**MULTI-CRITERIA COMPARISON OF THE EFFICIENCY OF MINOR ACTINIDES BURNING IN DIFFERENT NUCLEAR REACTORS BASED ON THE INPRO/IAEA KIND APPROACH**

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**Abstract**

The paper presents a comparison of the efficiency of minor actinides (MA) burning in various type of nuclear reactors. A set of criteria for comprehensive comparison of reactor technologies, based on the INPRO/IAEA KIND approach to multi-criteria assessment, has been prepared. This set of criteria includes indicators in such areas as the efficiency of MA burning, economics, safety, environment, readiness of reactor technology and infrastructure for its implementation. The evaluation and comparison procedure was carried out using the KIND-ET tool. It is shown that a comprehensive multicriteria analysis of various aspects of the technologies, as expected, led to estimates that differ from the approach in which technologies are compared only single criterion and without taking into account the influence of other equally important factors. And the cumulative assessment of technologies largely depends on the set development objectives. This means that each of the listed options can take the first place in the rating when certain priorities are selected.

## INTRODUCTION

Close attention to the problem of MA partitioning and transmutation is associated with their impact to the methods of SNF and RW management. Despite the fact that MA in reactor are produced in relatively small quantities, they make a significant contribution to the heat release and radiotoxicity of spent nuclear fuel in the long term.

If at the initial period the main contribution to the activity and heat release of SNF is made by the contained FP, after ~ 200 years the activity and heat release are determined by MA isotopes. At time intervals of more than 100,000 years, the radioactivity of SNF ore RW will be determined by ultra-long-lived radionuclides, including 237Np.

Extraction of MA from HLW formed after SNF reprocessing, will lead to a decrease activity which should be incorporated in the glass matrix and a reduction area of the geological repositories due to decrease heat release of the final HLW.

Theoretical studies of the possibility of MA transmutation in nuclear reactors demonstrate its fundamental feasibility. The features of the MA capture and fission nuclear cross sections indicate the preference of a fast neutron spectrum [1].

The main factors affecting to the success of MA transmutation in a nuclear reactor are the neutrons surplus, neutron spectrum, neutron flux, and the presence of a fertile material that capture neutrons which could be directed to MA transmutation [1].

In this regard, it becomes important to choose a reactor technology that is able to most effectively transmute MA and to most extent meets the assigned tasks.

## MA TRANSMUTATION TECHNOLOGIES

Within the framework of the existing R&D programs of the State Corporation Rosatom, the possibility of MA transmutation in four reactor technologies is being considered:

* studies on the homogeneous Am and Np transmutation in the MOX fuel of sodium fast reactors and the possibility of the heterogeneous MA transmutation are conducting;
* one of the tasks of the lead-cooled fast reactor under development is to achieve environmental characteristics of a closed NFC that are acceptable for society and the economy due to MA transmutation;
* the development of the MSR is underway, the main task of which is the transmutation of MA from SNF of thermal reactors;
* one of the tasks set for the developed fission-fusion hybrid reactor (FFHR) with subcritical blanket is the highly efficient MA transmutation.

 A distinctive feature of fast sodium reactors is the presence of operating research and power reactors, as well as the presence of experimental experience in MA transmutation in this type of reactors. The confirmation of the possibility of MA transmutation and the study of the behavior of nuclear fuel containing MA was implemented in a number of experiments at the French reactor Phenix [2-6], the Japanese Joyo reactor [7], the Russian BOR-60 reactor [8, 9], and at the US reactor EBR-II [10].

 However, the loss of energy by neutrons on the nuclei of structural materials and the coolant leads to the fact that the bulk of MA isotopes is converted to isotopes of heavier elements or to Pu isotopes. According to the study [11], even if Am is used as a fuel isotope, only 60% of the transmuted nuclei will pass into fission products, and the remaining 40% into the nuclei of other actinides, mainly 238Pu and 240Pu.

 Lead-cooled fast reactors are considered safer technology. Lead coolant has a higher boiling point than sodium, and is also inert when interacting with water and air. The use of nitride fuel is due to its high density, thermal conductivity and lower content of light elements that scatter neutrons. The high density of the nitride-based fuel (~ 1.4 times higher than the oxide fuel) contributes to an increase in the breeding ratio in the core and makes it possible to achieve a low value of the initial reactivity margin.

 According to computational studies, a 1200 MW(e) lead-cooled fast reactor is capable to transmute about 1.5 t of Am and Np during its operational life-time, which is equivalent the amount of MA generated during the operational life-time of one VVER [12]. But, despite the harder spectrum in reactors with a lead coolant than in sodium reactors, the mechanism of MA transmutation is similar - the main part of MA passes into heavier nuclides or Pu isotopes.

 Molten salt reactors, depending on the type of fuel salt, make it possible to achieve a significant initial loading of MA without significant damage to safety characteristics, as well as to use MA as fuel isotopes without feeding with fissile isotopes of U or Pu and, as a consequence, provide a high rate of MA transmutation. However, the neutron spectrum, close to the spectrum of fast solid fuel reactors, leads to the fact that only 30% of the Np and Am isotopes go directly to fission products, and the rest into Pu and Cm isotopes [13].

 Fission-fusion hybrid reactors potentially have a number of advantages over critical fission reactors [14]:

* deep subcriticality of the FFHR fission zone - this excludes accidents associated with uncontrolled acceleration on prompt neutrons;
* control of the FFHR power by changing the power of the fusion neutron source;
* high energy of fusion neutrons and the ability to provide a high neutron flux density;
* insignificant effect on the physical characteristics of the FFHR of the inclusion of MA in the blanket material, which makes it possible to achieve a high content of transplutonium elements without compromising the safety of the reactor;
* the possibility of achieving high burn-up.

 Calculation study [15] was shown that in a FFHR based on a tokamak technology possible to achieve very high rates of MA transmutation - up to 1170 kg / year depending on the initial loading of MA into the subcritical blanket. Although the average neutron energy in the subcritical blanket was quite high (3-3.5 MeV), only 40% of them have energies above 1 MeV, for which the fission cross section of the main MA isotopes is much higher than the radiative capture cross section. This is related to the accumulation of Pu isotopes (mainly 238Pu) due to the absorption of neutrons on the 237Np and 241Am isotopes, and the accumulation of Cm isotopes.

 Despite the differences in the design and neutron-physical characteristics of the considered reactor systems, the main mechanism of MA transmutation remains their conversion into Pu and Cm isotopes, rather than their transformation into FP.

 A correct comparison of the technologies under consideration cannot be limited only by indicators directly related to MA transmutation. Fast reactors with sodium or lead coolant, MSR and FFHR has significant differences not only in the technological aspect, but also in the degree of readiness of both reactor and associated fuel technologies. Also they have differences in the main tasks within the overall nuclear power system and, as a result, differences in the required financial, time and labor resources determine the need for a comprehensive analysis. Such a comparison is possible by using methods of ﻿multi-criteria evaluation and ranking.

## ﻿MULTI-CRITERIA EVALUATION AND RANKING OF MA TRANSMUTATION TECHNOLOGIES

In today's world practice, extensive experience has been accumulated in the application of multiple-criteria decision analysis (MCDA) methods to solve problems in various subject areas, related to the nuclear industry: comparison of nuclear and non-nuclear energy technologies, substantiation of options for the development of nuclear power, comparison of the effectiveness of nuclear technologies and fuel cycle technologies, decision support in the field of SNF / RW management and in many other areas.

A feature of the application of MCDA to assess prospects for the deployment of nuclear power technologies and NFC technologies at a project level is impossibility of formulating a universal set of comparison parameters. However, in the global expert environment, there is an understanding that, in the general case, the criteria used should characterize: technological readiness, safety, efficiency, resistance to proliferation and physical protection, waste management, environmental impact, national specifics and interests, including aspects of industrial infrastructure. For this reason, the criteria are determined for the specific problem under consideration based on the available information.

### Selection of criteria and methodology for comparing technologies

The assessment and comparison of these MA transmutation technologies was carried out in 4 key areas (high-level objectives), including 8 areas of assessment and 24 criteria (Figure 1).



FIG 1. The hierarchical structure of the objectives tree

 The selected structure of the objective tree allows to compose a large number of criteria within several important areas of technology assessment and more fully reflect their advantages and disadvantages. Although in the international practice of conducting MCDA, the aggregation of assessment areas into three high-level objectives (economy, environment, social sphere) is accepted, but the specifics of the problem under consideration and the features of technologies required changes in the structure of high-level objectives and in the assessment areas.

 *High-level objective "MA Transmutation"*

High-level objective "MA Transmutation" includes two areas of assessment: the efficiency of MA transmutation and the technical parameters of nuclear systems that determine their performance in terms of MA transmutation.

The area of ​​assessment "Efficiency of MA transmutation" contains two criteria: the average rate of MA transmutation and the efficiency of MA transmutation. The area of ​​assessment "Technical parameters of nuclear systems" includes the following set of criteria: the fuel residence time in the reactor core, the duration of the external fuel cycle, the average neutron energy and average neutron flux density in the reactor core, as well as the presence of a fertile isotope in nuclear fuel.

 *High-level objective “Economics”*

It is difficult to carry out a detailed economic analysis of the technologies under consideration, since most of them are at the initial stage of development, and the difference in target purpose of technologies (electricity generation or utilization of MA) does not allow using LCOE as an assessment criterion. Proceeding from these conditions, two assessment areas and three criteria were identified. This set allow for an assessment taking into account the sufficiency of the data used and in relation to the main problem under consideration - MA transmutation. The area of ​​assessment "Economic efficiency" includes one criterion - "CAPEX", which allows comparing the estimated unit cost of plant construction in relation to a unit with a VVER-TOI reactor.

The assessment area "R&D cost" includes two criteria: R&D cost estimate (reactor and related systems) and R&D cost estimate (partitioning of MA).

 *High-level objective “Environment”*

The high-level objective "Environment" include factors which potentially affecting to the environment through to safe operation of a nuclear power plants, formation of radioactive waste after the decommissioning of power plants and features of the nuclear fuel cycle of the reactors technologies under consideration.

 The area "Safety impact" combined 2 criteria: the effect of MA adding to the fuel on the neutron-physical characteristics of the reactor and the number of protective barriers.

 The area "Environmental Impact" includes three criteria: the operational lifetime of the facility, the MA amount in the last unloading + in the external fuel cycle at the moment of reactor shutdown, and MA losses in the reprocessing process during the operational lifetime of the reactor. These criteria directly affect to the amount of generated radioactive waste that will have to be handled after the decommissioning of nuclear reactor or nuclear fuel cycle facility.

 *High-level objective “Technology readiness”*

One of the most important aspects in prioritizing various technological options is the readiness of the technologies under consideration, which affects the level of costs for their implementation, the timing of their development, the need to develop new regulatory standards, etc. The high-level objective "Technology Readiness" includes two assessment areas: Level of the technology development and Infrastructure Readiness. These assessment areas include eight assessment criteria.

 The assessment area "Level of the technology development" includes six criteria: the current TRL of the reactor, the current TRL of the coolant, the current TRL of the primary circuit structural materials, the current TRL of nuclear fuel with MA, the probability of the project failure and the expected time to reach the technology readiness.

 The assessment area "Infrastructure Readiness" describes the components required for both the development and full operation of nuclear power facilities. This area includes 3 criteria: the presence of a regulatory framework, the availability of infrastructure (personnel, training centers, etc.) and the availability of a research reactor base.

Part of the quantitative assessments of the key criteria were based on published data. For example, assessments of the key criteria for the high-level objective "Transmutation" were based on information from [12, 13, 15-21]. The other part was prepared by interviewing a group of experts with subsequent averaging of the obtained estimates.

 Figure 2 shows the normalized values of the criteria, and Table 1 provides a description of hierarchical structure of the objectives tree.



FIG 2. Normalized values of evaluation criteria

TABLE 1. Summary table of criteria, areas of assessment and high-level objectives

|  |  |  |  |
| --- | --- | --- | --- |
| High-level objectives | Assessment areas | Short title of сriteria | Description |
| MA transmutation | Efficiency of MA transmutation | К1 | Average rate of MA transmutation, kg/year‧GW(th) |
| K2 | Efficiency of MA transmutation, % |
| Technical parameters of nuclear systems | К3 | Fuel residence time in the reactor core, EFPD |
| К4 | Duration of the external fuel cycle, years |
| К5 | Average neutron energy, MeV |
| К6 | Average neutron flux density, neutron/(sm2‧s) |
| К7 | Presence of a fertile isotope, score |
| Economics | Economic efficiency | К8 | CAPEX, relative to the CAPEX of the VVER reactor |
| R&D cost | К9 | R&D cost estimate (reactor and related systems), millions $ |
| К10 | R&D cost estimate (partitioning of MA), millions $ |
| Environment | Safety impact | К11 | Effect of MA adding to the fuel on the neutron-physical characteristics of the reactor, score |
| К12 | Number of protective barriers, units |
| Environmental impact | K13 | Operational lifetime of the facility, years |
| K14 | MA amount in the last unloading + in the external fuel cycle, t HM |
| K15 | MA losses in the reprocessing process, kg HM |
| Technology readiness | Level of the technology development | К16 | Current TRL of the reactor, score |
| К17 | Current TRL of the coolant, score |
| К18 | Current TRL of the primary circuit structural materials, score |
| К19 | Current TRL of the nuclear fuel with MA, score |
| К20 | Probability of the project failure, score |
| К21 | Expected time to reach the technology readiness, years |
| Infrastructure Readiness | К22 | Presence of a regulatory framework, score |
| К23 | Availability of infrastructure (personnel, training centers, etc.), score |
| К24 | Availability of a research reactor base, score  |

### Weighting options

The Equal Weights option is used as a starting point for analyzing and comparing the technologies under consideration. It is assumed that all aspects of technology assessment at each level of the objective tree are weighted equally. This approach is used in the absence or insufficient detail information on the importance of certain criteria from experts and decision-makers. In combination with subsequent detailed sensitivity and uncertainty analysis, the Equal Weights approach provides an opportunity to draw conclusions about the potential of each option depending on various aspects of the assessment.

Further, to evaluate the technologies, four sets of weights were used, which differ from the basic variant "Equal Weights" in that each high-level objective was assigned a high weight in turn. It was assumed that the weight of the highlighted high-level objective is 0.5 points, and the remaining 0.5 points are divided equally among the other three high-level objectives. This method makes it possible to analyze the integral assessments of technologies in the case of prioritizing one of the aspects of comparison.

### Aaggregation procedure

 Comparative assessment and ranking of the technologies under consideration was based on the Multi-Attribute Value Theory (MAVT method). The calculation of integral value carried out using the KIND-ET tool developed by the IAEA INPRO section. This tool is intended for multicriteria comparative assessment of various technologies and analysis for sensitivity and uncertainty in relation to criteria and weighting factors.

## RESULTS OF ASSESSMENTS AND THEIR ANALYSIS

### Assessment of the overall score

 It should be noted that all the considered MA transmutation options are not dominant. This means that each of the listed technologies can take the first place in the rating if the priorities are chosen accordingly.

A comprehensive multicriteria analysis of various aspects of the technologies selected for comparison, as expected, led to estimates that differ from the approach in which technologies are compared only according to one criterion without taking into account the influence of other equally important factors. Figure 3 shows an integrated assessment of each of the options under consideration, taking into account the contribution of high-level objectives.



FIG 3. Contribution of high-level objectives to the overall score of the technologies under consideration in the "Equal weights" option

As can be seen from the graph, the option of MA utilization in fast reactors with a sodium coolant received the highest assessment. First of all, this is due to the readiness and demonstration of the main components of the technology at the operating power reactors, the availability of an experimental and legal basis. It will also require much less financial resources and time to complete the main R&D programs and organize the fabrication of fuel with the MA. However, BN reactors have the lowest MA transmutation rate associated with limiting the amount of MA loading into the reactor core in order to minimize the impact on safety and the main function of the power plant - economically efficient power generation.

A FR with a lead coolant, with comparable or large estimates for the high-level goals "MA Transmutation" and "Environment" and the declared low capital costs, has less development at the moment and requires much higher financial R&D expenditures to demonstrate reactor technology and fuel cycle technologies.

MSR has a multiple higher rate of MA transmutation than in a FR with sodium or lead coolant, but at the same time it has a much higher initial loading and final MA discharge, and, consequently, large absolute MA losses during operational life-time. Also, for MSR, structural materials and an effective technology for reprocessing fuel salt to remove accumulated FP have not been demonstrated at present.

 The FFHR with a fusion part based on a tokamak has the lowest overall score, although it has the highest transmutation rate, the best neutron-physical characteristics, and safety parameters, since the MA fuel is supposed to be placed in a subcritical blanket. However, the development of this technology is only at an early stage, which is associated with significant R&D costs. Also, according to work [22], the capital cost of a FFHR, based on tokamak, is proportional to the square of the large radius of the torus of the thermonuclear fusion chamber. If we compare it with ITER, then CAPEX, at least of the first samples, will significantly exceed the capital costs of the remaining options under consideration.

 Figure 4 shows a comparison of the change in the overall score depending on the prioritization of a particular high-level objective.

|  |  |
| --- | --- |
|  |  |
| *(а)* | *(b)* |
|  |  |
| *(c)* | *(d)* |

FIG 4. Change in the overall score depending on the prioritization of the high-level objective (a) "MA transmutation", (b) "Economics", (c) "Environment" and (d) "Technology readiness"

With the sequential prioritization of high-level objectives, the general trend in the distribution of score between technologies remains. It can be noted that the allocation of a high-level objective "MA transmutation" leads to the convergence of the total scores of the options under consideration. Which means the equivalence of the choice between the technologies already mastered, but less effective in terms of MA transmutation, and promising technologies that allow MA transmutation at a high rate, but which are at the initial stage of development.

The same effect with the estimates convergence is obtained when highlighting the high-level objective "Economics". However, for this option, the estimate of the FFHR drops significantly, having high R&D costs and potential high capital cost.

Increasing the weight for the high-level objective “Environment” brings the estimates of the FR with lead or sodium coolant; for the other variants, the distribution remains similar to the distribution in the variant of equal weights.

 On the contrary, prioritizing the high-level objective "Technology Readiness" increases the difference in the overall score of the compared options. The difference between fast reactors with sodium or lead coolant, which have similar scores for equal weights of high-level objectives, becomes especially significant.

### Sensitivity and Uncertainty Analysis

The above integral estimates were obtained for five variants of weights, determined in advance. At the same time, it is advisable to analyze the selected technologies for the case of significant uncertainty in the weights. That is, how the absence of any information on priorities will affect the final scores and ranks of the options under consideration.

Uncertainty analysis for weights was carried out for two options: in Option I, all weights are undefined, in Option II, only weights of high-level objectives were indeterminate. The number of combinations of weights used was 10,000, provided that the weights are evenly distributed within [0,1] and their sum for each combination is equal to 1. We considered both the probability of getting a certain integral assessment of each of the options, and taking the corresponding rank in comparison with other options. The first rank corresponds to the highest total score for the considered alternative, and the fourth - to the lowest.

|  |
| --- |
|  The spread in the final scores and ranks of technologies for the case with the uncertainty of all weights is shown in Figure 5, and for the case with the uncertainty of the weights of high-level objectives in Figure 6. The probabilities for options to take a certain place in the rating are presented in Table 2. The colors of cells in Table 2 indicate the magnitude of probability to take first place in the ranking, and the numbers indicate quantity value of the probability. *Option I* |
|  |  |
| (а) | (b) |
| FIG 5. The spread of the overall scores (a) and the probability of taking a certain place in the rating (b) with the uncertainty of all weight coefficients |
| *Option II* |
|  |  |
| (а) | (b) |
| FIG 6. The spread of the overall scores (a) and the probability of taking a certain place in the rating (b) with the uncertainty of all high-level goals |

TABLE 2. The probabilities for the technologies under consideration will take a certain place in the rating

|  |
| --- |
| *Option I* |
|

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Rank | FR (sodium) | FR (lead) | MSR | FFHR |
| 1 | 47 | 20 | 9 | 24 |
| 2 | 20 | 45 | 22 | 13 |
| 3 | 22 | 17 | 37 | 24 |
| 4 | 11 | 18 | 31 | 40 |

 |
| *Option II* |
|

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Rank | FR (sodium) | FR (lead) | MSR | FFHR |
| 1 | 63 | 18 | 9 | 10 |
| 2 | 21 | 55 | 21 | 3 |
| 3 | 4 | 27 | 44 | 25 |
| 4 | 11 | 0 | 27 | 62 |

 |

Option I shows that, with a certain probability, all the options under consideration can get the highest score and take first place in the rating. However, the sodium-cooled FR has the greatest potential to obtain the highest score, and the lead-cooled FR is next in the ranking. The opposite situation is observed for MSR, for which the probability of taking a leading position is small. The FFHR technology has the greatest scatter of scores and in case of uncertainty of all weight coefficients it has a significant probability of taking the first place, but also the probability of taking the last place for installing the FFHR is the highest among the options under consideration.

Option II demonstrates that the sodium fast reactor is the most attractive technology for MA utilization, while for a lead cooled fast reactor it is most likely to take a place in the middle of the rating, but with a relatively high probability it can also receive the highest score. Moreover, the probability of taking the last place is close to zero. In case of uncertainty of priorities for high-level objectives, the probability of the options with the MSR and FFHR to take first place is extremely small. It should be noted that in the variant of changing the weights only for high-level objectives, all four technologies under consideration have an insignificant scatter of points.

## CONCLUSION

 The presented attempt to analyze various technologies for MA transmutation showed that the comparison of MA transmutation technologies only on the basis of a single indicator - average rate of MA transmutation, without taking into account factors related to economic, technological aspects, availability and safety of the technology, gives a one-sided picture. The use of a multicriteria approach made it possible to present a comprehensive assessment for each of the options and to compare them.

 If it is necessary to implement MA transmutation as soon as possible, taking into account the current development of reactor technologies, the most attractive option is to transmutate MA in fast sodium reactors, especially if the solution of this problem requires minimizing the resources and time spent. The variant of a fast reactor with a lead coolant is also close in the estimation. However, the lack of the technology of fast reactors with sodium or lead coolant is a small load of external MA and a low rate of their utilization. This explains the main advantage of the innovation reactor technologies MSR and FFHR - specialization in reducing the MA volumes accumulated in SNF of other reactors, and the high rate of their annual afterburning. But with a multi-criteria assessment, these options received the least overall scores, since their implementation will require significant resources and time to develop the necessary technologies and find suitable structural materials.

The analysis of the sensitivity of technology assessments, depending on the prioritization of various areas of assessment, showed that the technologies of fast reactors with sodium or lead coolant have the smallest scatter of points and the most likely to receive a high rating. The MSR and FFHR reactors are much less likely to be the leaders, which is due to the less elaboration of these projects at the present time. However, as they are developed and if indicators related to the rate and volumes of MA transmutation are selected as a priority, these technologies will come out on top.

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