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ORIGINAL RESEARCH

The Evaluation of Reactor Performance by using Flibe and Flinabe Molten Salts in the APEX Hybrid Reactor

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Abstract The modeling of APEX hybrid reactor, produced by using ARIES-RS hybrid reactor technology, has been performed by using the MCNP-4B computer code and ENDF/B-V-VI nuclear data. Around the fusion chamber, molten salts Flibe (Li_2BeF_4) and Flinabe ($LiNaBeF_4$) were used as cooling materials. APEX reactor was modeled in the torus form by adding nuclear materials of low significance in the specified percentages between percent 0–12 to the molten salts. The result of the study indicated that fissile material production, UF_4 and ThF_4 heavy metal salt increased nearly at the same percentage and it was observed that the percentage of it was practically the same in both materials. In order for the hybrid reactor to work itself in terms of tritium, TBR (tritium breeding ratio) should be lower than 1.05. When flibe molten salt was utilized in the APEX hybrid reactor, TBR was calculated as >1, 22 and when flinabe molten salt was used, TBR was calculated as >1.06.

Keywords APEX · MCNP · Flibe · Flinabe · Hybrid · Blanket

Introduction

The Advanced Power Extraction (APEX) study is aimed at exploring innovative concepts for fusion power technology that can tremendously enhance the potential of fusion as an attractive and competitive energy source. APEX provides a research environment conducive to innovation [1]. In the APEX studies, the conventional first solid wall facing with the plasma is replaced with fast flowing thin liquid wall layer. 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 [2]. In this study, in case of usage of the Flibe and Flinabe molten salt at the hybrid APEX reactors, fissile material production per source neutron, tritium production speed, total fission rate, energy reproduction factor has been calculated, the results obtained for both salt solutions are compared. Hybrid (Flibe+Flinabe) reactors are reactors that the fusion and fission reactions are realized together. In these kinds of reactors, the combustion chamber is covered by low caliber passive nuclear materials such as (U-238 and Th-232.). The low caliber nuclear materials U-238 and Th-232 may react with fast neutrons. The fast neutrons that these materials require for reaction may be met by a fusion reaction provided by high energy 14 MeV neutrons similar to the hydrogen combustion that occurs in plasma. Very valuable nuclear fuels like Pu-239 and U-233 are maintained as a result of the reaction of U-238 and Th-232 with fast neutrons. Thus, very high quality fissile fuel may be obtained in an environment which is rich in energetic neutrons.

$$^{238}U + n \rightarrow ^{239}U \xrightarrow{\beta^-} ^{239}Np \xrightarrow{\beta^-} ^{239}Pu$$

$$^{232}Th + n \rightarrow ^{233}Th \xrightarrow{\beta^-} ^{233}Pa \xrightarrow{\beta^-} ^{233}U$$

The shape of the torus, the plasma and the blanket lithium around the plasma, and the structural element that contains U and Th is illustrated in Fig. 1. The neutrons that are

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radiated as a result of the fusion reactions that occur at the plasma are captured at the blanket by uranium a thorium and the production of fissile fuel is provided. It is not possible to combust U-238 in most reactors because the fusion impact incision is very low and the activation energy is too high. Th-232 also is not an appropriate material for combustion. Nevertheless, the knowledge that the known reserves of Th-232 in the world is 3 times the reserve of Uranium, is alone sufficient to emphasize the importance of this material which has no value as a nuclear fuel, to be converted into a very valuable nuclear fuel by processing at a hybrid nuclear reactor. While a portion of this obtained fuel is used as fuel at the reactor, a large amount is transferred out of the reactor with appropriate methods and used as fuel at the thermal reactors While hybrid reactors enable an important portion of the constitution and continuity of the conventional nuclear reactors where they are used, because of the fact that these reactors work under critical, high security factor in the working conditions and a more flexible fuel renewal conditions are in application.

Again, at these reactors, the combustion of the wastes of the nuclear reactor with a high efficiency or transformation to highly valuable fissile materials like Am-242 and Cm-245 is provided. A hybrid reactor produces 30 times as much nuclear fuel per unit clear energy it exposes compared to the fast reactors. We can say that the nuclear fuels that a type hybrid D–D reactor working with 1,000 MW power can meet the requirements of about 160 nuclear plants working with the same power and also may produce fuel for 6 separate fusion reactors of various types. Besides all these, the main disadvantage of a hybrid reactor is the fact that it contains two complex technologies which we name as fusion neutron source and complex fissile blanket within its structure. This condition states that an even greater complexity will emerge if these two are approached separately.

Tritium Breeding at the APEX Hybrid Reactor

A commercial fusion reactor must have a tritium breeding ratio of (TBR >1.05 to be self sustaining. As expected the

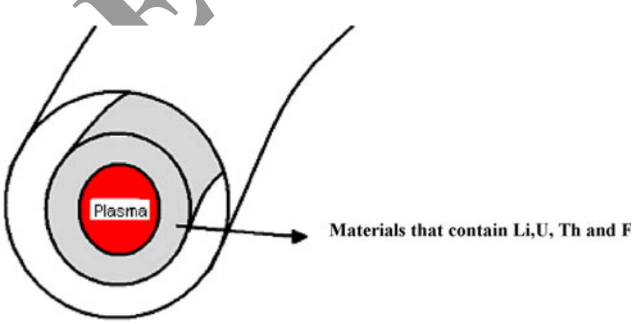

Fig. 1 The torus geometry of the apex reactor

TBR decreases with increased heavy metal content. In order to keep the fusion reactions in the plasma to be continuing in the fusion reactors, the speed of tritium breeding (TBR) should be kept above a certain value. To provide this, appropriate materials that contain lithium are placed around the plasma. Tritium is extracted from the breeding reactions of and ^{7}Li isotopes. The TBR from ^{6}Li is the main contributor to the integrated TBR [3].

$$^{6}\mathrm{Li} + \mathrm{n} \rightarrow {}^{3}\mathrm{H} + {}^{4}\mathrm{He}\ (4{,}784\ \mathrm{MeV})$$
$$^{7}\mathrm{Li} + \mathrm{n} \rightarrow {}^{3}\mathrm{H} + {}^{4}\mathrm{He} + \mathrm{n}\ (-2{,}467\ \mathrm{MeV})$$

In order to prevent the tritium which is the essential fusion fuel to decrease in the plasma, the below materials that will provide the necessary facilities for the breeding of necessary tritium may be used around the plasma.

(a) Liquid metals; Li, PbLi, SnLi
(b) Molten salts; Flibe, Flinabe
(c) Solid Producers; Li_2SiO_4, $LiAlO_2$, Li_2ZrO_3

In case the first wall that faces is constructional material, (solid material), even if the necessary amount of tritium breeding is obtained, the damages that will occur at the wall does not deem the usage of solid walls as convenient as is necessary. This wall will be exposed to the high energy neutron flow that is radiated from the plasma and the positions of the atoms will be changed due to the collision of the neutrons and the atoms which form the structural material and as a result of the nuclear reactions of the (n, p), (n, t), (n,) and (n, d) gas production will occur in this material. In case the proton isotopes that are radiated at the nuclear reactions that have occurred in the structural material possesses sufficient energy, they can get out of the structural material but α particles can‘t manage this and form helium gas spheres within the structural material.

Liquid Wall Structure in APEX Fusion Reactor

In APEX hybrid blankets, the highest material damage occurs in the first wall because it is exposed to the highest neutron, gamma-ray, X-ray and charged particle currents, which are produced in the fusion chamber [4, 5]. The apex study was initiated as part of the US Fusion Energy Sciences program initiative to identify a vision for an attractive fusion energy system. At the construction of the liquid wall, it is possible to use liquid metals but it might be necessary to use electric isolators to manage magnetic-hydrodynamic drafts at the liquid metal flows, and as this will affect the plasma stability which maintains vital importance for fusion reactors, is an important disadvantage for the usage of liquid metals. MHD impacts are quite unimportant for Flibe and Flinabe salt solutions. It is important that the surface vapor pressure of the salt that is used as liquid wall is low. The liquid metal SnLi has been included in the APEX studies due to its relatively low surface vapor pressure particularity even at high temperatures. The liquid viscosity and vapor pressure increases in salt solutions along with the BF_2 concentration. Thus, when choosing salts, salts which have low melting point and low BF_2 concentrations are preferred.

In terms of these problems which will occur in case of structural materials being used, liquid first wall concept is more suitable choice in APEX fusion reactors. At the APEX fusion reactor a fast flowing thin liquid wall has replaced the solid first wall concept of the traditional reactors. Behind the fast flowing thin liquid wall, a slower and thicker second liquid wall (coat) is present. While the liquid first wall traps the charged particles radiating from the plasma, the thick liquid wall at the behind traps the energy and converts it into heat. The liquid must be thick enough to reduce the neutron induced damage to the structural members so that they will last the life of the plant. Displacements per atom (DPA) are a measure of neutron damage [6]. Wall concept has these important advantages compared to the traditional solid wall concept; With its feature of renewable wall it provides possibility for high power density (>2 MW/m^2),has better tritium potential, reduces the radiation damage and activation on the structural materials significantly from the neutronic angle, facilitates the maintenance of the equipments inside the reactor cover, reduces the problems and damages related to the materials in the reactor,reduces the requirement of R&D both from the cost and time efficiency angles, provides high thermodynamic yield. (>40%) [7]. The liquid wall idea evolved during the APEX study into a number of concepts based on:

(a) Using liquid metals (Li or Sn-Li) or a molten salts (Flibe, Flinabe) as the working liquid
(b) Utilizing electromagnetic, inertial and/or other types of forces to restrain the liquid against a backing wall and control the hydrodynamic flow configurations
(c) Employing a thin (∼2 cm) or thick (∼40 cm) liquid layer to remove the surface heat flux and attenuate the neutrons [7, 8].

In APEX model, as shown in Fig. 2, temperature values at various points for flibe liquid flow are given as °C (degrees centigrade). According to this when the entrance degree of the liquid to the system is 500°C, the surface temperature at the exit is around 600°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 initial fusion energy (IFE).The neutron source is volumetric in magnetic fusion energy systems, whereas the target represents a point neutron source in IFE plants. The (D, T) fusion neutron driver of MFE for hybrid reactor has been evaluated for the NWL of 10 MW/m^2. Hence, this corresponds to the fusion neutron flux of 1,014 (14.1 MeV) n/cm^2/s at FW for conventional (D, T) driven hybrid reactor [9].

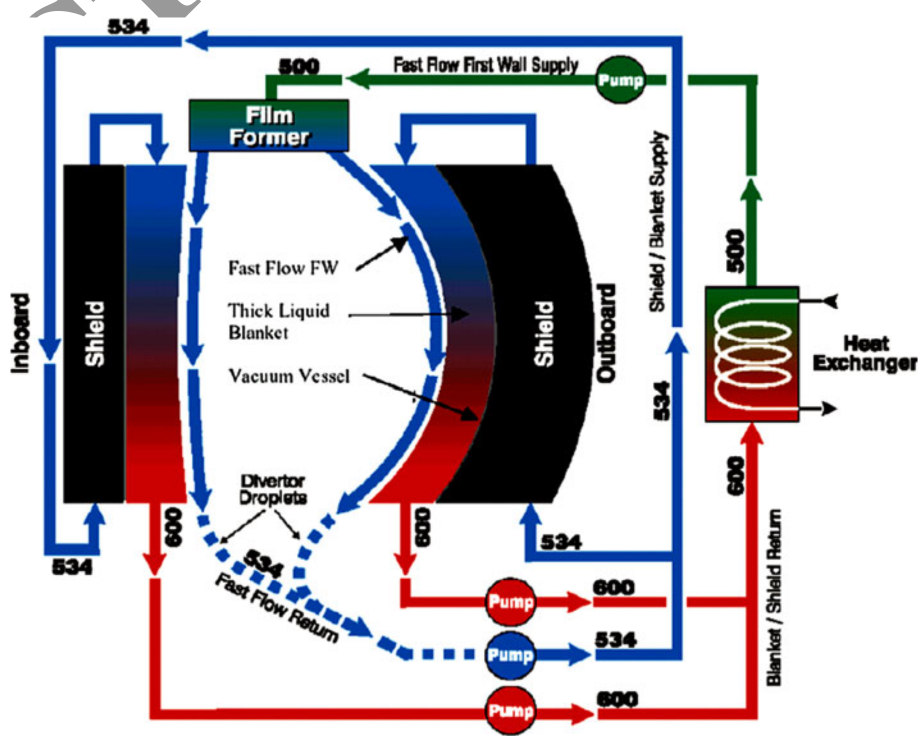

Fig. 2 Temperature chart for flibe liquid flow [1]

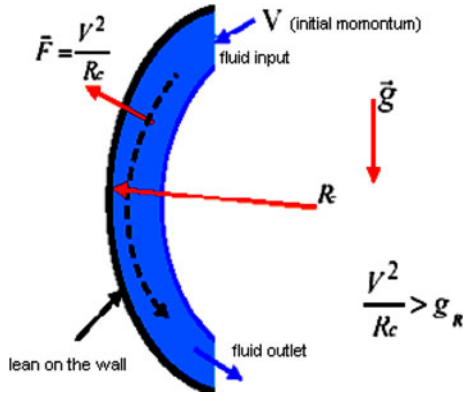

Fig. 3 Gravity–momentum driver method (GMD) [1, 7]

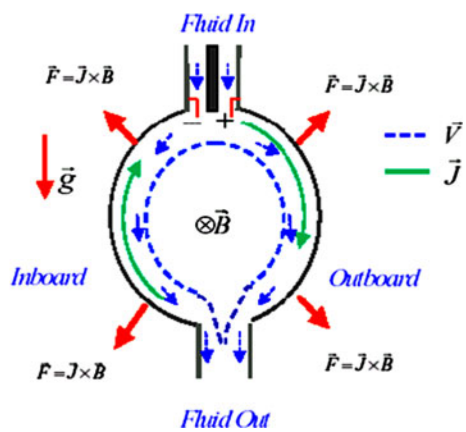

Fig. 4 Electromagnetic retention method (EMR) [1, 7]

At Fig. 3, the balance of the liquid around the plasma, enabling the liquid flow is provided by various forces applied in order to hold the liquid against an appropriate leaning wall. The variety of these forces provides instruments for obtaining various liquid wall grasps. One of these forces is named as Gravity–Momentum Driver (GMD). At Fig. 3 schematic view of principles of GMD liquid wall concept (V = fluid velocity, g = gravitational acceleration, R_C = radius of curvature) [4, 5].

In order to keep the liquid in balance by this method, the centripetal force has to be bigger then gravital force. When this condition is met, the liquid is injected to the wall with a tangential angle. The liquid which sticks to the leaning wall by the effect of the centripetal force is collected at the base of the ring and drained to a channel. Another method of retention is Electromagnetic retention (EMR) which is only applied to liquid metals and have only been used for lithium blanket at the tokamak configuration. In this method, as seen in Fig. 4, the applied magnetic field $\vec{B}$ that will form an angle at 90° with the electric field applied at the figure ($\vec{J}$) constitutes force $\vec{F} = \vec{B} \times \vec{J}$ which pushes the liquid to the wall. Along with the forces used to keep the liquid stable, the thickness of the used liquid also creates a difference at the construction of the liquid wall. Although both thick and thin liquid walls are eligible to eliminate high surface heat flow, the force of depth of the neutrons in the liquid wall before having reached the back wall shows differences for both wall structures. At the thick liquid wall, the radiation damage that the neutrons may cause by passing through the liquid wall to the structural materials at the back and activation are at far less dimensions compared to the thin liquid wall [1]. Several APEX liquid wall alternatives are shown in Table 1. Also inside-out cell and surface cross sections of the APEX model at MCNP-4B is shown in Fig. 5.

Table 1 APEX liquid wall alternatives [1]

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)

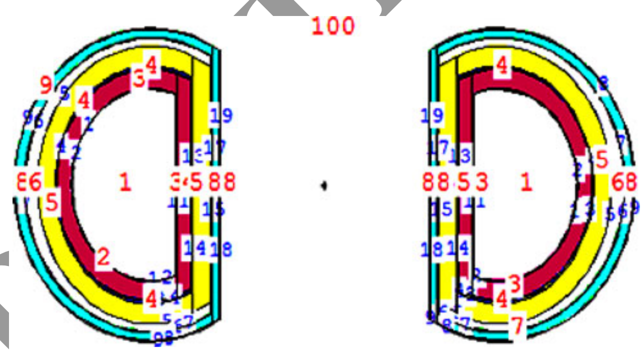

Fig. 5 Inside-out cell and surface cross sections of the APEX model at MCNP-4B [2, 11]

The liquid density equations at the same temperature, heat capacities, and viscosity values of the salt solutions given at various percentages are compared at the Table 2. Both viscosity and heat capacity are almost the same for flibe and flinabe at the same temperature and the same BF_2 concentration.

In this context, let us explain shortly the contents of flibe and flinabe and the outstanding attributes that have affected our decision of finding these salt solutions appropriate for the APEX liquid wall structure. The main attributes of the low viscosity salt solution composed by the combination of

Table 2 Comparison of the thermodynamic attributes of the candidate salt solutions used in the APEX scope

Composition (% mole)	Melting point (°C)	Liquid density(g/cm^3) $\rho = A - BT(°C)$		Heat capacity (at 700°C cal/g)	Viscosity $\eta = A \cdot e^{B/T(K)}$		600°C
		A	B × 10^{-5}		A	B	
Li-BeF$_2$ (69–31)	505	2,16	40	0,65	0,118	3,624	7,5
LiF-BeF$_2$ (50–50)	350	2,46	40	0,67	0,0189	6,174	22,2
NaF-BeF$_2$ (57–43)	360	2,27	37	0,52	0,0346	5,164	12,8
NaF-ZrF$_4$ (50–50)	510	3,79	93	0,28	0,0709	4,168	8,4
LiF-NaF-KF 46,5-11,5-42	454	2,53	73	0,45	0,0400	4,170	4,75
LİF-NaF-BF$_2$ (35-27-38)	338	2,22	41	0,59	0,0338	4,738	7,8

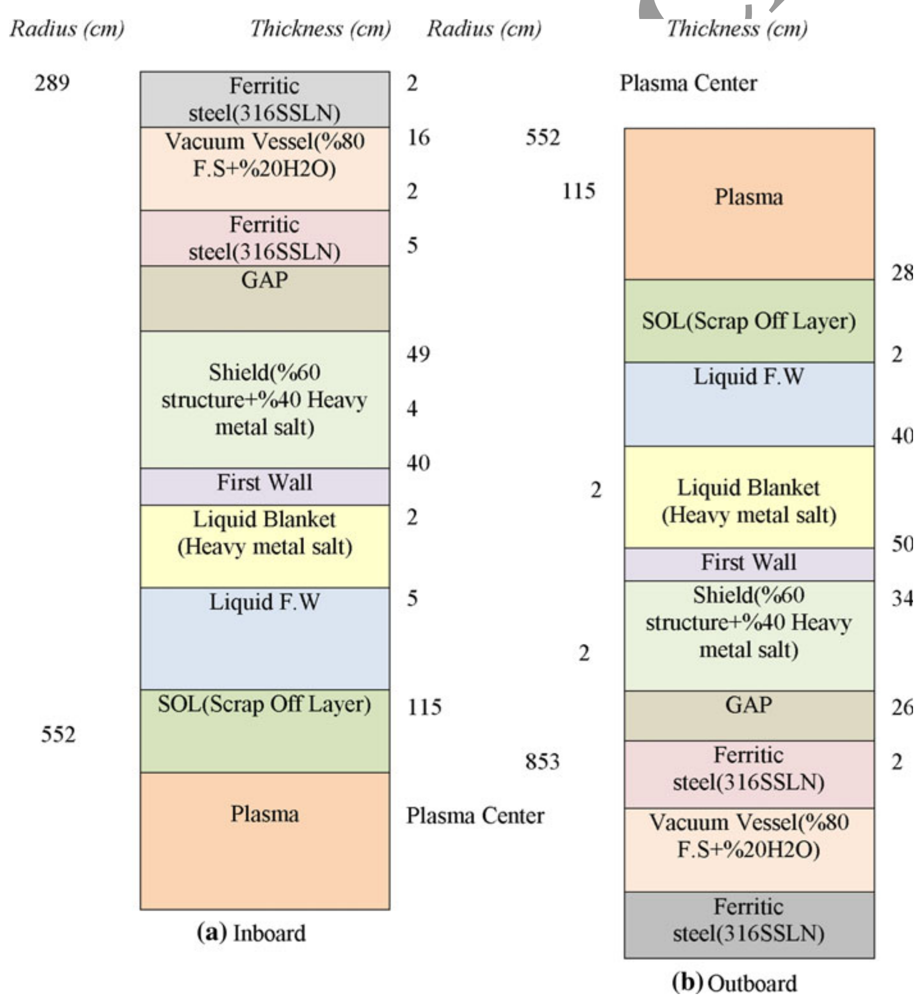

Fig. 6 The cross section of the single dimensional APEX hybrid reactor geometry [1, 7]

Flibe (Li_2BeF_4); LiF and BF_2 at the ratio of 2:1 are as, Low activation, Low tritium hold, Low density changes on melting, Low chemical reaction with water and air, Low electrical conductivity (MHD deems the effects unimportant, good neutron screening. However, the attributes of high boiling point (495°C), low thermal conductivity and wide tritium penetration should be taken into consideration.

Modeling of the APEX by using MCNP

MCNP is a general-purpose Monte Carlo N-Particle code that can be used for neutron, photon, and electron or coupled neutron, photon, electron transport, which is developed by Los Alamos National Laboratory [10]. Nowadays, the complexity in the nature of the industrial problems unfortunately makes analytical solution impossible. On

Table 3 Equipments used at the study, atomic densities and the isotopes that these equipments contain

Reactor zone	Material	Isotopes contained in	Atomic ratio		Mass density (g/cm^3)		Atomic density (Atom/Barn cm)	
			Flinabe	Flibe	Flinabe77	Flibe	Flinabe	Flibe
1. Zone	Vakum							
2. Ve 3. Zone	Liquid wall	Li-6	3,50E−02	1,50E−01	2,08	1,98	7,76E−02	8,44E−02
		Li-7	1,40E−01	1,85E + 00				
		Na	1,35E−01	–				
		Be	1,27E−01	1,00E + 00				
		F	5,63E−01	4,00E + 00				
4. Zone	Steel wall	Fe	8,86E−01	8,86E−01	8,03	8,03	8,33E−02	8,33E−02
		Cr	9,00E−02	9,00E−02				
		W	2,00E−03	2,00E−03				
		V	2,50E−03	2,50E−03				
		C	1,00E−03	1,00E−03				
		Ta	7,00E−04	7,400E−01				
5. Zone	Protective	Li-6	1,40E−02	6,02E−02	5,55	3,05	8,09E−02	8,42E−02
		Li-7	5,60E−02	7,40E−01				
		Na	5,40E−02	–				
		Be	5,07E−02	4,00E−01				
		F	2,25E−01	1,60E + 00				
		Fe	5,31E−01	5,31E−01				
		Cr	5,40E−02	5,40E−02				
		W	1,20E−02	1,20E−02				
		V	1,50E−02	1,50E−03				
		C	6,00E−04	6,00E−04				
		TA	4,20E−04	4,20E−01				
7. And 8. Zone	SS316	Fe	6,53E−01	6,535−01	8,01	8,01	8,54E−02	8,54E−02
		Cr	1,75E−01	1,75E−01				
		Mn	1,80E−02	1,80E−02				
		Si	2,50E−03	2,50E−03				
		Ni	1,20E−01	1,20E−01				
		Mo	2,50E−02	2,50E−02				
		Nb	1,50E−03	1,50E−03				
		Co	2,50E−03	2,50E−03				
		Cu	2,52E−03	2,52E−03				
8. Zone	Vaccum vessel	H	1,33E−01	4,00E−01	6,78	5,28	8,80E−02	9,12E−02
		O	6,67E−02	2,00E−01				
		Fe	5,22E−01	5,22E−01				
		Cr	1,40E−01	1,40E−01				
		Mn	1,44E−02	1,44E−02				
		Si	2,00E−02	2,00E−02				
		Ni	1,20E−03	9,60E−02				
		Mo	2,00E−03	2,00E−02				
		Nb	1,20E−03	1,20E−03				
		Co	2,00E−03	2,00E−03				
		Cu	2,02E−03	2,02E−03				

contrary to the analytical approaches, simulation models are more successful in modeling and solution of complicated problems. Monte Carlo technique is randomly number selection technique from one or more probabilistic distribution in a special trial or simulation study [2]. MCNP computer software provides instruments to solve nuclear

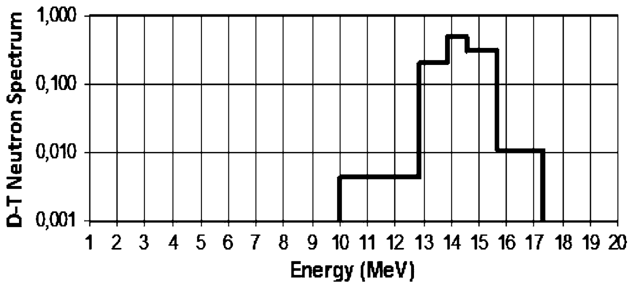

Fig. 7 Source neutron spectrum used at calculations

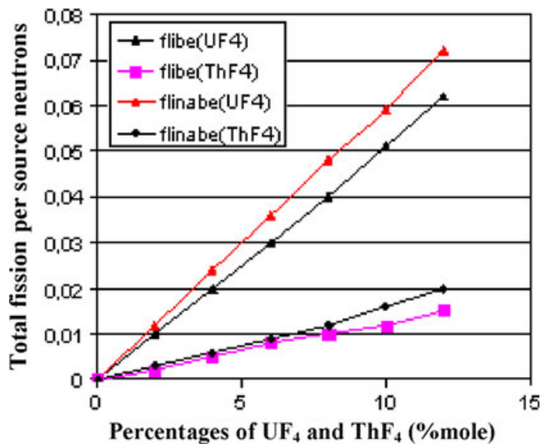

Fig. 8 Variation of the total fissile material production (first wall+blanket+armor area) due to the ratio of UF_4 and ThF_4

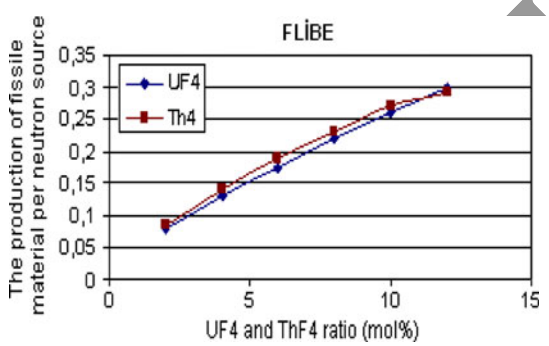

Fig. 9 Variation of the total fissile material production speed (first wall+blanket+armor area) for flibe due to the ratio of UF_4 and THF_4

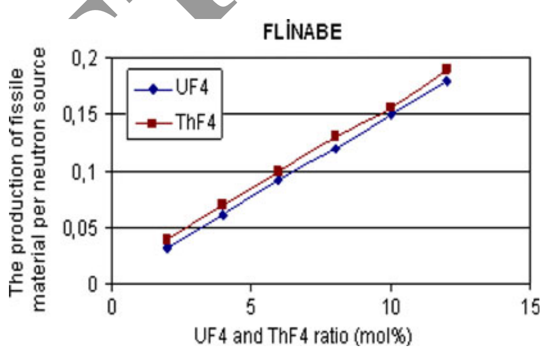

Fig. 10 Variation of the total fissile material production speed (first wall+blanket+armor area) for flinabe due to the ratio of UF_4 and THF_4

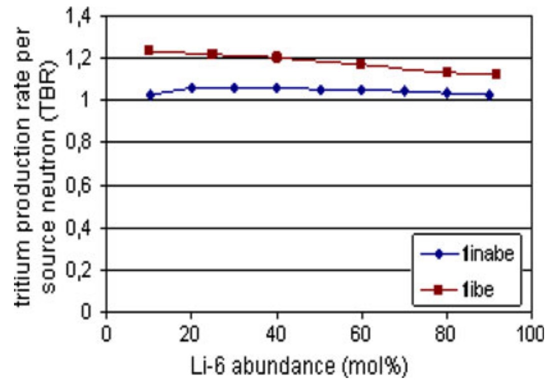

Fig. 11 Variation of the tritium production speed (first wall+blanket+armor area) for flibe and flinabe due to the substance of Li-6

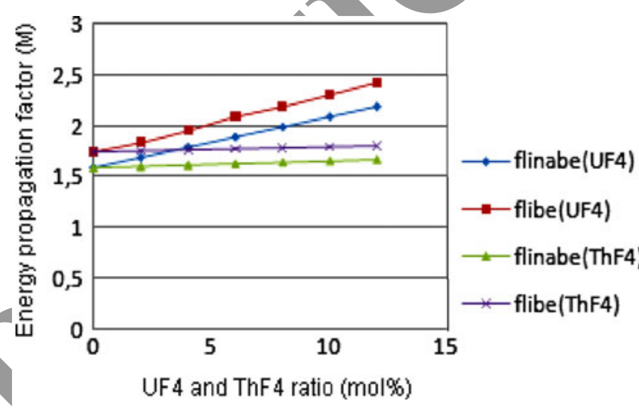

Fig. 12 Energy increasing factor (M) (liquid wall+blanket+armour area) changes due to UF_4 and ThF_4 ratios

problems by simulating the neutron activities. The APEX hybrid reactor used in this study has been designed in 3 dimensional torus shapes by using the MCNP-4B computer software that uses the Monte Carlo technique, using the ARIES-RS reactor model which has been realized in the scope of APEX studies. The cross section of the APEX which has been modeled by the computer software MCNP-4B can be seen in Fig. 6. In the figure, the numbers illustrated on the Torus cross section are the symbols given to the surface and cells in the MCNP-4B computer software [11]. The innermost area at the figure consists of plasma and cavities. This is followed by liquid wall, coat, steel wall, armor, stainless steel, vacuum vessel and stainless steel areas consequently. According to the model, the radius of the torus is 552 cm and small radius is 143 cm. The height of the torus is measured as 250 cm from the first liquid wall center. The dimensions and materials used in this work are shown in Fig. 6. Figure 6 is taken both for Flibe and Flinabe salt solutions. The calculations for flibe and flinabe have been shown at reactors of the same dimensions and with the same reactor equipments. At Table 3, Material contents, isotope ratios and atomic densities of Flibe and Flinabe depending upon the districts are illustrated.

Calculations

In this study, the neutron transport calculations have been carried out with Monte Carlo Methods, using the widely known 3-D particle transport code MCNP, the most version MCNP4B. The primary source of nuclear data used by MCNP code is evaluations from the Evaluated Nuclear Data File (ENDF) system. ENDF/B-V and ENDF/B-VI are the Evaluated Nuclear Data Files [9]. In the calculations, the plasma liquid has been modeled as the neutron source which the inside surface of the first wall has been subject to homogenously, and the fusion neutron spectrum which has been shown at Fig. 7 has been used for the calculations of both flibe and flinabe.

The total fission variations per source neutron related to the amount of low quality passive nuclear fuels UF_4 and ThF_4 present in the liquid wall structure, added to flibe and flinabe salt solutions, are as seen at Fig. 8. In the study, we have also produced fission energy while converting the fertile fuel to fissile fuel in the blanket by adding UF_4 between 0 and 12% intervals or ThF_4 between 0 and 12% intervals, to the flibe and flinabe salt solutions.

Fissile fuel production for flibe and flinabe related to the amount of added fertile fuel are as seen on Figs. 9 and 10. The increase of UF_4 or ThF_4 ratio at the blanket means the increase of the number of ^{238}U and ^{232}Th isotopes in the blanket. Along with this increase, the probability of the colliding of the neutrons emerging from the plasma increases. It is possible to observe the related transformation for both Flibe and Flinabe in Fig. 9. Besides, we can observe the collision possibility at Figs. 9 and 10 together with the increase at the fissile fuel production for both flibe and flinabe separately. The collision number per neutrons and fertile fuel added to the Blanket, total fusion and fissile material increases while tritium production rate decreases. Because of the fertile fuel nucleuses increasing in the blanket, the probability of the interaction of the neutrons that are radiated at the plasma with the lithium isotopes and the TBR ratio related to this, decreases. However, all this argument is valid due the condition that the lithium ratio at the blanket is stable.

The decrease that realizes at the TBR is faster for ThF_4 than it is for UF_4. Although sufficient fuel production can be maintained at the blanket with Thorium, sufficient neutron flow can't be provided because of the fact that the fission rate is low. Due to the richness of Li-6, the variation of the production speed of tritium for flibe and flinabe is as shown below at Fig. 11. Related to the UF_4 and ThF_4 ratios at the blanket, the energy increasing factor for flibe and flinabe (M) is as seen at Fig. 12. It is observed that the energy increase factor is ascending due to the UF_4 and ThF_4 ratios blended into the blanket in flibe and flinabe.

Conclusion

In the advanced power extraction (APEX) project, safety and environmental concerns considered up front, as designs evolve; so that the goal of safety and environmental attractiveness is realized [8]. Current concepts for fusion energy systems will have clear environmental and safety advantages. In this study, Flibe and Flinabe salt solutions are used in the liquid wall of the reactor. The results obtained for both salt solutions are compared. Fissionable metal salt in flowing liquid enables one to breed high quality fissile fuel by maintaining the tritium self sufficiency condition TBR >1.05 for the DT fusion driver [4, 5]. At the situation when there are no additions made to the blanket, the values TBR = 1,22 for flibe and TBR = 1,057 for flinabe are observed. In Flibe salt solution, the necessary value for the continuity of the fusion has been obtained until the addition of TBR 8% ThF_4, afterwards, with the following addition of 10–12% ThF_4, it has been observed that it was impossible for the reactor to operate. For Flinabe, it has also been observed that for the ThF_4 ratios over 6% ThF_4 additions, the reactor did not operate. A UF_4 added APEX hybrid reactor which works with a wall load of 10 MW/m^2 also works about twice as powerful as the original APEX Fusion reactor. Besides, the fissile fuel production provided at the reactor is also of great importance. At this reactor working with 10 MW power, a yearly net of 2,637, 9,365 kg ^{239}Pu may be produced. Taking into consideration that the sales price of ^{238}Plutonium is 80.000 $/kg, a yearly income of $ 211.000.000 may be obtained. In both flibe and flinabe, fissile material production is relatively high due to the fact that the TBR required for 12% UF_4 is provided. Similarly, at the APEX hybrid reactor working at a wall load of 10 MW/m^2 total load increases approximately by 13% compared to an original APEX fusion reactors' load (4,388 MW). Taking into consideration that the market price of the U-238 produced in the blanket is 300.000 kg/$ and the net ^{233}Uranium amount produced in a year is 2,150,227 kg, a yearly total income of $ 645.068.100 will be obtained. Electric kilowatt-hour cost is very low in APEX hybrid reactor [1].

$$COE = \frac{C.\dot{I} + R + O}{P.AM.n}$$

(n = net thermodynamic yield, C = establishment cost of nuclear plant, O = annual operation and maintenance costs, İ = permanent charge ratio, R = annual renovation cost, A = availability of the plant, P = power of the nuclear plant, M = energy multiplier for vacuum vessel system).

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