Contribution ID: **1101** Type: **Regular Poster**

NUCLEAR PHYSICAL PROPERTIES OF AUSTENITIC CHROMIUM-NICKEL AND CHROMIUM-MANGANESE STEELS UNDER NEUTRON IRRADIATION IN NUCLEAR FAST FISSION AND FUSION REACTORS

Friday, 14 May 2021 18:25 (20 minutes)

On the basis of the calculation complex ACDAM-2.0, comparative studies of the nuclear physical characteristics of austenitic chromium-nickel steel EK-164 (Fe-16Cr-19Ni-2Mo-2Mn-Nb-Ti-B) and its manganese modifications EK-164Mn (Fe-16Cr-20Mn-2Mo-Nb-Ti-B) and EK-164MnW (Fe-16Cr-20Mn-2W-Nb-Ti-B) irradiated in typical neutron spectra of cores of fast (BN-600) and fusion (DEMO-C) reactors, and long after reactor exposures (nuclear cooling) have been performed. A complete set of nuclear physical characteristics of steels under neutron irradiations (up to 5 effective years) and under long exposures (nuclear cooling up to 1000 years) after neutron irradiations has been obtained and their comparative analysis has been given. The nuclear physical characteristics of EK-164, EK-164Mn, and EK-164MnW steels have been determined, including primary radiation damage, nuclear activation and transmutation, radioactivity, gamma radiation power, nuclear energy release, nuclear hydrogen and helium production, nuclear cooling after irradiation, and isotopic contributions. The influence of the element composition of steels (alloying and impurity elements) on their nuclear physical characteristics under neutron irradiation and after irradiation has been studied. Time intervals after neutron irradiation that meet the criteria for low activation of irradiated steels (gamma dose rate less than 10 mSv/hour, radioactivity less than 1010 Bq/kg, energy release less than 10 W/m3) of less than 100 years after neutron irradiation, depending on the duration of neutron irradiation, have been determined.
Currently, austenitic chromium-nickel steels ChS-68 (Fe-16Cr-15Ni-2Mo-Mn-Ti-V-B) and EK-164 (Fe-16Cr-19Ni-2Mo-2Mn-Nb-Ti-B) are used or planned for use as structural materials (SM) for the cores of Russian fission (fast) (BN-600, BN-800, BN-1200, MBIR, etc.) and fusion (DEMO-C, DEMO-FNS, etc. projects of the NRC "Kurchatov Institute") reactors. Limiting factors for the use of austenitic chromium-nickel steels in nuclear application are their swelling, high-temperature (helium) radiation embrittlement (HTRE), corrosion, the highly active and long-lived radioactive wastes. To reduce swelling during neutron irradiation, the nickel concentration in the element composition of EK-164 steel was increased (relative to ChS-68 steel). However, increasing the concentration of nickel in austenitic chromium-nickel steels increases the difficulties of their nuclear application (radioactivity, HTRE, corrosion, cost). To reduce the difficulties of using austenitic chromium-nickel steels, austenitic chromium-manganese steels of the Fe-(10-18)Cr-(10-30)Mn-2Mo(W) type are proposed and developed. Austenitic chromium-manganese steels are potentially competitive in their respective properties and less radioactive compared to austenitic chromium-nickel steels. The nuclear use of chromium-manganese steels can potentially increase the radiation and temperature loads on the reactor core structure elements during their operation and increase radiation safety when handling irradiated steels. It is important to use austenitic chromium-manganese steels for fusion reactors, for which the use of low-activated and non-magnetic SMs is an important advantage for magnetic plasma retention (TOKAMAK type reactors). The available results on pre-reactor and reactor studies of austenitic chromium-manganese steels show their potential competitiveness compared to austenitic chromium-nickel steels in their respective properties and justify the prospects for their further development and application in nuclear (fast) and fusion reactors. To optimize the element compositions and properties of chromium-manganese steels, studies of their nuclear physical properties during long-term neutron irradiations in fission (fast) and fusion reactors and long exposures (nuclear cooling) after neutron irradiations are important and relevant. Studies of these properties allow us to determine the compliance of the obtained nuclear and radiation characteristics of austenitic chromium-manganese steels with the criteria of low activation of SMs for nuclear applications (gamma radiation power, radioactivity, nuclear energy release), the possibility and timing of radiochemical reworking of irradiated steels.
Primary radiation damage (NRT-standard) of all steels in all neutron spectra has been determined by close values of 47-50 dpa/year. When irradiated in the fast fission neutron spectrum, all steels (EK-164, EK-164Mn, EK-164MnW) are practically not low activated (the time of the gamma-dose power decline to the level of 10 mSv/hour is more than 1000 years, even after very short durations of neutron irradiations). In this case (fast reactors), the re-use (recycling) of irradiated steels is possible at times more than 1000 years after irradiation. When irradiated in the fusion neutron spectrum, only EK-164MnW steel belongs to the class of low-activated SM. Re-use (recycling) of irradiated steel EK-164MnW is possible for less than 50 years after long-term (up to 5 effective years) neutron irradiations in DEMO-C. The EK-164 and EK-164Mn steels meet the requirements of low activation type only for very short neutron irradiation durations (less than 1 effective year) in DEMO-C. It is only EK-164MnW steel for which the decrease in radioactivity to the level of 1010 Bq/kg under neutron

irradiations in fast fission (BN-600) and fusion (DEMO-C) reactors (up to 5 effective years) is achieved in less than 100 years after irradiation. For other steels (EK-164, EK-164Mn), the time of this decrease in radioactivity is more than 1000 years. Nuclear hydrogen accumulation in EK-164Mn and EK-164MnW steels is almost identical for all neutron spectra, but less than in EK-164 steel approximately 4 times for fast and approximately 2 times for fusion reactors. Nuclear hydrogen accumulation in steels in the fusion neutron spectrum is significantly higher than in the neutron fission spectrum: for EK-164 steel is about 3.4 times higher, for EK-164Mn and EK-164MnW steels is about 9 times higher. The nuclear formation of helium in EK-164Mn and EK-164MnW steels under neutron irradiation in all the reactors is almost identical and half as much as for EK-164 steel. For all steels, helium production during neutron irradiation in the fusion reactor is significantly (6-7 times) higher than the corresponding values for neutron irradiation in the fast reactor.
Radiogenic changes in the concentration of B (B10+B11) for all steels are the same and are determined only by the type of neutron spectra (fast or fusion reactor). When irradiated in the reactor BN-600, the concentration of B in all steels decreases by 15%, while the concentration of B10 decreases by 90%, and the concentration of B11 increases by 3%. When irradiated in the reactor DEMO-C, the concentration of B in all steels increases by 2%, while the concentration of B10 decreases by 5 %, and the concentration of B11 increases by 4% (the initial concentrations of isotopes in natural B are determined by the values of 19.8% for B10 and 80.2% for B11).
Radiogenic production of helium in steels under irradiation in fusion neutron spectrum practically does not depend on the concentration of B in them. Isotopes that determine the dynamics of changes in the nuclear physical properties of steels under irradiation in the neutron spectra of fast and fusion reactors have been determined. Table lists the main isotopes that determine the radioactive properties of EK-164 and EK-164MnW steels.

Table. The main isotopes that determine radioactivity, gamma radiation power and energy release in EK-164 and EK-164MnW steels 31 years after they were irradiated for 5 years in the BN-600 and DEMO-C reactors. Isotopes with a half-life of more than 31 years are marked out.

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**EK-164**                          **EK-164MnW**
 BN-600                  DEMO                  BN-600      DEMO-
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Ni63,Nb93m,Fe55,xxxxxxxxCo60,Fe55,Nb93m,xxxxxxxNb93m,Fe55,xxxxFe55,Nb93m,H3,
Co60,**Ni59,Mo93,Nb94**xxxxxx**Nb91**,H3xxxxxxxxxx**Nb94**,C060xxxxxCo60,**Nb94**

Conclusion: austenitic (non-magnetic) steels of chromium-manganese type EK-164MnW (Fe-16Cr-20Mn-2W-Nb-Ti-B) are potentially promising for use as SM in cores of fusion reactors (the low-activation SM with a reduced propensity to HTRE) and fission (fast) reactors (the SM with a reduced level of radioactivity, a reduced propensity to HTRE and a reduced propensity to corrosion).

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Session Classification: P8 Posters 8

Track Classification: Fusion Energy Technology