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Research Article

Ultrasonic monitoring of the VVER-1000 FA form change*

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Abstract

A procedure has been developed to determine the geometrical parameters of fuel assemblies (FA) by an ultrasonic pulse-echo technique used for all types of light-water reactor FAs. The measurement of geometrical parameters is achieved through the pairwise installation of ultrasonic transducers opposite the FA spacer grid faces at a distance of not more than a half of the transducer acoustic field near-region length such that the acoustic axes of the pairwise transducers are parallel to each other. The advantages of the presented technique is that it enables monitoring of any FA modifications, including the VVER reactor assemblies with a different number of spacer grids.

The paper presents a mathematical model of the acoustic path developed in a geometrical acoustics approximation and its verification results. The model was used for computational and experimental studies of the ultrasonic test technique, and engineering formulas have been developed to calculate the errors of the transducer-measured distance to the FA surface. A code has been developed to simulate the FA form change monitoring and can be used to design new monitoring systems.

The developed technique to determine the VVER-1000 FA geometrical parameters was introduced at units 1 and 2 of the Temelin NPP, the Czech Republic, for the TVSA-T FA form change monitoring. The successful use of the proposed technique makes it possible to recommend it for use in inspection benches at other NPPs.

Keywords

Ultrasonic technique, fuel assembly, form change, model, natural convection

Introduction

In the process of irradiation in the reactor core, a fuel assembly (FA) is subjected to thermal, radiation and vibration impacts and loads. This leads to all kinds of strain, such as deflection, torsion and elongation, variation of the flat-to-flat dimension, and spacer grid (SG) warps. A deformed FA may result in abnormal operation of control rods and the control and protection system, so FA form change is a topical issue and requires special attention.

The FA form change as a result of service inside the reactor is investigated either in shielded boxes at material test centers or at inspection benches deployed in spent fuel pools (SFP) directly at NPPs. One example of a material test center is JSC SSC RIAR engaged, specifically, in testing irradiated VVER-1000 FAs from all NPPs in Russia (Polenok et

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al. 2010, Zvir et al. 2019). The reason for the widespread use of inspection benches across the world is that they provide for the rapid and cost effective acquisition of information on the FA state right after the withdrawal from the reactor core as compared with safety boxes. The new VVER NPP designs under development in Russia are expected to include FA inspection benches (Ivanov et al. 2017a).

The inspection and repair bench developed for the NPP 2006 project uses contact differential transformer linear displacement transducers (Ivanov et al. 2017b). Alternatively, noncontact technique is used in inspection benches. The absence of contact with the tested item and simple design simplify the FA inspection process and improve the bench reliability (Voronina 2018). An ultrasonic pulse-echo technique is used to determine geometrical parameters in an inspection bench developed in China (Xu Yuanhuan and Nie Yong 2009). The ultrasonic waves (UW) used by the transducer propagate in water up to the FA surface and, after being reflected, are received by the same transducer. The distance from the transducer to the FA surface can be determined from the known speed of sound in water and the UW propagation time. The combination of the FA surface point coordinates obtained in the course of the inspection allows determining the FA surface geometry. Apart from the China-built inspection bench based on an ultrasonic pulse-echo technique, there are other designs differing in the measurement pattern and method: the TVSA FA inspection bench developed at NRNU MEPhI (Aullo et al. 2012); DAMAC, a French system built for the FA bow determination (Martynenko 2012); an inspection bench developed for the Balakovo NPP by NIIAR and OKB Gidropress (Pavlov 2006). The design and the action of laboratory and commercial measuring monitoring systems based on ultrasonic techniques are presented in (Pavlov and Voronina 2021a).

Despite the extensive use of ultrasonic techniques in technology, there are no currently common tools for developing ultrasonic FA geometry inspection systems. Besides, complexities arise with estimating the error in the obtained results when using ultrasonic techniques.

The paper describes a new ultrasonic pulse-echo technique to identify the VVER FA form change in the NPP cooling pool successfully implemented at the Temelin NPP for the TVSA FA inspection. The paper also presents a mathematical model of the pulse-echo technique acoustic path to measure the distance between the transducer and the FA surface and the model verification results. A code has been developed to simulate the FA form change process that can be also used to develop new measurement systems and FA monitoring techniques.

Functional diagram of the measurement system

A method has been developed for the FA inspection in the NPP SFP to determine the FA geometry by ultrasonic technique that consists in the following (Amosov et al. 2020). Ultrasonic transducers are installed around the FA periphery opposite the SG faces at a distance of not more than a half of the acoustic field near-region length for these transducers, X_6 (Fig. 1).

The near-region dimension, X_6, is equal to

$$X_6 = R^2 \cdot f/c, \qquad (1)$$

where R is the radius of the piezoelectric element, m; f is the UW frequency, Hz; and c is the speed of sound in the medium, m/s.

For example, for a transducer with a radius of R = 0.01 m that generates UWs with a frequency of f = 5 MHz, the near-region dimension will be equal to X_6 = 0.33 m.

With the investigated surface being at a distance not exceeding 0.7 X_6, the amplitude of the reflected UW pulse echo does not practically change (Pavlov 2006). Therefore, measuring at a distance of not more than 0.5 X_6 will make it possible to stabilize the metrological characteristics of the ultrasonic technique.

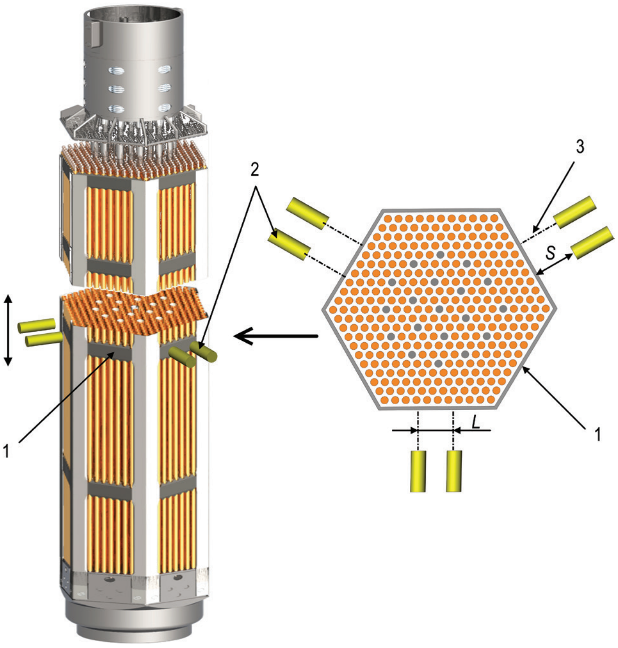

Figure 1. Arrangement of ultrasonic transducers for the FA geometry determination: 1 – SG; 2 – ultrasonic transducer; 3 – acoustic axis.

The system with ultrasonic transducers is moved along the FA longitudinal axis to determine the distance between the transducers and the SG faces using the following formula

$$S = c \cdot \tau/2, \qquad (2)$$

where τ is the time of the UW propagation from the transducer to the FA and back, s.

The pairwise arrangement of the transducers allows determining the face rotation angle, α:

$$\alpha = \mathrm{arctg}(\Delta S_n/L_n), \qquad (3)$$

where S_n is the deviation in the readings of the transducers installed opposite the nth face, m; and L_n is the distance between the acoustic axes of the transducers installed opposite the n^{th} face, m.

The computed angle permits an allowance to be made in determining distance S and the error reduced in the UW angular incidence. The mentioned error is the result of the UW oblique reflection from the slanted surface. The distance measured with regard for the angular allowance will be

$$S = c\cdot\tau\cdot[1 + 1/\cos(2\alpha)]^{-1} + R\cdot\text{tg}\alpha, \tag{4}$$

where R is the radius of the piezoelectric element, m; and α is the face rotation angle computed using formula (3), degrees.

To employ the angular allowance, it is required to determine initially the distance from the transducers to the surface based on formula (2), determine further the face rotation angle, α, and the distance with regard for the allowance using formula (4), and then calculate again angle α. This approach used in measurements will make it possible to reduce the influence of the angular incidence on the technique results.

The torsion angle, ψ, for each FA cross-section can be determined by determining the rotation angle of all faces with respect to the FA upper or lower SG using formula

$$\psi = \psi_0 - \psi_i, \tag{5}$$

$$\psi_i = \frac{1}{n}\left(\sum_1^n \text{arctg}\frac{\Delta S_n}{L_n}\right) \tag{6}$$

where ψ_0 is the upper or lower SG rotation angle, degrees; ψ_i is the i^{th} SG rotation angle, degrees; and n is the number of the FA faces.

The deflection is calculated from the array of the SG surface point coordinates obtained in the inspection using algebraic computations.

This method can be used for all types of the light-water reactor FAs, including square-shaped FAs.

Mathematical model of the pulse-echo technique acoustic path

A boundary layer occurs during the inspection of an irradiated FA near the FA surface due to the nuclear fuel decay heat. This layer is characterized by a temperature gradient growing in the upward direction along the FA longitudinal axis. The temperature profile in the natural convection conditions depends on the liquid flow pattern, the SFP water temperature, and the decay heat value.

Since ultrasonic speed depends on the wave propagation medium temperature, an error takes place in determining the distance between the transducer and the SG face. In addition, an error occurs depending on the UW angular incidence onto the surface. Besides, a refraction phenomenon, a curved UW propagation path, needs to be taken into account in a medium with a temperature gradient.

To determine the dependence of the distance measurement error on the factors described herein, a mathematical model of the ultrasonic technique acoustic path has been developed (Voronina and Pavlov 2020). The model makes it possible to determine the time for the UW propagation from the transducer to the surface and back in the transducer's near-region. It was developed in a geometrical acoustics approximation and takes into account the temperature profile and the UW refraction.

We shall introduce the following notation: τ_1 (time for the UW propagation from the transducer to the boundary layer); τ_2 (time for the UW propagation in the boundary layer); τ_3 (time for the reflected UW propagation to the transducer after traveling through the boundary layer); $\Delta\tau_A$ (time defined by the pulse-echo leading-edge recording technique); X (distance from the transducer to the inspected surface along the transducer's acoustic axis), m; α (FA surface slope, degrees); δ_t (thickness of the thermal boundary layer, m); $c(T_\infty)$ (constant sound speed value at the SFP water temperature of T_∞ far from the FA, m/s); $T(x)$ (boundary layer temperature profile); f (UW frequency, Hz); k (ratio of threshold amplitude A_0 and maximum signal amplitude, $A_{\max}$).

The UW propagation time can be presented then by the following expression

$$\tau = \tau_1 + \tau_2 + \tau_3 + \Delta\tau_A = \frac{X - R\cdot\text{tg}\,\alpha - \frac{\delta_t}{\cos\alpha}}{c(T_\infty)}\cdot\left(1 + \frac{1}{\cos 2\alpha}\right) + 2\cdot\int_0^{\delta_t}\frac{dx}{c(T(x))\cdot\sqrt{1-\left(\frac{\sin\alpha}{c(T_\infty)}c(T(x))\right)^2}} + \\ + \frac{2\sin^2\alpha}{c(T_\infty)^2\cos 2\alpha}\cdot\int_0^{\delta_t}\frac{c(T(x))dx}{\sqrt{1-\left(\frac{\sin\alpha}{c(T_\infty)}c(T(x))\right)^2}} + \frac{1}{2\pi f}\cdot\arcsin(k). \tag{7}$$

The first three summands are determined from the UW propagation path in the medium between the transducer and the SG surface. The final summand characterizes the pulse-echo recording method. Due to being steep, the pulse-echo leading edge causes an additional distance determination error that depends on the threshold level of A_0, from which time τ is measured. When A_0 increases, $\Delta\tau_A$ and, accordingly, the error increase (Voronina and Pavlov 2020).

According to (7), calculating the UW propagation time requires data on the boundary layer thickness and temperature profile. To determine the temperature profile in the natural convection conditions near the FA surface, one can use the results of the natural convection computational and experimental investigation or undertake numerical simulation using computational fluid dynamics (CFD) methods.

Based on semi-empirical relations known in literature to determine the heat-exchange characteristics during natural convection, a program was developed for calculating the speed of sound in water (Pavlov and Voronina 2018). The program also calculates the boundary layer parameters, the preheat temperature, and the temperature profile along the ultrasonic transducer's acoustic axis. A code, ANSYS Fluent, was used for the CFD simulation of natural convection near the VVER-1000 FA outer surface submerged in water (ANSYS Fluent 2021). Use of CFD simulation involves a problem of choosing the particular turbulence model and estimating the degree of confidence of the results obtained on its basis. It is shown in (Voronina and Pavlov 2021a) that an RNG k-ε model is recommended to be used to simulate natural convection near the FA surface.

In the process of justifying the applicability of the developed acoustic path model, its verification procedure was undertaken (Voronina and Pavlov 2021b). The influence of factors on the technique results, namely, that of decay heat and the inspected surface slope, was simulated full-scale and numerically.

Fig. 2 shows the absolute error value of the measured distance from the transducer to the heated surface of the FA simulator $|\Delta X|$ as a function of Rayleigh number for two series of experiments. Measurements were undertaken at different elevations for the heat flux surface density in a range of 0 to 7 kW/m^2 with a constant distance from the transducer to the inspected surface. The calculation and experiment results agree well across the range of Rayleigh numbers, specifically for a turbulent mode with Ra > $1 \cdot 10^{14}$.

The influence of the slope on the ultrasonic measurement results is shown in Fig. 3. The slope of the UW reflecting plate varied in a range of 0 to 3° relative to the radiant surface of the transducer's piezoelectric element. The initial distance between the transducer and the surface was ~ 120 mm. The plate was moved with the use of a micrometric table in the direction away from the transducer. The increment value, dX, for the distance from the slanted surface was 6 mm. The error of the transducer-measured distance increment, $\Delta(dX)$, is shown on the ordinate axis in Fig. 3.

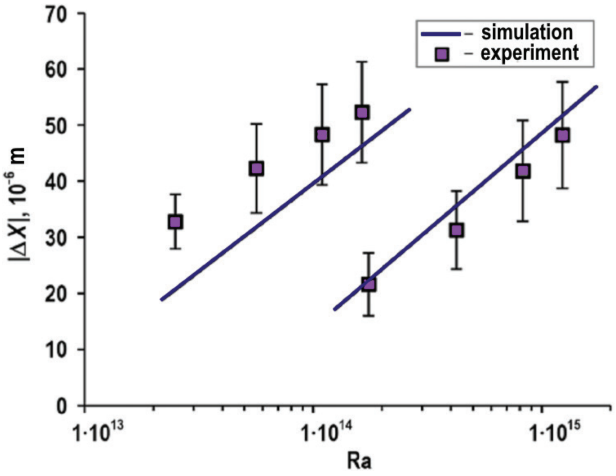

Figure 2. Measurement error $|\Delta X|$ as a function of Rayleigh number (Pavlov et al. 1991).

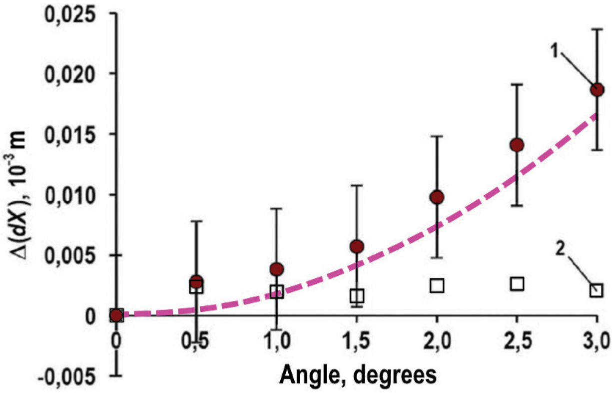

Figure 3. Distance increment measurement error, dX, as a function of the surface slope angle: 1 – initial experimental data; 2 – experimental data with angular allowance; dash line shows the simulation results.

It can be seen that the error is the larger the larger is the slope. The experimental data numbered 1 (discs) are above the reference line, but the dependences of errors are identical. The data numbered 2 (squares) demonstrate the results of employing the angular allowance when calculating the distance between the transducer and the surface using formula (4). When the proposed allowance is used, the error is smaller and does not exceed 5 μm in a range of 0 to 3°. It can be concluded based on this that the given allowance needs to be used for the distance calculation since it makes it possible to reduce considerably the measurement error.

Investigating the influence of natural convection on the ultrasonic dimensional measurement results has shown that the error of measuring the distance from the transducer to the inspected item for a turbulent convection mode is several times as large as for a laminar mode and is defined primarily by the boundary layer thickness and water temperature drop. For a turbulent natural convection mode that starts at Ra > $4 \cdot 10^{13}$, nomograms were obtained for determining the boundary layer thickness, the temperature drop, the origin of the turbulent mode coordinate near the FA surface, and the absolute error value for the measured distance between the transducer and the surface (Voronina and Pavlov 2021c).

Fig. 4 shows a nomogram to determine the error with the SFP water temperature being equal to 25 °C. The heat flux density, q, varies between 0.5 and 6.0 kW/m^2 with an increment of 0.5 kW/m^2. The ordinate axis shows the absolute error value, that is, the measured distance is smaller when the heat flux density and the FA longitudinal axis transducer coordinate are larger.

Fig. 4 also shows the experimental data presented in (Pavlov et al. 1991). The measurements were undertaken at an elevation of 0.86 and 1.4 m with a heated FA simulator with the heat flux density being equal to 1.25, 2.80 and 5.00 kW/m^2. A comparison of the calculated and experimental data shows these to agree satisfactorily.

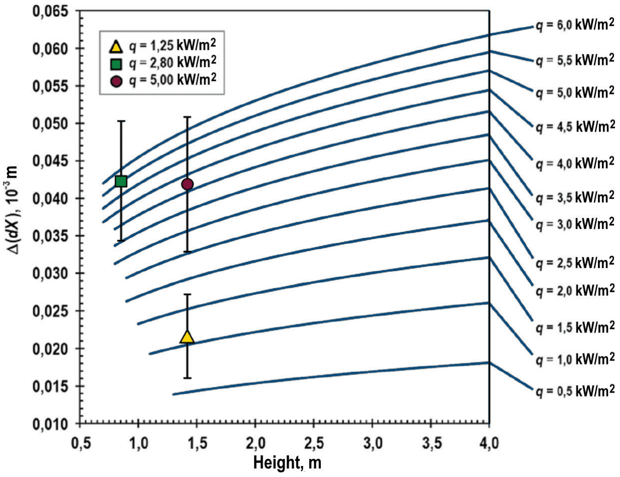

Figure 4. A nomogram to determine the absolute error value obtained as a result of nuclear simulation; the experimental data for values q = 1.25, 2.80, and 5.00 kW/m^2 have been taken from (Pavlov et al. 1991).

The nomograms were processed to obtain engineering formulas to calculate the measured distance error for a turbulent convection mode (Voronina and Pavlov 2021c):

$$|\Delta X| = \frac{q \cdot y^2}{\alpha} \cdot \left(\mathrm{Ra}_y\right)^{-0.44} \cdot 10^{-2} + \chi \cdot q^{\gamma} \cdot \left(\frac{y}{q} \cdot 10^{3}\right)^{\varepsilon} \cdot 10^{-6}, \quad (8)$$

$$y_{\text{т}} = \omega \cdot q^{-0.25} \quad (9)$$

where $|\Delta X|$ is the absolute error value, m; $y_{\text{т}}$ is the turbulent mode onset coordinate, m; y is the coordinate along the FA vertical axis, m; q is the heat flux density near the FA surface, W/m^2; $\mathrm{Ra}_y = \mathrm{Pr} \cdot g \cdot \beta \cdot q \cdot y^4/(\lambda \nu^2)$ is the local Rayleigh number; Pr is the Prandtl number; g is the free fall acceleration, m/s^2; β is the liquid bulk thermal expansion factor, 1/K; λ is the liquid conductivity factor, W/(m·°C); and ν is the liquid kinematic viscosity factor, m^2/s.

The factors in formulas (8), (9) are determined depending on the SFP water temperature (Voronina and Pavlov 2021c).

The decay heat value for the random burn-up and FA cooling time values can be determined using different codes or calculated by linear interpolation of the decay heat values shown in (RB-093-20 2020). Therefore, formula (8) can be used to estimate the ultrasonic technique error or determine the error of the experimental form change data obtained in the process of inspection for any light-water reactor assembly with different burn-up and FA cooling time.

Examples of simulation and technique application at NPPs

A code has been developed based on the acoustic path mathematical model to simulate the VVER FA form change monitoring be ultrasonic technique (Pavlov and Voronina 2021b). The FA is represented by a heated hexagon with the side width equal to the FA SG face width. The deflection, torsion angle, FA heat flux and SFP water temperature values are used as the code input. The code makes it possible to analyze an ultrasonic system with transducers variously arranged relative to each other and to the FA surface, as well as for different values of the transducer's piezoelectric element radius.

The developed mathematical model and the code were used to simulate computationally and experimentally the VVER-1000 FA form change monitoring process (Voronina and Pavlov 2021d). The simulation was undertaken for an FA with a burn-up of 10 to 65 MW·day/kgU, with a deflection amount not exceeding 20 mm, and a torsion angle of not more than 3°. It has been shown that the maximum deflection determination error, without taking into account the allowance for the torsion angle, is ~ 0.54 mm, and that with the allowance taken into account is nearly 10 times as small (0.06 mm); the torsion angle determination error does not exceed 0.03°. An example of the simulation results is presented in Fig. 5.

The diagram presents dependences of the transducer-measured distance error, ΔX, for different distances X between the transducers and the VVER-1000 FA surface. The piezoelectric element radius was assumed to be equal to 9 mm, the resonant frequency was assumed to be equal to 5 MHz, while the distance between the transducer's acoustic axes was selected as equal to 25 mm. The face deflection value was 20 mm, and the FA torsion angle was not more than 3°. The data were obtained for a turbulent mode with $\mathrm{Ra} = 3 \cdot 10^{16}$, the water temperature being equal to 20 °C.

The dependence of the error on distance X is linear. It can be seen that the straight line oblique factor depends on the torsion angle. A torsion angle increase leads to the straight line slope increase the farther is the transducer from the SG surface, and the measured distance error is smaller. The presented calculated dependences demonstrate the results obtained without the angular allowance taken into account. As noted earlier, the allowance made permits reducing substantially the measurement error. As shown by the calculation results, the use of the allowance neutralizes the surface slope, while reducing the error to the values of the error defined by the FA decay heat. The values of this error in the diagram fit the data obtained for the angle equal to 0°.

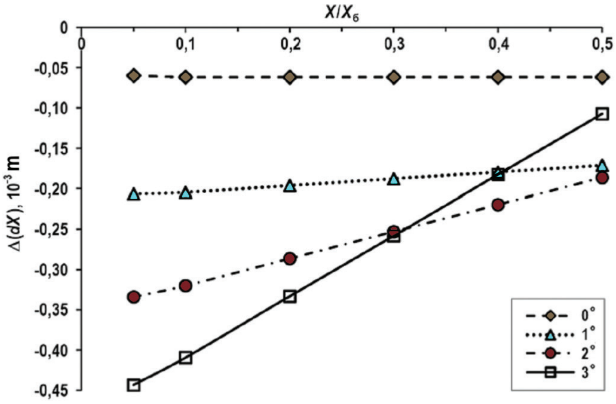

Figure 5. Simulation of the VVER-1000 FA inspection process using ultrasonic technique.

The developed technique has been introduced in the TVSA-T FA inspection bench at the Temelin NPP. About 40 TVSA-T FAs of different modifications with a burn-up of ~ 11 to ~ 52 MW·day/kgU were inspected. Most of the TVSA-Ts were inspected practically a few days after having been withdrawn from the reactor core, while only some had been cooled in the SFP for about two years.

The process of the FA scanning in the bench using ultrasonic transducers for the deflection and torsion angle determination takes about 10 minutes, which proves ultrasonic inspection to be near real-time. A positive experience of using the developed technique at the Temelin NPP makes it possible to recommend it for being employed at other NPPs.

Conclusions

1. A noncontact ultrasonic pulse-echo technique has been proposed to measure the VVER-1000 FA transverse dimensions, deflection and torsion angle in the NPP cooling pool conditions. Specific to the technique is simplicity and versatility in terms of its applicability

for monitoring different FA designs, including TVSA and TVS-2M with any number of spacer grids.

2. A mathematical model of the acoustic path has been developed and verified in a geometrical acoustics approximation, taking into account the ultrasonic wave angular incidence onto the FA surface and the UW propagation in the natural convection conditions along the FA surface.
3. A code was developed based on the mathematical model and engineering formulas were obtained which make it possible to simulate the VVER FA form change monitoring, and design new monitoring systems based on ultrasonic pulse-echo technique for measuring linear dimensions.
4. The developed technique was used to build equipment for the VVER-1000 TVSA FA form change monitoring at units 1 and 2 of the Temelin NPP, the Czech Republic. The results of measuring ~ 40 assemblies with a burn-up of 11 to 52 MW·day/kgU and the cooling time of several days to two years after the withdrawal from the reactor core have proved the technique to be reliable and efficient.

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