FUSION SOLUTION TO DISPOSE OF SPENT NUCLEAR FUEL, TRANSURANIC ELEMENTS, AND HIGHLY ENRICHED URANIUM

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Abstract

The disposal of the nuclear spent fuel, the transuranic elements, and the highly enriched uranium represents a major problem under investigation by the international scientific community to identify the most promising solutions. The investigation of this paper focused on achieving the top rated solution for the problem, the elimination goal, which requires complete elimination for the transuranic elements or the highly enriched uranium, and the long-lived fission products. To achieve this goal, fusion blankets with liquid carrier, molten salts or liquid metal eutectics, for the transuranic elements and the uranium isotopes are utilized. The generated energy from the fusion blankets is used to provide revenue for the system. The long-lived fission products are fabricated into fission product targets for transmutation utilizing the neutron leakage from the fusion blankets. This paper investigated the fusion blanket designs for small fusion devices and the system requirements for such application. The results show that 334 MW of fusion power from D-T plasma for thirty years with an availability factor of 0.75 can dispose of the 70,000 tons of the US inventory of spent nuclear fuel generated up to the year 2015. In addition, this fusion solution eliminates the need for a geological repository site, which is a major advantage. Meanwhile, such utilization of the fusion power will provide an excellent opportunity to develop fusion energy for the future.

1. Introduction

Fusion can provide a complete and attractive solution for the national and the international disposition problems of the spent nuclear fuel, the transuranic elements, and the highly enriched uranium. In addition, the fusion technical requirements for these functions are very modest, and the current nuclear technologies are adequate. This will provide an excellent opportunity to develop fusion as an energy source for the future while providing a near term solution for these problems. For example, in the United States, the inventory of the spent nuclear fuel will reach 70,000 tons by the year of 2015. In this spent nuclear fuel, a small fraction of the uranium fuel is utilized for energy production, producing fission products and transuranic elements. This inventory

of spent nuclear fuel consists of about 67,000 tons of uranium, 600 tons of transuranic elements, and 2400 tons of fission products. Most of the fission products have relatively short half-lives, tens of years. To dispose the spent nuclear fuel, uranium, fission products, long lived fission products (Tc^{99} , I^{129} , etc.), and transuranic elements are separated. Uranium can be recycled in fresh fuel or disposed as low-level radioactive waste (Class-C waste). The fission products will be processed for disposal in a temporary repository to decay. The long-lived fission products will be fabricated into fission product targets for transmutation utilizing the neutron leakage from the fusion blanket to the shields. The transuranic elements will be fissioned in fusion blankets and the generated energy is used to generate revenue for the system. Also, fusion option can be used to dispose of the current

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inventory of the transuranic elements and the highly enriched uranium by utilizing its energy content and transmuting its long lived fission products, which represents a complete and attractive solution for this problem.

The main objectives of this investigation are to introduce the fusion solution and to size the required fusion system for solving the US spent fuel problem as an example for such application. In this solution the transuranic elements and the long-lived fission products are eliminated, the radioactive waste volume is minimized, the generated energy from the transuranic elements is used for generating revenue for the system, and the need for a geological repository is eliminated. D-T fusion neutrons are used for achieving these goals with minimum fusion power.

2. Molten Salt Blanket Concept

The self-cooled molten salt blanket concept is considered as an example to quantify the performance of the fusion solution and the results are used to size the required fusion system to achieve the elimination goal for solving the US spent fuel problem. Flibe molten salt (Li_2BeF_4) was developed and used for the Molten Salt Breeder Reactor (MSBR) [1 and 2]. Molten salt technologies were developed for MSBR in the 1960's, for the fuel cycle of the fast breeder program in the 1990's, and for decommissioning the molten fuel salt of the MSBR in the 1990's. Flibe characterization included the physical properties, the corrosion issue, the chemical processing, and the solubility of the fuel compounds and the fission products in the salt [2 and 3]. UF_4 , ThF_4 , and PuF_3 are the fuel compounds selected for the MSBR. For the disposal of transuranic elements, PuF_3 is the material of interest. PuF_3 is a solid with a density of 9.32 g/cm^3 and it has a melting point of 1425°C . The solubility of PuF_3 in Flibe was measured [3] for composition ranging in BeF_2 from 28.7 to 48.3 mole in the temperature range of 450 to 650°C .

A poloidal blanket configuration is considered where the inlet and the outlet manifolds are located at the top section of the reactor. The salt coolant is

first introduced to the front section of the blanket to remove the surface heat flux from first wall. Then, the flow direction changes at the bottom of the reactor to leave the blanket module at the top. This flow pattern simplifies the reactor manifold system.

At the start, it is foreseen to operate the blanket without transuranic elements to confirm and calibrate the operation of the different systems. This mode of operation reduces the shielding capability of the blanket due to the absence of the neutron absorbers, the transuranic elements. Therefore, the blanket radial thickness was first defined with pure Flibe as a function of the blanket radial thickness, where the Flibe zone thickness was varied from 0.2 to 0.6 m. The results show that a 0.5-m Flibe zone thickness is required to reduce the energy deposition in the shield to $\sim 4\%$ of the total energy deposition. At this blanket thickness, all the shielding performance parameters are quite satisfactory.

The second step defined the blanket performance with PuF_3 dissolved in the Flibe. The PuF_3 weight fraction varied parametrically in the range of 0.0025 to 0.0275, which is consistent with the experimental results. The results show that the blanket performance parameters change monotonically in this range. The first two blankets of Table 1 give the main blanket performance parameters for the extreme values of the range. As the PuF_3 concentration in the Flibe salt increases, all the blanket performance parameters improve. At the highest PuF_3 concentration, the plutonium transmutation rate is 4.4 kg/MW.y of fusion power. The corresponding tritium-breeding ratio and the blanket energy multiplication factor are 2.2 and 15.3, respectively. This high tritium-breeding ratio indicates that the lithium-6 concentration can be reduced to increase the plutonium transmutation rate and to reduce the tritium-breeding ratio.

The blanket performance analyzed parametrically as function of the lithium-6 concentration in the range of 2.5 to 7.5 (natural) % with constant PuF_3 concentration. As the lithium-6 concentration decreases, the blanket performance parameters improve monotonically. The plutonium transmutation rate changes from 3.4 to 48 kg/MW.y as the lithium-6 concentration varies

from 7.5% (natural lithium) to 2.5%. However, the local tritium-breeding ratio is very high, it has a value of 10.8 for the 2.5% lithium-6 concentration as shown in Table 1. This suggests that the 2.5% lithium-6 concentration is high and it can be reduced further allowing more neutrons for transmuting plutonium. Also, the PuF_3 concentration can be reduced for the same transmutation rate, which enhances the safety characteristics of the system. The blanket energy multiplication factor reaches 160, which provides good revenue to recover the transmutation cost. Then the blanket configuration analyzed with 100% lithium-7 and the PuF_3 weight fraction in the flibe iterated to get K_{eff} of 0.98 for sub-critical operation. Table 1 gives the performance parameters for such blanket configuration. The plutonium transmutation rate is 72.6 kg/MW.y of fusion power, which is quite satisfactory. The blanket energy multiplication and the energy fraction in the shield are 242.6 and 0.018. However, the tritium-breeding ratio of this blanket is 0.488, which is not adequate for tritium self-sufficiency. Therefore, a very small concentration of lithium-6 needs to be used for a small operating period to accumulate enough tritium for self-sufficiency. Therefore, a lithium-6 concentration of 0.25 % is utilized and the PuF_3 concentration adjusted to get K_{eff} of 0.98. The resulting performance parameters are given in Table 1, which are quite satisfactory. The analyses show that lithium-6 act as a burnable absorber. As its concentration increases, the required concentration of PuF_3 is increased to maintain the same K_{eff} value. The lithium-6 concentration decreases as the reactor operates as well as the PuF_3 concentration. The tritium-breeding ratio with low lithium-6 concentration is very high, which allows the reactor to operate without lithium-6 for extended periods. Since the accumulated tritium will be adequate to insure tritium self-sufficiency. It is possible to use a lower value and consequently a lower PuF_3 concentration. A system analysis is required to define the optimum lithium-6 and PuF_3 concentrations taken into consideration economic, safety, and material issues.

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3. Fusion power requirements for disposing of the US inventory of the spent nuclear fuel

The total amount of transuranic elements in the US inventory of the spent nuclear fuel will reach 600 tons by the year 2015. A molten salt fusion blanket with k_{eff} of 0.98 can transmute ~79.7 kg of transuranic elements per MW.y of fusion power as shown in Table 1. To transmute the total US inventory, a fusion fluence of 7528 MW.y is required. A 334-MW of fusion power can provide such fluence over 30 years assuming an availability factor of 0.75. However, the thermal output from the blanket is too large for a single unit. For example, five fusion reactors with 33.5 MW of fusion power each can perform such function. The thermal power from each reactor is 7258 MW, which generates a gross electrical power of ~2468 MW. Such fusion reactors can be constructed based on the current technology with driven plasma, which provides near term solution for the spent nuclear fuel disposition and an opportunity to develop fusion energy.

In addition, the analysis of the molten salt blanket shows that the transmutation rate and the blanket thermal output can be adjusted over a wide range, which provides a large flexibility to choose the reactor parameters including the fusion power level. Such flexibility is important for the long-term development of fusion reactors. For example, a larger fusion power can be used if it is required for the development of the plasma physics or the reactor technology where the concentration of the lithium-6 and the transuranic elements can be adjusted to achieve the target values of thermal output, transmutation rate, and tritium breeding ratio. Also, the number of the long-lived fission product targets inserted in the fusion reactor for transmutation can be adjusted to regulate the thermal output as required.

4. Conclusions

Fusion blankets with liquid carrier for the transuranic elements and the uranium isotopes achieve the elimination goal, which is the top rated solution for the disposition of the spent nuclear

fuel, the transuranic elements, and the highly enriched uranium. This type of blankets reaches a transmutation rate up to 80 kg/MW.y of fusion power. The energy from the transmutation process is utilized to produce revenue for the system. For the disposition of the spent nuclear fuel, the fusion solution eliminates the need for a geological repository, which is a major advantage. Flibe molten salt and lithium-lead eutectic are identified as the most promising liquids for this application where both materials are under development for future fusion blanket concepts.

Meanwhile, this application will provide an excellent opportunity to develop the fusion energy for the future by building small fusion devices. A 334-MW of fusion power for thirty years with an availability factor of 0.75 can transmute all the transuranic elements and the long-lived fission products in the 70,000 tons of the US inventory of spent nuclear fuel generated up to the year 2015. These devices will have an operating flexibility, which can be achieved by adjusting the blanket parameters to maintain an acceptable thermal output for generating revenue. The small fusion power and the operating flexibility will provide a mechanism to develop the fusion energy for the future.

Further analyses and studies are needed to develop such system considering previous work including non-fusion options. Definition of the different system components, identification of the technical issues that require resolution, schedule and plan to resolve these issues, total cost estimate of the system, and comparison with the other options

under consideration need to be included in these studies. Blanket concept development requires special attention since its performance has a major impact on the whole system. These developments can utilize the existing technologies to minimize the R&D cost and the schedule to complete the disposition process.

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Table 1. Flibe blanket performance parameters with different plutonium weight fractions and lithium-6 enrichments.

PuF ₃ weight fraction	0.0025	0.0275	0.024	0.024	0.00051	0.0056
Lithium-6 enrichment	Natural	Natural	2.5	Natural	0.0	0.25
Blanket energy multiplication factor	1.765	15.052	157.2	1.98	242.6	264.0
Total energy multiplication factor	1.819	15.262	160.0	12.15	251.5	270.9
Local tritium breeding ratio	1.214	2.180	9.469	1.956	0.488	10.740
Shield energy fraction	0.030	0.014	0.018	0.014	0.0352	0.0252
Fission reactions per D-T neutron	0.049	0.986	10.78	0.770	16.301	17.902
Pu transmutation rate, kg/MW.y	0.219	4.390	47.98	3.428	72.560	79.689
K _{eff}	0.125	0.741	0.969	0.691	0.979	0.981