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S.N. Pelykh, DSc, Prof.,
M.A. Frolov,
A.V. Nalyvayko,
Huiyu Zhou, PhD
Odessa National Polytechnic University, 1 Shevchenko Ave., Odesa, Ukraine, 65044, e-mail: 1@pelykh.net

THE PROBLEM OF MINIMIZING THE RADIOACTIVE LEAKAGE INTO THE VVER CIRCUIT UNDER NORMAL CONDITIONS

С.М. Пелих, М.О. Фролов, А.В. Наливайко, Хуййю Чжоу. **Проблема мінімізації радіоактивних протікань в контур ВВЕР за нормальних умов експлуатації.** Відповідно до Плану стратегічних енергетичних технологій Європейська комісія при розвитку енергетики керується двома пріоритетами: розробляти енергозберігаючі системи та підвищувати їх ефективність; підвищувати безпеку використання ядерної енергії. Метою роботи є розробка основ для поліпшення балансу безпеки та економічності експлуатації реактора типу ВВЕР, для цього запропоновано новий підхід до мінімізації радіоактивних протікань в перший контур за нормальних умов експлуатації реактора, на основі мінімізації параметра деформаційного пошкодження оболонок твелів. Використовуючи ЕВТП-метод розрахунку параметра деформаційного пошкодження оболонок твелів, запропонований новий метод управління параметрами, що визначають об'єм радіоактивних протікань в перший контур крізь мікротріщини оболонок твелів, за нормальних умов експлуатації реактора. Показано необхідність і умови розробки автоматизованої системи управління для мінімізації радіоактивних протікань в контур ВВЕР за нормальних умов експлуатації, шляхом оптимізації режима навантаження реактора та перестановок ТВЗ.
Ключові слова: оболонка твела, параметр пошкодження, мінімізація радіоактивних протікань, ВВЕР

S.N. Pelykh, M.A. Frolov, A.V. Nalyvayko, Huiyu Zhou. **The problem of minimizing the radioactive leakage into the VVER circuit under normal conditions.** According to the Strategic Energy Technologies plan, two priorities have been accepted by the European Commission: develop and strengthen energy-efficient systems; increase safety in the use of nuclear energy. The aim of the research is working out grounds for improvement of the VVER operation safety-efficiency balance, for that a new approach to minimizing the radioactive leakage into the VVER circuit under normal operating conditions, based on minimizing the damage parameter of fuel claddings, has been proposed. Using the CET-method for calculating the cladding damage parameter, a new method for control of parameters determining the dose of radioactive leakage through microcracks of fuel claddings into the reactor circuit, under normal operating conditions, has been described. The conditions and a need for development of an automated control system minimizing the radioactive leakage into the VVER circuit under normal conditions, by means of optimizing the VVER loading mode and rearrangements of fuel assemblies in the core, have been shown.
Keywords: fuel cladding, damage parameter, radioactive leakage minimization, VVER

Introduction. According to the Strategic Energy Technologies plan (SET-plan), a number of energy technologies have been identified as key to Europe's effort to decarbonise its energy sector and increase energy efficiency. Two priorities of the SET-Plan have been accepted by the European Commission [1]:

– develop and strengthen energy-efficient systems,

– increase safety in the use of nuclear energy.

Considering the problem of nuclear energy safety, we come to the problem of nuclear fuel cladding tightness because there are continuing pressures to improve fuel cycle economics and safety in

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increasingly challenging PWR/VVER operating environments, while fuel cladding is a very important safety barrier when operating nuclear reactors. There are many possible causes of cladding failure for PWR/VVER fuel and the unknown causes for PWR (in the world) and VVER-1000 fuel (in Russia) come to 25 and 80 % (2002 – 2006), respectively, hence:

1. The cause of cladding failure in PWRs/ VVERs is not known reliably [2].

2. To guarantee the fuel operation safety and reliability, complex methods for controlling the cladding failure probability must be developed, considering different physical mechanisms leading to cladding failure, including damage accumulation [3].

Though the share of European NPPs with PWRs/ VVERs operated without fuel failures has been considerably increased, the following issues can be mentioned among the fundamental problems in developing energy-efficient nuclear systems and increasing nuclear safety [4]:

1. The published corporate data on fuel failure rates and the root cause of failures are not fully reliable. The so-called “zero failure rate” does not mean that there are no microcracks in claddings delivering the radioactive gas leaking.

2. The cost of nuclear fuel and reactor designing is very high.

3. The cost of safety systems for new reactor designs is extremely high.

4. High normative safety coefficients for reactor/fuel parameters limit the reactor/fuel operation efficiency.

5. There is no data on the distributed mechanical state of claddings at the start moment of an accident, depending on the real sequence of sets of reactor/fuel operating parameters (load history).

6. There is no implemented control system to limit the probability of cladding leaking depending on the real reactor/fuel load history.

Following from the SET-plan priorities, it is proposed to improve the VVER safety-efficiency balance by means of ensuring the hermeticity of fuel element (FE) claddings based on the creep energy theory method (CET-method) [5, 6], in order to minimize the radioactive leakage through fuel claddings into the VVER circuit, for normal operation conditions including variable loading modes.

The aim of the research is working out grounds for improvement of the VVER operation safety-efficiency balance, for that a new approach to minimizing the radioactive leakage into the VVER circuit under normal operating conditions, based on minimizing the damage parameter of fuel claddings, is proposed. The physical grounds of improved controlling the VVER fuel properties are to be worked out in order to enhance the VVER competitive ability, especially by minimization of the microcracks growth in fuel claddings influencing the radioactive pollution of the reactor circuit.

Materials and Methods. As cladding damage parameter $\omega(\tau)$ is an integral characteristic of the microcracks growth [7], we can minimize the radioactive leakage through fuel claddings into the VVER circuit, for normal operation conditions including variable loading modes, by minimization of $\omega(\tau)$. So the idea is to use the CET-method for minimization of FE cladding fracture due to damage accumulation under reactor variable loading and, as a result of intrinsic features of the method, to take into account the loading history of any fuel assembly as well as the distribution of damage parameter among FEs of any fuel assembly. The CET-method developed using the experimentally verified creep energy theory [7] has got the following features [5]:

Universality, as it allows us to make optimization of fuel design and operation parameters simultaneously with optimization of reactor parameters, for different VVER core materials and designs, as well as for different reactor loading modes.

A considerably lowered uncertainty of cladding damage parameter estimations.

A decrease of the fuel design cost, an increase of the fuel operation safety/efficiency.

The CET-criterion and the efficiency criterion allowed us to develop a criterion to minimize the probability of cladding failure due to accumulation of damage parameter describing the growth of microcracks in FE claddings [3]. The importance of cladding damage parameter used in the CET-criterion comes from its cumulative nature describing the evolution of microcracks delivering radioactive gas leaking [6]. The structure of the CET-criterion made it possible to propose a generalized

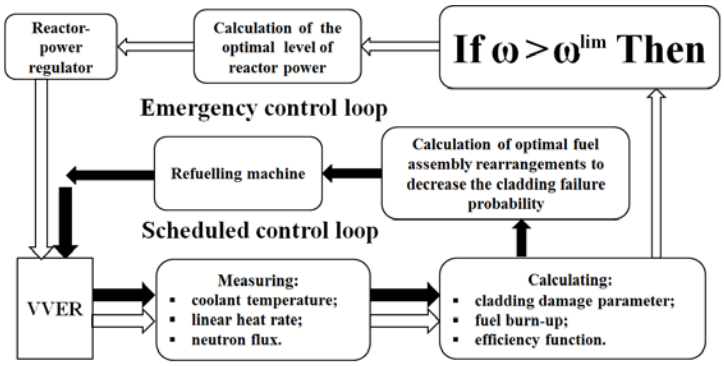

Fig. 1. The principal scheme of VVER FE cladding tightness control

method for fuel rod behavior control. Using this generalized method, the probability of failure of FE claddings in the whole core can be considerably decreased [8].

Taking into account, that the FE maximum linear heat rate (LHR) is the chief factor determining $\omega(t)$, the value of $\omega(t)$ can be controlled first of all by optimizing [9]:

– the VVER loading mode;

– rearrangements of fuel assemblies in the core.

So, based on the CET-method, an innovative technology for VVER FE cladding tightness control including the control of parameters determining the dose of radioactive leakage through microcracks of fuel claddings into the reactor circuit, under normal operating conditions, can be proposed – see Fig. 1.

Results. In order to implement this innovative method for VVER cladding tightness control, the following actual tasks are to be solved:

Verification of the CET-method by means of its application to a real case in which cladding failures and VVER power cycles are known.

Based on the CET-method, development of know-how for ensuring the maximum tightness of claddings in VVERs.

To say more exactly, to implement the method into practice, we are to find the dependence of the radioactive leakage $A(\tau)$ through microcracks in fuel claddings on $\omega(\tau)$ – see Fig 2.

Though the dependence $A(\omega,\tau)$ can be derived theoretically based on some model, this dependence $A(\omega,\tau)$ must be specificated using correcting coefficients which could be obtained at experiments, e.g., in the Halden reactor. The principal moments of the plan of measurements are:

1. As the main part of experiments, in the frame of the project, should be devoted to finding the dependence of the radioactive leakage $A(\tau)$ through fuel claddings on $\omega(\tau)$ under normal operating conditions, while there is a great dependence of the 2-nd creep stage (stable creep) duration on LHR, the duration and cost of experiments should be decreased by applying increased LHRs.

2. Aiming to implement this method into industry, it would be valuable to verify the laboratory results of [7] and [10] under real core conditions, e.g., in the Halden reactor. This is important because the CET-method for FE cladding behavior control is based on the results of [7] and [10] stating that, when a thin cylinder cladding is loaded at frequencies $\nu << 1\,\text{Hz}$, creep is the main physical process of deformation damage accumulation. The CET-method should be verified by means of its application to a real case in which cladding failures and power cycles are known.

3. Having obtained the dependence $A(\omega,\tau)$ and having verified the CET-method in the Halden reactor, it seems reasonable to take into account the system effect arising from a joint influence of different physical mechanisms leading to cladding failures. For example, to study the synergic (combined) action of stress corrosion cracking (SCC) and creep. This SCC arises when LHR jumps are so great that circumferential stresses in a cladding exceed some limit value.

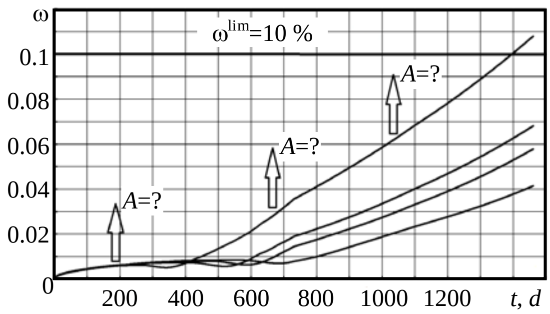

Fig. 2. The question of the radioactive leakage $A(\tau)$ dependence on $\omega(\tau)$

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Though such situations are quite possible when operating VVERs, the synergic action of SCC and creep has not been studied enough yet.

In order to plan the project aiming to minimize the radioactive leakage through fuel claddings into the VVER circuit, for normal operation conditions including variable loading modes, let's discuss some commonly accepted project evaluation criteria (EC):

EC1: Need for research activity – there is a need for the following research activity:

1. When using a cladding failure criterion for control of the cladding hermeticity, meeting the requirement that limiting components in the criterion must be independent of the fuel loading history is a significant problem. Therefore, taking into account the variability of limiting components in the normative SC4 criterion [11] which is an intrinsic shortcoming of the approach based on SC4, the CET-method has been developed. Based on the CET-method, taking into account for each fuel assembly its loading history and the distribution of cladding damage parameter $\omega(t)$ among the FEs included in this assembly, the method for forecasting of cladding failures due to increasing $\omega(t)$ has been developed. The constant limiting component A_0 in the CET-criterion corresponding to an assigned cladding material must be determined by experiment or using the calculation procedure proposed in [5, 6].

2. The optimal number of conservative FE groups distinguished in any fuel assembly should be found [3]. This matter influences on the calculated maximum damage parameter and on the distribution of FEs among conservative groups. As this will increase the predicted number of failed FEs, a special optimization procedure should be developed and implemented when choosing the number of FE groups in a fuel assembly.

3. The limit value of cladding damage parameter $\omega^{\lim}$ should be grounded. Though the normative safety coefficient such as 10 in the SC4 failure criterion is built in the method, and consequently the limit value of cladding damage parameter $\omega^{\lim}$ is supposed to be 10 %, there is no clear understanding on the kind of cladding failure this $\omega^{\lim}$ corresponds to (e.g. is it a gas leak or a direct fuel-coolant contact? [3]). What is the dependence of the radioactive leakage through fuel claddings into the VVER circuit (i.e. the radioactive pollution of the reactor circuit) on $\omega(t)$ under normal operating conditions ? This should be clarified in the frame of the project.

4. Though the proposed method for limiting cladding failures due to damage accumulation means that the known methods for preventing failure due to SCC will be used also, the dependence of cladding creep strain rate on corrosion rate is taken into account in the calculation model, and the influence of corrosion rate on cladding damage parameter was studied in [9]. In order the model could take into account the influence of corrosion on $\omega(t)$ correctly, the exact data on cladding corrosion rate for the exact VVER fuel design and operation mode must be used, as the contribution of oxide thinning accelerates significantly the cladding failure [3].

5. Codes applicable to an assigned VVER design and fit for core and fuel behavior analysis should be chosen/developed, in order to adopt the CET-method to a selected type of VVER and verify it by means of application to a real case in which cladding failures and power cycles are known.

6. In order to minimize the radioactive leakage into the VVER circuit under normal conditions, by means of optimizing the VVER loading mode and rearrangements of fuel assemblies in the core, an automated control system should be developed.

EC2: The technical area is the subject of research within Europe. The results will be available to NUGENIA association. The proposed research complements an existing work financed by the Ukrainian government. The work is novel.

EC3: Applicability – the proposed activity is applicable to currently operating VVERs and PWRs, as well as to prospective PWR/VVER designs. The developed approach to limiting FE cladding failures based on the CET-method is universal. The value of this analytical approach consists of its eligibility for different core materials and designs. This universality could be useful aiming to decrease the fuel design cost and increase the fuel operation safety. Practically the prediction of cladding failure is made on the basis of an adopted limit damage parameter $\omega^{\lim}$, as well as knowing the limit value A_0 for specific dispersion energy which is constant for a given material. For different sets of fuel design and operating parameters, the proposed method allows to make comparisons on the basis of the predicted number of failures due to cladding damage accumulation.

EC4: Reality – the planned objectives are realistic in the case of establishing a consortium of European institutions.

EC5: Contribution – the activity contributes to the integration of European research and harmonisation of approaches. It contributes to the maintenance of key nuclear skills and facilities within Europe and the development of young engineers.

Conclusions.

1. In order to improve the safety-efficiency balance when operating VVER reactors, a new approach to minimizing the radioactive leakage into the VVER circuit under normal operating conditions, based on minimizing the damage parameter of fuel element claddings and using the CET-method, has been proposed.

2. To implement this method into practice, experiments under real core conditions, e.g. in the Halden reactor, to find the dependence of the radioactive leakage through microcracks in fuel claddings on cladding damage parameter, as well as to verify the known laboratory results [7, 10], should be conducted. Though the CET-method is based on the experimentally proved creep energy theory, the method should be verified under real core conditions by means of its application to a real case in which cladding failures and power cycles are known. When considering the evolution of fuel cladding microstructure and, specifically, the evolution of microcracks, the synergic action of stress corrosion cracking and creep should be studied in detail.

3. To develop an automated control system minimizing the radioactive leakage into the VVER circuit under normal conditions by means of optimizing the VVER loading mode and rearrangements of fuel assemblies in the core, the limit value of cladding damage parameter corresponding to any kind of cladding failure, under VVER normal operating conditions, should be grounded.

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