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UWFDM-1313

Presented at the 17th ANS Topical Meeting on Fusion Energy, 13-15 November 2006, Albuquerque NM.

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ENGINEERING ISSUES FACING TRANSMUTATION OF ACTINIDES IN Z-PINCH FUSION POWER PLANT

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The initiation of the Global Nuclear Energy Partnership includes nuclear-based transmutation devices to recycle the spent fuel. Fusion can offer an alternative to the use of fast reactors for the transmutation of actinides. At a modest fusion power of 20 MW, a Z-Pinch driven sub-critical blanket can burn actinides and produce power. Several engineering issues have been examined: the effect of the sub-critical blanket and its internal fission neutrons on tritium breeding, radiation damage to structure, energy deposition and extraction, and chamber activation. Our initial assessment indicates the Z-Pinch could be an attractive option for burning actinides, but special attention should be paid to the challenging engineering issues.

I. INTRODUCTION

As part of the Advanced Energy Initiative, the U.S. Department of Energy has recently announced the Global Nuclear Energy Partnership (GNEP) 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. 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 fission fuel reprocessing plants.[1] 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. The In-Zinerator seems to offer advantages over fast reactors in terms of transmutation efficiency and support ratio.[1] This application may shorten the fusion development path, offering a more near-term application while providing valuable experience in designing a net power producing power plant.

References 1 and 5 address the rationale for the coolant choices, effect of internal fission neutrons and fission products on neutronics of sub-critical blankets, tritium and fission product removal, first wall (FW) protection scheme, and safety aspects of In-Zinerator. Here, we focus our attention on the chamber related issues, namely the impact of the sub-critical blanket and its internal fission neutron source on tritium breeding, radiation damage to structure, energy deposition and extraction, and chamber activation. The core, shown schematically in Fig. 1, is a pool-type design that has the best safety features of fast reactors. The tubes containing the liquid actinide mixture [$(LiF)_2$-AcF_3] are submerged in a Pb pool. Two candidate structural materials proposed for the FW and tube wall: Hastelloy-N nickel-based alloy and MF82H ferritic steel.

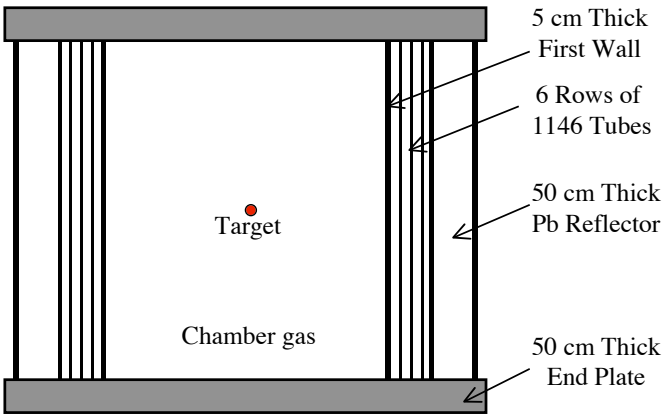

Fig. 1. MCNP model for In-Zinerator chamber. A simplified version of the actual design.[1]

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. The 5-6 m high cylindrical model, shown in Fig. 1, 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[7] that models all pulses (2.86 million/y) and explicitly includes the effect of the projected 85% plant availability.

II. STRUCTURE LIFETIME

The life-limiting criterion for Hastelloy is a key factor in determining the service lifetime of the first wall 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. 2 for the reference case of 5% Li-6 enrichment. The radial variation of the peak dpa[8] indicates a higher dpa level at the tubes containing the actinide mixture due to the higher flux within the blanket relative to the FW. This means the tubes should be replaced more frequently than the FW. Well-protected by the blanket, the damage to the back wall is relatively low and remains below the 200 dpa limit at all times. 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,[8] approaching 40 FPY for the FW.

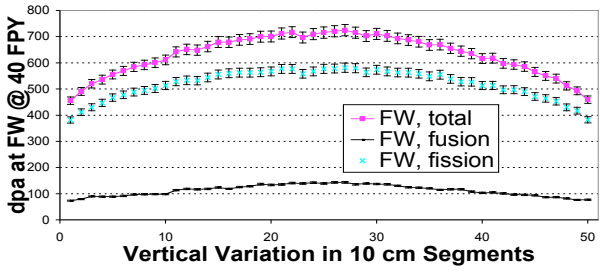

Fig. 2. Vertical variation of dpa along the 5 m high first wall (20 segments, 10 cm each).

III. 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. 3), 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 high 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 only 2 mm as illustrated in Fig. 4. 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} (~0.98), actinide burnup, and power balance should be carefully examined.

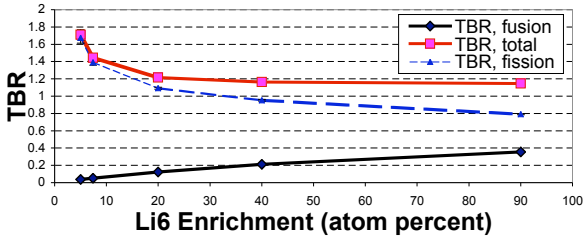

Fig. 3. Sensitivity of TBR to Li enrichment.

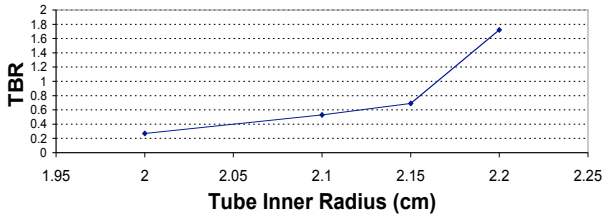

Fig. 4. Sensitivity of TBR to tube inner radius.

IV. 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.[8]

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 ~260 for the 3940 MW thermal plant. The variation of the heating with Li enrichment is displayed in Fig. 5. M_n exhibits similar behavior, peaking at ~260 at 5% enrichment and dropping to ~13 at 90% enrichment. 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.

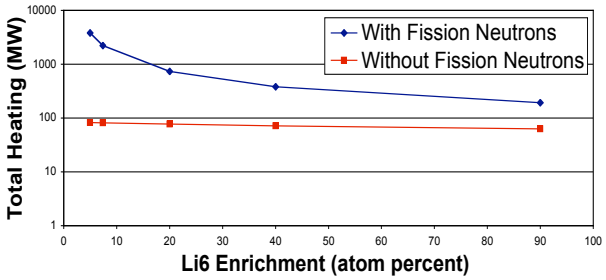

Fig. 5. Sensitivity of total nuclear heating to Li enrichment.

V. 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.[8] 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 (F_4Li_2Be) 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 Flibe has a melting temperature of 459°C. The steel structure for the present is Hastelloy alloy. Table II gives the heating values and the resulting temperature rise based on a pulse rate of 0.1 Hz. It is apparent that the heating in the Flibe is excessive, especially if the initial temperature of the Flibe is 600°C, or about 140°C above its melting temperature. This makes the peak temperature of the Flibe 1696°C in row # 4. The melting temperature of Hastelloy is 1370°C. Only refractory metals can withstand those kinds of temperatures. For example, Mo can be used up to 1930°C, W up to 2455°C and Nb up to 1827°C. Other considerations that have to be taken into account include the thermal stresses in the tube walls because of the wide fluctuations in temperature. Isochoric heating should be investigated since the duration of the pulse is so short (10 ns). Finally, compatibilities of the materials at these temperatures have to be investigated.

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°C and the Pb is 600°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°C and the Pb temperature is 692°C. The amount of Pb that must be circulated to return its temperature to 600°C in 10 s is 27,476 kg/s or 2.4 m^3/s. A few general 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.
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°C.
3) The Pb in the chamber also must be circulated through a heat exchanger to maintain its temperature at 600°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.

TABLE II Nuclear Heating and Temperature Rise

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

Potential solutions that mitigate problems arising from the large temperature spike following each shot include diluting the actinides in more LiF and/or decreasing the thermal power by a factor of 3-4.

VI. ACTIVATION OF HASTELLOY STRUCTURE

As a source term, the activity has been generated 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 helps explain the results.[8] 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. 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.[8] Note that ^{14}C dominates the SiC WDR due to the relatively high population of the low-energy fission neutrons. It is mainly produced through two successive reactions [^{14}C(n,γ)^{13}C(n,γ)^{14}C].

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)

VII. 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. 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°C, the structure temperature will exceed 1000°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°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.

ACKNOWLEDGMENTS

This work has been performed through grants from Sandia National Laboratories.

REFERENCES

1. B.B. CIPITI, P.P.H. WILSON, P. PHRUKSAROJANAKUN, and L. EL-GUEBALY, "Transmutation of Actinides using Z-Pinch Fusion," these proceedings.
2. W.M. STACEY, J. MANDREKAS, and E.A. HOFFMAN, "Sub-Critical Transmutation Reactors with Tokamak Fusion Neutron Sources," *Fusion Science and Technology*, **47**, No. 4, 1210-1218 (2005).
3. E.T. CHENG, "Performance Characteristics of Actinide-Burning Fusion Power Plants," *Fusion Science and Technology*, **47**, No. 4, 1219-1223 (2005).
4. Y. GOHAR, "Fusion Solution to Dispose of Spent Nuclear Fuel, Transuranic Elements, and Highly Enriched Uranium," *Fusion Engineering and Design*, 58-59, 1097-1101 (2001).
5. P. PHRUKSAROJANAKUN, P.H. WILSON, L. EL-GUEBALY, B.B. CIPITI, and R. GRADY, "Isotopic Analysis of the In-Zinerator Actinide Management System," these proceedings.
6. X-5 Monte Carlo Team, "MCNP-A General Monte Carlo N-Particle Transport Code, Version 5-Volume II: Users Guide," LA-CP-03-0245, Los Alamos National Laboratory (April 2003).
7. P. WILSON and D. HENDERSON, "ALARA: Analytic and Laplacian Adaptive Radioactivity Analysis Code Technical Manual," University of Wisconsin Fusion Technology Institute, UWFDM-1070 (1998).
8. L.A. EL-GUEBALY, B. CIPITI, P.H. WILSON, P. PHRUKSAROJANAKUN, R. GRADY, and I. SVIATOLAVSKY, "Initial Engineering Assessment of Actinide Transmutation in Z-Pinch Power Plant," University of Wisconsin Fusion Technology Institute Report, UWFDM-1297 (2006). Available at: http://fti.neep.wisc.edu/pdf/fdm1297.pdf.
9. L.A. EL-GUEBALY, "Overview of ARIES-RS Neutronics and Radiation Shielding: Key Issues and Main Conclusions," *Fusion Engineering and Design*, **38**, 139-158 (1997).
10. S. FETTER, E.T. CHENG, and F.M. MANN, "Long Term Radioactive Waste from Fusion Reactors: Part II," *Fusion Engineering and Design*, **13,** 239 (1990).
11. Nuclear Regulatory Commission, "10CFR61, Licensing Requirements for Land Disposal of Radioactive Waste," Federal Register, FR47, 57446 (1982).