**A $^{208}\text{Pb}$ coolant for a multipurpose nuclear reactor**

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**Abstract.** Natural lead containing 52.3% of stable isotope $^{208}\text{Pb}$ can be applied in the nuclear small power engineering as such a coolant for fast reactors of various purposes. In this case unique consumer properties of $^{208}\text{Pb}$ might be realized which are the following: the low inelastic scattering and small absorption of neutrons by $^{208}\text{Pb}$ nuclei.

In the paper is shown that a high-enough neutron spectrum can be achieved in a small dimensions core fueled with a plutonium-zirconium alloy ($\text{Pu-Zr}$) and cooled with natural lead. In fulfilling these conditions, an average neutron energy in the core center is equal to 0.869 MeV and a share of hard neutrons ($E_n>0.8$ MeV) reaches the value of 35%.

The replacement of the lead coolant with a $^{208}\text{Pb}$ coolant leads to further increasing the average core neutron energy up to the value of 0.991 MeV and increasing the share of hard neutrons in the neutron spectrum up to 42%.

An interest for creating hard neutron spectrum reactors is high-enough mainly thanks to their potential ability to transmute (to inverse into fission products) the most dangerous from the radiotoxicity point of view minor actinides ($\text{Np, Am, Cm}$). As is generally known, a hard spectrum of neutrons in FR core is preferable for incineration of MA.

Some other possibilities of the hard spectrum reactor usage exist, for instance, production of radio isotopes for medicine and investigation of radiation damages in materials of nuclear engineering.

**1. Introduction**

Last time at the Obninsk Institute for Nuclear Power Engineering a concept of a small power fast reactor (FR) with high-enough core neutron energy has been developed [1-5]. The goal desired was achieved by selecting a core of small dimensions, innovative metallic fuel and low neutron moderating lead coolants containing natural lead ($\text{Pb}$) or enriched lead ($^{208}\text{Pb}$).

An interest for creating hard spectrum reactors is high-enough mainly thanks to their potential ability to transmute (to inverse into fission products) the most dangerous from the radiotoxicity point of view minor actinides ($\text{MA – Np, Am, Cm}$). As is generally known, a hard spectrum of neutrons in FR core is preferable for incineration of MA.

Some other possibilities of the hard spectrum reactor usage exist, for instance, production of radio isotopes for medicine and investigation of radiation damages in materials of nuclear engineering.

**2. Design parameters of hard neutron spectrum reactors**

At the Obninsk Institute for Nuclear Power Engineering a series of reactors named BRUTS was designed under conceptual study. The first reactor BRUTS [1] was of 0.5 MW thermal capacity and of core dimensions $D \times H = 0.62 \times 0.62$ m$^2$. Uranium dioxide as such a fuel and natural lead as such a
coolant were used. A low-enough (26%) share of coolant in the core was selected. The calculated average neutron energy in the core center was equal to 0.554 MeV with a share of hard (E\textsubscript{n}>0.8 MeV) neutrons equal to 18.11%. The replacement of the natural lead coolant with the \textsuperscript{208}Pb coolant did not change dramatically the core neutron spectrum.

In the BRUTS-M (0.5 MW of thermal capacity, D x H = 0.7 x 0.7 m\textsuperscript{2}) \cite{2} fueled with U-Zr10wt% and cooled with natural lead (70% of coolant shares in the core) the average core neutron energy was equal to 0.592 MeV with the share of hard neutrons in the neutron spectrum equal to 20.17%. The replacement of lead with \textsuperscript{208}Pb led to increasing the average core neutron energy up to 0.643 MeV and increasing the share of hard neutrons up to 23.06%.

As the next step, design of BRUTS-M2 \cite{3-5} fueled with U53wt%-Pu30wt%-Zr17wt% was performed. At thermal capacity of 15 MW, coolants of Pb/\textsuperscript{208}Pb the average core neutron energy grew up to 0.724/0.874 MeV and the share of hard neutrons increased up to 28.45/34.14%.

At last, the hardest core neutron spectrum was obtained in the project named as BRUTS-M5 – the reactor fueled with an uranium free plutonium-zirconium alloy (Pu52wt%-Zr48wt.%). At thermal capacity of 25 MW, neutron flux density of 3·10\textsuperscript{15} cm\textsuperscript{-2}·s\textsuperscript{-1}, coolants of Pb/\textsuperscript{208}Pb the average core neutron energy was equal to 0.869/0.991 MeV and the share of hard neutrons was equal to 34.61/42.34%.

Thus, using the \textsuperscript{208}Pb coolant instead of the natural lead coolant allows increasing the average core neutron energy at 14% and increasing the share of hard neutrons at 22%.

A harder spectrum, than spectra in known fast sodium and molten salt reactors, has been obtained thanks to the selection of relatively small core dimensions, metallic fuel and lead (Pb or \textsuperscript{208}Pb) as such a coolant.

In the calculations of these compositions, increased average neutron energy and a high share of hard neutrons in the spectrum (with energies greater than 0.8 MeV) are achieved that is caused by the low inelastic neutron-fuel and neutron-coolant interactions thanks to the usage of a fuel without light chemical elements and a coolant containing \textsuperscript{208}Pb, a low moderating isotope.

An interest for creating hard neutron spectrum reactors is explained by the fact that such reactors can be practically used as burners of minor actinides as well as isotopic and research reactors with new consumer properties.

With the uranium oxide fuel (UO\textsubscript{2}) replaced by the plutonium fuel (Pu-Zr) in lead fast reactors, the one-group (averaged upon the neutron spectrum) fission cross section of \textsuperscript{241}Am increases from 0.3 to 0.6 barn and the probability of \textsuperscript{241}Am fission increases from 22 to 45%.

It is suggested that fuel resulting from regeneration of irradiated fuel of sodium fast reactor to be used in future burner reactors. It contains unburnt plutonium isotopes and some 1% of minor actinides which transmute into fission products in the process of being reburnt in a harder spectrum. This will make it possible to reduce the MA content in the burner spent fuel and facilitate so the long-term storage conditions for high-level nuclear waste in dedicated devices.

Additionally, the hard neutron spectrum reactor can be used for production of radio isotopes for medicine via nuclear reactions of (n, p), (n, 2n) and (n, α) types which do not run in modern isotopic reactors with thermal or intermediate neutron spectra.

At last, the hard neutron spectrum reactor may be also used as such a research reactor thanks to the high share (35-42%) of hard neutrons which are able to cause stronger damages in the materials of nuclear engineering than modern research reactors can do it.

3. Conclusions

- In fast reactors of small core dimensions (D x H = 0.5 x 0.5 m\textsuperscript{3}) fueled with a plutonium-zirconium alloy and cooled with natural lead, the average neutron energy at the core center reaches the value of 0.8 MeV with a high share (35%) of hard neutrons (E\textsubscript{n}>0.8 MeV) in the neutron spectrum.

- The replacement of the natural lead coolant with the \textsuperscript{208}Pb coolant leads to increasing the average core neutron energy and the share of hard neutrons in the neutron spectrum at 14% and 22%
respectively. Thus, for the hard neutron spectrum reactor, about 42% of neutrons in the core center have energies above 0.8 MeV, while for known sodium fast reactors, the share of such hard neutrons in the core center does not exceed 15%.

- The hard neutron spectrum reactors have some consumer properties while no such properties exist in the modern power and research reactors:
  - In using the hard neutron spectrum reactor for transmutation minor actinides, is possible to reach the $^{241}\text{Am}$ fission probability as high as 45% while in sodium fast reactors it does not exceed 15%.
  - In using the hard neutron spectrum reactor for production of radio isotopes for medicine, is possible to obtain some rare radio isotopes via nuclear reactions $(n, p)$, $(n, 2n)$ and $(n, \alpha)$ which run only in hard neutron spectra.
  - In irradiating materials of nuclear engineering in the hard neutron spectrum reactor, is possible to obtain in them greater radiation damages as compared with these materials irradiating in modern research reactors.

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**References**

[1] Samokhin D S, Khorasanov G L, Tormyshev I V, Zemskov E A, Gostev A L, Terehova A M and Kuz’michyov S A 2015 *Izvestiya Vissikh Uchebnikh Zavedeniy. Yadernaya Energetika* issue 3 pp 135–141 (in Russian)

[2] Khorasanov G L, Samokhin D S and Zevyakin A S 2017 *Proc. Int. Conf. on Ecological, Industrial and Energetical Safety* (Sevastopol’: Sev. State University) pp 1467–71

[3] Khorasanov G L and Samokhin D S 2017 *Theses of the 2nd Int. Conf. of Young Scientists, Specialists, Postgraduates and Students on Innovative Nuclear Reactors of Small and Ultra-Small Power* (Obninsk: INPE NRNU MEPhI) pp 19–21 (in Russian)

[4] Khorasanov G L, Samokhin D S and Zevyakin A S 2017 *Theses of the All-Russian Scientific and Practical Conf. on Materials of Nuclear Engineering* (Moscow: AS VNIINM) pp 43–5 (in Russian)

[5] Khorasanov Georgy, Samokhin Dmitry and Zevyakin Alexander 2017 *Transactions of the American Nuclear Society* 117 pp 1083–85