**Increase of the safety of nuclear reactors and extension of the lifespan of nuclear fuel by covering the surface of the fuel elements with anticorrosion polycrystalline diamond layers**



Deposition from the gas phase – Surface of the Zr element covered by a polycrystalline diamond layer – Zr alloy – Standard surface of the Zr element

Based on the results of a series of tests, zircalloy fuel assemblies covered with anticorrosion protective polycrystalline diamond layers were selected in 2017 by Westinghouse as possible candidates for Accident Tolerant Fuel in commercially operated reactors after 2020. In February 2017, long-term tests began of nuclear fuel covered with PCD layers (Zr fuel assemblies filled with UO2 pellets) in the active environment of a research nuclear reactor in Halden, Norway. The effective method of the protection of zircalloys with polycrystalline diamond layers was proposed by experts from the Institute of Physics of the CAS, the Faculty of Mechanical Engineering of the CTU and the company Westinghouse. Czech patent Nr. 305059: “*Layer protecting the surface of zircalloys used in nuclear reactors”* was granted in March 2015. At the same time, the PCT application (WO2015039636-A1) entitled *"Layer protecting the surface of zirconium alloys used in nuclear reactors"* was registered in the international database <https://www.google.com/patents/WO2015039636A1?cl=en>. In 2016, the applications were submitted with the patent offices of the EU, USA, Japan and South Korea.

The composite polycrystalline diamond layers were prepared in the laboratories of the Institute of Physics of the CAS by the method of deposition from the gas phase. The layers were tested in simulations of emergency and standard conditions of a nuclear reactor at the facilities of the FS (Faculty of Mechanical Engineering) of the CTU, ICT in Prague, IP of the CAS, UP Olomouc, Karlsruhe Institute of Technology and Westinghouse Electric. The PCD cladding significantly lowered the corrosion of the zircalloy elements not only under standard working conditions but also under an emergency increase of temperatures to 1000oC. Building on the very good results of the inactive tests, the samples were covered with PCD irradiated with Fe2+ (3 MeV, 1.95 × 1016 at/cm2) at the accelerators at Texas A&M, USA.  Short-term irradiation with relatively heavy ions is standardly used for the simulation of the damage of a material by long-term irradiation with thermal neutrons and in the case of the PCD material there was no significant changes in the structural integrity of the layer after irradiation with Fe2+. Among others, the journals Science Daily and Materials Performance (2015) reported on the research:

<https://www.sciencedaily.com/releases/2015/10/151019104151.htm>, http://www.fzu.cz/en/scientists-help-safeguard-nuclear-reactors

Besides the fact that the PCD layers can serve as a passive element for increasing nuclear safety, they also extend the lifespan of the nuclear cladding and subsequently also the period of the safe usage of nuclear fuel. Long-term tests (40-170 days) in the autoclaves of the laboratories of Westinghouse Electric (according to the norms of the ASTM) showed that the cover with PCD layers lowers the oxidation of the Zr samples by 40% as compared to the standards. The significant reduction of the corrosion of the cladding can extend the life of the use of nuclear fuel, which is currently removed from the reactor for the reason of the high corrosion of the cladding (Zr alloys) and not for the reason of sufficient burning.

Unlike the usual methods of the anticorrosion protection of the surface of the Zr alloys with compact layers with minimal permeability, the nonhomogeneous PCD layers prevent the corrosion of the Zr alloys in a complex way. PCD are comprised of two different phases of carbon, namely the hard diamond and the soft graphite; hence they are flexible and at the same time solid, thanks to which they withstand the heat load in the course of the work cycle of the reactor. Besides the fact that the PCD layer prevents direct contact of the Zr alloys with the surrounding environment, the carbon from the PCD layer permeates into the underlying material and changes it to deteriorate the corrosion conditions of the zirconium alloys in the nuclear reactor significantly.

**The results were published in**

**Scientific Reports**/Nature Publishing Groups *Scientific Reports* **7**, Article number: 6469 (2017) “Nanocrystalline diamond protects Zr cladding surface against oxygen and hydrogen uptake: Nuclear fuel durability enhancement” https://www.nature.com/articles/s41598-017-06923-4.

**Applied Surface Science** 359 (2015) 621-628 *Thin polycrystalline diamond films protecting Zirconium alloys surfaces: from technology to layer analysis and application in nuclear facilities*,

**J. Mater. Process. Technol**. 214 (2014) 2600 - 2605: *Nanosized polycrystalline diamond cladding for surface protection of zirconium nuclear fuel tubes*,