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Influence of Nuclear Fuel Cycle Duration and Reprocessing Losses Level on the Nuclear Power System Structure

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It is shown that three-component Nuclear Power (NP) system consisting of thermal reactors (TR), fast reactors (FR) and molten salt reactors-burners (MSR) can operate in mode when actinides in system are not stored up proportionally to energy generated but are practically at steady level proportionally to system power.

In the paper there was considered the influence of nuclear fuel cycle (NFC) duration and level of irretrievable reprocessing losses on NP structure and fuel consumption efficiency.

U-Pu and U-Th variants of NP systems were considered with various levels of irretrievable reprocessing losses for all actinides - 0%, 0.1% и 1%, and various duration of cooling and reprocessing time of TR fuel cycle (TRR time) – 3 years, 6 years, 9 years, 20 years. Steady state calculations were performed for three-component NP systems and there were obtained steady state amounts and radioactivity of actinides for main components of NFC closed by actinides. Also, there were obtained rates and radioactivity of accumulation of actinide irretrievable reprocessing losses.

KEYWORDS: actinides, molten salt reactor-burner, nuclear fuel cycle duration, reprocessing losses, steady state calculations, three-component Nuclear Power, U-Pu, U-Th

1. Introduction

It is shown [1] that three-component Nuclear Power system consisting of TR, FR and MSR can operate in mode when actinides in system are not stored up proportionally to energy generated but are practically at steady level proportionally to system power. MSR has a considerable potential to improve efficiency of NFC closed by actinides without decreasing the level of safety of solid fuel reactors with respect to reactivity accidents. In addition, it seems possible after gathering experience to improve MSR efficiency by varying input nuclide compositions.

This system can operate during long time in conformity with ecological requirements. Parameters of this system depend considerably not only on reactor parameters but also on actinide irretrievable reprocessing losses and NFC duration.

2. Nuclear Fuel Cycle Modeling

2.1 Radioactive Waste Minimization

Nuclear fuel cycle consists of different types of nuclear reactors, nuclear fuel cycle plants (fabrication, reprocessing, intermediate storage, final repository) and radioactive nuclides processed in them.

Nuclear power lifetime can be divided into 3 stages:

Initial stage – energy production grows and structure forms;

Equilibrium stage – energy production and nuclear power structure are stable and only fuel to compensate burning and radioactive waste (RAW) losses is extracted, and new components are only constructed to replace decommissioned ones with the same type and power;

Final stage – gradual decommission of nuclear power plants and RAW problem final solution.

It is reasonable to expect that equilibrium stage must be much longer then initial and final stages.

Therefore, the equilibrium stage determines both problem of minimization of RAW generation and accumulation and problem of elimination of all dangerous nuclides and fission products on the final stage. This statement allows us later to consider mainly equilibrium stages of nuclear power lifetime. We assume that acceptability of equilibrium stage of nuclear power is an essential condition of long-term nuclear power acceptability.

Nuclear power structure modeling for equilibrium stage allows performing NFC optimization to minimize RAW amount and improve fuel (^{238}U and/or ^{232}Th) consumption efficiency.

It is clear that fission products amount is proportional to energy production and cannot be reduced. It is possible only to transmute more dangerous fission products into less dangerous ones, with additional neutron consumption. But problem of fission products is not developed enough to formulate real requirement for fission product transmutation. Therefore, this problem does not consider in this work.

On the other hand, minimization of fissile RAW (actinides and mainly transuraniums) amount is based on the understanding that transuranium is not a waste but a fuel [1] that was produced by neutron consumption, so it must be used for energy production with maximal efficiency. All transuraniums accumulated must return to the fuel cycle, so NFC must be closed for heavy nuclides. In this case, neutron balance is improved and amount of transuraniums in fuel cycle decreases and becomes proportional to system power and not to energy production. This amount strongly depends on nuclear power structure and we can manage this structure to optimize neutron balance and amount of radionuclides in system.

2.2 Considered Variants of Nuclear Power System

U-Pu (fed by ^{238}U) and U-Th (fed by ^{232}Th) variants of NP system were considered [3, 4] with various levels of irretrievable reprocessing losses for all actinides - 0%, 0.1% и 1%, and various duration of cooling and reprocessing time of TR fuel cycle (TRR time) – 3 years, 6 years, 9 years, 20 years. Steady state calculations were performed for three-component NP systems and there were obtained steady state amounts and radioactivity of actinides for main components of NFC closed by actinides. Also, there were obtained rates and radioactivity of accumulation of actinide irretrievable reprocessing losses.

For NFC modeling the following nuclear power components were selected:

(TR) – thermal reactor VVER-1000 type, average neutron flux $3\cdot10^{14}$ neutron/(cm$^2\cdot$s), fuel irradiates during 3 years; spent fuel cooling and reprocessing time was assumed 3 years, 6 years, 9 years and 20 years;

(FR) – fast reactor BN-1600 type, average neutron flux $2\cdot10^{15}$ neutron/(cm$^2\cdot$s), fuel irradiates during 3 years; spent fuel cooling and reprocessing by existing technology take 3 years;

(MSR) – molten salt reactor-burner [2], average neutron flux $5\cdot10^{15}$ neutron/(cm$^2\cdot$s) was adopted for MSR transmutation zone.

Three levels of irretrievable losses at fresh fuel fabrication and spent fuel reprocessing for all heavy nuclides were adopted:

Ideal level – without losses;
Desired level – losses are 0.1% of heavy nuclide equilibrium amount at reprocessing;
Level assumed now – losses are 1.0% of heavy nuclide equilibrium amount at reprocessing.

All results are normalized to system power of 1 GW (electrical).

2.3 Nuclear Fuel Cycle Models

Models of U-Pu and U-Th nuclear fuel cycles are shown on Figure1 and Figure 2.

FR is fed by ^{238}U or ^{232}Th and produce Pu or ^{233}U accordingly for TR and MSR to support neutron balance in system. TR also is fed by uranium or thorium. TR and MSR are fed by Pu or ^{233}U from FR. Other transuranium nuclides are burned in MSR making easier TR and FR operation and reducing irretrievable losses in fuel element fabrication. It is shown in Table 1 that in those NFC models closed by heavy nuclides a small part of MSR provides practically total minor actinides burning.

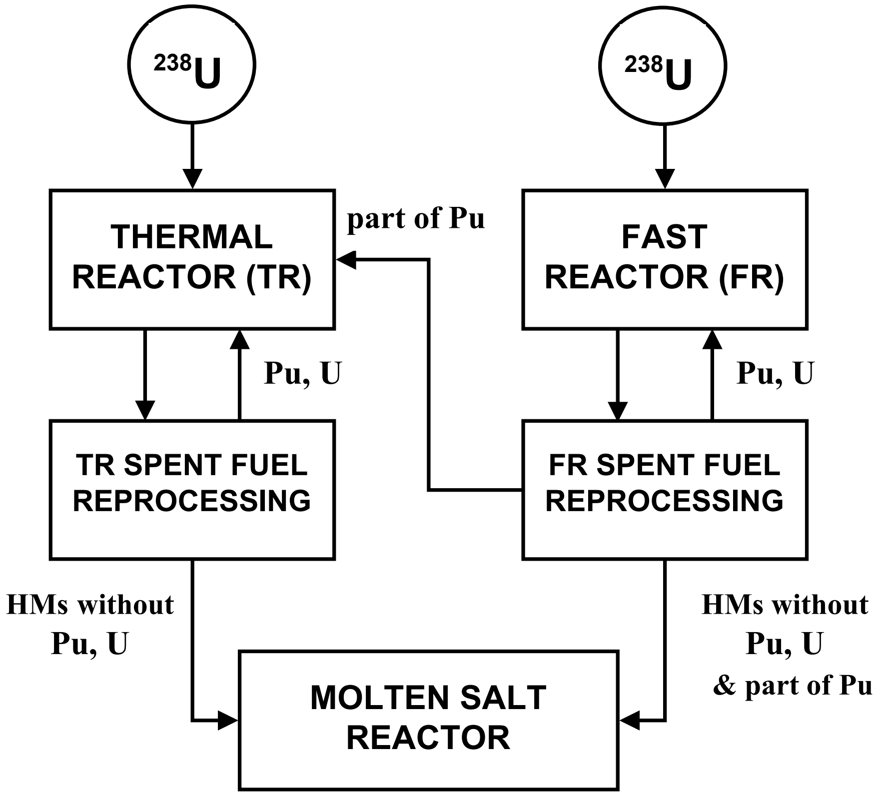

Fig. 1 U-Pu nuclear fuel cycle model

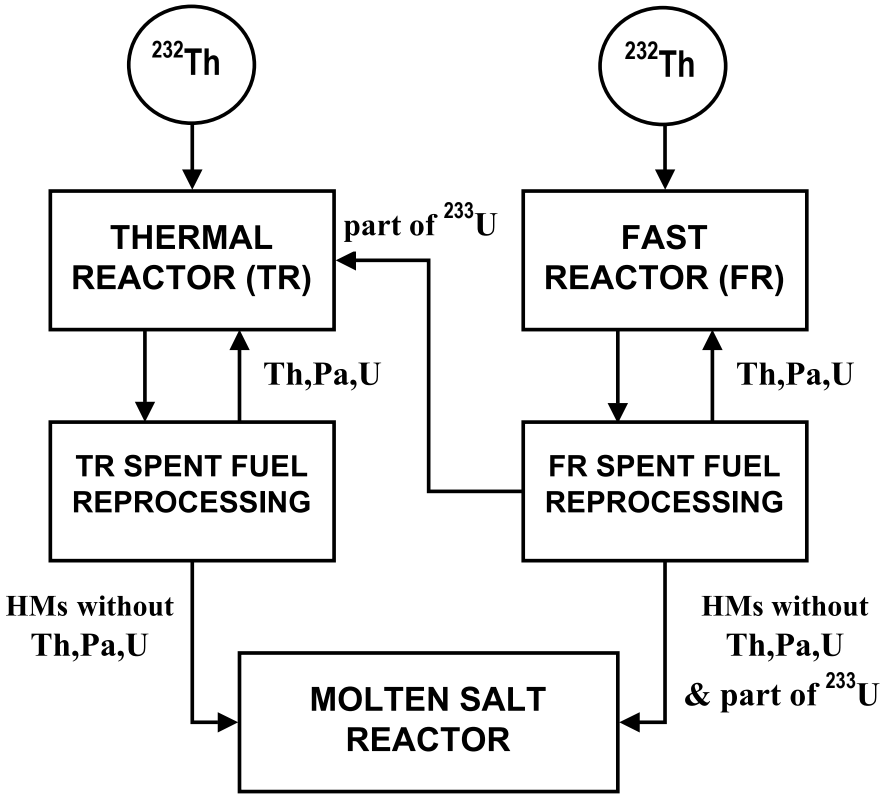

Fig. 2 U-Th nuclear fuel cycle model

2.4 The Analysis of the Obtained Results

Contribution of TR, FR and MSR to system power in dependence of TRR time and reprocessing losses level is presented in Table 1.

In NP system with U-Th NFC these values practically don't depend on TRR time but vary considerably with irretrievable reprocessing losses level varying. At 1% losses level FR contribution to system power is about 63% and MSR contribution – 2% for various TRR time. At losses level 0.1% FR contribution decreases to 48% but MSR contribution grows to 2.5%. Further decreasing of losses level practically has not an effect on system power distribution. The explanation is the fact that in U-Th NFC neutron potential is provided by long-lived ^{233}U that amount in irradiated fuel is practically stable during 20 years of TRR time. Losses of ^{233}U affects considerably on TR and FR contributions to system power because of insignificant difference in breeding characteristics of these reactors: in fast neutron spectrum thorium is less effective than ^{238}U, and in thermal neutron spectrum ^{233}U is more effective than plutonium.

The external thorium feed distribution is presented in Table 2. Similarly to component contribution to system power, this parameter practically does not depend on TRR time and depends even more on losses level.

Internal ^{233}U feed from FR (source of neutrons storied in ^{233}U) is presented in Table 3. This parameter practically does not depend on TRR time and varies with losses level varying similarly to contribution to system power.

In U-Pu NFC contribution to system power varies insignificantly with losses level decrease from 1% to 0.1% (FR contribution grows on 3%), and TRR time increasing from 3 years till 20 years results in growing of FR contribution to system power on 30%. It speaks that breeding characteristics of ^{238}U are essentially different in thermal and fast reactors, and loss of 1% of plutonium slightly affect on these reactors contribution to system power. But the increase in time of the irradiated fuel cooling and reprocessing results in essential decrease in amount of ^{241}Pu and ^{244}Cm in fuel and their corresponding replacement on essentially neutron-deficient ^{241}Am and ^{240}Pu. The MSR contribution to system power at increase in TRR time duration from 3 years up to 20 years varies practically twice.

Table 1. Component contribution to system power, %

	U-Pu nuclear fuel cycle				U-Th nuclear fuel cycle			
TRR time	3 years	6 years	9 years	20 years	3 years	6 years	9 years	20 years
Irretrievable reprocessing losses 0%								
TR	60.9	57.6	54.0	47.1	51.1	51.1	51.1	50.5
FR	32.2	34.4	36.5	40.7	46.4	46.4	46.4	47.0
MSR	6.9	8.1	9.5	12.2	2.6	2.6	2.6	2.5
Irretrievable reprocessing losses 0.1%								
TR	60.8	57.5	53.9	47.0	49.6	49.6	49.6	49.1
FR	32.4	34.5	36.7	40.9	47.9	47.9	47.9	48.4
MSR	6.9	8.1	9.4	12.1	2.5	2.5	2.5	2.5
Irretrievable reprocessing losses 1.0%								
TR	59.8	56.2	52.7	46.0	35.4	35.4	35.4	35.2
FR	33.6	35.9	38.0	42.2	62.6	62.6	62.6	62.8
MSR	6.6	7.9	9.2	11.8	2.0	2.0	2.0	2.0

Table 2. External feed distribution, for 1 GW (e)

	U-Pu nuclear fuel cycle, kg/year ^{238}U				U-Th nuclear fuel cycle, kg/year ^{232}Th			
TRR time	3 years	6 years	9 years	20 years	3 years	6 years	9 years	20 years
Irretrievable reprocessing losses 0%								
TR	509	476	443	379	509	509	509	503
FR	491	524	557	621	491	491	491	497
Total	1000	1000	1000	1000	1000	1000	1000	1000
Irretrievable reprocessing losses 0.1%								
TR	529	496	461	394	502	502	502	496
FR	501	534	568	633	514	514	514	519
Total	1030	1030	1028	1027	1015	1016	1015	1015
Irretrievable reprocessing losses 1.0%								
TR	707	659	613	525	403	403	402	401
FR	596	637	675	748	756	756	757	759
Total	1303	1296	1288	1274	1159	1159	1159	1159

Table 3. Internal feed from FR to TR and MSR, % of equilibrium mass per year

	U-Pu nuclear fuel cycle, ^{239}Pu feed				U-Th nuclear fuel cycle, ^{233}U feed			
TRR time	3 years	6 years	9 years	20 years	3 years	6 years	9 years	20 years
Irretrievable reprocessing losses 0%								
TR	5.9	5.6	5.1	4.4	0.4	0.4	0.4	0.4
MSR		0.4	0.8	1.5	0.5	0.5	0.5	0.5
Irretrievable reprocessing losses 0.1%								
TR	5.9	5.5	5.1	4.4	0.4	0.4	0.4	0.4
MSR		0.4	0.8	1.5	0.5	0.5	0.5	0.5
Irretrievable reprocessing losses 1.0%								
TR	5.6	5.2	4.8	4.1	0.3	0.3	0.3	0.3
MSR		0.4	0.8	1.4	0.3	0.3	0.3	0.3

3. Conclusion

Thus, the three-component NP system consisting of thermal reactors, fast reactors and molten salt reactors-burners can operate in mode when actinides in system are not stored up proportionally to energy generated but are practically at steady level proportionally to system power. This system can operate during long time in conformity with ecological requirements.

As might be expected the amount of actinides in NFC increases with TRR time prolongation whereas total radioactivity remains practically the same. The increase of losses at short TRR time (3 years) causes slight increase of amount of actinides in NFC and at long TRR time it causes reduction of amount of actinides (without taking into account actinide irretrievable losses). The actinide irretrievable losses do not practically depend on TRR time (assuming reprocessing technology does not modify with TRR time prolongation) whereas losses radioactivity reduces about two times in interval from 3 to 20 years.

It is natural, that reactor contribution to system power is determined by characteristics of reactor. But not to a lesser degree, than reactor characteristics, NP structure is determined by a kind of a nuclear fuel cycle, a level of reprocessing losses of heavy nuclides, duration of an external fuel cycle. Influence of losses level and TRR time are essentially various for U-Th and U-Pu nuclear fuel cycles.

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