Investigation of neutronic performance of a peaceful nuclear explosive reactor (PACER) evaluating UF_4 and ThF_4 nuclides

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Abstract. In this study, neutronic behaviour of a peaceful nuclear explosion reactor (PACER) producing approx 1.2 GWe power from fusion explosions is analysed considering ThF_4 and UF_4 as fissile zones. UF_4 and ThF_4 are put in to the system adjacent to the inner-side of the flibe coolant zone positions (distance between explosive region and fuel zone, $DR = 50, 100, 200, 400, 500$ and 700 cm). Flibe percentages are taken to be 25, 50, 75 and 100%. It is found that optimum combinations of fissile zone thickness, coolant zone position and coolant percentages are 10 cm, 200 cm and 25% flibe for UF_4 and 10 cm, 50 cm and 25% flibe for ThF_4 . The behaviour of fuels mentioned above has been observed over a period of 30 years at discrete time intervals, $\Delta t = 30$ days. In the case of UF_4 , M values at $DR = 200$ cm reach 5.35, 5.22, 4.88, and 4.88 from 3.12, 2.98, 2.83 and 2.83, for 25, 50, 75, 100% flibe respectively. For ThF_4 at $DR = 50$ cm, M values reach from 1.61, 1.54, 1.50 and 1.46 to 1.93, 2.00, 2.04 and 1.99 for 25, 50, 75, 100% flibe respectively. Cumulative fissile fuel breeding (CFFE) values reach up to 5.5 from 0.7 at $DR = 200$ and 25% case for UF_4 , and up to 6.36% from 0%, at $DR = 50$ and 25% flibe, for ThF_4 , at the end of the operation period.

Keywords. Neutronic performance; peaceful nuclear explosive reactor; PACER; fusion explosions; flibe coolant.

1. Introduction

Motivation for pursuing controlled fusion is not based solely on technological and economic factors. Widespread introduction of fusion energy power plants could substantially reduce the environmental impacts of increasing worldwide demands for electricity. A reliable and secure electricity supply could ensure that energy needs associated with continued economic growth are satisfied. The safety of fusion power plants would provide additional ecological benefits that should help to promote public interest in the goal of substantial production capacity for fusion energy in the future. However, a number of issues associated with fusion power must be considered before controlled fusion can reach its potential as an environmentally benign source of energy.

There are three fusion reactor models. These are magnetic confinement fusion (MCF), inertial confinement fusion (ICF), and peaceful nuclear explosive reactors (PACER). MCF and ICF fusion reactors have some problems such as plasma instability, high material damage, high radiation, sensitive fluid jet design, high driver power requirement, expensive material requirement, higher cost of electrical power and other complex problems. In the near future, solutions to these problems appear almost impossible. However, problems in PACER are simpler to solve than those in MCF and ICF reactors. Hence, PACER reactors seem to be a more attractive option than other fusion reactors.

The PACER concept considered for electrical energy production from repetitive nuclear explosions has been studied in the literature (Teller *et al* 1968; Hammond *et al* 1982; Moir 1989; Call *et al* 1990; Szöke *et al* 1991a; Szöke *et al* 1991b; Sahin *et al* 1994b; Ünalán *et al* 2003; Ünalán *et al* 2004). In these concepts, the explosive chamber in cylindrical form or in spherical form has been considered; in an underground cavity, to provide high safety. The main parameters of the reactors considered such as explosion yields, repetition periods and cavity radii have been preferred up to 20-kt nuclear explosion, 7 hours and 100 m respectively (Hammond *et al* 1982; Moir 1989; Call *et al* 1990; Szöke *et al* 1991a; Szöke *et al* 1991b; Sahin *et al* 1994b; Ünalán *et al* 2003; Ünalán *et al* 2004). In these approaches, explosion energy is absorbed by various working fluids flowing vertically, protecting the chamber wall against the explosion effects and surrounding the explosive region in the chamber centre. Especially, in the last works, to reduce effects of shock forces from explosives on rock structure, the chamber with stainless steel liner was considered. Flibe (Li_2BeF_4) was preferred as work fluid because it has high nuclear (tritium breeding, neutron absorption etc.) and thermal (high evaporation temperature) performance. In past studies, structural features of the PACER reactor, the activation hazard, caused by fusion neutrons on rocks, the stainless steel liner with optimal coolant thickness, required in terms of more energy absorption, and enough tritium breeding have been investigated (Sahin *et al* 1994; Ünalán & Akansu 2003, 2004). However, chemical effects of the fission products released by the explosion on the flibe coolant have not been considered. If the effects of fission products on the reactor performance and flibe coolant are ignored, the use of fissionable nuclides such as UF_4 and ThF_4 should have been considered as a fuel in the PACER reactor to produce more energy and new fissile fuel enrichment.

2. Blanket geometry and problem description

In this study, emphasis is on a detailed neutronic performance of the PACER reactor, which uses fissionable nuclides such as UF_4 and ThF_4 . For this purpose, calculations were carried out for various positions of the coolant zone in the chamber and different masses of the fissionable fuels.

Neutronic analysis is carried out on the PACER blanket geometry described earlier Sahin *et al* (1994b) and Ünalán & Akansu (2003, 2004). Figure 1 shows the basic structure of the reactor adopted from Sahin *et al* (1994b) and Ünalán & Akansu (2003, 2004) for this work, where all steel structures such as pipelines and liners are made of SS-316, which is compatible with flibe. The realistic approach considered for determination of the coolant zone corresponds to a coolant zone configuration that occurs in practice. In this approach, before the explosion processes, the flibe zone geometry shown in figure 1 would occur approximately with injection of cold flibe by means of the injection system on the top of the chamber, and the explosion process would carry on simultaneously with this coolant zone configuration. At the same time, flibe injection would stop with the explosion process. According to previous study, the best neutronic performance and first wall protection have been shown by flibe (Li_2BeF_4)

Figure 1. Cross-sectional view of the blankets (dimensions in metres, not drawn to scale).

(Sahin *et al* 1994). Thus, in this work only flibe is preferred as a coolant. In the calculations, a mechanism such as fission or chemical bomb burned fusion fuel and the effects of the fusion bomb materials on the fusion neutrons are ignored. For simplicity, neutronic calculations were performed in one-dimensional spherical geometry. The normalization factor was based on the assumption that 1.2 GW electrical power is produced with 35% thermodynamic efficiency.

Neutronic calculations, the best position for the coolant zone (DR) in the reactor chamber and optimal coolant thickness (DR_c) for each position in terms of higher energy absorption and enough tritium breeding with lower flibe mass were investigated (Ünalan & Akansu 2003, 2004). In coolant zone (DR) of reactor chamber as determined, volume fraction applied was 100% flibe, 25% void + 75% flibe, 50% void + 50% flibe and 75% void + 25% flibe. Positions of coolant zone were selected as $DR = 50, 100, 200, 400, 500$ and 700 cm. Saturation coolant zone thicknesses (DR_c) were different according to tritium breeding ratio (TBR) and M . When flibe percentages were increased, DR_c was observed to reduce. However, while DR positions were increased, saturation thickness DR_c showed almost no change. Table 1 shows the DR_c saturation values all DR values and flibe percentages (Ünalan & Akansu 2003, 2004).

In this study, according to TBR saturated points in table 1, for all DR values, neutronic calculations are investigated using UF_4 and ThF_4 materials. For high neutronic performance, UF_4 and ThF_4 between the first wall and explosive region with the optimal coolant thickness can be considered. Neutronic calculations are performed on various thicknesses of the fissile zone (DR_f) consisting of UF_4 and ThF_4 in fluid state, flowing vertically adjacent to the coolant zone – between explosive region and the coolant zone. The flow process in vertical direction of fissionable nuclides can be provided by a pipe system coupled to the inner-side of the mechanism injecting flibe. Thus, the zone including UF_4 and ThF_4 can absorb neutrons released from explosive. Energy production is increased by fission reactions occurring in the fissile zone.

Table 1. DR_C saturation points for $TBR = 1.27$ and $M = 1.07$.

$DR(\text{cm})$	25% flibe	50% flibe	75% flibe	100% flibe
$TBR = 1.27$				
50	422	209	140	101
200	400	200	135	100
400	391	194	127	98
700	382	191	124	97
$M = 1.07$				
50	312	151	99	74
200	300	146	97	73
400	283	140	95	72
700	274	138	94	71

UF_4 and ThF_4 thicknesses change with fissile zone thickness (DR_f) 0–20 cm, which is put in to place according to saturation points in table 1. In addition, the calculations are repeated for different volume fractions of flibe and void. This serves an easier vaporization process because of expanding to larger volume. Namely, vaporization capability of flibe is to be increased. Volume fractions are preferred as 100% flibe, 25% void + 75% flibe, 50% void + 50% flibe and 75% void + 25% flibe. In these calculations, it has been thought that void is not affected by the neutronic behaviour. During the calculations, the most pertinent nuclear reactions, which have been considered in the course of burn-up calculations, are given in table I of Ünalán & Akansu (2003).

3. Numerical results

3.1 Calculation tools

Neutronic calculations have been performed on the Personal Computer with a P-III coprocessor at 500 MHz by solving the Boltzman transport equation with the neutron transport code ANISN/PC (Engle 1970) using the neutron transport and activity cross-section data libraries TRANSX-2 (Macfarlane 1993) and CLAW-IV (Al-Kusayer *et al* 1988). The latter represents an extended version of the Los Alamos National Laboratory (LANL) cross-section data library CLAW (Barrett & Macfarlane 1979). Neutron cross-sections are averaged over 30 energy groups using the Bondarenko (1964) flux approximation with fusion, fission, $1/E$ and thermal weight functions. The energy structure is such that it has 12, 9 and 9 neutron groups in the MeV, keV and eV ranges, including thermal regions respectively. The integration of the angular neutron flux has been done in S_{16-P_3} approximation by using Gaussian quadrature sets. The numerical output of the ANISN calculations have further been processed using the auxiliary code ERDEMLI (Sahin *et al* 1991) to evaluate specific information for this work.

3.2 Tritium breeding ratio

Neutronic variations occurring in the performance in case of the use of UF_4 and ThF_4 in fluid state vertically flowing with position adjacent to the coolant zone – between explosive region and the coolant zone providing enough tritium breeding are investigated. Certainly,

selected fissionable nuclides have to be used continuously in the PACER reactor because of very large fuel requirement and economic difficulties. Namely, the fissionable fuel used at start up of operation period will be evaluated up to end of operation period. For this purpose, certain mass of these fissionable fuels must be circulated for certain periods. After cleaning and separation processes, fissionable fuels can be injected again in the reactor chamber.

While the best position in the reactor chamber and the optimal coolant thickness were determined, main parameters were selected as neutron economy, enough tritium breeding and higher rate absorption rate of fusion neutron energy respectively. While many fusion neutrons should be absorbed by flibe to decrease the effects on first wall material (SS-304) and to capture the fusion energy, tritium breeding capability of a fusion reactor must be slightly higher than tritium consumption ($TBR > 1$).

Figure 2 shows plots of TBR values versus the fissile zone thickness (DR_f). According to this figure, maximum values of TBR are 25% flibe and $DR = 50$ cm. For UF_4 , TBR values increase up to $DR_f = 5$ cm in all flibe percentages and $DR = 50$ cm. In this point, TBR is maximum. However, for ThF_4 , TBR values decrease continuously with increasing DR_f . When flibe percentages increase, TBR values decrease. While TBR values reach a maximum value at a certain DR_f value for UF_4 especially, they decrease continuously with increasing DR_f for ThF_4 . For 25% flibe + 75% void and $DR = 50$ cm, TBR values calculated for UF_4 with $DR_f = 5$ cm increase from 1.3 to 1.42 respectively. After these maximal values of TBR, TBR values decrease when the DR and flibe percentage values increase. Generally, a fissile zone thickness of DR_f will be valid for all cases according to criteria $TBR = 1.1$ which also indicates enough tritium breeding.

3.3 Energy production

M values (the total energy released in the fuel zone in $MeV/14.1 MeV + 1$) characterize the energy multiplication ratio in the PACER reactor. Variation of M versus the fissile zone thickness (DR_f) is depicted in figure 3. According to this figure, energy production is not affected with increasing volume fraction of flibe in PACER reactor. Generally, fissionable nuclides composed of uranium show better performance than fissionable nuclides composed of thorium. For higher energy production with use of lower fissionable nuclides, the PACER reactor should be at a position adjacent to the explosion region. Table 2 shows DR_f thickness and M values with sufficient tritium breeding ($TBR = 1.1$).

As seen in table 2, M values vary between 3.69 and 1.37 for 25% flibe UF_4 , $DR = 50$ cm and 25% flibe ThF_4 , $DR = 700$ cm respectively. The maximal values of M are 3.69 and 1.37 in UF_4 and ThF_4 respectively. At start up, M increased 28% and 262% in UF_4 and ThF_4 materials respectively, with respect to absence of these materials. These values are most important regarding their future energy requirement as fissionable nuclides.

3.4 Temporal variation of the reactor performance

In order to study the temporal variation on the neutronic performance of the PACER reactor fuelled with UF_4 and ThF_4 , initial fuel mass required for an operation time of 30 years should be estimated at discrete time intervals of $\Delta t = 30$ days. Initial fuel mass can be varied during reactor lifetime in terms of economic feasibility and fuel management. Flibe coolant must be circulated as per certain circulation schedules. In this case, temporal performance of the PACER reactor varies because temporary performance of MCF-driven hybrid reactors have varied as a function of the rejuvenation period (Sahin *et al* 1994; Ünalán & Akansu 1998;

Figure 2. TBR values vary according to the fissile zone thickness (DR_f) respectively.

Figure 3. Variation of M versus the fissile zone DR_f .

Table 2. DR_f thickness and M values for TBR= 1.1.

$DR(\text{cm})$	25% Flibe		50% Flibe		75% Flibe		100% Flibe	
	Dr_f (cm)	M	Dr_f (cm)	M	Dr_f (cm)	M	Dr_f (cm)	M
<i>UF₄</i>								
50	16	3.69	13	3.42	12	3.31	12	3.32
200	10	3.12	9	2.98	8	2.83	8	2.83
400	9	2.99	8	2.84	8	2.84	8	2.85
700	8	2.84	8	2.85	8	2.85	8	2.86
<i>ThF₄</i>								
50	10	1.61	8	1.54	7	1.50	6	1.46
200	5.5	1.45	4.2	1.38	4	1.37	4	1.37
400	5	1.43	4	1.38	4	1.38	4	1.38
700	4	1.37	4	1.38	4	1.38	4	1.38

Ünalın 1998; Yapıcı *et al* 2000; Akansu & Ünalın 2002; Yapıcı 2002; Yapıcı & Ipek 2003). TBR values are not shown because if TBR is adequate initially, it increases during the operation period. Moreover, values of TBR versus the operation period show little increase (Sahin *et al* 1994; Ünalın & Akansu 1998; Ünalın 1998; Yapıcı *et al* 2000; Yapıcı 2002; Ünalın *et al* 2003; Yapıcı & Ipek 2003). For this reason, TBR values are not given.

Temporal variations of the PACER are investigated in table 2. Figures 4a and b depict M values versus the operation period for ThF₄ and UF₄ respectively. (In this figure, plots of 75% and 100% flibe percentages are not given). When the operation period is increased, M values also increase. In figure 4a, for $DR = 200, 400, 700$ cm and flibe percentages other than 50%, M values do not alter much. For $DR = 50$ cm and 25%, 50%, 75% and 100% flibe, M values reach 1.94, 2.01, 2.3 and 1.99 from 1.61, 1.54, 1.50 and 1.46 in 30 years respectively. UF₄ material has better performance than ThF₄ material. In figure 4b, M value is highest in $DR = 50$ cm for all flibe percentages. For $DR = 50$ cm, M values reach highest values 13.75, 11.9, 11.71 and 12.3 for 25%, 50%, 75% and 100 % flibe in eight years. However, M values decrease with increasing DR thickness and flibe percentages after 8 years. At the end of the operation period, M values reach 4.75, 5.35, 3.51, and 3.08 for 25% flibe and 75% void and $DR = 50, 200, 400$ and 700 cm respectively. As seen in this figure, M values are lower than $DR = 200$ cm for $DR = 50$ cm. With increasing flibe percentage, M values also increase but not too much.

Figures 5a and b show cumulative fissile fuel breeding (CFFE) values versus the operation period for ThF₄ and UF₄ respectively (In this figure, plots of 75% and 100% flibe percentages are not given). In figure 5a, for $DR = 200, 400, 700$ cm and all flibe percentages, CFFE values are seen to be unsuitable. For $DR = 50$ cm, CFFE values reach 6.3, 8.7, 10.05 and 11.58, for 25%, 50%, 75% and 100% flibe percentages respectively. While DR thickness is increased, CFFE values reduce. In figure 5b, rate of increase of CFFE values rises very fast up to 8 years. After 8 years, increase in rate of CFFE values decreases for $DR = 50$ cm of all % flibe values. It is observed that energy multiplication ratio of PACER reactor increases continuously as a function of reactor operation time. For $DR = 700$ and 400 cm, CFFE values do reach desired values. Therefore, it may be said that the best combination is $DR = 200$ cm and 25% flibe for UF₄. But, for ThF₄, DR thickness must be smaller than UF₄. Because, when DR increases,

Figure 4. Variation of energy multiplication rate versus reactor operation period in 25 and 50% flibe for ThF_4 (a) and UF_4 (b).

Figure 5. Accumulation of the fissile isotopes in the fissionable fuel present in the blanket during reactor operation period in 25 and 50% flibe for ThF₄ (a) and UF₄ (b).

CFFE values are even lower than the level that can be used. Then, for ThF_4 , $DR = 50$ cm distance and flibe percentage 25% are suitable.

Increasing flibe percentage is not a reasonable way, because pump, preparation and separation costs also increase. However, if DR thickness is reduced, M value is uncontrollable. If DR is increased, energy production increases for UF_4 . Therefore, we can say that $DR = 200$ cm is suitable in 25% flibe, 75% void.

3.5 Safeguard aspects of the plutonium component and the uranium component

It would be important to follow the non-proliferic level of the plutonium fuel during operation because of nuclear weapons hazard. The intensity of spontaneous fission neutrons in ^{240}Pu is about 50,000 times higher than that in ^{239}Pu so that only a few percent of ^{240}Pu would denature the plutonium generated to a non-proliferic level.

Previous analyses indicated that the ^{240}Pu content must be $< 5\%$ in weapon grades of plutonium fuel. Table 3 shows the isotopic percentages of important plutonium components versus reactor operation time. According to table 3, the isotopic percentages of ^{240}Pu in the plutonium component at the end of operation are found to be $\approx 5\%$ and $\approx 50\%$, 75% and 100% flibe for $DR = 200$ cm. In $DR = 200$ cm and 25% flibe case, ^{240}Pu is smaller than 5%. Hence, this plant power must be denatured.

4. Conclusions and recommendations

This study analysed the neutronic behaviour occurring in case of use of ThF_4 and UF_4 in PACER reactor chamber producing electrical energy of ≈ 1.2 GW with a thermodynamic efficiency of 35% from fusion explosions repeating in every 40 minutes and with different coolant zone positions having optimal thickness for enough tritium breeding and fusion energy absorption. The main conclusions are made as follows:

- (1) The maximal values of M are 3.69 and 1.37 in UF_4 and ThF_4 respectively. At start up, M increased 28% and 262% in UF_4 and ThF_4 materials, respectively, with respect to absence of these materials. These values are obtained by means of evaluation of fissionable nuclides, which is not attractive for present thermal reactors, but may prove to be very interesting in terms of the energy requirements of the future.
- (2) It is concluded that the optimum position for DR is 200 cm and 25% flibe for UF_4 because of the small amount of flibe, enough tritium, and more suitable energy production. However, for ThF_4 , DR thickness must be smaller than for UF_4 . This is because, when DR increases, CFFE values are even less than the level that can be used. Thus, for ThF_4 , suitable DR distance is 50 cm and flibe concentration is 25%.
- (3) CFFE (cumulative fissile fuel enrichment) values increase during operations. Therefore, if the values in parentheses indicate CFFE values required in order to use as fuel in a reactor, the fuel from PACER reactor can be used as fuel in CANDU ($\approx 0.8\%$)-advanced CANDU ($\approx 1\%$) at the beginning of operation period, LWR ($\approx 3.5\%$) at the middle of operation period (≈ 20 years) and in advanced LWR ($\approx 5\%$) at the end of operation period for $DR = 200$ cm, $DR_f = 10$ (UF_4) cm and 25% flibe.

The following recommendation can be made for future studies.

- (1) For cleaning and separation of the depositing fission products released from fission reactions, a mechanism, system or plant that can run continuously and a suitable PACER

Table 3. Isotopic fraction (%) of plutonium components during the period of operation (T).

T [years]	$DR = 50$ cm		$DR = 200$ cm		$DR = 400$ cm		$DR = 700$ cm	
	^{239}Pu	^{240}Pu	^{239}Pu	^{240}Pu	^{239}Pu	^{240}Pu	^{239}Pu	^{240}Pu
<i>25 % flibe + 75 % void</i>								
1	96.87	2.20	99.80	0.14	99.89	0.05	99.78	0.06
5	80.88	13.27	98.93	0.77	99.71	0.21	99.87	0.08
10	63.99	24.69	97.81	1.57	99.43	0.41	99.79	0.14
15	54.34	30.67	96.68	2.38	99.14	0.62	99.70	0.21
20	48.83	33.50	95.54	3.19	98.86	0.83	99.61	0.28
25	45.31	34.87	94.38	4.01	98.57	1.04	99.52	0.35
30	42.82	35.50	93.22	4.84	98.28	1.25	99.42	0.42
<i>50 % flibe + 50 % void</i>								
1	96.82	2.24	99.79	0.14	99.89	0.05	99.79	0.06
5	80.75	13.33	98.87	0.82	99.70	0.21	99.87	0.08
10	63.91	24.65	97.70	1.67	99.41	0.43	99.79	0.15
15	54.02	30.76	96.51	2.52	99.12	0.64	99.70	0.22
20	48.28	33.73	95.31	3.38	98.82	0.86	99.60	0.29
25	44.55	35.19	94.10	4.25	98.52	1.08	99.51	0.36
30	41.88	35.87	92.88	5.12	98.22	1.30	99.41	0.43
<i>75 % flibe + 25 % void</i>								
1	96.73	2.31	99.79	0.15	99.89	0.05	99.79	0.06
5	80.23	13.77	98.85	0.83	99.70	0.22	99.87	0.08
10	63.06	25.32	97.66	1.70	99.40	0.43	99.79	0.15
15	53.10	31.44	96.45	2.56	99.10	0.65	99.70	0.22
20	47.32	34.36	95.23	3.44	98.80	0.88	99.60	0.29
25	43.56	35.74	94.00	4.31	98.50	1.10	99.50	0.36
30	40.84	36.35	92.77	5.19	98.20	1.32	99.41	0.44
<i>100 % flibe</i>								
1	96.64	2.41	99.78	0.15	99.89	0.05	99.79	0.06
5	79.43	14.47	98.84	0.85	99.70	0.22	99.87	0.08
10	61.67	26.48	97.63	1.72	99.40	0.44	99.79	0.15
15	51.72	32.51	96.40	2.61	99.10	0.66	99.69	0.22
20	46.05	35.23	95.17	3.50	98.80	0.88	99.60	0.29
25	42.36	36.44	93.92	4.39	98.49	1.10	99.50	0.36
30	39.66	36.88	92.67	5.28	98.19	1.33	99.40	0.44

reactor structure has to be developed. Chemical reactions occurring between fission products, flibe and other reactor materials have to be determined by more detailed studies.

- (2) Some part of the energy produced by means of fissionable nuclides in PACER reactor will be spent in separation and cleaning processes. For this purpose, economic feasibility of this process must be calculated in future studies.
- (3) In future work, % flibe + % fuel (ThF_4 or/and UF_4) + % void mixture can be investigated.

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