Complex discussion of inherent safety fast reactors start-up with enriched uranium concept (strategical, economical aspects, problems of neutron physics etc.). R&D program proposal

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Abstract. Due to the growing population of Earth, the development of a full-scale nuclear power industry is becoming an increasingly challenging task in the 21st century and onwards. The Breakthrough («Proryv») Project is focused on inherently safe fast reactors which are expected to resolve, for a first time, the economic competitiveness problems of the nuclear power sector. In order to develop a full-fledged nuclear power industry based on such reactors within acceptable timeframe, these reactors must first be put into operation with enriched uranium.

The article provides the results of systemic calculations confirming this thesis. Moreover, it supports the economic benefits (in the nearest future) of the uranium-based start of fast reactors versus the uranium-plutonium start. For the first time, it demonstrates the possibility of a noticeably simpler transition from uranium fuel-based start to uranium-plutonium regime in the closed fuel cycle compared to the previous alternatives (reduced number of structural changes in the core during the transient mode, less restrictive requirements to the start load, etc.). An R&D program is proposed in order to justify the start of inherently safe fast reactors on enriched uranium.

Key words: inherently safe fast reactor, large-scale nuclear power, reactor start-up with enriched uranium, closed fuel cycle.

1. Introduction

Since 40-th years of previous century it was obvious, that creating large-scale nuclear energetics (NE) becomes possible only on the base of fast reactors (FR) with sufficient for full fuel usage breeding ratio (BR). Nevertheless even after more than 70 years since the first reactor was started-up nuclear energetics develops predominantly on the base of thermal reactors (TR), its share in the world power production is only ~ 11% and decreases, while there operates only 2 FRs in the whole world (BN-600 and BN-800).

In the «Breakthrough» project there is made an attempt to understand the reasons of nuclear energetics failure and it's assumed that it was determined by focusing of FR technical decisions on achieving high breeding ratio (which is necessary for large-scale energetics development when commissioning FR with Pu from TR spent fuel), which aggravates intrinsic for nuclear techniques problems of safety and associated with it economics. That's why first successful FRs became even more expensive than TRs and didn't have commercial redistribution.

It is assumed that switching of key technical means of the BR from the high plutonium breeding to solving the sum of safety problems will give NE a second birth, and mitigation of rules and regulations will lead to the improvement of its competitiveness. Choosing of principally new technological solutions leads to new solutions with respect to fuel balances: for the development on the basis of such reactors large-scale energetics required for the world in the 21st century, their start-up with enriched uranium is necessary.

Urgency of the work follows from the obvious considerations: the world population during the previous century has increased more than fourfold (from ~ 1.5 billions people in 1900 to ~ 7.3 billions in 2016), and is expected to increase by the end of 21st century twofold. Developing countries with a population amounting to 6/7 of the world's one, and much smaller than in the "Golden billion" countries energy consumption per capita, first time in the history have an urgent need for the development of large-scale NE. For example, China during last 16 years has developed much energetics than Russia during 60 years (at September 2016 there were put on 31.4 GW, and by mid-century it is planned to reach hundreds of Gigawatts. For instance, in materials of conference FR-09, Kyoto [1, p. 4], one can find that after starting up in 2011 the first experimental sodium-FR CEFR, China plans till ~ 2030 commissioning of a commercial FR with a capacity of 1000-1500 MW(e) and by 2050 aims to achieve a level of 250 GW predominantly on the base of FR, effectively consuming natural uranium (U_{nat}); in materials of conference in Paris FR-13 [2, p. 61] there is pointed even more ambitious nuclear capacity level – 400 GW.

2. Strategic Benefits of Starting FRs with U_{enr}

Consumption of U_{nat} for starting FR with U_{enr} is 4-6 times (depending on scenery of starting up and transient regime from start uranium fuel to balanced one) smaller than in the case of starting with Pu from TR spent fuel (this fact was proved by neutron-physics calculations). Significant reduction of U_{nat} consumption for starting FR makes low-content ore processing economically feasible. It means a substantial increase of $U_{natural}$ reserves (appreciably more than 4-6 times). That's why starting FRs with U_{enr} instead of Pu obtained from TR spent fuel enables to overcome inherent safety reactor power limitations (with reduced power density and BR ~ 1) and to reactor startup rate limitations.

Figure 1 illustrates that for countries lacking TRs and spent fuel reserves starting inherent safety FRs with U_{enr} (irrelevant of the considered U_{nat} reserve) by the mid- or end of the century would enable to have massively more FR power compared to starting such reactors on Pu obtained from TRs (in the latter case the TRs would have been also started, and significant amounts of Pu would have been generated). One can see, for example, that achieving by 2050 nuclear capacity planned by China on the base of inherent safety FRs becomes possible only using U_{enr} in start-up load.

3. Economic Benefits

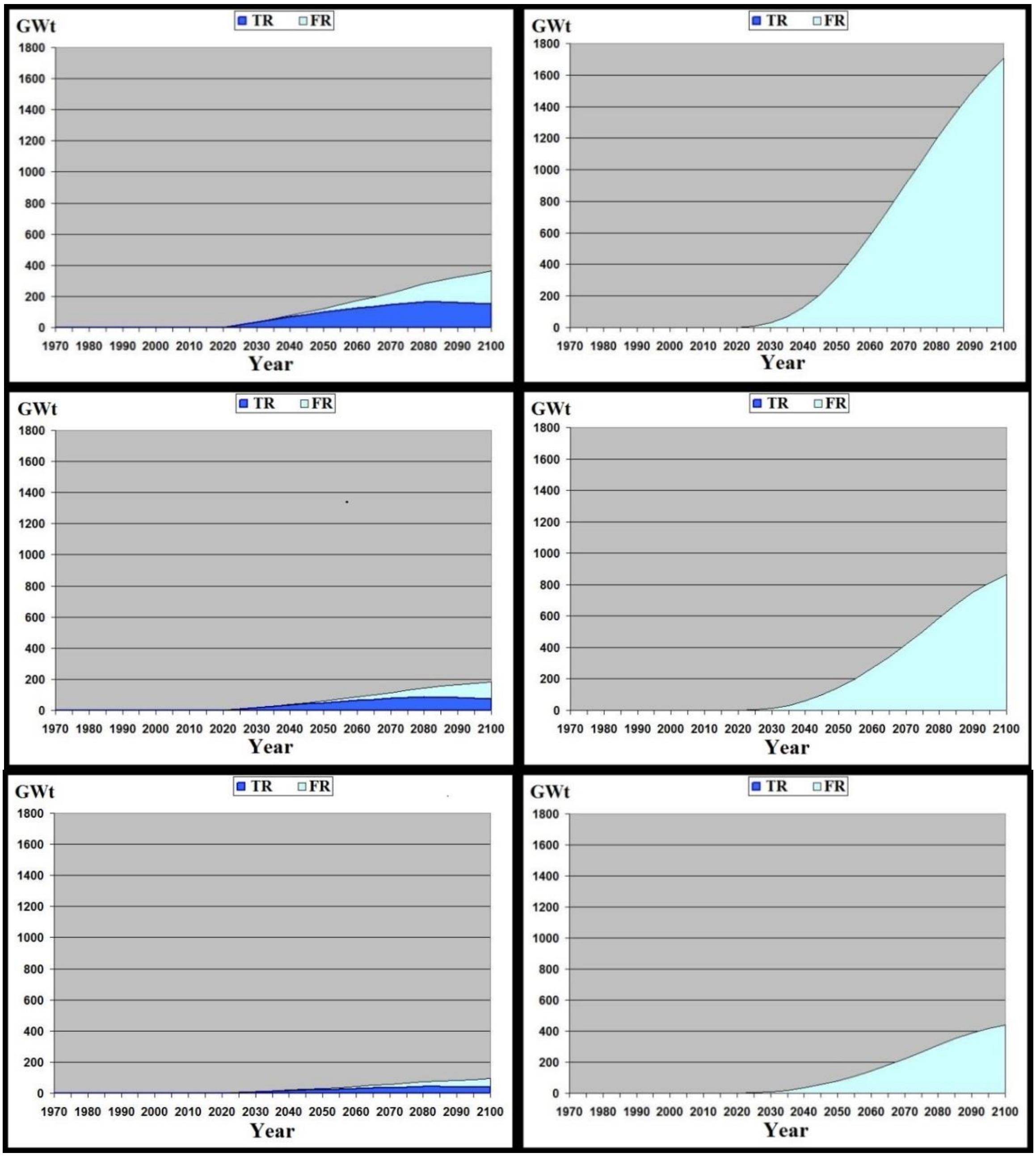
Starting a reactor with uranium is a way to improve financial indicators of the closed fuel cycle (CFC) due to a number of factors. First, manufacturing a low-active uranium startup core fueling is cheaper than U-Pu one. For this reason, all existing FRs have been started with uranium (oxide). Startup uranium core fuel rods can be manufactured at the existing centralized facilities; only a nitride process line is to be added. Centralized startup core fuel rod manufacturing would allow postponing a fuel fabrication/re-fabrication module (FFRM) construction by about 10 years; it is beneficial in terms of discounting. Due to low Pu content the TR spent fuel deep fractionation required to startup FR can also be postponed. It's also beneficial in terms of total cost, etc.

4. Key Engineering Challenges of Transferring CFC from U to U-Pu, and Proposed Solutions

One of the major disadvantages of starting FR on uranium with subsequent switching to CFC has traditionally been the engineering challenge of replacing U with U-Pu fuel while maintaining low reactivity margin for fuel burn-up compared to efficient delayed neutron fraction β_{eff} (it is important to minimize prompt neutron reactor runaway risk). Recently it was shown that such a switching is not as complicated as it seemed to be.

^{235}U in the FR range has fewer neutron yield per fission, and larger absorption cross section compared to ^{239}Pu; and if we replace U-Pu fuel with U_{enr} in a core designed for equilibrium reactivity operations, to reach criticality the initial uranium fuel enrichment would have been significantly increased as compared to U-Pu fuel. It would lead to reduced breeding ratio of the core (BRC) and higher negative scram. In order to reduce the scram as a FR is started with U_{enr}, it is required to increase initial BRC through applying advanced engineering solutions, such as:

- high density fuel;
- a canless core that reduces parasitic absorption in the core structure;
- Np additives to the startup fueling;
- increasing ^{15}N isotope concentration in nitrogen, etc.



Craphs on the left side show sceneries with FR start-up using only Pu-fuel achieving after TR spent fuel reprocessing, graphs on the right side illustrate sceneries with commissioning FRs only with U_{enr}. Graphs in upper, middle and lower arrays correspond to cases when U_{nat} reserves are 2400 kt, 1200 kt and 600 kt respectively

Figure 1 – Comparison of nuclear capacities development in 21th century in cases of inherent safety FR start-up using Pu fuel and U_{enr} with no TRs and spent fuel reserves at the start period

Figure 2 shows the reduction of an absolute scram value as the startup fuel BRC increase design solutions are used.

As CFC is switched from uranium to U-Pu fuel, the scram gradually goes from a significantly negative to a significantly positive range; to keep the reactivity margin for fuel burn-up matching the β_{eff} value for the entire reactor service life one have to either reduce the BRC, or, for instance, increase the burn-up rate (obviously, it is a preferable option), or combine both options. Conceptually the ways of providing feasible transient regime were analyzed in works of NIKIET [3] ant ITCP «Proryv», but before last 2 years calculations have been performed in regime of 5-years fuel lifetime without partial reloads considering. It followed from these investigations, that providing low enough reactivity margin through the whole period of reactor exploitation requires about 5 constructive changings in reactor core during this period. In the latest ITCP works calculations were made more precisely, taking into account partial reloads, which allowed to reveal opportunity of considerable reducing the number of required changings – from 5 to ~ 2 (taking into account that β_{eff} for uranium fuel is twice as high as for U-Pu). The number of constructive modifications in the on-site fuel fabrication facility may be lessened by 1 if start load is fabricated on centralized plant, especially if permutations and rotations of insufficiently burned fuel assemblies instead of reprocessing is used at the first period.

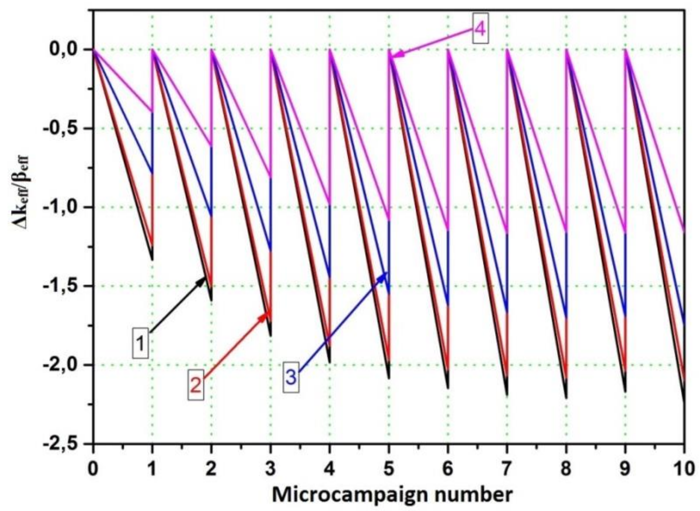


Figure 2 – Reactivity vs. fuel burn-up in the BR-1200 reactor being started with U_{enr}: 1) the core parameters match those of the current BR-1200 design; 2) the fuel rods have variable diameter instead of variable fuel column height; 3) a Np additive is also used; 4) a canless variant is considered

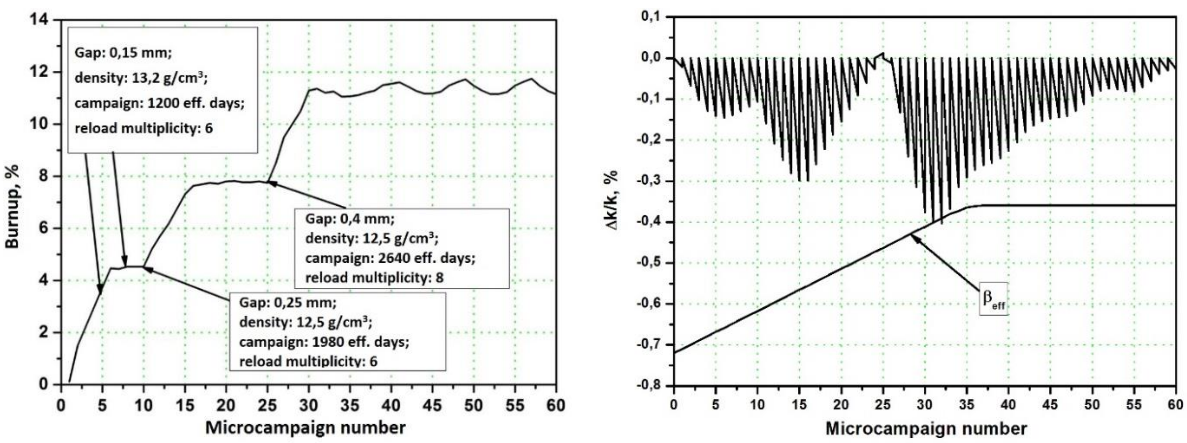


Figure 3 – Fuel burn-up and scram variations for a FR's uranium startup option with liquid metal substrate fuel rods with variable gap

The improved simulation of the recycle, taking into consideration partial refueling, helps find the potential to reduce the requirements for the startup uranium fuel load (investments for this load affect the NPP competitive capacity significantly, taking into account the large load volume and discounting) compared to the previous ones given by NIKIET [3], where the BRC of the startup load was increased due to the overshoot of reactivity derivative, so at the start of each lifetime of the transition period in order to provide low overshoot of reactivity for 5 years of the reactor operation was positive. The overshoot may be below zero in case of annual partial refueling – it is only important that the overshoot does not exceed β_{eff} for uranium fuel (twice more than for uranium-plutonium fuel).

When starting with U_{enr} the initial fueling is in most cases increased compared to an U-Pu option; subsequently, a part of it is removed (this part is already a U-Pu fuel with lower Pu and higher ^{235}U content as compared to the equilibrium mode); the removed part can be used as startup fueling, or for refueling the existing FRs. Increasing the startup fueling BRC (with design solutions applied across the entire core) and burn-up upon switching to U-Pu fuel helps decrease this part (or even reduce it to zero). Note that reducing the U_{nat} consumption for a FR startup is significantly (in tens times) more important that removing a part of the fuel during the reactor operation.

5. Current State of the Experimental Research

First of all, it should be noted that the PRORYV Project uses promising dense and heat-conducting (compared to oxide) nitride fuel, which increased density and is especially necessary to provide FR operation with an overshoot of reactivity around β_{eff} for a startup with $U_{enriched}$. In addition, some operating experience was achieved for FRs with UN fuel – in particular, BR-10 operated using this fuel for 18 years, but all this experience cannot be used 100% to justify BREST fuel rods, as there are substantially different general parameters of radiation and fuel rod shapes. In order to speed up the FR CNFC experimental justification and consider the amount of Pu already produced, the R&D plans of PRORYV Project are now directed at U-Pu fuel. Fuel will become uranium-plutonium during the first recycle if the FR is started up on $U_{enriched}$ with further CNFC operation (and the percentage difference of its content compared to fuel with a balanced content requires no extra experimental research), so research on MNUP fuel that has already been completed as well as planned, will certainly be useful. Furthermore – some existing and planned results for MNUP fuel may also be used to justify UN fuel (e.g. relating to inflation, corrosion, thermomechanical behavior, etc.). In any event, the transition from uranium fuel to U-Pu fuel within the FR CNFC under reactivity-balanced mode has not been performed experimentally in any reactor anywhere in the world, and requires extra R&D and reactor tests. In particular, it is considered just as feasible to install a nitride uranium insert into BN-800.

6. Required R&D for justification of starting with U_{enr}

For possibility of effective technological implementation of FR start with U_{enr} it is necessary to carry on groups of R&D listed below. The particular terms for R&D are not relevant, however, it is clear, that it is desirable and possible to finish mentioned works approximately till 2030.

R&D for justification of possibility to improve BRC:

- studies of high density fuel (in particular, a technology of increasing the ratio of open and closed porosity);
- studies of possibility to use low absorption construction materials;

- studies of fuel with increased content of ^{15}N isotope;
- studies of possibility of replacement of natural Pb as heat carrier by low absorption radiogenic Pb;
- studies of particular features of homogeneous Np involvement into UN and its burning out, et al.

System-economic studies:

- development of UN production technological line at existing plants of uranium fuel manufacturing; estimates of capital expenditures for construction of such a line;
- estimates of operational costs (taking into account possibilities of softening requirements to radiation protection and simplification of fuel fabrication technology);
- estimates of possibility to re-equip the lines at existing enrichment productions for producing higher enrichment U;
- systemic studies of reducing costs at the start-up period (nearest 10-30 years) in comparison with the first FR launch variant on U-Pu fuel;
- studies of scenario of FR export in CFC;
- determination of acceptable rate of burn-out at the original stage, taking into account low cost of producing uranium load, et al.

Study of non-proliferation issues:

- justification of possibility to exclude production of weapons-grade Pu during the first years of reactor operation (first of all – by adding into the starting load low activity fuel in comparison with Np plutonium);
- development of addendum to export control lists, improvements of methods and devices for accounting, control and protection of nuclear materials, revision of IEAE criteria, development of internationally accepted regulations for dealing with nuclear materials, radioactive waste depository et al.;
- development of technologies of physical (plasma) methods of separation (processing of SNF), excluding separation of U and Pu (in addition, improving economic efficiency of CFC; in particular, allowing to produce light isotopes efficiently, e.g. – ^{15}N).

Also required are R&D on:

- optimization of design-technology and technical-economic parameters of FR, used for U_{enr} (selection of optimum mass of start-up load, fuel density, burn-out; optimization of uranium to U-Pu fuel transient mode;
- development of technology of direct hydrogenation-nitration (considered in technological community as more advanced and economically efficient in comparison with carbothermal synthesis), etc.

7. Conclusions

An enriched uranium startup enables to overcome the basic inherent safety FR power and startup rate limitations while increasing the competitive edge of the new reactors. The neutronics analysis has shown that a CFC switch from U to U-Pu while preserving reactivity margin for fuel burn-up similar to β_{eff} can be significantly simplified (compared to previously suggested solutions) for the entire reactor service life. More R&D is required to implement uranium reactor startup.

8. References

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