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1. The use of MCNP code in APEX fusion reactor technology

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Abstract. In this study, new APEX hybrid model was developed by the way of using the APEX fusion technology. The superiority of the APEX fusion technology from the other fusion technologies is that a fluid wall was used in reactor, which flows instead the first solid wall. The advantage of this fluid wall is to extend the life the structural material of the reactor by reducing the rate of damage on the structrual material.It also allows high neutron wall loads.The meausures for the APEX hybrid model has been taken from the ARIE-RS reactor design which was made in the framework of studies.In the APEX studies, the conventional first solid wall facing with the plasma is replaced with fast flowing thin liquid wall layer. Free-surface first liquid wall concept is a revolutionary concept. 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. In the study, the flowing molten salt (first wall and blanket) composed of Flibe (Li_2BeF_4) was considered as the main constituent mixed with different mole fractions (0-12%) of heavy metal salt ThF_4 to increase the energy multiplication. Self sufficient Tritium Breeding Ratio (TBR>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.

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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 worse than uranium; despite there has been interest in utilizing thorium as a nuclear fuel over the last 30 year. The 2009 IAEA-NEA "Red Book" gives a figure of 4.5 million tones of thorium reserves and additional resources, but points that this excludes 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 Fusion 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 fission component located adjacent to plasma. The main products of hybrid reactors are fissile fuel and/or energy. 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.

First wall in APEX fusion technology

The primary objective of APEX is to identify and explore novel, possibly revolutionary, concepts for the Chamber Technology that can substantially improve the attractiveness of fusion energy systems. The primary objective of APEX is to identify and explore novel, possibly revolutionary, concepts for the Chamber Technology that can substantially improve the attractiveness of fusion energy systems.

A number of promising ideas for new innovative concepts have already emerged from the first phase of the APEX study [2-5]. While these ideas need extensive research before they can be formulated into mature design concepts, some of them offer great promise for fundamental improvements in the vision for an attractive fusion energy system. These ideas fall into two categories. The first category seeks to totally eliminate the solid "bare" first wall. The most promising idea in this category is a flowing liquid wall concept. The liquid wall idea is "concept rich". These concepts vary 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 thick 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. All these advantages make the thick liquid wall approach a strong candidate in the APEX study. The second category of ideas focuses on extending the capabilities, particularly the power density and temperature limits, of solid first walls. A promising example is the use of high temperature refractory alloys (e.g. tungsten) in the first wall together with an innovative heat transfer and heat transport scheme based on vaporization of lithium.

APEX fusion reactor model

The liquid wall idea evolved during the APEX study into a number of concepts that have some common features but also have widely different issues and merits. These concepts can be classified, as shown in Table -1, according to: thickness of the liquid, type of liquid used, and the type of restraining force used to control the liquid flow [6,17,18]. 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.

Table 1. APEX liquid wall alternatives [2].

Thickness	• Thin (~2 cm) • Moderately Thick (~15 cm) • Thick (>40 cm)
Working Liquid	• Lithium • Sn-Li • Flibe
Hydrodynamic Driving / Restraining Force	• Gravity – Momentum Driven (GMD) • GMD with Swirl Flow • Electromagnetically Restrained • Magnetic Propulsion
Liquid Structure	• Single, contiguous, stream • Two streams (fast flowing thin layer on the plasma side and slowly flowing bulk stream)

One of the promising idea 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 reduced volumes of radioactive waste, and increased structure lifetime

APEX/ARIES-RS modifications

In the APEX study and adapt the GMD (gravity momentum driven) geometry concept, several changes were required to the baseline ARIES-RS design. The ARIES-RS consists of high temperature shield following first wall in the inner blanket where breeding blanket does not exist. The outher blanket has an advanced "dual cooled " breeding blanket with flowing lityum and He-cooled ferritic steel structures [8, 9,14]. First the density was approximately doubled to obtain the correct surface heat flux and neutron wall load specified by APEX design goals. A list of the ARIES-RS Parameters and APEX modifications are listed in Table 2. The majority of the work reported here was carried out for the tokamak. Specifically, the ARIES-RS geometry was utilized whenever possible, with modifications for the unique structures and high flow rates required for CLIFF (Convective Liquid Flow First Wall). This means, however, that the ARIES-RS fusion power needs to be scaled-up 4500 MW to give the 10 MW/m^2 peak neutron wall load and 2MW/m^2 peak surface heat flux goals of the APEX study. Tokamak present a difficult challenge for liquid walls due to the fact that the plasma chamber is relatively closed with short scrape-off lengths, and so, vaporized liquid wall material must be screened by the edge plasma to keep it from penetrating to the core.

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;

$$^{6}Li + {}^{1}n \rightarrow {}^{3}H + {}^{4}He + Q \;\; (4{,}784 \text{ MeV})$$

$$^{7}Li + {}^{1}n \rightarrow {}^{3}H + {}^{4}He + {}^{1}n + Q \;\; (-2{,}467 \text{ MeV})$$

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 (Magneto hydrodynamics) 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.

Table 2. ARIES-RS parameters and APEX modifications [2].

Structural Modification	**ARIES-RS Reactor**	**APEX reactor**
Major radius(m)	5,52	5,52
Minor radius(m)	1,38	1,38
Plasma aspect ratio	4	4
Number of sectors	16	16
Fusion Power(MW)	2171	~4000
Neutron Power(MW)	1736	~3400
Alpha Power(MW)	433	~600
Fusion Power density(MW/m^3)	6,38	~12
Average neutron load (MW/m^3)	4,03	7
Peak neutron load(MW/m^2)	5,67	10
Average FW surface heat flux(MW/m^2)	0,4	1,5
Peak FW surface heat flux(MW/m^2)	0,47	2

Design for APEX by MCNP-4 code

MCNP is a general-purpose Monte Carlo n-particle code that can be used for neutron, photon, electron or coupled neutron/photon/electron transport, which is developed by Los Alamos National Laboratory nowadays, the complexity in the nature of the industrial problems unfortunately, makes analytical solution impossible. On contrary to the analytical approaches, simulation models are more successful in modeling and solution of complicated problems [6, 11, 12]. Monte Carlo technique is randomly number selection technique from one or more probabilistic distribution in a special trial or simulation study. 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 is 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 the reel 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. 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 Integra -differential evaluation problems [6, 12]. 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. APEX fusion reactor used in the study was designed by using MCNP-4 computer code, using Monte-Carlo technique, as 3-D torus. 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 1. APEX fusion reactor used in the study was designed by using mcnp-4 computer code, using Monte Carlo technique, as in three dimensional torus the dimensional 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 major 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. A radius and thicknesses in one dimensionally are shown detail in figure 1 in APEX model; temperature values at various points for Flibe liquid flow are given as ^{o}C (degrees centigrade). According to this when the entrance degree of the liquid to the system is 500 ^{o}C, the surface temperature at the exit is around 600 ^{o}C [2]. in the apex studies liquid walls concept, although containing many common aspects, the variability related to the liquid used, liquid thickness and the methods utilized to control the liquid flow have been shown at table. A hybrid reactor is based on either magnetic fusion energy (MFE) or inertial fusion energy (IFE) the neutron source is volumetric in magnetic fusion energy systems, whereas the target represents a point neutron source in plants. The (D, T) fusion neutron driver of MFE for hybrid reactor has been evaluated for $10 MW/m^2$. Hence, this corresponds to the fusion neutron flux of 10^{14} (14.1 MeV) $n/cm^2 \cdot s$ at FW for conventional (D, T) driven hybrid reactor.

Numerical calculations

Cross-sectional view of APEX designed by using MCNP-4B computer code is shown in Figure 2. 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. One of the main neutronic parameters for a fusion or hybrid reactor is the energy multiplication factor (*M*). Fusion neutron energy can be amplified in the blanket by the fissions of ^{233}U and ^{232}Th mainly. Exothermic and endothermic neutron capture reactions by ^{6}Li and ^{7}Li, respectively, also affect the *M* values. These reactions are given as follows:

$$^{6}\mathbf{Li} + n \rightarrow \alpha + T + 4.784\ \mathrm{MeV}$$

$$^{7}\mathbf{Li} + n \rightarrow \alpha + T + n - 2.467\ \mathrm{MeV}$$

M can simply be defined as below:

$$M = \frac{200 * < \Phi \bullet \Sigma_f > + 4.784 * T_6 - 2.467 * T_7 + 14.1}{17.6}$$

where d*E* d*V* is total integral fission rate, $T_6 = \iint \Phi \bullet \Sigma_{(n,\alpha)T}$ d*E* d*V* on ^{6}Li and $T_7 = \iint \Phi \bullet \Sigma_{(n,n'\alpha)T}$ d*E* d*V* on ^{7}Li represent the integral fission rate per D-T fusion neutron. One can observe that the addition of ^{233}U to the salt improves the fission rate significantly, as expected, since ^{233}U, having much higher fission cross sections, is very effective to enhance fission reactions compared to ^{232}Th.

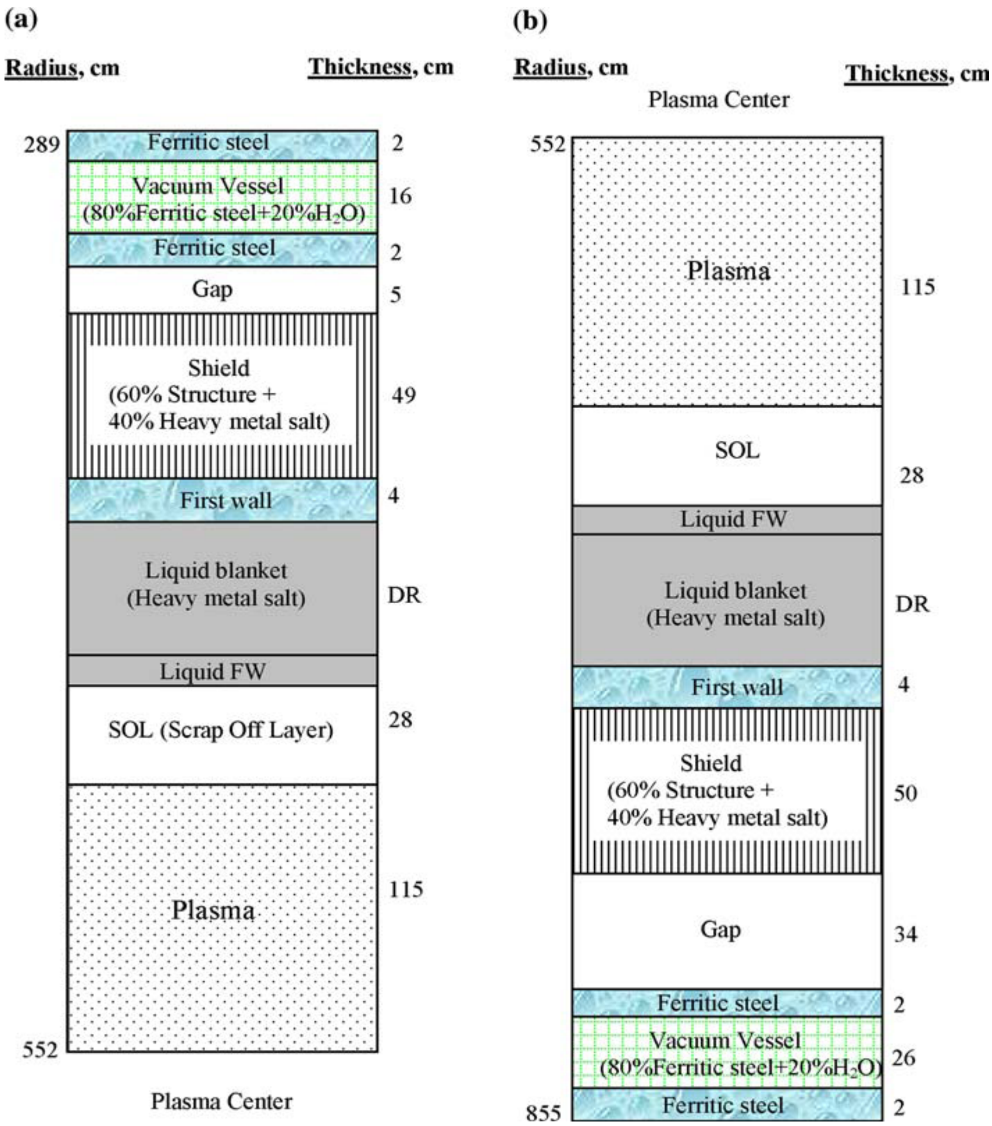

Figure 1. One-dimensional APEX model (a) inboard, (b) outboard [2].

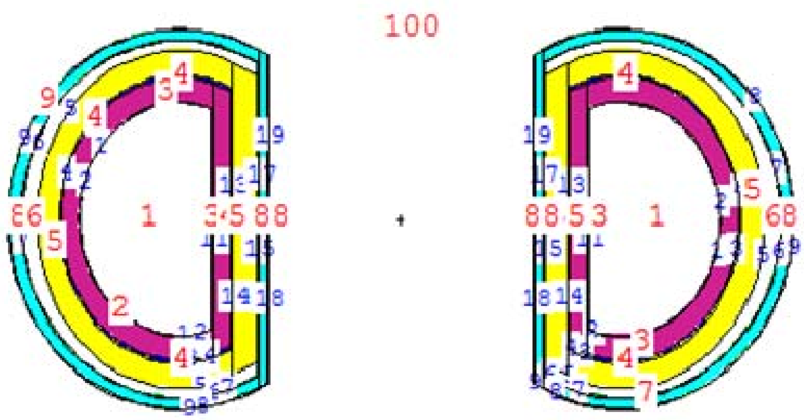

Figure 2. Cross-sectional view of APEX fusion reactor model designed in MCNP-4B [6].

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 are necessary for self sufficient fusion reactor. On the other hand for Uranium, TBR requirement are met even at 12% UF_4 content [14, 15, 17]. 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.

Tritium breeding

There are only two candidate liquids that might meet all the criteria, especially that of being able to breed enough tritium: Li, Flibe (Li_2BeF_4)[2,3,5]. A commercial fusion reactor must have a tritium breeding ratio of (TBR>1.05) self sustaining. Fig 3 shows the variation of TBR with the heavy metal content in mole % in the flowing liquid. As expected, the TBR decreases with increased heavy metal content. Tritium self sufficiency has been maintained in the range of molten salt mixtures. The tritium production reactions are as follows

$$^{6}Li + {}^{1}n \rightarrow {}^{3}H + {}^{4}He + \quad (4{,}784\ MeV)$$

$$^{7}Li + {}^{1}n \rightarrow {}^{3}H + {}^{4}He + {}^{1}n \quad (-2{,}467\ MeV)$$

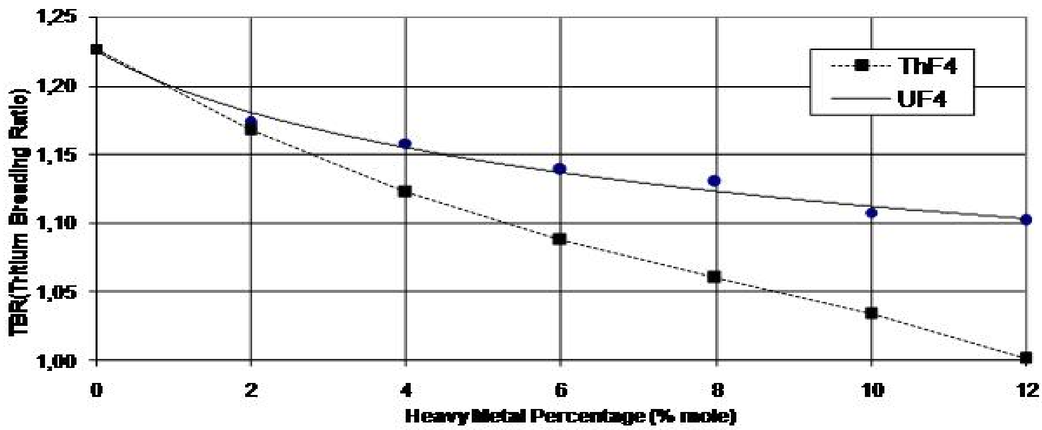

Figure 3. The variation of TBR values versus the heavy metal fraction in the liquid medium.

The effect of Uranium and Thorium was investigated by using the 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 a 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

The Energy Multiplication Factor (M) is defined as the ratio of the total energy deposited in the system to the incident neutron energy. A Pure fusion reactor of APEX design using Flibe as a liquid wall has a fusion power of 4000 MW a blanket energy multiplication of M=1.72 and produces ~4880 MW total power. The change in energy multiplication with respect to heavy metal content is illustrated in Fig 4. At the left ordinate. M has a very similar shape to the fission rate [21]. The ThF4 content has a very minor effect on energy multiplication, whereas UF4 can lead to remark able energy amplification. The nuclear heat production in the ThF4 and lithium are fairly comparable so that a gradual replacement of lithium by ThF4 does not vary the gross plant power remarkably. One of the main neutronic parameters for fusion reactor is the energy multiplication factor. Fusion neutron energy can be multiplied in the blanket by the fissions of ^{233}U and ^{232}Th mainly 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 first liquid wall and blanket on the other hand, provides additional energy generation through fission reactions with fusion neutrons. One of the main neutronic parameters for a fusion or hybrid reactor is the energy multiplication factor *M* which is defined below:

M, energy multiplication factor is defined as the ratio of the ratio of the total energy release in the blanket to the incident fusion neutron energy. Total energy release in blanket can be calculated as

$$\text{Total energy release in blanket} = 200 * \langle \Sigma_F * \Phi \rangle + 4{,}784\, T_6 - 2{,}467\, T_7$$

$$M = \frac{200 * \langle \Sigma F * \Phi \rangle + 4{,}784\, T6 - 2{,}467\, T7 + 14{,}1}{17{,}6}$$

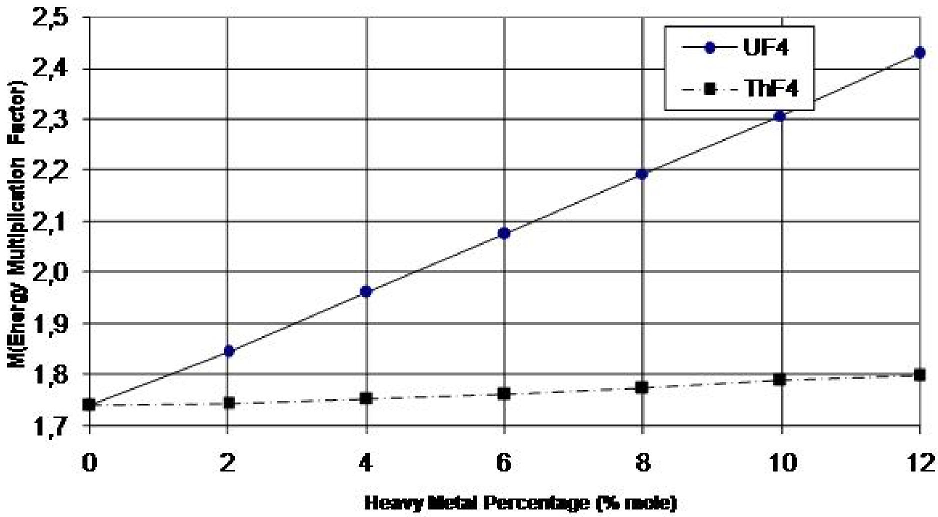

Figure 4. The variation of M with the heavy metal fraction in the liquid medium.

Where, Σ_f is total fission rate, T_6 and T_7 are tritium produced by ^{6}Li(n,t) and ^{7}Li(n,n',t)reactions,

Respectively

$$<\Sigma_F*\Phi>=\int\int\Sigma_F*\Phi\, dE\, dV=total\ integral\ fission\ rate,$$

$$T_6=\iint\Phi*\Sigma(n,\alpha)_T dEdV$$

$$T_7=\iint\Phi*\Sigma(n,n'\alpha)_T\, dE\, dV$$

represents the integral fission rate per D-T fusion neutron [10,12]. One can observe that the addition of ^{233}U to the salt improves the fission rate significantly, as expected, since ^{233}U, having much higher fission cross sections, is very effective to enhance fission reactions compared to ^{232}Th. Energy multiplication increases with heavy metal salt content. The rate of increase for UF_4 is much higher compared with that of ThF_4.

Fissile fuel production

The Fissile fuel production calculations are done for a neutron wall load of 10 MW/m^2 fissile fuel production rates of ^{238}U(n, γ)^{239}Pu increase almost linearly with increased heavy metal content as can be seen in Fig 5. A substantial amount of fissile fuel would be produced by using heavy metal molten salt. The fissile fuel production result from the fertile-fissile conversion with (n ,γ) reaction in the fertile blanket, and tritium breeding takes place in the tritium breeding zone, which is positioned behind the fuel layer and contains Li_2BeF_4. The production of fissile fuel from the fertile fuel in the fuel zone of the blanket result from the following fission reaction. The neutron, which is on the left-hand side of equation, n starts the reaction, is a fast neutron, is the D –T fusion reaction. Utilization of the molten salt mixture Flibe+ThF_4 produces a precious nuclear fuel ^{233}U .The ^{239} Pu fissile fuel can be produced by $^{238}U(n, \gamma)^{239}Pu$ reaction

$$\textit{Fertile fuel} + n \rightarrow \textit{Fissile Fuel} + \nu n' + 200 MeV$$

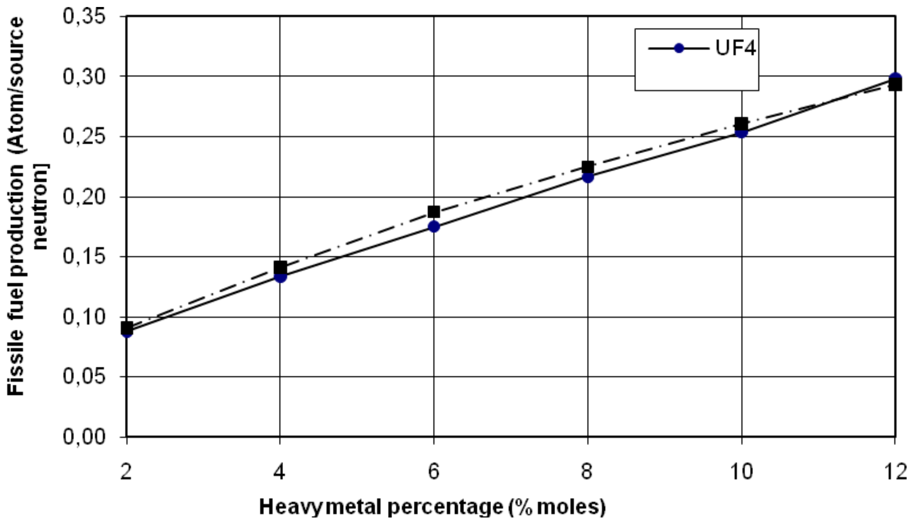

Figure 5. Fissile fuel production in the liquid wall versus the heavy metal percentage.

Conclusions and discussion

In a commercially available fission reactor, only a few percentage 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 worse than Uranium; despite there has been interest in utilizing Thorium as a nuclear fuel over the last 30 years The 2009 IAEA-NEA "Red Book" gives a figure of 4.5 million tons of Thorium reserves and additional resources, but this excludes 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. In this study, the main neutronic parameters, energy multiplication and fissile fuel breeding were examined for the APEX fusion reactor with various thorium and uranium molten salts. In addition to this, the new APEX hybrid model has been developed by the way of using the APEX fusion technology and this model on the first liquid wall, blanket and shield zones fertile which changes between %0-12 is used together with (%100 flibe). Sufficient trityum amount is needed for the reactor to work itself. In the TBR>1.05 APEX fusion model TBR (trityum breeding rate) nearly 1.22 TBR values decreases when UF_4 and ThF_4 proportion increases between %0-12 range. This decrease for ThF_4 is faster when compared with the UF_4 and M the energy production factor is nearly 1.74 these values are for % 100 natural Flibe. In APEX model Fisil material production speed per fusion neutron increases linear to heavy metal salt percentage. For further studies radiation damage to structural materials, in particular inner and outer first walls can be investigated futher.

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