ULTRASONIC SYSTEM FOR NUCLEAR FUEL GEOMETRICAL CHANGES EVALUATION

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ABSTRACT

The periodic measurements of the dimensional changes of the fuel assemblies during their lifetime are valuable for evaluation of the fuel assembly design performance, for the quantification of the margins and for the early indication of anomalies. The simplest approach is to use the visual inspections to obtain the data on the fuel assembly bowing and rod to rod gap closure, but these methods have low precision. The ultrasonic (UT) systems applied in poolside inspections to measure the fuel assembly deformation are in development for several decades worldwide. CVR has been working on this equipment for the application with WWER-1000 fuel assemblies. The tests in a water tank with the shortened FA mockup were very promising, reaching the precision of around 0.1 mm. The UT probes have to be qualified for their reliability in a radiation field before implementation at the power plant. Such a test was conducted in a gamma chamber along with the calibration of the probes before and after irradiation and the system has passed this test. The mockup of the deformed fuel assembly was measured in the spent fuel pool environment to investigate the maximal achievable accuracy of the measurements with different UT probes and methods of data evaluation. In the current state, the UT measuring system developed by CVR is prepared to be used with the existing fuel inspection stand at Temelin NPP or with any new fuel inspection equipment.

1. Introduction

The paper is focused on LWR fuel assembly (FA) geometry measurements using an ultrasonic (UT) system which is under development in Centrum výzkumu Řež (CVR). The team consisting of specialists from CVR and ÚJV Řež (UJV) have a long experience with fuel inspections at Temelin NPP. Periodic fuel inspections are crucial to verify the design behaviour model with the real fuel condition and possibly discern any anomaly that can exclude the fuel assembly from further insertion into the core for a following cycle.

The experience of CVR in nuclear fuel inspection have brought up the problem of lower precision of the measurement evaluation done from the postprocessing of visual inspection [1], [2]. The systematic and random error of the perspective, including the fuel – camera position, low resolution and the subjectivism of the operator have resulted in the accuracy above 1.5 mm. This called for a more precise measurement method. The analysis of pros and cons showed the ultrasonic system as the most promising. A couple of years of the R&D activities allowed obtaining a high-precision UT system. The preliminary tests conducted in our laboratory allowed estimating the accuracy of fuel assembly bow measurements for less than 1 mm.

CVR´s team has made wide range tests of the UT probes that can be used in spent fuel pool conditions. The tests include the water condition in the laboratory where a WWER-1000 fuel mock-up was placed in a water tank and measured with the UT system using CNC positioning system, and the radiation resistance tests were conducted in gamma chamber.

This paper presents the results of the investigation into the ultrasonic measuring system showing its general overview and advantages when compared to standard postprocessing from the visual inspection.

2. Experimental Devices and Facilities

The technology of ultrasonic measurements of nuclear fuel assembly has been investigated in CVR since 2013. During this time, CVR has developed a complementary and precise method for FAs poolside inspection. Over the years, the UT laboratory has been developed from relatively basic components and instrumentation to an automatic system performing the experiments on the mock-up of WWER-1000 fuel assembly. The UT laboratory at CVR is meant to simulate normal operating conditions of nuclear fuel inspection environment without the influence of radiation. It comprises a 300-liter water tank and fuel assembly simulation equipment. The water tank works only at atmospheric pressure. It is possible to simulate the as-real cooling medium solution e.g. the additives of boric acid or changes of coolant temperature and flow. Those are the conditions for the bow-twist-tilt simulation of a single spacer grid or its mock-up and the mock-up of WWER-1000 fuel assembly. The inspection activities are simulated with the use of vertically moveable rig propelled with a CNC system. The rig can house the required instrumentation such as a camera or UT probes. The system can utilize from 1 up to 4 probes for whole FA geometry measurements. The whole measuring system, including data acquisition system for UT probes signal, is controlled by a computer.

The total projection of the WWER-1000 mockup FA geometry is derived from 3 profiles of the vertical axis. The signal at the spacing grids is most pronounced. Over the fuel rods areas, the signal is more dispersed due to the curvatures of the rods surfaces. By analyzing the intense of the signal reflection, it is possible to distinguish the measuring points at the spacing grids. The geometry is then put together as the relative position of adjacent measuring points on each of the three profiles. This principle of the measurement allows for the full automatization of the measuring process. The instrumentation, i. e. the UT probe(s), can be implemented on a camera rig and the measurements can be taken over the course of a regular visual inspection of nuclear fuel. Such approach offers a significant reduction of time while retaining or even improving the precision of the measurements when compared with e.g. image postprocessing. All of this is possible with very small consumption of the camera/surrounding space (no limitation for the camera itself) and in principle any possible speed of the rig’s axial movement. The system designed by CVR is flexible and can be easily adjusted to almost all types of nuclear fuel and specific requirements of nuclear power plants. The typical setup of the measuring system for WWER type fuel in the laboratory facility is shown in Fig 1.

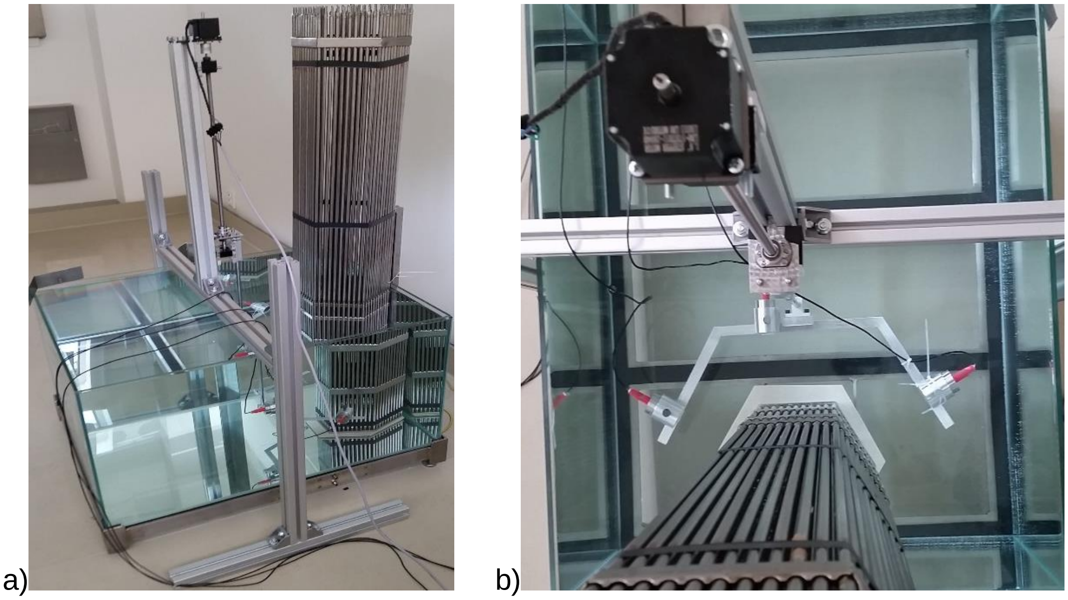

Fig 1: The experimental system setup outline; a) general overview, b) probes position against the fuel assembly mock-up

For testing the UT probes in the radiation field a gamma chamber is used. It uses Co-60 with the activity of 200 TBq and is suitable to irradiate the components, materials from cryogenic temperaturesup to 400 °C (for radiation and temperature aging as well as to simulate the operating conditions of the nuclear power plants). The gamma chamber allows to take out the cabling of irradiated electronics which is convenient for online measurements during UT probes testing.

3. UT Probes Assessment Process

The UT measurement technology is widely known and applied [3], [4]. Its advantages have been distinguished and appreciated since several decades, what resulted in a wide utilization of the UT systems in medicine and as NDT method for material inspection. The nuclear industry has also introduced this system for fuel assembly measurements [5], [6]. So UT probes have to be properly assessed to ensure their reliability and endurance in their harsh working condition including radiation.

For nuclear industry application, a very important issue is the probe degradation after receiving the maximal allowed radiation dose, given by the manufacturer – the cumulative dose is usually not traced online and getting the maximal dose can affect the outputs of the probe. The assessment is a constant learning process, how the system can behave in the real working conditions and how the operator of the system should work with the system to obtain relevant data.

This approach brought CVR to specify two tests for the probes. The first test was devoted to the radiation resistance of the probes that can potentially be used in the measuring system, and the second set refers to the probes performance and accuracy, which was done before and after the irradiation tests. The tests were conducted using the pulse-echo technique where the signal distance amplitude and the energy of the reflected signals were collected and analyzed. The highest the signal’s energy detected, the better measurements can be performed. Therefore the satisfactory energy level was estimated for 90% and more.

3.1 Accuracy Test Before Irradiation

To perform the UT probe accuracy assessment, a calibration block in a step-like shape was fabricated. The designed intervals between the steps were: 0.4 mm, 0.2 mm, 0.1 mm, and 0.05

mm. The calibration block was verified by the use of a laser pointer of high precision to ensure the proper reference for the UT probes assessment.

For the tests, two probes were selected: one radiation resistant (RR) – a regular of-the-shelf product for nuclear application - for its assessment for further utilization and one regular (non-radiation resistant (nRR) – customized according to specifications from CVR; a prototypic probe - for the dose damage model tracking. The RR probe was a 5 MHz probe with 8 mm crystal diameter and a beam spread of 2,4° at -20dB. The nRR probe has also 5 MHz with a crystal diameter of 28 mm and inherent focus. Due to the parameters, given by the manufacturers of both probes, the radiation resistant probe could distinguish only one step interval with 100 % precision, i.e. 0.4 mm. The regular probe succeeded up to its inherent accuracy, i.e. 0.1 mm. Nevertheless, the possibly steady conditions of the measurements allowed the radiation resistant probe to measure even the smaller steps of the calibration block. The system that was used by CVR during this test has a signal threshold set for 90 % of the signal reflection, which assures almost perpendicular position of the block against the probe and neglecting the signal reflected at the edges of each step. The output before irradiation for the radiation resistant probe is presented in Fig 2. The lower accuracy of the radiation resistant probe worked as a kind of inherent filter – was less sensitive for signals buckling than the nRR. The more precise probe, the non-radiation resistant, generated more fluctuating outputs with more noise (see Fig 5). The detailed analysis allowed although recognizing and measuring the calibration block with satisfying precision.

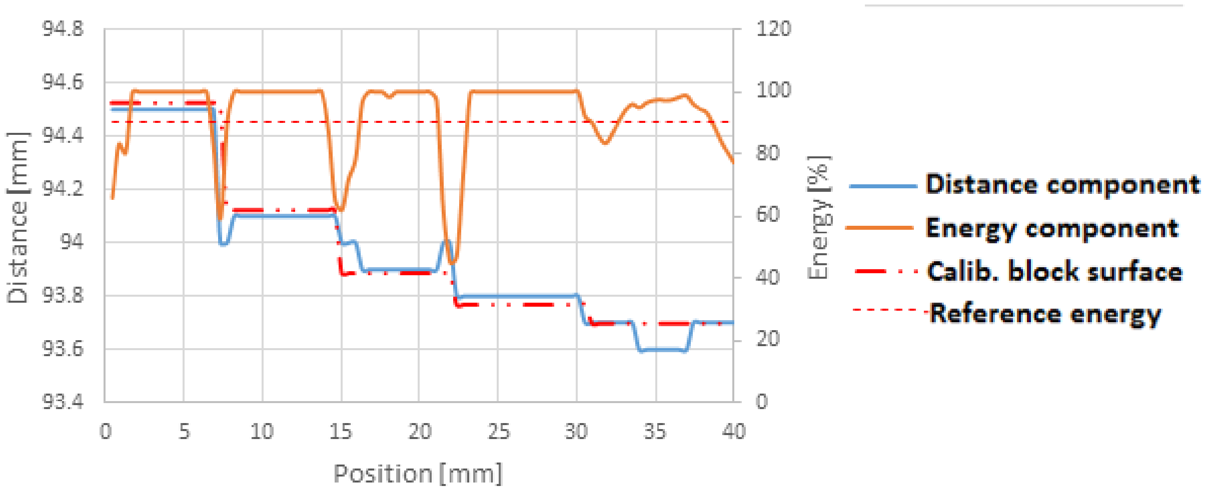

Fig 2. Measurement on the calibration block before the irradiation test of the RR probe

The Fig 2 shows a typical output obtained during the calibration block test, where the “Distance component” series represents the distance between the probe and the measured object; the “Energy component” series represents the energy level obtained during the measurements; “Calib.block surface” series represents the precise dimensions of the calibration block obtained with the laser pointer (plotted along to the right site of the block); the “Reference energy” represents the signal’s energy level taken as the border value for the specification of satisfying step answer according to our experience.

3.2 Gamma Irradiation Test

Both probes used for the accuracy test were placed in a water tank of 16 °C, facing towards the source to obtain maximal radiation damage to crystals. Both probes have the operating frequency of 5 MHz. The maximal cumulative dose of the RR probe which was selected for the test was 1 MGy. The position of the probes installation allowed reaching the dose of maximum 1 kGy/hr. The total test duration was 213 hours so the total dose was at least 200 kGy per probe. The UT probes were both constantly measuring the prepared object with the source being inside.

After launching the test, the background echo was estimated for 23 % of the total signal plot with suppressing tendency at the distances of 51.3 mm for RR UT probe and 26.6 mm for nRR UT probe respectively. The maximal energy peaks from the probes were 98 % and 60 % respectively according to the mentioned order. The energy signal of the non-radiation resistant probe was dampened by 30 % within the first 10 minutes of the test. Then, after another 15 minutes, it reached the background level (ca. 23 - 25 %) and basically dispersed below the threshold level. Such behaviour was anticipated hence it was suspected that it will take more time to reach such severe damage.

The nRR probe behaviour showed a descending tendency of energy peak dissipation while retaining the nominal measured distance with the accuracy of 0.5 mm during the first 0.5 hour of the test. The accuracy of the probe, given by the manufacturer was 0.1 mm. As the error excesses this value, the radiation impact is also visible on the distance signal component. The differences in the object-probe distances measured in the gamma chamber during the irradiation process might also come from the micro-vibrations of the measuring system, the gamma chamber, and the building itself. As the nRR UT probe is highly sensitive, the fluctuations in the measured distance were more developed in this case.

The first hour of the test, with 40 % of signal energy threshold filter, is shown in Fig 3. The echo from the RR UT probe saturates within first 30 minutes of the test and maintains the maximal value. The nominal energy (98 %) fluctuates at most to the lowest value of 82 % after 3.5 minutes of the test. As the changes in the signal outline of the nRR UT probe were more rapid than anticipated, the threshold filtered the signal of less than 40 %. The observation conducted during the experiment showed that the signal of the nRR UT probe was dampen below the background echo (23 %) within 25 minutes of the test and in this way was not possible to be tracked.

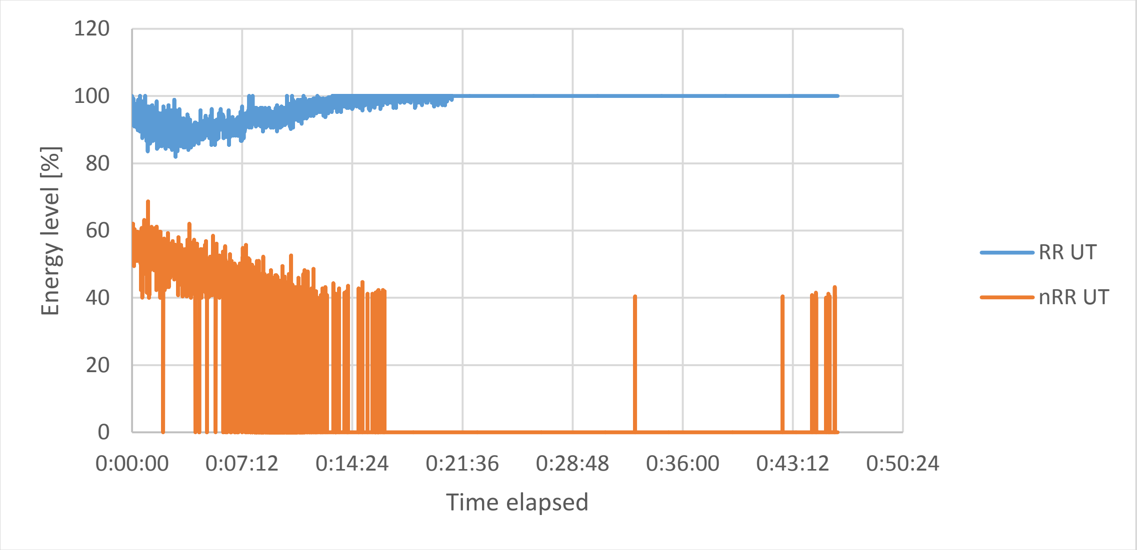

Fig 3. First 45 minutes of the test with 40 % of signal energy threshold filter

After saturated to the background level, after about 1 hour from the beginning of the test, the energy component of the signal from the nRR UT probe started to appear above the background echo. After 20 hours, it reached the level of about 30 %. Then, the signal continued to increase for the remaining time of the experiment and at the end of the test, it saturated on nominal 70 %. The signal's energy component had increasing trend. The UT probes behaviour during the first 12 hours of the test after the saturation of the nRR UT probe with energy threshold 25 % is shown in Fig 4.

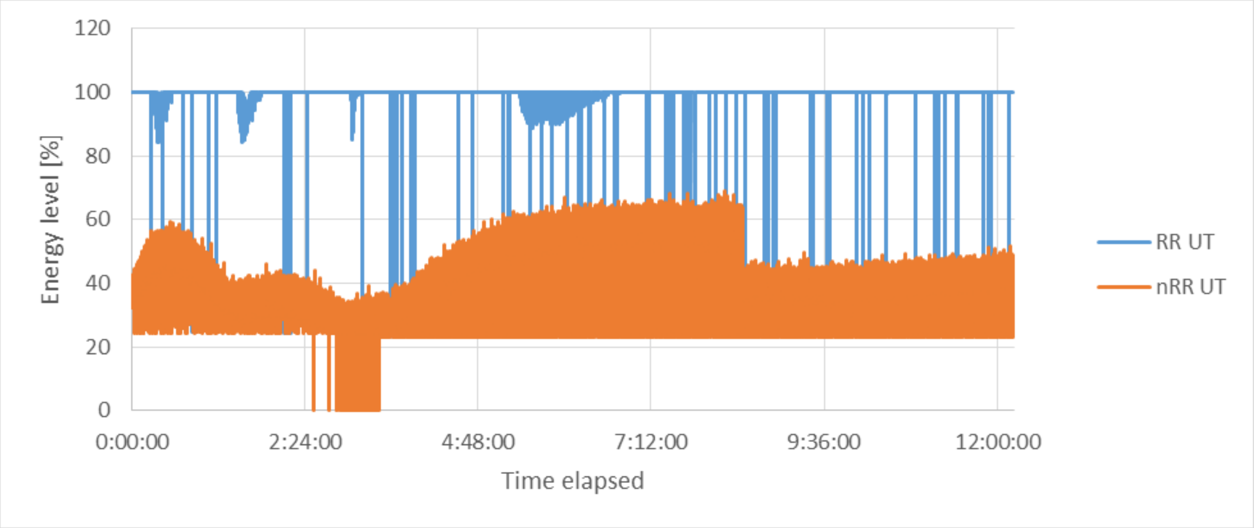

Fig 4. The first 12 hours of the test

At the end of the experiment, the signal from the nRR UT probe was very smooth, when compared to the beginning. With the mentioned linear tendency, it reached even higher values than the nominal, i. e. ca. 70 %. The signal from the RR UT probe maintained the values of above the nominal one. The last 2 minutes of the test are shown in Fig 5.

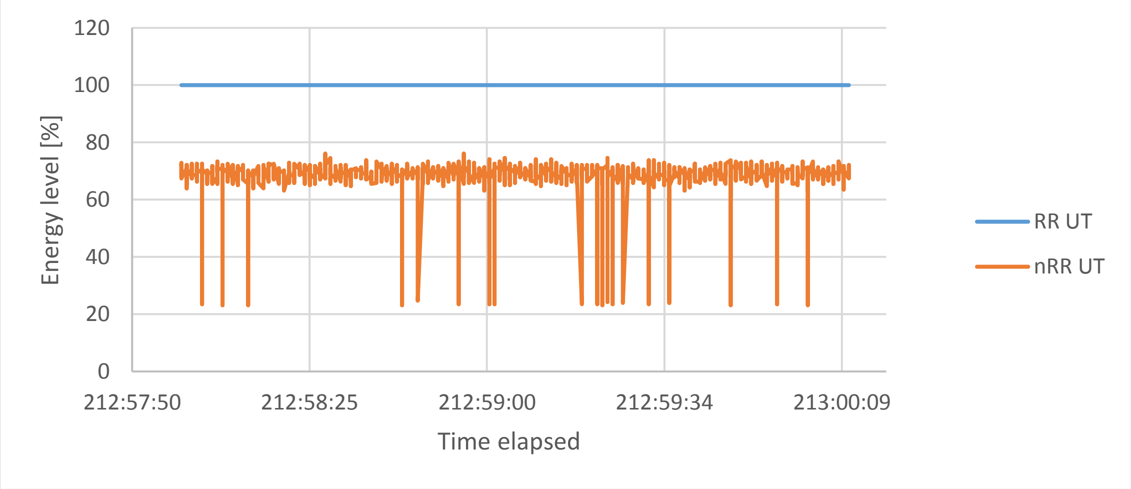

Fig 5. The last 2 minutes of the test

As can be seen in Fig. 5, the signal from the nRR UT probe is very hectic with quasi-periodic changes in its outline. This behaviour is taking the origin in electromagnetic interference with the probe housing, which is much thicker in this special design of the probe. This problem does not affect the RR UT probe of the optimized design. Furthermore, the problem can be linked with the very high sensitivity of the nRR UT probe. It is supposed to be solved by changing the design of the probe.

The visual examination of the nRR UT probe after the end of the test did not show any distinguishable changes on the surface of the acoustic matching layer. The plastic and rubber parts (insulation, cabling, sealing, etc.) were embitteled, what was anticipated. The microstructural analysis of the piezo crystal is scheduled for this year.

The RR UT probe seems to be untouched by the radiation field. It holds the energy peak at the level of 82 - 100 % during the whole test duration with some negligible fluctuations. The distance component varied for 0.4 mm, what is the accuracy given by the manufacturer.

The visual examination of the RR UT probe after the end of the test showed no changes of the acoustic matching layer and also no changes within the plastic or rubber parts. As mentioned above, the received cumulative dose during the irradiation test was lower so no changes were anticipated.

3.3 Accuracy test after irradiation

The accuracy test was repeated after the irradiation test in the gamma chamber. The radiation resistant probe was the only one used in the repeated experiment. The results showed no changes in its accuracy. The example outputs are presented in Fig 6.

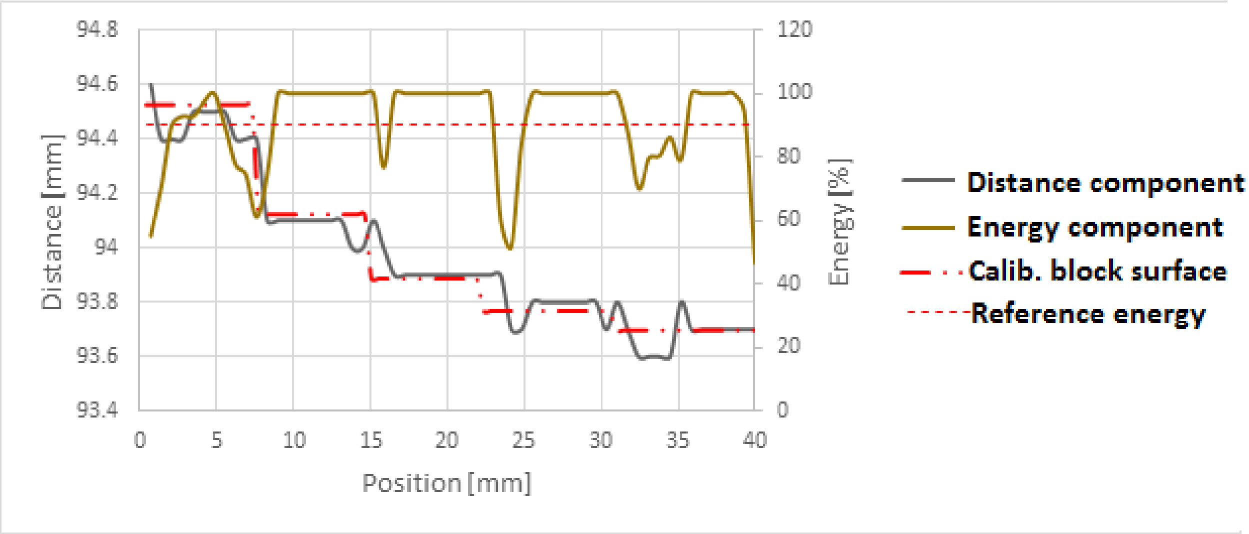

Fig 6. Measurement on the calibration block after the irradiation test

The series plotted in Fig 6 are presented in similar way as in the case of Fig 2,where the "Distance component" series represents the distance between the probe and the measured object; the "Energy Component" series represents the energy level obtained during the measurements; "Calib.block surface" series represents the precise dimensions of the calibration block obtained with the laser pointer (plotted along to the right site of the block); the "Reference energy" represents the signal's energy level taken as the border value for the specification of satisfying step answer according to our experience. The differences in energy plot (mostly at first and fifth step) may come from the energy dissipation at impurities of water and the water fluctuation itself. Nevertheless, the important factor is that the energy echo at each step exceeded 90% taken as the reference.

4. Conclusions

The ultrasonic measurement of nuclear fuel geometry distortions is a technique that allows more precise measurements of the fuel assemblies. Taking the use of the known advantages of this technology, but implementing constant analysis of both signal's components – energy and distance – CVR has developed a reliable system. This system is capable to perform high precision measurements while in motion along the fuel assembly, which is a standard mode during visual inspection. High reliability, small dimensions, and high flexibility for the fuel design make it a helpful tool for post-irradiation inspection program of nuclear fuel assemblies and a good complementary system for standard fuel inspection activities. The system developed by CVR has been tested in two sets of measurement: (1) testing during gamma irradiation of defined conditions and (2) testing at as-normal conditions in the laboratory. These two sets verified the system's reliability after irradiation and its performance for long term, industrial utilization at power plants. The goal defined before the described experiments was to reach the accuracy of less than 1 mm with the entire system. The experiments confirmed this requirement with reasonable recurrence hence the maximal discrepancies during the measurements on calibration block did not exceed 0.1 mm and the maximal deviation during the irradiation test was as high as 0.4 mm. The typical CNC-technology-based moving systems have the inherent accuracy estimated to 0.1 mm, as it was in the case of calibration block measurement test, so the accuracy of below 1 mm is met. The system succeeded all tests for its reliability and is ready to be implemented as an auxiliary system to simplify and speed up the measurements of the nuclear fuel deformation.

5. References

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