J Fusion Energ (2013) 32:155–163
DOI 10.1007/s10894-012-9539-z

ORIGINAL RESEARCH

Different Mechanisms for Establishing Liquid Walls in Advanced Reactor Systems

Aybaba Hançerlioğullari · Mesut Cini

Abstract The APEX study is investigating the use of free flowing liquid surfaces to form the inner surface of the chamber around a fusion plasma. In this study the modeling of APEX hybrid reactor produced by using ARIES-RS hybrid reactor technology, was performed by using the Monte Carlo code and ENF/B–V–VI nuclear data. The most important feature of APEX hybrid reactor is that the first wall surrounding the plasma is liquid. The advantages of utilizing a liquid wall are high power density capacity, good power transformation productivity the magnitude of the reactor's operational duration, low failure percentage, short maintenance time and the inclusion of the system's simple technology and material. Around the fusion chamber, molten salt Li_2BeF_4 and natural lithium were used as cooling materials. The result of the study indicated that fissile material production UF_4 and ThF_4 heavy metal salt increased nearly at the same percentage.

Keywords Apex · MCNP · Liquid wall · MHD

Abbreviations

T_6	Tritium breeding rate obtained from reaction $^6Li(n,\alpha)T$
T_7	Tritium breeding rate obtained from Reaction $^7Li(n,\alpha,n')T$
TBR: $T_6 + T_7$	Tritium breeding ratio
GMD	Gravity momentum driver
COE	Cost of electricity
V	Fluid velocity (m/s)
g	Gravitational acceleration (m/s^2)
R_c	Radius of curvature (m)
MHD	Magneto hydrodynamic
M	The energy multiplication factor

Introduction

The APEX hybrid reactor has a good potential to utilize uranium and thorium in the future. In this study Flibe ($LiBeF_4$) salt solutions are used in the liquid wall of the reactor. The results obtained for salt solutions are compared. We present a design for the chamber of about 4,000 MW fusion reactor based on the configuration for the chamber and magnets from ARIES-RS but with a fast flowing molten salt of mixed Be, Li fluorides for the first wall and divertor and molten salt blanket with a ferritic steel structure [11]. The molten salt Flibe is a mixture of tree fluorides; the nominal 2:1 mixture is Li_2BeF_2. The APEX reactor was modeled in the torus form by adding nuclear materials of low significance in the specified percentages between 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 should be higher than 1.05. When Flibe (Li_2BeF_4) molten salt was utilized in the APEX hybrid reactor [1]. 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.

There are three lithium-containing candidate liquids for the walls: (1) a good neutron absorber and inconspicuously electrical conducting medium of molten salt Flibe; (2) a

A. Hançerlioğullari (✉) · M. Cini
Physics Department, Kastamonu Arts and Sciences Faculty,
Kastamonu University, 37100 Kastamonu, Turkey
e-mail: aybaba@kastamonu.edu.tr

Table 1 ARIES-RS parameters and APEX modifications [3, 13, 14]

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)	2,171	~4,000
Neutron power (mw)	1,736	~3,400
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

low *Z* material and more likely compatible with plasma operation of lithium and (3) an extreme low vapor pressure fluid of tin-lithium. The primary objective of the 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, as shown in Table 1. Both lithium and tin-lithium are good electric conductors. Utilization of these two materials will have to deal with MHD effects not just in the surface flows, but in supply lines and feed systems, and it requires electrical insulating coatings. The hybrid reactors must be economically competitive for energy market penetration for this reason they must compete primarily with fission reactor. Requirements for a commercially competitive power plant with low cost of electricity are high power density (HPD), high power conversion efficiency (>40 %), higher availability (lower failure rate, faster maintenance) and, finally, simpler technological and material constraints High neutron fluxes can be tolerated, either by a liquid wall adjacent to the plasma or with refractory metals as the first wall material. In an extensive study Abdou and his team have evaluated the key elements for a competitive fusion [2–4].

Liquid Wall/Blanket Concept

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 [4]. Liquid 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. 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 effect the plasma stability which maintains vital importance for fusion reactors, is an important disadvantage for the usage of liquid metals. 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. In fusion 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. The major damage mechanisms will be displacements of the atoms from their lattice sites as a result of collisions with highly energetic fusion neutrons and gas production in the metallic lattice resulting from divers nuclear reactions, mainly through helium production. These reactions will limit the lifetime of the first structural wall of the fusion reaction chamber [2, 9]. 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 [12, 13]. A substantiation of liquid walls for inertial fusion reactor appears easier to accomplish within the possibilities of present day technology. Disseminated research is required to demonstrate the feasibility of a liquid wall protected chamber for magnetic fusion and on the feasibility of a conducting liquid metal flowing along field lines. Extensive analysis on the thermo hydraulics and MHD (magneto hydrodynamic) effects of different types of liquid protection have been conducted. The following liquid wall concept has more advantages than the solid first wall concept [2]. These can be briefly summarized as; I) very high power density II) renewable first wall surface III) lower radiation damage and activation in structural materials IV) improved tritium breeding potential. 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 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. 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

Table 2 Comparison of the thermodynamic attributes of the candidate salt solutions used in the APEX scope [17]

Composition	Melting point (°C)	Liquid density (g/cm^3) $\rho = c - dT$		Head capacity (at 700 °C cal/gram)	Viscosity		
					$\eta = c.\exp(d/T)$		600 °C
		c	d×10^{-5}		c	d	
Li–BeF$_2$	505	2.16	40	0.65	0.118	3,624	7.5
LiF–BeF$_2$	350	2.46	40	0.67	0.0189	6,174	22.2
NaF–BeF$_2$	360	2.27	37	0.52	0.0346	5,164	12.8
NaF–ZrF$_4$	510	3.79	93	0.28	0.0709	4,168	8.4
LiF–NaF–KF	454	2.53	73	0.45	0.0400	4,170	4.75
LİF–NaF–BF$_2$	338	2.22	41	0.59	0.0338	4,738	7.8

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. 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 Flibe(Li$_2$BeF$_4$); 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.

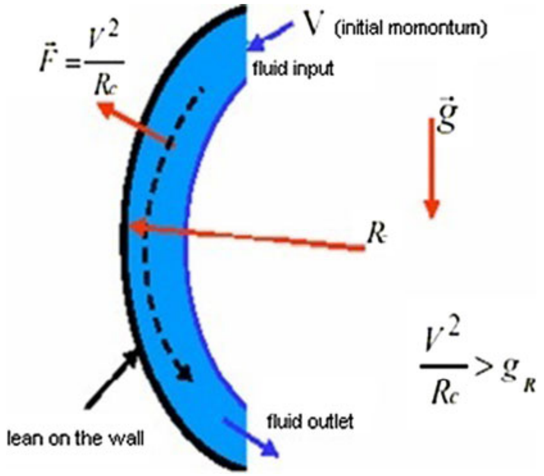

Fig. 1 Gravity-momentum driver method (GMD) [4]

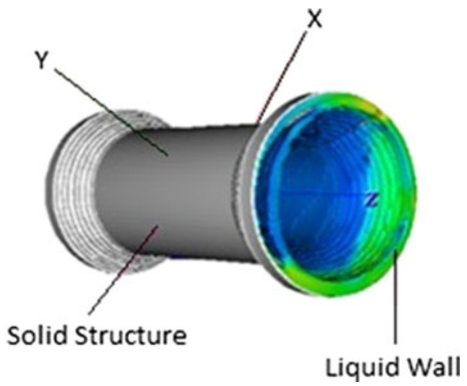

Fig. 2 3-D fluid distribution of FRC [4]

Field Reversed Configuration

Field-reversed configuration (FRC) power plants possess cylindrical geometry, which facilitates the design of tritium breeding blankets, shields, magnets and input-power systems. The FRC equilibrium configuration is a compact plasma toroid immersed in an axially aligned solenoidal magnetic field. Different liquid wall concepts have emerged from applying various forces to drive the liquid flow and restrain it against a backing solid wall. One of these forces is the gravity-momentum driven (GMD) method for moderate aspect ratio tokamaks that uses the liquid at the top of the chamber with an angle tangential to the curved backing wall, schematically shown in Fig. 1.

Another useful method for restraining the liquid against a backing solid wall is a GMD method with with a swirl flow concept that is obtained by giving the fluid an azimuthal velocity to produce rotation, schematically shown in Fig. 2 [4]. The swirl flow causes a substantial increase in centrifugal acceleration(<35 m/s^2) toward the back wall and better adherence to the wall, while the backing wall curvature in poloidal direction is large and the toroidal curvature is comparable to the poloidal curvature. At Fig. 1, 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).

Numerical Calculations

Modeling of the Apex By Using MCNP

On 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 [15]. The MCNP-4B code was used for reactor designs and calculations. MCNP was run for approximately 8.5×10^5 Particle histories per calculation [15]. MCNP is a general purpose Monte Carlo N-particle code that can be used for neutron, photon, electron for, or coupled neutron/photon-electron transport. Design and calculations of APEX are carried out as 3-D torus by using MCNP computer code [13, 14].

The effects of the first load wall layer thickness and of different blanket configurations and the various mixture compositions of molten salt and heavy metals on many parameters of fusion reactor, such as tritium production rate, energy multiplication factor, fissile fuel breeding, first wall material radiation damage, and heat deposition were investigated.

Apex Fusion Geometry

In the APEX studies liquid walls concept, although containing many common aspects, the variability related to the liquid used. The dimensions and materials used in this study are given in Fig. 3. The fast-flowing liquid first wall is 2 cm thick and the slow-flowing layer constitutes the blanket and is taken to be 40 cm thick [16].

A backing solid wall of 4-cm thickness follows the liquid first wall/blanket zone. A shielding zone of 50-cm thickness (outboard) and 49-cm thickness (inboard) is located behind the backing solid wall for the outboard and inboard builds, respectively, and is assumed to have a structure-to-breeder (coolant) volume ratio of 60:40. The vacuum vessel wall is 2 cm thick and made of Type 316LN stainless steel, and the interior is 16 cm thick (inboard) and 26 cm thick (outboard) with Type316 stainless steel cooled with water by a structure-to-water ratio of 80:20. In this study Flinabe salt solutions are used in the liquid wall of the reactor. The results obtained for salt solutions are compared. 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 effect the plasma stability which maintains vital importance for fusion reactors, is an important disadvantage for the usage of liquid metals. 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.

The APEX Fusion reactor materials used in the study are given in Table 3, and radius and thicknesses in one dimensionally are shown detail in Fig. 3. The cross section of the apex which has been modeled by the computer software MCNP-4B can be seen in Fig. 3. The numbers illustrated on the torus cross section are the symbols given to the surface and cells in the MCNP-4B computer software. 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 has better tritium potential, reduces the radiation damage and activation on the structural materials significantly from the neutronic angle, reduces the problems and damages related to the materials in the reactor. In the apex study and adapt the GMD (gravity momentum driven) concept geometry (Table 4).

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 outer blanket has an advanced “dual cooled” breeding blanket with flowing lithium and he-cooled ferritic steel structures [8, 9]. 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.

Where, M is the energy multiplication factor, Σ_γ is fissile fuel production ratio, $v\Sigma_f$ is ratio of total fission neutron, Σ_f is ratio of the total fission and v is total number of fusion neutron.

Tritium Breeding and Energy Multiplication

There are three candidate liquids that might meat all the criteria, especially that of being able to breed enough tritium Li, flibe [9, 10]. In order for the hybrid reactor to work itself in terms of tritium, TBR should be lower than 1.05. When flibe molten salt was utilized in the APEX hybrid reactor, TBR was calculated as >1.05. In the reactor, in addition to the fissile fuel production, increasing energy multiplication and decreasing energy cost (COE) were also intended. Natural lithium is composed of 7.56 % of ^{6}Li and 92.44 % of ^{7}Li isotopes.

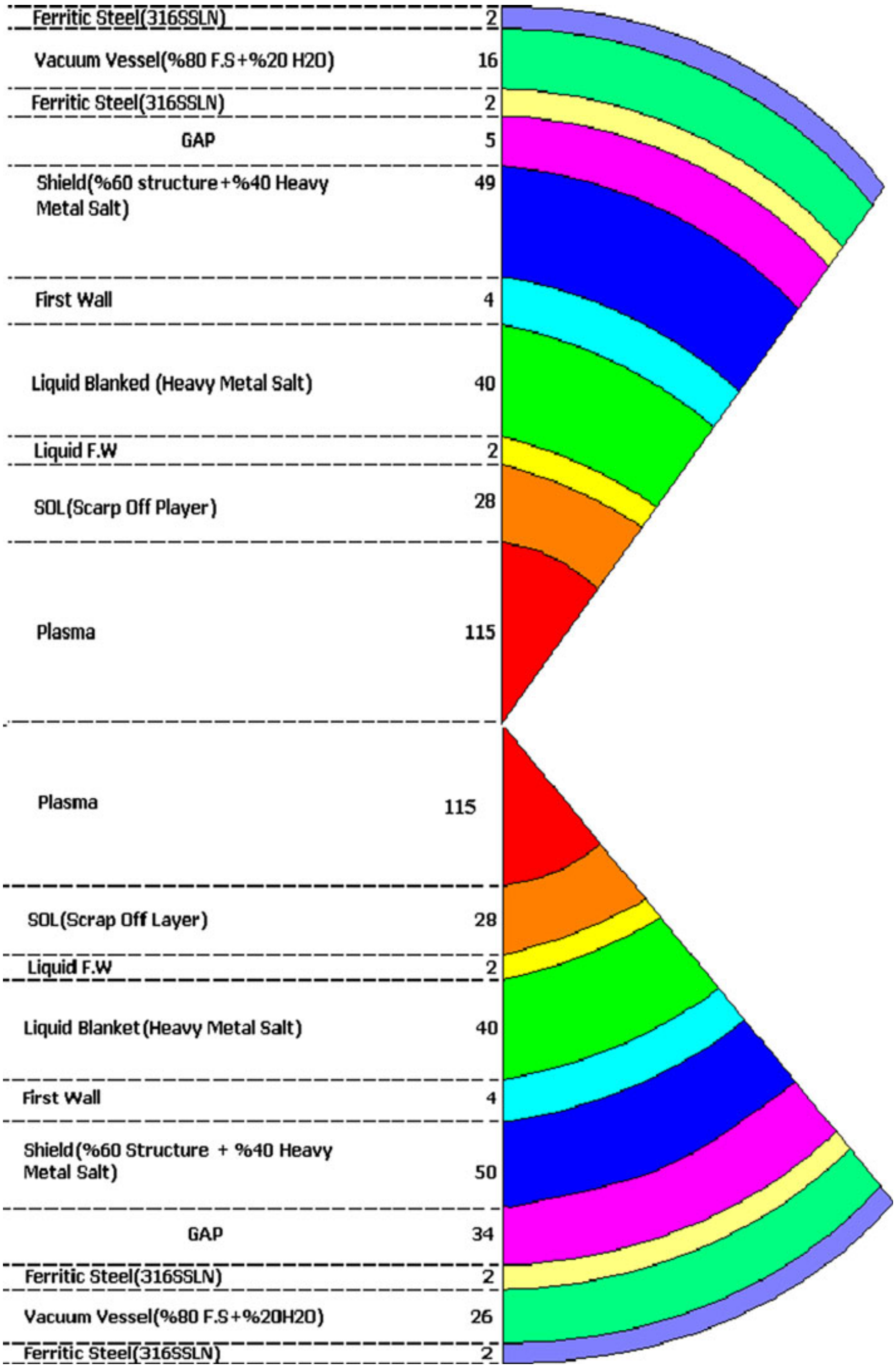

Fig. 3 Inside-out cell and surface cross sections of the APEX model at MCNP [8, 10, 11]

^{6}Li(n, α)T reaction is produced with thermal neutrons, ^{7}Li(n,α,'n)T reaction with fast neutrons [5–7]. To ensure the tritium self-sufficiency, the calculated achievable TBR should be equal or greater than the required TBR. 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:

$$^{6}\mathrm{Li} + n \rightarrow \alpha + T + 4.784\ \mathrm{MeV}$$
$$^{7}\mathrm{Li} + n \rightarrow \alpha + T + n - 2.467\ \mathrm{MeV}$$

represents the integral fission rate per D-T fusion neutron then the only practical liquids for first wall and blanket are

Table 3 Materials used in the design of the apex fusion reactor (90 % Flibe + 10 % ThF4)

Reactor zones	Material	Isotopes included in the material	Isotope %	Mass density gr/cm^3
1st zone	Vacuum			
2nd & 3rd zone	(Liquid wall)	L-6	0.135360	2.3881420
	98 % flibe + 10 % ThF4	Li-7	1.664640	
		F	4.000000	
		Be	0.900000	
		Th-232	0.100000	
		U-235	0.000000	
		U-238	0.000000	
4th zone	Ferritic steel	C	0.001000	8.0300000
		V	0.002500	
		Cr	0.090000	
		Fe	0.889560	
		Ta	0.000000	
		W	0.020000	
5th zone	Shield	F4	1.600000	3.45550968
	60 % F.S +	Li-6	0.054144	
	+ 40 % (98 % flibe + %2 ThF4)	Li-7	0.665856	
		Be	0.360000	
		W	0.012000	
		V	0.001500	
		Cr	0.054000	
		Fe	0.531480	
		Ta	0.000420	
		C	0.000600	
		Th-232	0.000066	
6th zone	Gap			
7th & 9th zone	SS316LN	Fe	0.652818	8.0166100
		Cr	0.175079	
		Mn	0.018009	
		Si	0.002501	
		Ni	0.120055	
		Mo	0.025012	
		Nb	0.001501	
		Co	0.002501	
		Cu	0.002525	
8th zone	Vacuum vessel	Ni	0.096044	5.2867890
	80 % ferritic steel + 20 % H_2o	Mo	0.020009	
		H	0.040000	
		O	0.020000	
		Fe	0.522255	
		Cr	0.140063	
		Mn	0.014407	
		Si	0.002001	
		Nb	0.002001	
		Co	0.002001	
		Cu	0.002019	

Table 4 Calculated nuclear data by using MCNP-4B

Model	Type of cooling	TBR = $T_6 + T_7$	M	Σ_f	$\nu\Sigma_f$	Σ_γ
Model-1	Natural flibe (100 %)	1.227474	1.739449	0.000000	0.000000	0.000000
Model-2	2 % UF4 + 98 % flibe	1.172823	1.843493	0.010133	0.036183	0.087884
Model-3	4 % UF4 + 96 % flibe	1.158448	1.959874	0.020251	0.072209	0.133702
Model-4	6 % UF4 + 94 % flibe	1.139097	2.074655	0.030377	0.108164	0.175173
Model-5	8 % UF4 + 92 % flibe	1.30319	2.193454	0.040554	0.138864	0.216420
Model-6	10 % UF4 + 90 % flibe	1.107934	2.307206	0.050669	0.180059	0.253408
Model-7	12 % TF4 + 88 % flibe	1.101521	2.428811	0.060970	0.216755	0.298196
Model-8	2 % TF4 + 98 % flibe	1.167730	1.742355	0.002493	0.008498	0.090951
Model-9	4 % TF4 + 96 % flibe	1.22966	1.750408	0.004975	0.016969	0.141386
Model-10	6 % TF4 + 94 % flibe	1.087566	1.760502	0.007418	0.025304	0.187406
Model-11	8 % TF4 + 92 % flibe	1.060310	1.773000	0.009877	0.033596	0.224965
Model-12	10 % TF4 + 90 % flibe	1.034242	1.787573	0.012275	0.041894	0.260624
Model-13	12 % TF4 + 88 % flibe	1.001521	1.796771	0.014606	0.049865	0.293447

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, are as seen in Fig. 7. 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.

We used for neutrons all reactions given in a particular cross- section evaluation (ENDF/B–VI–V) are accounted 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. Related to the UF_4 and ThF_4 ratios at the blanket, the energy increasing factor for Flibe and Lithium (M) is as seen at Fig. 4. It is observed that the energy increase factor is ascending due to the UF4 and ThF4 ratios blended into the blanket in flibe and Lithium. 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 Lithium salt solutions (Fig. 5). 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 lithium salt solutions are as seen in Fig. 6. Fissile fuel breeding and radian damage calculations are done for a NWL of 10 MeV/m^2. Fissile fuel breeding rates of [^{238}U(n,γ)^{239}Pu] and [^{232}Th(n,γ)^{233}U] increase almost linearly with increased heavy metal content as can be seen in Fig. 6 [2].

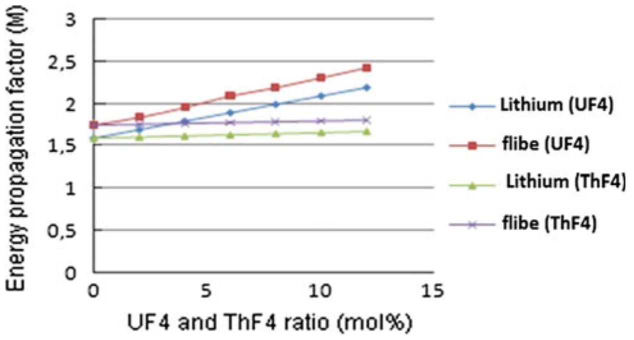

Fig. 4 Energy increasing factor (M) (liquid wall + blanket + shield) changes due to UF4 and ThF4 ratios

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 realises at the TBR is faster for ThF4 than it is for UF4. Although sufficient fuel production

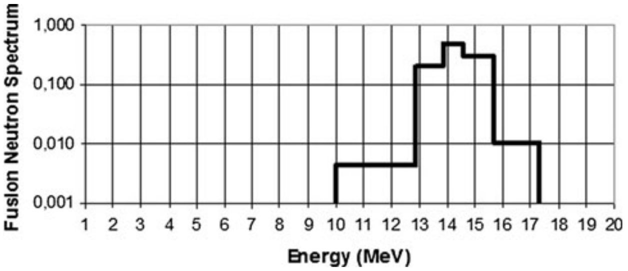

Fig. 5 Fusion Neutron Spectrum

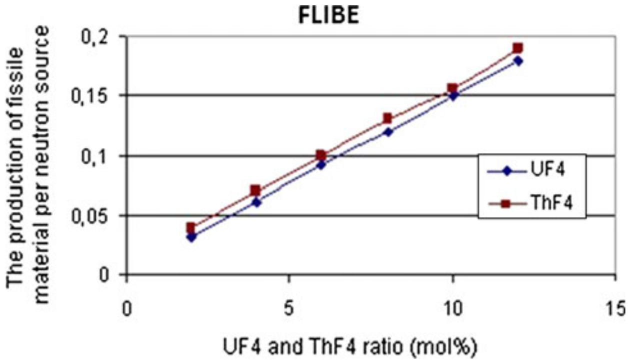

Fig. 6 Variation of the total fissile material production speed (first wall + blanket + shield) for flibe due to the ratio of UF4 and ThF4

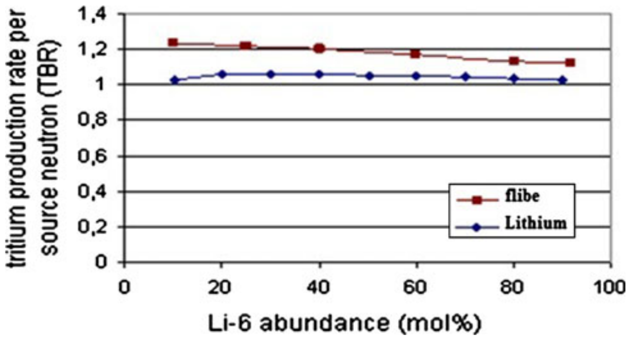

Fig. 7 Variation of the tritium production speed (first wall + blanket + shield) for flibe and lithium due to the substance of Li-6

can be maintained at the blanket with Torium, sufficient neutron flow can not 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 Lithium is as shown below in Fig. 7. Related to the UF4 and ThF4 ratios at the blanket, the energy increasing factor for flibe and Lithium (M). It is observed that the energy increase factor is ascending due to the UF4 and ThF4 ratios blended into the blanket in flibe and Lithium. 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 Fig. 4.

Fusion Neutron Spectrum

Fusion neutrons from D-T plasma have several characteristics that result in attractive performance for such application. The spatial distribution reduces the power density in the blanket materials, which facilitates the heat removal process. Most of the fusion energy, ~80 %,are carried by the D-T neutrons that reduces the first wall surface heat flux of the fusion blanket. The high neutron energy enhances the neutron multiplication through (n,2n), (n,3n), and the fast fission reactions, which increases the disposal rate of the rate of long-lived fission products. Cross-sectional views of apex designed by using MCNP-4B computer code are shown in Fig. 5 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 Fig. 5.

Conclusion and Comments

In fusion and hybrid reactors, it is necessary to provide the TBR > 1.05 terms in order to maintain the continuity of the operation of the reactors. At the situation when there are no additions made to the blanket, the values TBR = 1.20 for Flibe is 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 Lityum, it has also been observed that for the ThF_4 ratios over 10 % ThF_4 addition, 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 3637, 6766 kg ^{239}Pu may be produced. Taking into consideration that the sales price of Plutonium 238 is 85.000 $/Kg, a yearly income of $ 311.000.000 may be obtained. In both flibe and lithium, fissile material production is relatively high due to the fact that the TBR required for 10 % TF_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 ^{238}U produced in the blanket is 300.000 kg/$ and the net Uranium-233 amount produced in a year is 3,850,677 kg yearly total income of $ 746.068.100 will be obtained. Electric kilowatt-hour cost is very low in APEX hybrid reactor.

References

1. A. Hançerlioğullari, Determining of energy multiplication in the APEX hybrid reactor by using ThF4 and UF4 heavy metal salts. Int. J. Energ Res. (2011). doi:10.1001/er.1919
2. S. Şahin, M. Übeyli, Modified APEX reactor as a fusion breeder. Energ. Convers. Manag. Elsevier, **45**, 1497–1512 (2004)

3. M.A. Abdou,The APEX team, exploring novel high power density concepts for attractive fusion systems. Fusion Eng. Des. **45**, 67–145 (1999)
4. M.A. Abdou, A. Ying et al., The APEX team. On the exploration of innovative concepts for fusion chamber technology. Fusion Eng. Des. **54**, 181–247 (2001)
5. R.E. Rognlien, T.D. Rensink, M.E. Smolentsev, S.S. M.Z. Youssef, A. Sawan et al., Fusion reactor design with a liquid first wall and divertor. Fusion Eng. Des. **72**, 181–221 (2004)
6. M.Z. Youssef, N. Morley, A. El-Azabet, X-rays surface and volumetric heat deposition and tritium breeding issues in liquid-protected FW in high power density devices. Paper presented at the 13th topical meeting on the technology of fusion power. Nashville, Tennessee, June 7–11 (1998)
7. M.A. Abdou, Preface Fusion Eng. Des. **72**, 1–2 (2004)
8. J. Bremister, MCNP-4A general Monte Carlo code N-particle transport code, Version 4A, La-12625, November (1993)
9. R.W. Moir, Liquid first walls for a magnetic fusion energy configurations. Nucl. Fusion **37**, 557 (1997)"
10. M.A. Abdou, Fusion Eng. Des. **45**, 145–167 (1999)
11. M.A. Abdou, A. Ying, N. Morle, Fusion Eng. Des. **54**,181–247 (2001)
12. S. Şahin, M. Übeyli, Energ. Convers. Manag. **45**, 1497–1512 (2004)
13. M. Übeyli, J. Fusion Energ. **26**(4), 317–321 (2007)
14. X.P. Lio, T.Y. Tong, FDS group, Development and application of Mcnp auto-modeling tool: Mcam 3.0. Fusion Eng. Des. **75–79**, 1275–1279 (2005)
15. B. Şarer, M. Günay, M.E. Korkmaz, A. Hançerlioğulları, Fusion Sci. Technol. **52**(1), 107–115 (2007)
16. K.A. McCarty, D.A. Petti, R.L. Moore, B.J. Merrill, Safety issues associated with mobilized activation products in selected APEX designs. Fusion Eng. Des. **51–52**, 549–554 (2000)
17. M.Z. Youssef, M.E. Sawan, D.-K.Sze, The breeding potential of "Flinabe" and comparison to "Flibe" in "Cliff" high power density concept. Paper presented at the 6th international symposium on fusion nuclear technology, San Diego, California, 2001