls the interface temperature with steels. Means to raise the interface temperature include: 1) coating the steel with a thin, plasma sprayed layer of W, and 2) plating the steel with a thin layer of Ta using plasma spraying or explosive welding techniques.[10] Fabrication of the nozzles from W would alleviate the corrosion/erosion problem.

Flibe dissociates under irradiation and has a compatibility problem with FS if the radiolysis byproducts cannot be controlled by chemical means. Neutrons interact with Flibe and produce the extremely corrosive free fluorine and the less corrosive tritiated hydrofluoric acid (TF).[11] A reduction and oxidation (REDOX) agent, such as beryllium, is essential for the viability of the Flibe breeder to control the free fluorine and TF and minimize the corrosion. As successfully demonstrated for the fission molten salt program, the use of Be as a REDOX agent and the kinetics of the basic reactions need to be demonstrated for fusion applications. Experimental work on REDOX to limit the corrosive effects of F and TF is being performed at Idaho National Laboratory as part of the US-Japan Jupiter-II program.

TABLE IV. Impact of Breeder and Steel Type on Operating Temperature and Power Output

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

\# Advanced oxide dispersion strengthening (ODS) steel with nano-sized TiO_2 and Y_2O_3 particles, offering high operating temperature 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.
& Oxygen in LiPb should be excluded or minimized.

A radiological concern for the LiPb breeder arises from the neutron-induced ^{210}Po and ^{203}Hg radionuclides. The ^{209}Bi inventory is also of interest because, as a precursor to ^{210}Po, control of its concentration to 10 appm can serve as a mechanism to limit the ^{210}Po inventory. An online purification system is necessary to remove the ^{210}Po and/or ^{209}Bi generated by Pb during operation.

Additional advantages and drawbacks for both breeders are documented in Ref. 3. Both systems have low tritium inventory, but the control of the tritium permeation to the environment (external pipes, heat exchanger, etc.) will be more of a concern for Flibe. Another point of concern relates to the steep radial profile and large temperature gradient.[4] Flibe and LiPb behave somewhat differently under intense X-ray flux. However, both breeders will likely experience vaporization and ionization at the surface and will expand as the X-rays penetrate the fluid.[12] The impact of the breeder behavior on the chamber structure needs further investigation.

VII. CONCLUSIONS

The chamber assessment has been a fundamental element of the Z-Pinch design process. Certain features of the design activity focused on areas unique to the Z-Pinch, including innovative ideas to establish the jet flow, breeding potential of jets and pool, chamber wall dimensions, damage profile at chamber wall, and life-cycle waste classification. Several important engineering features have been incorporated to improve the Z-Pinch performance. For instance, advanced high-temperature steel-based structure could operate near 800°C, advanced power cycle could achieve high thermal conversion efficiency approaching 50%, low-activation F82H steel with controlled Nb and Mo impurities will generate only low-level waste, and an innovative idea has been developed to establish the jet flow using a sluice valve.

We performed detailed assessments for the two candidate breeders (Flibe and LiPb) in the nuclear, activation, thermal, and power conversion areas. A comparative study, highlighting the pros and cons of both breeders, covered the chamber dimensions, breeder properties and performance, and impact on the net output power. The study suggests that:

- Both Flibe and LiPb breeders are technically feasible for the Z-pinch concept, breeding sufficient tritium and protecting the chamber wall
- The volume (and cost) of the breeder and chamber should be valued low compared to other criteria
- 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.

On common design issues for both breeders, the following items need to be addressed in the future:

- Inventories: F, TF, ^{16}N for Flibe and ^{210}Po, ^{209}Bi, and ^{203}Hg for LiPb
- Tritium extraction, permeation, and migration
- Feasibility of lining the chamber wall with 1 mm W using plasma spraying or explosive welding techniques.

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