Engineering Issues Facing Transmutation of Actinides in Z-Pinch Fusion Power Plant

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Why Transmutation?

- DOE announced Global Nuclear Energy Partnership (GNEP) that would recycle spent fuel to expand capacity of geological repositories.
- Essentially, GNEP initiative aims at closing fission fuel cycle by recycling spent fuel headed for Yucca Mountain.
- Supporting activities would include scoping assessment and design of:
  - Fuel reprocessing and separation systems
  - **Transmutation of actinides using fast reactors and accelerator-driven systems.**
- SNL* initiated scoping level design for sub-critical transmutation blanket driven by Z-Pinch fusion as alternate option to fast reactors.
- Initial assessment* indicates that In-Zinerator offers advantages over fast reactors in terms of transmutation efficiency and support ratio, but attention should be paid to challenging engineering issues.
- This application may shorten fusion development path, offering more near-term application while providing valuable experience in designing net power producing power plant.

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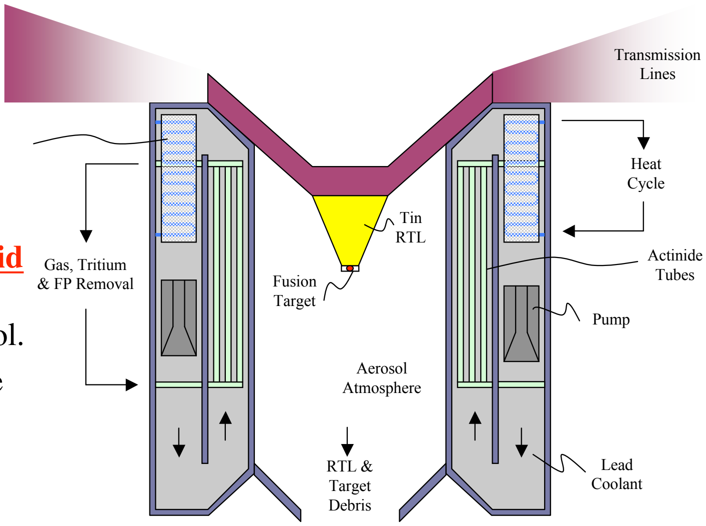
* G. Rochau, "Z-Pinch Fusion Driven Systems for IFE Transmutation, and GNEP," Power Plant Studies Oral Session on Tuesday @ 3 PM.
B. Cipiti et al., Transmutation of Actinides Using Z-Pinch Fusion," Alternate Non-Electric Application Oral Session on Wednesday @ 1 PM.
P. Phruksarojanakun et al., "Isotopic Analysis of the In-Zinerator Actinide Management System," Alternate Non-Electric Application Oral Session on Wednesday @ 1 PM.

In-Zinerator*

- Designed to burn actinides (Pu, Np, Am, Cm) **and** produce power.
- 200 MJ Z-Pinch target injected every 10 s.
- Sub-critical blanket with 1146 tubes containing **liquid actinide mixture** $[(LiF)_2\text{-}AcF_3]$ submerged in Pb pool.
- Hastelloy high-temperature structural material.
- ~3 GW thermal power and 1 GW net electric power.



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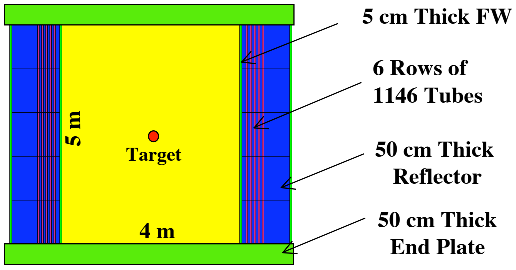
* B. Cipiti et al., Transmutation of Actinides Using Z-Pinch Fusion," Alternate Non-Electric Application Oral Session on Wednesday @ 1 PM.

Chamber Engineering Issues and Parameters

- **Design issues**: Impact of sub-critical blanket and its internal fission neutron source on:
  - Tritium breeding
  - Radiation damage to structure
  - Energy deposition and extraction
  - Operating temperature
  - Activation of structural components
  - Radwaste classification.
- **Simplified model** developed for 3-D neutronics analysis.
- **Design parameters and assumptions**:
  - Depleted LiF (5% Li-6 enrichment)
  - Fission products (FP) removed online and concentration maintained at 0.05 atom%
  - 3940 MW thermal power @ t=0
  - 40 FPY plant lifetime
  - 85% projected availability.

MCNP 3-D Model



Main Features

- Separation of neutron source and actinide inventory with sub-critical blanket represents safety advantage.

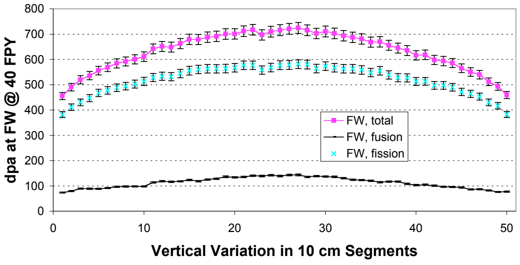
- Salient feature of In-Zinerator is the liquid actinide mixture that allows online feeding of fresh materials, adjustment of Li enrichment, and FP extraction.

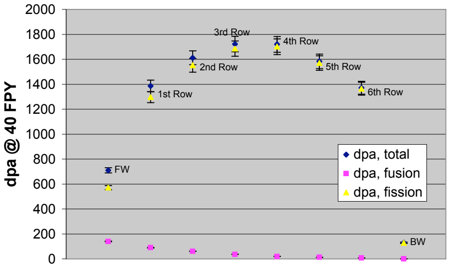
- Actinides change neutron environment:
  - Blanket performance continuously changes due to actinide burning and fission products (FP) generation
  - Neutron flux peaks within blanket, not at FW
  - Fission neutrons are dominant, not fusion neutron source.

- Results reported herein represent a snapshot at beginning of operation (t=0).

FW and Tube Structure Require Frequent Replacement Even for 20 MW P_f

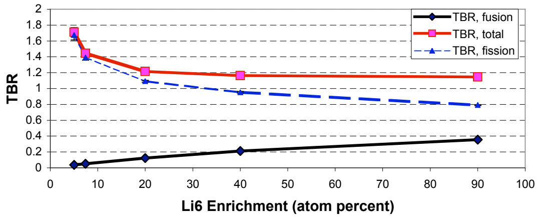
- Without actinides and fission neutrons, FW could be permanent component with peak dpa of ~130 @ EOL.
- dpa peaks at midplane of chamber.
- Higher dpa at tubes due to higher flux within blanket relative to FW.
- No life-limiting criteria for Hastelloy. 200 dpa limit for advanced FS used.
- Lifetimes: 11 FPY for FW,
  ~ 5 FPY for tubes.

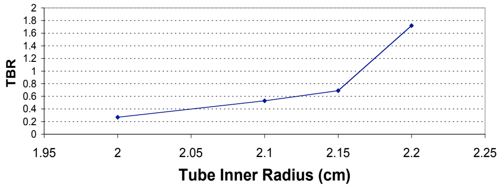




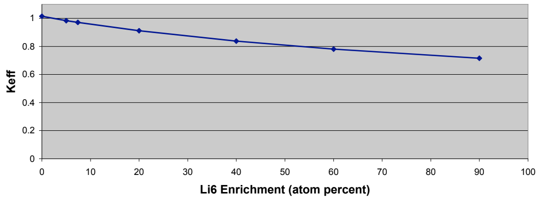
Highly Sensitive TBR to Li-6 Enrichment and Tube Radius

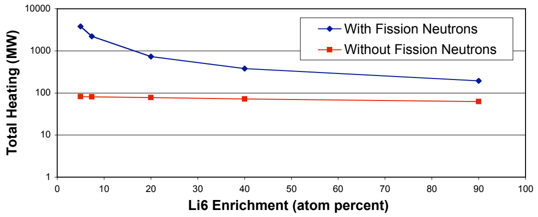
- 10% change in tube radius reduces TBR by factor of 5-6.
- TBR changes with time due to actinides burning and FP generation.
- Flexible design could adjust time-integral net TBR to 1.1 (breeding requirement).
- Effective tools to lower breeding include:
  - Higher Li-6 enrichment
  - Lower LiF concentration
  - Higher FP concentration.
- In-Zinerator should rely on online adjustment of breeding during operation.
- Practicality and interrelated impact of these options on k_{eff}, actinide burnup, and net output power should be carefully examined.





Sensitivity of Criticality and Nuclear Heating to Li Enrichment





- 90% of power generated in 1146 tubes submerged in Pb coolant, meaning fission process within blanket accounts for majority of produced power.
- Neutron energy multiplication (M_n) reaches 260 and drops with time.
- Means to stabilize net output power should be investigated.

Thermal Analysis

Component	Row	Peak Heating (MW/cm^3)	Mass (kg)	Peak ΔT (°C)
Flibe	1	4.7e-4	15.2	969
	2	4.9e-4	"	1038
	3	5.3e-4	"	1094
	4	5.3e-4	"	1096
	5	5.1e-4	"	1054
	6	4.8e-4	"	1002
Tube steel	1	1.5e-5	2.89	40
	2	1.6e-6	"	42
	3	1.6e-5	"	44
	4	1.6e-5	"	44
	5	1.6e-5	"	42
	6	1.5e-5	"	40
		Avg. Heating		
Chamber wall		1.3e-7	28,183	0.3
Pb coolant		7.0e-6	356,655	40
Pb reflector		4.6e-7	511,388	2.6
Equilibrated Pb			868,043	18

- No thermal properties for actinide mixture $(LiF)_2$-AcF_3. Flibe (F_4Li_2Be) properties used.
- Heating in mixture is excessive, especially if initial temperature ~600°C.
- Peak temperature (600°C + ΔT) exceeds melting temperature of Hastelloy (1370°C).
- Refractory metals (Nb, Mo, or W) or SiC/SiC composites can withstand these high temperatures.

Heat Removal

- Initial heating values are high, making cooling of actinide mixture difficult.
- Mixture in tubes has to be pumped out of chamber after each shot, and replaced with fresh mixture at 600°C.
- Pb also must be circulated through heat exchanger to maintain its temperature at 600°C.
- Nuclear heating in FW is very low (0.13 W/cm^3). It will be cooled by Pb of chamber and its temperature will not exceed 700°C.

Hastelloy Structure Generates High-Level Waste (WDR > 1)

WDR	Lifetime	Hastelloy	MF82H	SiC
First Wall	11 FPY	6,540 (^{99}Tc,^{94}Nb)	5 (^{94}Nb,^{99}Tc)	0.1 (^{14}C)
Tubes	5 FPY	10,600 (^{99}Tc,^{95}Ni)	14 (^{94}Nb,^{192n}Ir)	0.4 (^{14}C)

- Low activation ferritic steel (MF82H) and SiC/SiC composites included for comparison.
- Only SiC could qualify as low-level waste.

Summary and Concluding Remarks

- Burnup of actinides, buildup of FPs, and their impact on interrelated TBR, k_{eff}, and M_n should be closely monitored. Action taken in one area impacts others.
- Active control system is required to adjust TBR and net output power online during operation.
- Fission neutrons are dominant source of tritium breeding, radiation damage, and heating.
- For 4000 MW_{th} plant, structure temperature exceeds 1000^{o}C. Only refractory metals (Mo, Nb, or W) and SiC/SiC composites can withstand these high temperatures.
- Hastelloy (and refractory metals) generates high-level waste. Only SiC could qualify as low-level waste.
- Because of pulsed nature of In-Zinerator, isochoric heating and thermal stresses in tube structure should be investigated in future studies.
- Potential solutions to heating problem include diluting actinides in more LiF and/or decreasing thermal power level by factor of 3-4. These alleviate design problems, but may negatively impact economics.