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Safety issues as a start point for further investigations of fusion hybrids

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Abstract. Nuclear power plants supply nearly one sixth of the world electric energy production. Though nuclear power is a very efficient source of energy, it produces dangerous radioactive waste composed of nuclides characterized, among others, by a long decay time and containing also significant quantities of fissible and even fissile materials. Therefore, spent nuclear fuel must be carefully stored for at least hundreds of years, all this time needing permanent supervision. Simultaneously this cumbersome waste contains also important amounts of energy that should not be simply buried forever. Thus, in spite of the fact that ultimate disposal of spent nuclear fuel in adequate geological formations is recognized as safe for the energy hungry world that tries at the same time to avoid CO_2 emissions, this is a hardly acceptable solution. Fortunately, there is an effective approach, namely – spent fuel recycling, particularly with the help of nuclear fusion. Simultaneously, one has to admit that this concept has not attained yet technological maturity, thus lengthy and costly investigations still are necessary before nuclear fusion achieves development level adequate to industrial application. Since every nuclear device must be generally safe, therefore this article raises a safety issue of fusion-fission hybrid design. In order to ensure the required reliability of evaluations the development of heterogeneous model of the device was assumed as the starting point for further respective research. The performed calculations have indicated that maintenance of subcriticality even in the case of system collapse is achievable.

Key words: fusion hybrid • radiation damages • safety • transmutation

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Introduction

Homogeneous models of fusion hybrid systems were already investigated long ago, for instance, by one of the authors [5, 6]. However, this simple and convenient for simulation case is only an approximation that may be insufficiently exact for ultimate, reliable calculations. Therefore, a heterogeneous model of hybrid system where fuel takes the form of rods assembled in fuel elements is considered. Such solution requires prior mechanical and chemical processing for selection of the fuel composition for optimization of burn-up and transmutation processes. In fusion-driven subcritical system one can expect incineration of minor actinides and even Pu isotopes in fissioning induced by 14 MeV neutrons.

The core of discussed fusion hybrid reactor is 10 m long, the first wall radius amounts to 0.65 m whereas the reflector radius to 1.22 m. The central cylindrical space comprises plasma that is kept by magnetic field generated by superconducting coils. The fuel volume is divided into three zones, each of different composition according to the rule: the farther distance from plasma the higher fraction of plutonium containing fissile nuclides (^{239}Pu, ^{241}Pu). The cross section of fusion hybrid

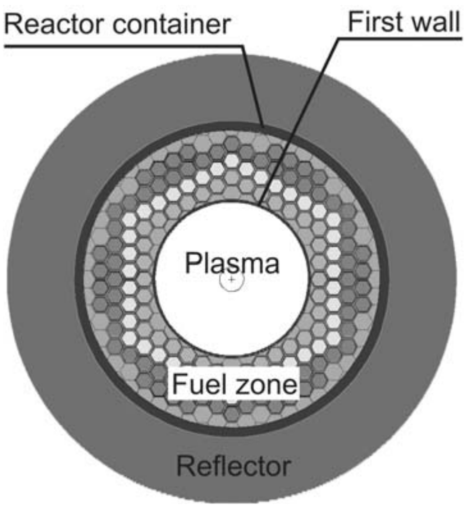

Fig. 1. Hybrid reactor cross section.

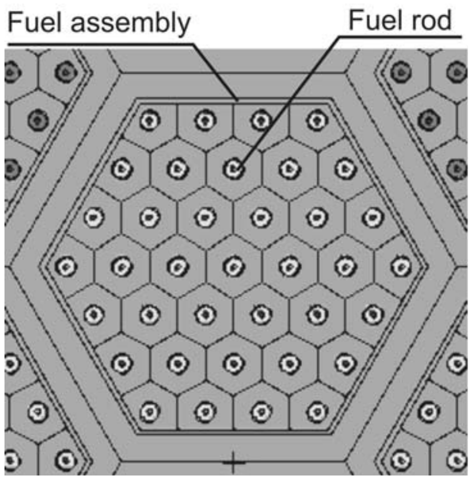

Fig. 2. Fuel element cross section.

model is shown in Fig. 1, while the cross sections of fuel element and of fuel rod are shown in Figs. 2 and 3, respectively. Each fuel element contains 37 rods laid out in hexagonal lattice. In this phase of preliminary calculations no control rods have been assumed in such subcritical system thanks to the desired safe low value of neutron multiplication factor k_{eff}.

The orientation of the device can be set either horizontal or vertical. The positioning of the installation has not been settled yet, since more investigations are still needed, particularly of cooling in case of a breakdown of the system. It is fundamental to assure the passive self--sufficiency of cooling in any circumstances in order to prevent over-heating that threats with destruction of the whole system and release of enormous radioactivity.

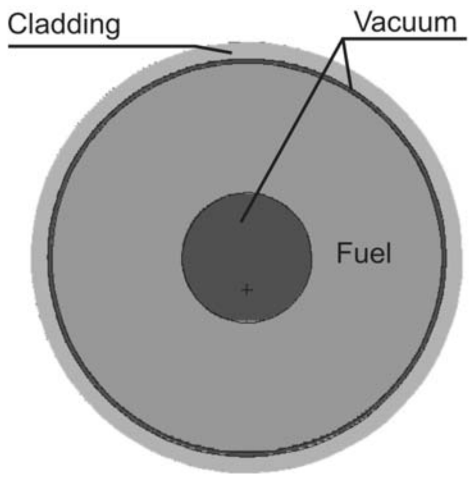

Fig. 3. Fuel rod cross section.

Another important issue concerns mechanical properties of device components and fixing manner of superconducting coils.

Calculations and results

In order to illustrate some features of the present concept various calculations have been carried out with the MCNP4c using JEFF3.1 libraries [1]. Table 1 shows the fuel composition in individual fuel zones.

The precondition of licence acquisition and thus of use of any nuclear device is to demonstrate the safety of its operation, thus a key issue is to prove keeping the value of k_{eff} less than 1 in various scenarios of breakdown and failure which may occur during work of the system. Fusion hybrid as externally driven subcritical system allows for maintaining the value of k_{eff} sufficiently low that it cannot exceed 1. The most probable faults (section 'Discussion and conclusions') seem to be the leakage of coolant or system collapse and both cases should be first tested on the basis of computer model before the system is constructed. The obtained results regarding both above-mentioned items can be seen in enclosed figures. Figure 4 shows the relationship between the value of k_{eff} and the remaining amount of coolant dur-

Table 1. Composition of fuel in individual zones

Isotope	Zone 1		Zone 2		Zone 3	
	Atomic fraction (atoms/A^3)	Mass fraction (u/A^3)	Atomic fraction (atoms/A^3)	Mass fraction (u/A^3)	Atomic fraction (atoms/A^3)	Mass fraction (u/A^3)
^{16}O	4.42E–02	7.07E–01	4.42E–02	7.07E–01	4.42E–02	7.07E–01
^{237}Np	1.83E–03	4.35E–01	1.67E–03	3.95E–01	1.50E–03	3.55E–01
^{238}Pu	3.45E–04	8.22E–02	3.13E–04	7.46E–02	2.82E–04	6.71E–02
^{239}Pu	4.83E–03	1.15E+00	6.04E–03	1.44E+00	7.25E–03	1.73E+00
^{240}Pu	2.76E–03	6.63E–01	2.51E–03	6.02E–01	2.25E–03	5.41E–01
^{241}Pu	1.10E–03	2.66E–01	1.38E–03	3.33E–01	1.66E–03	3.99E–01
^{242}Pu	1.10E–03	2.67E–01	1.00E–03	2.43E–01	9.02E–04	2.18E–01
^{241}Am	5.50E–03	1.32E+00	4.99E–03	1.20E+00	4.49E–03	1.08E+00
^{242}Am	3.67E–05	8.89E–03	3.34E–05	8.07E–03	3.00E–05	7.26E–03
^{243}Am	4.58E–03	1.11E+00	4.16E–03	1.01E+00	3.74E–03	9.09E–01

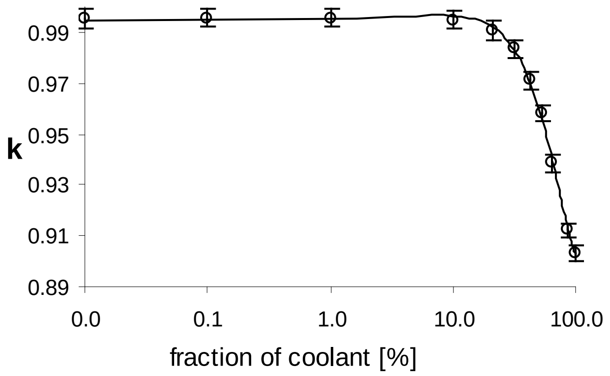

Fig. 4. Neutron multiplication factor k vs. the coolant fraction remaining in the system.

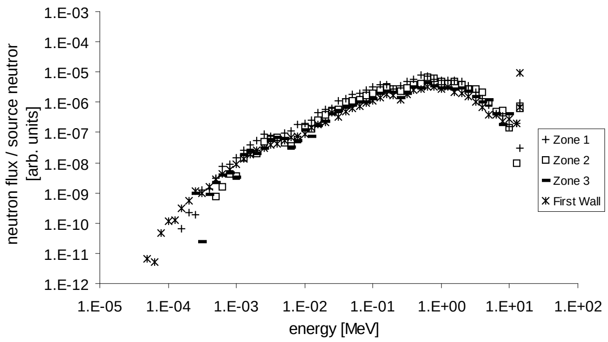

Fig. 6. Neutron flux spectra per source particle per lethargy unit in individual zones.

ing loss of coolant accident (LOCA). As one may see, the k_{eff} factor suddenly grows up when the amount of coolant decreases, however it still does not exceed 1 even after total leakage of coolant and finally reaches a maximum value of 0.9951 with a standard deviation (SD) equal to 0.0012. This subcriticality level is very tiny and in view of neutron data accuracy and even more of non-ideal modelling of the system the k_{eff} value still should be slightly lower for the sake of system safety. The case of collapse is as well disquieting, as indicate the calculations carried out for the rearrangement that can be seen in Fig. 5. The respective value of k_{eff} is equal to 0.9974 with a SD equal to 0.0003, what means that in such a scenario subcriticality is only hardly maintained. This warning situation differs from the one of homogenous (mixed fuel and coolant) hybrid model [6], where after collapse the value of k_{eff} factor increases from 0.94 to mere 0.97.

Radiation damage is important when considering mechanical properties of the materials [3, 4, 8–10] used for reactor construction and the costs connected with necessity of periodical replacement of used device components. One should remember that such a system has never been built and when first becomes operational many new practical problems of different significance will surely arise. The evaluated here level of dpa in the first wall, as in the most sensitive, therefore most important place, amounts to 80/yr (for assumed energy production equal to 1000 MWe). This result compared

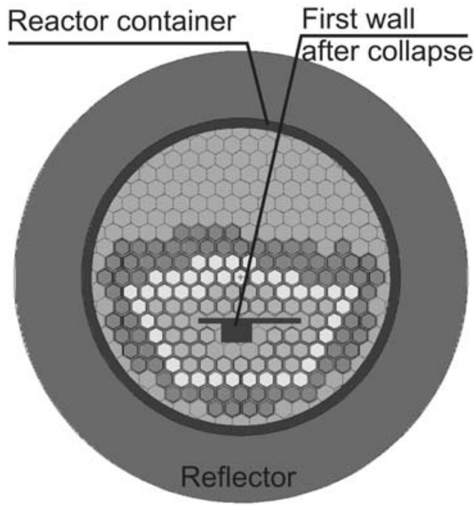

Fig. 5. Simplified model of collapse accident.

to the dpa values in other research [8, 10], seems quite reasonable. Gas production rate (especially helium) is important as well as dpa. Estimated He yield amounts to 344 appm/yr (calculated for identical conditions as the dpa) and compared to other investigations [2, 4, 7] meets the requirements.

Neutron flux spectra have fundamental meaning for nuclide burn-up process and waste transmutation and are shown in Fig. 6 in particular zones of the device, respectively. The spectra show a clear 14 MeV peak that may result in extra heating from threshold fissioning of minor actinides, first of all in zone 1. The extra neutrons in question from these fissions do not contribute to the neutron chain, thus leaving the k_{eff} unchanged, i.e. the system safety unaffected. However, the calculations concerning this problem have to be shifted for further investigations, since the selection of fuel composition and its distribution is a complex question. This belongs to the optimization issues that still now lie beyond the scope of the present study.

Discussion and conclusions

Properly working fusion hybrid system maintains desired subcriticality and assures acceptable margin of safety. However, designing of device such as nuclear reactor must assume predictable faults and its consequences. Most likely initiators of fault are: material fatigue, blunder/mistake of service crew, sabotage, terrorist attack, natural disaster, etc. Most of them, for example, numerous mistakes of crew can be prevented by dedicated safety systems and appropriate training schedule, however, there is impossible to predict all options, especially the time and place of occurrence of components failure, or of natural disasters. On the other hand, we are able to construct a plant in such a manner that the consequences of terrorist attack and/or of natural disasters can be minimized. Nevertheless, the a possibility of such effects as power supply perturbations with all negative outcomes, e.g.: magnetic field instabilities and plasma disruptions, cooling system disturbances and mechanical damages of moving components (e.g. pumps) cannot be excluded. Therefore, most dangerous of known possible accident must be postulated, namely the coolant leakage and system collapse. The goal of performed simulations is the proof of safety of the discussed hybrid system, i.e. the criticality accident test in the case of LOCA or collapse. The presented results clearly point at shallow subcriticality state in these conditions. Though such situation is hypothetical and rather improbable, it forces us to search correct solution to ensure safety during the worst scenario. The conservative attitude suggests keeping k_{eff} factor slightly lower than previously assumed 0.9. In the case of LOCA, such condition ensures enough time to take steps to prevent the system against overheating and collapse, i.e. allows to undertake appropriate actions.

Radiation damages matters for components durability and indirectly influences safety conditions as well as the operation and maintenance costs. The first wall is of special importance among others in this issue due to higher neutron flux that includes 14 MeV neutrons. The evaluated dpa and helium production value according to other research [2, 7, 9, 10] still remains at safe level. Suggested fuel composition brings out quite uniform neutron flux, however, as one may notice a series of important issues has been neglected in the present study (e.g. neutron flux and nuclear heating distributions, fuel composition selection etc.) Thus, these issues will be investigated in detail within further research, according to plans of the authors.

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