The possibility of reducing the requirements for radiation resistance of constructional materials in the nuclear power system

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Abstract. Decades of research into the damage of structural materials of nuclear power plants have not yet led to a clear and consistent understanding of the mechanisms of a significant number of phenomena and processes occurring in metals and alloys under the influence of high-energy neutron irradiation. Creation of construction materials resistant to radiation exposure requires very significant financial and time resources. In this paper, we consider several problems that were actualized in the transition to the development of nuclear power as a system under uranium resource constraints.

1. Introduction
Currently, there is no adequate understanding of the mechanisms of a significant number of phenomena and processes occurring in the constructional materials of the nuclear reactor core under irradiation [1,2]. In this regard, it is necessary to evaluate the system requirements to the materials of fuel pin claddings of fast neutron reactors, in particular, limits for accumulation of hydrogen and helium, which have a significant impact on the strength characteristics of steels and other structural materials under irradiation [3,4]. It is also important to consider the change of nuclide composition of steels under irradiation, as it not only leads to a change in the physical properties of steels, but also affects the allowable time of exposure not only from the point of view of changes of the strength properties, but also problem of solving treatment after irradiation, in particular the problems of storage, utilization opportunities and recycling of construction materials.

Modeling of changes in the composition and properties of constructional materials under irradiation is a necessary step in the development of the concept of designing of reactor materials with desired properties. It is obvious that the process of designing of a new reactor materials on the specified requirements should be built on the basis of use of modern methods and means of physical and chemical research, based on the use of neutron and x-ray spectroscopy; modern methods of monitoring and control of physical, thermodynamic and chemical state of the system and methods of computer simulation and numerical experiments as the most effective tool for the study of condensed matter. Of particular importance is the use of super-computer and information technology (including parallel
programming) to simulate the change of properties of a wide class of the systems studied in various conditions.

This approach will allow to predict the nature and degree of changes in complex compositions on the basis of verified models of the microstructure and atomic dynamics of transport processes in them, as well as to carry out the adjustment of the operating characteristics of these objects by the given criteria by using alloying additives. This is the concept design of reactor materials with desired properties which can be productive for the design of nuclear reactors for different purposes.

2. Materials and Methods

In the present work there are several basic problems which became topical in the transition to the development of nuclear energy as a system in the context of resource constraints:

1. On the one hand, the increase in the fuel burn-up depth, which is relevant in the case of expensive production of fresh fuel and the high cost of handling irradiated fuel with unlimited uranium resources, leads to an increase in the dose of constructional materials to the values at which it is impossible to use previous theories of predicting changes in the properties of constructional materials under irradiation. This in turn requires the development of radiation-resistant constructional materials. But the critical attitude of different authors to different theories, self-criticism of authors using existing theories, uncertainty of dependence of experimental data on many parameters of irradiation speak about inadequacy of the used theories in modern practice of use of constructional materials at the increased doses of irradiation [2]. And the search for acceptable constructional materials to ensure deep burnout of nuclear fuel may either require long experimental tests, or do not give a positive solution;

2. On the other hand, with the closure of nuclear fuel cycle and the transition to the effective use of uranium 238 and thorium 232, there is no need for deep fuel burn-out, which allows, in the absence of reliable theories for predicting changes in the properties of constructional materials under irradiation, to use the existing proven constructional materials in practice;

3. For large-scale development of nuclear power, it is necessary to recycle constructional materials and minimize problems with their utilization and/or isolation, which requires prediction of changes in their nuclide composition under irradiation [3];

4. Modern computational codes allow us to realize the possibility of calculation reliable actual data, which can now be used with great reliability to expand the theoretical set of prediction of constructional materials properties, in particular: changes in the isotopic composition of constructional materials; accumulation of hydrogen and helium in constructional materials.

Recycling of constructional materials becomes relevant in the large-scale development of nuclear power. In recent years, the problem of accumulation of greenhouse gases, associated with the increasing consumption of electricity by the population of the planet, has become more acute. A possible scenario to limit the increase in the average global temperature to less than 2° C is the fast development of nuclear power. The accelerated development of nuclear energy production, starting in 2020, will greatly facilitate the implementation of restrictions on the consumption of organic energy resources, which must be carried out to stabilize global temperatures until 2100. In particular, one of the possible scenarios for the development of nuclear power is to increase the total capacity up to 20000 GW by 2100 [5].

In such a scenario, the issue of nuclear reactor constructional materials recycling becomes very relevant. For the recycling of structural materials, it is necessary to prevent the formation of nuclides in them with a half-life of 30 years and above – those nuclides that can significantly slow the process of returning constructional materials to the cycle of their use in nuclear power or in other sectors of economic activity.

We will conduct analysis and calculations based on the materials of the fuel cladding of the MBIR reactor (table 1) [6].
| Nuclide | Concentration in the material $10^{24}$ cm$^{-3}$ | Mass G cm$^{-3}$ |
|---------|-----------------------------------------------|-----------------|
| B-10    | 3.48E-06                                      | 1.99E-04        |
| B-11    | 1.40E-05                                      | 8.79E-04        |
| C-00    | 2.76E-04                                      | 1.89E-02        |
| N-14    | 6.73E-05                                      | 5.37E-03        |
| N-15    | 2.47E-07                                      | 2.11E-05        |
| Al-27   | 8.75E-05                                      | 1.35E-02        |
| Si-28   | 6.98E-04                                      | 1.11E-01        |
| Si-29   | 3.53E-05                                      | 5.83E-03        |
| Si-30   | 2.35E-05                                      | 4.01E-03        |
| P-31    | 3.05E-05                                      | 5.38E-03        |
| S-32    | 1.68E-05                                      | 3.06E-03        |
| S-33    | 1.33E-07                                      | 2.49E-05        |
| S-34    | 7.44E-07                                      | 1.44E-04        |
| S-36    | 3.53E-09                                      | 7.24E-07        |
| Ti-46   | 3.16E-05                                      | 8.26E-03        |
| Ti-47   | 2.88E-05                                      | 7.70E-03        |
| Ti-48   | 2.91E-04                                      | 7.95E-02        |
| Ti-49   | 2.17E-05                                      | 6.05E-03        |
| Ti-50   | 2.13E-05                                      | 6.06E-03        |
| V-51    | 1.85E-04                                      | 5.38E-02        |
| Cr-50   | 6.51E-04                                      | 1.85E-01        |
| Cr-52   | 1.26E-02                                      | 3.71E-01        |
| Cr-53   | 1.42E-03                                      | 4.29E-01        |
| Cr-54   | 3.54E-04                                      | 1.09E-01        |
| Mn-55   | 1.46E-03                                      | 4.57E-01        |
| Fe-54   | 3.08E-03                                      | 9.47E-01        |
| Fe-56   | 4.87E-02                                      | 1.55E-01        |
| Fe-57   | 1.17E-03                                      | 3.79E-01        |
| Fe-58   | 1.49E-04                                      | 4.91E-02        |
| Co-59   | 1.60E-05                                      | 5.38E-03        |
| Ni-58   | 8.49E-03                                      | 2.80E+00        |
| Ni-60   | 3.27E-03                                      | 1.12E+00        |
| Ni-61   | 1.42E-04                                      | 4.93E-02        |
| Ni-62   | 4.53E-04                                      | 1.60E-01        |
| Ni-64   | 1.15E-04                                      | 4.20E-02        |
| Mo-92   | 1.61E-04                                      | 8.41E-02        |
| Mo-94   | 1.00E-04                                      | 5.36E-02        |
| Mo-95   | 1.72E-04                                      | 9.32E-02        |
| Mo-96   | 1.81E-04                                      | 9.87E-02        |
The calculations carried out in [4] showed that the concentrations of hydrogen and helium obtained in the structural materials of fast neutron reactors due to the interaction of neutrons with the nuclei of iron, chromium and nickel can reach the values at which they have a significant impact on the strength properties and, accordingly, the permissible service life of structural materials in the neutron field.

3. Results

After analyzing the nuclides of the fuel cladding materials, we note that the formation of nuclides with a "dangerous" half-life for the recycle is possible (table 2).

### Table 2. Nuclides with a "dangerous" half-life, the formation of which is possible as a result of nuclear reactions

| Nuclide | Half-life |
|---------|-----------|
| Al-26   | 2.2E+6 y  |
| Ni-63   | 100.1 y   |
| Ni-59   | 7.5E+4 y  |
| Si-32   | 330 y     |
| Ti-44   | 47.3 y    |
| Ar-39   | 269 y     |
| Mo-93   | 3500 y    |
| Zr-93   | 1.5E+6 y  |

Using the MCNP6 [7] software package, burnout in the fuel cladding (steel CHS-68) of the MBIR reactor was calculated after 600 days of irradiation in the neutron field (table 3).

### Table 3. Isotopic composition of structural materials of fuel cladding after 600 days of irradiation

| Nuclide | Concentration in the material $10^24$ cm$^{-3}$ | Mass g | Activity Ci | Specific activity Ci/g |
|---------|-----------------------------------------------|--------|-------------|------------------------|
| Li-7    | 1.18E-06                                      | 4.73E-05 | 0.00E+00 | 0.00E+00 |
| Be-9    | 5.02E-11                                      | 2.58E-09 | 0.00E+00 | 0.00E+00 |
| B-10    | 2.29E-06                                      | 1.31E-04 | 0.00E+00 | 0.00E+00 |
| B-11    | 1.42E-05                                      | 8.92E-04 | 0.00E+00 | 0.00E+00 |
| C-00    | 2.76E-04                                      | 1.89E-02 | 0.00E+00 | 0.00E+00 |
| C-12    | 1.92E-09                                      | 1.31E-07 | 0.00E+00 | 0.00E+00 |
| C-13    | 2.24E-09                                      | 1.66E-07 | 0.00E+00 | 0.00E+00 |
| N-14    | 6.68E-05                                      | 5.33E-03 | 0.00E+00 | 0.00E+00 |
| N-15    | 2.48E-07                                      | 2.12E-05 | 0.00E+00 | 0.00E+00 |
| Na-23   | 3.18E-11                                      | 4.17E-09 | 0.00E+00 | 0.00E+00 |
| Mg-24   | 3.83E-09                                      | 5.23E-07 | 0.00E+00 | 0.00E+00 |
| Mg-25   | 6.89E-08                                      | 9.81E-06 | 0.00E+00 | 0.00E+00 |
| Mg-26   | 1.02E-08                                      | 1.52E-06 | 0.00E+00 | 0.00E+00 |
| Al-27   | 8.75E-05                                      | 1.35E-02 | 0.00E+00 | 0.00E+00 |
| Si-28   | 6.98E-04                                      | 1.11E-01 | 0.00E+00 | 0.00E+00 |
| Element | Si-29 | Si-30 | P-31 | S-32 | S-33 | S-34 | S-36 | Cl-35 | Ca-43 | Ca-44 | Ca-46 | Sc-45 | Ti-46 | Ti-47 | Ti-48 | Ti-49 | Ti-50 | V-50 | V-51 | Cr-50 | Cr-52 | Cr-53 | Cr-54 | Mn-55 | Fe-54 | Fe-56 | Fe-57 | Fe-58 | Co-58 | Co-59 | Ni-58 | Ni-59 | Ni-60 | Ni-61 | Ni-62 | Ni-64 | Cu-63 | Cu-65 | Zn-64 | Zn-66 | Zr-90 | Zr-91 | Zr-92 |
|---------|-------|-------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Value   | 3.56E-05 | 2.34E-05 | 3.05E-05 | 1.67E-05 | 1.36E-07 | 7.44E-07 | 3.53E-09 | 3.80E-11 | 1.32E-09 | 9.32E-09 | 1.08E-10 | 7.44E-10 | 3.15E-05 | 2.88E-05 | 2.91E-04 | 2.25E-05 | 2.14E-05 | 1.02E-06 | 1.88E-04 | 6.46E-04 | 1.25E-02 | 1.43E-03 | 3.63E-04 | 1.46E-03 | 3.06E-03 | 4.87E-02 | 1.23E-03 | 1.98E-04 | 9.55E-06 | 1.67E-05 | 8.40E-03 | 3.03E-05 | 3.26E-03 | 1.51E-04 | 4.53E-04 | 1.15E-04 | 8.80E-09 | 2.86E-07 | 1.13E-11 | 6.62E-10 | 3.23E-11 | 2.94E-09 | 6.89E-09 |
| Value   | 5.87E-03 | 4.00E-03 | 5.38E-03 | 3.05E-03 | 2.56E-05 | 1.44E-04 | 7.24E-07 | 7.58E-09 | 3.23E-07 | 2.33E-06 | 2.83E-08 | 1.91E-07 | 8.24E-03 | 7.70E-03 | 7.94E-02 | 6.27E-03 | 6.08E-03 | 2.90E-04 | 5.45E-02 | 1.84E-01 | 3.71E+00 | 4.32E-01 | 1.12E-01 | 4.56E-01 | 9.42E-01 | 1.55E+01 | 3.99E-01 | 6.53E-02 | 3.15E-03 | 5.60E-03 | 2.77E+00 | 1.02E-02 | 3.03E-05 | 1.11E+00 | 5.24E-02 | 1.60E-01 | 4.19E-02 | 3.15E-06 | 1.06E-04 | 4.10E-09 | 2.49E-07 | 1.65E-08 | 1.53E-06 | 3.61E-06 |
It should be noted that for a clearer picture of the total danger associated with long-lived radionuclides, the activity of radionuclides is given only if it exceeds $10^3$ Ci/g. The most dangerous radionuclides are shown in bold. Almost all the total activity is due to short-lived radionuclides. Among the long-lived radionuclides that complicate the recycling of structural materials, the greatest contribution is given by Ni-59 and Tc-99. This allows us to conclude that when burnup fuel in reactors on fast neutrons, not to exceed 7 - 8% h.a. and damaging dose 70 - 80 dpa it can be recommended to use steel with a lower content of Nickel and molybdenum.

4. Conclusion

There are several main problems that have been actualized in the transition to the development of nuclear power as a system under uranium resource constraints and that can lead to a revision of the requirements for constructional materials of fast reactor fuel assemblies and fuel rods when operating in the nuclear power system:

1. On the one hand, the increase in the fuel burn-up depth, which is relevant given the high cost of producing fresh fuel and the high cost of handling irradiated fuel with unlimited uranium resources, leads to an increase in the radiation dose of constructional materials to values at which it is impossible to reliably use previous theories of predicting changes in the properties of constructional materials under irradiation. This in turn requires the development of radiation-resistant constructional materials. But the critical attitude of different authors to different theories, self-criticism of authors using existing theories, uncertainty of dependence of experimental data on many parameters of irradiation tell about inadequacy of the used theories of modern practice of use of constructional materials at the increased doses of irradiation. And the search for appropriate constructional materials for high burn up of nuclear fuel can require many experimental tests, or simply may not produce positive decisions.
2. On the other hand, in the case of nuclear fuel cycle closure and transition to the effective use of uranium 238 and thorium 232, there is no need for high fuel burn up, which allows, in the absence of reliable theories for predicting changes in the properties of constructional materials under irradiation, to use the existing proven materials in the permissible range of radiation damage;

3. Solving the problems of handling constructional materials after irradiation, in particular the problem of storage, utilization and recycling of structural materials for the large-scale development of nuclear power requires prediction of changes in their nuclide composition under irradiation.

4. One of the main causes of degradation of constructional materials is helium, formed under irradiation by \((n, \alpha)\) reaction on Fe, Ni, Cr, N, B and other elements. Accumulating in the irradiated material and interacting with radiation defects and impurities in the substance, helium forms easily mobile complexes and bubbles, both in the grain body and along the boundaries. It is also important to take into account the change in the nuclide composition of steels under irradiation, since this not only leads to a change in the physical properties of steels, but also affects the allowable time of their irradiation. Modern computational codes allow us to realize the possibility of calculation of reliable actual data, which can now be used with great reliability to expand the theoretical set of prediction of constructional materials properties, in particular: changes in the isotopic composition of constructional materials; accumulation of hydrogen and helium in constructional materials.

References

[1] Devyatko Yu N, Plyasov A A and Khomyakov O V 2014 Primary processes after neutron irradiation of structural materials [in Russian] Nuclear physics and engineering (Moscow: National Research Nuclear University MEPhI) vol 5 № 7–8 pp. 606–621

[2] Blokhin A I, Devyatko Yu N, Demin N A, Zabolotnyi V T, Plyasov A A and Chernov V M 2010 Methods of calculation of initial damage of structural materials of nuclear power plants [in Russian] Nuclear physics and engineering (Moscow: National Research Nuclear University MEPhI) vol 1 № 5 pp. 408–419

[3] Denisov E A, Kompaniets T N, Yukhymchuk A A, Fighters I E and Malkov I L 2013 Hydrogen and helium in nickel and 12KH18N10T steel [in Russian] Technical physics vol 83 № 6 pp. 3-10

[4] Subbotin S A, Efremov V V and Blandinsky V Yu 2017 Forecasting System Requirements to The Materials of the Shell of Fuel Elements of Innovative Fast Reactors 15th International School-Conference “New materials – Materials of innovative energy: development, characterization methods and application” (KnE Materials Science) pp. 280–286

[5] Berger A et al 2017 How much can nuclear energy do about global warming? Int. J. Global Energy Issues vol. 40 Nos.1/2 pp.43–78

[6] Poglyad N S and Kozolup A N 2011 Justification of the choice of the design of TVS reactor MBIR and results of thermal-hydraulic calculations conditions for its radiation [in Russian] Team of works of JSC NIIAR vol.1 pp.51-55

[7] Fesnin M L, James M R, Hendricks J S and Goorley J T 2012 The New MCNP6 Depletion Capability Proceedings of ICAPP12

Acknowledgments
The authors appreciate the support and effort of National Research Nuclear University MEPhI. This work was supported by Competitiveness Program of National Research Nuclear University MEPhI.