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NUMERICAL MODELING OF HIDDEN DAMAGE ACCUMULATION DUE TO RADIATION EXPOSURE AND HYDROGEN EMBRITTLEMENT

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Hydrogen is generated by nuclear transmutation reactions in fusion and fission reactors, spallation neutron sources, and high-energy charged particle environments. Additionally, hydrogen is generated by environmental sources such as corrosion, radiolytic decomposition and recoil injection, particularly in systems involving water cooling and moderation, such as pressurized water reactors (PWRs) and boiling water reactors (BWRs). In Western-design PWRs and in some BWRs a hydrogen overpressure is also maintained on the coolant to suppress the buildup of corrosive chemical species. Notably, hydrogen has been shown to play a crucial role in the evolution of damage microstructure, which can in turn influence the mechanical properties and cracking behavior of structural materials.

This study examines the computational finite element modeling (FEM) of irreversible deformation and damage accumulation in the material of structural elements subjected to the combined influence of thermal, force, and irradiation fields.
A detailed description is provided of the calculation methodology employed for the determination of the stress-strain state and the long-term strength of austenitic steel. The results obtained with this methodology are also presented. The method is based on a complete mathematical formulation of the boundary-initial value problems of creep accompanied by irradiation effects. The following phenomena are considered: elastic, thermoelastic, plastic, thermal, and irradiation creep, irradiation swelling strains, damage due to thermal and irradiation creep, and hydrogen embrittlement. The constitutive equations for the numerical modeling were constructed using qualitative and quantitative data from experimental studies conducted at the micro, meso, and macro levels. The effect of hydrogen embrittlement is represented by the data from experiments performed at the macro level, which include changes in the modulus of elasticity. The constructed constitutive equations allow the description of the essential non-linear interaction of processes. The numerical solution of the boundary value problems is performed by FEM, and the initial value problems are solved by time integration. To estimate the effects of cyclic deformation and fracture, the procedures of asymptotic methods and averaging over cycle periods are employed.
The obtained results reveal that deformation and damage accumulation caused by irradiation effects in the material, including irradiation creep, irradiation swelling, and embrittlement, can significantly limit the safe operation of nuclear reactor vessel internals when interacting with thermal creep. The analysis suggests that the primary contributor to the accumulation of hidden damage is the synergistic interaction between irradiation swelling and hydrogen embrittlement. Furthermore, our findings indicate that on the surfaces of the elements, where the maximum values of the dose accumulation rate are present, hydrogen embrittlement processes significantly intensify the damage accumulation rate. Such a behavior can be attributed to the growth of stress components caused by increased strains of irradiation swelling.

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