Identification and Analysis of Dominant Factors Affecting the Fuel Failure Rates in WWER-1000 Units in Czech Republic, Bulgaria, Ukraine and Russia

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Abstract

Recently, a “Driving to a zero failure rate” program has been initiated in Russia. It is aimed at gradual decrease of the fuel failure rates and tending to operation of WWER units with no fuel failures in the reactor core. A prerequisite to elaboration of adequate solutions for higher fuel reliability and avoiding of abnormal fuel operation is an analysis of available data on fuel failures in WWER units in Russia and abroad.

In order to prepare recommendations and guidelines concerning fuel reliability and lower rates of abnormal fuel operation, a study on WWER-1000 fuel was carried out. It involved the following issues:

- Systematization of data on fuel failures in WWER-1000 units in Czech Republic, Bulgaria, Ukraine and Russia over the period of 2003 to 2014. Analysis of dominant factors affecting the observed failure rates.
- Consolidation of available experience in application of inspection & repair facilities as well as consideration of the best practices in enhancement of fuel reliability in BWRs and PWRs.

The paper reviews the major findings of this study.

1. Introduction

An international “Zero Failure Rate (ZFR)” project has been initiated by TVEL Fuel Company for WWER-1000 community in 2012. Tree major attributes of a “failure” were defined in the frame of the project:

- mechanical damage to a fuel assembly (FA),
- assembly bow or twist,
- traditional rod failures with formation of through-wall defects in cladding (leaking fuel).

The ZFR project is aimed at elaboration and implementation of guidelines to achieve the lowest possible (in prospect – “zero”) failure rate in WWER-1000 units. The keystone to elaborate corrective actions lies in consolidation and analysis of available data on fuel failures in WWERs over the last 10-12 years.

Since 2003, the most contribution to overall number of fuel “failures” was due to leaking fuel rods. That is why significant efforts in the ZFR project are focused on identification and elimination of leak-related failure causes.

A list of 143 leaking FAs of different design was specified in the frame of the project. These leaking FAs were identified in WWER-1000 units in Czech Republic, Bulgaria, Ukraine and Russia over the period of 2003 through 2014.

In order to issue recommendations for decreasing the failure rate in WWER-1000 units a study has been performed involving systematization of available data on leaking fuel assemblies from the ZFR project list. The scope of this study is as follows.

Operation conditions and the level of fuel degradation were compared for the leaking FAs. Fuel degradation was assessed by different methods:

- post-irradiation examinations (PIE) in hot cells,
- poolside inspections by means of inspection & repair equipment,
- visual FA inspections in the mast of the refueling machine.

Degradation of leaking fuel rods is governed by hydrogen uptake in cladding. Hydrogen concentration in zirconium affects the risks of cladding rupture when the leaking fuel rod is forced out from the FA skeleton during repair actions. Criteria to avoid cladding rupture during repair of leaking FAs were elaborated on the basis of post-irradiation examinations [1]. These criteria were compared to the results of the test repair of one of the leaking FAs in the inspection facility at Kalinin NPP.

Available data on primary coolant activity during reactor operation were examined and radiological effect of fuel failures was evaluated for FAs of different design. An impact of recent innovations

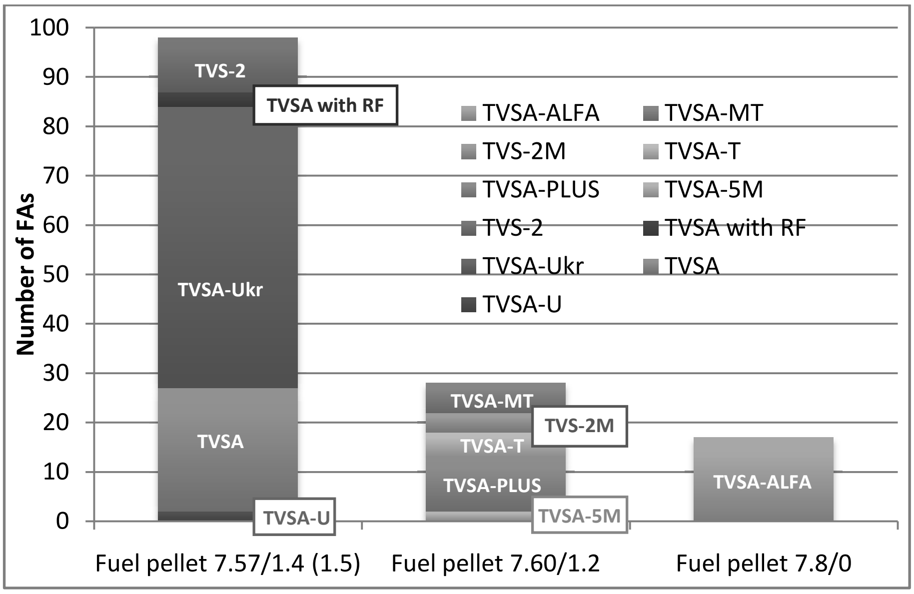

Figure 1. Fuel pellet form factor in different FA modifications

in fuel design on activity levels after a failure was trended.

In addition, occurrence of fuel failures was correlated to changes in reactor power. It was estimated if the risk of a failure was higher under steady state operation or during power transients.

Statistics on failure rates was reviewed for WWER-1000 units in Czech Republic, Bulgaria, Ukraine and Russia in years 2003 through 2014. Dominant factors affecting the observed failure rates were estimated.

A separate study in the frame of the ZFR project was devoted to consolidation of international experience in fuel poolside inspections and application of inspection & repair facilities. The best practices and fuel reliability programs aimed at “zero” failure rates for BWR and PWR fuel were reviewed as well. Adaptability of these best practices to WWER-1000 fuel was assessed.

Major findings of the present study are summarized below.

2. Characteristics of Leaking FAs

Fuel assemblies of different design are included into the list of the ZFR project. In total 9 modifications of TVSA and 2 modifications of TVS-2 are considered. Fuel rods in these FA modifications are equipped with fuel pellets of one of the three standard form factors: 7.57/1.4[1], 7.6/1.2 or 7.8/0 mm (see Fig. 1).

The first step in the present study was a development of a database specifying operation conditions for 131 FAs from the list of the ZFR project[2]. The database comprises information on reactor power history, primary coolant activity, operation regime of the letdown purification system, FA power history. Results of the leakage tests during reactor outages were also included into the database.

Many operation characteristics are related to a fuel campaign, not to a particular FA. For example, it is reactor power variations, evolution of coolant activity in primary circuit, changes in letdown system performance. It is possible that fuel rods may fail in several FAs during one fuel cycle. Hence, the number of fuel campaigns to be analyzed in the frame of the ZFR project is less than the number of the leaking FAs. Operation data for 131 leaking FAs correspond to 62 fuel campaigns.

Fig. 2 shows the number of fuel campaigns with different amount of leaking FAs identified after the reactor shutdown.

3. Failure Rates for Fuel of Different Design

Trends in fuel reliability may be characterized by various parameters. Most frequently, the ‘fuel failure rate’ is calculated. Other worldwide indicators to trend fuel reliability are derived from evolution of primary coolant activity or from the number of failure-free reactors [2].

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[1] Outer pellet diameter/inner pellet diameter. Form factor 7.8/0 mm implies solid fuel pellets.

[2] Systematic data on operation conditions for 12 of 143 FAs were absent at the time of this study.

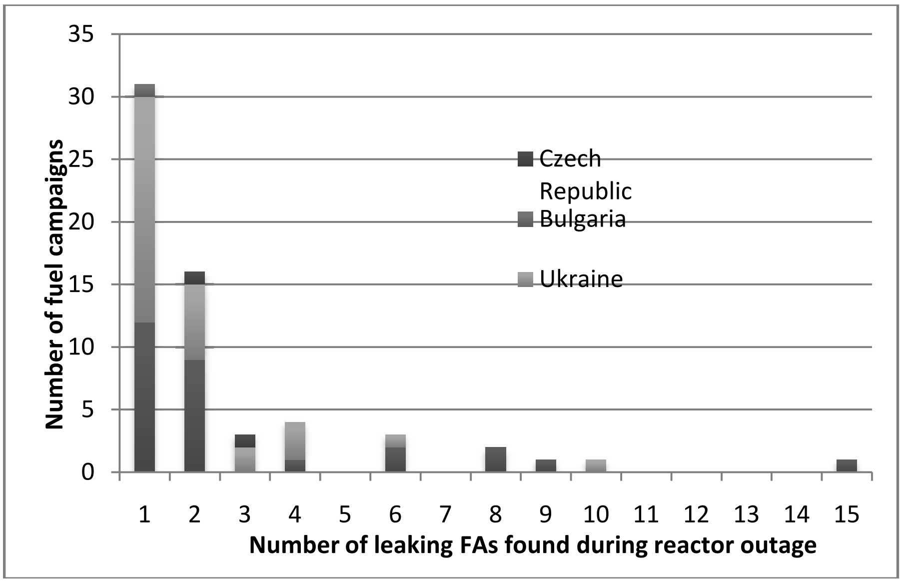

Figure 2. Statistics on fuel campaigns with different number of leaking fuel assemblies found in the core during the refueling outage

The ‘failure rate’ may be calculated by different methods. The most popular approach is to estimate the ‘rod failure rate’. It is found (with some nuances) as a ratio of the number of leaking rods to the overall number of fuel rods in FAs discharged from the selected group of power units. However, hot cell examinations or detailed poolside inspections to determine the exact number of defective fuel rods in the leaking FA are carried out far from always. So, some average number of leaking fuel rods per leaking assembly is used in calculations[3]. In the IAEA review [2] it is noted that the rod-based failure rate may lead to inconsistencies when different authors report the same data. According to the IAEA recommendations, the better way to trend fuel reliability is to monitor the number of leaking fuel assemblies. As far as the leaking fuel is repaired occasionally it is the number of leaking FAs that properly indicates the cost of fuel failures and associated financial losses.

In time period of 2003 to 2014 advanced types of fuel assemblies were widely introduced in WWER-1000 units. Many power units were operated with mixed reactor cores. Fuel batches discharged after different campaigns sometimes were composed of different FA types in varying proportions. At the moment, systematic information on composition of unloaded fuel batches in WWER-1000 units in Russia, Ukraine, Bulgaria and Czech Republic is not available. However, there are data on chronology of fresh fuel loadings for FAs of different type. These data were used in the present study to derive the fuel reliability indicator (the failure rate). It was calculated as the ratio of the number of leaking FAs to the total number of loaded fuel assemblies of a particular design.

Evaluations of the failure rates for different fuel types are summarized in Fig.3. Statistics shows that reliability of TVSA series seems to be somewhat lower than that for modifications of TVS-2. Nevertheless, the failure rate for TVSA and TVS-2 produced by the same manufacturer (NCCP) is similar.

Fig.4 demonstrates the expanded statistics for the failure rates with taking into account FA modification, fuel pellet form factor, manufacturer and country where the fuel was put into operation.

Fig.4 does not show data on pilot TVSA-U as well as on TVSA-MT and TVSA-ALFA with the “plain” rim of the spacer grid. These FA designs featured high failure rates.

TVSA-U was the only fuel type for WWER-1000 units to suffer from grid-to-rod fretting. The problem occurred when anti-vibration grids were implemented for the first time. The root causes were eliminated promptly and fuel failures due to grid-to-rod fretting have never been revealed in WWER-1000 units afterwards.

The first batches[4] of TVSA-MT and TVSA-ALFA incorporated spacer grids with the “plain” rim. With burnup these rims experienced noticeable deformation. Sometimes it led to FA damage during reloading operations in the core. Fragments of spacer grids contributed to debris in the primary circuit. Since 2010, spacer grids for these FA types started to be fabricated with the so-called “kremlin

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[3] E.g., for PWRs this average value in 1994-2006 varied from 1.3 to 1.6 [2].

[4] TVSA-MT and TVSA-ALFA were used only in Kalinin-1.

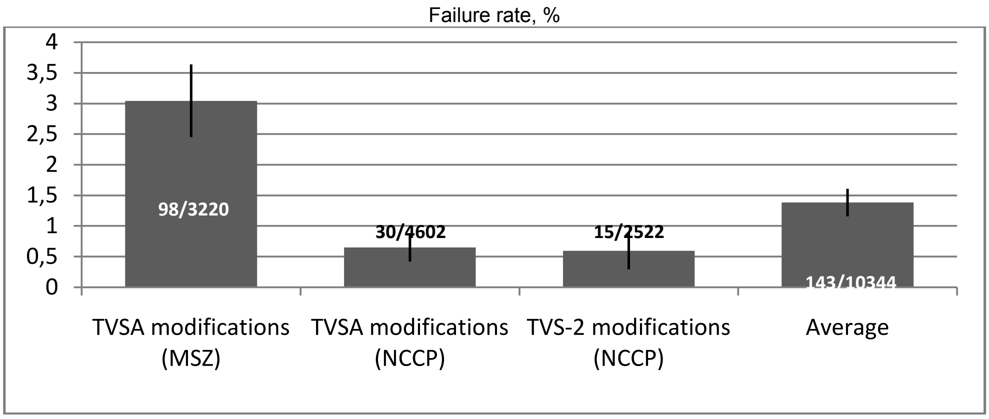

Figure 3. Consolidated data on the failure rates for TVSA and TVS-2 modifications (slash mark separates the number of leaking FAs and the total number of loaded FAs). Vertical dark lines represent the data uncertainty

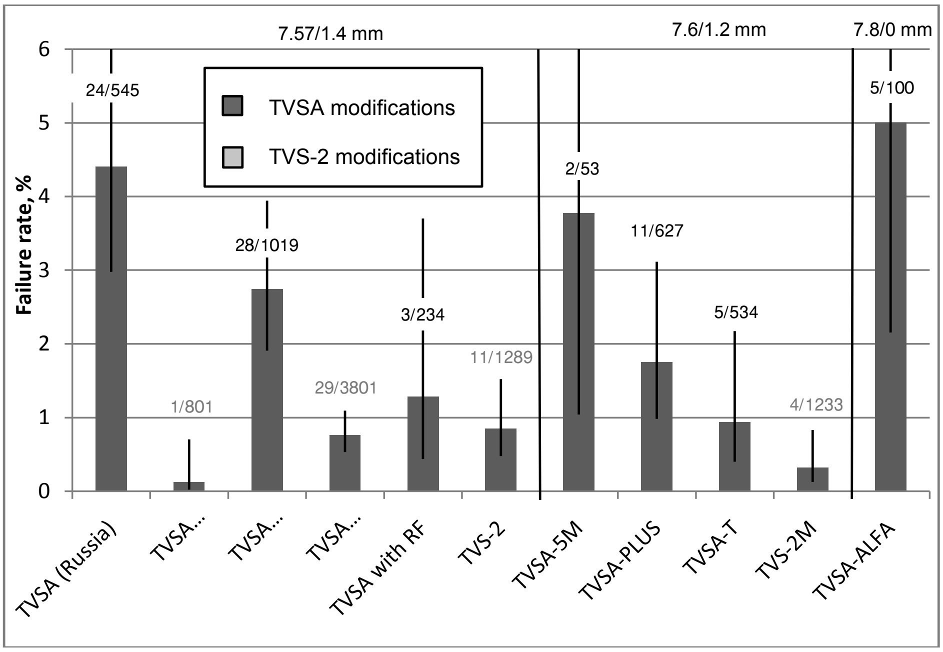

Figure 4. The failure rates for FAs of different design (slash mark separates the number of leaking FAs and the total number of loaded FAs). The light color indicates the fuel manufactured by NCCP

wall” rim. TVSA-MT and TVSA-ALFA with “plain” rim spacer grids were gradually discharged. Finally, the failure rate diminished significantly.

In particular, Fig.4 demonstrates that FAs of similar design may show different failure rates even though they are equipped with fuel rods of the same type and are produced by the same manufacturer. It can be also seen that the same fuel design may exhibit rather different reliability in power units of different countries (e.g., see data on TVSA).

Worth noting is that FAs with both the highest and the lowest failure rates (see Fig.4) were equipped with coarse-grain fuel pellets (grain size no less than 25 μm). Consequently, one may conclude that coarse-grain pellets are not the governing factor from the viewpoint of a failure.

4. Radiological Effects of Fuel Failures

Available data on primary coolant activity during reactor operation were examined for fuel campaigns relevant to the ZFR project. This study was aimed at evaluation of radiological effect of fuel failures for FAs of different design. Evaluations were made on the basis of the WANO fuel reliability indicator (FRI) [2,3].

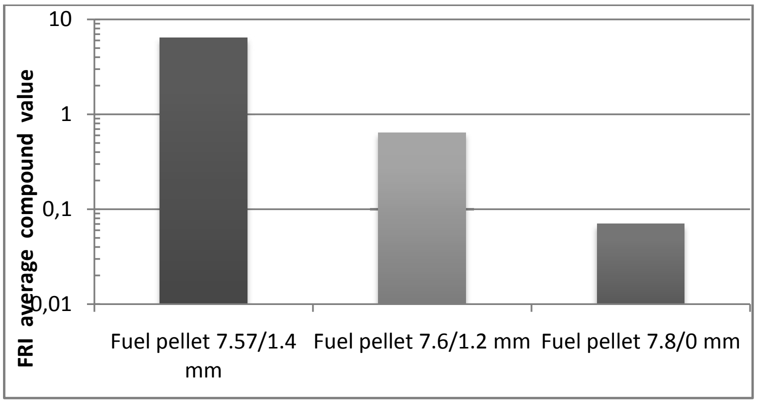

Figure 5. Average values of the FRI(^{131}I) indicator (μCu/kg) as a function of fuel pellet form factor

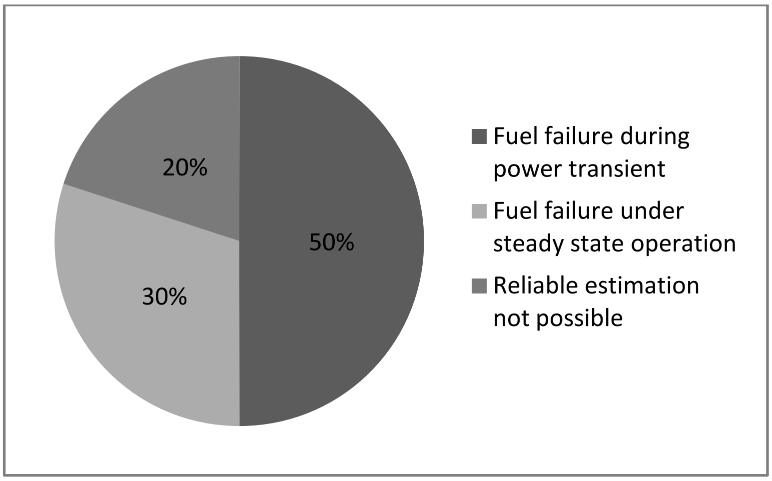

Figure 6. Reactor operation regime at the moment of fuel failure (by data on 40 fuel campaigns in 2003-2014)

Primary coolant activity after a failure depends on fuel rod design. Handling of the NPP data showed (Fig.5) that average activity levels for advanced fuel with 7.6/1.2 mm pellets were lower in comparison with the traditional fuel (7.57/1.4 mm pellets). In case of fuel pellets of the 7.8/0 form factor, fuel failures led to the least average activity levels. These trends are mainly due to peculiarities in fission product release from coarse-grained fuel and to diverse conditions of mass transfer inside leaking fuel rods of different design.

The above conclusions are valid both for iodine and noble gas activity.

5. Power Transients and Failure Risks

In addition, the data on primary coolant activity was used to correlate occurrence of fuel failures to changes in reactor power (Fig.6). It was estimated if the risk of a failure was higher under steady state operation or during load follows.

The study showed that in the most cases fuel failures occurred during power transients. However, load follow is not the root cause of a failure. In combination with power transient there must be some extraneous negative factors which can lead to a breach in cladding. Such negative factors may be related to, e.g., disturbances in the primary circuit during the transients. These ‘disturbances’ may contribute to relocation of foreign material with coolant flow. Impact of foreign material on fuel cladding may be aggravated due to this ‘disturbances’ as well (for instance, because of more intensive vibration of fuel rods).

If extraneous negative factors are absent, fuel behavior was demonstrated to be normal both under steady state reactor operation and during power transients.

6. Degradation of Leaking Fuel During Operation

Degradation of leaking fuel rods and state of FA elements at the end of operation was analyzed on the basis of the following data (Fig.7):

- post-irradiation examinations of leaking fuel in RIAR hot cells,
- examinations and measurements for leaking FAs made in inspection & repair facilities at Kalinin and Temelin NPPs,
- visual inspections of leaking FAs in the mast of the refueling machine.

6.1. Major Findings of Post-Irradiation Examinations

The most comprehensive information on degradation of leaking fuel is provided by post-irradiation examinations in hot cells. Up to the present moment, only 5 leaking FAs from the ZFR project list have been examined in RIAR. The failure cause

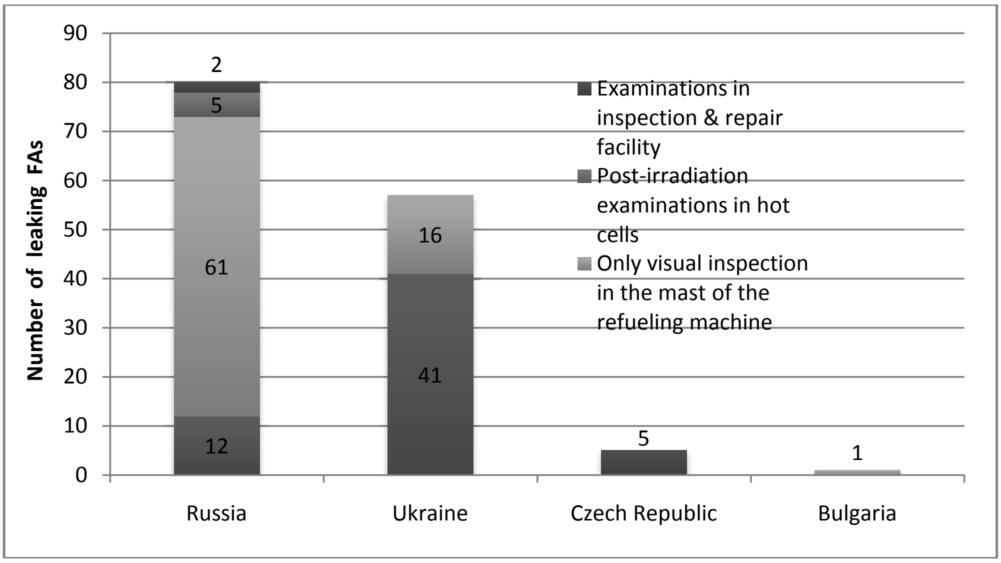

Figure 7. Scope of leaking fuel inspections in different countries (for FAs from the list of the ZFR project)

was identified for all of the examined leaking fuel. In 4 from 5 cases the failures took place because of debris-fretting owing to ingress of foreign material into primary circuit. Only in one case (for the pilot TVSA-U) the failure was due to grid-to-rod fretting in the area of anti-vibration grid (see section 2).

A single defective fuel rod was identified in each leaking FA. Massive hydriding led to secondary cladding degradation in all the leaking rods. Fuel rods failed during their 1st cycle (when operated at elevated power) exhibited through-wall secondary defects below the upper end of fuel stack. In the area of plenum, sunburst hydrides formed in cladding along the contact line with the spring lock in the fuel rod. In fuel rods failed during their last cycle of operation, secondary cladding degradation took place only in the plenum area. No through-wall cracks were observed here.

Defective fuel rods in leaking FAs after the 1st year of operation were up to ~ 2 mm shorter than the neighboring intact fuel rods. In leaking FAs of high burnup, no difference in elongation between defective and intact rods was detected (within the accuracy of measurements).

No abnormalities in the FA state which could promote fuel failure were observed during the PIE of leaking fuel in RIAR (the only exception was the pilot TVSA-U).

6.2. Poolside Examinations of Leaking Fuel Using Inspection & Repair Facilities

Up to the present moment, only 7 leaking FAs from the ZFR project list have been examined in inspection & repair facilities. In none of the cases the failure cause was identified definitely. Only in 2 of 7 cases foreign material was found in the leaking FAs in course of visual inspections by facility cameras. It is an implicit indication of debris-fretting as the root cause of the failure. No one of defective fuel rods was extracted from the leaking FA. Hence, the state of leaking fuel rods was estimated visually only when the leakers were at the FA periphery.

Ultrasonic test (UT) to identify the leaking fuel rod was conducted only for 3 of 7 examined FAs. In all these cases a single defective fuel rod was found by the UT technique in each leaking assembly. Traces of secondary degradation were observed for each of the visually inspected leaking fuel rods. Visual inspections gave no answer whether the secondary defects were through-wall or not.

At present time, the ultrasonic test to identify the leakers is the only proven technique which makes inspection & repair facilities for WWER-1000 fuel more informative than visual inspections in the mast of the refueling machine. When the exact number of the leaking fuel rods is found in each leaking FA, it is helpful to determine failure causes. Moreover, it is important for correct failure analysis during reactor operation. In particular, it makes identification of the moment of the failure more accurate (for instance, it is possible to distinguish between the primary and the secondary failure). Given the moment of the failure occurrence, the time of operation of leaking fuel at power becomes known. These data are important to estimate the risks of cladding rupture during repair actions when the defective fuel rod is forced out from the FA skeleton (see section 5.4)

6.3. Visual Inspections of Leaking Fuel

Visual inspections in the mast of the refueling machine were carried out for 90 leaking FAs from the ZFR project list. In more than half the instances no signs of abnormal fuel state or behavior were observed. Even if some untypical features were revealed, in most cases they obviously had no relation to fuel failure causes. Defective fuel rods were identified by visual images in small fraction of leaking FAs.

The failure cause was not determined definitely for any FA inspected in the mast of the refueling machine. Foreign material was found in ~ 15% FAs. Detection of foreign material is just an indirect indication of debris-fretting as the possible failure cause. Capturing of debris in fuel assembly does not always produce a leak. So, detection of debris in fuel assembly without regard to identification of the leaking fuel rod and the primary defect in cladding may hide the actual cause of the failure.

Commonly, video cameras used in the mast of the refueling machine have insufficient resolution and poor magnification/zoom. Sometimes it leads to ambiguous interpretations of peculiarities observed in the images. For example, a piece of debris can look like a surface flaw in cladding and vice versa. Moreover, the area for observations may be limited due to design features of the mast. That is why it is more reasonable to examine fuel in inspection facilities with better cameras (e.g., several cameras simultaneously) and applying ultrasonic leak testing.

6.4. Effect of Operation Conditions on Degradation of Leaking Fuel

Degradation of cladding properties after a failure is mainly due to intensive hydrogen uptake and secondary hydriding. High hydrogen content in cladding of the defective fuel rod may lead to its rupture under excessive mechanical load (including activities during repair of a leaking FA). The highest risks of the cladding rupture are in the areas of secondary degradation. Such areas were revealed for most of the examined defective fuel rods.

Data on destruction of defective fuel rods in hot cells (during their extraction from the FA skeleton or during transport operations) show that formation of secondary hydride blisters in cladding is not a sufficient condition for its rupture under mechanical load. The risks of cladding rupture depend on the angular size of the hydrided area (visible hydride spot on fuel rod surface). Limitations on the size of hydride spots might be used as one of the criteria for safe extraction of leaking fuel rods from fuel assembly. But such criteria hardly would be applicable in practice. As a matter of fact, it is visual inspection that is the only way to estimate the angular size of hydride spots in cladding at present time. Capabilities of visual inspections are limited even for peripheral fuel rods. Other fuel rods cannot be visually inspected prior to extraction. Bearing this in mind, a conservative criterion was proposed to assure extraction of leaking fuel rods without cladding rupture [1][5]. Formation of secondary hydride blisters is not allowed in cladding according this conservative approach. Additional condition for successful removal of the leaking fuel rod is related to limitations on hydrogen uptake by cladding. These criteria are expressed in terms of 3 parameters:

- linear heat generation rate in the leaking fuel rod,
- time of operation at power after the failure has occurred,
- fuel burnup.

Differences in elongation between leaking and neighboring intact fuel rods may be also taken into account to narrow uncertainties of the risk assessment. Elongation of fuel rods may be measured in inspection & repair facilities.

The criteria [1] were compared to the results of the test repair of one of the leaking FAs at Kalinin NPP. It was a retrospective analysis and was performed several months after the test repair took place. Defective fuel rod was found at the FA periphery. Estimations based on the operation history showed that there was high risk of cladding rupture during extraction of the defective fuel rod. This statement agreed with the test results. After the leaking fuel rod was displaced from its initial position, a crack was observed in the hydride-like spot on cladding surface. This crack was absent in images of the primary visual inspection. After the crack initiation was detected, the test repair activities were terminated.

7. Good Practices Inferred from BWR/PWR Fuel Reliability Programs

The best known international programs with a comprehensive and systematic approach to enhancement of fuel reliability are “Zero by 10” and “Driving to zero” initiatives [4]. One of the key elements of success in these programs lied in coordinated efforts by different industry organizations: fuel ven-

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[5] The repair criteria [1] were elaborated in TRINITI Research Center under financial support by TVEL Fuel Company.

dors (including engineering and fuel manufacture companies), nuclear operators and utilities with wide involvement of research institutes.

An important issue realized in the “zero failure” programs was ‘as quick as possible’ identification and addressing fuel and operation-related problems.

General fuel failure mechanisms are known for more than 25 years [2]. A starting point for elaboration of activities aimed at elimination of fuel failures was clear identification of failure causes and mechanisms for particular fuel types in particular operating units. That made possible the transition from ‘general understanding’ to guidance. The cornerstone in revealing the actual failure mechanisms and failure margins was increased number of inspections for both leaking and healthy fuel. The next step was to develop fuel reliability guidelines for the key failure mechanisms with directives and recommendations how to avoid or mitigate the corresponding fuel failures.

Another focus in analysis of international fuel reliability programs was made on available experience in application of inspection & repair facilities in PWR and BWR units in the US, France, Switzerland, Korea and Japan. In most PWR and BWR utilities the spent fuel pool is separated from the reactor containment building. With such an arrangement, fuel inspections and repair activities may be carried out in course of reactor operation. In this case fuel inspections do not affect the duration of a refueling outage. Nevertheless, significant amount of inspections in PWRs/BWRs is performed for fuel intended for reload into the core for the next fuel cycle. So, most developers of inspection facilities try to minimize the time necessary to install and dismantle the equipment and to inspect or repair a fuel assembly. This fact clears the way to adopt the best PWR & BWR fuel inspection practices to WWER fuel.

The common worldwide practice is that it is responsibility of a fuel company to provide and arrange the most part of equipment and activities needed for fuel inspections and repair. Fuel companies finance the development of necessary devices and facilities. In many cases fuel companies also provide experts and personnel who come to nuclear utilities and carry out fuel inspections and/or repair.

A good practice for quick identification and perception of fuel and operation-related problems (besides increased number of fuel inspections) was a launch of the industry database (FRED) on fuel reliability and fuel failures. To quickly address the arising problems it happened to be effective to form teams of experts (involving staff of research organizations) in order to provide a continuous monitoring of fuel operation and immediate analysis for all the encountered failure cases.

At present time debris-fretting is the only failure mechanism which is definitely confirmed for WWER-1000 fuel. So, the primary efforts should be focused on study and adaptation of international experience in the area of foreign material (FM) exclusion from reactor systems and prevention of FM-related failures. The key points in eliminating the risks of FM intrusion into the primary circuit are as follows.

- Nuclear utilities should not be alone in addressing the problem of debris-fretting. A defense-in-depth approach is required. It is to cover activities at nuclear power plants as well as new standards for fuel, material and service providers that preclude the introduction of foreign material into reactor components and systems.
- Besides precluding the intrusion of foreign material, additional programs are needed that systematically search for and remove existing debris from plant systems.
- Foreign material exclusion programs should be revised on a regular basis to be tuned to the current situation in the particular nuclear unit and over the industry.
- Nuclear utilities should more readily introduce advanced and more robust fuel types with enhanced resistance to debris-fretting.
- Fuel suppliers should continue development and improvement of debris filters and debris-fretting resistant designs for their fuel products. These improvements are possible in the following domains:
    - Development of advanced debris filters is needed (debris filters of the third generation are introduced in PWRs and BWRs and engineering efforts in this area do not stop).
    - Debris filters never provide a 100% filtration of foreign material and small pieces of debris penetrate into fuel assemblies. It turned out to be effective to optimize the spacer grid design so that small debris penetrated through the filter would not be trapped in a FA and would be carried away with coolant flow.
    - Standardized techniques are under development for PWRs/BWRs for testing debris-filtering capabilities of fuel of different design, including all types of variable-sized

debris and hydraulic conditions.
    - Additional measures are possible such as application of longer lower end plugs and pre-oxidation of lower part of fuel rods to enhance hardness of the outer cladding layers.
- To elaborate corrective measures for plants with chronic debris failures it is reasonable to perform separate studies of the particular reactor components and systems.

8. Conclusions

The paper reviews the major findings of the study in the frame of the “Zero Failure Rate” project for WWERs. The study included analysis and systematization of available data on leaking fuel assemblies found in 2003 through 2014 in WWER-1000 nuclear units in Russia, Ukraine, Czech Republic and Bulgaria. The study was intended to be used in preparation of recommendations and elaboration of corrective measures for enhancement of reliability and decrease of the failure rates for the WWER-1000 fuel.

One of the key areas in successful implementation of the industry ‘zero failure’ goal is a challenge of significant increase of inspections of WWER-1000 fuel assemblies. It may be reasonable (with account taken for international experience) to think of development of more effective equipment for prompt fuel inspections & repair in WWER-1000 spent fuel pool. Another challenge is the elaboration of unified fuel inspection guidelines to ensure that limited industry resources are spent in the most productive way. In the frame of this work it may be helpful to implement in practice the criteria for safe removal of defective fuel rods from the leaking FA under repair.

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