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RISK-INFORMED METHOD FOR PREDICTING THE OPERATION LIFE EXTENSION PERIOD OF ACTIVE SAFETY SYSTEMS AT NUCLEAR POWER PLANTS

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An original method has been developed for predicting the operation life extension period of thermal mechanical equipment of safety systems based on the assessment of the residual resource by the number of thermohydrodynamic and mechanical cyclic loads and the test frequency during design operation life. Based on the developed method, as well as the results of technical inspection of pump and armature bodies of emergency core cooling and steam generator emergency feedwater systems, it was found that the permissible operation life extension period is 4 years for the design test frequency, 8 years if the test frequency is reduced by 2 times, 16 years if the test frequency is reduced by 6 times, 20 years if the test frequency is reduced by 10 times. However, the possibility of reducing the test frequency requires additional substantiation for optimizing the test frequency, taking into account the effects of equipment wear and the accumulation of critical defects between tests. The need to optimize the test frequency determines the relevance of further research.

INTRODUCTION

Typical programs for the extended operation life of thermomechanical equipment (pumps, armature) of safety related systems (SRS TME) at nuclear power plants (NPP) include the following main stages [1–9].

1. Analysis of design documentation, reliability and operation experience, testing, maintenance and repair.
2. Technical inspection of the condition of SRS TME structures.
3. Analysis of strength reserves of metal structures of SRS TME during extreme external effects (earthquakes, floods, falls of large objects, etc.) taking into account the results of inspection of the technical condition.
4. Qualification (substantiation) of ensuring the reliability and operability of TME in the event of accidents and disturbances in normal operating conditions at the NPP (for example, [10–12]).
5. Summarizing the results of the implementation of the main stages of programs for the extension of the operation life and predicting the allowable operation life of SRS TME.

Active safety systems with electric pumps include:

High pressure safety injection system and emergency core cooling system (HPSIS and ECCS);

Boric acid injection system;

Steam generator emergency and auxiliary feedwater systems (EFW and AFW pumps);

Containment spray system.

The main feature of the operation of such active safety systems is that they operate in standby, test and operation modes. To reveal and restore possible “hidden” failures, the design documentation and the Technological Regulations for Safe Operation (TRSO) of WWER reactors provide for periodic tests of each independent channel of the active safety system during the operation of the reactor at power, during the exit of the power unit from repair or after the restoration of revealed failures/disturbances.

The analysis of the results of the programs for the extension of the operation life of SRS armature and pumps at NPPs with WWER showed that the prediction of the extended operation life is the least substantiated. In most cases, the time of the extended operation life in the over-design period was determined subjectively on the basis of “expert assessments” without analysis of the actual condition of the equipment at the end of the design life and experience of operation, tests, maintenance and repairs. The lack of sufficiently adequate methods for predicting the time of extended operation life is the possible reason for this situation. It determines the relevance of this work.

MAIN PROVISIONS OF THE METHOD FOR PREDICTING THE TIME OF THE EXTENDED OPERATION LIFE OF ACTIVE SAFETY SYSTEMS

1. Periodic tests during which there are cyclic mechanical and thermohydrodynamic loads on the equipment are the dominant factor in the wear and degradation of TME structures of active safety systems.
2. Pump and armature bodies are critical design elements to substantiate extended operation life.
3. The stress-intensity factor $K(a, \sigma)$ is the key parameter of the allowable reserve of load cycles for the TME bodies in active safety systems during the over-design operation life. It depends on the size of the defects in the metal a and the stress of cyclic loads under normal operating conditions (NOC), disturbances in normal operating conditions (VNOC) and accidents (for example, [13, 14] et al.).

Fig. 1 presents the known results of the dependence of the rate of propagation of fatigue cracks K.

It is possible to identify three characteristic areas of propagation of fatigue cracks of equivalent size a depending on K (see Fig. 1):

I – stage of threshold growth of fatigue crack ($0 < da/dn < 5\cdot10^{-5}$ mm/cycle),

II – stage of stable fatigue crack growth ($5\cdot10^{-5} < da/dn < 10^{-3}$ mm/cycle), III – stage of accelerated growth of fatigue crack ($da/dn > 10^{-3}$ mm/cycle).

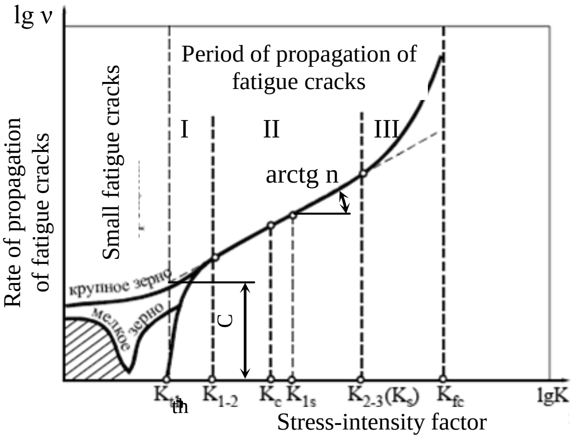

Рис. 1. Kinetic diagram of fatigue failure [13]

The distribution of defects by their size from the experience of operation for pump and armature bodies is determined from the known semi-empirical dependence [13]:

$$n = 241.7a^{-1.58}.$$

Cyclic load stresses σ during NOC, VNOC and accidents are determined by the rate of change of dynamic and thermal actions.

As an example Fig. 2 presents the calculated values of the rate of change of dynamic and thermal loads for the start/stop of the pump (NOC), reducing the supply of feed water to the steam generator (VNOC) and the accident with the armature not closing [8].

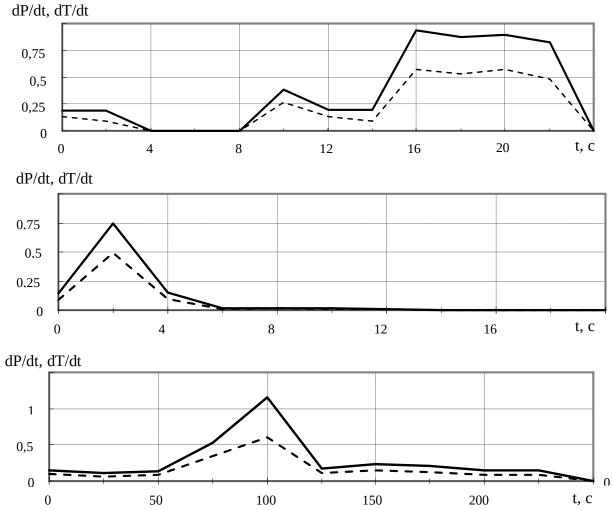

Fig. 2. Rate of change of dynamic and thermal loads during NOC, VNOC and accidents [8]

Taking into account the accepted assumptions, the residual resource for the number of activations of the active safety system N_{OR} at the end of the design operation life T_D:

$$N_{OR} = N_D - N(T_D) + \Delta N(K, T_D), \quad (1)$$

where N_D – design permissible number of actuations during tests, VNOC and accidents, which is regulated by the design and technical documentation of the equipment and WWER TRSO; $N(T_D)$ – total number of actuations at the end of the design operation life T_D; $\Delta N(K, T_D)$ –allowable reserve of the number of actuations at the end of the design operation life, which can be estimated by the formula:

$$\Delta N(K, T_D) = N_D \frac{K(a_{max}, \sigma_{max}, t = 0)}{K(a_{max}, \sigma_{max}, t = T_D)}. \quad (2)$$

Critical values K are calculated by the maximum possible operation load σ_{max} and the maximum size of the revealed defects a_{max}.

Predictable frequency of cyclic loads in the over-design operation period for a time Δt:

$$f_0 = \frac{N(t > T_D)}{\Delta t}. \quad (3)$$

Then the maximum allowable operation period follows from equations (1) – (3):

$$T_0 = \frac{N_D\left[1 + K_{max}(t = 0)/K_{max}(t = T_D)\right] - f_D T_D}{f_0(t > T_D)}, \quad (4)$$

where f_D = 12/(channel·year) – проектна за ТРБЕ періодичність випробувань і спрацьовувань каналів активної системи безпеки design frequency of tests and actuations of active safety system channels according to TRSO.

Fig. 3 shows the results of the calculation justifications (4) of the allowable period of continued operation life of the pump and armature bodies of HPSIS, ECCS and AFWP at NPP with WWER, taking into account the results of technical inspection [8, 13].

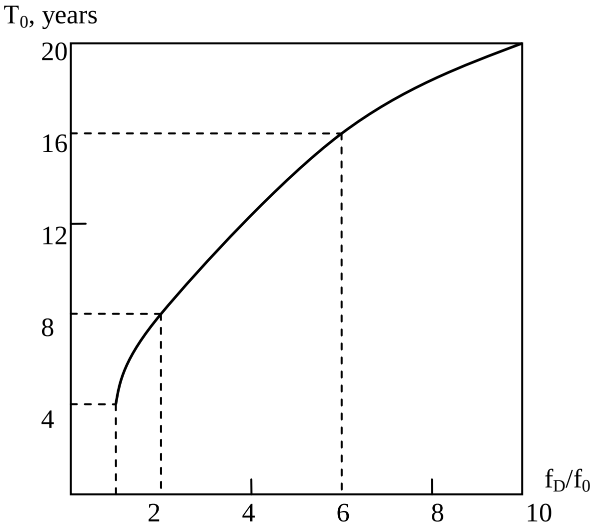

Fig. 3. Predicted maximum allowable time of the extended operation life of HPSIS, ECCS, AFWP depending on the test frequency

Subject to maintaining the design test frequency ($f_D/f_0 = 1$) the maximum admissible time of extended operation life, multiple of overhaul frequency of power units, is 4 years. Subject to reduction in test frequency by 2 times time of extended operation life is 8 years, by 6 times – 16 years, by 10 times – 20 years.

However, the possibility of reducing the test frequency of active safety systems during over-design operation life requires additional substantiation. Reducing the test frequency reduces equipment wear and, consequently, the probability of failure to perform assigned safety functions. While time of “standby” modes and the probability of failure due to the accumulation of “hidden” critical defects are increased. Therefore, it is necessary to optimize the test frequency of active safety systems during the over-design operation life, taking into account the above effects.

CONCLUSIONS

1. An original method has been developed for predicting the operation life extension period of thermal mechanical equipment of safety systems based on the assessment of the residual resource by the number of thermohydrodynamic and mechanical cyclic loads and the test frequency during design operation life.

2. Based on the developed method, as well as the results of technical inspection of pump and armature bodies of emergency core cooling and steam generator emergency feedwater systems, it was found that the permissible operation life extension period is 4 years for the design test frequency, 8 years if the test frequency is reduced by 2 times, 16 years if the test frequency y is reduced by 6 times, 20 years if the test frequency is reduced by 10 times. However, the possibility of reducing the test frequency requires additional substantiation for optimizing the test frequency, taking into account the effects of equipment wear and the accumulation of critical defects between tests. The need to optimize the test frequency determines the relevance of further research.

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РИЗИК-ОРІЄНТОВАНИЙ МЕТОД ПРОГНОЗУВАННЯ СТРОКІВ ПРОДОВЖЕННЯ ЕКСПЛУАТАЦІЇ АКТИВНИХ СИСТЕМ БЕЗПЕКИ ЯДЕРНИХ ЕНЕРГОУСТАНОВОК

В.І. Скалозубов, О.М. Вєрінов, С.І. Косенко, М. Алалі, В.Ю. Кочнєва

Розроблено ризик-орієнтований метод прогнозування строків продовження експлуатації тепломеханічного обладнання систем безпеки на основі оцінки залишкового ресурсу по кількості теплогідродинамічних і механічних циклічних навантажень і частоти випробувань у проектний строк експлуатації. На основі розробленого метода, а також результатів технічного дослідження корпусів насосів і арматури систем аварійного охолодження активної зони реактора та аварійного підживлення парогенераторів установлено, що при збереженні проектної періодичності випробувань припустимий строк продовження експлуатації складає 4 роки, при скороченні частоти випробувань у 2 рази – 8 років, у 6 разів – 16 років, у 10 разів – 20 років. Однак можливість скорочення періодичності випробувань потребує додаткових обґрунтувань щодо оптимізації частоти випробувань з урахуванням ефектів зносу обладнання і накопичення критичних дефектів у періоди між випробуваннями. Необхідність оптимізації періодичності випробувань визначає актуальність подальших досліджень.

РИСК-ОРИЕНТИРОВАННЫЙ МЕТОД ПРОГНОЗИРОВАНИЯ СРОКОВ ПРОДЛЕНИЯ ЭКСПЛУАТАЦИИ АКТИВНЫХ СИСТЕМ БЕЗОПАСНОСТИ ЯДЕРНЫХ ЭНЕРГОУСТАНОВОК

В.И. Скалозубов, А.Н. Веринов, С.И. Косенко, М. Алали, В.Ю. Кочнева

Разработан оригинальный метод прогнозирования сроков продления эксплуатации тепломеханического оборудования систем безопасности на основе оценки остаточного ресурса по количеству теплогидродинамических и механических циклических нагрузок и частоты испытаний в проектный срок эксплуатации. На основе разработанного метода, а также результатов технического обследования корпусов насосов и арматуры систем аварийного охлаждения активной зоны реактора и аварийной подпитки парогенераторов установлено, что при сохранении проектной периодичности испытаний допустимый срок продления эксплуатации составляет 4 года; при сокращении частоты испытаний в 2 раза – 8 лет, в 6 раз – 16 лет, в 10 раз – 20 лет. Однако возможность сокращения периодичности испытаний требует дополнительных обоснований по оптимизации частоты испытаний с учетом эффектов износа оборудования и накопления критических дефектов в периоды между испытаниями. Необходимость оптимизации периодичности испытаний определяет актуальность дальнейших исследований.