

INCREASING THE RADIATION SAFETY OF NUCLEAR POWER PLANTS USING THE METHOD OF CONTROLLING THE TIGHTNESS OF FUEL ELEMENTS

O. Mamontov, I. Nevliudov, T. Stytsenko, A. Belikov, O. Tokarieva
¹*Kharkiv National University of Radio Electronics, Kharkiv, Ukraine*

E-mail: olena.tokarieva@nure.ua;

²*PSACEA "Prydniprovsk State Academy of Civil Engineering and Architecture",
Dnipro, Ukraine*

The problem of monitoring the tightness of fuel elements at the stage of their manufacture to improve the radiation safety of nuclear power plants is considered. A vibration method is proposed for non-destructive testing of the tightness of cylindrical fuel rods. The method makes it possible to perform accelerated testing of a batch of fuel rods and remove samples with gross leakage under conditions of mass production. A description of the method is given, a mathematical model of free vibrations of a fuel element is developed. The time dependences of the pressure and the period of free oscillations of the fuel element were obtained by calculation. The assessment of the influence of the inhomogeneity of the fuel element structure on the test result is carried out. Inhomogeneity causes an error in measuring the oscillation period up to 1%, which can lead to a false result. Three-dimensional plots were constructed, reflecting the main form of free vibrations of a homogeneous and inhomogeneous section of a fuel element. On the basis of the performed assessment, recommendations were given for conducting fuel rod tightness control, excluding a false result.

INTRODUCTION

The issues of improving the safety and energy efficiency of nuclear power plants remain one of the highest priorities in the nuclear power industry. The increase in the energy efficiency of nuclear power plants is associated with an increase in the unit capacity of power units and the duration of fuel campaigns. This is possible due to a high level of fuel burnup, an increase in energy intensity, and a tightening of the operating conditions for fuel elements. These reasons intensify the leakage of radionuclides outside the cladding of the fuel elements, and tighten the technological requirements for their tightness.

An increase in the content of radionuclides in the primary coolant is permissible up to the operational limit. The violation of this condition has serious medical, environmental and social consequences. Prevention of these problems is a complex organizational and technical task. Its solution leads to the objective need to improve the reliability of fuel cells at the stage of their manufacture.

The relevance of this work is dictated by the need to improve the radiation safety of nuclear power plants. Safety is based on the control and removal of leaky fuel rods at the stage of their manufacture.

LITERATURE ANALYSIS AND PROBLEM STATEMENT

Non-destructive methods of tightness control are known to be used in the technological process of manufacturing fuel elements. These include radiation, ultrasonic, optical, electromagnetic, thermal and mass spectrometric methods. However, they all have drawbacks, as a result of which there is no single universal method. Radiation methods are based on the interaction of ionizing radiation with the fuel element

cladding [1, 2]. Ionizing radiation negatively affects the working personnel as a harmful production factor. Radiation is absent in ultrasonic [3, 4] and optical methods [5–7] non-destructive testing. However, ultrasound is also a harmful production factor that adversely affects the human being. Optical methods are divided into visual measuring and electronic measuring. In the first type of optical methods, workers experience increased stress on the visual analyzer. Both varieties are characterized by a relatively low reliability of detecting defects, which is limited by the analysis of the outer surface of the shell. Information on the internal state of the shell material can be obtained by electromagnetic [2, 6] and thermal methods [8, 9]. Electromagnetic methods are based on the analysis of the interaction of an external electromagnetic field with the electromagnetic field of eddy currents excited by an electrically conductive shell. This study also becomes harmful to humans, especially in the microwave range. Thermal methods are based on the registration and analysis of temperature field inhomogeneity on the surface of a heated shell.

The presence of a defect inside the shell material (delamination, cavity, foreign inclusions) is not a quantitative indicator of helium pressure, tightness or leakage. Thus, all considered methods provide limited information on the state of the fuel element cladding and characterize its state indirectly. Leaks can be found with time-consuming helium leak detectors [1].

In addition to the indicated disadvantages, the considered methods are associated with the processing of large amounts of information. This limits the speed of control, even with automation tools.

Measurements of the helium pressure inside the fuel elements can be carried out by passing through ultrasound in the region of the compensation volume [1]. The intensity of ultrasonic vibrations that passed through

the inner cavity of the fuel element is proportional to the square of the gas pressure. It is also possible to measure the pressure inside the fuel element using normalized local heating of the shell in the area of the compensation volume [9]. The internal gas pressure is determined from the temperature field on the shell surface. The speed of control operations is significantly limited by the performance of auxiliary actions.

On the basis of the analysis, it should be noted that there is no method of accelerated control and detection of leaking fuel elements. This explains the expediency of developing a vibration method for non-destructive testing of fuel rod tightness, which has an increased response rate [10]. The introduction of this method will make it possible to reduce the process of inspection of a technological batch of fuel elements by accelerating the identification and removal of leaky samples.

PURPOSE AND OBJECTIVES OF THE RESEARCH

The aim of the study is to prove the possibility of using the vibration method to control the tightness of cylindrical fuel elements.

To achieve the goal it is required to solve the following tasks:

- provide a description of the proposed method for non-destructive testing of fuel elements;
- to develop a mathematical model of fuel rod vibrations in case of gas leakage;
- to determine the dependence of the holding time between measurements of the oscillation period on the permissible leak, taking into account the metrological accuracy of the frequency meter;
- to evaluate the influence of fuel element inhomogeneity on the control result.

DESCRIPTION OF THE VIBRATION METHOD OF NON-DESTRUCTIVE CONTROL OF TIGHTNESS OF FUEL ELEMENTS

The method is based on the dependence of the free vibration period on the gas pressure inside the shell.

The period of oscillation of the non-hermetic fuel element is reduced over time due to the decrease in the gas pressure and the reduction of the tension of the shell.

The method is implemented as follows. The monitored fuel element 1, after helium injection and sealing, is installed on the supports of stand 2 and fixed with clamps 3, Fig. 1. The exhilaration of free damped vibrations similar to the vibrations of a string is activated. The free vibration period (main tone) is measured using sensor 4 and frequency meter 5.

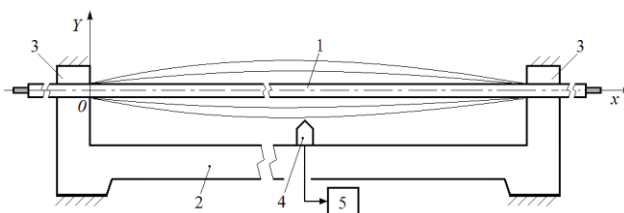


Fig. 1. Fuel element at the control and test stand

Then the fuel element is removed from the stand, held for a given time Δt , and the period of free oscillations is re-measured. If there is a leak during this time, the gas will flow out from under the shell, the tension will decrease and the oscillation period will increase. The holding time Δt depends on the permissible leak rate. It should be sufficient for reliable registration of the change in the oscillation period taking into account the metrological accuracy of the frequency meter. The temperature of the fuel elements at which the periods of oscillations are measured before and after holding must be the same. Therefore, before measuring the periods of oscillations of the fuel elements, the specified temperature is adjusted. For sealed fuel elements, the oscillation periods do not differ.

Thus, an express control method has been proposed which makes it possible to identify and remove leaking fuel elements. Exposure of fuel rods can be carried out in a group manner in storage facilities. It does not require additional material costs or the time spent. The speed of direct control in manual mode is not less than 150 pcs/h. This makes it possible to use this method in automated complexes for non-destructive testing of fuel elements. The rest of the fuel elements can be monitored by traditional methods [1–9]. This will significantly reduce the total time for testing the tightness of a technological batch of fuel elements.

This method can be applied in the areas of final inspection of fuel rod manufacturers. It can also be used in the areas of incoming inspection of nuclear power plants.

DEVELOPMENT OF A MATHEMATICAL MODEL OF FREE VIBRATIONS OF A FUEL ELEMENT WITH A GAS LEAK

The mathematical model of cylindrical fuel rod vibrations is based on the one-dimensional wave equation of vibrations of a homogeneous string fixed at two points [11]:

$$\frac{\partial^2 Y}{\partial t^2} = c^2 \frac{\partial^2 Y}{\partial x^2} = \frac{F}{\rho_x} \cdot \frac{\partial^2 Y}{\partial x^2}, \quad (1)$$

where Y is the vertical displacement of a point on the fuel element surface relative to the equilibrium position (see Fig. 1); t – time; c – coefficient depending on tension and inertia; x – horizontal coordinate of a point on the Ox axis; F is the shell tension along the Ox axis; ρ_x – linear density.

Model (1) does not take into account vibration damping. This is due to the insignificant influence of this factor on the period of natural oscillations, and, consequently, on the control result.

Natural fluctuations are possible with strictly defined periods:

$$\tau_n = \frac{2L}{n \cdot c} = \frac{2L}{n} \sqrt{\frac{\rho_x}{F}}, \quad (2)$$

where L is the distance between the clamping points, m ; n is an integer corresponding to the waveform.

Equation (2) assumes fuel element uniformity (quasi-uniformity), in which the mass is evenly distributed along its length. Also, equation (2) does not take into account

the damping of oscillations. This condition is quite acceptable for linear systems due to the insignificant influence of damping on the frequency (period) of oscillations. Due to this, mathematical calculations are greatly simplified.

The design of the fuel element used in WWER-1000 reactors [1, 12] was taken as a basis, subject to quasi-uniformity. The following data were taken as an example: the mass of the moving part of the fuel element was 1.4 kg, the distance between the fixation points was 2 m. The initial tension of the cladding under normal conditions before helium injection was 1120 N. After helium injection, the pressure inside the cladding was $25 \cdot 10^5$ Pa. Helium inside the shell was considered as an ideal gas. Its volume was $6 \cdot 10^{-5}$ m³.

The decrease in the shell tension over time is explained by the drop in gas pressure, which is similar to transient processes in electrical circuits:

$$\Delta F(t) = \Delta P(t) \cdot S = \Delta P(t) \cdot \frac{\pi \cdot d^2}{4}, \quad (3)$$

where t – the gas outflow time, s; $\Delta P(t)$ – time dependence of pressure decrease, Pa; S and d – the area, m², and diameter, m, of the cross section of the inner cavity of the fuel element, respectively.

$$\Delta P(t) = \Delta P_0 \cdot e^{-\frac{t \cdot Q}{V \cdot \Delta P_0}}, \quad (4)$$

where ΔP_0 – initial overpressure, Pa (Fig. 2); V – volume, m³; Q – leak, Pa · m³ · s⁻¹.

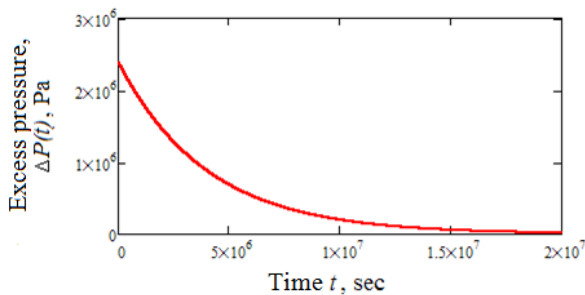


Fig. 2. Graph of the dependence of the excess pressure inside the fuel element on time

The dependence of the period of the fundamental tone of natural vibrations of a fuel element on time (duration of exposure) is presented by formula (5) and is shown in Fig. 3:

$$\tau(t) = 2L \cdot \sqrt{\frac{\rho_x}{F_0 + \Delta F(t)}}. \quad (5)$$

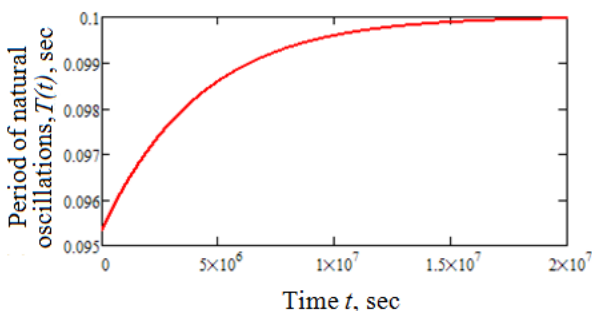


Fig. 3. Graph of the dependence of the period of natural oscillations of a fuel element on time

Equations (1)–(5) represent a mathematical model of fuel rod vibrations during gas leakage.

An important condition for this control is the required holding time Δt of the fuel elements between the measurements of the vibration periods. The holding time depends on the amount of leak that is allowed for the given control method. This time should be sufficient to reliably record changes in the oscillation period, taking into account the metrological accuracy of measuring the oscillation period. The measurement accuracy of the oscillation period is limited by a number of destabilizing factors (temperature fluctuations, vibration damping, frequency meter error), and is ± 0.0001 s.

Fig. 4 shows the dependence of the holding time Δt (represented by a logarithmic scale) on the value of the permissible leak Q .

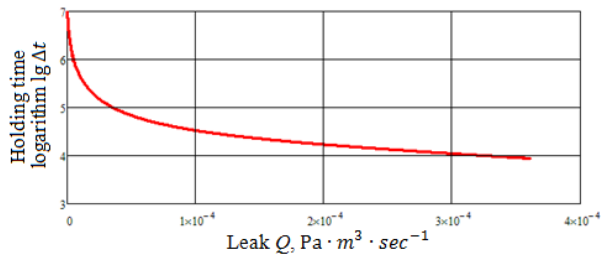


Fig. 4. Dependence of the logarithm of the holding time on the magnitude of the permissible leak

The dependence in Fig. 4 is necessary for making a decision on the use of the method in specific conditions.

ESTIMATION OF THE INFLUENCE OF FUEL INHOMOGENEITY ON THE CONTROL RESULT

The design of a cylindrical fuel element is shown in Fig. 5.a. The design is a heterogeneous structure in which the mass is unevenly distributed.

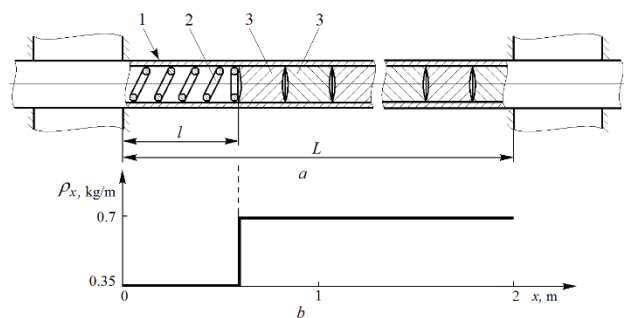


Fig. 5. Inhomogeneity of the fuel element structure: 1 – shell; 2 – spring; 3 – fuel pellets

Fig. 5,b shows a graph of the approximate dependence of the linear density of an inhomogeneous section of a fuel element on the x coordinate. This dependence is represented by the empirical formula (6):

$$\rho_x^* = 0.7 \left(\frac{\text{sgn}(x - l)}{4} + 0.75 \right), \quad (6)$$

where l is the length of the section with reduced density, m.

To assess the effect of fuel element inhomogeneity on the oscillation period, it is required to solve the wave

equation (1) taking into account dependence (7). An analytical solution is difficult. To solve this problem, the finite difference method was applied, in which the derivatives are represented by finite difference approximations [13, 14]. Dividing the region of integration into a finite number of steps, we rewrite equation (1) in finite-difference form:

$$\frac{Y_{j,i+1} - 2Y_{j,i} + Y_{j,i-1}}{h^2} = c^2 \frac{Y_{j+1,i} - 2Y_{j,i} + Y_{j-1,i}}{k^2} = \frac{F}{\rho_x^*} \cdot \frac{Y_{j+1,i} - 2Y_{j,i} + Y_{j-1,i}}{k^2}, \quad (7)$$

where j and i are the numbers of steps (grid nodes) along the Ox and Ot axes, respectively; k and h are the lengths of steps along the Ox and Ot axes, respectively.

We transform expression (7), reflecting the dependence of the wave function at the next time step $i + 1$ on the previous steps i and $i - 1$:

$$Y_{j,i+1} = \frac{1}{a^2} Y_{j+1,i} + 2Y_{j,i} \left(1 - \frac{1}{a^2}\right) - Y_{j,i-1} + \frac{1}{a^2} Y_{j-1,i}, \quad (8)$$

$$a = \frac{k}{c \cdot h} = \sqrt{\frac{\rho_x}{F}} \cdot \frac{k}{h}.$$

Fig. 6 shows 3-D plots using equation (8). They reflect free vibrations of a fuel element in the form of a standing wave with one antinode (fundamental tone). In Fig. 6,a – vibrations of a homogeneous section of a fuel element ($l = 0$) with a linear density $\rho_x = 0.7$ kg/m and a length $L = 2$ m. In Fig. 6,b – vibrations of a non-uniform area. For the sake of clarity, the length of the lightweight part was conventionally taken equal to $l = 1$ m. The linear density corresponded to the graph in Fig. 5,b. Both options were considered under the same (normal) conditions under which the tensile force did not change.

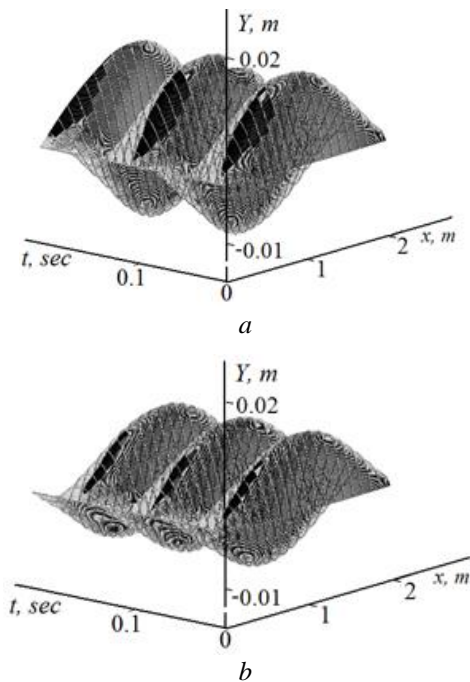


Fig. 6. Basic form of free vibrations (Mathcad):
 a – a homogeneous section of a fuel element,
 b – heterogeneous area

The comparison of the graphs shows that the inhomogeneity of the fuel element leads to a change in the period of free oscillations. Under the conditions considered, the oscillation period of the inhomogeneous section of the fuel element has noticeably decreased (by about 12%). This is due to a decrease in the mass of the vibrating element with a constant tension force. Taking into account the real length of the inhomogeneous section ($l = 0.2$ m), the oscillation period decreases by about 1% (0.001 s). This value exceeds the measurement error of the oscillation period. Obviously, when testing fuel elements, this factor will cause a false result (measurement error). To prevent it, when measuring the oscillation period before and after holding, it is required to fix the fuel element in the same places.

Oscillations with more than one antinode were not considered due to significant damping caused by friction.

CONCLUSIONS

The article describes an express method and a test bench for identifying and removing leaking cylindrical fuel rods.

The method is based on the dependence of the period of free oscillations of a fuel element on the gas pressure inside the cladding. The period of oscillation of a leaky fuel element decreases with time due to a decrease in gas pressure and a decrease in cladding tension. The detection of leaking fuel elements is carried out on the basis of registration of a decrease in the period of free oscillations during the holding time.

On the basis of the studies carried out, a mathematical model has been developed that reflects the dependence of the period of free oscillations of a fuel element on time. The model is based on the one-dimensional wave equation of oscillations of a homogeneous string and the method of the analogy of transient processes in electrical circuits.

The dependence of the holding time between the measurements of the oscillation period on the value of the permissible leak is obtained. This dependence is necessary for making a decision on the use of the method in specific conditions.

Using the finite difference method, the influence of fuel element inhomogeneity on the test result was estimated. It has been established that heterogeneity can lead to a false result. To prevent it, when measuring the oscillation period before and after holding, it is required to fix the fuel element in the same places.

As a result of the studies carried out, the possibility of monitoring the tightness of fuel rods using the proposed express method was confirmed. The introduction of this method in combination with the existing control methods will improve the radiation safety of nuclear power plants.

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ПІДВИЩЕННЯ РАДІАЦІЙНОЇ БЕЗПЕКИ АТОМНИХ ЕЛЕКТРОСТАНЦІЙ ЗА ДОПОМОГОЮ МЕТОДУ КОНТРОЛЮ ГЕРМЕТИЧНОСТІ ТВЕЛІВ

О.В. Мамонтов, І.Ш. Невлюдов, Т.Е. Стищенко, А.С. Беліков, О.В. Токарева

Розглянуто проблему контролю герметичності твєлів на етапі їх виготовлення для підвищення радіаційної безпеки АЕС. Запропоновано вібраційний метод неруйнівного контролю герметичності твєлів циліндричної форми. Метод дозволяє виконати прискорений контроль партії твєлів і видалити зразки з грубими порушеннями герметичності в умовах серійного виробництва. Наведено опис методу, розроблена математична модель вільних коливань твєла. Розрахунковим шляхом отримані залежності тиску і періоду вільних коливань твєла від часу. Виконано оцінку впливу неоднорідності конструкції твєла на результат контролю. Неоднорідність викликає похибку вимірювання періоду коливань до 1%, що може привести до помилкового результату. Побудовано тривимірні графіки, що відображають основну форму вільних коливань однорідної і неоднорідної ділянок твєла. На підставі виконаної оцінки дані рекомендації з проведення контролю герметичності твєлів, які виключають помилковий результат.

ПОВЫШЕНИЕ РАДИАЦИОННОЙ БЕЗОПАСНОСТИ АТОМНЫХ ЭЛЕКТРОСТАНЦИЙ С ПОМОЩЬЮ МЕТОДА КОНТРОЛЯ ГЕРМЕТИЧНОСТИ ТВЭЛОВ

О.В. Мамонтов, И.Ш. Невлюдов, Т.Е. Стищенко, А.С. Беликов, О.В. Токарева

Рассмотрена проблема контроля герметичности твэлов на этапе их изготовления для повышения радиационной безопасности АЭС. Предложен вибрационный метод неразрушающего контроля герметичности твэлов цилиндрической формы. Метод позволяет выполнить ускоренный контроль партии твэлов и удалить образцы с грубыми нарушениями герметичности в условиях серийного производства. Представлено описание метода, разработана математическая модель свободных колебаний твэла. Расчетным путем получены зависимости давления и периода свободных колебаний от времени. Выполнена оценка влияния неоднородности конструкции твэла на результат контроля. Неоднородность вызывает погрешность измерения периода колебаний до 1%, что может привести к ошибочному результату. Построены трехмерные графики, отражающие основную форму свободных колебаний однородного и неоднородного участков твэла. На основании выполненной оценки даны рекомендации по проведению контроля герметичности твэлов, исключающих ложный результат.