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URANIUM MULTIPLE RECYCLE FUEL CYCLE FOR FUSION-FISSION HYBRID

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A uranium multiple recycle fuel cycle is analyzed using a simple numerical model. Three types of uranium are used as additives before each fuel cycle: depleted and natural uraniums and the spent nuclear fuel without any reprocessing. While two first showed almost identical results, the spent nuclear fuel cycle is characterized by slightly increased radioactivity and enhanced heat release of the recycled fuel.

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INTRODUCTION

Fast reactor fuels variety is much wider than of light water reactor. It can burn ^{238}U within the multiple recycle fuel cycle (MRFC) [1]. Since ^{238}U is the main isotope in mined uranium with abundance of 99.3%, the fuel resources for fast reactors become really huge. The transition of nuclear power from ^{235}U to ^{238}U usage is of global importance.

The MRFC for which the ^{238}U could be the major fuel component consists in burning of the fuel in a fast nuclear reactor, then, after the mitigation of heat release, reprocessing it with deleting of fission products, adding fissile materials (in our case these are different kinds of uranium), fabricating new fuel from this ingredients and repeating these all in a cyclic way.

The ^{238}U is mainly available as a major component of three substances. These are the natural uranium, the depleted uranium and the spent nuclear fuel (SNF). While the natural uranium is available in common way, the depleted uranium, being a coproduct of enrichment process, has been accumulated in big amounts, mainly in form of uranium hexafluoride. The SNF contains 96% of uranium, other components are fission products and transuranic elements. Uranium isotope content is ^{238}U (98.8%), ^{235}U (0.8%), and ^{236}U (0.4%).

The physics of burning of both fissile and fertile elements is the following. The basic nuclear energy generating process is fission. It is caused by the neutron impact and results in break of the nuclei into debris (fission products) and generation of some number of neutrons. The major energy, about 200 MeV per fission, is carried by fission products and is normally collected by the reactor coolant. This useful neutron reaction is accompanied by other neutron reactions, the most important among which is neutron capture. In this reaction, a new isotope with bigger mass is created which can be stable or radioactive. For radioactive isotopes, two ways of spontaneous decay are the most probable: the alpha- and beta-decays. The representative energy released in the alpha-decay is 5 MeV. In beta-decay it is much less. Each alpha-decay decreases the charge of the nuclei by two and mass by four. Beta-decay increases the charge leaving the mass the same.

Due to the neutron capture and decays, in nuclear reactor the fuel isotopes create a chain of other heavy isotopes which have different abilities to fission and neutron capture. The difference in mass between the fuel nuclide and the produced one equals the number of consecutive neutron captures. Each neutron capture competes with fission and, therefore, the probability of having many consecutive neutron captures is low. As a result, the heavier the nuclide, the smaller its quantity is. For this reason, the number of the important nuclides is limited in the reactor core.

Uranium-238 is not fissile, but fertile isotope. This means that the ratio of produced via fission neutrons to lost (incident) neutrons, k_{eff}, is less than unity. So, the chain reaction with uranium-238 only is not possible. The way to extract energy from it consists in breeding plutonium-239 by means of neutron capture by ^{238}U and two rapid beta-decays $^{239}\text{U}\rightarrow{}^{239}\text{Np}\rightarrow{}^{239}\text{Pu}$. Plutonium-239 is a fissile isotope with fission cross-section bigger than the neutron capture one.

The safety is the major concern for nuclear energy. The nuclear reactor controllability is essentially based on delayed neutrons which appear with some time delay after immediate fission neutrons. Their number do not exceed 0.6% for light water reactor. In the fast reactor burning uranium-238 they are less. This factor leads to decrease of flexibility of the reactor control and lowering its sustainability. Another flaw pertinent to the fast reactor is low insistence to the accidents, especially to the lost of coolant accident (LoCA).

The fission-fusion hybrid reactor (see, e.g. [2]) has a sub-critical nuclear reactor core and a fusion neutron source. The last one can control fuel burning at any amount of delayed neutrons. The k_{eff} value less then unity allows a hybrid to mitigate main kinds of LoCAs [3].

1. NUMERICAL MODEL

Earlier calculations for pure uranium-238 fuel that confirm good perspective of it, were made using a simple model which includes 8 isotopes of uranium, plutonium and americium [4].

Fuel isotope content for initial fuel. “Equilibrium” fuel content within depleted and natural uranium and SNF based MRFCs

Isotope		FP	^{234}U	^{235}U	^{236}U	^{237}Np	^{238}U	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	^{241}Am	^{242m}A	^{243}Am	^{243}Am	^{242}Cm	^{243}Cm	^{244}Cm	^{245}Cm
Normalized content	Init. fuel	0.0	0.0	0.0	0.0	0.0	0.84	0.0	0.10	0.04	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	SNF	0.06392	0.00034	0.00102	0.00393	0.00073	0.77708	0.00155	0.10697	0.03409	0.00346	0.00270	0.00270	0.00008	0.00070	0.00000	0.00002	0.00038	0.00011	0.00009
	Dep. uranium	0.06139	0.00024	0.00050	0.00055	0.00013	0.78585	0.00110	0.10739	0.03337	0.00336	0.00236	0.00247	0.00007	0.00060	0.00000	0.00002	0.00032	0.00009	0.00007
	Nat. uranium	0.061521	0.000252	0.000857	0.000934	0.000195	0.785071	0.001137	0.107289	0.033346	0.003358	0.002365	0.002476	0.000077	0.000600	0.000004	0.000021	0.000321	0.000096	0.000077

Usage of the natural and depleted uranium as major fuel components causes a necessity to include lower mas uranium isotopes, as well as neptunium-237 and plutonium-238. As for the spent nuclear fuel usage modeling, ^{242m}Am and isotopes of curium up to 246th mass need to be included.

The isotope chain is ended by ^{246}Cm at the top and by ^{234}U at the bottom of the chain. In calculation, the percentage of above isotopes should be small, otherwise the chain of isotopes should be extended.

To analyze possibilities given by the MRFC, we introduce a simple 0D isotope balance model [4]. The nuclear reactions are described by the following equations (1):

$$\frac{dN_i}{dt} = -\sigma_{c,i}\Phi N_i - \sigma_{f,i}\Phi N_i - \Lambda_i N_i + \Lambda_l N_l + \sigma_{c,m}\Phi N_m + I_i. \quad (1)$$

Here N_i is the isotope normalized content; index i enumerates isotopes; σ denotes cross-sections; indices f and c denotes fission and neutron capture; Λ_i=ln(2/$T_{1/2,i}$) is the decay rate of i type nucleus; $T_{1/2,i}$ is the half-life for beta-decay; Φ is the scalar neutron flux; I is the fuel supply (sink) rate; l and m are the numbers of nuclides that donate to i-th nuclide after alpha- and beta-decays respectively.

The chosen cross-sections [2] are representative for a fast reactor. The fission products quantity is counted by the number the source nuclei (2):

$$\frac{dN_0}{dt} = \sum_i \sigma_{f,i}\Phi N_i - I_0. \quad (2)$$

Note that in the calculations several beta decays, e.g. of ^{239}U to ^{239}Np and ^{243}Pu to ^{243}Am are assumed to be immediate. Thus, ^{239}U and ^{243}Pu are not considered. The neutron capture process is blocked for ^{246}Cm isotope, and on which the nuclear chain ends.

The calculations were performed for fixed neutron flux Φ = 0.0003 barn^{-1}·day^{-1}. The duration of fuel exposition in reactor is 600 days. It follows by 800 days of cooling in a water-filled spent fuel pool. At the end of each period the fuel is reprocessed. A part the fission products (70%) is deleted and substituted with the corresponding quantity of fresh fuel (natural or depleted uranium or SNF of light water reactors). During recycles, the efficient neutron multiplication factor, k_{eff}, the ratio of neutron production and loss rates, is calculated. In the computations, the k_{eff} values neglect neutron losses in slug material, coolant, etc., and, therefore, the values of k_{eff} exceeding unity will appear.

The important factor for the fuel reprocessing technology within MRFC is fuel radioactivity. Even if the reprocessing is fully robotized and well-isolated of the radioactive species leakage, the radioactivity induced heating matters. An example of the unbearably high heating gives ^{238}Pu isotope that produces about 570 W/kg of heat. Fissile components of the spent nuclear fuel (SNF) of light water nuclear reactors produce much less heat of 1 W/kg after 1 yearlong cooling in water pool which can be considered as quite tolerable. The heat release calculation results are discussed below for different MRFC scenarios.

2. CALCULATION RESULTS

As it is known, the MRFC tends to become more repetitive with each cycle [2]. This feature prompts a method how to start the MRFC: the startup fuel can be chosen the same as within the periodic cycle. Then the MRFC periodicity will be established just from the very beginning. Unfortunately, the manufacturing of such a fuel may be too costly and complicated since it has excessively many components. Cheaper and simpler alternative is a fuel consisting of uranium and plutonium. The proportions of these two components should be chosen to provide k_{eff} value close to those ones of the k_{eff} at the “periodic” stage of MRFC. The isotopic content of the initial fuel used for each calculation presented here is given in Table.

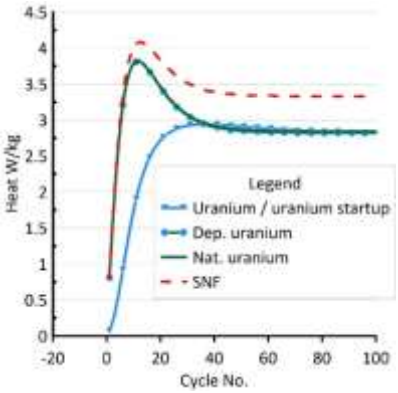
In all the calculations k_{eff} variations both between cycles and within cycles does not exceed 0.5% of calculated k_{eff} =1.42 value. The typical variation within the cycle is 0.2%. Such a small variation facilitate the technical realization of the MRFCs.

In Table the “equilibrium” fuel content (before reprocessing) is given for tree versions of MRFC with different fresh fuels: depleted uranium, natural uranium

and SNF. The equilibrium fuel contents are very similar for depleted and natural uranium. The small difference can be found for light nuclides of uranium. It becomes invisible for heavier nuclides, americium and curium.

Since in SNF MRFC all nuclides, including the heaviest, are supplied to the fuel each cycle, the isotope content for this MRFC is different. However, for the major isotopes, uranium-238, plutonium-239 and -240 the concentration is almost the same, just within 1% difference.

The calculated heat release is presented in Figure.



Heat release variation from cycle to cycle for depleted and natural uranium MRFCs and for SNF MRFC. Blue curve with triangle markers is for natural uranium MRFC with uranium (75% ^{238}U and 25% ^{235}U) startup fuel

The heat release starts from low values, reaches maximum near 12th cycle (3.8 W/kg for depleted and natural uranium MRFC and 4.1 W/kg for SNF MRFC) and then decreases to stationary values, 2.8 W/kg for depleted and natural uranium MRFC and 3.3 W/kg for SNF MRFC. The heat releases for the depleted and natural uranium MRFC are very close. The increase of the heat release at the initial dozens of cycles can be avoided if another startup fuel based on highly enriched uranium (75% ^{238}U and 25% ^{235}U) is used (see Figure).

SUMMARY AND CONCLUSIONS

The paper addresses the multiple recycle fuel cycles (MRFC) which are repetitive and virtually infinite. These MRFCs burn abundant uranium-238 and ultimately minimize the waste production reducing their output to the fission products. The MRFCs are studied using 0D model which includes uranium, neptunium, plutonium, americium and curium isotopes and simulates nuclear transformations under neutron irradiation. Three fresh fuels, fuels that substitute the fission products, are used: natural and depleted uranium and SNF.

Two important parameters of the fuel cycle are calculated. They are the neutron multiplication factor, k_{eff}, and the heat release owing the alpha-decays occurring for the fuel components. In calculations for the neutron multiplication factor only the fissions and neutron captures in the fuel are accounted for and other neutron losses, such as neutron capture by the coolant and reactor materials, are disregarded. Thus, the calculated neutron multiplication factor should be higher than unity, and its bigger values mean more possibilities to design a compact reactor. The heat release of recycled fuel hampers or, if it is very high, even makes impossible fuel reprocessing between the fuel cycles. It must be checked for each version of MRFC.

All three MRFC have k_{eff}>1.4. k_{eff} variation during the cycles is very small in all cases. The startup with uranium-plutonium fuel is smooth. The heat release is about 3 W/kg which is close to the heat release of pure plutonium fuel. These three MRFCs looks good for practical use and can make revolutionary change in nuclear energy since they uses abundant uranium-238 as fuel and produces minimum minimorum of waste. Besides this, the SNF MRFC burns SNF thereby decreasing amount of SNF accumulated.

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БАГАТОРАЗОВИЙ УРАНОВИЙ ПАЛИВНИЙ ЦИКЛ У ГІБРИДНОМУ ЯДЕРНО-ТЕРМОЯДЕРНОМУ РЕАКТОРІ

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Паливний цикл багаторазового використання урану аналізується за допомогою простої числової моделі. Перед кожним паливним циклом в якості добавок використовуються три види урану: збіднений і природний уран і відпрацьоване ядерне паливо без будь-якої переробки. У той час як два перших показали майже однакові результати, цикл на базі відпрацьованого ядерного палива характеризується дещо підвищеною радіоактивністю та підвищеним виділенням тепла з реакторного палива.