Research loops for the water chemistry, corrosion and crud depositing after deco

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Introduction

Water chemistry plays an important role in the operation of nuclear reactors, especially from the standpoint of ensuring reliable operation. Extensive experience exists in the area of water chemistries and the behaviour of crud in the primary circuit, gained from the operation of water-cooled (PWR and BWR) reactors. In recent years, the management of water chemistries has been faced with new challenges that issued from two basic requirements. The first is the extension of nuclear reactor lifetimes beyond their initial design values. The second requirement consists of efforts to achieve a higher level of fuel utilization, primarily through higher fuel burn-up, extension of fuel cycles and load changes. Along with these two main requirements, other circumstances that impose increased demands on chemistry management are also taken into account. Among these are, for example, new changes and design modifications of fuel elements, including grids. The stated requirements increase the need of address certain technical issues to which so much attention was not paid before. Efforts to increase lifetime and efforts to increase fuel burn-up utilization are faced with real technical problems with facilities and components such as facility aging, fuel cladding corrosion, crud deposition and fuel fretting, the transport of activated crud from the active zone to other parts of the primary circuit, and the subsequent need for frequent decontamination.

Reliability of nuclear fuel and radiation fields surrounding primary systems are important aspects of overall nuclear reactor safety. Therefore, a study of causes of fuel leakage is still needed. Crud deposition is currently one of the key industry issues and has been implicated in several recent cases of crud-related fuel failures and core plugging. Activated crud is deposited on out-of-core surfaces, mainly steam generators tubes, resulting in high radiation fields and high doses of plant staff. Due to radiation build-up in primary circuit systems, decontamination of primary systems components and steam generators is used. Several issues involving decontamination were observed in some cases. After decontamination higher corrosion product release occurs, followed by subsequent crud deposition on fuel surfaces.

1. The research reactor LVR15

The LVR-15 research reactor is located in Řež, near Prague, at the Nuclear Research Institute (NRI). The reactor was commissioned in 1957; since then it has undergone reconstruction twice, where the last reconstruction took place in 1989, when all reactor components and systems were replaced, including the vessel. The reactor’s architecture was created by Russian organizations, and the last reconstruction was performed by the SKODA Company. The LVR-15 reactor is a tank type and currently uses fuel manufactured by the NZCHK Company in Novosibirsk with 36% enrichment (IRT-2M fuel type). The reactor’s systems permit an output up to 18 MW from the standpoint of cooling capacity; due to the fuel type used the output is limited to 10 MW. The thermal neutron flux reached is $1.5 \times 10^{18} \text{n/m}^2\text{s}$ and
the fast neutron flux is $2.5 \times 10^{18}$ n/m²s. Due to the nature of its usage, the reactor’s duty cycle is 21 days, with the number of cycles being 8-10 per year.

![Fig. 1: Research reactor LVR-15, loops and rings](image)

The reactor’s design and active zones permit the usage of various diameters of irradiation channels and thus flexibility from the standpoint of optimal neutron usage in the zone (Fig. 1). The water level height above the active zone is 4 m, which permits the location of the top part of irradiation channels above this surface and thus also good installation and manipulation access. For materials research, when long environmental sample exposures are necessary, the loops are operated and maintained within parameters even during reactor shutdown and nuclear fuel replacement. During shutdown, a maximum of 1-2 elements are replaced, and this operation can be performed with several days. Sample exposure times in loops can thus reach – and this actually happens – up to ca. 5000 hours, which represents a half-year of uninterrupted loop operation.

## 2. Research loops

Reactor water 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 loops construction permits the attainment of high flow velocities (>1 m/s, Reynolds number 104), which is necessary for a corresponding mass transfer. All loops are equipped with high-efficiency cleaning apparatus in order to achieve the high water purity necessary for tests. The loops thus permit flexible change of water chemistry, where direct injection of gaseous oxygen or hydrogen according to requirements.

There are three main research loops in the corrosion, crud deposition after DECO and water chemistry in VVER and PWR reactors problematic: RVS-3 loop, RVS-4 loop and Zinc loop.
2.1 RVS-3 loop

The RVS-3 loop (Fig. 2) simulates a PWR/VVER reactors environment and was commissioned in 1983. The loop serves for research into fuel element cladding corrosion, the deposition of corrosion products in the loop, the fuel cladding interaction with the electrically heated fuel model rods and the study of PWR/VVER reactors environment. Parameters of the loop are in Tab. 1.

Tab. 1: Main parameters of RVS-3 loop

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>16.5 MPa</td>
</tr>
<tr>
<td>Temperature</td>
<td>345 °C</td>
</tr>
<tr>
<td>Water flow rate</td>
<td>10 000 kg/hr</td>
</tr>
<tr>
<td>Neutron flux</td>
<td>~1x10^18 n/m²/s</td>
</tr>
<tr>
<td>Electrical heating capacity</td>
<td>100 kW</td>
</tr>
</tbody>
</table>

The loop is a closed stainless steel piping system with usual technological auxiliary systems, which can provide experimental services in wide area of interest, e.g.:

- Investigation of structural materials mechanical properties degradation and corrosion behaviour under irradiation and PWR/VVER water chemistry and thermal-hydraulic conditions.

- Investigation of behaviour (corrosion, hydriding) of fuel cladding materials under influence of irradiation, thermal flux and water chemistry conditions.

- Investigation of radioactivity transport and behaviour under PWR/VVER conditions (e.g. influence of water chemistry, pH regime, zinc injection ammonia etc.).

- Testing of high-temperature and high-pressure sensors for water chemistry monitoring.
2.2 RVS-4 loop

The RVS-4 loop as commissioned in 1998 is used for research into VVER reactor water chemistry (Fig. 3, Tab. 2). Currently it is being used for experiments for the study of the influence of corrosion product deposition on the surface of fuel elements and the surface of steam generator tubes after circuit decontamination.

Tab. 2: Main parameters of RVS-4 loop

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>15.7 MPa</td>
</tr>
<tr>
<td>Temperature</td>
<td>325 °C</td>
</tr>
<tr>
<td>Water flow rate</td>
<td>2,000 kg/hr</td>
</tr>
<tr>
<td>Neutron flux</td>
<td>~1x10^{14} n/m²s</td>
</tr>
<tr>
<td>Electrical heating capacity</td>
<td>40 kW</td>
</tr>
</tbody>
</table>

The loop models basic thermohydraulic, chemical and radiation parameters of VVER reactor primary circuits. The circuit is composed of an irradiation part, so-called active channel located in the reactor’s active zone, as well as of a main circulation pump, primary circuit coolers, and primary piping. Located in the internal area of the active channel is a so-called installation, which is formed by a field pipe, inside which are installed four fuel ingot simulators in a square grid. The simulators are composed of heating rods that ensure the heating of the primary medium to the required temperature.

Besides the primary circuit, the loop also contains systems and facilities permitting the preparation and addition of chemically treated water into the primary circuit, primary circuit coolant sampling, dissipation of heat from the cooler, supplying power to the electrically heated fuel element simulators, and others.

The primary circuits cooler, which represents an SG model, permits the dissipation of excess heat created both by radioactive heating of the active channel, and by the heating of the fuel ingot simulators in the active channel. In principle, it is a counterflow heat exchanger of “tube within a tube” type. The internal part of the cooler consists from a removable tube, which is...
the basic sample for the study of passivation/pre-condition, corrosion layers, surface deposits and data regarding radioactive contamination of the inside surface, which is on the primary medium side. The cooler is connected to the primary circuit via special demountable flanges, which permits simple dismantlement and replacement. The cooler, like the entire circuit, is manufactured out of CSN 17 247 titanium-stabilized austenized steel (08Ch18N10T). The loop’s primary circuit further includes 3 chambers before and 3 chambers after the active channel.

2.3 Zinc loop

The loop (Fig. 4, Tab. 3) with zinc doping is a specialized facility which fully models primary circuit parameters, not only with regards to temperature, heat transfer and flux, but also with regards to the ratio of surface and coolant volume to the surface of zirconium and stainless steel. The loop has been used to study the effect of zinc on the deposition, transport and release of corrosion products in the primary circuit, with a goal of lowering the radiation dosage to operational personnel and minimizing of corrosion and primary water stress corrosion cracking (PWSCC) of SG tubes.

Tab. 3: Main parameters of Zn loop

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>15.5 MPa</td>
</tr>
<tr>
<td>Temperature</td>
<td>350 °C</td>
</tr>
<tr>
<td>Water flow rate</td>
<td>828 kg/hr</td>
</tr>
<tr>
<td>Neutron flux</td>
<td>( \sim 1 \times 10^{18} ) n/m²s</td>
</tr>
<tr>
<td>Electrical heating capacity</td>
<td>100 kW</td>
</tr>
</tbody>
</table>

![Fig. 4: Zinc injection loop](image)

3. Research

Available data from operated VVER power stations indicates, that the primary cause of undesirable, excessive deposit formation in the primary circuit is the use of decontamination, which when coupled with insufficient knowledge of the events taking place and without the use of necessary parameters and limits for managing the process taking place, has as its result the creation of surface deposit layers, and can lead to limited coolant flow. The composition and characteristics of surface layers are dependent on the nature and contents of coolant
additives, and are primarily composed of corrosion products produced during the interaction of the water environment with the materials of the circuit. Previous studies showed, that during normal operating conditions, the layers are formed from magnetite and other spinel-type oxides, whose thickness on the surface of steam generator pipes does not exceed 10 – 20 µm. When decontamination of steam generators is performed, crud deposits are to a certain degree eliminated, but if the subsequent flushing process is insufficient, they remain in the circuit or are subsequently further released only once in operation, and can thus precipitate in greater amounts on fuel and the internal surfaces of heat exchange pipes. Evidently the decisive factor in the extent, integrity and composition of deposits is the presence of organic substances from decontamination agents that remain in the circuit, primarily organic acids, which can produce compact, coherent and relatively adhesive layers of surface deposits.

3.1 Past experiences

During the period 1995 to 2001 a programme of loop irradiation tests have been performed to confirm the effectiveness of zinc additions on PWR circuit chemistry and corrosion, with use of Zinc loop. The programme included two loop irradiation experiments, and subsequent PIE; the experiments were a baseline test (no added zinc) and a test with added zinc (10 ppb). The findings are relevant to overall corrosion of the reactor primary circuit, the use of zinc as a corrosion inhibitor, and activation and transport of corrosion products. The irradiation experience provides information on the equilibration of the loop chemistry, with deliberate injection of zinc. The results of the PIE, under normal chemistry and zinc chemistry, indicate the effect of zinc on the deposition and activation of corrosion products on Zircaloy. It was found that corrosion product deposition on Zircaloy is enhanced by the addition of zinc (but corrosion product deposition on other materials was reduced in the presence of zinc). A computer model has also been used to simulate the corrosion product deposition and activation, to assist in the interpretation of the results.

With the aim of assessing the corrosion behaviour of the developed alloys under PWR water chemistry conditions in comparison to the base alloys, long-term (up to 432 days) tests of their cladding samples were carried out in the research loop RVS-3 under conditions of boron-lithium (2.7-3.5 ppm Li) water chemistry with surface and volume boiling of the coolant (the steam content of up to 5% mass). In 2004 start a two years project between TVEL and NRI (Исследование коррозионного поведения российских циркониевых сплавов в условиях, аналогичных эксплуатационным в реакторе PWR, Контракт № 203/45046040/030302) where four different types of Zr alloys (E110, E110M, E635, E635M) were tested in the experimental loop RVS-3 [4][5]. Main goal of this experiment was to measure and compare the thickness of oxide layers by eddy current method during the experiment and metalography measurement after the experiment. Last year were decided to prolong the contract with TVEL. With using previous experiences and new calculations, few changes at the research loop RVS-3 will be needed to be done.

For gaining data for proposing conditions and recommendations for NPP operation from the standpoint of decontamination procedure and subsequent operational strategy, the research loop RVS-4 was used. The experimental program was aimed at investigating the influence of the presence of organic substances (TOC), concretely the influence of trace amounts of organic acids after decontamination, on the development and stability of passivation layers and deposits both on the surface of heating rods (fuel elements) and on interfaces with spacer grids (stainless steel – Zr with 2.5% Nb) and on the inside surfaces of SG pipes. These experiments were part of the international technical cooperation project RER/0/076, held by IAEA, during 2001-2009.
3.2 Present and future experiments

The extension of NPP lifetimes above their design values and an effort to make greater use of fuel are the main interests of operators, while power plant chemistry is important for smooth operation of the facility as a whole. Activities performed by chemistry teams in nuclear reactors do not usually show directly observable benefits precisely because of the preventive nature of their activities. Study of water chemistry regimes in NRI led to the creation of the water chemistry guidelines for Czech NPPs (VVER-400, VVER-1000).

In past years, lot of research was done in NRI. With use of research loops many experiences in the field of corrosion, CRUD deposit on fuel, minimizing of PWSCC of SG tubes etc. were obtained, and NRI have the ability to continue in these tests.

From 2009, NRI is participating at PIIP (Post Irradiation Inspection Program) at NPP Temelin. The main work is oriented for the inspection and repair of the fuel assemblies with use of FRIE (Fuel Repair and Inspection Equipment) designed by Westinghouse. In addition to fuel repair, the PIIP is also oriented to study of damaged fuel rods and causes of these damages, too. Together with bowing and elongation of FR measurements, oxide layers thickness measurements by eddy current method is performing. Moreover, the feasibility study for crud scrapes examinations (VVER-440 and VVER-1000) in the region is proposed, to understand the correlation between water chemistry and fuel crud deposition:

- to support data collection and analysis of crud and cladding corrosion samples taken from operating VVER fuel to gather information related to fuel reliability,
- analyses of corrosion samples from fuel and primary circuit.

Further research is concentrating on the areas of analysis of corrosion product deposits on VVER fuel surfaces in operational nuclear power plants, and on better understanding of the mechanism of deposition on grids and fuel cladding.

4. Conclusions

Reliability of nuclear fuel and radiation fields surrounding primary systems is an important aspect of overall nuclear reactor safety. Corrosion product (crud) deposition on fuel surface has implications for fuel performance through heat transfer and local chemistry modifications. It is important to pay attention to the studies of organic substance behaviour in the circuit, especial in light of the influence of decontamination on the corrosive behaviour of materials and on crud deposition on fuel. Therefore, further research is still needed.

The LVR-15 reactor is an important facility, which serves for research into nuclear generating station materials and water chemistry. 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. Experience that has been gained during the operation of research loops at NRI (RVS-3, RVS-4, Zinc loop) is now used as water chemistry guidelines base ground for Czech NPPs. Together with the experiences from fuel inspection equipment at Temelin NPP; NRI has perfect tools for studying and improving of VVER water chemistry regimes.


References


