UDC 621.039.7 Doi: https://doi.org/10.32918/nrs.2021.4(92).05

Methodology for Determining the Thermal and Thermal-Stress States of a Concrete Storage Container for Spent Nuclear Fuel for Assessment of Its Service Life

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The work is devoted to the development of methodologies for determining the thermal and thermal-stress states of the main equipment in dry container storage facilities for spent nuclear fuel. Storage facilities of this type are most common for spent fuel of nuclear power reactors. The safety of storage equipment in terms of assessing its service life is not covered widely enough in the world scientific literature. In particular, there are no effective methods for calculating the thermal and thermal-stress states of the equipment that would take into account the influence of many external factors throughout the life of a storage facility. To assess the thermal state of the containers, forward conjugate heat transfer problems, accounting for the mutual heat transfer in both a solid body and in the fluid environment (air), are proposed to be solved. Based on the solution of the conjugate heat transfer problems, the boundary conditions are to be determined to further assess the thermal-stress state of storage containers using inverse heat transfer problems. The proposed approach to determining the thermal and thermal-stress states of a concrete spent fuel container will promote more effective methods for assessing the service life of dry spent fuel storage facilities, which is, in turn, necessary in the development of ageing management programs for storage equipment and long-term safe operation.

Keywords: safety, thermal processes, thermal-stress processes, spent nuclear fuel, lifetime.

Introduction

Dry container storage is a widespread method for long-term storage of spent nuclear fuel (spent fuel) from power reactors. Dry container storage facilities are commonly operated for a long period of time, which can exceed 100 years. The condition of structural materials may change significantly throughout long-term operation under the influence of ionizing radiation and other external factors and, hence, their physical properties would not meet those incorporated in the design and, potentially, such fuel or storage equipment may not meet safety criteria. In this regard, the operation of any dry spent fuel storage facility necessitates the implementation of an ageing management strategy, both for the fuel and for basic storage equipment, since the physical condition of these main components is the key to the safety of the entire storage facility.

Analysis of the Literature

Ageing management aspects for nuclear power plant (NPP) equipment have been addressed in many papers of leading national and foreign scientists. In particular, these aspects for the final stages of the nuclear fuel cycle are covered in [1], (2 etc.]. According to open literature sources, the use of effective methods for assessing the physical condition of equipment materials is crucial in the development of effective ageing management programs.

Hence, the paper [3] analyzes the deformation and impact brittleness of a concrete container that change with time and the effect of these characteristics on its damageability. The paper proposes fitting dependences for the above physical quantities and accounts for the effect of ionizing radiation but does not consider factors such as container overheating resulting from insolation or periodic changes in temperature on the container surface resulting from daily temperature fluctuations.

The paper [4] provides rather a detailed thermal analysis for a dry storage container for spent fuel but does not demonstrate that the data obtained can be used to analyze the thermal-stress state of the container and further assess its service life.

The strict requirements for the technical characteristics of structures operating in harsh conditions (for example, containers with spent fuel) confirm that the improvement of methods for their calculation is a relevant problem. Such structures can be reliably assessed through numerical simulation of variations in their thermal and thermal-stress state, accounting for all current climatic and power factors [5], [6]. Nevertheless, any methods that would be effectively used to assess the service life of concrete storage containers for spent fuel and further justify their operational safety have not been found in the literature and thus their development is relevant.

Statement of the Problem

Dry spent fuel storage is becoming increasingly popular in the world and has been already in use in many countries. According to the IAEA [7], 73 % of the existing spent fuel storage facilities are of dry type.

The spent fuel storage systems can be classified by many features, including the type of equipment used for storage. The placement of spent fuel into containers to be then located in open or closed storage facilities is one of the common storage methods [8], [9].

Concrete ventilated [10] or non-ventilated [11] casks are used in many cases in container storage and are one of the protective barriers to the spread of radiation. The storage containers are maximally exposed to the effect of external factors in operation [12], [13]. In this connection, to determine the thermal and thermal-stress state of storage containers to further assess their service life, considering the influencing factors, is an important aspect in the development of ageing management programs for spent fuel storage equipment.

Ukraine currently operates two storage facilities for spent fuel from the Zaporizhzhia NPP and Chornobyl NPP. After commissioning of another storage facility – Centralized Spent Fuel Storage Facility – Ukraine's needs for storage capacities for spent fuel from all power reactors are expected to be fully covered.

SSTC NRS ДЕРЖАВНЕ ПІДПРИЄМСТВО ДЕРЖАВНИЙ НАУКОВО-ТЕХНІЧНИЙ ЦЕНТР З ЯДЕРНОЇ ТА РАДІАЦІЙНОЇ БЕЗПЕКИ

It should be noted that ageing management programs have been developed and agreed for all three storage facilities in line with IAEA requirements, but the physical processes that occur throughout their service life still need to be understood extensively and effective scientific support needs to be ensured.

The operating experience for storage containers in the on-site facility at the Zaporizhzhia NPP shows that cracks appearing on the container concrete surface are indicative of a degradation mechanism. The previous papers (for example, [12]) hypothesized that this ageing effect might be caused, among other factors, by the effects resulting from weather factors and insolation. To justify this hypothesis and assess the effect of such factors on the service life of storage equipment, a series of research efforts intended to determine the thermal-stress state of the container body have been initiated.

The objective of this effort is to develop a comprehensive methodology for determining the thermal and thermal-stress state of spent fuel storage containers throughout their service life, accounting for external influencing factors. This is required for assessing the container integrity in long-term operation of dry storage facilities and the influence of the above ageing effect on their operational safety.

Methodology for Determining the Thermal State of a Container

The first step in the definition of boundary conditions for assessing the thermal-stress state of a spent fuel storage container is to determine its thermal state. Since a concrete container is a structure of rather complex shape, the determination of heat exchange conditions on the concrete container surfaces is not a trivial problem and requires the mechanisms for solving forward and inverse heat transfer problems to be involved. Therefore, the general approach is as follows: forward heat transfer problems are solved to determine the thermal state of a concrete container and inverse heat transfer problems are solved to determine the boundary conditions on its surfaces.

Since spent fuel storage containers are commonly placed on open storage sites, their thermal state should be determined using forward conjugate heat transfer problems [14], [15]. In this case, the system of differential equations will include:

– continuity equation

$$\frac{\partial \rho}{\partial t} + \operatorname{div}(\rho \mathrm{v}) = 0, \tag{1}$$

where ρ is the density of fluid environment, t is time, and v is the velocity vector;

– atmospheric air motion equation

$$\rho \frac{d\mathrm{v}}{\partial t} = -\mathrm{grad}\left(p + \frac{2}{3}\mu_{\mathrm{eff}} \operatorname{div} \mathrm{v}\right) + \\ +2\operatorname{div}\left(\mu_{\mathrm{eff}} \dot{\mathrm{S}}\right) + \rho \mathrm{g}, \tag{2}$$

where p is the pressure of fluid environment; μ_{eff} is the effective (accounting for turbulent component μ_t) dynamic viscosity; $\dot{\mathrm{S}}$ is the strain rate tensor; and g is the acceleration of gravity;

– energy equation

$$c_p \rho \frac{dT}{dt} - \frac{dp}{dt} = \operatorname{div}\left(\lambda_{\mathrm{eff}} \mathrm{grad} T\right), \tag{3}$$

where c_p is the specific heat capacity at constant pressure and λ_{eff} is the effective (accounting for turbulent component λ_t) heat conductivity;

– heat conductivity equation for solids

$$c_p \rho \frac{\partial T}{\partial t} = \operatorname{div}\left(\lambda \mathrm{grad} T\right) + q_V, \tag{4}$$

where λ is the heat conductivity of the material and q_V is the spent fuel decay heat;

– model turbulence k-ε

$$\frac{\partial(\rho k)}{\partial t} + \operatorname{div}(\rho k \mathrm{v}) = \\ = \operatorname{div}\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\mathrm{grad} k\right) + \\ +G_k + G_b - \rho\varepsilon,$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \operatorname{div}(\rho \varepsilon \mathrm{v}) = \\ = \operatorname{div}\left(\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\mathrm{grad} \varepsilon\right) + \\ +C_{1\varepsilon}\frac{\varepsilon}{k}\left(G_k + C_{3\varepsilon} G_b\right) - C_{3\varepsilon}\rho\frac{\varepsilon^2}{k}, \tag{5}$$

where G_k is the term describing the generation of turbulent kinetic energy induced by velocity gradients (according to Boussinesq's hypothesis, $G_k = \mu_T S^2$);

G_b is the term describing the generation of turbulent kinetic energy induced by Archimedes forces (for ideal gas:

$$G_b = -\frac{\mu_T}{\rho \mathrm{Pr}_T}\left(g_x \frac{\partial p}{\partial x} + g_y \frac{\partial p}{\partial y} + g_z \frac{\partial p}{\partial z}\right);$$

$C_1\varepsilon$, $C_2\varepsilon$ and $C_3\varepsilon$ are the model constants equaling 1.44, 1.92, and 0.09;

σ_k = 1.0 is the turbulent Prandtl number for k;

σ_ε = 1.3 is the turbulent Prandtl number for ε;

the turbulent component of dynamic viscosity is found as

$$\mu_T = 0.09\rho\frac{k^2}{\varepsilon}; \quad (6)$$

and the turbulent component of fluid environment heat conductivity is found as

$$\lambda_T = \frac{c_p \mu_T}{\mathrm{Pr}_T}, \quad (7)$$

where Pr_T = 0.85 is the turbulent Prandtl number.

The justification for the choice of the turbulence model and its constitutive equations is described in more detail in [15].

The analysis of thermal processes in a spent fuel storage facility uses air as fluid environment at relatively low pressures and temperatures, allowing air to be regarded as ideal gas, i.e., the following dependence to be accepted for specific internal energy:

$$U = c_v T, \quad (8)$$

and the Clapeyron–Mendeleev relation to be used as the equation of state:

$$\rho = \frac{p}{RT}, \quad (9)$$

where c_v is the specific heat capacity at constant volume and T is gas temperature;

R is gas constant of 8.314 J/(K·mole).

Uniqueness conditions for the conjugate heat transfer problem in analysis of the thermal state of containers with spent fuel include:

geometrical data on the system being considered;

thermal properties of solids and air;

initial conditions consisting of temperature, pressure, and velocity fields and possibly other physical parameters in solids and air at initial time;

data on internal heat sources (decay heat from spent fuel);

boundary conditions (atmospheric air temperature, wind pressure and speed).

Conditions of equal heat flows and zero mass flow are set at the interface between solids and air.

The results obtained from the solution of the forward conjugate heat transfer problem are used to determine the boundary heat transfer conditions on the surface of a container with spent fuel. The inverse heat transfer problem is considered only for the solid, which is the container concrete body. The calculation procedure involves multivariate solution to the forward heat transfer problem for the container concrete body. The boundary conditions are varied so as to minimize the mismatch between the temperature field resulting from calculation of the forward heat transfer problem and the temperature field resulting from calculation of the forward conjugate heat transfer problem.

Methodology for Determining the Thermal-Stress State of a Container

To simulate the thermal-stress kinetics of structures considering complex rheological characteristics and damageability of their materials exposed to temperature and power fields, a special procedure and software were developed for solving a wide range of nonlinear nonstationary problems with relatively low computational efforts employing the 3D finite-element method [16], [17]. The calculation procedure can be improved and used to develop a methodology for assessing the thermal and thermal-stress state of dry storage containers for spent fuel of power reactors to promote their long-term operation in variable weather conditions.

In the development of computer models for dry spent fuel storage containers, the input data are set through topologically regular decomposition of the body into macroelements as arbitrary hexagons, and their geometry and external influencing factors can be assigned in different coordinate systems (Cartesian, cylindrical, spherical, toroidal) arbitrarily oriented relative to the global Cartesian coordinate system. The properties of container materials are set as a function of temperature and organized into a table with specific temperature values. For other temperature values, they are determined with linear or quadratic interpolation.

The boundary conditions are set as those distributed along the edges of macroelements. Their components may change in coordinates and time and be assigned with special functions for specific moments of time. For the heat conductivity problem, third-type boundary conditions and radiative heat exchange should be set. For the global mechanical problem, stress components or displacements in a global or local coordinate system simulating different loads are set. The boundary conditions allow the actual environmental effects on the thermal and thermal-stress state of spent fuel containers to be taken into account. The initial conditions are obtained from the solution of the stationary problem at given boundary conditions.

The initial boundary-value problem is solved with the time-step method. Explicit and implicit finite-difference schemes involving an automatic choice of the steps are used. Iteration process is allowed to be employed to determine the parameters of linearized problems in each step. To solve the system of finite-element equations, the square root method, considering the variable ribbon thickness, is applied and coefficients for the system of equations are calculated with the two-point Gaussian quadrature rule.

To solve the nonlinear nonstationary heat conductivity problem, the following functionality is used:

$$I=\frac{1}{2}\iiint_V\left\{K_x(V_\propto,T)\left(\frac{\partial T}{\partial x}\right)^2+K_y(V_\propto,T)\left(\frac{\partial T}{\partial y}\right)^2+\right.$$
$$+K_z(V_\propto,T)\left(\frac{\partial T}{\partial z}\right)^2+$$
$$+K_{xy}(V_\propto,T)\left(\frac{\partial T}{\partial x}\right)\cdot\left(\frac{\partial T}{\partial y}\right)+$$
$$+K_{xz}(V_\propto,T)\left(\frac{\partial T}{\partial x}\right)\cdot\left(\frac{\partial T}{\partial z}\right)+$$
$$+K_{yz}(V_\propto,T)\left(\frac{\partial T}{\partial y}\right)\cdot\left(\frac{\partial T}{\partial z}\right)-$$
$$\left.-2Q(x,y,z)\Phi_Q(t)T+2\rho c(V_\mu,T)\frac{\partial T}{\partial t}\cdot T\right\}dV+$$
$$+\iint_{S_q}q(S)f_q(t)TdS+\iint_{S_{q_{ins}}}q_{ins}(S)f_{q_{ins}}(t)TdS, \qquad (10)$$

where K_x, K_y, K_z, K_{xy}, K_{xz}, and K_{yz} are the heat conductivity coefficients; ρc is the specific heat capacity of material per volume unit; Q is the intensity of internal heat sources; q is the heat flow through the region boundary; q_{ins} is the insolation power; $\Phi(t)$ and $f(t)$ are the functions controlling the change in boundary conditions with time; T is temperature; t is time; V_μ and S_μ are subregions and surface areas of subregions with different properties and boundary conditions.

Nonstationary heat conductivity problems are solved in time with the implicit Crank–Nicolson method [16]:

$$\frac{\partial T(t+\Delta t)}{\partial t}=(T(t+\Delta t)-T(t))\cdot\frac{2}{\Delta t}-\frac{\partial T(t)}{\partial t}. \quad (11)$$

To solve the mechanical problem, a variant of the incremental theory of the modified Lagrange approach is applied with modified Kirchhoff stress tensors and Green strain tensors [5].

The linearized equation of physical law

$$\Delta^*\sigma_{ij}=C_{ijkl}\Delta^*\varepsilon_{ij}+\Delta^*\sigma_{ij}^0 \qquad (12)$$

is a strain growth tensor as a sum of elastic, temperature, and plastic components:

$$\Delta^*\varepsilon_{ij}=\Delta\varepsilon_{ij}^e+\Delta\varepsilon_{ij}^T+\Delta\varepsilon_{ij}^p. \qquad (13)$$

The growth in elastic strain is determined by Hooke's law

$$\Delta\varepsilon_{ij}^e=A_{ijkm}(T^{(n+1)})\Delta^*\sigma_{km}+\Delta A_{ijkm}{}^*\sigma_{km}, \qquad (14)$$

where A_{ijkm} is the elastic compliance tensor at temperature at the end of the n+1-th time step

$$\Delta A_{ijkm}=A_{ijkm}(T^{(n+1)})-A_{ijkm}(T^{(n)}). \qquad (15)$$

The growth in temperature strain components is

$$\Delta\varepsilon_{ii}^T=\alpha_i\left(T^{(n+1)}\right)\cdot T^{(n+1)}-\alpha_i\left(T^{(n)}\right)\cdot T^{(n)};$$
$$\Delta\varepsilon_{ij}^T=0, i\neq j. \qquad (16)$$

The growth in plastic strain components depends on the theory used. For isotropic material with isotropic hardening under active load, the plastic strain growth components are calculated with the following equation [17]:

$$\Delta\varepsilon_{ij}^p=\left(\frac{3}{2\sigma_i}\right)^2\left(\frac{1}{E_k}-\frac{1}{E}\right)\times$$
$$\times S_{ij}\left(S_{km}\Delta\sigma_{km}+\frac{2(\sigma_i-\sigma_T)}{3}\right), \qquad (17)$$

where σ_i and σ_T are the stress intensity and yield stress at the beginning of time step; E and E_k are Young's modulus and tangent modulus determined from the material strain diagram at the end of time step; and S_{ij} is the stress deviator. The use of modified strain and stress tensors allows the application of conventional plasticity theories as material noncompression conditions are approximately met.

It should be noted that this methodology can be applied to any type of ventilated dry storage containers for spent fuel. Depending on how the container geometry and associated processes are detailed [18] for simulating the thermal and thermal-stress state of spent fuel containers, axisymmetric or three-dimensional calculation models that take into account the design features, actual boundary conditions, and external climatic factors can be employed.

Conclusions

In ensuring the safe operation of dry container storage facilities for spent nuclear fuel, it is important to determine the service life of equipment and develop effective ageing management programs. Numerous factors, particularly weather and climatic ones, should be taken into account for open storage facilities since they may exert a significant effect on storage equipment throughout the service life.

The proposed approach to determining the thermal and thermal-stress state of concrete spent fuel containers will promote more effective methods for assessing the service life of dry container storage facilities for spent fuel. In turn, this is necessary in developing ageing management programs and their long-term safe operation.

The theoretical information on the methodology for determining the thermal and thermal-stress state of a concrete spent fuel storage container is the first step in solving the complex problem of assessing the impact of ageing on the container design functions in long-term operation and potential extension of the service life beyond the design period. The next stages of this effort are intended for analytical and experimental studies to confirm the correctness and reliability of the results obtained using the proposed methodology.

This research effort was funded by the National Academy of Sciences of Ukraine (NASU) within the special-purpose and competitive program "NASU Grants for Research Laboratories/Groups of Young NASU Scientists for Research in Priority Areas of Development in Science and Technology 2020-2021" and within the NASU target research program "Scientific and Technical Problems of Condition Monitoring and Service Life Assessment and Extension for Long-Term Operation Structures, Equipment, and Buildings".

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Методологія визначення теплового та термонапруженого станів бетонного контейнера зберігання відпрацьованого ядерного палива для оцінки ресурсу його експлуатації

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Робота присвячена створенню методологій визначення теплового та термонапружного станів основного обладнання сухих контейнерних сховищ відпрацьованого ядерного палива (ВЯП), які є найбільш розповсюдженим видом зберігання використаного палива ядерних енергетичних реакторів. Зазначено, що питання безпеки обладнання зберігання щодо оцінки ресурсу його експлуатації в світовій науковій літературі висвітлено не достатньо широко. Зокрема, не існує ефективних методик розрахунку теплового та термонапруженого станів обладнання, які б враховували вплив багатьох зовнішніх факторів протягом всього строку експлуатації сховища. Для оцінки теплового стану контейнерів зберігання ВЯП запропоновано використовувати розв'язання прямих спряжених задач теплообміну, які дозволяють враховувати взаємне перенесення тепла як в твердому тілі, так і в оточуючому його рухомому середовищі (повітрі). На основі результатів розв'язання спряжених задач теплообміну пропонується із застосуванням обернених задач теплообміну визначати граничні умови для подальшого визначення термонапруженого стану контейнерів зберігання. Запропонований підхід до визначення теплового та термонапруженого станів бетонного контейнера з ВЯП дозволить створити більш ефективні методи оцінки ресурсу експлуатації сухих контейнерних сховищ ВЯП, що, зі свого боку, є необхідним під час розробки програм управління старінням обладнання зберігання та забезпечення його довгострокової безпечної експлуатації.

Ключові слова: безпека, теплові процеси, процеси термопружності, відпрацьоване ядерне паливо, ресурс експлуатації.

Отримано 16.09.2021