The Role of CVR in the Fuel Inspection at Temelín NPP

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Abstract. Since first reload, NPP Temelín together with the fuel vendor (Westinghouse Electric Company LLC) is performing post irradiation inspection on the fuel assemblies as additional proof of PWR material compatibility in VVER water chemistry. However, after 10 years of successful operation the fuel vendor is changing and new plans for the fuel inspection are ready. Paper describes the past experiences with the fuel inspections and repairs at the NPP Temelín and the role of Research Centre Rez, Ltd. (CVR) in the cooperation with the new fuel vendor.In addition, Research Centre Rez Ltd. is a non-profit organization devoted to activities that require research reactors LR-0, LVR-15 and several experimental loops and devices. The Centre was founded in 2003 by the Czech Ministry of Education that fully endorsed a research proposal for all scientific and R&D activities. It is a unique institution providing a sophisticated infrastructure for research and development focused on advancement of analytical methods. The main purpose of the Research Reactors Division in CVR with aim of the fuel on-site post irradiation inspection and water chemistry research are also presented in paper.

1. INTRODUCTION

Reliability of nuclear fuel and radiation fields surrounding primary systems are important aspects of overall nuclear reactor safety. In recent years, the management of nuclear fuel operation has been faced with new challenges. The extension of nuclear reactor lifetimes beyond their initial design values, a higher level of fuel utilization (higher fuel burn-up, extension of fuel cycles, higher power), shortening of outages, etc. are present requirements in evolution of nuclear energy. Along with these requirements, other circumstances that impose increased demands on chemistry management are also taken into account. However, new changes and design modifications of fuel assemblies are still needed.

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 are showing high reliability and operational stability, the probability of their failure is not so low (Fig. 1.1, [1]). 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.

There are different types of fuel failures which are characteristic for all type of reactors like fretting (debris, grid-to-rod), pellet cladding interaction, hydration of fuel rod cladding, corrosion and CRUD at the fuel rod cladding, which can also lead to the problem with axial offset (AOA), failures during fuel handling, manufacturing defects (weld contamination), cross-flow/baffle jetting; as well as

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anomalies leading to deterioration in fuel operation like fuel assembly/rod bow, leading to the problems with incomplete rod insertion (IRI), fuel assembly twist, unexpected fuel assembly/rod elongation; and the combinations of all these fuel problems. However, only few of these problems are still occurred and these are the most dominant for:

- PWR/VVER: grid-to-rod/debris fretting,
- BWR: crud and corrosion.

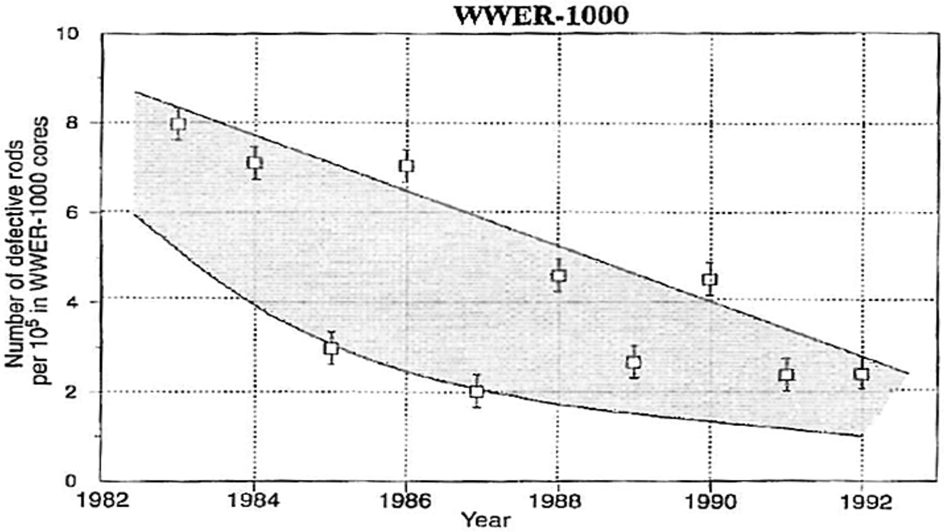


FIG. 1.1. The number of defective rods in VVER-1000 reactors in 1983–1992.

2. TEN YEARS OF TEMELÍN NPP

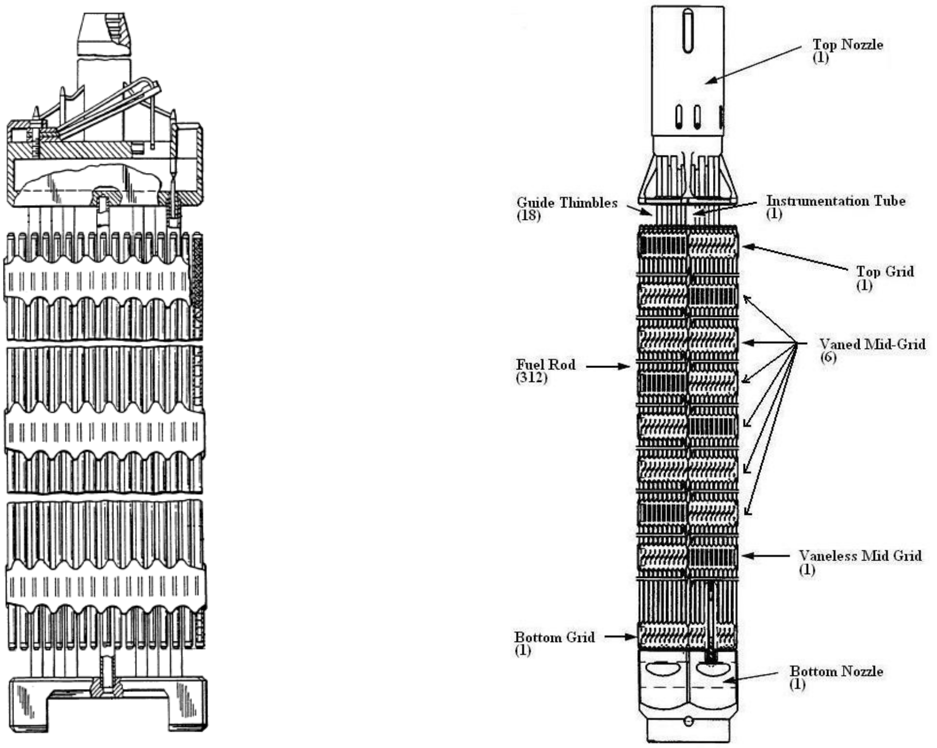
In December 2010 ten years have passed since the first unit of the Temelín NPP has been builded. Test operation of the first unit started June 10^{th} 2002, and the second unit started April 18^{th} 2003. The operation on 100% power started in the years 2002 to 2003. Temelín NPP finally allowed replacing obsolete and gradually shut units at the North Bohemian coal power plants. The total quantity of electric production made in the Temelín NPP since its start is 100 billion kWh. This would cover nearly seven years in consumption of all Czech households.

The Temelín nuclear power plant is situated about 24 km away from České Budějovice. Electricity is generated in two production units with VVER-1000 type V-320 pressurized water reactors. Technological scheme of the power plant corresponds to the latest world parameters. The reactor core contains 163 fuel assemblies, each with 312 fuel rods, and 61 regulating rods. Fuel rods are fuelled by UO_2, uranium dioxide enriched by an average of 3.5% of the fission isotope ^{235}U (maximum allowed enrichment is (4.95±0.05)%). Since the beginning, the fuel for the Temelín NPP is supplied by the Westinghouse Electric Company LLC, which also supplied the new instrumentation and control system.

NPP Temelín is operated on a modified water chemistry optimized for minimization of the level of transport activities and the reduction of radiation field creation via the creation and maintenance of constant chemical conditions in primary coolant. Optimal pH at 300°C is set at 7.1±0.1, initial concentration of alkali about 20 mg·kg^{-1}. Dosing of ammonia is used for hydrogen generation.

2.1 Fuel description

Since first reload in 2002 at unit 1 and 2003 at unit 2, fuel assemblies from American fuel vendor Westinghouse VVantage-6 are used (at unit 1 until August 2010, at unit 2 until May 2011, [2]). VVantage-6 design is Westinghouse pilot assembly with hexagonal shape, which became from the square design VVantage-5 (Fig. 2.1). Westinghouse fuel assemblies for PWR reactors have undergone significant evolutionary changes, from the early standard fuel assembly with Inconel spacer grids to the VVantage-5. VVantage-5 PWR fuel already included state-of-the-art features such as removable top nozzle (RTN), debris filter bottom nozzles, low-pressure-drop Zircaloy structural grids, Zircaloy intermediate flow mixing grids, optimized fuel rods, in-fuel burnable absorbers (IFBAs) and increased burn-up capability to region average values of 48 000 $MW \cdot d \cdot Mt^{-1}$ U. These advanced product features have been adapted for the VVER reactors in order to update VVER fuel and provide increased fuel reliability, more efficient uranium utilization, and enhanced performance margins, and the VVANTAGE-6 fuel assembly was designed.



a) b)

FIG. 2.1. Illustration of Westinghouse fuel assemblies, a) VVantage-5, b) VVantage-6.

2.2. Fuel operational experiences

Although the VVantage-6 as a pilot design of the fuel assembly for VVER-1000 promised successful operation, the late experience showed several problems with this design. Flexibility in the fuel designs (different types of enrichment) and in fuel batch design allowed to absorb important and dynamic changes in the cycle length, especially cycle shortening, mostly caused by unexpected fuel failures. In several cases the fuel failures was so high, that the cycle needed to be shut down with the unburned fuel. Due to these unexpected problems, very often during fuel reloading (when the number of leakers was found) redesign of whole core was needed. Although all of these problems, the effectiveness of ^{235}U utilization in individual cycles has gradually stabilized on the very favorable values fully comparable with other VVER-1000 reactors. Average BU of spent fuel loaded out of the core was approximately 37800 $MW \cdot d \cdot t^{-1}$ U. The maximum achieved average BU of fuel assembly was then around 44500 $MW \cdot d \cdot t^{-1}$ U.

2.3 Fuel failures at Temelín NPP

Mechanical deformation of fuel assemblies and rods, as bow and twist, growth, dynamic vibrations, etc. are already under consideration during fuel designing. However, some deformations are very unpredictable, especially the progress of deformations, and fuel failures and anomalies are occurred during unit operation. The situation at Temelín is similar, and several about mentioned fuel problems were occurred as well.

Some RCCAs (on both units) do not drop fully to the bottom position (incomplete rod insertion), which is quite large problem from the nuclear safety point of view. The worst case was at unit 1 in June 2007, where the test showed that two RCCAs stopped above the level of the hydraulic dashpot. In other words, they failed to meet the limit condition and caused unscheduled outage for refueling. Due to large post irradiation inspection program (PIIP) and very precise fuel inspections, the root cause was found – fuel assembly bow and twist [3].

Some fuel rods which were visually inspected had the *leaker in the upper weld connection* (mostly occurred at fuel assemblies, used in first several cycles). This type of defect was in that times quite common, and it was primary problem due to manufacturing of the fuel rods (incorrect weld between upper end-seal and the cladding tube). This type of fuel failure was occurred only several times at Temelín site, and was solved with manufacturing improvements.

Most common fuel failure for the Temelín unit 1 and 2 was and unfortunately still is, *grid-to-rod fretting* (Fig. 2.2, [3]). Grid-to-rod fretting failures are due to rod/assembly vibrations induced by turbulence and flow heterogeneities which are always present, particularly in the inlet range up through the bottom grid. Failure occurs if either turbulence is higher than anticipated in design, or fuel rod support in the spacer grid is not sufficient. This type of fuel failure is still present on the Temelín site. However, it was minimize due to several design changes of the fuel assembly. At US PWRs, this issue was also minimized due to grid design change (grid springs in 45 degree angle were change into vertical position).

FIG. 2.2. Grid-to-rod fretting failure on several fuel rods at Temelín site.

Even due to the leakers in the core, maximal total activities in the coolant through all cycles was in the range from 2.4–8.5 $MBq \cdot l^{-1}$, which is by 3 orders less than a limiting value for the emergency conditions 3700 $MBq \cdot l^{-1}$. Therefore, this activity is negligible from the nuclear safety point of view and there was no reason of any restricts changes and remedies for fuel operation from the site of Czech Nuclear Regulatory Body (SUJB).

2.4 Fuel inspections and repairs at Temelín NPP

Since first reload, fuel operator (CEZ) together with the fuel vendor (Westinghouse Electric Company LCC) is performing post irradiation inspection on the fuel assemblies with the use of fuel repair inspection equipment (FRIE). There were several reasons for using this equipment like additional proof of PWR materials compatibility in VVER water chemistry, analytical method support and verification, overall thermo mechanical performance demonstration, independent check of the fuel system in-core behavior, root causes examination of an eventual fuel rod and fuel assembly failure or unexpected deformation; and fuel assembly repair.

FRIE is mobile equipment, which means that it can be used at both units. This equipment is stored in several boxes in the fresh fuel storage during reactor operation, and during outage is transported to the reactor hall where is assembled and placed into the spent fuel pool next to the reactor. After the fuel assembly is placed into the FRIE, several procedures can be done:

- FA measurement (Visual inspection, bow and twist measurements, overall FA length measurements, peripheral FR corrosion inspection, grid cell geometry measurements),
- Single FR measurements (Visual inspection, corrosion measurements, profilometry measurements),
- RCCA inspections (The measurements of total wear of the tube cross section, the distribution of the wear around the circumference of the rodlet).

With use of these inspections, the root causes of fuel deformation and failures were identified and minimized by the changes in fuel assembly design. Since first startup four different types of fuel assemblies were used at Temelín site. The first-one called VVantage6 T1 design was the first prototype of VVantage6 fuel assembly for VVER-1000 reactors and was used only for the first batch at the unit 1. The second design VVantage6 T2 was used at both units till 2006 and according to T1 design only small changes in the fuel assembly design were made. The bigger changes were made in 2005–2006, where the VVantage6-Phase 0 and in 2007 VVantage-Phase 1X were designed. The main design changes were [3–4]:

- Tube-in-tube dashpot design and top nozzle modifications (Phase 0),
- Fuel rod loading equipment alignments,
- New structural materials of FR cladding and other FA components (Phase 1X).

After these design changes the problem with Incomplete Rod Insertion was solved, as well as the fuel assembly bow and twist and the grid-to-rod fretting was minimized on the as low as achievable level. The unit 1 is a proof of these successes, where no leakers were occurred during the last cycle with Westinghouse fuel.

2.5 New fuel for Temelín NPP

Unfortunately due to large problems with fuel operation at Temelín NPP in 2003, ČEZ started a tender (bid) for new fuel supplier and two main companies were involved – American Westinghouse Electric Company LLC and Russian TVEL. 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.

According to the contract between ČEZ and TVEL, the first load of whole core was in August 2010 at unit 1, and in May 2011 at unit 2. The fuel assemblies TVSA-T was designed and assembled by MSZ Elektrostal. The main differences between VVantage6 fuel assembly and TVSA-T fuel assembly are:

- different construction of the top nozzle (also removable, but under different processes),
- 6 corner plates (for better stiffness of whole assembly),
- different grids design (to minimize grid-to-rod fretting,),
- debris filter in the bottom nozzle (to avoid any debris fretting),
- main materials of the whole fuel assembly are E110 and E635,
- etc.

3. THE ROLE OF CVR

Research Centre Řež, Ltd. (CVR) is a non-profit organization and its activities are restricted only to fundamental research and development. The centre was established in 2003 for R&D in areas, where the research reactors and experimental devices can be used. The overviewed research program was supported by the Ministry of Education of the Czech Republic. The main activities are:

- Fundamental research in natural sciences using neutrons,
- R&D in nuclear energy related fields as corrosion processes, radiation induced damages in reactor construction materials, as well as in innovative neutron sources,
- R&D of radio-pharmaceuticals prepared by using nuclear reactors, design of new treatment procedures using neutrons.

CVR plays an important role in the Czech nuclear research market. Division of Research reactors besides the material irradiation and radioisotopes research is involved in the water chemistry research for PWR, BWR and VVER reactors and its impact on the crud deposition and fuel cladding reliability. For this purpose light water research reactor LVR-15 and several experimental loops are used.

The research reactor LVR-15 is a tank type and currently uses two types of fuel manufactured by the NZCHK Company in Novosibirsk with 36% (IRT-2M) and <20% enrichment (IRT-4M). The reactor's systems permit an output up to 10 MW. The reactor's design and active zone permit the usage of various diameters of irradiation channels and thus flexibility from the standpoint of optimal neutron usage in the core (Fig. 2.3).

Experimental loops are used to study the effect of environment on materials in the active zone of power reactors. Phenomena under study include corrosion, the influence of physical and radiation stresses on the rate of crack propagation, the interaction of fuel and coolant coverage, including cladding corrosion and the deposition of corrosion products on the surface of the fuel elements, further for the research of water chemistry of PWR, BWR and VVER reactors, including the development and testing of special measurement technology such as, for example ECP measurement. The main goal of the reactor's facilities is to model conditions that are as close as possible to real conditions, and thus secure the reproducibility and utilization of measured values.

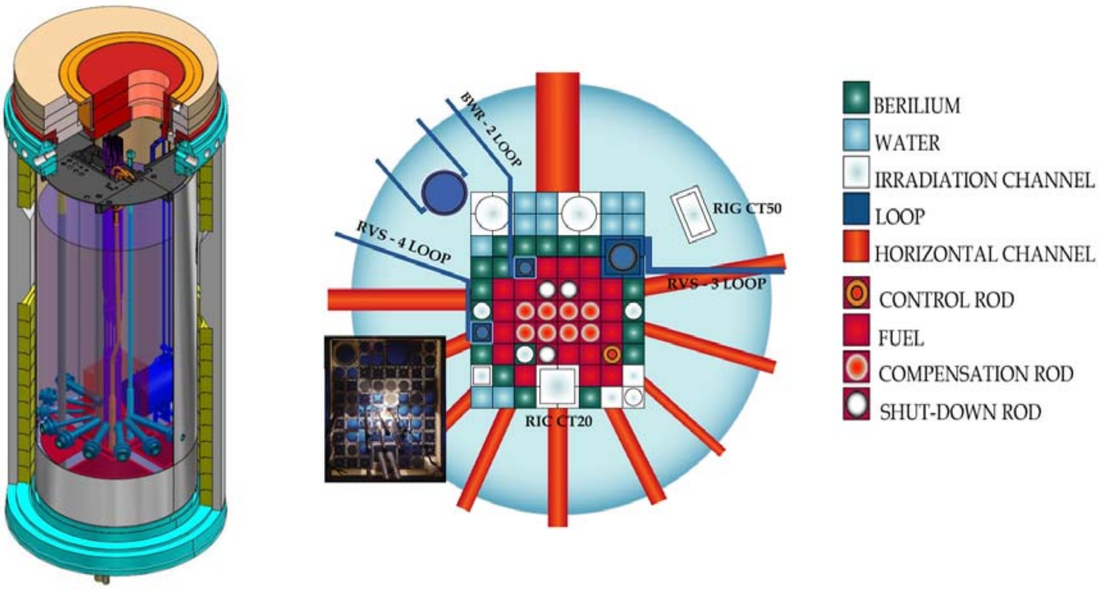


FIG.2.3. Research reactor LVR-15, loops and rings.

Besides, CVR together with NPP Temelín and Westinghouse Electric Company LLC is cooperating on the fuel inspection and repair since 2009. Due to the fuel vendor change at Temelín, new PIIP program will be implemented to avoid any fuel problems in the future operation. During the unit outage several fuel assemblies will be chosen and inspected on the fuel repair and inspection equipment (FRIE). The main operations, which were set up to present, with the fuel assemblies at FRIE are:

- Inspections
  - Visual inspection of fuel assemblies, extracted fuel rods, and RCCA,
  - ultrasound inspection (to detect leaking fuel rod).
- Measurements
  - Fuel assembly and rod bow and twist,
  - fuel assembly and rod length measurement (growth).
- Fuel assemblies repair.

All activities at FRIE will be covered by present fuel vendor – TVEL. However, CVR will participate on the fuel inspections and measurements to support the independent long term monitoring and evaluation of fuel behavior at Temelín NPP. These measurements will be used for the codes validation (for better understanding of fuel failure processes to make more realistic models) and as a main basis for the future experiments for fuel failure behavior study under normal and abnormal conditions.

4. CONCLUSIONS

NPP Temelín is a first VVER-1000 reactor, where the Russian reactor design meets the American fuel design. Since first load, VVantage-6 fuel assemblies from Westinghouse Electric Company LLC were used at both units. During past ten years, Temelín gets lot of operational experiences with Westinghouse fuel. Besides successful operation, several fuel problems were occurred too, like incomplete rod insertion due to strong bow and twist of the fuel assemblies and fission product release into the primary coolant due to primary cladding failures by grid-to-rod fretting. Since first startup of Temelín NPP, 63 leaking fuel assemblies at both units were found and 27 of them were repaired and successfully reused in next cycles.

PIIP was specified, and different inspections were done to get large amount of data from the bow, twist and growth measurement. In several years many data were measured, root causes were found and many recommendations for new fuel design were applied.

All these changes led to the successful operation with Westinghouse fuel assemblies. The problem with IRI, as well as the fuel assembly bow and twist was removed in 2005, and the leaking fuel due to grid-to-rod fretting was minimized. From 63 leaking fuel assemblies only 23 were repaired, however the effectiveness of the leaking fuel rod extraction from the fuel assembly is quite high, 93% [2]. From these fuel operational problems, the fuel vendor (ČEZ) as well as their subcontractors (NRI, CVR, ŠJS, etc.) made a big lesson and these experiences are now fully prepared to use on the new Russian fuel TVSA-T in fuel operation as well as fuel inspection and repair.

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