Initial Engineering Assessment of Actinide Transmutation in Z-Pinch Power Plant

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FUSION TECHNOLOGY INSTITUTE

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Abstract

As part of the Advanced Energy Initiative, the U.S. Department of Energy recently announced the Global Nuclear Energy Partnership that would recycle spent fuel to expand the capacity of geological repositories. Initiation of the supporting activities is underway. These include a scoping assessment and design of the fuel reprocessing and separation systems and the transmutation of actinides using fast reactors and accelerator-driven systems. Our initial assessment indicates the Z-Pinch could be an attractive option for burning actinides (Pu, Np, Am, Cm) and/or minor actinides (Am, Cm) produced by the fission fuel reprocessing plants. A Z-transmuter would need a 200 MJ target injected every 10 seconds to transmute the actinides and deliver a net electric power of 1 GW. Numerous engineering issues are being examined: effect of fission products on neutronics of a sub-critical blanket, coolant choices, tritium breeding potential, radiation damage to structure, energy deposition and extraction, tritium and fission product removal, radwaste classification, and safety aspects of such a device. The Z-Pinch seems to offer advantages over fast reactors in terms of transmutation efficiency and support ratio, but attention should be paid to challenging engineering issues.

1. Introduction

The U.S. position on handling the fission waste has been to dispose of the fuel waste in geological salt formations that exist unperturbed for millions of years. The Yucca Mountain repository for high-level waste (HLW) is currently being characterized and, at present, all spent fuels are stored onsite in spent fuel pools or concrete casks within the reactor facilities. Several alternates have been proposed over the past 50 years to handle the fission waste:

- **Extraterrestrial (or space) disposal** where the waste is packaged on a space vehicle and launched either to the solar system or in permanent orbit around the sun
- **Seabed disposal** of HLW in geological formations under the oceans.
- **Ice sheet disposal** of highly radioactive waste in ice sheets. Both Greenland and Antarctic ice sheets are suitable.
- **Island disposal** of radioactive waste within deep stable geological formations beneath an island.
- **Transmutation of nuclear waste** using nuclear reactions to transform the radioactive elements to stable, short lived, or less toxic elements.

The most attractive alternative that received much attention is the transmutation of nuclear waste as it reduces the perceived 10,000-100,000 year problem to a 300-600 year problem. The former problem still exists but at a reduced volume, meaning the Yucca Mountain HLW repository is still required. As such, the U.S. Department of Energy (DOE) has recently announced the Global Nuclear Energy Partnership (GNEP) that would recycle the spent fuel to expand the capacity of geological repositories. Essentially, the GNEP initiative aims at closing the fission fuel cycle by recycling the spent fuel headed for Yucca Mountain. Initiation of the supporting activities is underway and includes scoping assessment and design of:

- Fuel reprocessing and separation systems
- Transmutation of actinides using fast reactors and accelerator-driven systems.

Recently initiated at Sandia National Laboratories (SNL), a scoping level design for a sub-critical transmutation blanket driven by Z-Pinch fusion [1] has been proposed as an alternate option to the use of fast reactors for recycling spent fuel. Numerous fusion-based designs have been developed over the past three decades based on other concepts [2-4]. The initial SNL assessment indicates the Z-Pinch could be an attractive option for burning tons of actinides (Pu, Np, Am, Cm) or minor actinides (Am, Cm) produced by the fission fuel reprocessing plants [1]. The In-Zinerator, shown in Fig. 1, would need a 200 MJ target injected every 10 seconds to transmute the actinides and deliver a net electric power of 1 GW. The In-Zinerator seems to offer advantages over fast reactors in terms of transmutation efficiency and support ratio. Furthermore, this application may shorten the fusion development path, offering a more near-term application while providing valuable experience in designing a net power producing fusion power plant.

The separation of the fission neutron source and actinide inventory along with the sub-critical blanket represents a safety advantage for the fusion-based systems. Regardless of the fusion concept, all actinide burners have common inherent features:

- Actinide burnup rate varies with irradiation time.
- Tritium breeding ratio (TBR), energy multiplication (M_n), and criticality change during operation with actinide burnup and accumulation of fission products.
- Accumulation of fission products (FP) degrades the nuclear performance and may lead to a large power swing.
- FPs are poisonous and should be kept below 1 atom% to the extent practicable and feasible. They drop TBR as well as k_{eff}, and M_n.
- Criticality may increase during accidents calling for a reasonable safety margin.

Means to stabilize the output power and tritium supply should be carefully examined as breeding, criticality, and energy multiplication are all interrelated. Previous designs have been optimized under a various set of assumptions. Their overall performance depends to a great extent on the actinide form and blanket choices. Fusion neutrons act only as a trigger for the fission process. This means any fusion concept can potentially burn actinides at a comparable rate when normalized to the same power level. The actinides change the overall neutron environment of all burners. For instance, the In-Zinerator exhibits the following features:

- Neutron flux peaks within the blanket, not at the first wall
- Fission neutrons are dominant, not fusion neutrons
- Blanket performance continuously changes due to actinide burning and FP generation.

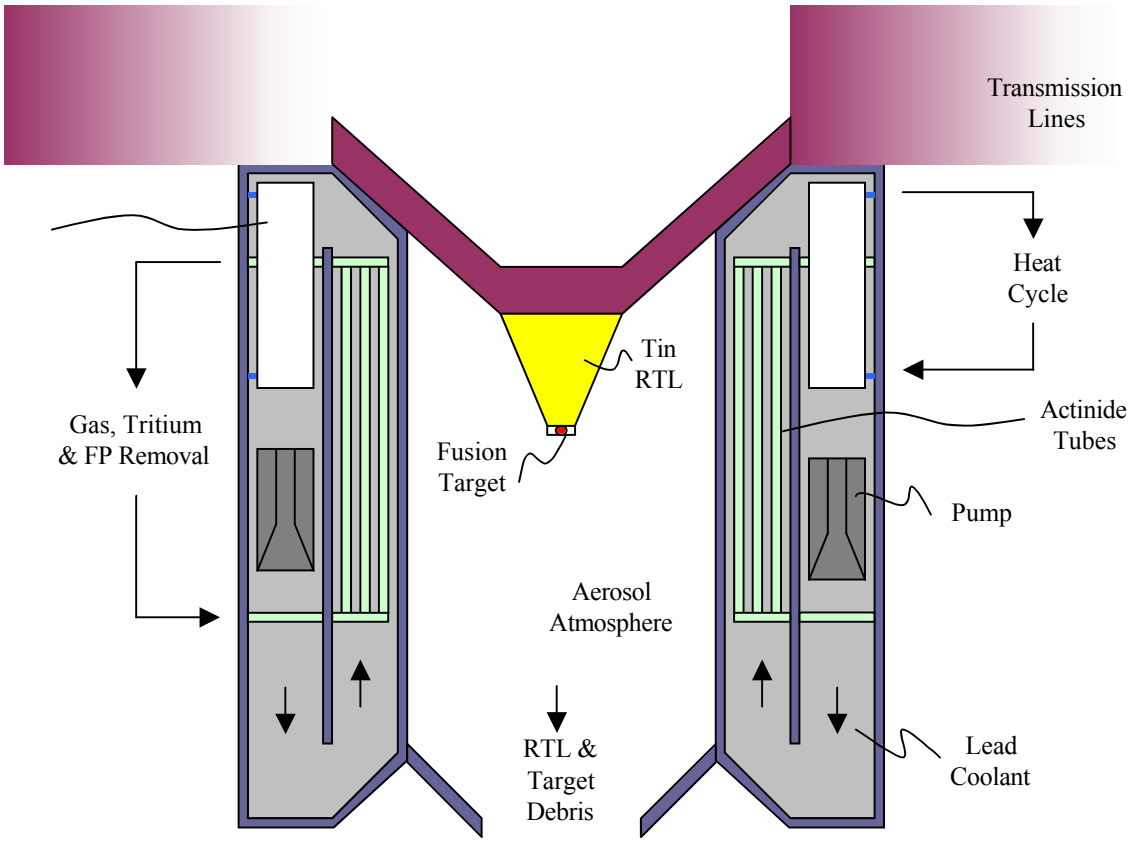

Fig. 1. Vertical cut through In-Zinerator showing actinide tubes and Pb pool.

The In-Zinerator offers a unique advantage as the liquid actinide mixture allows online feeding of fresh materials, adjustment of Li enrichment, and FP extraction that all help stabilize the system. The core, shown in Fig. 1, is a pool-type design that has the best safety features of fast reactors. The sub-critical blanket includes 1146 tubes containing the liquid actinide mixture [$(LiF)_2$-AcF_3] submerged in a Pb pool. The high $(LiF)_2$-AcF_3 eutectic temperature (675^{o}C) allows a narrow operating temperature window, forcing the design to operate at high temperature > 680^{o}C. Two candidate structural materials proposed for the first wall (FW) and tube wall: Hastelloy-N nickel-based alloy and MF82H ferritic steel. References 1 and 5 address the rationale for the coolant choices, effect of internal fission neutrons and fission products on neutronics of the sub-critical blanket, tritium and fission product removal, and safety aspects of In-Zinerator. Here, we

focus our attention on the chamber related issues, mainly the impact of the sub-critical blanket and its internal fission neutron source on:

- Tritium breeding level
- Radiation damage to structure and service lifetime
- Energy deposition and extraction
- Operating temperature
- Chamber activation and radwaste classification.

A series of 3-D analyses using the MCNPX code [6] and its data library was established to guide the design process and identify the time dependent parameters, such as the actinide inventory, burnup, reactivity, and tritium breeding [5]. The results reported herein represent a snapshot at the beginning of operation and pertain to a blanket with 0.05 at% fission products (FP) and 3940 MW thermal power. Previous supporting analyses performed for interim designs are included in Reference 7. The 5-6 m high cylindrical model, shown in Fig. 2, included the essential elements that impact the nuclear parameters: the details of the target at burn, 5 cm thick first wall at 2 m from the target, 1146 actinide tubes with 2.2 cm inner radius submerged in ~60 cm thick Pb pool and surrounded with 50 cm thick Pb reflector. The activation, decay heat, and waste disposal parameters were computed using the ALARA pulsed activation code [8] that models all pulses (2.86 million/y) during the plant lifetime (40 full power years [FPY]) and explicitly includes the effect of the projected 85% plant availability.

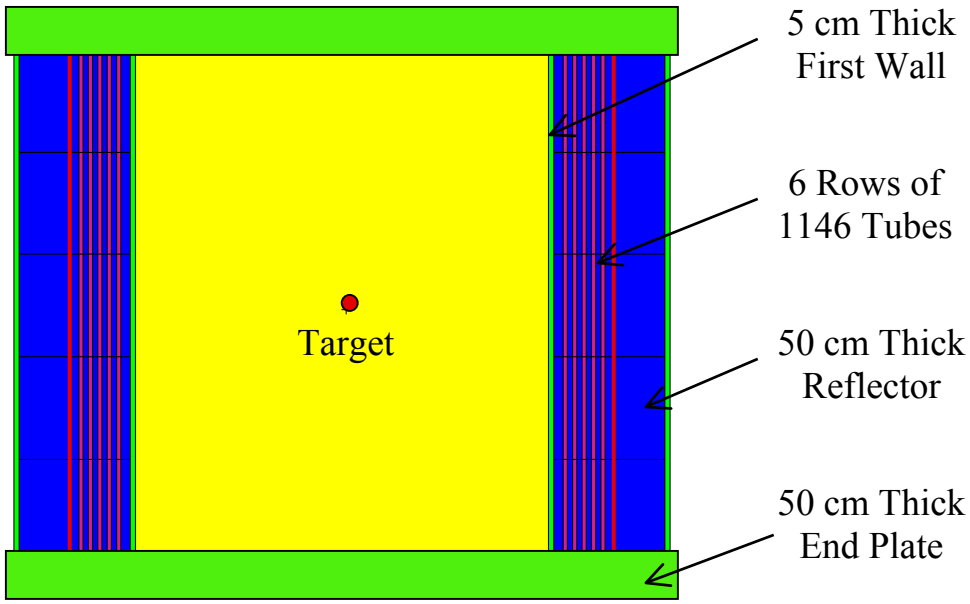

Fig. 2. In-Zinerator MCNP model.

2. Structure Lifetime

The life-limiting criterion for Hastelloy is a key factor in determining the service lifetime of the first wall (FW) and tube walls. Historically, the thermal and mechanical stresses, thermal creep, and atomic displacement have led to a failure mechanism, therefore prematurely ending the service lifetime of the structural components. There are no firm guidelines for Hastelloy as for the ferritic steel (FS) components of fusion systems where the life-limiting criterion has traditionally been the displacement of atoms, ranging between 100 and 200 dpa. In this analysis, we have considered a displacement per atom (dpa) limit of 200 dpa for the Hastelloy structure.

In the absence of actinides and fission neutrons, the FW would be a permanent component that performs properly during the entire life of the plant (40 FPY) with a peak dpa of ~130. The actinides change the neutron environment and result in a notable increase in the dpa level, calling for three FW replacements after 11, 22, and 33 FPY of operation. The dpa peaks at the midplane of the chamber as shown in Fig. 3 for the reference case of 5% Li-6 enrichment. The radial variation of the peak dpa displayed in Fig. 4 indicates a higher dpa level at the tubes containing the actinide mixture due to the higher flux within the blanket relative to the FW, as will be discussed later. This means the tubes should be replaced more frequently than the FW (see Fig. 5). Well-protected by the blanket, the damage to the back wall is relatively low and remains below the 200 dpa limit at all times, as illustrated in Fig. 6. A deviation from the reference 5% Li-6 enrichment indicates a lower damage to the structure and even a longer service lifetime with higher enrichment, approaching 40 FPY for the FW (refer to Fig. 7).

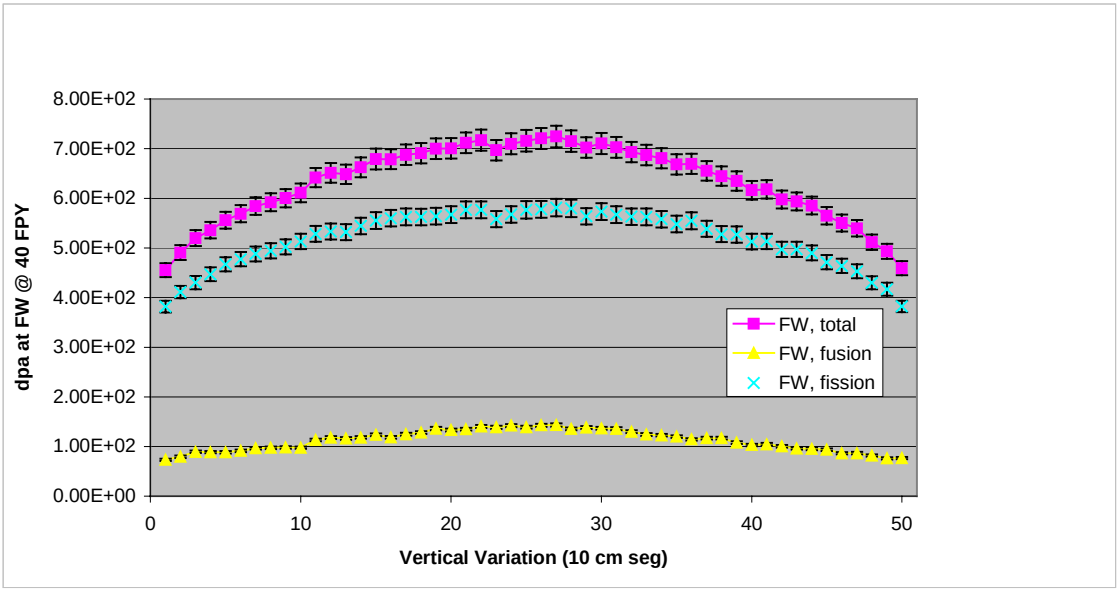

Fig. 3. Vertical variation of dpa along the 5 m high first wall (20 segments, 10 cm each).

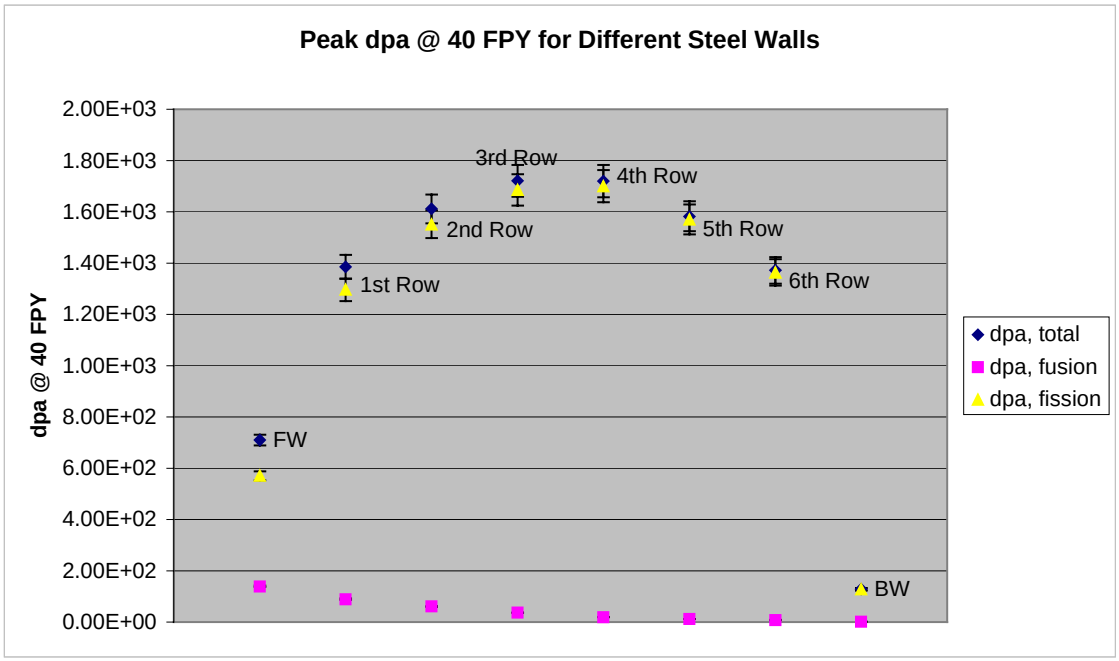

Fig. 4. Peak dpa at the midplane of the FW, tubes of 6 rows, and back wall.

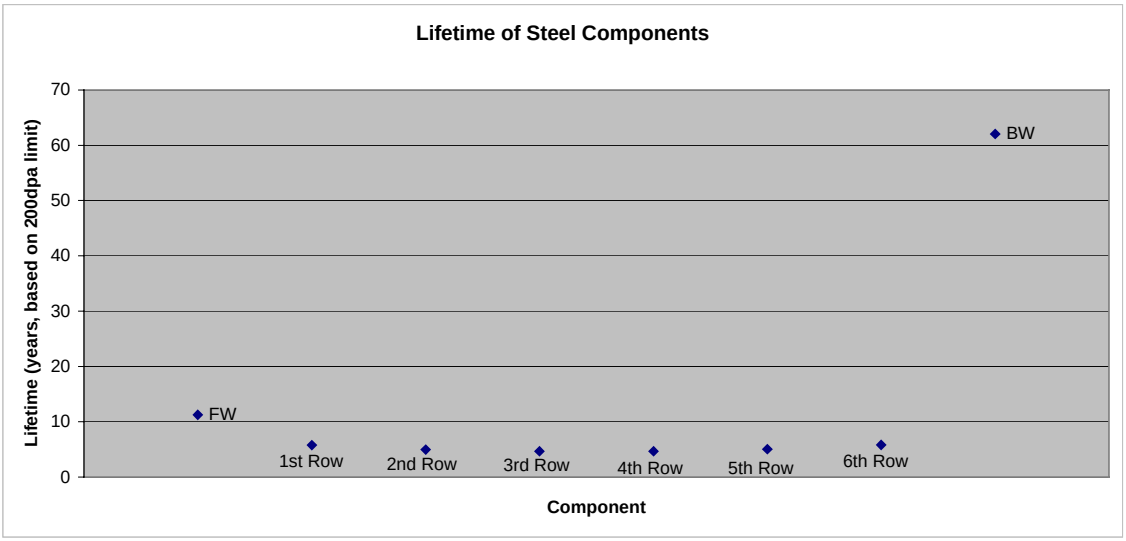

Fig. 5. Service lifetimes of FW, tubes, and back wall.

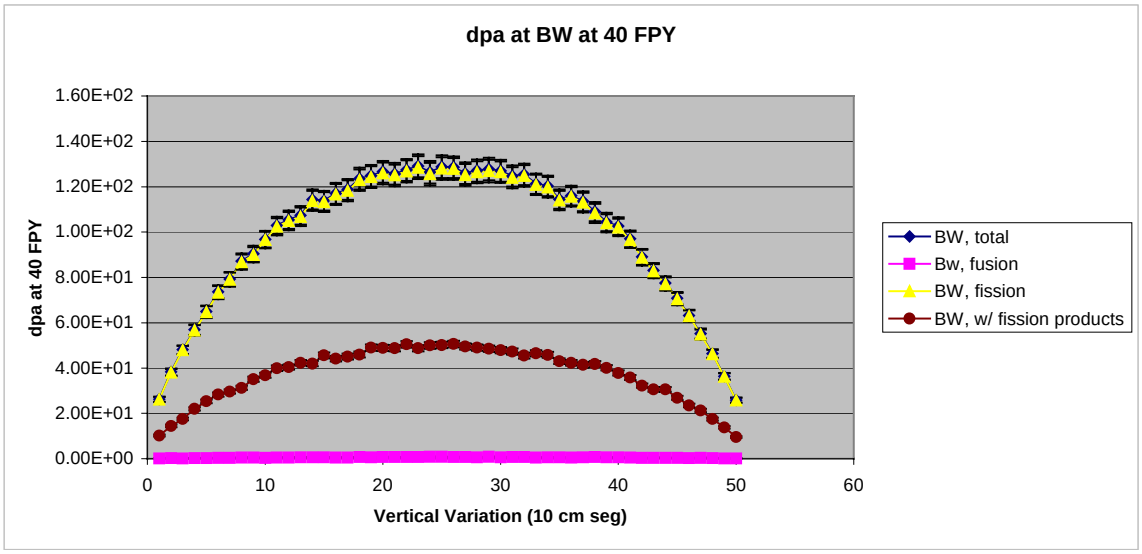

Fig. 6. Vertical variation of dpa along the 5 m high back wall (20 segments, 10 cm each).

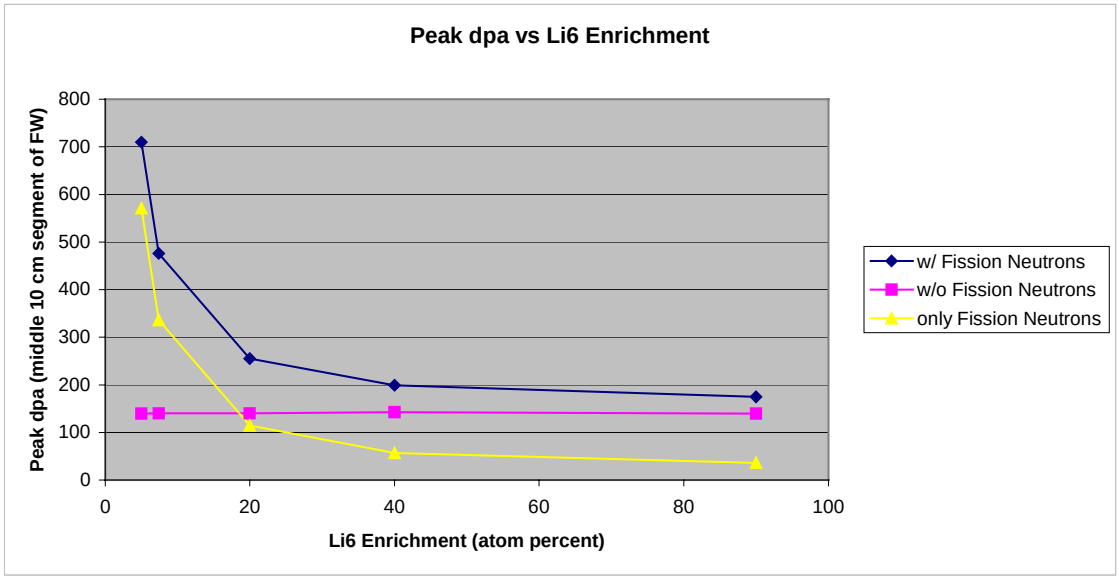

Fig. 7. Sensitivity of peak dpa at FW to Li enrichment.

3. Tritium Breeding Issues

A tritium-breeding ratio (TBR) of 1.1 assures tritium self-sufficiency. The 10% breeding margin accounts for the uncertainties in the cross section data, approximations in geometric model, and losses during T reprocessing. Reference 9 provides a more detailed breakdown of the breeding margin. The blanket performance continuously changes due to the actinide burning and FP generation. The net TBR at the beginning of operation could be high, approaching 1.77, and drops with time. A flexible design could adjust the time-integral net TBR to 1.1. Effective tools include the LiF concentration, Li-6 enrichment (see Fig. 8), and FP concentration. As the Li-6 enrichment increases, the breeding decreases because Li competes with actinides in absorbing neutrons, yielding less fission neutrons, lower flux, and eventually less breeding. Of interest is the sensitivity of TBR to the tube radius. For the reference 5% Li enrichment and fixed 0.2 cm tube wall thickness, the TBR drops from 1.77 to 0.24 when the inner radius decreases by 2 mm, as illustrated in Fig. 9. This design should rely on the online adjustment of breeding during operation. In case of over-breeding (net TBR > 1.1), higher enrichment than 5% and/or time periods without breeding (i.e., no LiF feed) help bring the tritium inventory to an acceptable level. The practicality and interrelated impact of these options on k_{eff} (refer to Fig. 10), actinide burnup, and power balance should be carefully examined.

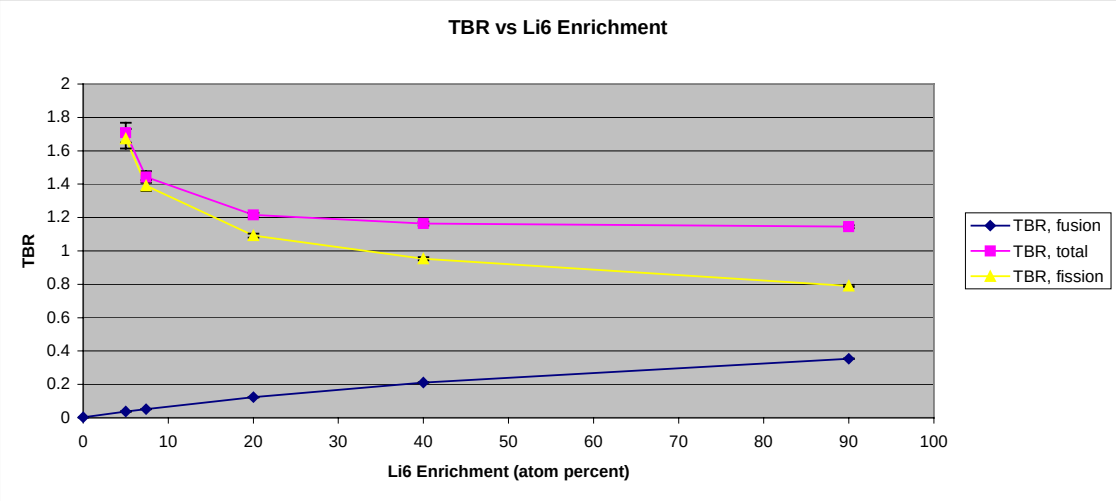

Fig. 8. Sensitivity of TBR to Li enrichment.

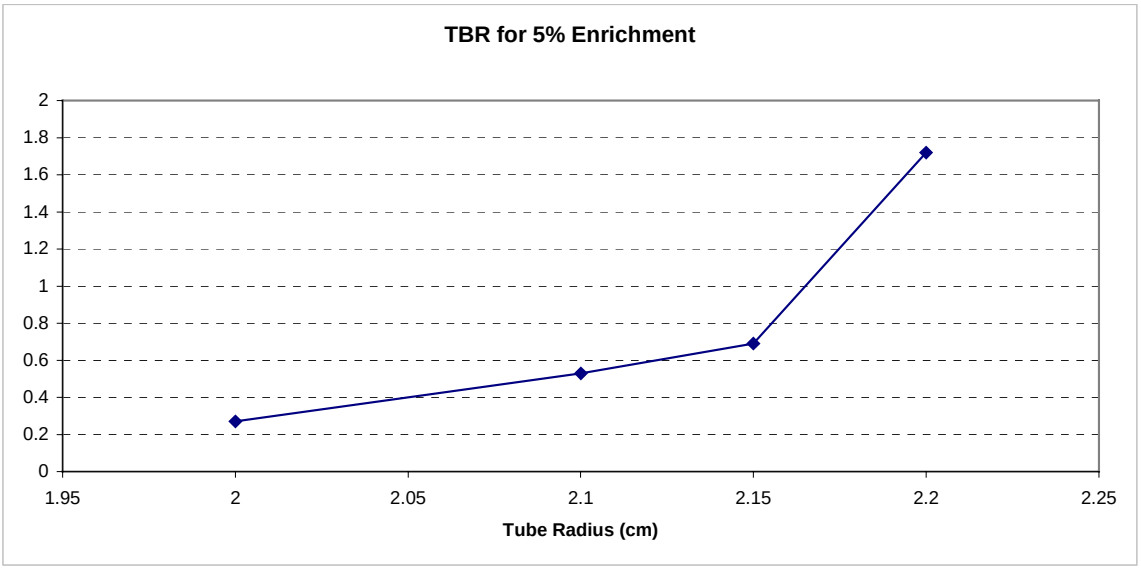

Fig. 9. Sensitivity of TBR to tube radius.

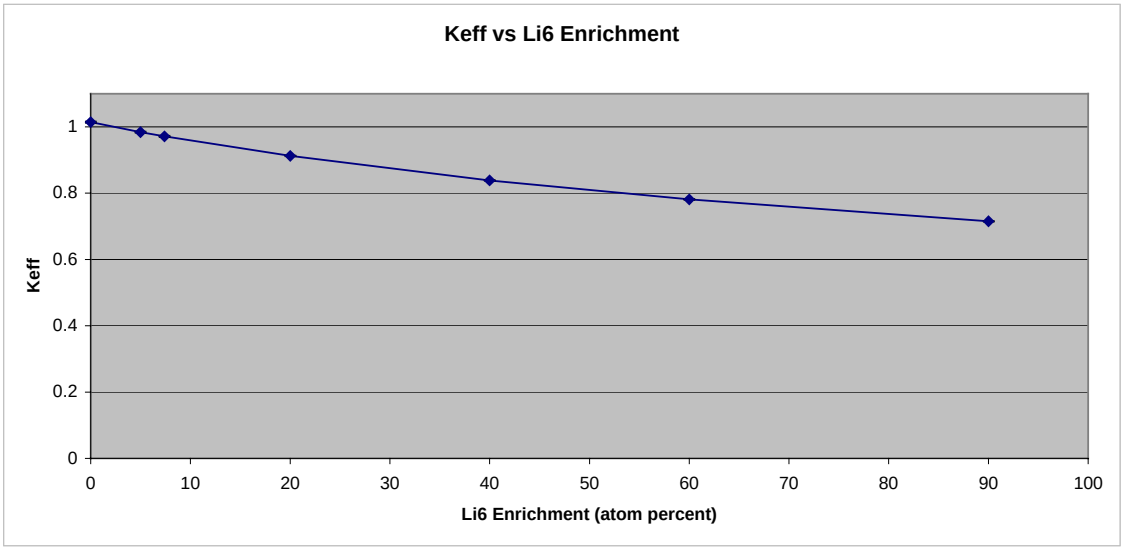

Fig. 10. Sensitivity of K_{eff} to Li enrichment.

4. Nuclear Heating and Energy Multiplication

All components are power producing components, meaning the nuclear heating recovered from the FW, blanket, actinide tubes, reflector, and surrounding structures will be high grade heat. A small fraction (< 0.1%) leaks from the back wall and top/bottom structures. The breakdown of the heating indicates 230, 3570, and 21 MW deposited in the Pb coolant of the blanket, actinide tubes, and Pb reflector, respectively, totaling 3940 MW for the entire system. Most of the power (90%) is generated in the 1146 tubes submerged in the Pb coolant. This means the fission process within the blanket accounts for the majority of the produced power. The blanket, not the target, is the dominant source of neutrons. The radial heating across the six rows of tubes is almost uniform. It peaks at 3.3 MW in each tube of the third row and drops slightly to ~3 MW per tube of the first or last rows.

The 200 MJ target injected every 10 seconds produces a fusion power of 20 MW. The 14.1 MeV source neutrons interact with the target materials and lose a small fraction of their energy, reaching the FW with an average energy of 12.8 MeV. The neutron energy multiplication (M_n) (defined as the thermal power divided by 12.8 MeV average neutron energy) is 262 for 3940 MW thermal power. The variations of the heating and M_n with Li enrichment are displayed in Figs. 11-14. Note the significant impact of the 5-20% Li-6 enrichment. The heating results serve as a source term for the detailed thermal analysis of the following section.

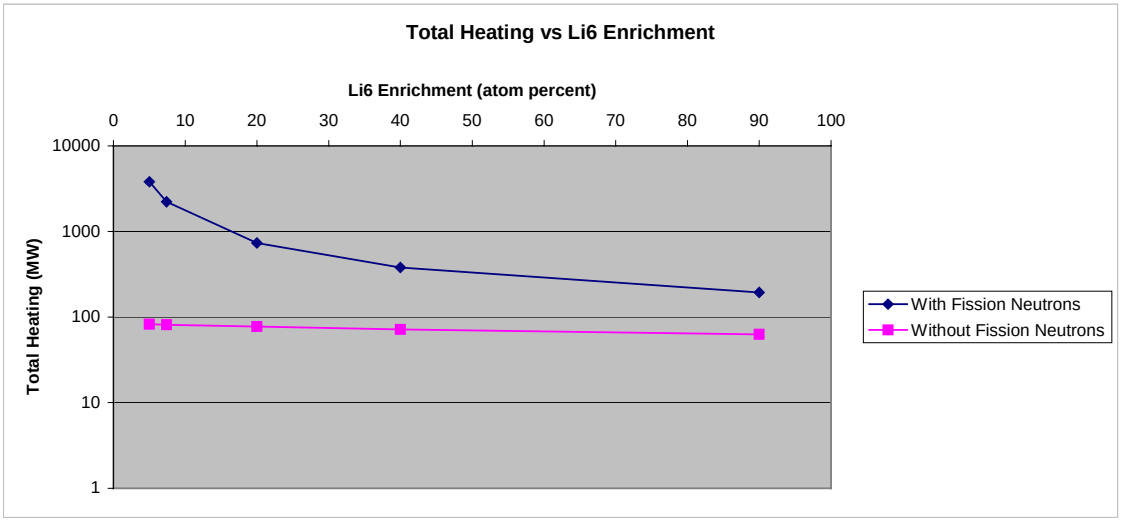

Fig. 11. Sensitivity of total nuclear heating to Li enrichment.

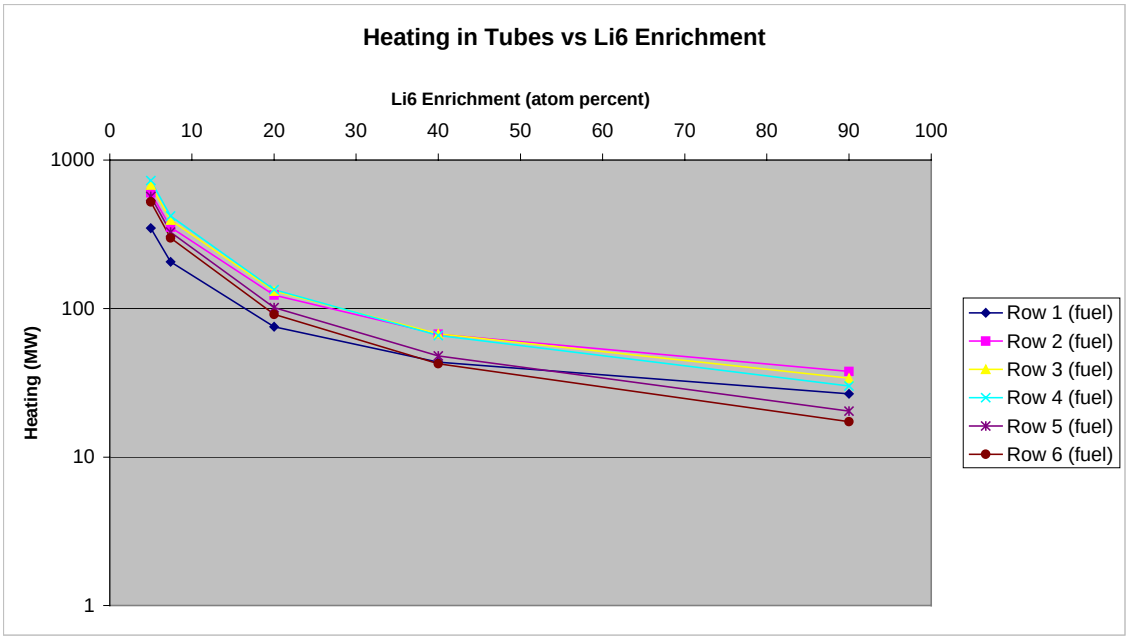

Fig. 12. Sensitivity of actinide mixture heating to Li enrichment.

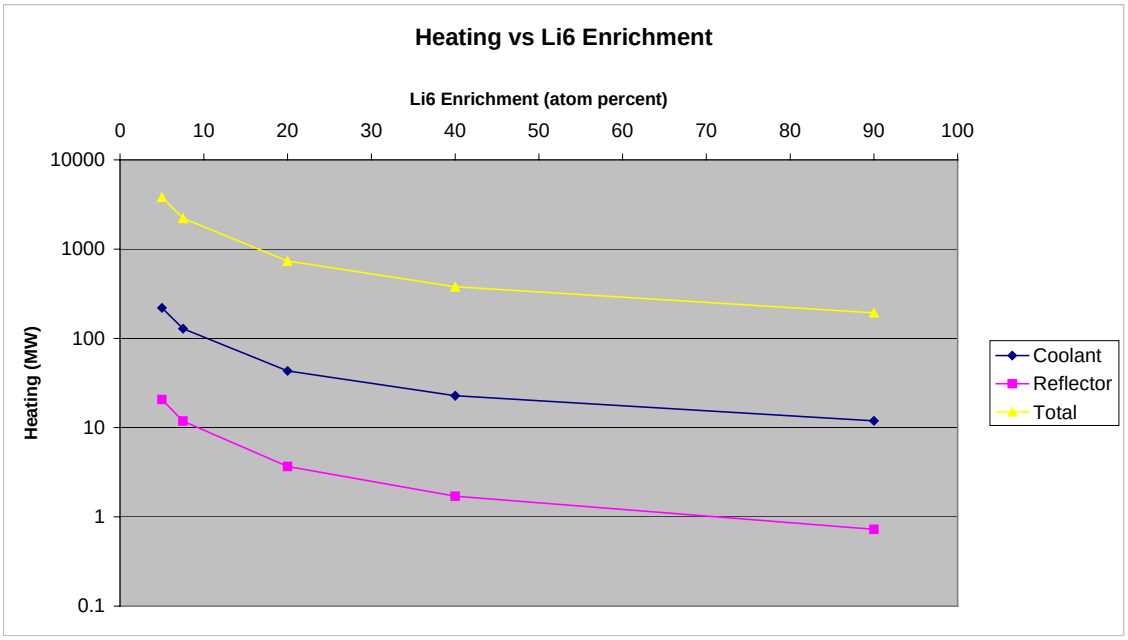

Fig. 13. Sensitivity of heating in Pb coolant and reflector and total heating to Li enrichment.

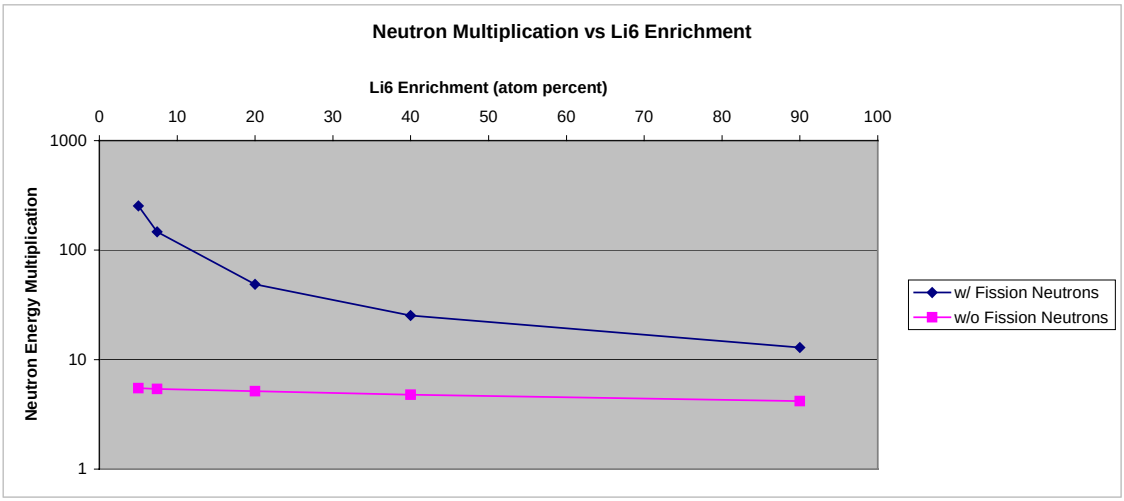

Fig. 14. Sensitivity of M_n to Li enrichment.

5. Thermal Analysis and Heat Removal

This thermal analysis has been generated from the first nuclear data, which was obtained for the actinide mixture without fission products. Heating values were available for the actinide mixture in the tubes, the steel walls of the tubes, the Pb coolant surrounding the tubes, the Pb reflector, and the steel wall of the chamber. Since thermal properties of the actinide mixture $(LiF)_2$-ACF_3 is not available, we are using Flibe ($2LiF$-BeF_2) properties to perform the thermal analysis. Table I gives the pertinent dimensions used in calculating masses.

Table I. Key Dimensions for the Thermal Analysis

Flibe tube OD (cm)	4.8
Flibe tube ID (cm)	4.4
Length of tube (m)	5.0
Number of tubes	1146
Chamber wall IR (m)	2.0
Chamber wall OR (m)	2.05
Chamber height (m)	5.0
Pb coolant IR (m)	2.05
Pb coolant OR (m)	2.62
Pb reflector IR (m)	2.62
Pb reflector OR (m)	3.12
Depth of Pb (m)	5.0

Peak heating values were given for the Flibe/actinide mixture, the steel wall of the tubes, and the chamber steel wall. Total heating values were given for the Pb coolant and reflector. The composition of Flibe is LiF_2BeF_2, which has a melting temperature of 459 C. The steel structure for the present is Hastelloy alloy. There are 6 rows of tubes in the chamber, spaced on some configuration, with 191 tubes in each row for a total of 1146. Table II gives the heating values and the resulting temperature rise based on a pulse rate of 0.1 Hz. These heating values are based on steady state time between pulses. Therefore, these values are multiplied by 10 to obtain the heating in Joules.

Table II. Nuclear Heating and Temperature Rise

Component	row	Peak Heating (MW/cm^3)	Mass (kg)	Peak ΔT (^oC)	Avg. ΔT (^oC)
Flibe	1	4.65e-4	15.2	968.8	807
	2	4.89e-4	″	1037.5	865
	3	5.25e-4	″	1093.8	911.5
	4	5.26e-4	″	1095.9	913.3
	5	5.06e-4	″	1054.2	878.5
	6	4.81e-4	″	1002.1	835.1
Tube steel	1	1.48e-5	2.89	39.9	33
	2	1.55e-6	″	41.8	35
	3	1.63e-5	″	44.0	37
	4	1.64e-5	″	44.3	37
	5	1.57e-5	″	42.4	35
	6	1.48e-5	″	39.9	33
		Avg. Heating (MW/cm^3)			
Chamber wall		1.26e-7	28,183	0.34	0.34
Pb coolant		7.03e-6	356,655	40.0	40.0
Pb reflector		4.59e-7	511,388	2.61	2.61
Equilibrated Pb			868,043	18.0	18.0

It is apparent that the heating in the Flibe is excessive, especially if the initial temperature of the Flibe is 600^oC, or about 140^oC above its melting temperature. This makes the peak temperature of the Flibe 1696^oC in row # 4. The melting temperature of Hastelloy is 1370^oC. The recommended maximum temperature for this alloy would be 2/3 of melting, or 913^oC. The boiling temperature of many molten salts is $>1400^oC$ at atmospheric pressure, and obviously greater at higher pressure. Therefore, it appears that, although these temperature increases are high, there may be some room to work within their domain.

As far as structural materials are concerned, only refractory metals can withstand those kinds of temperatures. For example, Mo can be used up to 1930^{o}C, W up to 2455^{o}C and Nb up to 1827^{o}C. Activation of refractory metals should not be a problem since the whole assembly will be very radioactive to begin with.

Regardless of the tube materials, there are several other considerations that have to be taken into account. Thermal stresses in the tube walls because of the wide fluctuations in temperature are an issue to be dealt with. Isochoric heating should be investigated since the duration of the pulse is so short (10 ns), but the Grüneisen parameter for Flibe is on the order of 1.0 so it may not be a major issue. Finally, compatibilities of the materials at these temperatures have to be investigated.

If for the moment we assume that the materials used are compatible with each other and the temperatures (e.g. if refractory metals are used for the tube material), then we can estimate the temperature of the Pb in the chamber from the heat deposited in it by the flowing actinide in the tubes. The energy transferred to the Pb can be estimated from:

$$Q = 2 \pi k l (T_1-T_2) / \ln (r_2/r_1)$$

where Q is the total heat transferred per cm, k is thermal conductivity of the tube metal, l is the length of tube taken here as 1.0 cm , T_1 is the temperature of the actinide fluid and T_2 the temperature of the Pb, r_2 is the OR of the tube and r_1 is the IR of the tube. The actinide/Flibe mixture in the tubes is pumped at 0.5 m/s and takes 10 seconds to clear the chamber. The Pb is also pumped at some rate, going to a heat exchanger and then returned to the main chamber. The rate at which the Pb is pumped depends on the rate at which energy is transferred to the Pb.

As a first estimate, we calculated the heat transferred to the Pb from the tubes assuming a static Pb bath. At the 0.5 m/s velocity of the Flibe, the heat transfer coefficient on the tube inside is so low that it is neglected. The initial average temperature of the Flibe is 1468^{o}C and the Pb is 600^{o}C. As the Flibe in the tubes moves down, its temperature decreases while the Pb temperature increases. At the end of 10 seconds, the temperature of the remaining Flibe is 1200^{o}C and the Pb temperature is 692^{o}C. The amount of Pb that must be circulated to return its temperature to 600^{o}C in 10 s is 27,476 kg/s or 2.4 m^3/s. Figure 15 shows the temperature profiles in the Flibe and in the Pb. The inventory of actinide/Flibe mixture in the tubes is 8.713 m^3, or 17,426 kg. This inventory must be pumped out in 10 s and replaced with new mixture at 600^{o}C. This pumping rate is 0.87 m^3/s.

A few remarks can be made:

1) The initial heating values for the Flibe/actinide solution in the In-Zinerator are high enough as to make cooling it difficult. At these temperatures, Hastelloy cannot be used for the tubes, and must be replaced with a refractory metal.
2) All of the mixture in the tubes has to be pumped out of the chamber after each shot, and replaced with fresh mixture at 600^{o}C. The pumping rate is 0.87 m^3/s. The temperature of the mixture leaving the chamber is ~ 1200^{o}C and must go to a

heat exchanger where it is further cooled to 600°C before it is returned to the chamber for additional processing.

3) The Pb in the chamber also must be circulated through a heat exchanger to maintain its temperature at 600°C. The pumping rate for the Pb is 2.4 m^3/s, which is quite high, most likely requiring multiple pumps. Another option is to add cooling to the Pb by circulating He gas at high pressure through tubes immersed in the Pb. These tubes could be Hastelloy, since their temperature will not exceed 700°C.
4) The nuclear heating in the chamber first wall is very low (0.13 W/cm^3). The chamber first wall will be cooled by the Pb in the chamber and its temperature will not exceed 700°C.

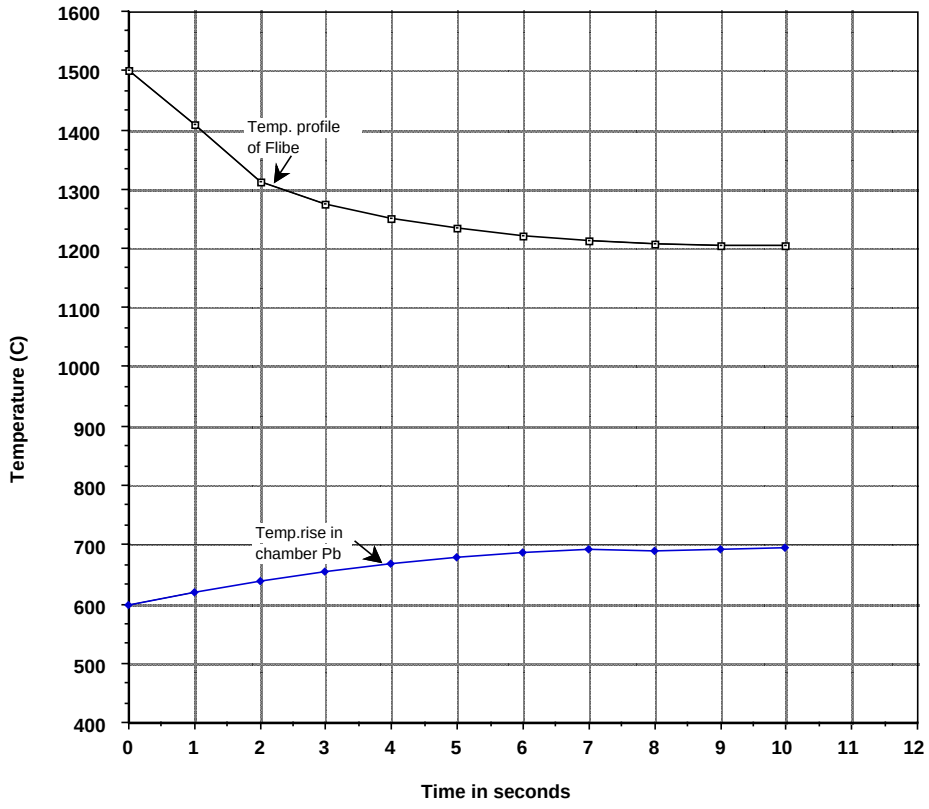

Fig. 15. Flibe and Pb temperature profiles.

6. Activation of Hastelloy Structure

As a source term, the activity, shown in Fig. 16, has been used to evaluate the radiological hazards of the individual components at the end of their service lifetimes (11 FPY for FW and 5 FPY for tubes). The order of magnitude higher and harder neutron flux below 14.1 MeV at the tubes displayed in Fig. 17 helps explain the results. The radwaste results reported herein pertain to the fully compacted structure. No attempt has been made yet to assess the activation of the coolants. We evaluated the waste disposal rating (WDR) for a fully compacted waste using the most conservative waste disposal limits developed by Fetter [10] and NRC-10CFR61 [11]. By definition, the WDR is the ratio of the specific activity at 100 y after shutdown to the allowable limit summed over all radioisotopes. A WDR < 1 means low-level waste (LLW) and WDR > 1 means high-level waste (HLW). Table III summarizes the WDRs and the main contributors to the waste. All values exceed one, meaning the FW and tube structures qualify as HLW at the end of the 100 y interim storage after decommissioning. The best candidate low-activation MF82H steel for fusion designs is included for comparison. Figure 18 displays the Hastelloy decay heat. Slightly lower decay heat is identified for the MF82H structure. An active decay heat removal system is needed during shutdown or in case of loss of coolant or flow accidents. The use of SiC/SiC composites as the main structural material for the FW and tubes could be beneficial. If compatible with the actinide mixture, SiC can operate at high temperatures and offers salient activation characteristics in terms of Class C low-level waste (see Table III) and rapid drop of decay heat within a few hours after shutdown, as Fig. 18 indicates. Note that ^{14}C dominates the SiC WDR due to the relatively high population of the low-energy fission neutrons (refer to Fig. 17). It is mainly produced through two successive reactions [$^{14}C(n,\gamma)^{13}C(n,\gamma)^{14}C$].

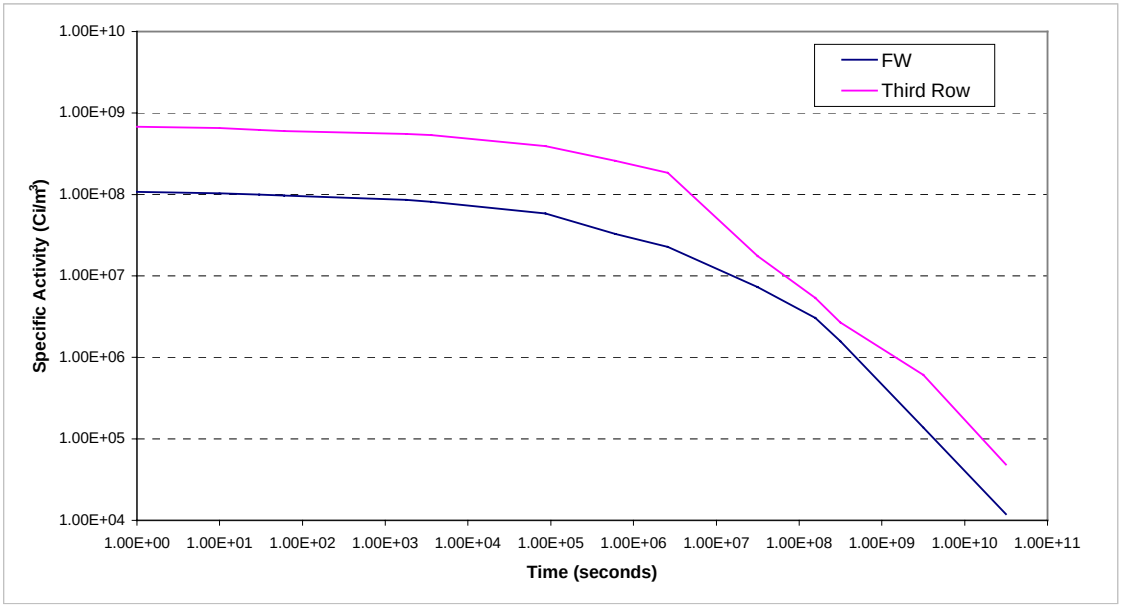

Fig. 16. Variation with time after operation of specific activities of FW and third row of tubes.

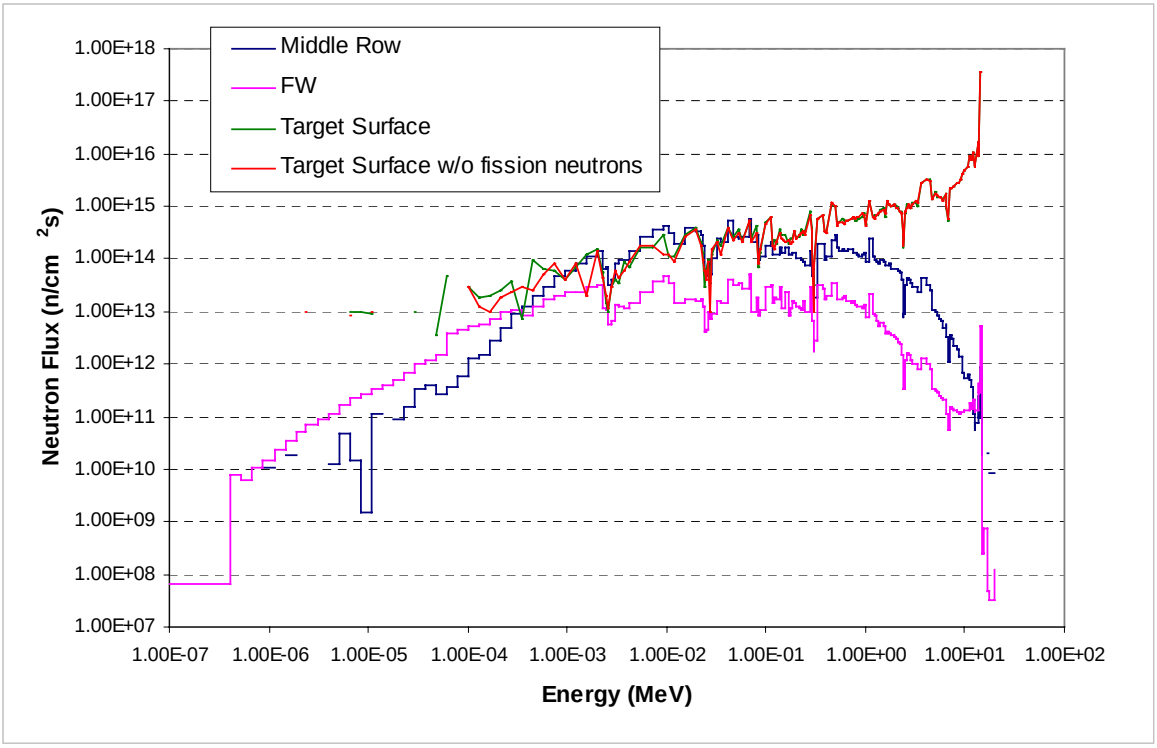

Fig. 17. Neutron flux spectra at FW and third row of tubes.

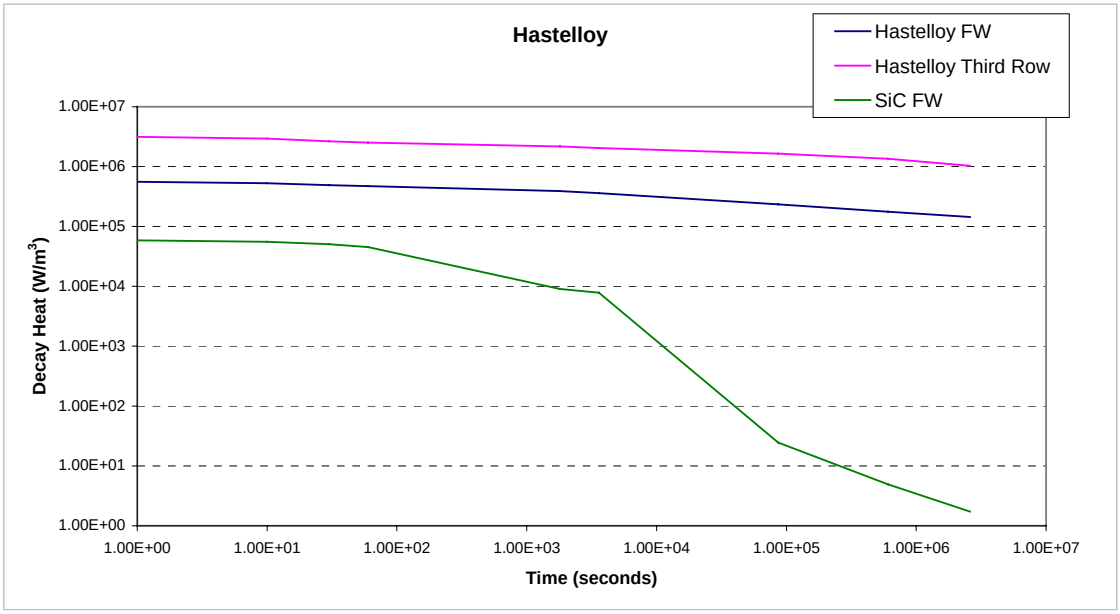

Fig. 18. Variation with time after operation of decay heats in Hastelloy FW and tubes of third row. The SiC FW is included for comparison.

Table III. WDR of FW and Tubes for Hastelloy, MF82H steel, and SiC/SiC composites

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)

7. Summary and Concluding Remarks

We examined the major factors that determine the In-Zinerator engineering parameters, namely the tritium breeding ratio, radiation damage to structure and service lifetime, energy deposition and extraction, and radwaste classification. The time-dependent neutronics analysis[5] determined the sub-critical blanket dimensions and actinide parameters that are essential to our assessment. The intent is to push all the constraints to better understand the limitations to develop an attractive design.

The key engineering constraints that impact the In-Zinertor performance are the fission products, Li enrichment, and actinide-containing tube radius. The fission products are poisonous and should be kept below 1 atom% to the extent practicable and feasible. A salient feature of this design is the liquid actinide mixture that allows online feeding of fresh materials, adjustment of Li enrichment, and FP extraction. We examined the sensitivities of the tritium breeding level to Li enrichment and tube radius. The TBR should be tailored to satisfy the 1.1 breeding requirement. During operation, the burnup of actinides, buildup of FPs, and their impact on the interrelated TBR, k_{eff}, and M_n should be closely monitored. The action taken in one area will have a significant impact on the others. An active control system is required to adjust the breeding online during operation. In case of over-breeding (net TBR > 1.1), higher enrichment than 5% and/or time periods without breeding (i.e., no LiF feed) help bring the tritium inventory to an acceptable level.

The actinide mixture of the 3940 MW_{th} plant generates high nuclear heating. If the initial actinide temperature is ~600^{o}C, the structure temperature will exceed 1000^{o}C. Only refractory metals (Mo, Nb, or W) and SiC/SiC composites can withstand these high temperatures. However, these refractory metals along with the reference Hastelloy steel generate very high-level waste. The low-activation, low decay heat SiC/SiC composites offer a distinct advantage in this regard. Potential solutions to the actinide heating problem include diluting the actinides in more LiF and/or decreasing the thermal power by a factor of 3-4. These will certainly help the radiation damage, heating, and activation issues, but may negatively impact the economics. Because of the pulsed nature of the device, the isochoric heating and thermal stresses in the structure of the actinide containing tubes should be investigated. In summary, the following points can be made for the 3940 MW_{th} In-Zinerator plant:

- There are major impacts on the blanket parameters for 5-20% Li-6 enrichment.
- The design should be flexible to adjust the time-integral net TBR to 1.1.
- The interrelated impact of changes to the Li-6 enrichment on k_{eff}, actinide burnup, and net output power should be carefully examined in future studies.
- The recommended 0.05 atom% fission products have an insignificant impact on the design performance.
- The actinide mixture generates 90% of the thermal power.
- The fission neutrons are the dominant source of tritium breeding, radiation damage, and heating.
- Due to radiation damage, the actinide tubes should be replaced on a more frequent basis (every 5 FPY) compared to the first wall (11 FPY).
- The nuclear heating for the actinide mixture is quite high and its exit temperature approaches 1200^{o}C. At these temperatures, Hastelloy cannot be used for the tubes, and must be replaced with refractory metals or SiC/SiC composites.
- According to the U.S. waste classification, the reference Hastelloy structure qualifies as high-level waste, requiring deep geological burial. Refractory metals would also generate HLW.
- SiC/SiC composites offer high operating temperature, Class C low-level waste, and very low decay heat.
- Compatibilities of structural materials (Hastelloy and SiC) with actinide mixture at high temperatures should be investigated.

ACKNOWLEDGMENT

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