ENERGY MULTIPLICATION BY UTILIZING URANIUM AND THORIUM IN APEX HYBRID REACTOR MODEL

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ABSTRACT

The first wall facing with the plasma will be exposed to high energy neutron, gamma ray and charged particle fluxes that originate from the plasma of fusion reactor. In case this first wall is structural material (solid), the highest damage will occur at this region and the lifetime of the wall will be limited with a few years. In the Advanced Power Extraction (APEX) study, however, the first solid wall facing with the plasma is replaced with fast flowing thin liquid wall the first liquid wall flows very fast and detains charged particles, and followed by the thick liquid wall (blanket) which flows slowly and absorbs generated energy and converts it to heat. This approach has a challenging potential to enhance the vision of fusion by extending the life of the structural material to that of the reactor.

In a pure fusion reactor, the 14.1 MeV fusion neutrons are not utilized at their full potential. On the other hand, the hybrid (fusion + fission) solutions try to use the 14.1 MeV neutrons to produce extra neutrons. The best neutron multipliers in this respect seem to be beryllium and uranium-238. These extra neutrons can be used to increase the power produced by fission in the blanket beside tritium production. In the study, the flowing molten salt (i.e., first wall and blanket) composed of Flibe (Li₂BeF₄) was considered as the main constituent mixed with different mole fractions (0-12%) of heavy metal salt (ThF₄ or UF₄) to increase the energy multiplication. Self sufficient Tritium Breeding Ratio (>1,05) has been taken into account to determine the upper limit of the fraction of heavy metal salt in the mixture. Design and calculations of APEX were carried out as 3-D torus by using MCNP-4B computer code. Plasma was designed as neutron source that the inner surface of first liquid wall exposed to neutrons homogeneously and the calculations were conducted with the fusion neutron spectrum of D-T reaction.

The results showed that by using 12% natural uranium in the molten salt mixture the generated energy in the hybrid reactor increased about 35% in comparison with the pure fusion reactor. It was also seen that natural uranium has much better energy multiplication affect comparing to thorium.

1. INTRODUCTION

In a commercially available fission reactor, only a few percent of Uranium is utilized for energy generation. More than 97% of Uranium fuel is removed from the reactor as spent fuel. Hence Uranium is not utilized at its full potential by fission reactors. The situation for Thorium is worsen than Uranium; despite there has been interest in utilizing Thorium as a nuclear fuel over the last 30 years, it hasn’t been utilized yet.

The 2005 IAEA-NEA “Red Book” gives a figure of 4.5 million tones of Thorium reserves and additional resources, but points but that this exclude data from much of the world [1]. Thorium, like Uranium-238 is fertile. Thorium (Th-232) absorbs a neutron to produce Uranium-233, which is fissile. These fertile materials can also make fission with high energy neutrons.

The hybrid reactor has a good potential to utilize uranium and thorium in the future. The term hybrid reactor refers to nuclear reactors which are driven by a fusion neutron source and include fertile or fissile material. The general idea of a hybrid reactor is to have fusion component to provide a source of high energy fusion neutrons which are to interact with a sub-critical fissile component located adjacent to plasma. The main products of hybrid reactors are fissile fuel and/or energy.[2]

2. APEX FUSION REACTOR MODEL

The primary objective of Advanced Power Extraction (APEX) study is to explore innovative concepts for fusion power technology that can tremendously enhance the potential of fusion as an attractive and competitive energy source. [3]
One of the promising ideas for new innovative concepts emerged from the APEX study seeks to totally eliminate the solid first wall. This most promising idea is a flowing liquid wall concept. The concept varies from “liquid first wall”, where a thin layer (<2 cm) of liquid is flown on the plasma-side of the first wall, to “thick liquid wall”, where an all-flowing thick (>40 cm) liquid serves as liquid wall/liquid blanket. Liquid walls offer many potential advantages that represent an excellent opportunity to substantially enhance the attractiveness of fusion energy systems.

The replacement of the first wall with a flowing liquid offers the potential advantages of high power density, high reliability and availability (due to simplicity and low failure rates), reduced volumes of radioactive waste, and increased structure lifetime.

### 3. TRITIUM BREEDING AND ENERGY MULTIPLICATION

Tritium breeding ratio, TBR, is defined as the ratio of the rate of tritium production in the system to the rate of tritium burned in plasma. In order to provide adequate tritium breeding, the flowing liquid must be a lithium containing medium. The tritium production reactions are as follows:

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\begin{align*}
^6\text{Li} + ^{1}\text{n} & \rightarrow ^3\text{H} + ^4\text{He} + Q (4,784 \text{ MeV}) \\
^7\text{Li} + ^{1}\text{n} & \rightarrow ^3\text{H} + ^4\text{He} + ^1\text{n} + Q (-2,467 \text{ MeV})
\end{align*}
\]

Then the only practical liquids for first wall and blanket are lithium, lead-lithium, Flibe, and Sn-Li. Flowing liquid metals may require the use of electrical insulators to overcome the MHD drag, while for Flibe free surface flows, MHD (Magnetohydrodynamics) effects caused by the interaction with the mean flow are less significant.

In case Flibe, TBR is maximum with natural lithium-6 enrichment and it is reduced with Li-6 enrichment. Hence, Flibe has advantage of utilizing lithium without enrichment.

The Energy Multiplication Factor (M) is defined as the ratio of the total energy deposited in the system to the incident neutron energy. About 80% of fusion energy, 14.1 MeV, is carried with neutron that penetrates the first wall and blanket and dissipates its energy through exothermic nuclear reactions. The presence of Uranium or Thorium in the in the liquid first wall and blanket on the other hand, provides additional energy generation through fission reactions with fusion neutrons.

### 4. DESIGN FOR APEX BY MCNP-4 CODE

The complexity in the nature of the industrial problems unfortunately makes analytical solution impossible. The nature of problems becomes complicated and the number of integrated systems increases very fast with the technological developments.

On contrary to the analytical approaches, simulation models are more successful in modeling and solution of complicated problems. It is easier to follow the interactions between the variables in simulation designs. But, it requires too much computer usage. It is aimed to get numerical results by applying the data collected from

![Figure 1. Schematic Presentation of APEX Model.](image_url)
the reactor system to the model developed on the computer. By evaluating and interpreting the results, some estimates are done for system performance criterions. By using simulation models the worst condition scenarios can also be investigated. [4]

Calling the simulation technique as Monte-Carlo technique was done by Von Neumann and Ulam, and first applications was carried out in neutron diffusion problems. Monte-Carlo technique is randomly number selection technique from one or more probabilistic distribution in a special trial or simulation study. The method was then adopted easily for solution of much more complicated and non-statistical problems such as integrodifferential evaluation problems. Some authors suggested classification of the method for using only for sampling works of variance reduction techniques. However, the usage of the method nowadays is generally in selection of values randomly from the probabilistic distributions. [5]

APEX fusion reactor used in the study was designed by using MCNP-4 computer code, using Monte-Carlo technique, as 3-D torus (14)(15)(16). The dimensions for the APEX reactor has been taken from the ARIES-RS reactor design which was made in the framework of APEX studies. In this model, the radius of torus is 552 cm and minor radius starting from inner surface of first wall is 143 cm. The height of torus starting from center of first wall is 250 cm. The radius and thicknesses in one dimension are shown in detail in Figure 2. [6]

![Figure 2. One Dimensional APEX Model](image)

5. RESULTS

Cross-sectional view of APEX designed by using MCNP-4B computer code is shown in Figure 3. The inner region is consisting of plasma and vacuum. Following this, first liquid wall, blanket, ferritic steel, shield, stainless steel and ferritic steel zone take place.
Following modeling, plasma was designed as neutron source that the inner surface of first liquid wall exposed to neutrons homogeneously and the calculations were conducted with the fusion neutron spectrum shown in Figure 4.

The effect of Uranium and Thorium on energy multiplication was investigated by using APEX model. The molten salt ThF$_4$ and UF$_4$ were separately added to the first liquid wall and blanket up to 12%.

The total tritium production amount per source neutron (TBR) in first liquid wall, blanket and shield zones was calculated with respect to percentage of heavy metal content in the mixture. Considering Thorium, up to 9% ThF$_4$ content in the mixture, TBR meets the requirement of TBR > 1.05 which is necessary for self sufficient fusion reactor. On the other hand for Uranium, TBR requirement are met even at 12% UF$_4$ content.

The results showed that by using 12% of natural Uranium in the molten salt mixture, the generated energy in the hybrid reactor is increased about 35% in comparison with the pure fusion reactor. Energy multiplication increases with heavy metal salt content. The rate of increase for UF$_4$ is much higher comparing that of ThF$_4$. 

![Figure 3. Cross-Sectional View of APEX Fusion Reactor Model Designed in MCNP-4B](image)

![Figure 4. Neutron Spectrum Used In The Calculations](image)
Figure 5. The variation of TBR values versus the heavy metal fraction in the liquid medium

Figure 6. Total fission amount versus the heavy metal fraction in the liquid medium
6. REFERENCES


