On-line fuel and control rod integrity surveillance in BWRs

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ABSTRACT – Surveillance of fuel and control rod integrity in a BWR core is essential to maintain a safe and reliable operation of the nuclear power plant. Any actions to be taken in the event of a fuel failure during reactor operation should be based on the best available information regarding the failure and expected consequences. The detection of fuel and control rod failures in BWRs is usually performed by analyzing samples of off-gases and coolant taken with a certain time intervals, e.g. once a week or once a month. This procedure can, however, leave the failure undetected in the core for quite some time. Therefore, a sufficient improvement of the surveillance of fuel and control rods can be achieved by simultaneous measurements of He and gamma emitting noble gases on-line in the off gas system. In this paper, experiences of such measurements performed at Kernkraftwerk Leibstadt (KKL) in Switzerland and Forsmark nuclear power plant (NPP) in Sweden will be presented.

1. Introduction

Continuous monitoring of fuel behavior is essential to maintain a stable and reliable reactor operation. Measurements of the fuel integrity in BWRs are normally performed by regular analyses of reactor coolant samples and gas samples from the reactor off-gas system. A measured increased level of gamma emitting fission gases in the off gas system is an indication of a fuel failure or a degradation of an already existing failure. In case of a fuel failure, fission gases, such as xenon (Xe) and krypton (Kr) nuclides, will leak out of the fuel rod into the coolant and be transported to the off-gas system, where off-gas samples are taken, either manually or on-line. On-line measurements of gamma emitting fission gases have proven to be an efficient system for the surveillance of fuel rod integrity and detection of fuel failures [1-4]. Such a system allows continuous surveillance of the fuel integrity and gives fast response during the operation. By using “release-to-birth” analysis one can also follow the development and possible degradation of the fuel failures. On-line measurements of gamma emitting fission gases is also very useful during the power suppression testing/flux tilting [1-4]. However, it can be difficult to distinguish the occurrence of a new primary failure from the degradation of existing failure(s) in the core. On-line measurements of the helium (He) concentration, in connection to the gamma emitting noble gas measurements, in the off-gas system could therefore be a helpful tool for detecting fuel failures and separating new primary failure(s) from the degradation of already existing failure(s) since He will be released along with the radioactive fission gases in case of a primary fuel failure but only an increased level of fission gases will be released in case of a secondary failure [5]. The main source of the He in a fuel rod originates from the manufacturing process, during which the fill gap between the pellets and cladding is filled with He to improve the fuel-cladding conductance. If the free volume of a fuel rod and the fill up pressure are known, the He amount in the rod can be calculated. In a standard BWR rod, pressurized to 4 bar, the He amount is 3.3x10-3 mole [6], which corresponds to about 80 ml at standard pressure and room temperature. Although the He production in a fuel rod during operation is very small and can be assumed negligible, three main sources of He production can be distinguished: 1) alpha-decay of some heavy actinides, 2) (n, alpha) reactions of ^{16}O, and 3) ternary fissions [7]. A He measuring system is also able to detect control rod failures [5,8,9]. He is present in control rods containing boron carbide due to the continuous production during the reactor operation when the boron is irradiated with neutrons, and would be released in case of a control rod failure and transported to the off-gases where it can be detected by a He detector system. Experiences from the nuclear power plant Leibstadt (KKL), where such a system has been in operation since 2008 and control rod failures have been identified [10,11], have shown the effectiveness of an on-line He measuring system. Already in the 1990s, there were attempts to detect fuel failures by continuously measuring He in the off gases at the Isar Nuclear Power Plant (NPP) in Germany [4]. However, without complimentary on-line nuclide specific measurements, the He measurements were not able to provide any clear and reliable detection of the fuel failures in the core. Since each fuel failure is unique in its size, shape and rod burn-up, and depends on the environmental conditions in the reactor, it is difficult to predict the behavior of a fuel failure and estimate the amount of gas leaking out from a specific failure. However, it is expected that the He and fission gases will be released rapidly after the first penetration of the cladding. There are also other uncertainties that might influence the detection of the gas release from a fuel rod, such as the gas mixing in the core, blocking of the pellet-cladding gap due to fuel pellet swelling, fragmentation, and pellet and cladding oxidation. This will influence the amount of gas that will reach the sampling point in the off-gas system. In addition to the off-gas activity monitoring, analysis of reactor coolant grab samples are also performed on a regular basis, where iodine (I), cesium (Cs) and neptunium (Np) nuclides are monitored in order to follow-up a failure and its possible degradation. Detection of an increased concentration of I isotopes in the coolant is a signature of fuel in direct contact with the reactor coolant, and at some units an increased level of I in the coolant is used as the main indication of a fuel failure. This method gives however a slower response and might not be as reliable as off-gas samples, since small fuel failures might exist in the core without causing an increased level of I. Release of the long-lived iodine, particularly ^{131}I, is also of concern from the radiological point of view during the outage. The inhaled ^{131}I concentrates in the thyroid gland and can cause an enhanced risk of thyroid cancer later in life, or even acute health effects. An increased level of Cs concentration in the reactor coolant is also an indication of a degradation of a failure and an increased water intrusion in the leaking fuel rod. Finally, Np nuclides in the coolant are an indication of fuel pellets, or other fissile material, in direct contact with the coolant with the subsequent wash out of the fissile material from the failure. However, Np cannot be used as a measure of released amount of fissile material if hydrogen water chemistry (HWC) is applied, since then insolvable Np components are also created that are not released in the reactor water, or released and deposited in the crud.

This paper describes two combined detector systems for on-line measurements of gamma emitting noble gases and He at KKL in Switzerland and at Forsmark NPP in Sweden. The gamma emitting noble gases are measured with HPGe-detector systems, while the He detection systems are based on a mass spectrometer.

2. On-line measuring system at KKL

The on-line measuring system for detection of fuel and control rod failures at KKL includes both measurements of gamma emitting nuclides and He. This combined system is located in the off-gas system after the condenser, recombiner and gas coolers, and before the charcoal filters of the chimney, as shown in Figure 1. There are two different measuring locations for the sampling. At one location direct measurements are performed where the off-gases are taken directly after the recombiner and gas coolers. The second location is after a delay of the radionuclides, where the sampling line is attached to the off-gas flow pipe after an additional delay line, as can be seen in Figure 1. The delay line consists of several tanks, allowing short-lived nuclides to decay to long-lived daughters or to stable isotopes. The gas in the sample line is flowing through the combined detection system with a constant flow and pressure, regulated by electronic flow and pressure regulators.

2.1 System for detection of gamma emitting noble gases

The activity of gamma emitting noble gases at KKL is continuously surveyed by the “Abgas Online Monitoring” (AOM) system, which was developed at KKL in 2003-2004. The AOM system is based on a high purity collimated Broad Energy Germanium detector, BEGe, with electrical cooling. BEGe detectors are efficient over a broad energy region, which is important for measurements of the relevant noble gases [1-4]. The detector is operated by a single unit including a high voltage supply, an amplifier and a digital signal processor. The communication with the PC is performed via a USB interface. A special gamma spectroscopy software called TS-Online-Monitoring, which is based on Genie 2000, has been developed by Canberra for the continuous measurements and data analysis. The data are stored in a SQL data base and are also visualized in real time in the KKL Core Monitoring System “MinuteMan” in the main control room via Ethernet [4]. An activity increase of the monitored nuclides (mainly Xe and Kr nuclides and their ratios) is a strong indication of a fuel failure and an alarm is triggered, which requires immediate actions by the control room personnel and the station nuclear engineer.

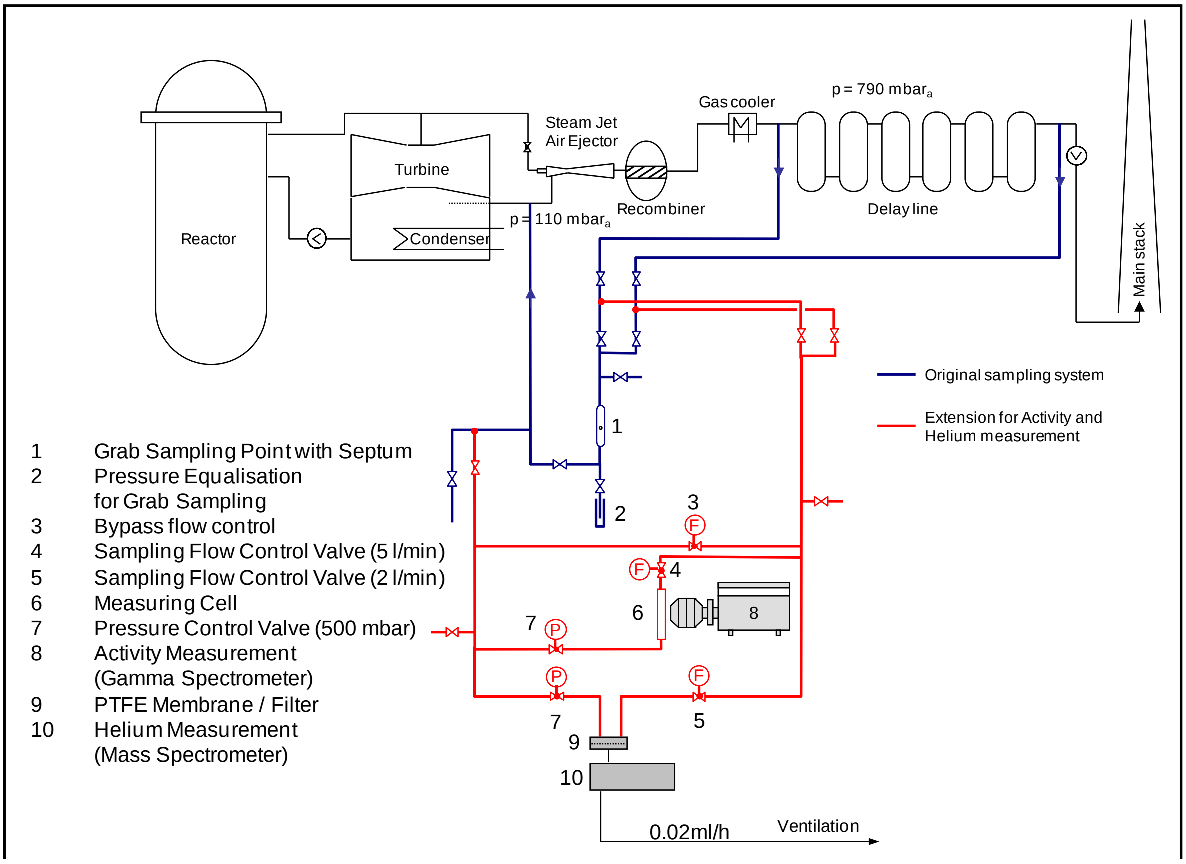

Figure 1. Schematic set up of the gamma and He measuring system at KKL.

2.2 System for He measurements

In September 2008, a He measuring system was installed at the same gas line as the BEGe detector in the off-gas system at KKL. The main purpose of this He measuring system was to monitor the control rod integrity. The system is based on a He leak detector with a built in mass spectrometer, PhoeniXL 300 from Oerlikon Leybold Vacuum Company. The vacuum of the analyzing cell is provided by TRIVAC E2 dual stage rotary vane vacuum pump and TURBOVAC TW 70 wide-range turbomolecular pump. In the vacuum mode, which is used for measurements at KKL, the minimum detectable He leak rate is $5x10^{-12}$ mbar l/s at an inlet pressure lower than 0.2 mbar. The maximum He leak rate, which can be displayed by the detector, is 0.1 mbar l/s. The highest sensitivity of the detector is $1x10^{-12}$ mbar l/s [12].

A gas separation cell with a Polytetrafluoroethylene (PTFE) membrane is also included in the He detection system. To avoid contamination of the He leak detector with radioactive noble gases present in the off-gas system, and provide stable conditions for the detector operation, a gas separation cell is installed before the detector inlet. A schematic set up of the gas separation cell is shown Figure 2. Gas is flowing through the upper part of the gas separation cell with constant flow of 2 l/min at an absolute pressure of 500 mbar. The data is directly read from the detector into the same SQL data base which is used for the on-line gamma spectroscopy system. The data are again visualized in real time in the "MinuteMan" system in the main control room.

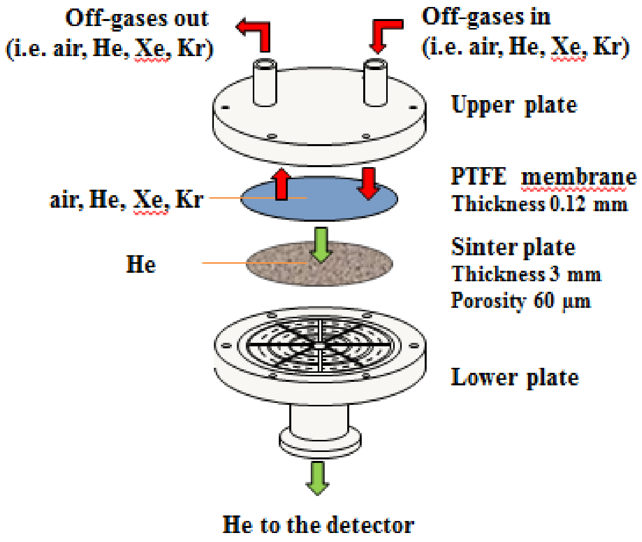

Figure 2. Schematic set up of the gas separation cell.

3. On-line measuring system at Forsmark

The detection system at Forsmark 3 (F3) combines measurements of gamma-emitting noble gases [1-3] with measurements of He [5]. The combined on-line system is installed in the off-gas system, after the recombiner and gas coolers and before the delay system, as shown in Figure 3. The delay system at F3 consists of two sand tanks and several charcoal columns, which ensures the separation and recirculation of long-lived Xe isotopes and delays other harmful radioactive fission gases until they have decayed into stable nuclides. The flow and pressure of the gas in the sample line passing through the measuring system are regulated by valves. A flow meter is installed for the monitoring of the gas flow rate through the sampling line.

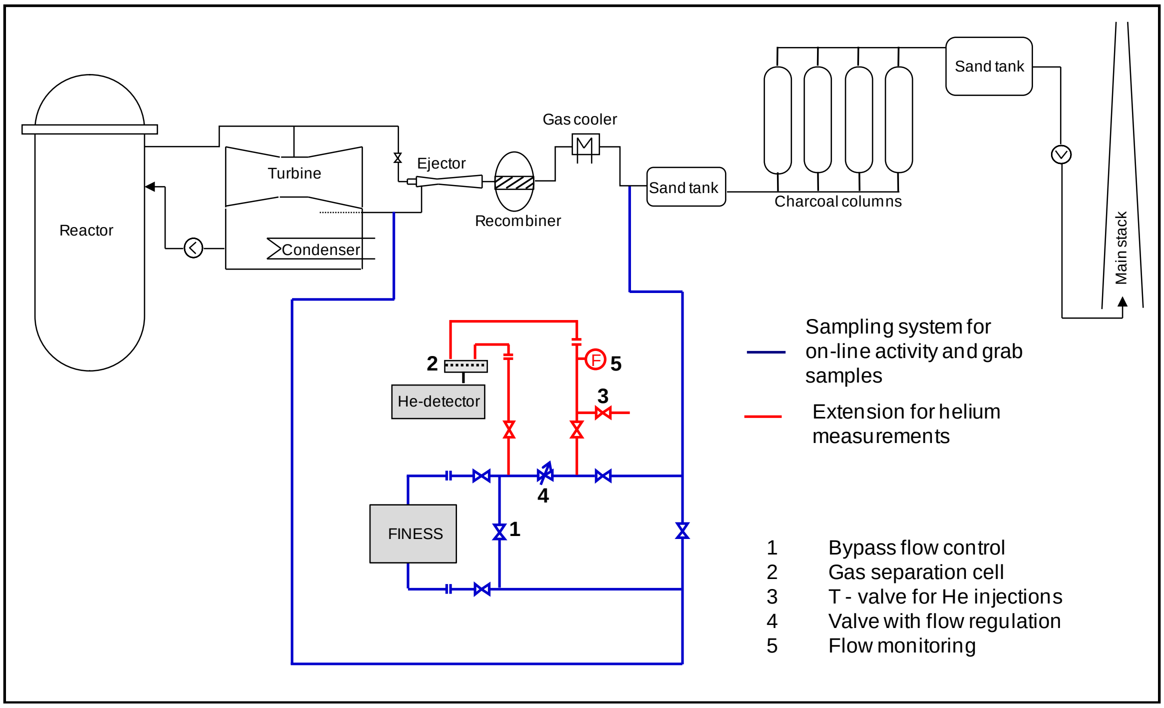

Figure 3. Schematic set up of the gamma and He measuring system at F3.

3.1 System for detection of gamma emitting noble gases

At Forsmark NPP, a slightly modified version of the Fuel INtegrity Evaluation and Surveillance System (FINESS) [1-3] system is used as the nuclide specific measuring system for gamma emitting noble gases in the off-gas system.

3.2 System for He measurements

The He measuring system at F3 includes a He leak detector with a built-in mass spectrometer and a stainless steel gas separation cell, similar to the system at KKL. The detector used at F3 is the Adixen ASM 142 He leak detector from Alcatel Vacuum Technology Company. The analyzing cell includes dual filaments. The required vacuum for the analyzing unit is provided by a rotary wane pump and a molecular drag pump. The detector is operating in a vacuum mode allowing the highest sensitivity of $1x10^{-11}$ mbar l/s, which is also the lowest detectable leak rate according to the documentation. The measured data are stored at a PC where it can be extracted for further analysis.

4. Experiences of on-line measurements

4.1 Calibration of detector systems

The HPGe detector can either be calibrated by a build in ^{241}Am source and a pulser (as e.g. in FINESS) as described in refs [1-3], or by using external gamma emitting calibration sources. The calibration of the He detector can also be performed in two different ways; either by an internal calibration, using a built-in leak test, or an external calibration using a test leak attached to the inlet port [12]. It is recommended by a detector vendor to recalibrate at regular intervals to validate the calibration [13].

4.2. Measurements at KKL

During the observation time of the He detection system, covered by this paper, KKL did not experience any fuel rod failures. Therefore no increases of gamma emitting noble gases were detected, and any significant He concentration increase detected in the core was assumed to come from failed control rods.

The duration and amount of the He released from a failed control rod vary depending on the conditions of the failed rod (e.g. ^{10}B depletion of the rod, severity of cracks) and eventual environmental changes in the core (e.g. power variations, control rod movements). In addition to the release of He from failed control rods, there are also other sources that may cause an increase of the He signal compared to the background/baseline. The main contribution to the background He concentration at KKL originates from He impurities in the hydrogen, injected into the feed water when applying On-line Noble Chemistry (OLNC). At KKL hydrogen injections started in mid-September 2008 [14], as a first step to introduce OLNC. Observations in older reactors show that Stress Corrosion Cracking (SCC), in particular Intergranular Stress Corrosion Cracking (IGSCC), in the primary system can cause severe problems. Adding hydrogen to the feed water reduces the production of oxygen in the reactor coolant and decreases the Electrochemical Potential (ECP) in the lower part of the core, which mitigates Stress Corrosion Cracking and, therefore, protects stainless steel components. However to reduce the IGSCC potential below the critical electrochemical corrosion potential (EPC) of a stainless steel, large amount of hydrogen needs to be injected [15]. This increases the main steam system radiation dose rate, mainly due to ^{16}N-γ-radiation [16]. The ECP can effectively be decreased by injections of noble metal together with smaller amounts of hydrogen [15]. Therefore, Noble Metal Chemical Addition (NMCA) together with small amounts of hydrogen was recommended by General Electric (GE) in 1996.

Other factors that influence the He measurements are variations of gas pressure in the sampling line, changes of off-gas flow and water refill into the feed water. He peaks that have not been influenced or triggered by operational actions, such as power reduction or control rod movements, are called spontaneous He release peaks in this paper. The spontaneous peaks can be indications of newly occurred control rod cracks or He released from the disintegrated B_4C matrix due to water intrusion. Examples of He releases from failed control rods can be seen in Figure 4 and 5. The durations of the peaks and the estimated amounts of released He are also indicated in the figures. In Figure 4, the peak has a narrow and well defined shape, while in the Figure 5, the peak is a result of a steep increase of the He concentration followed by a slow decrease of the signal. However, the most interesting observation was that after the first helium release, shown as peak in Figure 5, the signal remained above the baseline with several ppm (from 101 ppm before the peak to 106 ppm after the peak) for additional 42 hours. This suggests that there was a continuous release of small amounts of He into the reactor coolant. Detailed analysis of spontaneous releases and more examples can be found in ref. [17].

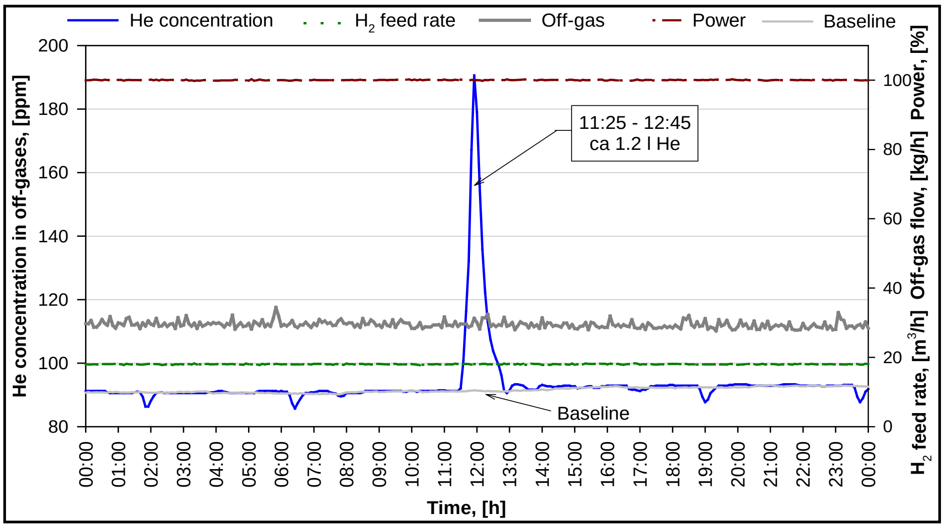

Figure 4. He concentration increase in the off-gas system of KKL.

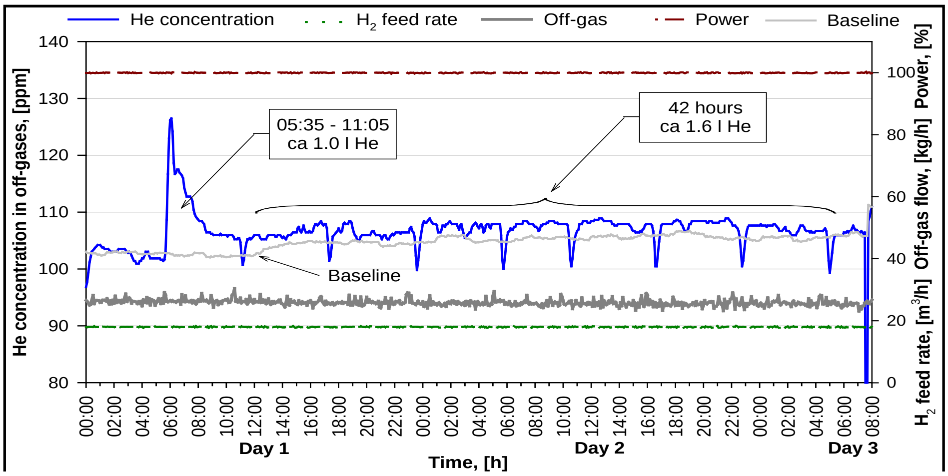

Figure 5. He concentration increase in the off-gas system.

4.3 Measurements at F3

As mentioned in paragraph 3.1, a slightly modified version of the FINESS [1-3] system is used as the nuclide specific measuring system for gamma emitting noble gases in the off-gas system at F3. The installed He measuring system is mainly focusing on improving the detection of fuel failures since after all the control rods at F3 were replaced, due to design construction issues in recent years; no control rod failure has been detected in the core.

The estimation of the He amount released from the core follows the same approach as at KKL. However, at F3, the background concentration is low and stable and not affected by impurities in the same way as at KKL, since F3 does not apply hydrogen injection.

While a primary fuel failure is usually characterized by a sudden release of long-lived nuclides accumulated in the fuel rod, an open secondary/degraded failure causes an increased release of short-lived nuclides, since then the time between their production and when they reach the measuring point in the off-gas system is not long enough to cause all of them to decay. Due to the short half-life of ^{138}Xe ($t_{1/2}$=14 min.), an increase of the concentration of that nuclide in the off-gases is an indication of a degradation of a primary failure to an open secondary failure or fuel washout.

After the installation of the He measuring system at F3, there were periods with a measured increase of the He concentration, which suggested a possible release of He from one or several fuel failures in the core. During one month, an increase of the He signal was detected twice. The first increase was registered for more than two hours with about 70 ml He released, as shown in Figure 6.

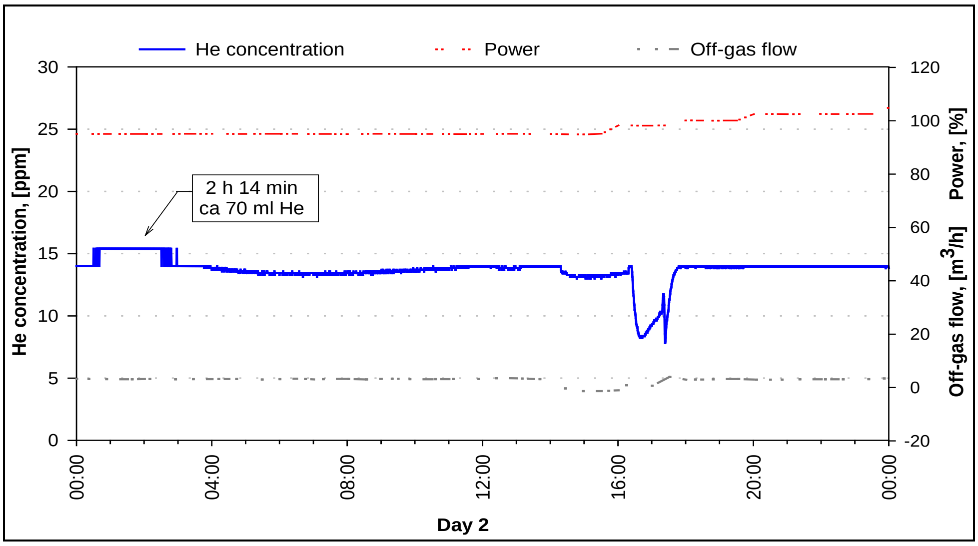

Figure 6. Increase of He concentration in the off-gases at F3.

A few hours later, a slight increase in the gamma activity was detected (primarily ^{138}Xe) as shown in Figure 7. It is, however, not clear if the activity increase was caused by a fuel failure or by some operational factors. It might be that the size of the failure was so small that the activity release was close to the detection limit so no fission gas release was detected in the immediate connection to the helium release, which would be expected for a fuel failure.

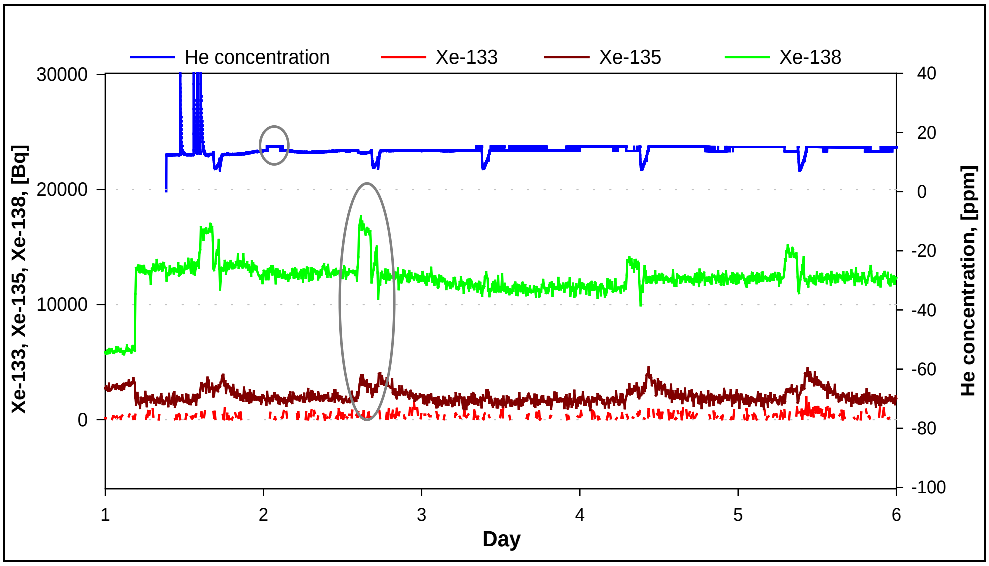

Figure 7. He concentration and gamma activity measurements at F3.

22 days after the first detected He increase, there was another 30 min increase in the He signal. The released amount of He was estimated to about 10 ml, which is shown in Figure 8. At the same time, an increase of gamma emitting noble gases was detected, as can be seen in Figure 9. The measured increase of both the He concentration and the concentrations of the gamma emitting fission gases indicated a fuel failure. A possible scenario is that after the first penetration of the fuel cladding, most of the He in a fuel rod leaked out and three weeks later, a small amount (approximately 10 ml) of the remaining He was released. Afterwards, a gradual increase of ^{133}X activity was observed, which can also be seen in Figure 9.

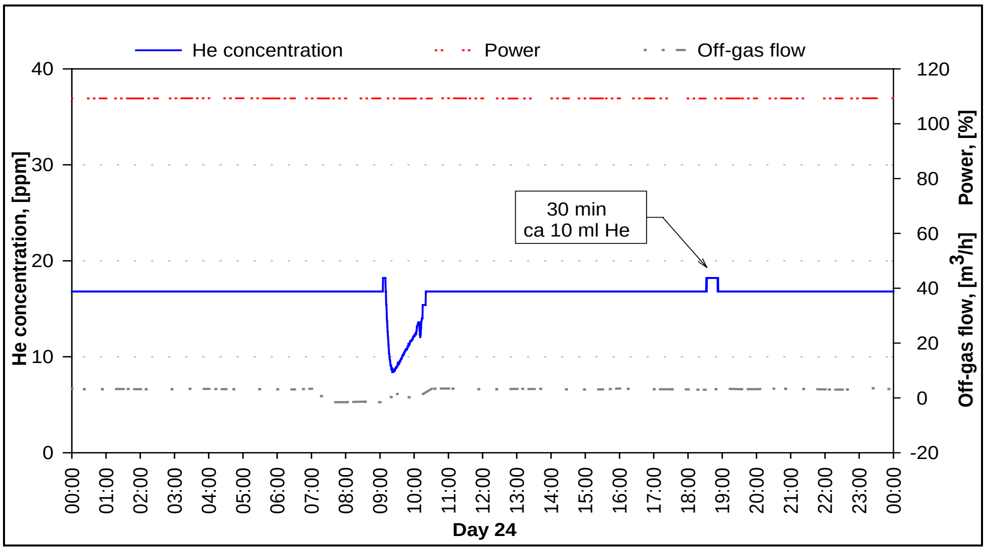

Figure 8. Increase of He concentration at F3.

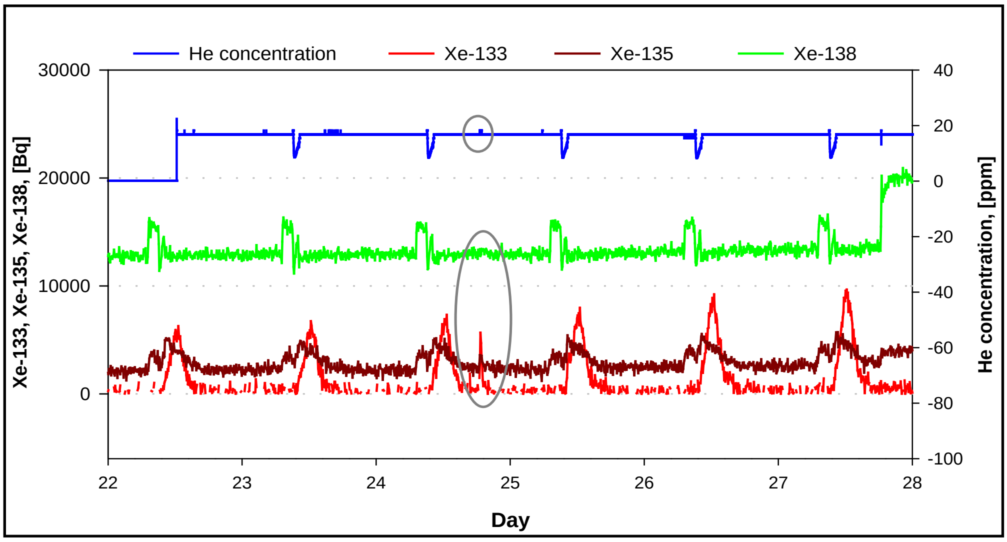

Figure 9. He concentration and gamma activity measurements at F3.

Several months later, another increase of the He concentration in the off-gases was detected at F3, as shown in Figure 10. The duration of this increase was almost 2.5 hours and the released

He amount was estimated to about 70 ml. Simultaneously, an increase of noble gas activity was measured, in particular of the long-lived isotopes, e.g. ^{133}Xe and ^{135}Xe, as can be seen in Figure 11. This might be an indication of the occurrence of an additional fuel failure.

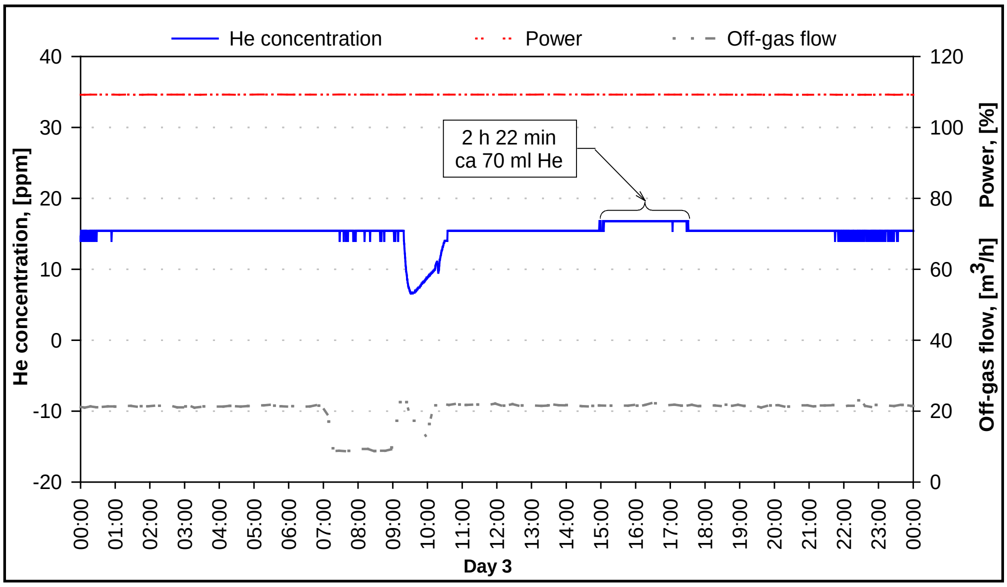

Figure10. Increase of He concentration at F3.

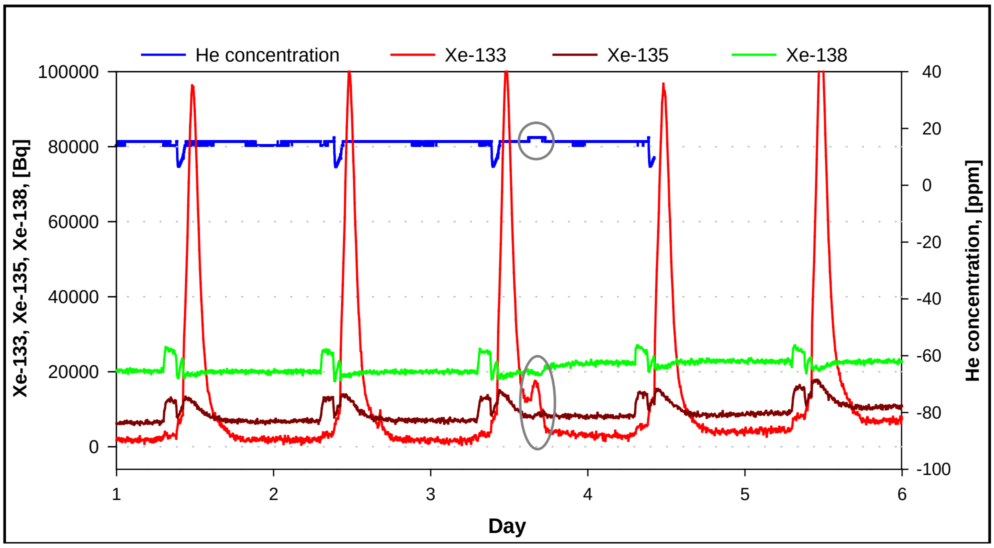

Figure 11. He concentration and gamma activity measurements at F3.

Our experiences of on-line measurements at F3 have showed that a He measuring system, installed in the off-gas system in connection to the system for nuclide specific measurements of gamma emitting noble gases, is very helpful when detecting fuel failures. However, the combined measurement system was not able to detect all the failed fuel rods, which were later identified by sipping during the outage. One possible reason to why not all of the failed fuel rods were identified could be that there were several periods of discontinuity of the measurements. Furthermore, there were significant disturbances of the He signal, e.g. due to the regeneration of adsorption columns and changes of the water levels in the Hotwell, which made it difficult to analyze the He signal. Finally, as already mentioned in the introduction, each fuel failure is unique with different size and behavior and they will therefore cause different release rates, which also needs to be studied further.

The obtained results showed however that an on-line He measuring system is able to detect He released from fuel failures and therefore provides a valuable support to nuclide specific measurements of gamma emitting noble gases, for detection of fuel failures. Yet, more measurements are needed to be able to improve the system and to verify its ability to detect fuel failures.

5. Summary and conclusions

This paper presents experiences of on-line measurements of He and gamma emitting noble gases in the off-gas systems of KKL and Forsmark 3. A combined He and gamma emitting noble gas detector system has shown to be a robust and reliable method for detection of fuel and control rod failures in BWRs, since fuel rods contain both He and gamma emitting noble gases, while control rods only contain He. Such a system gives fast response and a prompt detection of both the He gas and the noble gases that leak out into the coolant and are subsequently transported to the sampling point in the off-gas system.

The efficiency of the He detector system for the surveillance of control rod integrity in the core has been confirmed by experiences from measurements at KKL, where the main purpose of the system was detection of control rod failures. Control rod failures at KKL have been identified and followed by the on-line He detector system. Since 2012 the He measurement system is part of the process control and is also part of the KKL core supervision system “MinuteMan”, which includes monitoring of thermal operation parameters of the reactor core and relevant chemical parameters of the reactor water. For fission gas release, a triggering system which activates an alarm in case of fuel failure, has been added.

At Forsmark, the main focus has been to evaluate the ability of using a combined He and gamma emitting fission gas measuring system to detect fuel failures. The experiences from the measurements performed during this project showed good efficiency of the system and release of both helium and gamma emitting fission gases from fuel failures was clearly detected. However, when evaluating the measured results, a number of factors that can influence the measurements have to be taken into consideration. Furthermore, although the combined measuring system is simple, user friendly, robust and cheap, it needs a periodic maintenance and calibrations.

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