PERFORMANCE CHARACTERISTICS OF ACTINIDE-BURNING FUSION POWER PLANTS

E.T. Cheng

TSI Research, Inc., P.O. Box 2754, Rancho Santa Fe, CA 92067, etcheng@cts.com

Performance characteristics were summarized of two molten salt based fusion power plants. One of them is to burn spent fuel actinides, the other is to burn U238. Both power plants produce output energy larger than a fusion power plant would normally produce without including actinides. Additional features, obtainable by design for these actinide burning power plants, are adequate tritium breeding, sub-critical condition, and stable power output.

I. INTRODUCTION

Burning actinides with fusion neutrons appears to be a promising option to destroy large quantity of actinides associated with spent fuel actinides (SFA) and excess plutonium, and to utilize fertile fuel such as natural uranium to provide unlimited nuclear energy for mankind.[1,2] To determine feasibility of transmutation with fusion neutrons, studies have been performed using a near-term fusion device as a neutron source. The actinides in the spent fuel are mainly Pu isotopes, although some minor actinides (MA), namely isotopes of Np, Am and Cm are also present. The excess weapons-grade plutonium material is mainly Pu239. Sub-criticality, reduction of high level waste (HLW) volume, and reduction of long-term risk of disposed HLW are among the major advantages offered by transmutation. The disadvantages of transmutation comparing to the once-through cycle scenario are concerns for plutonium proliferation and safety in handling enhanced radioactivity due to that associated with minor actinides, mainly Am and Cm isotopes, which may accumulate in large quantities during transmutation. Large fraction of minor actinides in the transmutation system appears also to be an important factor to reduce the performance and efficiency. Similar conclusions could be drawn for the fertile-burning nuclear energy generation fusion power plants.

Molten salt, which is a mixture of lithium fluoride and beryllium fluoride, is one of the transmutation blanket concepts studied recently. Molten salt can dissolve a small quantity of actinide salt in it and a fusion power plant based on the molten salt can become very attractive because of the possibility to minimize the actinide inventory in the transmutation plant. Furthermore, on-line removal of fission products and replenishing of destroyed actinides can be, in principle, operated in a molten salt fusion power plant.[3]

The structural material is the reduced activation version of the martensitic ferritic steel, RAFS, normally considered as a promising candidate material under development in fusion energy programs.

In this paper, performance characteristics were summarized of two molten salt based actinide-burning fusion power plants investigated under a research grant supported by the USDOE. One of them is to burn spent fuel actinides, the other is to burn U238. Both power plants produce output energy larger than a fusion power plant would normally produce without including actinides.

II. BLANKET MODELS AND CALCULATIONAL METHODS

The spent fuel actinide burning power plant has two blanket options. One is a beryllium blanket to enhance the neutron multiplication and provide a soft neutron spectrum for better fission burning of the actinides. The other is a blanket without external beryllium, thus creating a hard neutron spectrum to minimize the transmutation of plutonium into higher actinides. A modest performance is expected for the hard-spectrum blanket. However, the power output is more stable during the transition of burning spent fuel actinides into equilibrium.

Scoping calculations were performed for actinide burning blankets with various thicknesses of transmutation region and reflector. The blankets considered for further investigation consist of a 5 mm first wall made of the RAFS, a transmutation region, and a reflector. The transmutation region has two zones. In the soft-spectrum blanket, the two transmutation zones are 0.3 m each. The first zone consists of 2% structure, 50% beryllium multiplier (95% dense), and 48% molten salt, all by volume. The second zone consists of 2% structure, 50% graphite, and 48% molten salt. The reflector for the soft-spectrum blanket is 0.4 m thick, and is made of graphite to further enhance the low energy neutron reactions.

The transmutation zones for the hard-spectrum blankets are 0.4 m each. The first zone consists of 5% structure and 95% molten salt. The second transmutation zone consists of 5% structure, 85% graphite, and 10% molten salt. The reflector is made of steel, and is 0.2 m thick.

The U238 burning blanket investigated is also a hard-spectrum blanket, and is thus identical as the hard-spectrum version of the spent fuel burning blanket, except the actinides added into the molten salt is the depleted uranium.

Neutronics calculations were performed using the one-dimensional model of the blankets described above, in cylindrical geometry, with the center of the inner toroidal field magnet as the center of the cylinder. The neutral particle transport Monte-Carlo code, MCNP-4B was used for all calculations, with the ENDF/B-VI based neutron and gamma-ray transport libraries.

III. SPENT FUEL BURNING POWER PLANTS

The performance characteristics of the molten salt based transmutation power plants were summarized and discussed in this section.

The concentration of total actinides dissolved in the molten salt for the soft-spectrum blankets is 15 mg/cc of molten salt. It is determined in scoping calculations to limit the maximum k-eff below the criticality of the lower plant, even when the vacuum vessel is breached and the molten salt coolant is filled in the vacuum vessel. The concentration of total actinides dissolved in the molten salt for the hard-spectrum blankets is 63 mg/cc of molten salt.

III.A. Soft-spectrum Blankets

The results of calculations were depicted in Figs. 1 and 2, and summarized numerically in Table 1 at several stages of burn-up. Figure 1 shows the k-eff, energy multiplication, and tritium breeding ratio as a function of actinide burn-up. The evolution of concentrations of actinides during the burn-up is shown in Fig. 2. Table 1 summarizes the performance parameters at certain burn-up stages. Also shown in Table 1 are compositions of actinides at several burn-up stages.

As seen in Fig. 1, the initial energy multiplication performance of this power plant is significant due to high fission rate in the soft neutron spectrum. It can be as high as 180 when the criticality factor, k-eff, is 0.952. But after destruction of 3 actinide inventories in the blanket, the performance drops dramatically, to an energy multiplication of 13 (k-eff 0.616).

Tritium breeding ratio has to be maintained during the burn-up at a level more than adequate for self-sustaining. It is achieved by adjusting the lithium-6 content in lithium. The Li-6 content in lithium is also shown in Table 2 at several burn-up stages. It is noted that at the late stage of burn-up, the Li-6 content has to be higher than the initial stages because the neutron multiplication in the blanket due to fission reactions is reduced as a result of decreased k-eff.

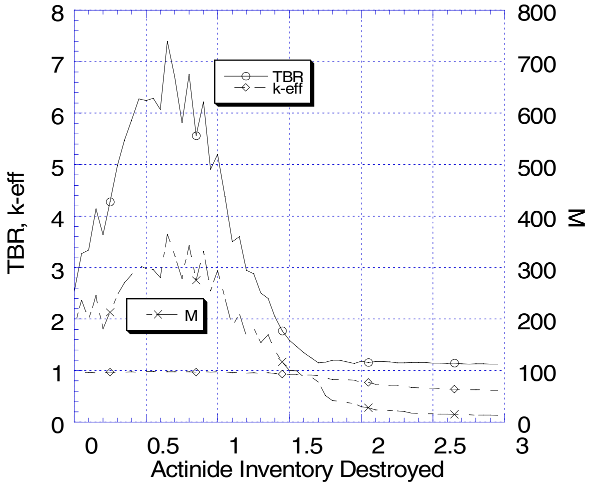

Fig.1. Performance parameters of a SFA burning, soft-spectrum blanket as a function of actinide destroyed.

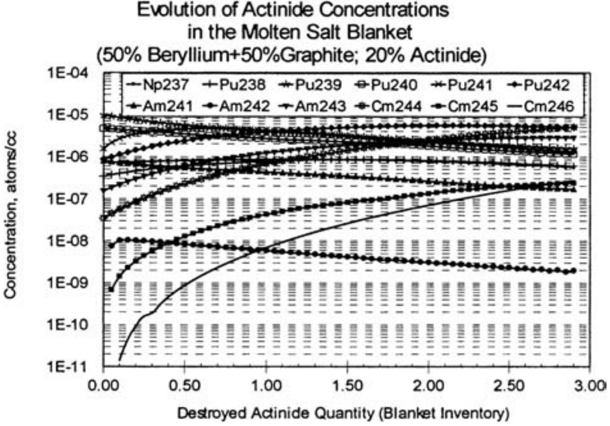

Fig.2. Evolution of actinide concentrations in the soft-spectrum SFA burning blankets.

The actinide compositions at a quasi-equilibrium stage when 3 inventories of actinides in the molten salt are destroyed are, as tabulated in Table 1, 2.9% Np, 50% Pu, 16% Am, and 31% Cm. The fraction of fissile Pu239 and Pu241 isotopes in plutonium is about 30%. Compared to the initial condition, where the plutonium in the spent fuel compositions is 91%, the plutonium content is reduced almost by a factor of 2. Compared to the spent fuel plutonium, of which 66% is fissile Pu239 and Pu241 isotopes, the fissile plutonium content in the equilibrium transmutation blanket is also reduced by more than a factor of 2. The increased content of higher actinides, particularly Am and Cm, however, may cause additional difficulties in reprocessing the actinides from the molten salt. More studies in this aspect have to be conducted in the future.

Table 1. Actinide concentrations at several burn-up stages for burning SFA in a soft-spectrum Flibe blanket (Total to in-blanket molten salt inventory ratio = 2).

Parameter	Burn-up Stages (MW-y/m^2)				
	0.0	0.12	0.256	1.20	2.34
Actinide Inventory Destroyed	0	1	2	2.5	3
Waste Reduction Factor	1	2	3	3.5	4
%Li6	0.02	0.02	0.025	0.035	0.035
k-eff	0.9519 0.995*	0.9716 0.990*	0.7693	0.6577	0.6162
TBR	2.53	5.2	1.18	1.147	1.127
M	181	294	29.4	15.9	13.1
Total Np	3.82%	4.57%	4.15%	3.53%	2.92%
Total Pu	91.1%	82.7%	67.3%	58.2%	50.1%
Pu39+41/Pu	66.0%	52.8%	36.1	31.9%	29.5%
Total Am	5.01%	8.85%	14.3%	15.8%	15.9%
Total Cm	0.182%	3.84%	14.3%	22.4%	31.0%

*k-eff under a severe accident condition.

III.B. Hard-spectrum Blankets

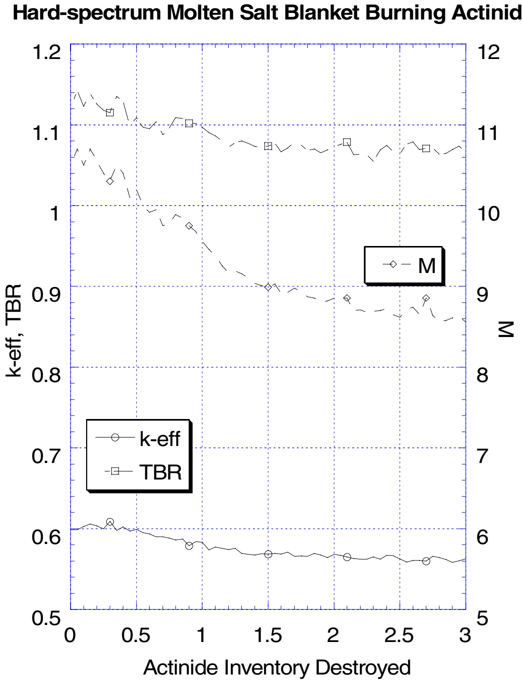

Fig.3. Performance parameters of a SFA burning hard-spectrum blanket as a function of actinides destroyed.

The results of calculations for the hard-spectrum blankets were depicted in Figs. 3 and 4, and summarized numerically in Table 2 at several stages of burn-up. Figure 3 shows the k-eff, energy multiplication, and tritium breeding ratio as a function of actinide burn-up. The evolution of concentrations of actinides during the burn-up is shown in Fig. 4. Table 2 summarizes the performance parameters at certain burn-up stages. Also shown in Table 2 are compositions of actinides at several burn-up stages.

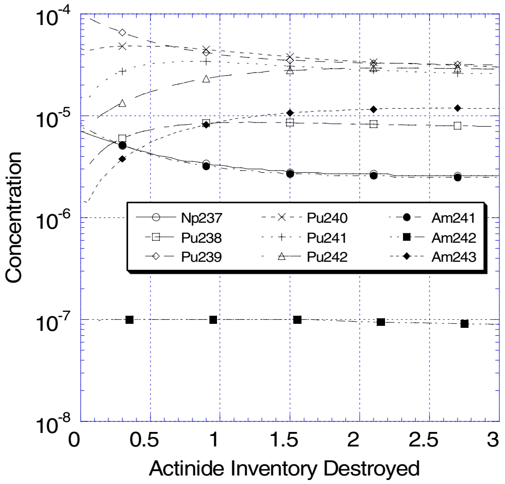

Fig.4. Evolution of actinide concentrations in the hard-spectrum SFA burning blankets.

Table 2. Actinide concentrations at several burn-up stages for burning SFA in a hard-spectrum Flibe blanket (Total to in-blanket molten salt inventory ratio = 2).

Actinides	Burn-up Stages (MW-y/m^2)				
	0.0	10.9	23.4	29.9	36.5
Actinide Inventory Destroyed	0	1	2	2.5	3
Waste Reduction Factor	1	2	3	3.5	4
%Li6	1.0	1.0	1.0	1.0	1.0
k-eff	0.5991	0.5832	0.5684	0.5628	0.5605
TBR	1.12	1.097	1.073	1.064	1.074
M	10.5	9.56	8.86	8.62	8.63
Total Np	3.82%	1.79%	1.53%	1.49%	1.49%
Total Pu	91.1%	84.0%	75.1%	72.6%	71.0%
Pu39+41/Pu	66.0%	48.7%	46.1%	45.6%	46.2%
Total Am	5.01%	6.92%	8.10%	8.25%	8.22%
Total Cm	0.182%	7.30%	15.3%	17.7%	19.3%

Due to a relatively harder neutron spectrum, modest performance is expected in this type of blankets. But the performance is more stable along the burning time. As seen in Fig. 3, the initial energy multiplication factor is about 11 at a criticality factor of 0.599. But after destruction of 3 actinide inventories in the blanket, the energy multiplication factor maintains at about 8.6, when k-eff is still kept at a moderate level of 0.5605.

Tritium breeding ratio is again maintained during the burn-up at a level more than adequate for self-sustaining. It is achieved also by adjusting the lithium-6 content in lithium. The Li-6 content in lithium is also shown in Table 2 at several burn-up stages. It is noted that during all stage of burn-up to reach concentration equilibrium, the Li-6 content is almost constant, as a result of leveling k-eff during the transitioning burn-up.

III.C. Comparison of Hard and Soft-spectrum Transmutation Blankets

Due to the presence of an external beryllium in the first transmutation zone, the soft-spectrum blanket not only produces a neutron spectrum with significant fraction of neutron population in the low energy range, it also generates a higher flux level due to neutron multiplication in the enhanced k-eff performance and by the threshold (n,2n) reactions in beryllium. The resulting neutron flux in the first transmutation zone is shown in Fig. 5, and compared to that from the hard-spectrum blanket without an external beryllium component.

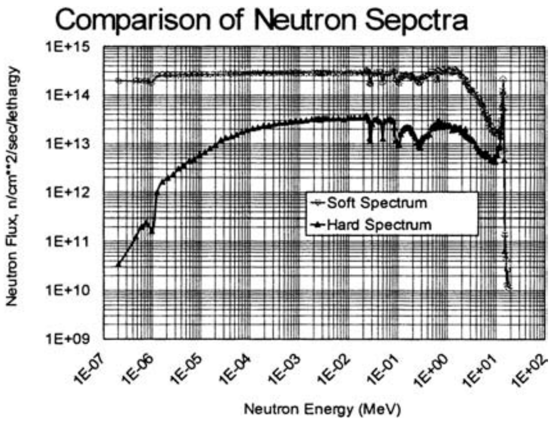

Fig.5. Comparison of neutron spectra of the hard and soft-spectrum SFA burning blanket. The first wall neutron loading is normalized to 1 MW/m^2.

The performance characteristics of these two blankets can be further divided into two categories. One category contains characteristics with common features. The other presents characteristics with opposite features. They are analyzed and discussed as follows.

III.C.1. Common Features

The common characteristics are obtainable by design for both blankets. These include:

- Sub-critical condition
- Adequate tritium breeding
- Steady-state (Equilibrium):

k-eff ~ 0.56-0.6 (highly sub-critical)

Energy multiplication factor, M ~ 9 - 13

III.C.2. opposite Features

Table 3 summarizes the opposite characteristics of the two blankets with different neutron spectra. Note that the soft-spectrum blankets have two unique features. One is that the higher initial energy multiplication factor can be favored for a fusion device that initially produces only low power such as starting an experimental program to produce fusion power. The other is that the actinide inventory is significantly lower than the hard-spectrum blankets.

Table 3. Opposite Characteristics in Soft- and Hard - spectrum Transmutation Blankets.

Parameter	Hard-Spectrum Blanket	Soft-Spectrum Blanket
Power Transition to Reach Equilibrium	Stable: ~ 20% (M: 10.5 – 8.6)	High: >10 (M: 180 – 13)
Equilibrium Actinides	70%Pu + 30%M.A.	50%Pu + 50%M.A.
Proliferation Resistance	46% Pu39+41 in Pu (Pu39+41 + M.A. = 62%)	30% Pu39+41 in Pu (Pu39+41 + M.A. = 65%)
Actinide Inventory (relative)	4	1 *Low actinide inventory

The advantage of the hard-spectrum blankets, however, is that the power swing is more stable during the transitioning burn-up. This fits well with a fusion device that operates at a constant power level. The hard-spectrum blankets accumulate less higher actinides in the actinides than the soft-spectrum blankets. This could be turned into an advantage if additional studies find that handling higher actinides may cause significant difficulties in reprocessing of actinides in the molten salt.

IV. U238 BURNING POWER PLANTS

The concentration of all actinides dissolved in the molten salt is 31 mg/cc of molten salt. It is determined by assuming a moderate performance at the beginning of the power plant operation when the starting fuel is weapons-grade plutonium. Using U238 as the starting fuel, although plausible when an external neutron multiplier is provided in the blanket, would make the power plant stay at low power output at an extensive operating time until Pu239 builds up.

Figures 6, 7, and Table 4, as those displayed for the spent fuel burning power plants, summarize results of the investigative calculations, except that the burn-up stage is only up to the burning of one actinide inventory.

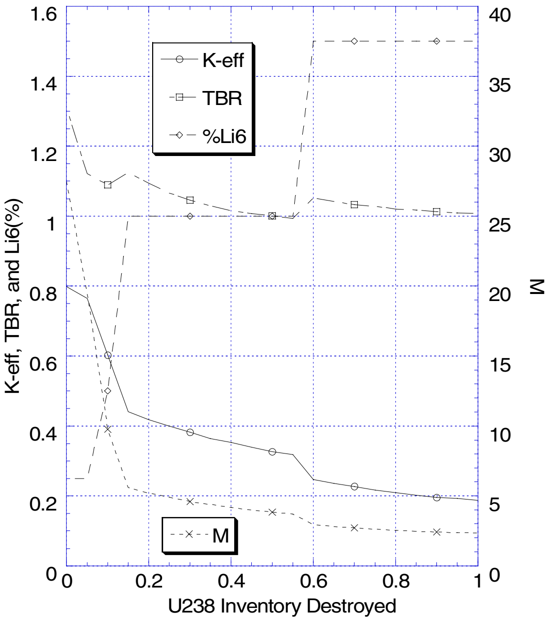

Fig.6. Performance parameters of a hard-spectrum U238 burning blanket as a function of U238 inventory destroyed.

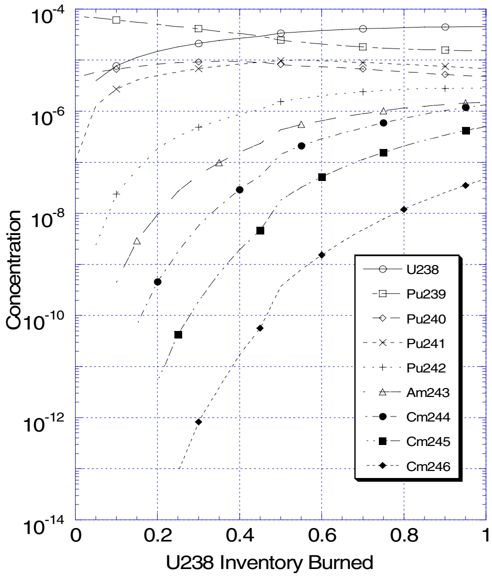

Fig.7. Evolution of actinide concentrations in the hard-spectrum U238 burning blankets.

As shown in Fig. 6 and Table 4, the U238 burning fusion plant has much lower performance than in a spent fuel burning plant, because the replenishing material does not have a fissile component. At the burning stage destroying one actinide inventory, the blanket energy multiplication factor is 2.3, which is more than a factor of 10 decrease from the initial operating power level.

Future studies should be attempted with a soft-spectrum blanket that contains a beryllium neutron multiplier. Such a blanket would enhance the nuclear performance and thus may provide a better chance for U238 burning to become attractive in power generation.

Table 4. Actinide concentrations at several burn-up stages for a U238 burning hard-spectrum Flibe blanket (Total to in-blanket molten salt inventory ratio = 2).

Parameter	Burn-up Stages (MW-y/m^2)				
	0.0	0.41	0.91	14.1	35.8
U238 Inventory Destroyed	0	0.1	0.15	0.6	1
%Li6	0.25	0.5	1.0	1.5	1.5
k-eff	0.7987	0.6022	0.4411	0.2469	0.1870
TBR	1.31	1.09	1.12	1.05	1.01
M	27.5	9.8	5.6	2.9	2.3
Total U	0%	14.5%	18.9%	48.2%	58.1%
Total Pu	99.7%	85.5%	81.1%	50.6%	37.6%
Pu39+41/Pu	94.2%	88.7%	86.6%	76.5%	74.5%
Total Am	0%	0.0037%	0.12%	0.83%	1.93%
Total Cm	0%	0.00008%	0.00059%	0.43%	2.40%

V. CONCLUSIONS

Destruction of spent fuel actinides in a molten salt cooled fusion power plant appears to be promising. Adequate tritium breeding, sub-critical condition, and stable power output, can generally be obtained by design. The energy multiplication factor due to actinide burning is about 9-13 at equilibrium of the actinide composition.

Burning U238 in a fusion power plant, generally produces a lower energy multiplication than destroying the spent fuel actinides. It is due to the absence of fissile content in U238 compared to the spent fuel actinides.

ACKNOWLEDGMENTS

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