Nondestructive Testing of Nuclear Reactor Components Integrity

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Abstract

Nuclear energy must respond to current challenges in the energy market. The significant parameters are increase of the nuclear fuel price, closed fuel cycle, reduction and safe and the final disposal of high level radioactive waste. Nowadays, the discussions on suitable energy mix are taking place not only here in Czech Republic, but also in many other European countries. It is necessary to establish an appropriate ratio among the production of electricity from conventional, nuclear and renewable energy sources. Also, it is necessary to find ways how to streamline the economy, central part of the nuclear fuel cycle and thereby to increase the competitiveness of nuclear energy. This streamlining can be carried out by improving utilization of existing nuclear fuel with maintaining a high degree of nuclear facilities safety.

Increasing operational reliability and safety together with increasing utilization of nuclear fuel place increasing demands on monitoring of changes during fuel burnup. The potential fuel assembly damages in light water reactors are prevented by the introduction of new procedures and programs of the fuel assembly monitoring. One of them is the Post-Irradiation Inspection Program (PIIP) which is a good tool for monitoring of chemical regime impact on the fuel assembly cladding behavior.

Main nondestructive techniques that are used at nuclear power plants for the fuel assembly integrity evaluation are ultrasonic measurements, eddy current measurements, radiographic testing, acoustic techniques and others. Ultrasonic system is usual tool for leak fuel rod evaluation and it is also used at Temelin NPP. Since 2009, Temelin NPP has cooperated with Research Center Rez Ltd in frame of PIIP program at both units WWER 1000. This program was established for US VVantage6 fuel assemblies and also it continues for Russian TVSA-T fuel assemblies.

Keywords: nondestructive testing, fuel cladding, ultrasonics, eddy current, radiographic testing, acoustic techniques, post irradiation inspection

Introduction

Increasing operational reliability and safety together with increasing utilization of nuclear fuel place increasing demands on monitoring of changes during fuel burnup. The potential fuel assembly damages in light water reactors are prevented by the introduction of new procedures and programs of the fuel assembly monitoring. One of them is the Post-Irradiation Inspection Program (PIIP) which is a good tool for monitoring of chemical regime impact on the fuel assembly cladding behavior. Since nuclear power plants have licenced the volatile fission products release to the environment, the careful monitoring of fuel cladding behavior becomes indispensable.

Nuclear fuel failures in PWR/VVER reactors caused by mechanical and physical-chemical aspects are quite often and were studied and described in late 70's. Although the zirconium cladding alloys show high reliability and operational stability. According to the IAEA studies, the fuel failure rate in the world is around 10^{-5}, which means 1-3 failed fuel rods from 100 000 fuel rods in operation (in average for VVER-440 1-2 failed fuel rod, for VVER-1000 2-4 failed fuel rods). However, with use of better alloys, different fuel design, advanced water chemistry, etc. the fuel failure rate is decreasing.

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Post Irradiation Inspection Program

The nuclear fuel reliability recieves the highest priority in the nuclear industry. Defect-free fuel operation programs cover as a rule fuel quality inspection at the fuel manufacture plants on the one hand and detailed on-site examination of spent fuel on the other hand. The poolside inspection of irradiated fuel assemblies to identify failed fuel rods (leakers) is the main part of fuel reconstitution technology. Another reason of leaker identifying necessity is to ensure the fuel assembly transmission feasibility for dry storage and reprocessing [1].

In spite of the low fuel failure rates in current operation of water cooled nuclear power reactors, there is continued high interest in fuel failures for two reasons. First, problems and inconveniences caused by fuel failures in plant operation can still be significant. Second, the generally accepted goal to move towards zero failure rates as closely as possible requires detailed knowledge of existing failure mechanisms, their root causes and remedies. Nuclear fuel continues to perform well around the world; however fuel failures still occur in all countries operating nuclear power reactors. According to the IAEA the current fuel rod failure rates vary in different countries around an average between 10^{-5} and 10^{-4}, except Japan where the reactors operate practically almost free of defect for more than ten years (Fig. 1, [2]).

Fuel failures and other fuel-related issues can have significant operational impacts on nuclear power plants. Fuel failures, have cost some nuclear power plants several millions per event to cover replacement power costs and the costs of a fuel reload. While the industry has made substantial progress in reducing the frequency of fuel failures, continued attention to technical gaps impacting fuel reliability is needed.

Post irradiation examination is periodically carried out to generate feedback information which is used by the fuel designers, fuel fabricators and the reactor operator to bring about changes for improved performance of the fuel [3]. A comprehensive underwater fuel inspection is used to confirm the integrity of the fuel assemblies to be reloaded in the next cycle. The underwater inspection of the fuel rods covers the examination items such as oxide layer thickness, wear, fuel defect identification, etc [4].

The situation in Czech Republic does not digress from the worldwide trends. Since the first reload, provider of the NPP Temelin (CEZ) together with the fuel vendor (Westinghouse Electric Company LCC) have performed post irradiation inspection on the fuel assemblies with the use of Fuel Repair Inspection Equipment (FRIE). There are several reasons to use of this equipment: additional proof of material compatibility, analytical method support and verification, overall thermomechanical performance demonstration, finding of a cause of an eventual FR or FA core component failure and independent check of the fuel system in-core behavior.

CV Rez together with NPP Temelin and Westinghouse Electric Company LLC have cooperated on the fuel inspection and repair since 2009. However, the fuel vendor changed and since August 2010 new type of fuel TVSA-T from Russian company TVEL has been used at Unit 1 of NPP Temelin. From the first cycle, PIIP program will be implemented and CV Rez will participate on the fuel repair and inspection together with TVEL.

Nondestructive methods

The post irradiation examination by nondestructive testing of nuclear fuel is widely used to find out the performance in the reactor core. From these tests the significant information and data are collected, mainly on the cladding degradation which is defined as the first safety barrier. The NDE techniques in post-irradiation examination allow evaluating the assessment of the fuel rod [5].

Leaking fuel assemblies are inspected during plant outage to identify and separate the leaking fuel rods because of preventing re-insertion and to help causal analyses. To prevent fuel failures during reactor operation, inspection methods are needed that can not only find failed fuel rods but also rapidly inspect the entire length of fuel rod for defects such as fretting wear, corrosion pits and cracks that may lead to fuel failure. The nondestructive post irradiation results are an indispensable tool not only for normal operational surveillance but also for fuel design qualification [5].

This paper contains a general desription of widespread nondestructive methods used as a post irradiation examination tool for power reactor fuels. The most widespread methods are the ultrasonic testing and the eddy current testing. Other methods mentioned in this paper are radiographic methods and acoustic methods.

Ultrasonics. In the framework of post irradiation examination, the ultrasonic testing is mostly used. This technique serves mainly for leaking fuel rods detecting and for the end plug weld control. This method detects the fuel cladding failure by sensing the presence of coolant between the cladding and the fuel and also the cross sectional variations of the fuel rod cladding can be measured accurately to know the wear characteristics of the cladding [6].

The ultrasonic method is aslo used for the bow and twist measurement of fuel assemblies. The technique is based on measurement of the distance between a side face of fuel assembly and the reference plate holding ultrasonic probe´s position. The fuel bow measurement corresponds to measure the fuel assembly profile and the offset between the top and bottom plate. The fuel twist measurement means to measure the torsion between the top and bottom plate. The measurement is carried out during the fuel assembly unload from the core to the spent fuel pool [7].

Other application of the ultrasonics is to monitor change in form of rod cluster control assemblies (RCCA). The method identifies the type of the cladding wear, determines the maximal wear depth and measures the rod cross size due to the swelling of the absorbing material [8].

In the cladding the waves of certain type are generated. At wave propagation in the cladding their decay occurs due to energy radiation into environment. If there is water under the cladding, the additional easing of waves occurs and reduction of the wave amplitude testifies that fuel element is leaky [8].

According to the way of wave generation in the cladding the ultrasonic methods can be divided into two classes. The first one is generation and detection of waves on the lateral surface of the cladding. At that thin probes with emitter and receiver of ultrasonic waves are inserted into the space between the fuel elements. The second method is generation and detection of waves on the fuel element top plug. The ultrasonic detector operated in a mode of radiation-reception is set on the plug. The wave is propagated along the fuel element cladding and detected by the same detector after reflection from the bottom plug. Sometimes a design does not allow to use methods where the thin probes with detectors are inserted into the space between the fuel elements in FA. In that case the monitoring is carried out from the side of the fuel element top plugs [8].

Laser ultrasonic technique is the other application of ultrasonics. This technique is used for the measurement of dispersion spectra of guided acoustic waves propagating in a fuel cladding. Hydride induced hydrogen embrittlement in cladding tubes is reported to be responsible for the tube´s degradation in mechanical properties while in reactor service. The degree of embrittlement is affected mainly by hydrogen concentration. And for the hydrogen concentration characterization, the laser ultrasound technique was applied. It offers advantages of remote and non-contact ultrasonic inspections and can be applied to the inspections in hostile or inaccessible environments. The laser's electromagnetic energy is partially absorbed by the surface and further converted to thermal expansion to generate ultrasonic waves [9].

Eddy current. This method is mostly used for measurements of oxide layer thickness on the outer surface of the cladding and other fuel cladding imperfections, such as cracks, wear of cladding, hydride formation and hardness of a cladding. Other use is for determination of a fuel core position and its properties for fuel elements of reactors VVER 440 and VVER 1000, the testing of a covering defects and detection of superficial defects [10]. The equipment usually consists of two differential coils through which the fuel rod is drawn. The signal output from the coil is displayed on the screen [5].

Pulsed eddy current method is used to detect microcracking, pellet-cladding interaction, to determine cladding thickness and to provide simultaneous data on rod diameter and rod bowing, including scratches, grooves, wear marks, adherent corrosion products, scuff marks, subsurface hydriding, etc. The operation principle of this method is similar to usual eddy current system. It consists basically of four major components. The first one is the electro-mechanical scanning fixture. After fuel rod operation the rod may be bowed or atherwise distorted. In order to keep the sensor coil-to-cladding distance constant, a servo-mechanism automatically positions the sensor coil laterally. The servo-mechanism uses two opposing linear variable differential transformers (LVTD) as a sensor. The LVTD also produces information on the rod diameter and extent of bowing. The fuel rod is scanned in the vertical position with the sensors being moved past the rod. The second component comprises the PEC sensors, the third one is electronics package and the fourth one, oscillograph, provides the readout of the data [11].

Radiographic testing. This method serves for inspecting materials for hidden flaws by using the ability of short wavelength electromagnetic radiation to penetrate various materials. As a source of photons, an X-ray machine or a radioactive source (Ir-192, Co-60, Cs-137) is be used. For X-rays generation, the betatron or linear accelerator can be applied

[12]. In the case of neutron radiographic testing that is a variant of radiographic testing, the neutron source is used. Neutron radiographics can see different things from X-rays method, because neutrons can pass easily through lead and steel but they are stopped by plastics, water and oils.

These methods are widely used for a testing of welded connections of stopper plugs in fuel elements, executed by a method of electron beam welding; for testing of separate units of equipment used by manufacture of fuel elements and the testing of fuel elements of research reactors too [10]. Other use is a measuring the spacings at the ends of fuel rods or a hydrogen concentration characterization, because the measuring of a degree of cladding embrittlement which is affected mainly by hydrogen concentration [9].

Radiographic inspection can serve as a secondary noncontact method of clad inspection too and may confirm allowable anomalies from the ultrasonic inspection [12].

Acoustic techniques. Acoustic emission differs from other nondestructive methods mainly in two recpects. First, the detected energy is released from within the test object rather than being supplied by the nondestructive method, as in ultrasonics or radiographic method. Second, the acoustic emission technique is capable to detect the dynamic processes associated with a degradation of structural integrity. Crack growth is one of the major sources of acoustic emission by virtue of its size.

Acoustic emission is defined as a transient elastic wave that is generated by the rapid release of energy within a material as a result of the application of external energy sources [13]. The acoustic emission source emits elastic waves into a material where the waves spread. When an acoustic emission wavefront encounters on the surface of a test object, negligible movements of the surface molecules occur. A sensor detects the mechanical movement and converts it into an electric signal.

Common mechanisms for the generation of acoustic emission activity include crack initiation, microcrack formation and crack propagation. Also this technique serves for closure welds monitoring. In one sense, acoustic emission techniques for nondestructive testing and evaluation are different from those usually associated with the field. The basis for most conventional nondestructive methods is interpretation of the interaction of a defect or discontinuity with some sort of energy (x-rays, ultrasonics, thermal energy, microwaves). In acoustic emission, the defect or discontinuity itself provides a source of energy, the release of which generates the acoustic emission. In this sense, the defect plays an active role in preference to the passive role it usually plays during the evaluation by conventional NDE methods [13].

A wide variety of micromechanical events are known to serve, or are suspected of serving, as acoustic emission sources. A partial list includes crack initiation and propagation, grain-boundary cracking, vacancy migration, etc. The sources of acoustic emission are associated with the micro- and macrostructural integrity of the material or component. Acoustic emission techniques can produce an immediate record of the progression of the part toward failure. The energy that is monitored in the acoustic emission test is generated internally in the test material; this is a unique feature of an acoustic emission monitoring [13].

NDE as a part of PIIP at Temelin NPP

The Czech NPP Temelin consists of two VVER 1000/V320 reactors and it started its operation in 2002. The reactor core consists of 163 fuel assemblies, each with 312 fuel rods, and 61 regulating rods. From the beginning, the fuel for the Temelin NPP was supplied by the Westinghouse Electric Company LLC. Since the first reload, VVantage-6 fuel assemblies with hexagonal shape were used (Fig. 2 a). However, nuclear fuel contract with Westinghouse company ended in 2010 (the last delivery) [14].

Due to large problems with fuel operation in 2003, the provider (CEZ) started a tender for new fuel supplier. After two years, the new supplier was nominated and the contract for the period 2010 - 2020 was signed in May 2006 with the Russian company TVEL. The first load of whole core was carried out in August 2010 at Unit 1 and in May 2011 at Unit 2 and the fuel assemblies TVSA-T are used since these reloads (Fig. 2 b). To avoid any fuel problems during future operation, large post irradiation inspection program was set as well. Therefore, during the unit outage several fuel assemblies will be chosen and inspected on the fuel repair and inspection equipment (FRIE).

During fuel reload all fuel assemblies are inspected by online sipping system. After the sipping system identifies the leaking fuel assembly, the assembly is installed in the FRIE equipment and the visual inspection is performed. The ultrasonic equipment serves to identify the leaking fuel rods to avoid fission product release into the primary coolant due to primary cladding failures because of debris or grid-to-rod fretting (Fig. 3), failures in the upper welds of fuel rods (Fig. 4) and a secondary hydridation (Fig. 5) due to primary cladding failure. The method is based on ultrasonic waves spreading in the fuel rod. A decrease of echo signal entails the presence of primary water in the inspected fuel rod.

In ten years of Temelin NPP operation, 63 leaking fuel assemblies at both units were found. The UT system from Westinghouse, previous fuel vendor, shows a high reliability in its operation, a practise proves a value around 97 %. Now, the new UT system [15] from the fuel vendor TVEL will be used during the fuel inspection at Unit 1 in August 2011.

Conclusion

Nondestructive methods are very widespread in many applications. One of them is fuel inspection, and in this field, many techniques are used, as ultrasonics, eddy current, radiographic testing and acoustic techniques. Besides these, other methods are in a procedure of development and waiting for future use. Interesting seems to be magnetostrictive guided wave technique and creep wave method based on good properties of spreading the wave through the thin part of a cladding surface.

The ultrasonic methods serve for the leaking fuel rods detecting, for the end plug weld control and also for the bow and twist measurement of fuel assemblies. Other application of the ultrasonics is to monitor change in form of rod cluster control assemblies.

Eddy current method is mostly used for measurements of oxide layer thickness on the outer surface of the cladding and other fuel cladding imperfections, such as cracks, wear of cladding, hydride formation and hardness of a cladding. Pulsed eddy current technique is used to detect microcracking, pellet-cladding interaction, to determine cladding thickness and to provide simultaneous data on rod diameter and rod bowing, including other small surface flaws. However, the radiographic method serves for inspecting materials for hidden flaws. There are two types of radiographics, the method based on photons and the method based on neutrons. They both give different results images.

Acoustic emission differs from other nondestructive methods, the detected energy is released from within the test object and it is capable to detect the dynamic processes associated with a degradation of structural integrity.

All these techniques are used in the framework of post irradiation inspection program at nuclear power plants. At Temelin NPP, the ultrasonic testing is used to identify the leaking fuel rods. Also the eddy current technique can be used for the oxide layer thickness measurement.

In the case of very widespread methods, there are still needs to develop new methods for confirming the results coming from existing methods, and for better examination because of increasing requirements on nuclear safety and reliability of nuclear power plants operation.

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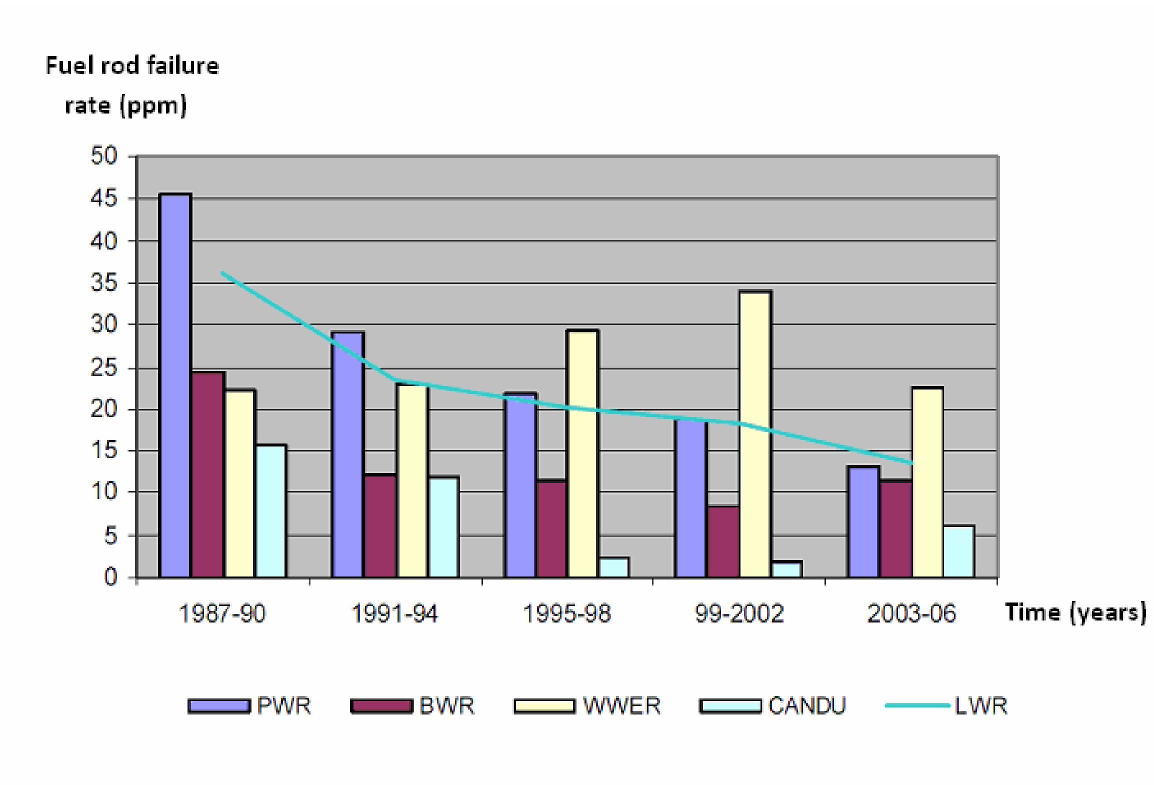
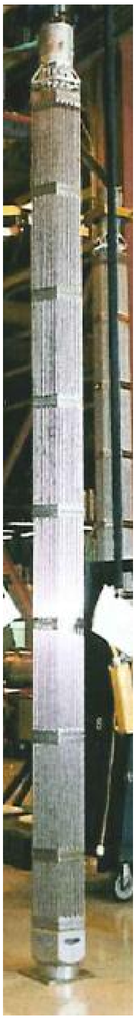
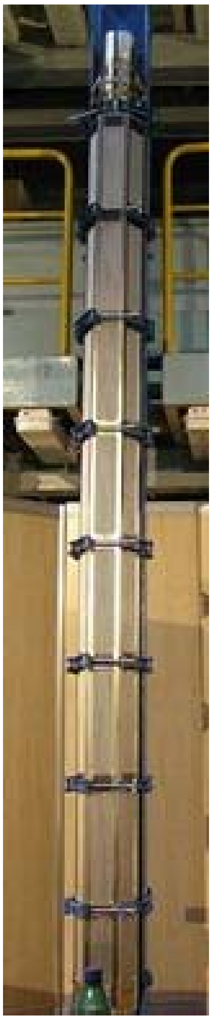


Fig. 1 Fuel failure rate according to IAEA [2]



a) VVANTAGE-6



b) TVSA-T

Fig. 2 Fuel assemblies used at Temelin NPP

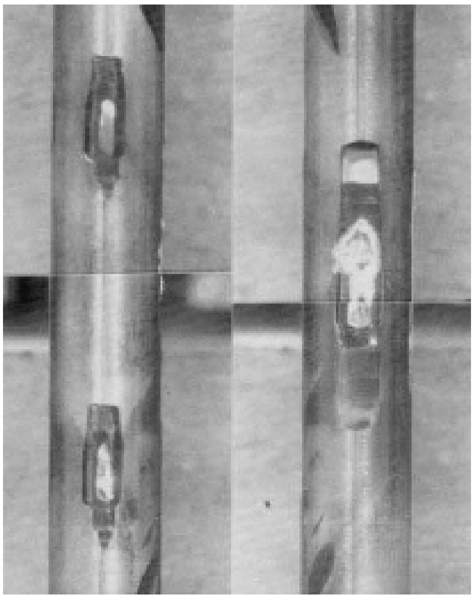


Fig. 3 Example of the fuel failure due to grid-to-rod fretting

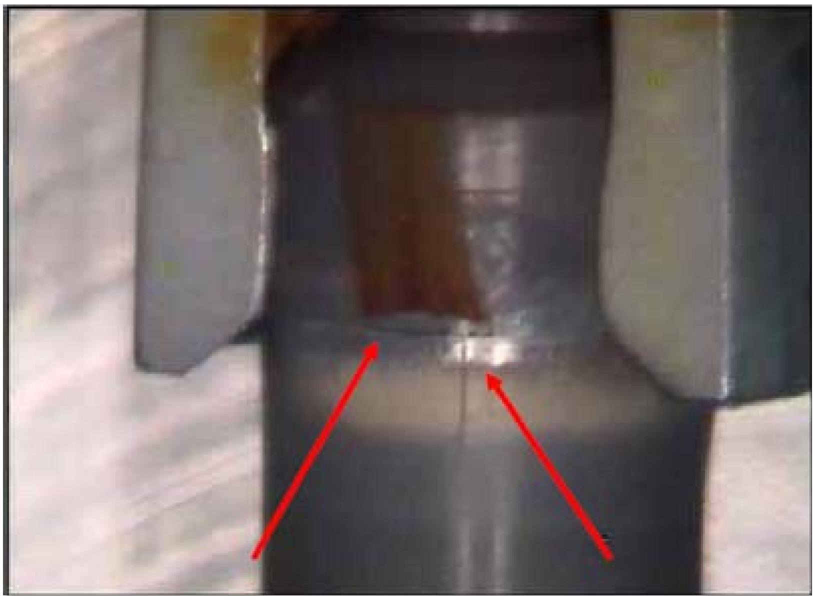


Fig. 4 An example of the upper weld leaker

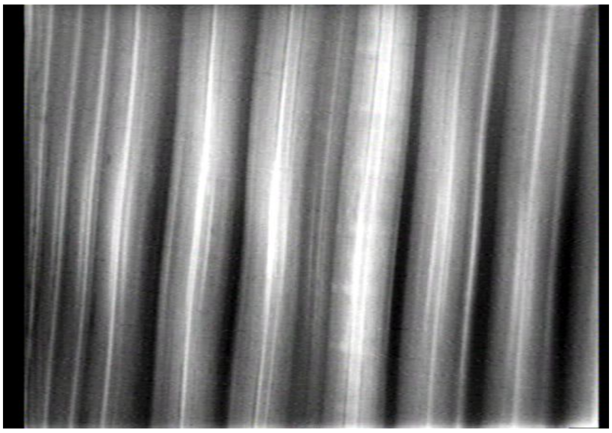


Fig. 5 An example of the secondary hydridation (bamboo effect)