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ORIGINAL PAPER

Utilization of Heavy Metal Molten Salts in the ARIES-RS Fusion Reactor

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Abstract ARIES-RS is one of the major magnetic fusion energy reactor designs that uses a blanket having vanadium alloy structure cooled by lithium [1, 2]. It is a deuterium–tritium (DT) fusion driven reactor, having a fusion power of 2170 MW [1, 2]. This study presents the neutronic analysis of the ARIES-RS fusion reactor using heavy metal molten salts in which Li_2BeF_4 as the main constituent was mixed with increased mole fractions of heavy metal salt (ThF_4 or UF_4) starting by 2 mol.% up to 12 mol.%. Neutron transport calculations were carried out with the help of the SCALE 4.3 system by solving the Boltzmann transport equation with the XSDRNPM code in 238 neutron groups and a S_8–P_3 approximation. According to the numerical results, tritium self-sufficiency was attained for the coolants, Flibe with 2% UF_4 or ThF_4 and 4% UF_4. In addition, higher energy multiplication values were found for the salt with UF_4 compared to that with ThF_4. Furthermore, significant amount of high quality nuclear fuel was produced to be used in external reactors.

Keywords Heavy metal molten salt · Fissile fuel breeding · Tritium breeding

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Introduction

Controlled nuclear fusion has a great potential to serve inexhaustible energy source for humankind due to the fact that fusion fuels are abundantly available in the nature. In addition a fusion energy system has attributes of an attractive product with respect to safety and environmental advantages. For this reason, there have been many research and development studies conducted especially on both inertial and magnetic fusion energy reactors during the last 40 years. Nevertheless, the market penetration of a fusion reactor will probably be in far future, probably later than 2050 even towards 2100.

One of the major fusion reactor design concepts is ARIES-RS, a magnetic fusion energy reactor. Several neutronic and design studies on pure ARIES-RS fusion reactor were made [1–5]. It is a design of commercial 1000 MW_{el} power plant based on a reversed shear tokamak, deuterium–tritium (DT) burning plasma [1]. The pure ARIES-RS fusion reactor, using a vanadium alloy structure cooled by lithium, has a fusion power of 2170 MW [2]. It has an energy multiplication ratio (M) of 1.2 [4] producing a total power of $\sim$2600 MW. In order to enhance the neutronic performance of the ARIES-RS fusion reactor, its hybrid version was proposed in previous works [6–8]. It was shown that rich neutronic economy of ARIES-RS could have been used to produce fissile fuel and increase energy multiplication factor by inserting a fissile fuel zone of 10 cm thickness in the inner lithium zone [6–8]. A 10 cm fission zone at the inner blanket with ThC fuel leaded to a blanket multiplication of $M = 1.946$ or $M = 3.03$ with UC fuel and increased the fusion power from 2170 to 4200 MW or to 6500 MW, respectively [6]. In addition to fusion power amplification, substantial fissile fuel namely, 4410 kg ^{233}U/year or 6500 kg ^{239}Pu/year could be produced at start-up conditions under a full fusion power of 2170 MW by providing sufficient tritium for the (DT) driver [6]. The similar improvements with respect to energy multiplication and fissile fuel breeding in the ARIES-RS fusion reactor using various dispersed uranium and thorium fuels were also observed in other two studies [7, 8]. Although substantial neutronic improvements can be reached by inserting a 10 cm fissile zone in the ARIES-RS fusion reactor, this would bring the structural changes in the design of the ARIES-RS reactor which is not easy. Instead of inserting a new fissile zone to the reactor, a coolant bearing nuclear fuels can also be used to improve the neutronic performance of this reactor. This would only need a chemical separation unit to extract fissile fuel to be used in either fission reactors using enriched fuel or breeder reactors.

This study investigates the neutronic analysis of the ARIES-RS fusion reactor with various heavy metal molten salts containing Li_2BeF_4 (Flibe) + UF_4 or ThF_4 with different molecular fractions.

The ARIES-RS Blanket Geometry

The pure ARIES-RS fusion reactor uses the blanket containing a vanadium alloy (V-4Cr-4Ti) structure cooled by natural lithium. Figure 1 shows the vertical cross-sectional view of the fusion reactor [1] and the one-dimensional blanket model used in this study for calculations is illustrated in Fig. 2 [4]. In this blanket the V-4Cr-4Ti is used as the first wall structure. And then, fuel breeding zone (FBZ) follows immediately the first wall. In this zone, the heavy metal molten salts consisting of Flibe + UF_4 or ThF_4 were considered as a coolant to breed both fusile and fissile fuel and increase energy multiplication (Table 1). The molecular fraction of the heavy metal fluoride content in the molten

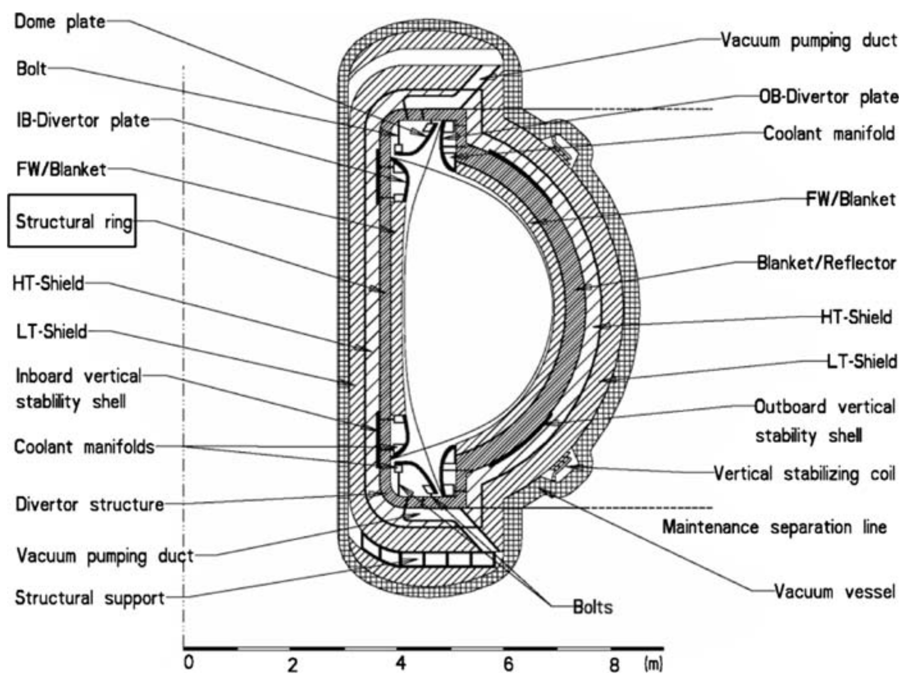

Fig. 1 Vertical cross-section of the ARIES-RS reactor

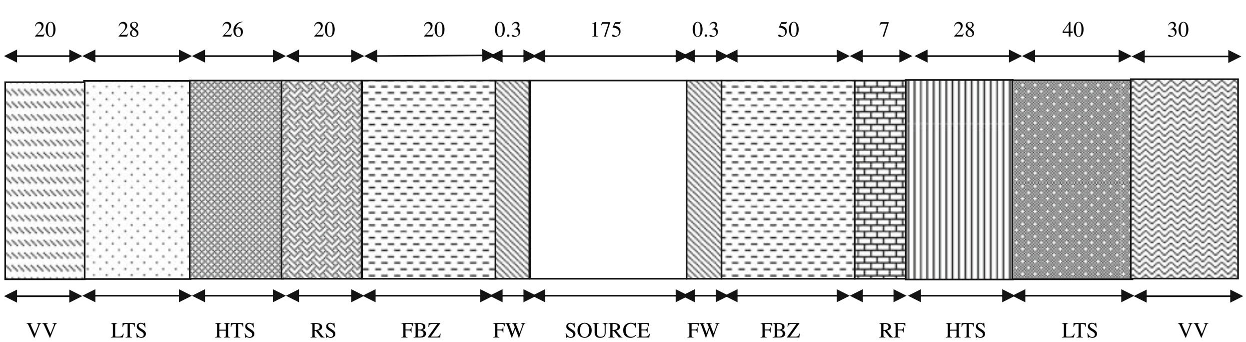

Fig. 2 One-dimensional blanket model of the ARIES-RS fusion reactor [4]. VV, vacuum vessel; LTS, low temperature shield; HTS, high temperature shield; RS, replaceable shield; FBZ, fuel breeding zone; FW, first wall; RF, reflector (dimensions are given in cm, not in scale)

Table 1 The blanket zones and their components [4]

Zone	Material
First wall	100% V alloy
Inner blanket	10% V alloy
Fuel breeding zone	90% Coolant
Outer blanket	10% V alloy
Fuel breeding zone	90% Coolant
Inner blanket (replaceable shield)	90% V alloy 10% Coolant
Outer blanket (reflector)	15% V alloy 10% Coolant 75% Tenelon
Inner blanket (high temperature shield)	15% V alloy 5% Coolant 76% Tenelon 4% W
Inner blanket (low temperature shield)	15% Tenelon 5% Helium 53% B_4C 27% WC
Outer blanket (high temperature shield)	15% V alloy 5% Coolant 73% Tenelon 7% W
Outer blanket (low temperature shield)	15% Tenelon 5% Helium 80% Borated tenelon
Inner blanket (vacuum vessel)	35% Tenelon 5% Helium 40% B_4C 20% WC
Outer blanket (vacuum vessel)	25% Tenelon 5% Helium 70% Borated tenelon

salts was gradually increased from 2% up to 12% by a step of 2%. The inner blanket is a cylindrical shell where a replaceable shield, called structural ring surrounds the inner FBZ. High and low temperature shields follow thereafter. On the other hand, the outer blanket has a torus shape in which a reflector zone surrounds the outer FBZ. Then, high and low temperature shields follow the reflector zone. The heavy metal molten salt as a coolant was also used in the zones of reflector, replaceable shield and high temperature shields. Table 1 gives the blanket zones and their components.

Calculation Method

One-dimensional S_N calculations were carried out for a cylindrical geometry with the aid of the SCALE 4.3 System using the 238 groups library, derived from ENDF/B-V [9]. The neutron transport calculations were carried out by solving the Boltzmann transport equation with transport code XSDRNPM [10] in S_8–P_3 approximation by using Gaussian quadratures [11]. The numerical output of XSDRNPM was evaluated with XSCALC [12] to get the main reactor parameters. The resonance calculations in the fissionable fuel element cell were made with

- BONAMI [13] for unresolved resonances and
- NITAWL-II [14] for resolved resonances.

CSAS control module [15] was utilized to extract the resonance self-shielded weighted cross-sections for XSDRNPM.

Results and Discussion

Neutron Spectrum

The neutron spectrum at various locations for the inner blanket using the coolant of 96% Flibe + 4% UF_4 is depicted in Fig. 3. It can be seen that the neutron spectrum

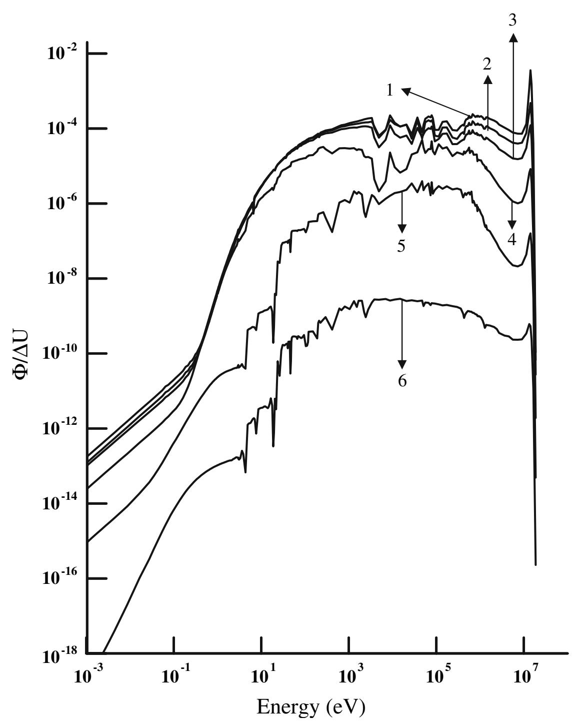

Fig. 3 Neutron spectrum at different locations of the inner blanket using 96% Flibe + 4% UF_4: (1) on the right side of the heavy molten salt zone, (2) in the middle of the heavy molten salt zone, (3) on the left side of the heavy molten salt zone, (4) on the left side of the shielding zone, (5) on the left side of the HT zone, (6) leakage spectrum

softening takes place by deeper penetration through the blanket. While the primary fusion neutrons coming from fusion plasma dominate at the right side of the FBZ, the secondary neutrons generating from fission and collisions become dominant in the FBZ. Neutron attenuation through the inner blanket is 5–6 orders of magnitude at intermediate and high neutron energies.

Figure 4 represents the neutron spectrum at different locations of the outer blanket containing the same coolant. Again, the neutron spectrum softening through this blanket can be observed clearly due to the same reason explained above. Higher neutron attenuation through the outer blanket reaching 5–10 orders of magnitude at intermediate and high neutron energies can be seen.

Tritium Breeding

A commercial (DT) driven fusion power plant must produce its own tritium. Tritium is an artificial fuel used in the (DT) fusion plasmas. It can be produced from the breeding reactions of ^{6}Li and ^{7}Li isotopes in the blanket as given below:

$$^{6}\mathrm{Li} + \mathrm{n} \rightarrow \alpha + T + 4.784\,\mathrm{MeV} \tag{1}$$

$$^{7}\mathrm{Li} + \mathrm{n} \rightarrow \alpha + T + \mathrm{n} - 2.467\ \mathrm{MeV} \tag{2}$$

Tritium breeding ratio (TBR) should be $\geq$1.05 to maintain tritium self-sufficiency of the (DT) fusion driver of the reactor. It can be achieved in the blanket containing lithium bearing coolants and/or materials.

TBR can be defined as follows:

$$\mathrm{TBR} = T_6 + T_7 \tag{3}$$

where, $T_6 = \iint \Phi \bullet \Sigma_{(\mathrm{n},\alpha)\mathrm{T}} \mathrm{d}E\, \mathrm{d}V$ on ^{6}Li, and $T_7 = \iint \Phi \bullet \Sigma_{(\mathrm{n,n}'\alpha)\mathrm{T}} \mathrm{d}E\, \mathrm{d}V$ on ^{7}Li.

Figure 5 shows the change in the TBR per incident fusion neutron for the blanket using two different molten salts with different mole fractions of heavy metals. One can observe that TBR decreases gradually with increasing heavy metal content of both molten salts. Higher TBR values can be reached for the molten salt with UF_4 than that with ThF_4 due to the fact that uranium increases neutron economy by making more fission compared to thorium (Fig. 6). Tritium self-sufficiency is maintained in the blanket only for the coolants; 98% Flibe + 2% UF_4, 96% Flibe + 4% UF_4 and 98% Flibe + 2% ThF_4. The major

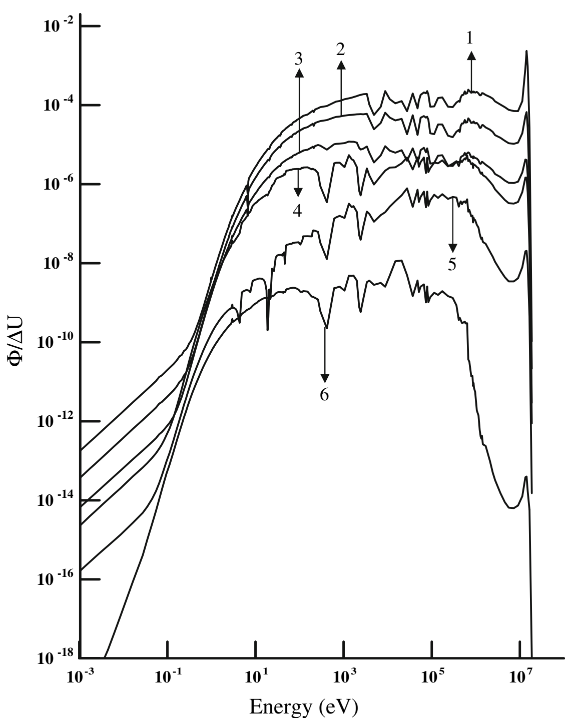

Fig. 4 Neutron spectrum at different locations of the outer blanket with 96% Flibe + 4% UF_4: (1) on the left side of the heavy molten salt zone, (2) in the middle of the heavy molten salt zone, (3) on the right side of the heavy molten salt zone, (4) on the right side of the shielding zone, (5) on the right side of the HT zone, (6) leakage spectrum

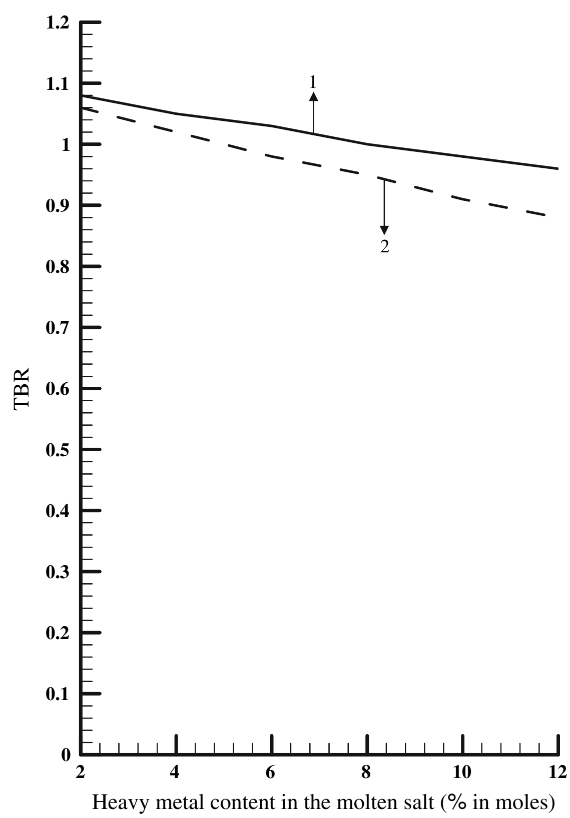

Fig. 5 TBR variation with respect to the molten salt composition for the blanket with: (1) Flibe + UF_4, (2) Flibe + ThF_4

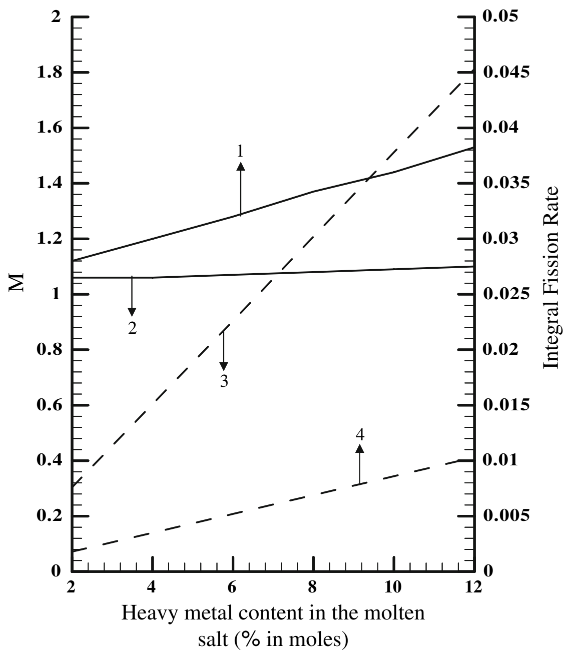

Fig. 6 Energy multiplication versus heavy metal content with (1) Flibe + UF_4, (2) Flibe + ThF_4 and integral fission versus heavy metal content with (3) Flibe + UF_4, (4) Flibe + ThF_4 (per incident fusion neutron)

part of tritium is bred by ^{6}Li (Table 2), whereas, almost all of it is produced in the FBZ of the blanket. The contribution of other zones (reflector, replaceable shield and high temperature) to TBR is very low.

Energy Multiplication

Incident fusion energy can be amplified in the blanket by exothermic nuclear energy reactions, namely neutron capture in ^{6}Li and fission by heavy metal in the molten salt in addition to the kinetic energy transfer of the fusion source neutrons. Although the fission is in a relatively modest level for the investigated blanket (Fig. 6), energy release per fission is considerably higher than per fusion event. Hence, there can be an important contribution of the fission energy release to total plant power production depending on heavy metal content in the coolant so that electricity generation can be increased remarkably. M can be defined as follows:

$$M = \frac{200 * \langle \Phi \bullet \Sigma_f \rangle + 4.784 * T_6 - 2.467 * T_7 + 14.1}{17.6} \quad (4)$$

where, $\langle \Phi \bullet \Sigma_f \rangle = \iint \Phi \bullet \Sigma_f dE\, dV =$ Total integral fission rate.

One can see from Fig. 6 that the M increases gradually with respect to UF_4 content reaches 1.53 for the coolant 88% Flibe + 12% UF_4. However, it slightly changes with respect to ThF_4 content and remains almost constant at relatively low levels. It is due to the fact that the integral fission rate in uranium is much more than thorium.

Use of heavy metal in the Flibe causes the production of gaseous fission products. However, the fission rate in the coolant remains modest and the flowing coolant is removed and circulated continuously out of the reactor chamber to extract fissile fuel. A very short residence time for gaseous fission products in the chamber would take place.

Table 2 Contribution of ^{6}Li (T6) and ^{7}Li (T7) on TBR in the blanket with various coolants

Heavy metal molten salt	T6	T7
98% Flibe + 2% UF_4	0.94	0.14
96% Flibe + 4% UF_4	0.92	0.13
94% Flibe + 6% UF_4	0.90	0.13
92% Flibe + 8% UF_4	0.88	0.12
90% Flibe + 10% UF_4	0.86	0.12
88% Flibe + 12% UF_4	0.85	0.11
98% Flibe + 2% ThF_4	0.93	0.13
96% Flibe + 4% ThF_4	0.89	0.13
94% Flibe + 6% ThF_4	0.86	0.12
92% Flibe + 8% ThF_4	0.83	0.12
90% Flibe + 10% ThF_4	0.79	0.12
88% Flibe + 12% ThF_4	0.76	0.12

Fissile Fuel Production

In addition to fission, fissile fuel breeding occurs in the heavy metal molten salt by converting the ^{238}U to ^{239}Pu, and ^{232}Th to ^{233}U via neutron capture reactions depending on the composition of the molten salt. One of the most important benefits gained from the heavy metal molten salt is the fissile fuel production to be used in conventional nuclear fission reactors. Fresh fissile fuel can be separated from the circulating molten salt in the blanket by a chemical process continuously. This would eliminate the partial burning of the new fissile isotopes in the blanket under energetic fusion neutrons.

Figure 7 shows the total fissile fuel breeding rate and the annual fissile fuel production with respect to the heavy metal content in the salt. It is clear that both of them increases linearly with increasing heavy metal. Although, the fissile fuel production is ~400 kg ^{239}Pu/year with the molten salt 98% Flibe + 2% UF_4, it reaches ~2400 kg ^{239}Pu/year for the molten salt 88% Flibe + 12% UF_4. The similar amount of fissile fuel breeding is available for the molten salt with thorium.

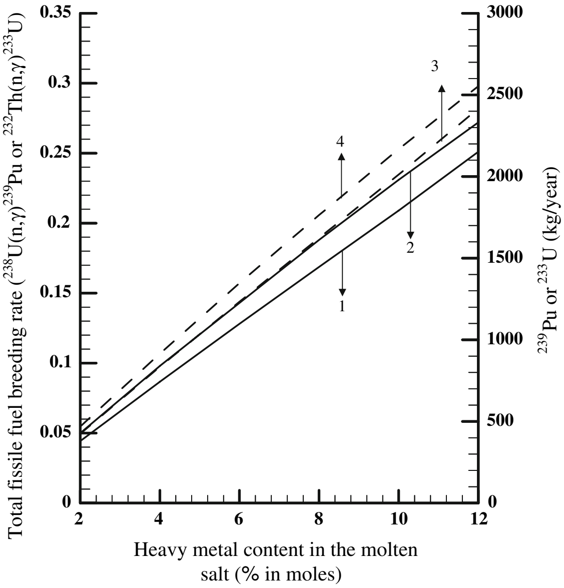

Fig. 7 Total fissile fuel breeding rate (1) $^{238}U(n,\gamma)^{239}Pu$, (2) $^{232}Th(n,\gamma)^{233}U$ and annual fissile fuel production (3) ^{239}Pu, (4) ^{233}U with respect to the heavy metal content

Use of the molten salt Flibe + UF_4 leads to the production of a precious nuclear fuel, ^{239}Pu with a market value of 80,000 \$/kg. The revenue from the fissile fuel breeding by the molten salt, Flibe + UF_4, can become 32 and 192 M\$/a for 2% UF_4 and 12% UF_4, respectively. In the case of Flibe + ThF_4 and for a market value of 300,000 \$/kg for ^{233}U, the revenue becomes 140 M\$/a for 2% ThF_4 and can increase up to 750 M\$/a for 12% ThF_4. This would greatly reduce total electricity cost per kWh.

Conclusions

Among the investigated salts, only the Flibe with 2% UF_4 or ThF_4 and 4% UF_4 supplied sufficient tritium breeding. Addition of higher heavy metal salts degraded tritium production and decreased below 1.05. Therefore, the molecular percentage of ThF_4 and UF_4 in the molten salt mixture should not exceed 3 and 4, respectively. Although, the energy multiplication was at low levels and practically not affected by the Flibe with ThF_4, it gradually increased with UF_4 content for the Flibe + UF_4. Substantial amount of fissile fuel was produced by using heavy metal molten salt in the blanket. This would have a significant positive impact on decreasing the cost of electricity generated.

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