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# Justification of the new approach to the testing of the candidate ITER materials in fission reactor

V.A. Nikolaenko *, V.I. Karpukhin, E.A. Krasikov, V.N. Kuznetsov

*Russian Research Centre Kurchatov Institute, Kurchatov sq. 1, 123182 Moscow, Russian Federation*

**Abstract**

Routine approaches to the candidate ITER materials reactor testing have to be modified by taking into account the large, difference between fusion and fission reactor gamma-quanta fluxes. Recent analyses have shown clear evidence of the relationship between the steel ductile to brittle transition temperature (DBTT) shift and the gamma-quanta flux during the reactor irradiation. For example, if during the reactor irradiation of the 25Cr3NiMo type steel gamma-quanta the flux increases from $5 \times 10^{11}$ to $5 \times 10^{12}$ $sm^{-2}$ $s^{-1}$ to obtain the DBTT = 160°C, it is necessary to increase the neutron fluence by one order of magnitude. Simultaneous neutron and gamma irradiation is characterized by an Irradiation Composition Factor (ICF) – neutron flux/gamma-quanta flux. For example, for a fast neutron fluence ($E > 0.5$ MeV) of $2.4 \times 10^{19}$ $cm^{-2}$ and $1.6 \times 10^{19}$ $cm^{-2}$ and corresponding values of ICF of 0.4 and 2.1, the DBTT shift is greater for the smaller neutron fluence. Hence, the smaller is the ICF the greater is the gamma-quanta of the nescient defects restoring (annealing) action. For the ITER first wall the ICF is 4, whereas for a nuclear reactor it is only 0.1–0.3. Therefore the new approach to the experimental procedure of the experimental procedure of the canditate ITER materials testing in a fission reactor is justified. 

The conditions of testing of ITER candidate materials in fission reactors are not adequate for conditions to a fusion reactor. For instance, a problem exists that is related to new notion: the Irradiation Composition Factor (ICF), which is defined as the ratio of neutron to gamma fluxes. In the fission reactor core, where ITER candidate materials are tested, ICF is equal to 0.1–0.3, while for the first wall of ITER ICF is approximately equal to 4, corresponding to relatively small gamma-quantum fluxes [1] and leading to a decrease of probability of radiation gamma-annealing of defects.

The effect of radiation gamma-annealing was detected for diamond [2,3] and was verified for graphite [4]; it also occurs on other materials [5,6]. In particular, the results on ductile–brittle transition temperature (DBTT) of Reactor Pressure Vessel (RPV) steels for decommissioned VVER reactors were analyzed in the present paper from the viewpoint of gamma-radiation annealing effects.

The gamma-ray effect is usually estimated in terms of heat release. However, at the time between the gamma-quantum onset and the subsequent heating, some processes and transformations occur, whose role and influence on the material properties have not been considered in details so far.

The effect of gamma-quanta on defect transformation and annealing is indirect. Fast electrons are produced by the photoeffect, Compton scattering and pairing, and only after that, electron flux interacts with regular or defect-lattice atoms.

The spectra and intensities of neutron and gamma-quanta in the reactor are such that neutrons mainly produce defects, while gamma-quanta primarily affect their transformation and annealing [7].

Fig. 1 presents the irradiation conditions (neutron flux, gamma flux and ICF) of steel 25Cr3NiMo, for which DBTT shift reaches 160°C. This indicates that the variation of properties of this steel depends on the gamma-radiation flux density and ICF. For example, if during the reactor irradiation of the 25Cr3NiMo type steel gamma-quanta flux increases from magnitude of $5 \times 10^{11}$ to $5 \times 10^{12}$ $sm^{-2}$ $s^{-1}$ to obtain the DBTT shift

* Corresponding author. Tel.: +7-095 196 99 66; fax: +7-095 196 17 01; e-mail: nikolaenko@nw.oirtorm.net.kiae.su

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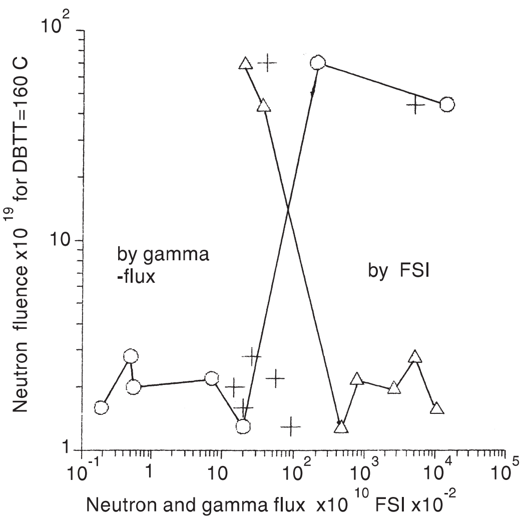


Fig. 1. Conditions of steel 25 Cr3NiMo at which DBTT shift reaches 160°C, (+) neutron flux; (○) gamma-flux; (△) ICF.

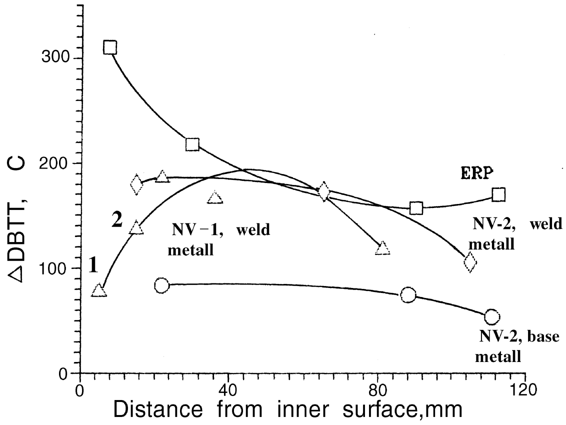


Fig. 2. Variation of the steel properties (DBTT) through the thickness of the reactor vessels: NV- NPP-1 (10CrMoVTi – △), NV-NPP-2 (10CrMoVTi – ◇, 15Cr2MoV – ○), ERP (25Cr3NiMo – □); points 1 and 2 received from Ref. [10].

equal to 160°C, it is necessary to increase the neutron fluence by one order of magnitude.

To evaluate the density of gamma flux in the middle of the core as well as at the core boundary for real heterogeneous reactor, the model homogeneous reactor of the same power and composition has been considered. Attenuation of gamma-radiation between the core periphery and the irradiation sources has been calculated by the equations for a flat source with account taken for the accumulation in alternating layers of water and iron of the heterogeneous reactor. For the inner surface of the vessel, an additional contribution of gamma-radiation due to iron activation by thermal neutrons has been estimated.

Fig. 2 presents data [8,9] on DBTT shift of steels through the vessel thickness from the inner surface to the outer surface for:

1. Novovoronezh NV-NPP-1 weld metal (10CrMoVTi).
2. Novovoronezh NV-NPP-2 base metal (15Cr2MoV) and weld metal (10CrMoVTi).
3. Experimental reactor-prototype (ERP) base metal (25 Cr3NiMo).

Fig. 2 shows that in contrast with expected character of DBTT change throughout the thickness of the pressure vessel, the shape of the curve varies from the curve with maximum DBTT at the inner surface of the pressure vessel to the curve with maximum DBTT in the middle [9].

In the present case the metallurgical and technological factors are not determining. For example, two different materials, base metal 15Cr2MoV (forged) and weld metal 10CrMoVTi (welded), irradiated in the same conditions in NV-NPP-2, demonstrate the same changes in DBTT. Thus, irradiation of steels differing in composition and treatment technology in identical conditions leads to identical character of properties variation. It means that the difference between these relationships is caused by irradiation conditions.

From Fig. 2 it is seen that the DBTT shift relationships are descending from the middle of the vessel thickness to the outer surface, and, in principle it correlates with monotonous decrease of fast neutron fluence. This is connected with the fact that in this zone gamma-radiation fluxes are attenuated by the vessel wall of steel. ICF is more than 2 here; therefore, radiation gamma-annealing does not demonstrate itself, and the whole effect of embrittlement is determined by the damage resulting from irradiation by fast neutrons.

Another situation can be observed in the zone from the inside surface to the middle of the vessel wall. DBTT shift can both decrease (for ERP) and increase (NV-NPP-1). NV-NPP-2 materials occupy an intermediate position – DBTT shift remains unchanged for both. This variety of actual relationships does not explain the neutron flux influence, but this may be explained by the effect of radiation gamma-annealing. For ERP, neutron absorption is small, as compared with gamma-radiation absorption, and ICF is equal to 4 on the inside surface of ERP, where steel screens are sited between the vessel and the core. Consequently, the effect of radiation gamma-annealing is suppressed in this zone, and, as in the case of steel irradiation in the distant layers of the vessel wall, embrittlement is determined by the fast neutron flux.

In contrast, at NV-NPP-1 and NV-NPP-2 there is a relatively large water gap between the vessel and the core, and gamma-radiation is attenuated to a lesser degree as compared with neutrons; FSI is 0.3–0.5. The

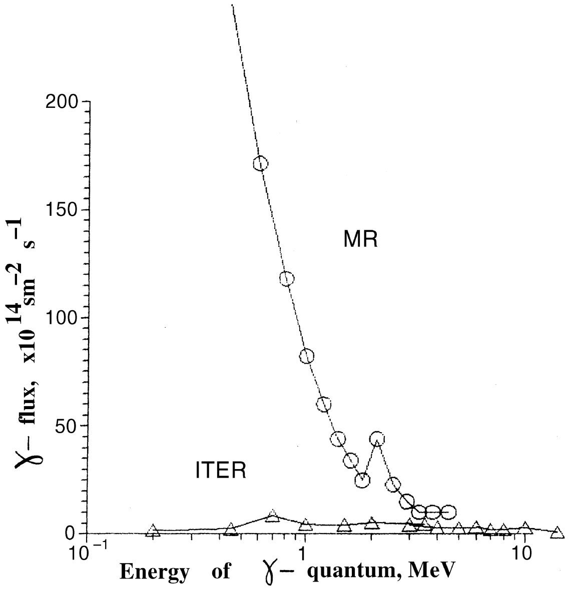


Fig. 3. Calculated spectra of gamma-radiation for MR reactor and on the first wall of ITER.

embrittlement slows due to radiation gamma-annealing: at NV-NPP-2 the embrittlement is practically the same on the inside surface and in the middle of the vessel wall, and at NV-NPP-1 the steel embrittlement on the inside surface of the vessel is less than in the middle, where the fast neutron fluence is less.

Thus, the DBTT shift of RPV steels depends not only on metallurgical and technological factors, irradiation temperature and neutron fluence, but on gamma-radiation flux as well. The greater is the gamma-quantum density, the less is the DBTT shift, all other factors being equal, and the zone of maximum degradation steel properties by irradiation may not coincide with neutron load maximum. For instance, for fast ($E > 0.5$ MeV) neutron fluences of $2.4 \times 10^{19}$ and $1.6 \times 10^{19}$ $sm^{-2}$ (distances from inner surface 22 and 50 mm, respectively, for NV-NPP-1 weld metall – see Fig. 2) and corresponding values of ICF 0.4 and 2.1, DBTT shift is greater for the smaller neutron fluence.

Fast neutron flux density is of the same order for the research fission reactors and for the first wall of the ITER reactor, but gamma-radiation is much less in the latter case. Fig. 3 presents calculated gamma-radiation spectra for MR reactor (RRC 'Kurchatov Institute') and ITER. From Fig. 3 it is seen that gamma-quantum flux in the fission reactor is several tens times greater than that in ITER. For example, the neutron ($E > 0.5$ MeV) and gamma-quantum ($E > 0.2$ MeV) fluxes in the fuel channel of MR and on the first wall of ITER are $1.4 \times 10^{14}$ and $2.3 \times 10^{14}$ $sm^{-2}$ $s^{-1}$, and also $1.2 \times 10^{15}$ and $5.3 \times 10^{13}$ $sm^{-2}$ $s^{-1}$. Therefore ICF for MR is equal to 0.13 and ICF for ITER is 4.3. Comparison of this result with the data for DBTT shift variation of different types of steel indicated above allows for the following conclusion: experimental methods on research into properties of the ITER candidate materials irradiated in fission reactors require considerable adjustment when gamma-radiation is taken into account.

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