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Helium measuring system for on-line fuel and control rod integrity surveillance in BWRs

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Cover: Simplified schematic of the operating principle of a mass spectrometer analyzing cell. Adapted from Figure 8.

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ABSTRACT

Accurate supervision of fuel and control rod integrity in a nuclear reactor core is very important for maintaining a safe and reliable operation of the reactor. Fuel rod failures can cause increased doses to personnel in the power plant, increased backend costs, limitations of the reactor operation and unplanned shut downs, which can lead to large economic losses. Control rod failures are normally not as severe as fuel rod failures, but can lower the reactor efficiency, cause operational restrictions and increase a need for control rod inspections during outage. Additional inspections can cause a prolonged outage, leading to economic losses.

A project with the main objective to improve the detection of fuel and control rod failures in boiling water reactors (BWRs) by implementing continuous helium measurements in the off-gas system was initiated in 2007. The work was performed in collaboration between Chalmers University of Technology in Sweden, Forsmarks Kraftgrupp AB in Sweden and Kernkraftwerk Leibstadt (KKL) in Switzerland. During the project, helium detector systems have been installed in the reactor's off-gas systems at both of the nuclear power plants (NPPs). The helium measuring system is a part of a combined on-line system which also includes nuclide specific measurements of gamma emitting noble gases. This combined system provides continuous information of both the fuel and control rod integrity.

The work described in this thesis can be divided into two parts. One part includes evaluation of helium measurements for detection of control rod failures at KKL, which was the main purpose for the installation of the system at KKL in 2008. The helium measuring system at KKL has shown to be able to identify and follow control rod failures on-line. Since 2012 the helium measurement system is part of the process control and is included in the KKL core supervision system, which monitors the thermal operational parameter of the reactor core and all the relevant chemical parameters of the reactor water.

The second part of the work was to investigate the ability of the helium measuring system to detect the small amount of helium that is expected to leak out in case of a fuel failure. This was also the main objective for the installation of the system at Forsmark 3 (F3) in 2010. Some helium releases from fuel failures at Forsmark 3 have been detected with the current system, however, further measurements might be needed to optimize the technique.

Several factors, including operational parameters, which are influencing the helium measurements, have been identified and implemented in the developed equation for calculation of the helium background level in the off-gases. When being programmed in the core supervision system, such an automatic calculation of the helium background level, will give an immediate estimation of the released amount of helium if the helium concentration increase relative to the background level was detected.

Keywords: fuel and control rod failures, helium release, helium measurements.

LIST OF PUBLICATIONS

This thesis consists of introduction to and summary of the work published in the following papers:

Paper I
I. Larsson, H. Loner, B. Schnurr, L. Sihver, and G. Ledergerber**,** "On-line Detection of Fuel and Control Rod Failures in BWR"**,** in the Proc. of WRFPM/Top Fuel 2009, International Water Reactor Fuel Performance Meeting/Top Fuel, (peer-reviewed), Paris, France, September 6-10, 2009.

Paper II
I. Larsson and L. Sihver, "On-line fuel and control rod management in BWRs"**,** in the Proc. of ICONE 19, 19th International Conference on Nuclear Engineering, (peer-reviewed), Chiba, Japan, May 16-19, 2011.

Paper III
I. Larsson, L. Sihver, H. Loner, G. Ledergerber and B. Schnurr, "Factors influencing Helium Measurements for Detection of Control Rod Failures in BWR", in the Proc. of PHYSOR 2012, International Conference on Advances in Reactor Physics - Linking Research, Industry and Education, (peer-reviewed), Knoxville, USA, April 15-20, 2012.

Paper IV
I. Larsson, L. Sihver, A. Grundin and J.-O. Helmersson, "Improvements of Fuel Failure Detection in Boiling Water Reactors using Helium Measurements", in the Proc. of ICAPP'12, 2012 International Congress on the Advances in Nuclear Power Plants, (peer-reviewed), Chicago, USA, June 24-28, 2012.

Paper V
I. Larsson, H. Loner, K. Ammon, L. Sihver and G. Ledergerber, "On-line monitoring control rod integrity using a mass spectrometer".
Submitted to Nuclear Instruments and Methods A (2012).

Paper VI
I. Larsson, H. Loner, J.-O. Helmersson, A. Grundin, K. Ammon, G. Ledergerber and L. Sihver, "Simulation of fuel failures in a BWR using helium injections".
Submitted to Nuclear Instruments and Methods A (2012).

Paper VII
I. Larsson, L. Sihver A. Grundin, and J.-O. Helmersson, "Evaluation of on-line helium measuring system for detection of fuel failures in a BWR".
Submitted to Nuclear Instruments and Methods A (2012).

LIST OF PUBLICATIONS NOT INCLUDED IN THIS THESIS

Paper I
I. Larsson and L. Sihver, "Evaluation of on-line fuel and control rod detection system at KKL during cycles 25-26", Chalmers report CTH-NT-239, Chalmers University of Technology, 2011.

Paper II
I. Larsson and L. Sihver, "Evaluation of on-line fuel and control rod integrity detection system at KKL during cycles 25-26", Chalmers report CTH-NT-257, Chalmers University of Technology, 2012.

Paper III
I. Larsson and L. Sihver, "On-line mätning av helium i avgassystemet på en kokvattenreaktor: detektering av styrstavs- och bränsleskador på F3", Chalmers report CTH-NT-261, Chalmers University of Technology, 2012.

CONTENTS

Chapter 1

INTRODUCTION

Fuel failures always lead to some release of fission gas accumulated in the rod during the operation, particularly noble gases and helium. Fuel failures can also result in the release of fission products, as e.g. volatile iodine isotopes, tramp uranium, other fissile materials and long-lived alpha-emitting transuranium nuclides. Such events can lead to a contamination of the internal surfaces of the Reactor Pressure Vessel (RPV), fuel and the turbine system. Consequences of such contamination can be operational restrictions, unplanned shut downs of the reactor, increased amounts of personnel radiation exposure during outages and increased amount of long-lived waste. Detection of fuel failures is normally performed by analyzing the off-gases since an increase of noble fission gases is a sign of a fuel failure. Off-line spectroscopy of grab samples of the off-gases and reactor water taken with a certain time intervals, e.g. once a week, is a standard procedure in BWRs. This procedure can, however, leave the failure undetected in the core for quite some time if the increase of the noble gases is not observed. Separation of additional primary fuel failures from the degradation of already existing failures can also be difficult when only analyzing grab samples since the mayor content of long-lived noble gases in a fuel rod is released within a short time period. When a failure and its location are detected, it is possible reduce or delay its degradation by adjusting the reactor operation [1-5]. Another possibility to monitor off-gas activity is by on-line measurements, where the system for nuclide specific measuring of gamma emitting noble gas has been proven to be an efficient system for the surveillance of fuel rod integrity and detection of fuel failures [1-5]. Such a system allows continuous surveillance of the fuel integrity and gives fast response during the operation. These possibilities are also very useful during the power suppression testing/flux tilting (PST) [1-5].

Control rod failures in form of small cracks might not have as crucial consequences as fuel failures. However, it is essential to know the control rod integrity in the core to minimize tritium (^3H) wash out and chemical transients in the reactor water. When an open crack develops in a control rod, boron carbide (B_4C), lithium hydroxide (LiOH), etc. are washed out. The boron washout might decrease the efficiency of the reactor and wash out of LiOH might change the coolant properties, e.g. increase the conductivity and pH level. Control rod

failures are usually detected by measurements of tritium levels in the reactor water since the irradiation of control rods containing B_4C leads to tritium production. If an open crack occurs, tritium can leak out and mix with the already existing tritium in the reactor water. Reactor water samples are usually taken once a week and will therefore not give an immediate indication of a control rod failure. Besides that, the interpretation of the measured data is sometimes difficult. Another method for detection of control rod failures is by monitoring the levels of boric acid in the reactor water. However, the concentration of the boron in the reactor water depends on the condition of the ion exchangers; therefore the measured results can sometimes be misleading. By optimizing the ion exchangers, the levels of the boron in the reactor water can be decreased although leaking control rods might still be present in the core.

In addition to the tritium production, helium is also produced during the irradiation of control rods containing B_4C. Therefore control rod failures can be detected by continuous monitoring of helium in the off-gas system. Helium measurements give also additional information about the presence of fuel rod failures, since fuel rods contain both helium and gamma emitting noble gases, while control rods only contain helium.

This work is built on the content of Papers I-VII. The idea of using helium measurements for control rods failure detection has been expressed a number of years ago [6]. In addition, whether such a method could be useful for fuel rod failure detection has also been discussed at some nuclear power plants (NPP). This thesis covers a study of the ability of on-line helium measuring system to be useful for detection of fuel and control rod failures.

Chapters 2 and 3 describe the fuel and control rod failure mechanisms and give an overview of different available methods for failure detection. Chapter 4 includes an explanation of the amounts and sources of helium in both fuel and control rods, which allows the implementation of a helium measuring system for fuel and control rod failure detection. In Chapter 5, a description of combined measuring system at both KKL and Forsmark is presented. It has been established that in order to be able to make a correct analysis of the measured data, there are number of factors that have to be taken into account. These factors are discussed in Chapter 6. Experiences from measurements to detect control rod failures at KKL are shown in Chapter 7, while experiences from fuel failure detection at Forsmark are presented in Chapter 8. Finally, Chapters 9 and 10, summarize the work and provide ideas for additional applications for the system, further improvements or modifications.

Chapter 2

FUEL ROD FAILURES

This chapter includes an overview of fuel failures and discusses some available methods for detection of fuel failures that are implemented at NPPs, also described in Paper II.

Continuous improvements and modifications of the fuel design have resulted in a significant reduction of fuel failures at NPPs. However, in case of a failure, accurate information of the failure is of high importance to be able to minimize the risk of its degradation and fuel washout.

Fuel failures always lead to some release of noble fission gases which allows the detection of failures by analysing the off-gases of the reactor. However, sometimes the size of the failure is so small that the release of radioactive noble gases is below the detection limit which can lead to that the failure remains undetected until wash out of iodine or fissile material occurs. If release of volatile fission products (VFP) such as iodine isotopes, fissile material and long-lived alpha-emitting transuranium nuclides will occur in the core, the consequences of the failure will be more severe and it may result in increased personnel radiation exposure during outages, increased amount of long-lived waste and operational restrictions. Additionally, an increase in ^{58}Co, ^{60}Co, ^{97}Zr activity, as well as an increase of active corrosion products, outside the core is often observed after severe fuel failures. This occurs due to tramp uranium fission and presumably due to knockout of these nuclides from the crud layer by fission recoils from the thin layer of tramp uranium, causing an indirect radiological consequence of fuel rod defects with loss of fissile material [1, 2]. Tramp uranium is free fissile material in the reactor core deposited on fuel rod surfaces or reactor pressure vessel surfaces. The origin of the tramp uranium in the core is fuel washed out from previous failures or due to uranium pollutions from newly fabricated and inserted fuel rods.

Depending on the type and size of a failure and subsequent release rates, operational restrictions might apply. In case of degradation and risk for fuel washout, the power plant might need to perform an intermediate shut down in order to remove leaking fuel from the

core. Guidelines regarding operation with a fuel failure in core may differ from one power plant to another, based on own evaluation and recommendations from corresponding responsible authorities.

Fuel failures are usually divided into primary and secondary failures. Failure of a fuel rod begins as a primary failure in a form of a small breach in the cladding caused by different mechanisms examples of which are given in Sec. 2.1.

2.1 Primary fuel rod failures

A primary failure is defined as the first penetration of the cladding. The most dominating type of primary failure today is due to fretting of foreign debris, which circulate in the reactor water. These debris can be trapped by the spacers in the fuel assembly or at the bottom/top plate and cause through-wall fretting of the cladding [3, 7, 8]. In addition, vibration of the rods towards trapped debris, a spacer or an adjacent rod may result in a wear failure.

There are also other types of failures, such as Pellet Cladding Interaction (PCI), Pellet Cladding Mechanical Interaction (PCMI), manufacturing defects, dry out, Enhanced Spacer Shadow Corrosion (ESSC), Crud Induced Local Corrosion (CILC), etc [7, 8].

If a small fuel failure has occurred, a failed fuel can still be used in the core if no significant amounts of iodine or fissile material are released. Although, after a while a primary failure can develop into a large open secondary failure (described in 2.2) either in the surrounding of the primary failure or at some distance away from it, leading to wash out of both volatile and non-volatile nuclides, including large amounts of fission products and fuel material.

2.2 Secondary fuel failures

After a primary failure occurs, steam enters the rod causing fuel and cladding corrosion and local hydriding (ZrH_2) of the cladding. If there is an open gap between the fuel pallets and the cladding, local massive hydriding can also develop through the oxygen starvation [7, 8]. The process, thus, begins when coolant enters the fuel rod. The coolant flashes into steam which reacts with the fuel pellets and the cladding inner surface. Oxygen is stripped from the steam according to the corrosion reactions (1) and (2). Such coolant intrusion into the rod, flashing into steam, continues until equilibrium with the system pressure is reached.

$$2H_2O + Zr \rightarrow ZrO_2 + 2H_2 \quad (1)$$

$$H_2O + \frac{1}{x}UO_2 \rightarrow \frac{1}{x}UO_{2+x} + H_2 \quad (2)$$

Normally, zirconium is covered by a thin protective oxide film that protects against hydride formation. Steam oxidation of both fuel and inner cladding can generate enough hydrogen to break down the protective properties of ZrO_2 and to cause excessive hydrogen pick-up. Due to the corrosion according to reaction (1), amount of H_2 is increasing replacing steam, i.e. H_2O in the gas phase. The ratio of H_2 to H_2O vapour increases with distance from the initial failure location as time progresses. This is due to the hydrogen diffusion along the tight gap between the fuel and the cladding while the steam reacts with the zirconium in the cladding wall. At a certain distance from the primary failure, the local partial pressure ratio p_{H2}/p_{H20} might exceed a threshold value of p_{H2}/p_{H20} above which local massive hydriding of the inner surface of the cladding occurs. This causes formation of brittle hydrogen blisters and bulges on the rod, due to the hydrogen migration from the hotter inner cladding surfaces to the colder outer surfaces. If the hydrated areas are exposed to internal or external stresses, it can lead to circumferential breaks or long axial cracks [7, 8].

The rods with circumferential breaks are sometimes classified by crack extension at least halfway around the cladding circumference, or when a rod is broken in two. The criterion for long axial cracks has been adopted at the beginning of the 90ths when a crack should be at least 6 inches long [9]. Such failures are the result of propagating axial splits caused by either PCI cracks or hydride blisters. The growth of a crack is maintained by the hoop stress in the cladding due to pellets thermal expansion. Long axial cracks can lead to a significant fuel wash out and therefore accounted as one of the most severe fuel failures.

2.3 Detection of fuel failures

2.3.1 During operation

The release of fission products, fissile material and transuranium nuclides from failed rods can be determined by off-gas and coolant activity analyses, which provides means to detect the occurrence of a failure and monitor the progression of a failure and its possible degradation.

In the coolant and in the off-gas system there is always some level of activity, induced by reactions between neutrons and different nuclides in the core, resulting in the creation of radioactive products, e.g. ^{3}H, ^{16}N, ^{19}O, ^{18}F, ^{13}N, ^{14}C, etc. In addition, the activated corrosion products, e.g. ^{51}Cr, ^{54}Mn, ^{59}Fe, ^{58}Co, ^{60}Co, ^{65}Zn and ^{124}Sb, would also give a contribution to the activity in the coolant and the off-gases [9].

Another important source of activity in the reactor water is tramp uranium. Fission of tramp uranium produces radioactive fission products, causing a built up of activity in the off-gas system. This is the main source of radioactive iodine isotopes at failure free operation.

Off-gas activity measurements

Surveillance of gamma emitting noble gases, the increase of which serves as an indication of an occurred failure in the core, is a standard procedure for monitoring fuel rod integrity in

most BWRs, since noble gases are the first nuclides to be released in case of a failure. The release of the noble gases is caused by fast pressure equilibration between the interior of a rod and the reactor pressure. After noble gases enter the coolant, they are transported together with a steam to the turbine system, and subsequently further on through the condenser and recombiner system before they reach the off-gas system. The transport time to the condenser is short (in order of 15-30 s at 100% power) which means that even short-lived nuclides are able to reach the turbine [9]. Indication of fuel failure is often an increase in concentrations of radioactive noble gases measured in the off-gas system which is the standard procedure in BWRs.

The integrity of the fuel in the core can be monitored by measuring activity increase due to increased release of gamma emitting noble gases, such as ^{133}Xe, ^{135}Xe, ^{135m}Xe, ^{137}Xe, ^{138}Xe, ^{85m}Kr, ^{87}Kr, ^{88}Kr and ^{89}Kr. Along with measurements of individual nuclides, a method based on the "release-to-birth" or "diffusion-to-production" is also implemented, where the ratios of long-lived to short-lived isotopes are evaluated, e.g. ^{133}Xe/^{138}Xe, ^{133}Xe/^{135}Xe, ^{133}Xe/^{137}Xe, ^{135}Xe/^{137}Xe, ^{88}Kr/^{135}Xe [9]. Such diffusion analysis is useful for the surveillance of fuel integrity, evaluation of the severity of a failure and distinguishing leaking fuel from tramp uranium in the core. Originating from a secondary failure or from tramp uranium in the core, more short-lived nuclides of the released noble gas will reach the off-gas system before decaying due to the immediate recoil release into the coolant and shorter transportation time to the coolant than the activity produced within the primary failed fuel rod due to diffusion mechanism.

Common practice to monitor off-gas activity is by analyzing grab samples or on-line measurements. Grab sampling is usually performed by Chemistry department personnel, where gas samples are frequently collected from an off-gas flow with different periodicity for different NPPs. Analysis of different noble gas nuclides in the samples are carried out with a germanium detector at an active laboratory. Gas samples taken from the off-gas system have a certain transport time from the core to the sampling point, e.g. 3-15 minutes depending on the construction of a plant and location of the grab sampling point. Additional transportation time from sampling point to the laboratory also has to be taken into account. This can be seen as one of the weaknesses of the method since short-lived nuclides may decay before the sample can be analyzed due to the transport from the sampling point to the germanium detectors at the laboratories. In addition, a failure can remain undetected in the core for quite some time, if the peak of the released noble gases is not observed. Separation of additional primary fuel failures from the degradation of already existing failures can also be difficult when only analyzing grab samples.

Continuous measurements or on-line off-gas sampling provides means for monitoring fuel integrity in the core. The systems for such continuous measurements can somewhat differ between different NPPs. Commonly implemented systems include measurements with NaI-detectors and ion chambers installed in several measurement points in the

off-gas system. Some NPPs also use on-line nuclide specific activity measurements of gamma-emitting noble gases.

NaI-detectors are more efficient for detection noble gas activity released at low release rates, e.g. due to a small primary failure, or after the delay system where most of radioactive gases have decayed, while ion chambers detectors are more suitable for measurements at more extensive failures. Usually measuring units, each including NaI-detector and an ion chamber, located between the recombinators and the off-gas reactor delay system, measuring the activity flow before the delay system. Additional NaI-detector is installed after the delay system in order to control the efficiency of the delay system and the gas activity released through the stack into the air. These detectors are connected to the control room with continuous supervision of the measured data. An alarm sets off if the measurements reach the threshold value.

A system for nuclide specific on-line measurements of gamma emitting noble gases based on a high purity germanium (HPGe) detector is an efficient system providing means for prompt, detailed and accurate fuel failure detection and evaluation of the failure severity. One of such systems is Fuel Integrity Evaluation and Surveillance System (FINESS) [1-3] that was developed by L. Sihver et al., at Westinghouse Atom in collaboration with Forsmarks Kraftgrupp AB.

The FINESS system is designed for the detection range corresponding to a release rate of 0.2-200 MBq/s for ^{133}Xe nuclide, which is equivalent to definition of 0.1-100 standard pin holes. The system is optimized for the detection of photon with the energy range of about 80-600 keV, while maintaining high resolution at high count rates [9]. The hardware of the FINESS is based on a digital gamma ray spectrometer with data acquisition system, with a built-in planar HPGe detector optimized for the energy of noble gas isotopes of interest (mainly the Kr and Xe isotopes), collimator and shielding. Shielding reduces the radiation from high energetic photons and suppresses Compton continuum. In addition, there is a sample chamber with manually or automatically adjustable volume, which can be optimized in order to yield required sensibility over a certain range of energies corresponding to specific nuclides. The sample chamber is also equipped with pressure and temperature transmitters. FINESS also contains ^{241}Am source and a pulser as an energy reference for internal calibration. The HPGe-detector can be cooled by a cryostat with liquid nitrogen or by electrical cooling [1-3]. The data is processed by the software Gamma Vision developed by ORTEC and a software developed by Westinghouse for normalization of measurements and for setting off alarms [1-3]. The analysed data is then transferred to a Microsoft Access database where it can be retrieved from for further analysis [1-3].

FINESS has also shown to be a useful tool at flux-tilting or PST procedure [3], since the optimized prompt measurements can reduce the time needed to complete the test, thus reducing costs for the plant and man dose to personnel present during the testing. PST is a procedure based on one at a time control rod movements and performed at reduced power

(normally between 50 and 80% of nominal power). The main purpose of flux tilting is to identify the location of a fuel cell with the leaking fuel rod or at least narrow the leaking area in the core. By partly inserting one control rod at the time in the fuel cell the power is suppressed locally which changes linear heat generation (LHGR). The insertion of a control rod will convey the temperature drop, resulting in shrinking of the pellet and thus opening the gap between pellet and the cladding. This improves the communication and distribution of the gas in a fuel rod. The effect will be an opposite one later during withdrawal of a control rod, e.g. the temperature will increase and pellet swells again. This behaviour cause the cracking of pellet releasing the gas from the UO_2 matrix to the free volume of the rod and consequently to the coolant. These control rod movements cause the cracks open and close, resulting in a transient release of noble gases from the failure. Radioactive noble gas released due to this cause is then transported to the off-gas system where the enhanced activity registered, showing the location of a leaking cell. However, to implement a successful power suppression testing test accurately determined delay time is an essential factor, where the delay time is the time it takes for gas to be transported from the core to the sampling point.

Coolant activity measurements

In addition to the off-gas activity monitoring, analysis of reactor coolant grab samples are also performed on a regular basis, where iodine, caesium and neptunium nuclides are monitored in order to follow-up a failure and its possible degradation.

Detection of increased concentration of iodine isotopes in the coolant is a signature of fuel in direct contact with the reactor coolant. Release of the long-lived iodine, particularly ^{131}I is 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. Increase of caesium 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, neptunium nuclides in the coolant is an indication of fuel pellets, or fissile in direct contact with the coolant with the subsequent wash out of the fissile material from the failure. However, neptunium cannot be used as a measure of released amount of fissile material if HWC is applied, since then unsolvable neptunium components are also created that are not released in the reactor water.

At some units an increased level of iodine in the coolant is used as an indication of a fuel failure instead of the off-gas activity increase. Although this method gives slower response and might not be as reliable, since small fuel failures might exist in the core without causing an increased level of iodine.

2.3.2 During outage

Sipping is the best method to detect and locate a leaking fuel assembly, however it can only be performed during outage when reactor is shut down and the lid of the reactor core is open. Often sipping is carried out after the flux tilting in order to verify the location of a failure in

the identified area of the core. Sometimes a whole core sipping can be necessary if there is an uncertainty in the location of a failure in the core or suspicion of several failures. Sipping is implemented at both BWRs and PWRs and often can be done without time loss during the fuel shuffling. There are several types of sipping methods that are available, below follows a short description of the most common sipping methods [3, 10, 11].

Elevate sipping. At elevate sipping a hood is placed over the rod, which is then elevated a bit (between 0.5 and 4 meters) before the water sampling is performed. The higher the elevation the more accurate the results of measurements due to the increase of the internal relative pressure of the rods in relation to the water pressure. Water sample is sampled and degassed. The gas, released from the leaking rod, is measured with gamma-sensitive NaI detector. At the same time water samples are taken out and degassed for nuclide specific estimation by measurements with a semi-conductor detector, usually Ge-detector. The method is often used in combination with PST/flux tilting. Only the assemblies suspected to be leaking and some of the nearby assemblies undergo elevate sipping.

TELESCOPE sipping. This method was developed by Westinghouse Electric Company (former ABB Atom). The technique is based on depressurisation of the elevated rod caused by elevation of a fuel assembly. Depending on redistribution or replacement of the fuel assembly it elevates 4 or 13 m respectively towards the reactor water surface. The pressure drop will cause the outflow of fission products from the failure into the coolant. Pipes collect water samples from a water channel inside a fuel assembly (BWR) or from the refuelling machine mast (PWR). The water samples are degassed, separating gas incorporated in the collected water and activity measurements of the gas are carried out. Gas analysis performed by TELESCOPE sipping shows mostly ^{133}Xe-isotope, which is dominating gas nuclide in a recently used fuel. This process can also be used for leakage determination on irradiated fuel assemblies which have been stored in the storage pool for up to 2-3 years. In that case the ^{85}Kr is the gas-isotope to be measured, because of short half-life of ^{133}Xe (5.3 days). The advantage of TELESCOPE sipping equipment is usage of two detectors: beta sensitive and gamma sensitive. The benefit of beta detector is that it has a low background activity level.

In-Core or **Hood sipping.** The technique was developed by General Electrics. The hood tightens to the upper end of fuel boxes covering from four to sixteen fuel assemblies at the time. By injection of compressed air over the upper part of the fuel stops the cooling water flow. This causes an increased heat generation and subsequent increase of temperature inside the rod, resulting in release of noble gases from the damaged rod. The collected water samples undergoes degassing, and gas activity is measured by the detector connected to the hood or analysed in the plant laboratory using spectroscopy. The water communication between the assemblies is terminated allowing separated water sampling from each assembly. Hood sipping does not affect the fuel by depressurisation as other methods since there is no need for moving assemblies or perform an elevation.

Canister sipping. This kind of sipping is performed in canisters in the spent fuel pools. By raising the temperature and reducing the pressure in the canister the fission products are released from a failed rod. Measurements are either carried out by analysing water and gas samples on-line or in the active laboratory.

In addition there are visual inspections performed during outage by using underwater cameras inserted in the core. Careful observations of monitored fuel assemblies in order to detect abnormalities, as for example gas bubbles from the elevated assembly, help the decision of actions to be taken or the interpretation of the sipping results.

Chapter 3

CONTROL ROD FAILURES

This chapter includes a brief description of the functions of the control rods in the core and presents an overview of the mechanisms leading to control rod failures, as described in Paper II. Available methods for detection of control rod failures at NPPs, presented in Paper II and Paper V, are also covered in this chapter.

The main function of control rods in a nuclear reactor is to shape the power distributions and control the reactivity. In a BWR, the output of the thermal power is regulated by control rods together with the reactor's re-circulation pumps. In addition to the regulation of power, control rods are also used for shutting down the reactor. The rods that are used for both regulating the power and for shutdown of the reactor are classified as regulating rods while rods that are only used for shutdown are called shutdown rods. Control rods in regulating position are partly to fully inserted in the core during the reactor operation and therefore the most exposed ones to the neutron irradiation which causes fast absorber depletion. Shutdown control rods are fully withdrawn during operation and are only inserted during the shutdown of the reactor. These rods are mostly irradiated at the tip due to neutrons leaking from the bottom of the core. Occasionally shutdown rods can also be partly inserted in the core which increases the exposure.

Although there is a number of control rod designs, only the most common designs will be described below. Generally control rods used in a BWR have a cruciform shape with four wings/blades which are inserted between fuel channels in predefined interstices. Control rods are filled with neutron absorber, which in BWRs can be either B_4C, a combination of B_4C and hafnium (Hf), or only Hf. In the. Marathon control rods designed and manufactured by General Electrics, a number of thin vertically oriented tubes are welded together forming a wing. The tubes are filled with capsules containing B_4C powder, Hf rodlets or empty capsules. The tubes serve as individual pressure vessels since there is no communication between the tubes in a control rod wing. Another common control rod design, used in BWRs is the CR99, designed and manufactured by Westinghouse Electric Company. It consists of four stainless steel blades with horizontally drilled channels filled with B_4C as the neutron absorber. In this

design B_4C is introduced in form of hot isostatic pressed (HIP) pins. The channels are communicating within a blade by a vertical channel on the outer edge of the blade, connecting all the channels.

3.1 Primary control rod failures

The operational life of a control rod in the core of a reactor is limited by its mechanical properties mainly due to a phenomenon called irradiation assisted stress corrosion cracking (IASCC). IASCC is a failure mechanism which can occur in steel components of a reactor, when exposed to a combination of certain conditions, such as extensive radiation, stress and corrosive environment. The operational function of a failed control rod is generally not affected, although the degradation of a failure and possible subsequent washout of some amounts of control rod contents (e.g. absorber material and reaction products) may lead to lower efficiency of the reactor due to boron wash out and/or might cause changes of the coolant properties, e.g. an increase of coolant conductivity and pH level due to LiOH release.

Radiation damage

The influence of the neutron fluence on ISSCC has been well established. Irradiation of metallic components of the reactor by neutrons can cause significant changes in the mechanical and metallurgical properties, which play a major role in stress corrosion cracking resistance. These changes can include radiation hardening, radiation enhanced creep, helium and hydrogen embrittlement and radiation induced segregation (RIS) [12]. In case of control rods, the effect of segregation is of high importance. When irradiated with fast neutrons, displacement of atoms occur creating vacancies and interstitial point defects. The vacancies and defects which do not recombine, migrate to surfaces, dislocations and grain boundaries. This leads to a redistribution of alloying elements in the material and segregation of impurities (e.g. S, Si, Ni, P [13]), creating enriched areas of certain elements near the surface or grain boundaries [12, 14, 15]. The conditions for segregation depend also on the ratio between temperature and the dose rate [14, 15], as shown in Figure 1.

Oxidizing environment

Corrosive environment, which is one of the factors contributing to IASCC, occurs due to the radiolysis of reactor coolant water. When water absorbs ionizing radiation present in the core, it is dissociated creating molecular, ionic and radical reaction products, such as H_2, H_2O_2, e^-_{aq}, H, OH, H^+, HO_2. These products in turn interact, and molecular products H_2, O_2 and H_2O_2 are formed [12]. Such molecular products affect the electrochemical potential which increases the susceptibility to IASCC with increase of dissolved oxygen. Numerous tests have shown that electrochemical potential of irradiated stainless steel increases significantly with increasing dissolved oxygen while it decreases in the hydrogenated water [12]. During tests performed on high-stress material and by applying slow strain rate on post-irradiated material, cracking was not observed in hydrogenated water. Material cracking appeared in hydrogenated water when a fluence 4 times greater than the fluence caused cracking in oxidizing

environment [16]. Another observation that was made shows that critical value for the electrochemical cracking potential decreases with increasing temperature [17].

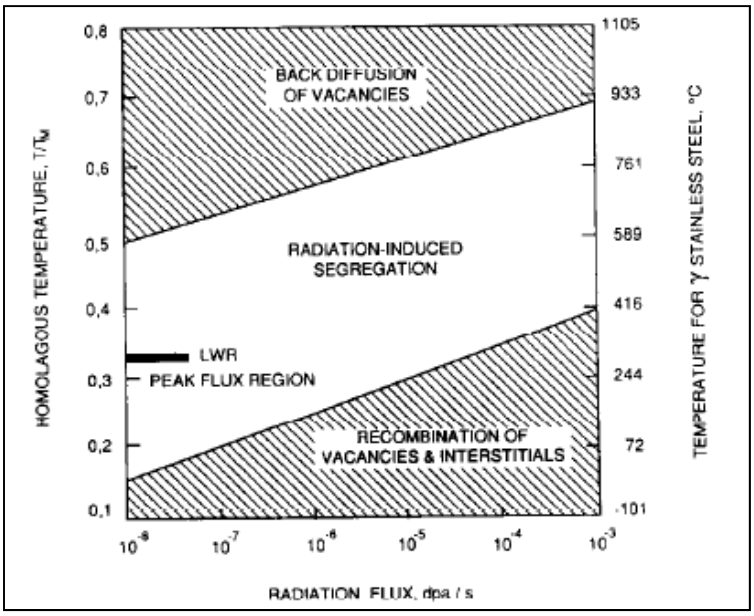

Figure 1. Effect of temperature/flux on radiation induced segregation [14, 15].

Stresses due to boron carbide swelling and helium gas pressure

The stress inside a control rod is induced by 1) consolidation and subsequent swelling of B_4C material, in particular if B_4C is in form of vibratory compacted powder, and 2) internal pressure build-up due to irradiation induced helium generation. The B_4C powder consolidates into a solid cake under the influence of radiation. This consolidation is already initiated at a very low burn up and is the reason why the original free volume of 30% for B_4C powder is not available for swelling accommodation [18].

When boron is irradiated by fast and thermal neutrons, reactions (3)-(6) are taking place, forming species like helium, tritium, lithium and others [19].

$$^{10}B + n_f \rightarrow {}^{3}H + 2\,{}^{4}He \qquad \sigma = 2.5 \cdot 10^{-26}\ \text{cm}^2\ (E_{th}\ 1.0\ \text{MeV}) \qquad \textbf{(3)}$$

$$^{11}B + n_f \rightarrow {}^{3}H + {}^{9}Be \qquad \sigma = 1.5 \cdot 10^{-26}\ \text{cm}^2\ (E_{th}\ 10\ \text{MeV}) \qquad \textbf{(4)}$$

$$^{10}B + n_{th} \rightarrow {}^{7}Li + {}^{4}He \qquad \sigma = 3.8 \cdot 10^{-21}\ \text{cm}^2\ (\text{thermal}) \qquad \textbf{(5)}$$

$$^{7}Li + n_f \rightarrow {}^{3}H + n + {}^{4}He \qquad \sigma = 8.5 \cdot 10^{-26}\ \text{cm}^2\ (E_{th}\ 2.4\ \text{MeV}) \qquad \textbf{(6)}$$

From the cross sections and threshold energies for the reactions (3)-(6), it is apparent that the reaction with thermal neutrons forming helium and lithium is dominating. The most

abundant product of these reactions is helium, which is mainly retained within the boron carbide structure forming internal pockets in the dislocations and the grain boundaries, as shown in Figure 2, which also causes swelling of the absorber material [20].

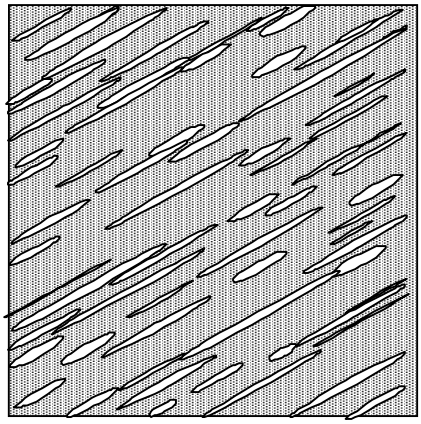

Figure 2. TEM image of irradiated B_4C and He bubbles [20].

A fraction of the formed helium diffuses through the boron carbide structure into the inner free volume of the rod, contributing to the rod's internal pressure build up [20, 21]. Due to the consolidation the propagation of the swelling neutron absorber into the free volume of a rod is limited, causing the increase of stress on the stainless steel of control rod walls [18]. The contents of helium in the rod and, subsequently, the swelling of the neutron absorber and the internal pressure are increasing with the depletion of boron.

3.2 Secondary control rod failures

When a primary crack occurs on a control rod, the gas inside the rod leaks out into the coolant due to the overpressure in the rod. Once the pressure equilibrium is reached, the neutron absorber becomes is to a coolant. Coolant eventually enters the rod and causes a disintegration of the neutron absorber leading to a release of the helium which was captured in the boron carbide lattice. Furthermore, small particles that are produced due to the disintegration of the absorber material might be washed out into the reactor coolant [18]. Boron can also leak out into the reactor water, which might lower the efficiency of the reactor.

Secondary cracks are either additional cracks that can occur after a primary crack or further widening and propagation of an already existing a primary crack. The occurrence of additional cracks has been mostly observed in rods containing hafnium due to its expansion as a result of the hydriding of the hafnium when in contact with the coolant. This results in hafnium crystal structure swelling which induces stress on the walls of a control rod with possible cracking [9].

A propagation of cracks occurs due to additional swelling of the material structure inside a control rod. This occurs due to a coolant reaction with lithium and formation of lithium hydroxide, which has larger volume than lithium, resulting in the swelling acceleration [9].

3.3 Detection of control rod failures

3.3.1 During operation

Detection of control rod failures is usually performed by monitoring the tritium activity ($t_{1/2}$ = 12.3 years) in periodically taken grab samples of the reactor coolant and charcoal samples from the off-gas chimney. Continuous production of tritium in a control rod due to irradiation was shown by reactions (3) - (6) and the amount of formed tritium in a control rod depends on rods positions in a core, i.e. whether a rod is used is a regulating position or in a shut down position. Another method implemented at some nuclear power plants, e.g. at KKL, is monitoring of the boric acid level in the coolant. Both monitoring methods assume the coolant ingress and release of some amounts of the rod content into the coolant, including tritium and boron particles. However, none of these methods gives an immediate indication of a failure since samples are only taken once a week or even less frequently. In addition, a release of the rod content assumes a disintegration of the boron carbide matrix by the coolant water, as e.g. most of the tritium is tied up in the matrix. Such decomposition of the irradiated boron carbide structure and subsequent release of material into a coolant are rather slow processes. Consequently, the immediate release of tritium from a primary crack would be insignificant. The analysis of coolant for increase of tritium or boric acid concentration could be further complicated by different amounts of coolant water replaced and refilled due to recycling or water leakage which changes the concentration of the species of interest in the coolant.

The detection using monitoring of boric acid in the coolant can be improved by applying a plant specific boron mass balance model, as has been done at e.g. KKL, and determining boron amount in the coolant water of the reactor, based on the measurements of the boric acid. This can give additional valuable information about the severity of a crack and the remaining effectiveness of the leaking control rod.

Although boron in the coolant can also originate from other sources than leaking control rods, such as standby liquid control systems, corrosion inhibitors, detergents, etc., the difference in isotopic ratio and depletion would point out the origin of the boron present in the coolant.

3.3.2 During outage

During outage the most efficient way to reveal cracks in control rods is by visual inspections by inserting a camera in the core after that the reactor pressure lid has been removed. It is however a time demanding process which might increase the time for outage. There is also a

risk of increased man dose rate during such procedure because of the open lid and close proximity to the reactor. However, because of the human factor, sometimes cracks can be missed and defect control rods left in operation for another cycle.

Chapter 4

HELIUM INVENTORY IN FUEL AND CONTROL RODS

Both fuel and control rods contain helium which would leak out is case of a failure. Details regarding helium's origin and its accumulation during operation in each case are presented in this chapter.

4.1 Helium inventory in fuel rods

The amount of helium in a fuel rod is generally considered to be about 80 ml, which will also be shown in Sec. 4.1.1 and Sec. 4.1.2. The main contribution to a helium amount contained in a fuel rod is due to injection of helium into a fuel rod during the manufacturing process. Furthermore, the production of helium in uranium dioxide fuels for BWRs during operation is insignificant and can be assumed negligible, as will be shown in Sec. 4.1.2.

4.1.1 Due to fuel manufacturing

During fabrication of fuel, inert gas, such as helium, is commonly used for pressurization of fuel rods. The gap between pellets and cladding is filled with helium to improve heat transport from the pellet and, particularly for PWR fuel, to withstand the higher external coolant pressures in the reactor core and prevent tube collapse. The design and requirements for a fabricated rod and, consequently, fill up pressure can vary depending on the type of reactor the fuel is to be used in, nevertheless, usually BWR fuel rods are pressurized to 3-4 bar atmospheric pressure. Using ideal gas law the amount of helium filled in at pressurization can be determined if the free volume of a rod and the fill up pressure are known. For a standard length rod pressurized to 4 bar, the amount of helium was determined to be $3\text{-}4 \times 10^{-3}$ moles [4], which corresponds to about 80-100 ml at standard pressure and room temperature conditions.

4.1.2 Helium production during operation

The contribution to the helium inventory in the fuel rod during operation is insignificant, since only a small part of helium is produced due to the irradiation of the fuel in a reactor. The main contributors to the helium production are listed below [4, 22]:

1) α-decay of transuranic elements, mainly ^{242}Cm and lesser extend of ^{244}Cm
2) ternary fission
3) $^{16}O + n \rightarrow {}^{13}C + \alpha$

Most of the transuranic elements decay by α-process, where the main contribution of helium in UO_2 fuels is from ^{242}Cm, which stands for about 90% of the helium production from transuranics. The occurrence of ^{242}Cm and ^{244}Cm in the fuel originates from respectively ^{241}Pu and ^{242}Pu. The production of helium in these cases is related to their short half-lives, compared to other α emitting transuranics: 163 days for ^{242}Cm and 18 years for ^{244}Cm. Helium production generated due to α-decay of transuranic elements is 0.3% helium atom per equivalent fission generated from transuranics. Apparently, generation of helium is considerably higher for MOX fuels since larger amount of plutonium isotopes are present in the fuel during operation. The neutron capture reaction ^{16}O(n,α)^{13}C, that requires fast neutrons with energies higher than 2.36 MeV and generates 0.6% helium atom per equivalent fission. Finally, ternary fission also has a low rate of helium atoms generation per fission, about 0.2-0.3%. Thus, the total helium production in a fuel rod during operation is 1.2% helium atom per equivalent fission [4, 22]. This number gives low contribution of helium to the build-up of the rod's internal pressure during operation, however, it might be of concern at a long time storage, particularly in case of MOX fuels.

An example of the accumulation of helium, xenon and krypton with burn-up of the rod is illustrated in Figure 3. The example is an output of STAV6 calculation for a selected fuel rod of SVEA-96 Optima2 design by Westinghouse Electric Company, with the enrichment of ^{235}U of 4.9% and fill-up pressure of the rod at room temperature of 0.4 MPa. The assembly, which contains the rod chosen for this example, has been in operation for four years and has a high average burn-up of 48.7 MWd/kgU. As it can be seen in the diagram the amount of helium in a selected fuel rod is 3.5×10^{-3} moles before the irradiation, i.e. due to fill up at fabrication, which is in a good agreement with the numbers given in Sec. 4.1.1. When the burn-up reaches almost 48 MWd/kgU, the inventory of helium increased by 0.6 moles, which is the amount gained in four years period of time. This corresponds to about 15 ml of helium at standard pressure conditions and room temperature.

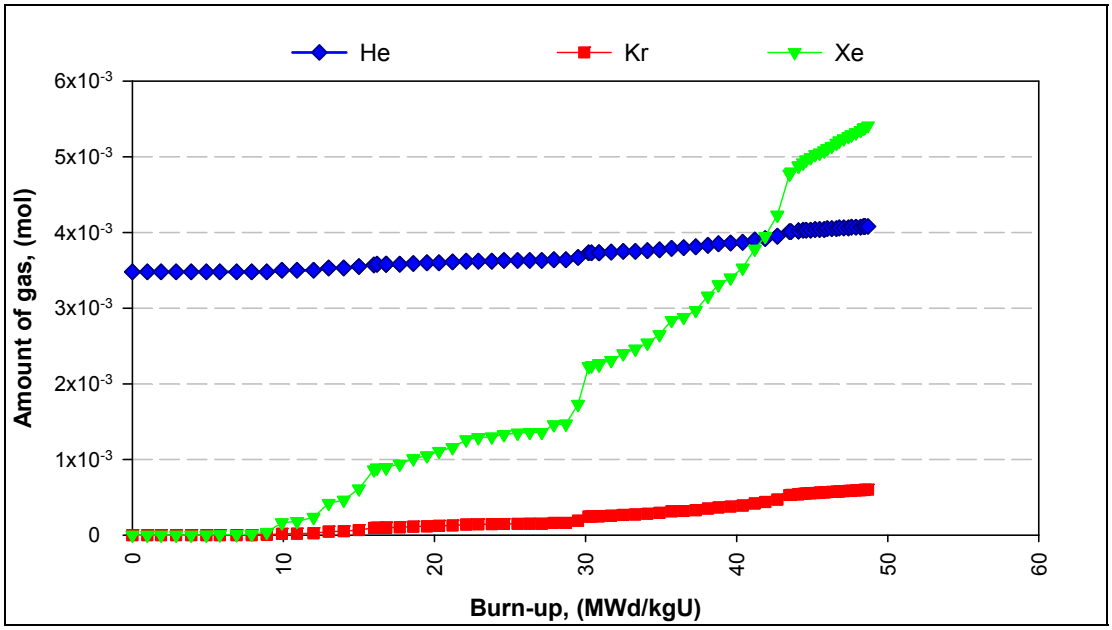

Figure 3. Gas inventory in a fuel rod due to the burn-up [4].

4.2 Helium inventory in control rods

The inventory of helium in a control rod is partly from manufacturing and partly from accumulation during operation due to the irradiation of boron with neutrons. However, on the contrary to the fuel rod, most of the helium inside a control rod is generated during operation.

4.2.1 Due to control rod manufacturing

In the Beginning of Life (BOL), a control rod contains a small amount of helium, which is injected during the fabrication of the rod. The amount of helium injected in the rod corresponds to a pressure of one atmosphere at room temperature, i.e. control rods are not pressurized in the same way as fuel rods. Yet, the injected helium is used for leak testing and welding tightness during quality control. A free volume of a tube (design 1) or a wing (design 2) of a control rod, described in Ch.3, was difficult to find out, however, it is assumed that amount of helium injected in a control rod at manufacturing is negligibly small compared to the helium generated during operation.

4.2.2 Helium production during operation

When boron carbide is exposed to a neutron fluence, several reactions are taking place, as it was described in Sec. 3.1. Based on the cross sections for different reactions, shown in Sec. 3.1, it was established that the reaction (5) is the dominating reaction for thermal neutrons. As was already mentioned, the generated helium mostly remains in the boron

carbide structure, but some part of it is released in the void volume of a tube or a control blade, depending on the design of the rod.

The amount of helium produced due to neutron irradiation ^{10}B during operation and subsequently released into the control rod's void volume, can be determined if the neutron absorber (B_4C) quantity in the rod is known. The estimation is based on the assumption that each ^{10}B atom produces one helium atom when undergoing a reaction with a thermal neutron [4].

The amount of He in the void volume can be estimated according to Eq. (7) [4].

$$\boldsymbol{n_{He} = \frac{m_{B_4C}}{M_{B_4C}} \cdot \sigma \cdot \tau \cdot U \cdot He_{B_4C}}, \quad \textbf{(7)}$$

where

n_{He} – amount of He released into the void volume, (mol),
m_{B_4C} – mass of B_4C, (g),
M_{B_4C} – molar mass of B_4C, (g/mole),
σ – ^{10}B abundance in naturally occurring B,
τ – number of B atoms in a B_4C molecule,
U – ^{10}B depletion,
He_{B_4C} – fraction of He release.

The amount of 1 mole corresponds to a 22.4 l gas at standard pressure and temperature conditions (STP), i.e. temperature of 0℃ and atmospheric pressure. However, the temperature at the sampling point is about room temperature, assume 25℃. Thus, the volume of the released gas can be calculated according to Eq. 8.

$$\boldsymbol{V_{He} = G_0 \cdot \frac{T}{T_0} \cdot n_{He}}, \quad \textbf{(8)}$$

where

V_{He} – volume of He released into the void volume of a blade/tube, (l)
G_0 – gas volume in 1 mole at STP, (l/mol),
T_0 – temperature at STP, (273.15 K),
T – temperature of interest, (K),
n_{He} – amount of He released into the void volume, (mol).

The release fraction of the generated helium from the boron carbide matrix depends on 1) boron depletion, and 2) the structural material of the absorber. The gas release from the B_4C powder is larger compared to that from a HIP pins, which can be obtained using respectively Eq. (9) and Eq. (10) [4].

$$He_{B_4C(powder)} = 0.04 + 0.16 \cdot U \quad (9)$$

$$He_{B_4C(HIP\ pins)} = \frac{7}{55} U \quad (10)$$

where
$He_{B_4C(powder)}$ – fraction of He release for B_4C powder,
$He_{B_4C(HIP\ pins)}$ – fraction of He release for B_4C HIP pins,
U – ^{10}B depletion.

The release fraction of helium increases with increased ^{10}B depletion. However, this fraction is lower for HIP pins compared to B_4C powder due to the higher density of HIP pins. Assuming that the mass of B_4C powder is less than 200 g in one tube of a control rod of Marathon design, helium amount released from a boron carbide structure and present in a void volume of a tube can be determined using Eqs. (7)-(9). The results of such calculation are shown in Figure 4. In the same way, assuming less than 2.5 kg of B_4C in form of HIP pins in a CR 99 design control rod [23], and implementing Eqs. (7), (8) and (10), the helium amount in a void volume of a CR 99 blade depending on its depletion can be calculated. This is also illustrated in Figure 5.

Using Figure 4 and Figure 5, the amount of helium present in the void volume of a tube or a blade in a certain rod which would leak out in case of a failure can be obtained, if the average boron depletion of a rod is known.

In Figure 6 and Figure 7 examples of two of the rod designs used in regulating positions in the reactor at KKL are shown. The accumulation of helium in a tube void volume of a Marathon control rod can be obtained by using Figure 4 and an average ^{10}B depletion of a rod. The average ^{10}B equivalent depletion can be obtained from the ^{10}B nodal depletion calculated by Helios/Presto2 code. The average equivalent depletion of a rod is 30.3%. Then the expected amount of helium accumulated in each tube of a rod is 1.5 liters, which was estimated by the intersection of curves of the released helium and the average ^{10}B depletion. In the same way, using Figure 5, the expected amount of helium accumulated in each of four blades was determined to be 5.3 liters if the average rod boron depletion of a CR 99 control is 22.0%, as shown in Figure 7.

The estimation of the helium amount in a control rod blade based on average ^{10}B depletion of the rod is a rough approximation. Since different parts of the rod have different depletion, because of the unequal exposure to neutron fluence, helium release fraction might also vary, as it is based on the depletion. A better accuracy of helium accumulated in the rod can be obtained from the nodal depletion of a rod. In addition, when talking about the equivalent average depletion of a Marathon control rod, Hf exposure to the neutron fluence is also taken into account. This may lead to some uncertainty, resulting in somewhat higher value for helium in a free volume of a rod. This has to be considered when more careful analysis is required.

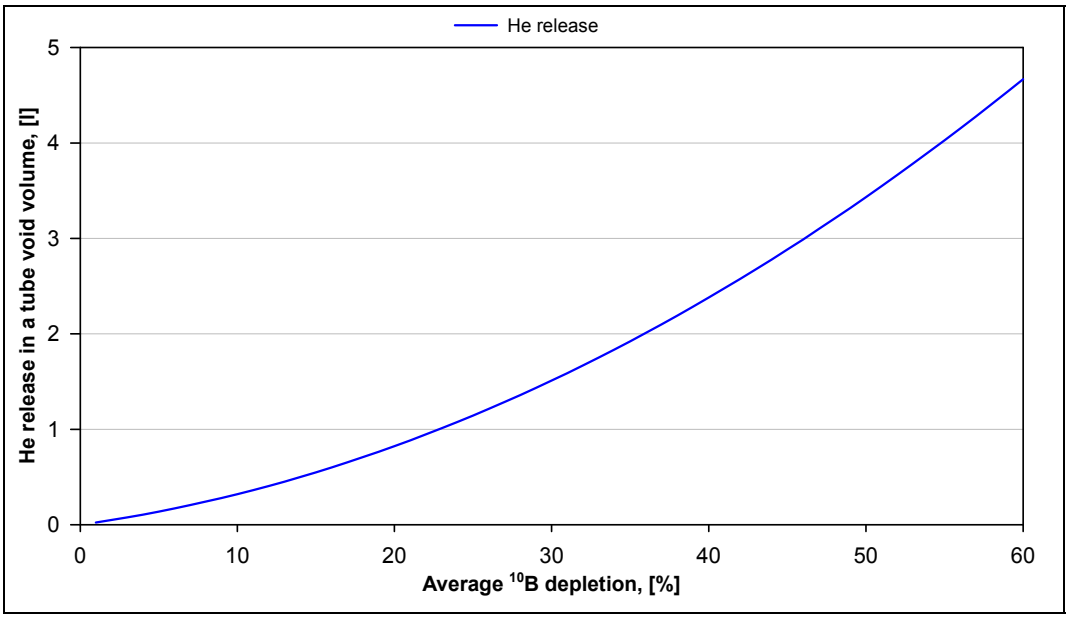

Figure 4. He inventory in a Marathon tube void volume at KKL depending on ^{10}B depletion.

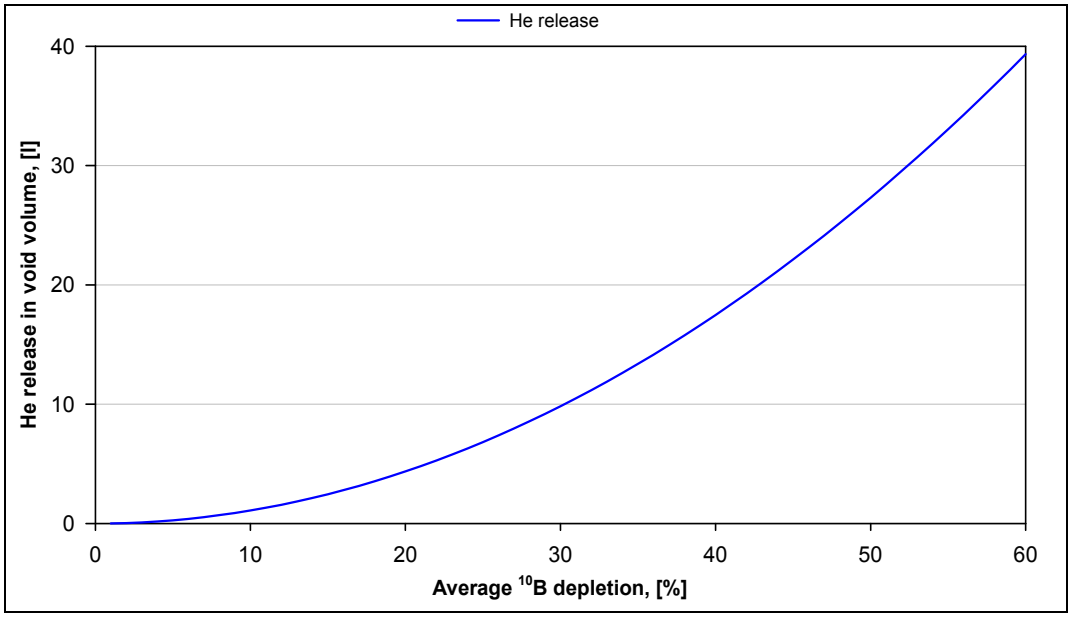

Figure 5. He inventory in CR 99 blade void volume used at KKL depending on ^{10}B depletion.

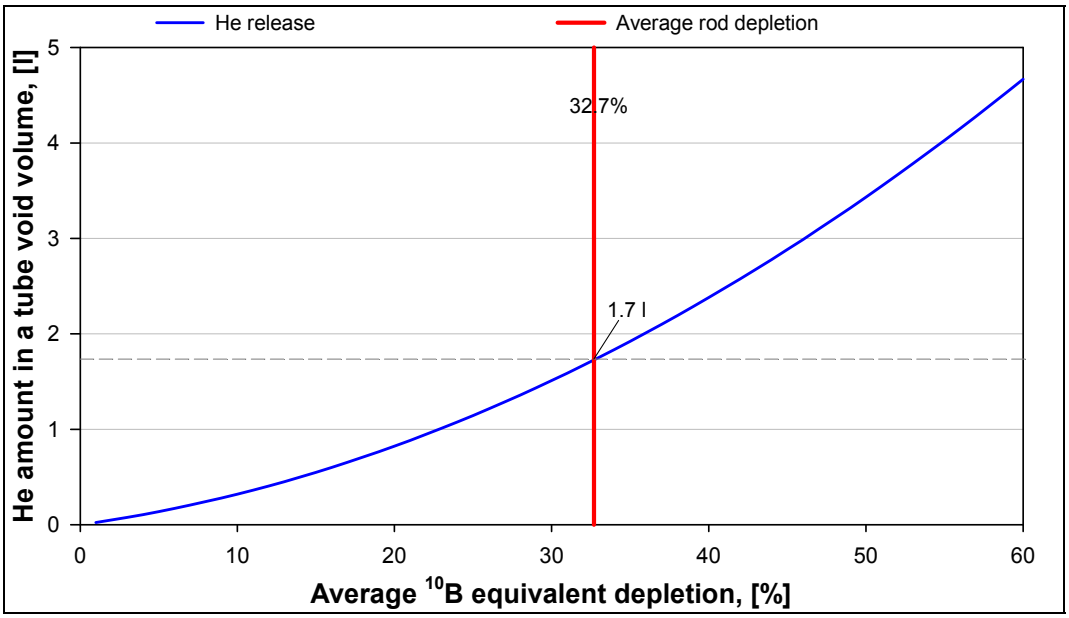

Figure 6. He in a tube void volume of a Marathon control rod.

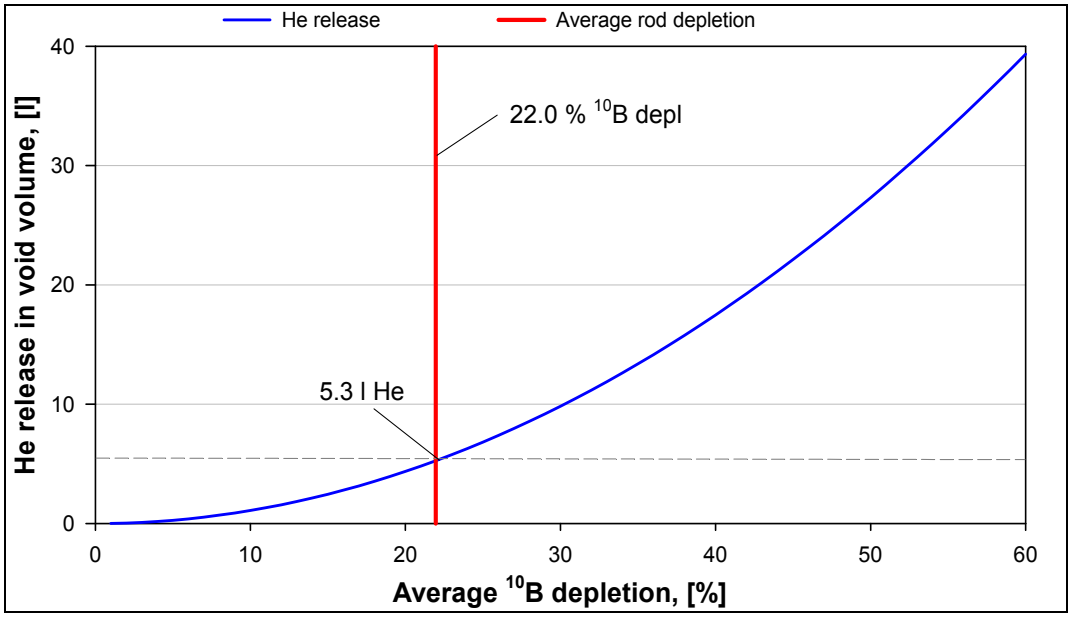

Figure 7. He amount in a blade void volume of CR 99.

Chapter 5

ON-LINE MEASURING SYSTEM AT KKL AND FORSMARK

In this chapter a system for detection of fuel and control rod failure is explained. Such a measuring system is installed at KKL and Forsmark 3. Details of each system at both NPPs and their differences are given in this chapter. This is also described in more or less details in Papers I, III-VII. A general description of how a mass spectrometer is working and the technique for measuring helium is also included in this chapter.

The measuring system at KKL and Forsmark is a combined detector system for on-line measurements of gamma emitting noble gases and helium. On-line spectroscopy for gamma emitting noble gases is based on an HPGe-detector, while the helium detection system is based on a mass spectrometer.

5.1 Principle of helium detection technique

The most efficient way to detect helium is to use a mass spectrometer. The measurements are based on measuring a stream of helium ions, which is proportional to the partial pressure of helium in the system. The principle of a detector design is shown in Figure 8. The main components of a mass spectrometer are an ion source with a cathode, a magnetic separator and an ion collector. Gas molecules flow into the mass spectrometer passing through an ionization chamber (3), where the molecules are ionized by the ion source. A filament (1) of heated tungsten is usually used as an ion source, which transmits the electron beam, that hits the gas molecules to achieve the ionization. These positively charged particles are then accelerated in the magnetic field. The purpose of the magnetic field is to deflect the ions and to force them to follow a circular path of a certain radius, which depends on mass-to-charge ratio (m/e) of the ions. The higher the m/e-ratio, the larger radius of circular path which the charged particles will follow. When m/e=4 is selected, which is normally the default setting when using a mass spectrometer for helium measurements, only the helium ions can pass the

diaphragm (5) and reach the ion collector ("target"). In the ion collector, the stream of ions is measured as an electrical current [24, 25]. The triode electrode (4) collects ions of higher mass than helium. It is also used for measuring the total pressure inside the analyzing cell. Some detectors are also equipped with "braking electrode" (6) placed before the target. Its function is to eliminate secondary, low energy ions [24].

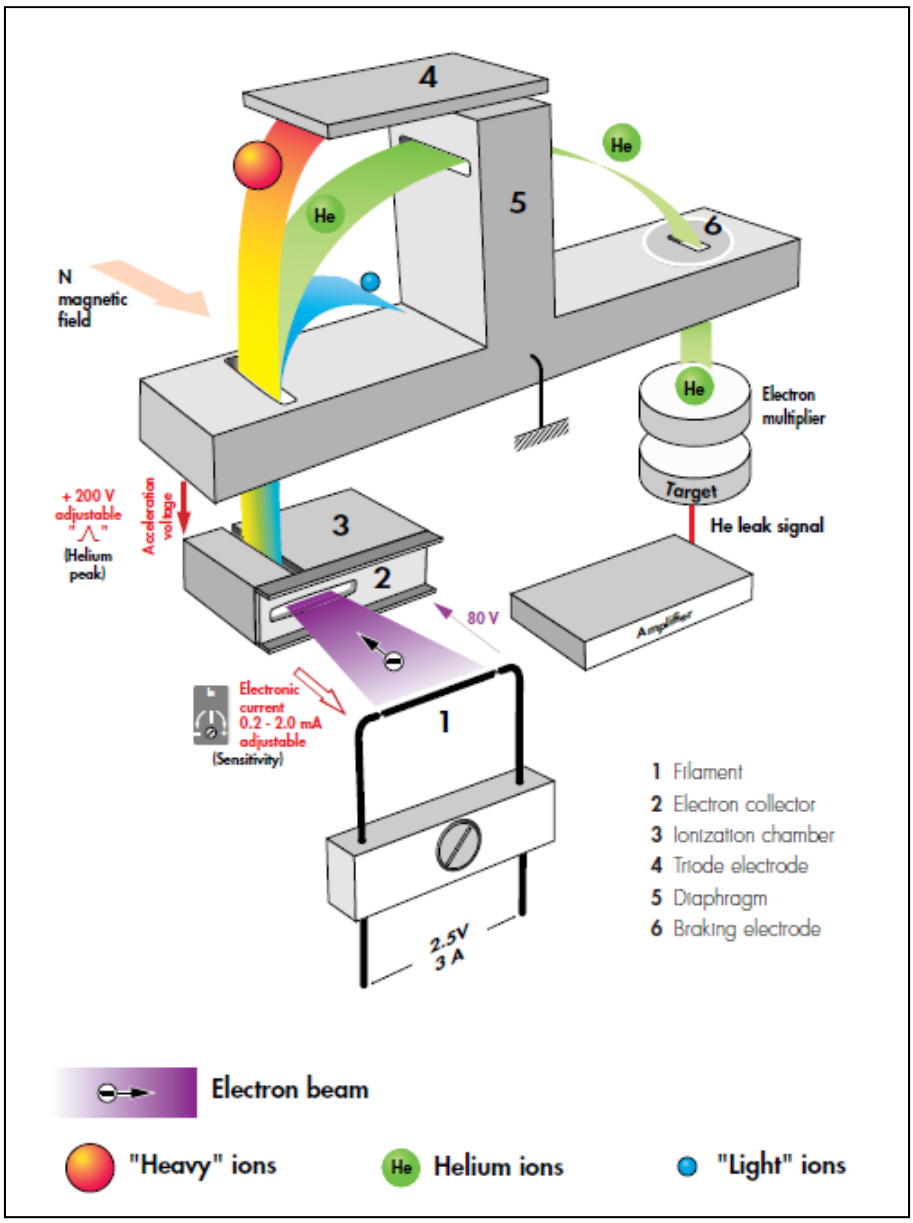

Figure 8. Operating principle of the analyzing cell of a mass spectrometer [24].

In order to prevent the measured stream of ions to be disturbed by other particles during the operation, the mass spectrometer requires a vacuum level below $1x10^{-4}$ mbar. This vacuum level is usually provided by the combination of a fore vacuum pump (e.g. rotary vane pump) and a turbo molecular drag pump [24, 25].

5.2 Measuring system at KKL

The measuring system at KKL includes a system for on-line measurements of gamma emitting nuclides and a system for measuring helium. This combined system for detection of fuel and control rod failures at KKL 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 9. There are two different measuring modes, depending on the location of sampling. The first mode is performing direct measurements, where the off-gases are taken directly after the condenser and gas coolers. The second mode is a delayed measurement mode, where the sample line is attached to the off-gas flow pipe after an additional delay line, as can be seen in Figure 9. The delay line consists of several tanks, allowing short-lived nuclides to decay to long-lived daughters or to stable isotopes in the fission products decay chain. The function of the delay line at KKL is presented in more details in Paper V. 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. A schematic set up of the measuring system at KKL is shown in Figure 9.

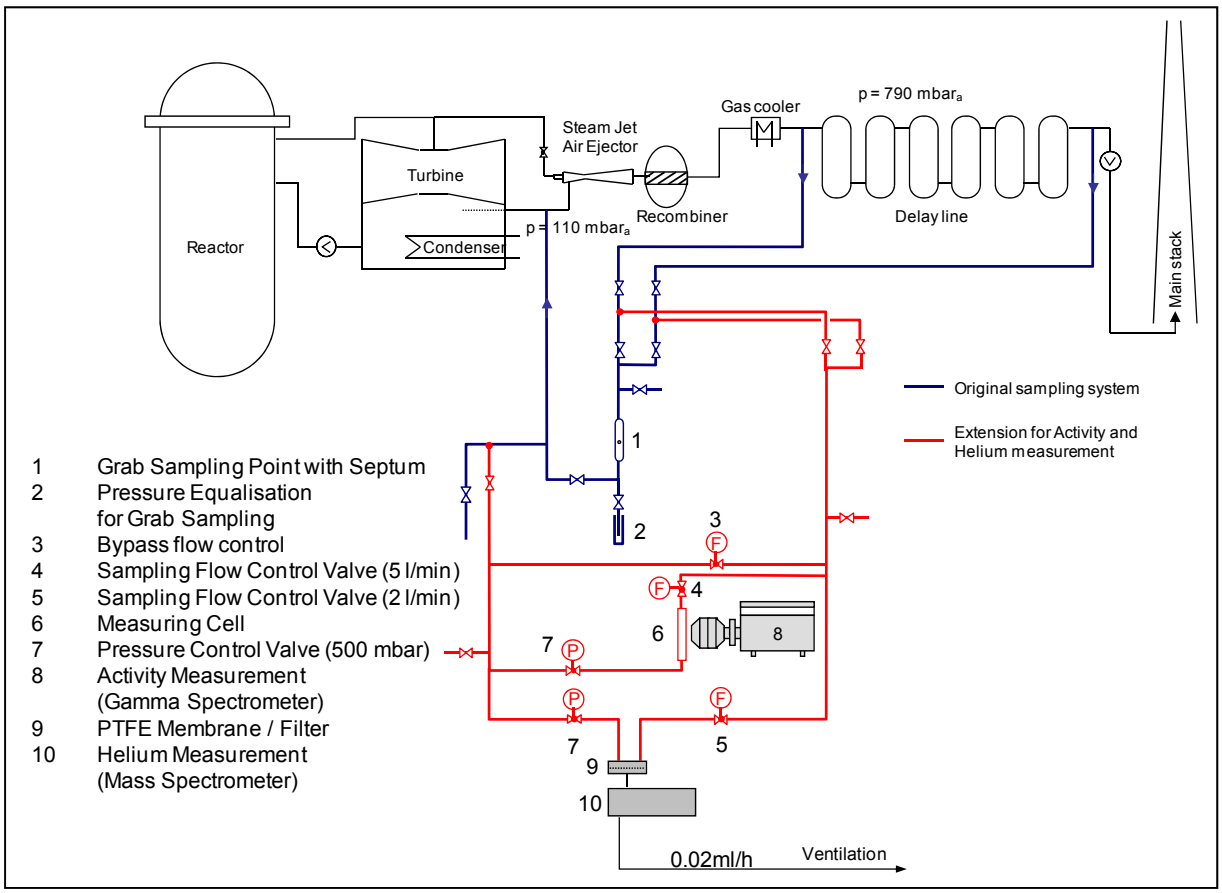

Figure 9. Schematic set up of the measuring system at KKL.

5.2.1 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 similar to the FINESS system described in 2.3, and 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 [1-3, 5]. The detector is operated by a single unit including high voltage supply, amplifier and digital signal processor at once. The communication with the PC runs via a USB interface. The gamma spectroscopy software is Genie 2000, developed by Canberra and used for continuous measurements and data analysis. The data are stored in a SQL data base. The data are visualized in the Core Monitoring System MinuteMan via Ethernet [5]. An activity increase of the monitored nuclides (mainly xenon and krypton nuclides and their ratios) is a strong implication of a fuel failure. A detailed description of the nuclide specific gamma emitting noble gas measuring system and its usefulness for detection of fuel failures are given in Paper I and Paper V. Furthermore, Paper I shows the efficiency of the system for identification of leaking fuel in the core during PST.

5.2.2 System for helium measurements

In September 2008, a helium measuring system was installed in the off-gas system in connection to the BEGe detector system. The main purpose of the helium measuring system at KKL is monitoring of control rod integrity. The system for helium measurements is based on a mass spectrometer which is build-in in a He-leak detector 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 vacuum mode, which is used for measurements at KKL, the minimum detectable helium leak rate is $5x10^{-12}$ mbar l/s at an inlet pressure lower than 0.2 mbar. The maximum helium 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 [25].

A gas separation cell with a PTFE membrane and a recorder for data acquisition and storage are also included in the helium detection system. To avoid contamination of the helium 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 in Figure 10. A detailed description of the cell and its purpose is given in Paper V. 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 recorder is connected to the Ethernet, and the accumulated data is stored in a file by the recorder and on a server where it can be retrieved for further analysis.

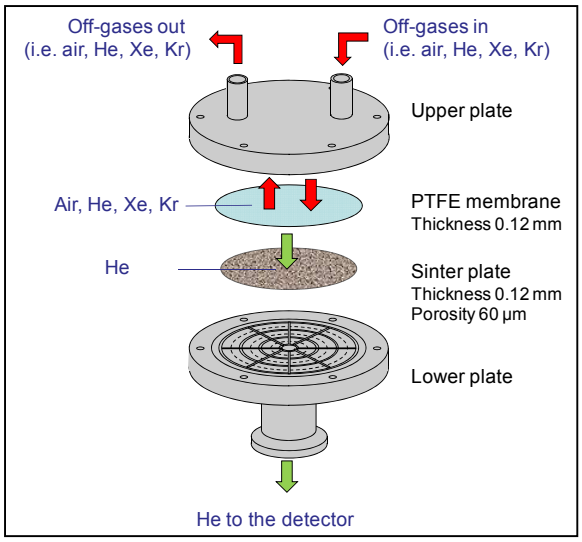

Figure 10. Schematic set up of the gas separation cell.

5.3 Measuring system at Forsmark NPP

The detection system at Forsmark 3 combines measurements of the gamma-emitting noble gases and measurements of helium. 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 11. The delay system at Forsmark 3 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 causing their disintegration. 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. Extensive description of the measuring system at Forsmark 3 NPP is given in Paper VI.

5.3.1 System for detection of gamma emitting noble gases

At Forsmark NPP the FINESS [1, 2] system is used as the nuclide specific measuring system for gamma emitting noble gases in the off-gas system. A detailed description of the FINESS system can be found in Sec. 2.3.1. However, the system used at Forsmark differs from the original system by some modifications that are presented in Paper VI, e.g. the HPGe detector used at Forsmark is not a planar detector. Furthermore, the system at Forsmark has a rigid non-adjustable collimator. An ^{241}Am source is available for internal calibration at the low energy part of the gamma spectrum, while the energy pulser with variable intensity for upper energy calibration, which is present in the original version of FINESS [1, 2], is not included in the installation. The measured data is stored at a PC. It can later on be extracted on an external HD connected to the USB port for further analysis.

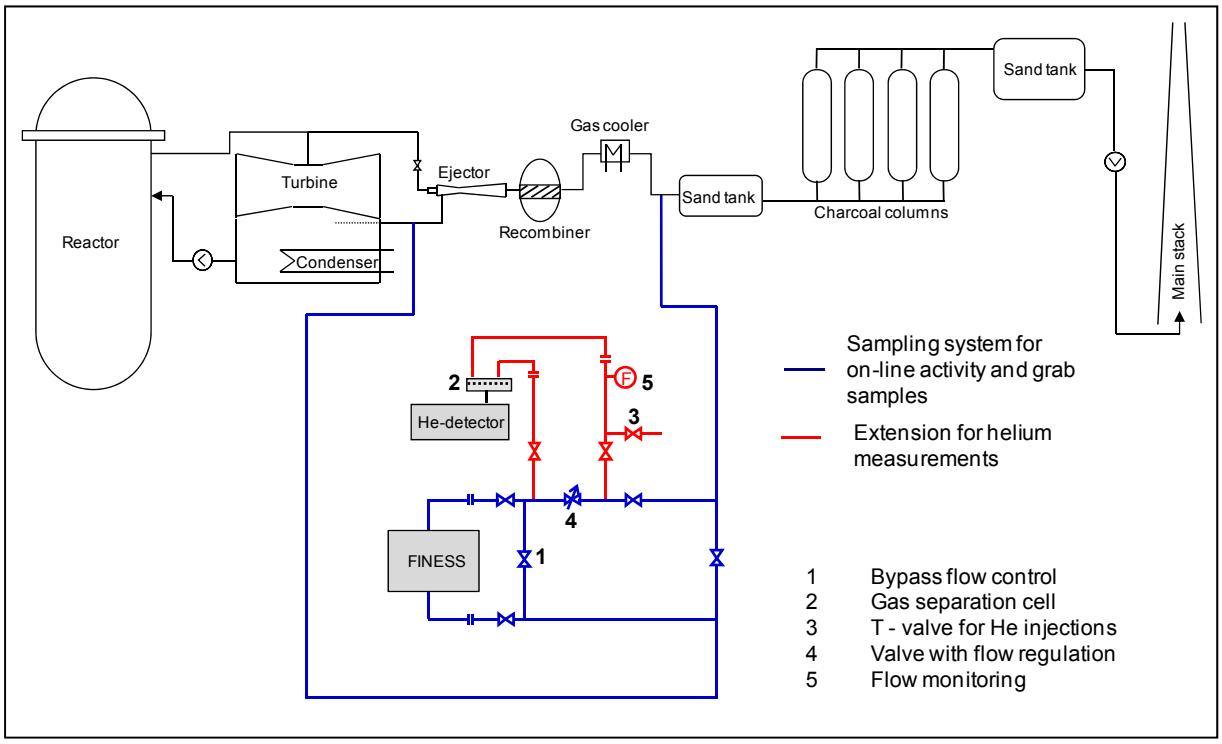

Figure 11. Schematic set up of the measuring system at Forsmark 3.

5.3.2 System for helium measurements

The system for helium measurements at Forsmark 3 is a demo system installed in 2010, in connection to the FINESS system, as shown in Figure 11. The main purpose of the helium measuring system at Forsmark 3 is to aid detection of fuel failures and separation of primary fuel failures from the degradation of already occurred failures that are detected by the on-line gamma emitting noble gas measurements. The helium measuring system includes a helium leak detector with a built-in mass spectrometer and a stainless steel gas separation cell, in similarity to the system at KKL. The detector used at Forsmark 3 is Adixen ASM 142 helium 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.

Chapter 6

FACTORS INFLUENCING HELIUM MEASUREMENTS

This chapter is based on Paper III and Paper VII, where the factors, which influence the helium measurements are analyzed. These factors may vary for different NPPs, which is also discussed regarding KKL and Forsmark 3.

During this project, several factors that might have an influence on the measurements with helium detector were distinguished. These factors can be categorized into two groups: 1) local adjustments made on the sampling line connecting the detector to the off-gas system, and 2) plant operational parameters.

6.1 Influences due to sampling line adjustments

During the measurements there are certain conditions regarding gas flow rate, pressure and temperature in the sampling line and subsequently in the gas separation cell. The stability of these parameters is obtained by controllers and measuring devices. However, adjustments made on the sampling line might have a direct affect on the gas separation cell and the conditions for helium measurements. To examine how the helium measurements are affected by variations in the gas flow rate and gas pressure in the sampling line, experiments at KKL were performed where these parameters were changed stepwise. Yet, the results are valid for other NPPs with such installations, e.g. Forsmark 3.

6.1.1 Gas flow

Normally the gas flow in the sampling line connected to the helium detector at KKL is about 2 l/min at 500 mbar absolute pressure. To study the influence of the off-gas flow rate variation in the sampling line, an experiment was conducted by increasing the flow rate 5 l/min and subsequently decreasing it stepwise with Δ = 1 l/min until it reached 1 l/min at a constant pressure, while continuously registering the helium signal. The results, presented in Figure 12, showed that the off-gas flow in the sample line does not influence the helium measurements,

since no deviation of the leak rate due to the variation in the gas flow rate was detected. However, it is important to distinguish between the gas flow rate in the sampling line and the total off-gas flow. The variation of the total off-gas flow has a direct influence on the measured helium leak rate since it changes the concentration of helium in the system.

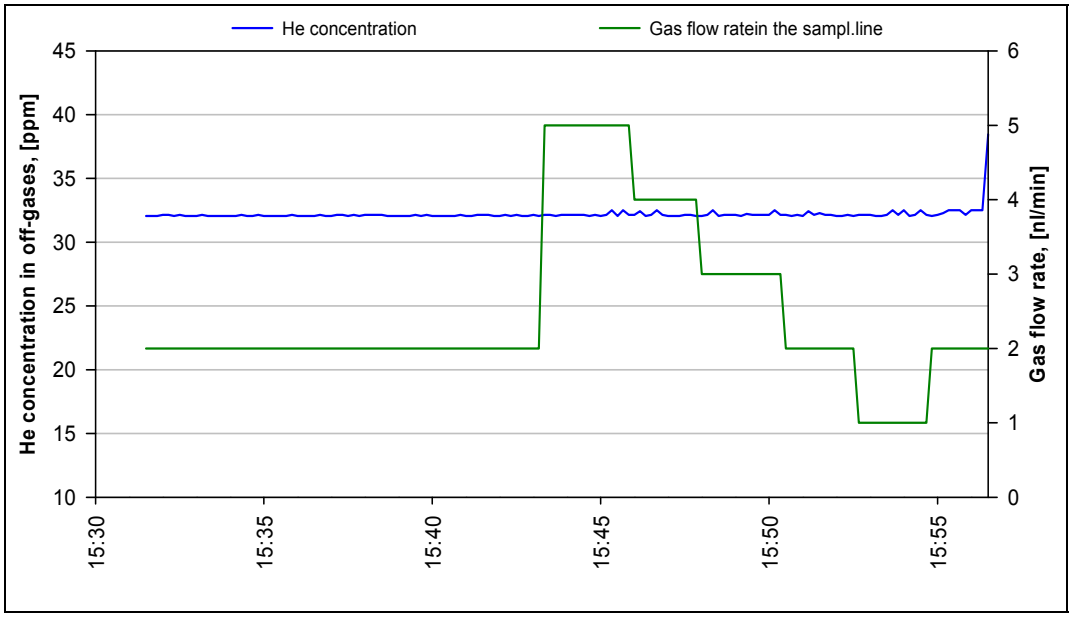

Figure 12. Influence of the sample line gas flow rate on He measurements.

6.1.2 Gas pressure

The dependency between the displayed helium signal and the pressure variation was studied at KKL by performing an experiment similar to the one performed when study the effect of the flow rate.Usually the gas pressure in the sample line at KKL, where the measurements are usually taken, is about 500 mbar. The pressure in the sample line was increased to above 600 mbar and then decreased stepwise down to just above 200 mbar. From the results of the experiment, illustrated in Figure 13, it can be seen that the measured helium leak rate is sensitive to the pressure variations.

From Figure 13 it is clear that the helium signal followed the pressure changes with a linear dependence. This is also shown explicitly in Figure 14. From this follows that the measured helium leak rate should to be compensated according to the changes of the pressure conditions in the sampling line, i.e. with a factor $\frac{P_{cal}}{P_{sampl.line}}$. Thus, if the calibration of the detector was performed at atmospheric pressure ($P_{cal} = 1000\ mbar$), while the pressure in the sampling line is $P_{sampl.line} = 500\ mbar$, the measurements are to be multiplied by factor 2, i.e. $\frac{P_{cal}}{P_{sampl.line}} = \frac{1000}{500} = 2$.

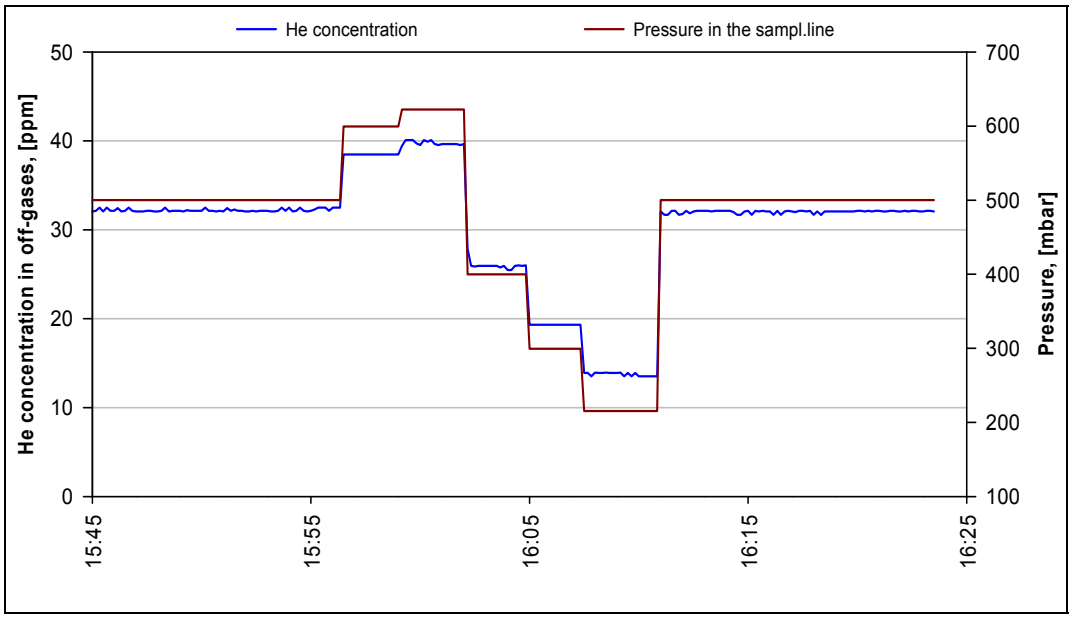

Figure 13. Influence of the sample line pressure on He measurements.

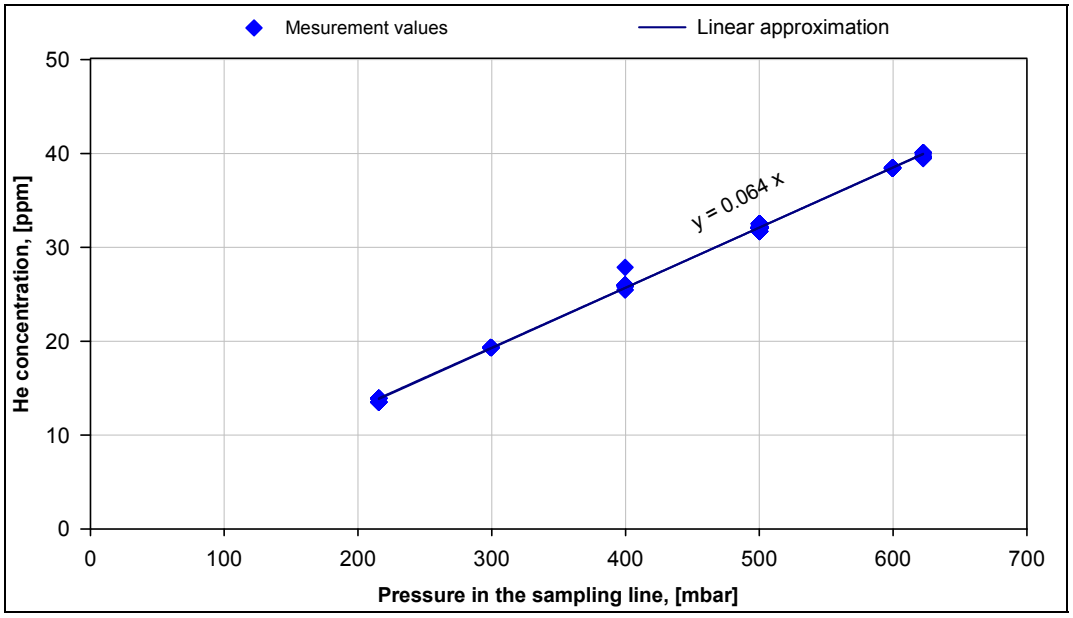

Figure 14. Linear dependence of He measurements on the sample line pressure variation.

6.2 Influences due to plant operational factors

Our study has shown that the measured helium concentration has a strong dependency on some operational factors, e.g. helium impurities in the injected hydrogen gas, variations of the total off-gas flow rate, water refill, back flushing of coal colons, etc.

6.2.1 Hydrogen injections at KKL

One of the factors that influence the helium measurements is the increase of helium concentration in the off-gases due to hydrogen injections. At KKL hydrogen injections started in mid-September 2008 [26], as a first step to introduce On-line Noble Chemistry (OLNC). Observations in older reactors show that Stress Corrosion Cracking, in particular 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 lowers 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 a critical electrochemical corrosion potential (EPC) of a stainless steel, large amount of hydrogen needs to be injected [27]. This increases the main steam system radiation dose rate, mainly due to ^{16}N-γ-radiation [28]. An effective lowering ECP can be achieved by injections of noble metal along with small amounts of hydrogen [27]. Therefore, Noble Metal Chemical Addition (NMCA) together with small amounts of hydrogen was recommended by GE in 1996.

Somewhat discontinuous helium measurements prior to the start of the hydrogen injection are presented in Figure 15. It shows the background level of helium in the off-gas system without the contribution from hydrogen injection. The concentration of helium in the off-gas flow during the first half of September was estimated to be about 12-13 ppm.

Some months later, in January 2009, the hydrogen feed rate was changed stepwise for a post OLNC benchmark test. The observed values of the helium concentration, measured continuously in the off-gas system, also showed these stepwise variations approximately 25 minutes after the hydrogen feed rate was changed, as shown in Figure 16. This confirmed the presence of helium in the injected hydrogen. One other observation was the variation of helium concentration due to the switching of hydrogen trailers, shown as red flags in Figure 16. This meant that different trailers contained different amounts of helium. The concentration of helium in the injected hydrogen was estimated to be about 100 ppm by analyzing corresponding helium measurements.

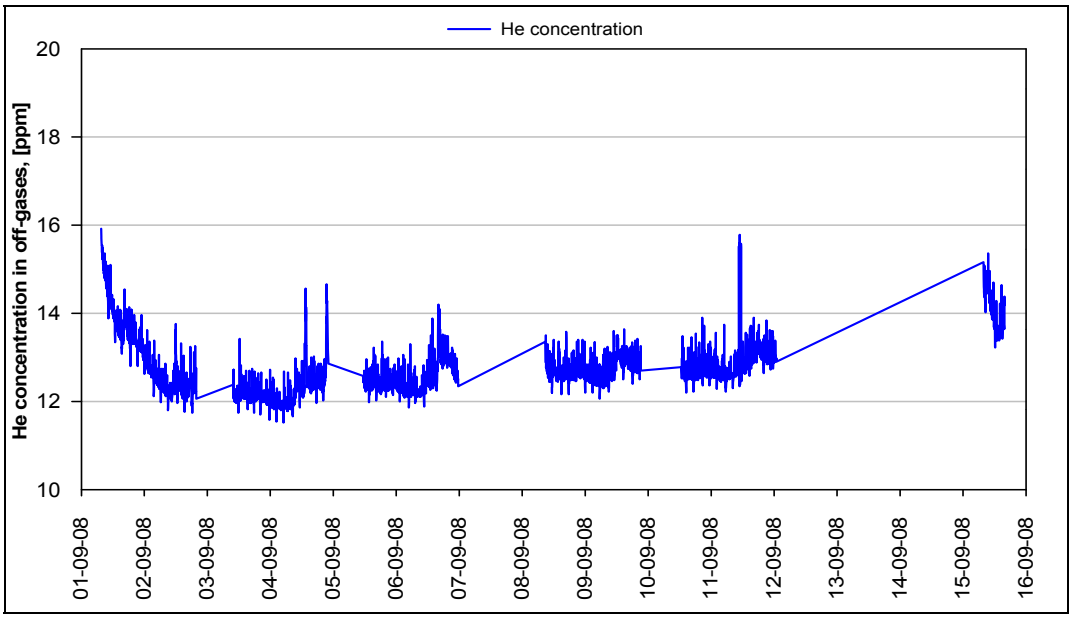

Figure 15. He measurements before the start up of H_2 injections at KKL.

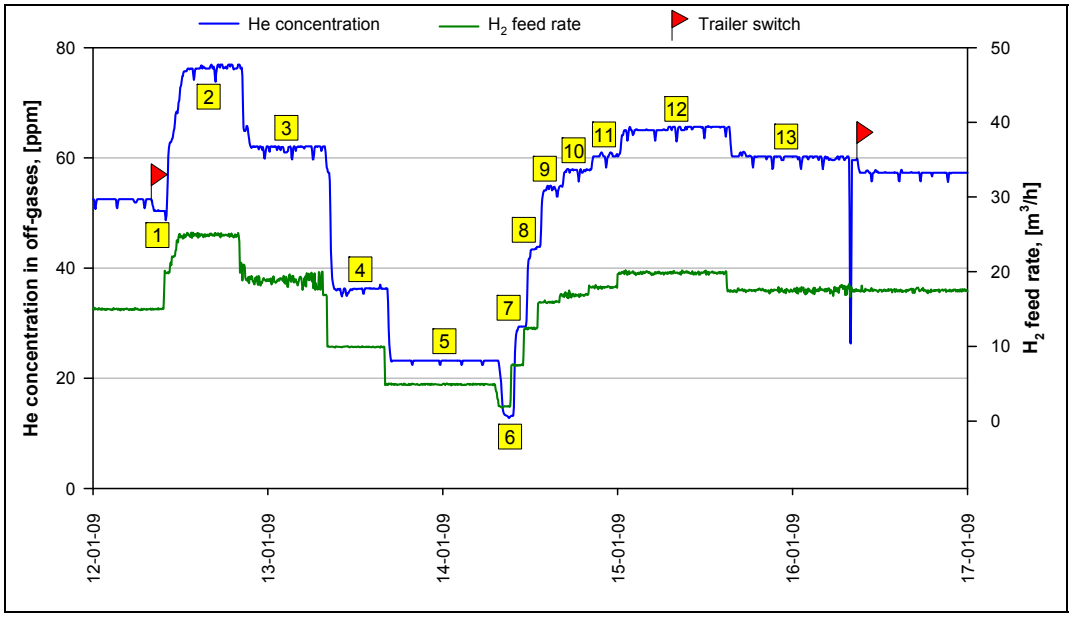

Figure 16. On-line Noble Chemistry benchmark test at KKL.

6.2.2 The total off-gas flow

Air is the main component of off-gases and all noble gases (He, Ne, Ar, Kr, Xe and Rn) are present in the air with a helium abundance of 5.2-5.6 ppm close to the earth's surface. Before the start up of the hydrogen injections at KKL, helium from the air was the main contribution of the helium background in the off-gas system. However, with the change of the water chemistry and introduction of hydrogen injection, the background level of helium had significantly increased. The flow rate of the air leakage in the condenser has a direct effect on the helium signal. The dependence of helium measurements on flow rate variations, when all other factors that could influence the helium signal were kept constant, can be seen in Figure 17. When the total off-gas flow increased, the concentration of helium decreased and vice versa.

A clear influence of the total off-gas flow on helium signal at Forsmark 3 was observed in April 2011, as shown in Figure 18. On April 9 the off-gas flow changed from 20.6 m^3/h to 21.5 m^3/h, which resulted in dilution of helium in the off-gas system and thus decrease of helium signal from 15.4 ppm to 14 ppm. After the shutdown in April 2011, the reactor started with the off-gas flow of 29 m^3/h and helium concentration below 10 ppm, which was significantly lower than before the shutdown, obviously due to increased off-gas flow rate.

6.2.3 Feed water refill

At KKL the cold condensate feed into the Hotwell to maintain the required level in the feed water tank, could also be observed from the helium measurements in form of dips, as shown in the diagram in Figure 19. Due to the injection of hydrogen, containing helium as an impurity, the concentration of helium in the off-gas flow was quite high. Consequently, when the water from the cold condensate tank entered the Hotwell, a dilution of helium occurred due to the degassing of water and, thus, the concentration of helium in the off-gases was reduced. From the variation of the helium concentration measured in the off-gases, the time interval between each feed water refill at KKL could be estimated to 2.5-4 hours.

The concentration of helium in the off-gas system at Forsmark 3 is low, since the main source of the helium is air, which has a helium abundance of ca 5.2-5.6 ppm, as shown in Sec. 6.2.2. This is the main contribution to the background level of helium in the off-gas system. There might also be small amounts of boron in the reactor coolant that give additional helium in off-gases. The experiences from our measurements show that the influence of the cold condensate feed into Hotwell, i.e. feed water refill, on helium measurements at Forsmark is minor; either observed as small variations of helium concentration in the off-gases or not observed at all during normal operation of a condenser. However, there have been observations of increases of helium concentration if the water level in the condenser decreases faster than during normal operation, e.g. caused by a condenser leakage. Such example is illustrated in Figure 20.

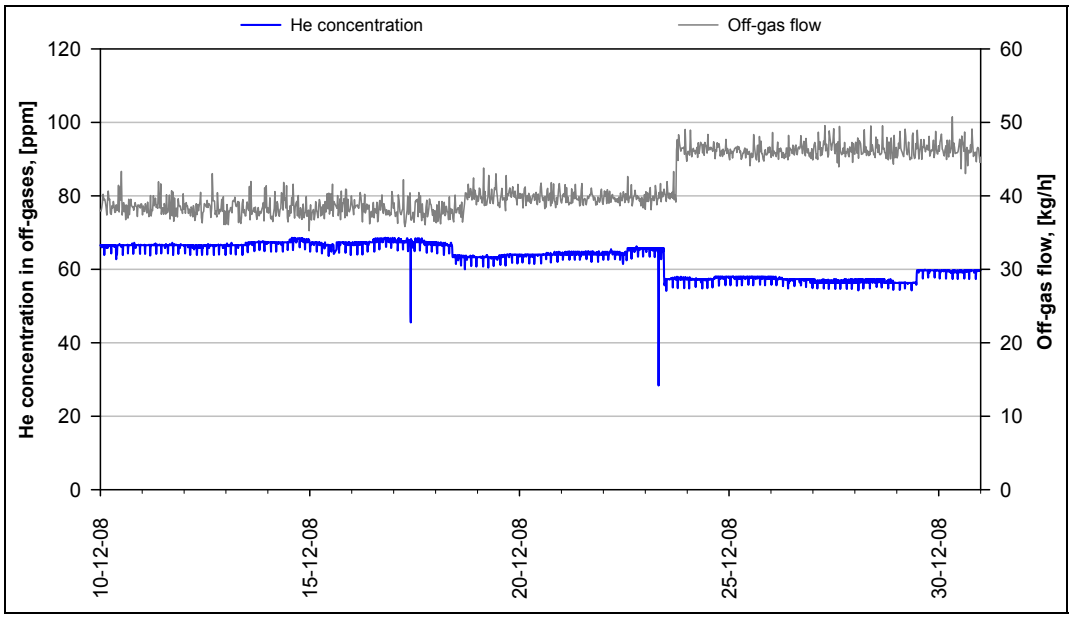

Figure 17. Influences of the total off-gas flow on He measurements at KKL.

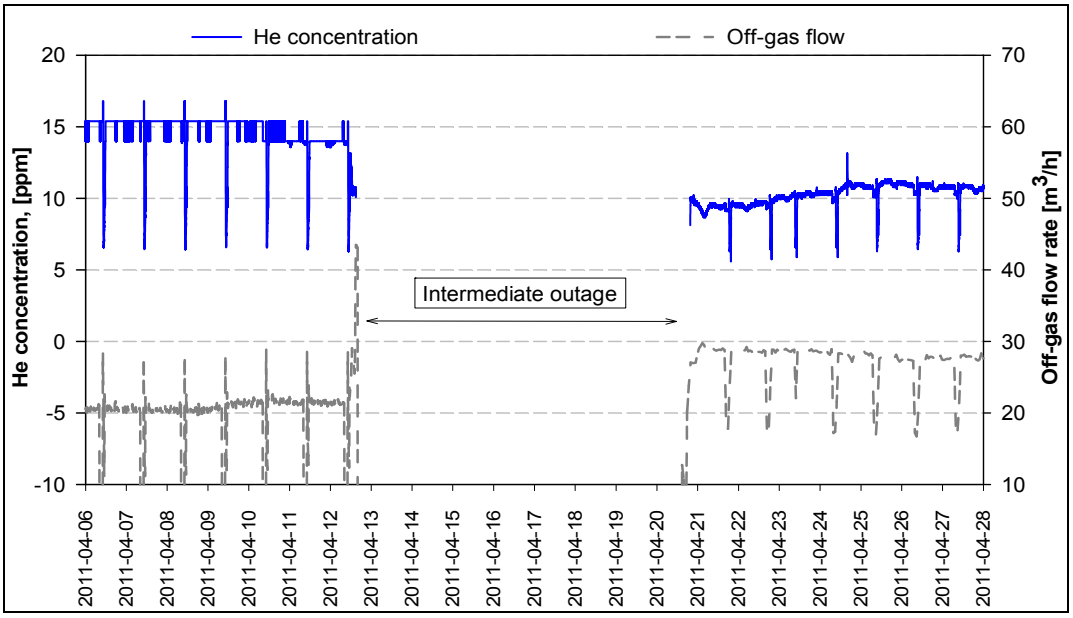

Figure 18. Influences of the total off-gas flow on He measurements at F3.

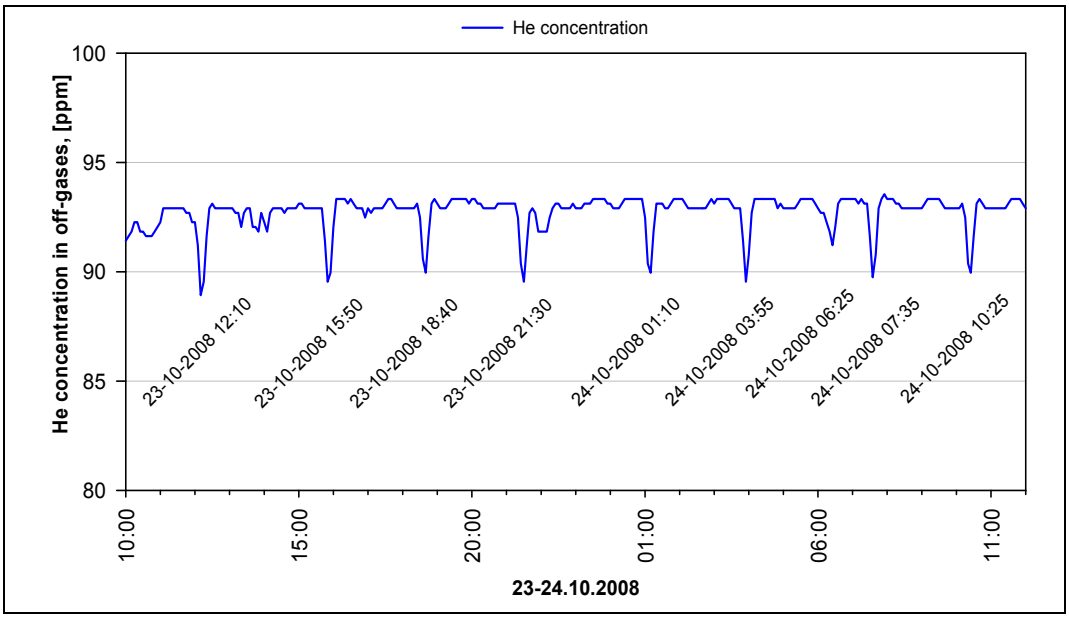

Figure 19. Water refill observed from the He measurements at KKL.

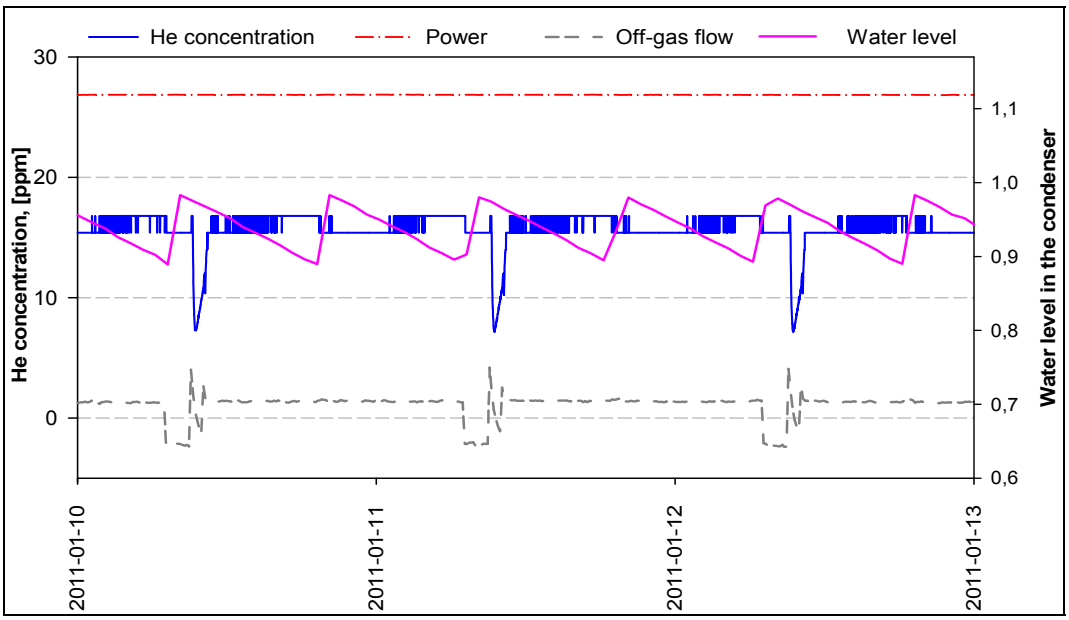

Figure 20. Water refill and He measurements at F3.

6.2.4 Back flushing of coal columns

Another cause of variations in the measured helium signal that have been observed at Forsmark 3 is connected to the back flushing of the adsorption columns. After passing the condenser, the off-gases flow through recombiner, where oxygen and hydrogen atoms form water molecules, which are removed from the off-gas system. Remaining gas enters the delay system consisting of two sand tanks and four charcoal columns. The system can be viewed in Figure 11. Sand tanks function is to slow down the gas flow and thus reduce the amount of short lived noble gases.

The adsorption columns are filled with activated charcoal and are used for separation and recirculation of the long-lived xenon isotopes mainly Xe-133 [29]. Two of the coal columns are operated at the same time while two other columns are regenerated. These charcoal columns operate in a cycle of 24 hours and are back flushed once a day, which affects the off-gas gas flow and thereby also the helium measurements. The back flushing means regeneration of the column N_2 and the part of the off-gas flow, including gamma emitting noble gas nuclides, which have not decayed yet, is reintroduced through a column into the system and passed on to the ejectors. This recirculation of noble gases forces them through the delay system again to achieve the decay of Xe and Kr into harmless nuclides before they are released though the stack. The variations of the off-gas flow rate related to the back flushing and following steps of the operational cycle of the adsorption columns normally observed early in the morning, usually around 07:00 or 08:00 and lasts about 3-3.5 hours. This has immediate impact on helium measurements. When the off-gas flow decreases, the helium concentration increases and vice versa, as illustrated in Figure 21.

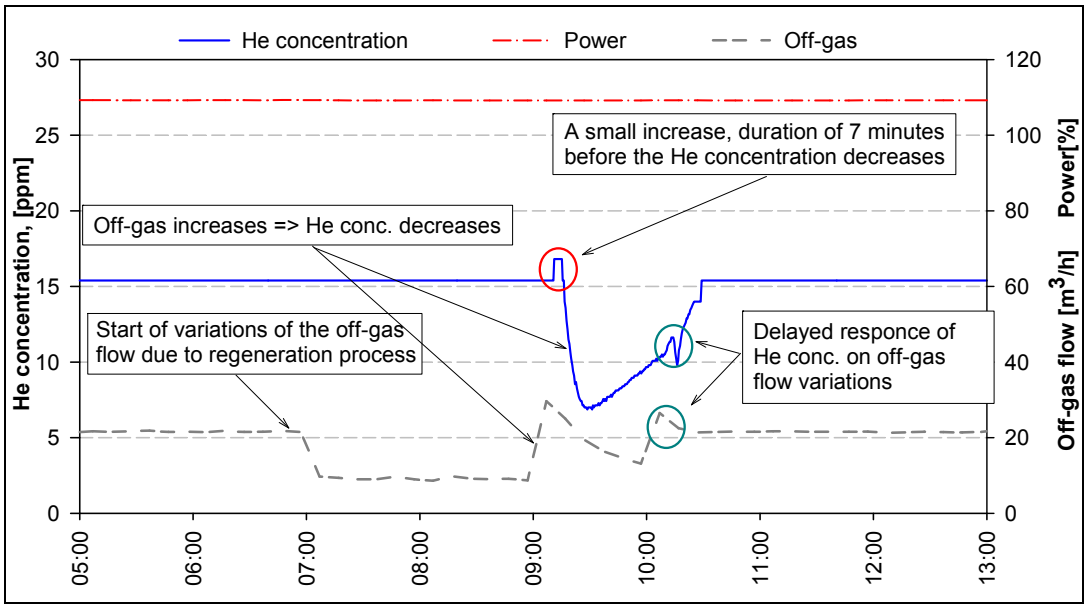

Figure 21. The influence of the adsorption column operation on helium measurements at F3.

Most often changes could be seen in helium concentration about 9-15 minutes after the off-gas flow was changed. The uncertainty could be explained by the recording interval of the off-gas flow rate. The available off-gas flow rate data that was recorded with 10 minutes intervals until April 21 2011, and after that with intervals of one hour.

The back flushing procedure affects the activity measurements, resulting in periodic increases of activity, as can be seen in Sec. 8.2. in Figure 35, Figure 37 and Figure 39 as has been observed in measurements performed by FINESS. Except for the influences from the off-gas flow variations, described above, the regeneration of adsorption columns is not affecting helium measurements. One suggestion is that since helium is light and volatile gas, it is transported through columns quickly. The charcoal columns have the following delay efficiency: Kr is delayed about 15 times and Xe about 300 times compared to air delay [29].

Chapter 7

EXPERIENCES OF MEASUREMENTS FROM KKL

This chapter is a summary of papers V and VI. It consists of an overview of the experiences from helium measurements at KKL, where the detection of control rod failures was the main purpose for the installation of a helium measuring system. Thorough analysis of such measuring experience is presented in Paper V. Furthermore, experiments with helium injections in two different systems and results of the experiments are also discussed, although full description of these experiments can be found in Paper VI.

7.1 Calibration of helium detector

The calibration of the helium detector can be performed in two different ways: an internal calibration can be carried out by means of a built-in test leak and nn external calibration can be performed using a test leak attached to the inlet port [25]. It is recommended by a detector vendor to recalibrate every calibrated leak at regular intervals to validate its value [30].

7.1.1 Internal calibration

Internal calibration is usually performed at start up, yet it can be performed at any time if in doubt regarding the proper operation of the detector or as assurance of correct measurements during heavy use. However, any calibration, including an internal auto-calibration, can only be performed if the detector is not in test mode, which means discontinuity of measurements. For internal calibration of PhoeniXL 300 leak detector at KKL a built–in calibration leak of type TL7 with leak rate of nominal value of 4.7×10^{-7} mbar l/s ± 15 % at 23°C is used.

7.1.2 External calibration

For the external calibration, Pfeiffer Vacuum Calibrated helium leak test of permeation type CT 408 and leak rate of nominal value of 2.9 x 10^{-8} mbar l/s ± 15 % at 23°C was used. The date of filling given at the standard leak test is 2002.12.16 and the leak rate decrease is less than 1 % per year. However, the leak rate is affected by the temperature by +3.5 % per °C when it is deviates from the nominal temperature value.

The temperature in the measurement room at KKL was well above 30°C and the temperature at the inlet of the detector was 37°C, which gives a deviation of 14°C from the nominal temperature value and consequently 49 % deviation from the standard leak rate. Thus, the expected leak rate of the standard leak at 37°C is: 2.9 x 10^{-8} mbar l/s · 1.49 = 4.32 x 10^{-8} mbar l/s ± 15 %, which means that the expected leak rate value should be within 3.67 x 10^{-8} and 4.97 x 10^{-8} mbar l/s. The value obtained by external calibration was 4.26 x 10^{-8} mbar l/s, which was within the specified limits.

7.1.3 Calibration and conversion equation

The calibration of the helium leak detector with the gas separation cell, including the PTFE membrane, was performed at atmospheric pressure (1 bar = 1000 mbar) before connecting the detector to the off-gas system of the reactor. A 150 ml gas container was filled with N_2, thereafter different concentrations of helium were produced by injecting certain amounts of helium with a micro syringe into the gas container. To make sure that the results were reproducible, several series of measurements were performed.

The results of the calibration are shown in Figure 22. According to Eq. (11) which was obtained by list square fit, the helium concentration can be presented as a linear function of the measured helium leak rate. In addition, the results of the measurements are dependent on the pressure conditions in the sampling line, which was discussed in detail in Sec. 6.1.2.

$$\boldsymbol{c(He_{OG}) = \frac{P_{cal}}{P_{sampl.line}}\, 1.0 \cdot 10^{9} \cdot LR(He)}, \qquad \textbf{(11)}$$

where

$c(He_{OG})$ – concentration of He in the off-gases, (ppm),
$P_{cal}(= 1000\ mbar)$ – pressure at the calibration of the detector, (mbar),
$P_{sampl.line}$ – pressure in the sampling line, (mbar),
$LR(He)$ – measured He leak rate, (mbar l/s).

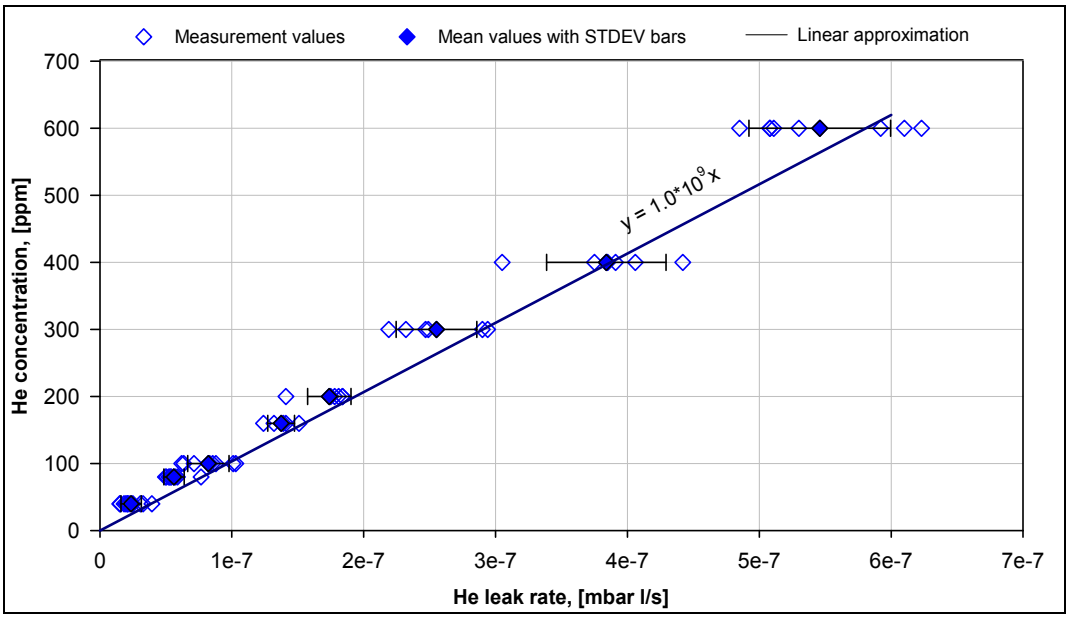

Figure 22. Linear dependence between concentration and leak rate.

7.2 Helium measurements during operation

The shape and duration of the peaks and the amounts of the helium released due to leaks from failed control rods vary depending on the conditions of the failed rod (e.g. ^{10}B depletion of the rod, severity of cracks) and eventual changes in the core (e.g. power variations, control rod movements). In addition to the release of helium from failed rods, there are also other sources that may cause deviations of the helium signal from the background/baseline and have to be taken into consideration. As was described in Sec. 6.2.1 and Paper III, the main contribution to the background helium concentration originates from helium impurities in the hydrogen, injected into the feed water when applying OLNC water chemistry. Other factors that have shown to have an influence on helium measurements are variations of gas pressure in the sampling line, changes of off-gas flow and water refill into the feed water.

7.2.1 Method for analysis of the measured data

By determining and implementing calculations of a continuous helium background level (baseline) of helium concentration in the off-gases, the surveillance of the eventual helium release can be more accurate. In addition, if such calculated baseline is programmed in and calculated for each measured value of helium concentration, it will allow on-line analysis and prompt calculations of the released helium amounts.

As was described in Sec. 6.2.1 and in Paper III, there are several factors that may have an influence on the helium concentration. Subsequently, the estimation of helium baseline includes several terms as shown in Eq. (12) where the main influencing factors are taken into consideration: 1) deviations of the helium baseline due to the variations of the off-gas flow

rate, 2) helium baseline response to the changes in H_2 feed rate, and 3) stepwise influence on the helium baseline due to H_2 trailer switching.

$$\boldsymbol{c_{He_{BL}}(t2) = c_{He_{BL}}(t1) \cdot \frac{F_{OG}(t1-t_{dOG})}{F_{OG}(t2-t_{dOG})} + 2.77 \cdot \Delta F_{H_2}(t2) + \Delta c_{trHe}(t2),} \qquad \textbf{(12)}$$

where

$$\boldsymbol{\Delta F_{H_2} = F_{H_2}(t2 - t_{dH2}) - F_{H_2}(t1 - t_{dH2})}\,, \qquad \textbf{(13)}$$

$$\boldsymbol{\Delta c_{trHe}(t2) = mean[\, c_{He}(t2 - t_{m1})] - mean[\, c_{He}(t2 + t_{m2})]} \qquad \textbf{(14)}$$

$c_{He_{BL}}(t2)$ – He concentration (baseline) in off-gas system at time t2; (ppm),

$c_{He_{BL}}(t1)$ – He concentration (baseline) in off-gas system at time t1, (ppm),

$F_{OG}(t1 - t_{dOG})$ – off-gas flow rate at time t1- t_{dOG}, (kg/h),

$F_{OG}(t2 - t_{dOG})$ – off-gas flow rate at time t2- t_{dOG}, (kg/h),

t_{dOG} – delay time for off-gas flow,

$F_{H_2}(t1 - t_{dH2})$ – H_2 feed rate at time t1- t_{dH2}, (m^3/h),

$F_{H_2}(t2 - t_{dH2})$ – H_2 feed rate at time t2- t_{dH2}, (m^3/h),

t_{dH2} – delay time for H_2 feed rate,

$\Delta\, c_{trHe}(t2)$ – correction of He concentration baseline at time t2 due to trailer switching, (ppm),

$mean[\, c_{He}(t2 - t_{m1})]$ – mean value of the He concentration over a suitable period before the step change of He signal due to a trailer switching, (ppm),

$mean[\, c_{He}(t2 + t_{m2})]$ – mean value of He concentration over a suitable period after a step change of He signal due to a trailer switching, (ppm),

$t2 - t_{m1}$ – period suitable for averaging He concentration before a step change of He signal at t2 due to a trailer switching,

$t2 + t_{m2}$ – period suitable for averaging He concentration after a step change of He signal at t2 due to a trailer switching.

The first term of Eq. (12) shows the inversely proportional dependency of helium measurements on the off-gas flow. Furthermore, the fact that the measuring point for the off-gas flow rate is situated before the delay line, while the helium measurements are usually performed after the delay line, has to be taken into account when analyzing the data. Thus, a helium concentration at time t1 corresponds to the off-gas flow rate at time (t1- t_{dOG}), where t_{dOG} is the delay time for off-gas flow, e.g. transport time through the delay line.

The second term of the Eq. (12) gives the dependency of helium measurements on the hydrogen feed rate. To determine the dependency of helium concentration on the hydrogen feed rate a period in January 2009, which is shown in Figure 16, was used. During this period the hydrogen feed rate was changed stepwise with the injection performed using the same trailer, i.e. no trailer switching occurred, eliminating the uncertainty caused by the variation of helium concentration in different trailers containing hydrogen. A linear approximation of values was obtained by list square fit and expressed by equation shown in Figure 23.

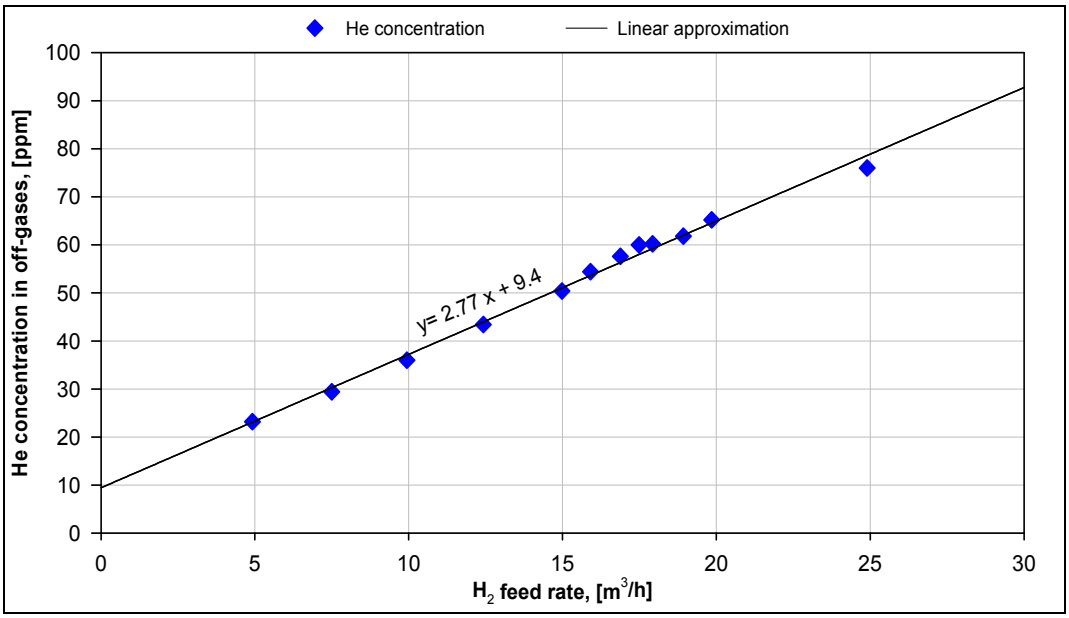

Figure 23. Linear approximation of He concentration in the off-gases due to injected H_2.

The point for hydrogen injections into the feed water is situated before the reactor, which has to be considered when analyzing the helium measurements and estimating the helium concentration baseline. Therefore, when performing helium sampling after the delay line, the variation in the hydrogen feed rate is usually observed in the helium signal about 30 minutes later, which is the delay time for hydrogen at the off-gas flow rate of about 45 kg/h. The delay time for hydrogen injections is about 13 minutes for helium measurements sampled before the delay line.

Finally, the third term of the Eq. (12) expresses the influence of hydrogen trailer switching on helium measurements. It is usually observed as a step change of the helium signal, which appears about 30 minutes after the switching, when the off-gas flow is ca 45 kg/h. The value of this step, $\Delta c_{tr}(He)$, is the difference between the mean value of the measured He signal over certain periods before and after the change due to the switching. If the switching of a trailer containing hydrogen occurred at time t_{tr} and $t2=t_{tr}+t_{dH2}$, then a step change of the helium concentration due to hydrogen trailer switching can be calculated using Eq. (14).

The calculation of the integrated helium amount corresponding to a peak of helium concentration in the off-gas system, probably released from a failed rod, can be done according to Eq. (15). The measured values, with the subtracted baseline calculated using Eq. (12), are multiplied by the off-gas flow rate and time intervals between the sampling points. The amounts of the measuring intervals are then summed up over the duration of the increase.

$$\boldsymbol{V(He) = \sum_{i}^{T/t}[c_i(He_{OG}) - c(He_{BL})] \cdot 10^{-6} \cdot F_{OG_i} \cdot t}\,, \qquad \textbf{(15)}$$

where

$V(He)$ – released He amount, (ml),
T – duration of the He peak, (s),
$c_i(He_{OG})$ – measured concentration of He in the off-gases, (ppm),
$c(He_{BL})$ –He baseline in the off-gases, (ppm), estimated using Eq. (12)
F_{OG_i} – off-gas flow rate, (ml/s),
t – sampling rate, (s).

The off-gas flow rate F_{OG} in Eq. (**15**) takes the delay time, i.e. the transportation time between the core and the sampling point, and is given in ml/s with the account of air density at room temperature, $\rho = 1.204\ m^3/kg$. The sampling rate between registered values at normal on-line measurements is usually 5 minutes, i.e. $t = 300\ s$, which can be adjusted according to requirements.

7.2.2 Analysis of measurements and interpretation

Since during this project KKL did not experience any fuel rod failures, any helium concentration increase detected in the core was from failed control rods.

Spontaneous helium release peaks

Helium peaks that have not been influenced or triggered by operational actions, such as power reduction or control rod movements, are called spontaneous helium release peaks. These spontaneous peaks could be indications of newly occurred control rod cracks or a helium release from the disintegrated B_4C matrix due to water intrusion. Examples of significant helium releases from failed control rods can be seen in Figure 24 and Figure 25, where the duration of the peaks and the determined amount of the released helium are shown. In Figure 24 the peak has a narrow and well defined shape, while in the Figure 25 the peak is a result of a steep increase of the helium concentration, followed by a slow decrease of the signal. However, the most interesting observation was that after the peak the signal remained increased over the baseline with several ppm (from 101 ppm before the peak to 106 ppm after the peak) for additional 42 hours, as can be seen in Figure 25. This suggests that there was a continuous release of small amounts of helium into the reactor coolant. Detailed analysis of spontaneous releases and more examples can be found in Paper V.

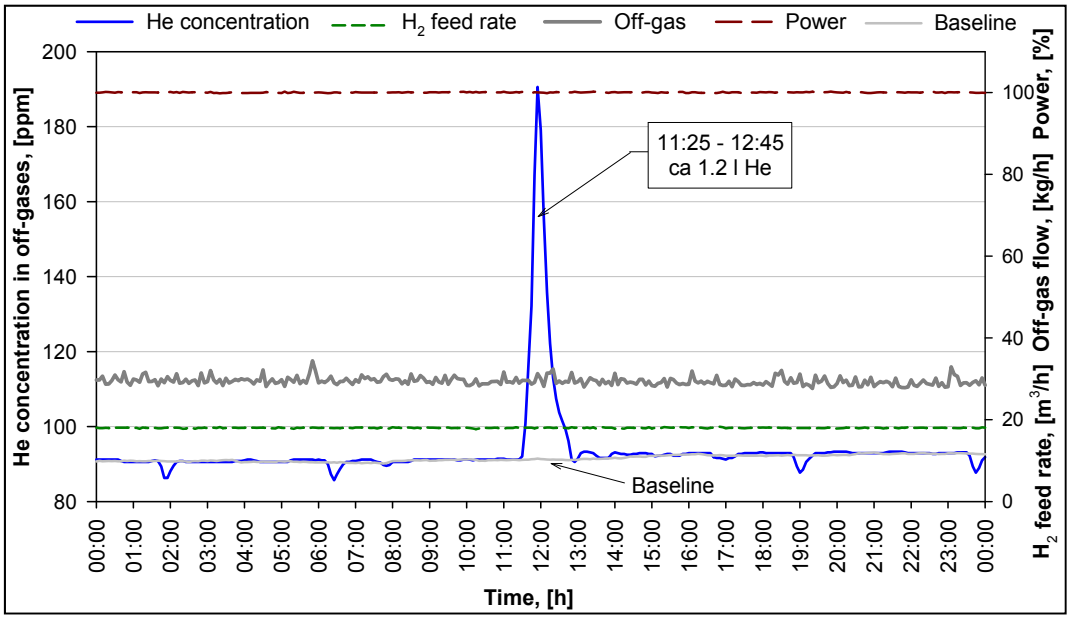

Figure 24. Helium concentration increase in the off-gas system of KKL.

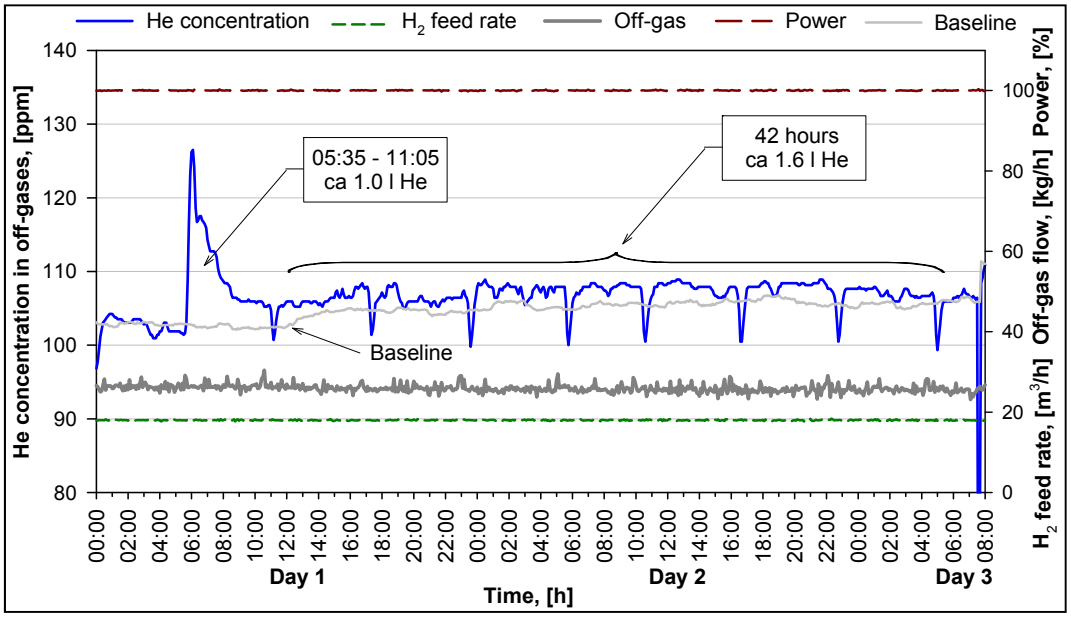

Figure 25. Helium concentration increase in the off-gas system.

Helium release due to power variations and control rod movements

Helium release from leaking control rods can also be associated with operational factors such as variations of the reactor power level and movements of control rods. Most often during such release, the increase of the helium concentration is within 20 ppm above the baseline, with a relatively short duration (usually less than 2 hours). This suggests that the amount of released helium is considerably less compared to the spontaneous releases, shown in Figure 24 and Figure 25. Examples of helium releases induced by the changing of the operational conditions (e.g. power variation, control rod movements, etc) are shown in Figure 26 and Figure 27. Figures include the peak duration and the determined amount of the release helium according to Eq. (**15**), along with the possible causes of the release

Such behavior of the helium signal implies a partial release from already existing failures, while the main release of helium had already occurred during the original crack. In control rods containing boron carbide, there is a continuous production and subsequent accumulation of helium, while being irradiated by neutrons. A release of the accumulated helium may occur again when the operational conditions around a failed control rod are changed due to the reduction of power level or the movement of a control rod which causes local power changes.

Figure 26 visualizes the increase of helium concentration due to power reduction, while in Figure 27 the helium release was caused by both power reduction and control rod movements. The release of helium shown in Figure 27 increased in two steps, the first step of increase was due to the power reduction and the second was due to control rod movement. The measured increases in helium concentration at KKL appeared 20-30 minutes after power reduction to 97.5 % of the full power level. While power was reduced, tests of control rods in regulating position were performed with movement of one notch, which also resulted in helium release with approximately the same delay time as for power reduction. For more detailed explanation and examples, see Paper V.

Another case of unstable behavior of the helium detector signal with a significant increase of helium concentration in the off-gas system, shown in Figure 28, was observed for more than one month following the start-up of the reactor after the outage. The baseline was determined according to Eq. (12) in Sec. 7.2.1, taking into account a decreasing off-gas flow and several switches of hydrogen trailers. Important operational parameters as reactor power, off-gas flow, hydrogen feed rate, trailer switches and control rod movements are also visualized in Figure 28.

The amount of helium released during the first month was estimated to be ca 190 liters and during the second month to about 90 liters, using Eq. (15). In total, a release of 280 liters helium was observed after the start up during these 50 days. Fast elevation and prolonged increase of the helium concentration in the off-gases could be explained by several leaking control rods present in the core. Simultaneously with the helium, an increase of boron in the reactor water was detected. This indicated the presence of more severely failed control rods. Using the boron balance model of KKL, described in Paper V, a helium amount, that

corresponds to a boron wash out in the coolant of more than 700 g, could be determined to 190 liters. This calculation assumed an average ^{10}B depletion of 57%, based on the measurements of reactor water during this cycle. Considering that not all of the cracks that are leaking helium would result in washout of boron, the estimation of the helium amount from the boron in the coolant is reasonable compared with the amount determined from the helium measurements in the reactor off-gas system.

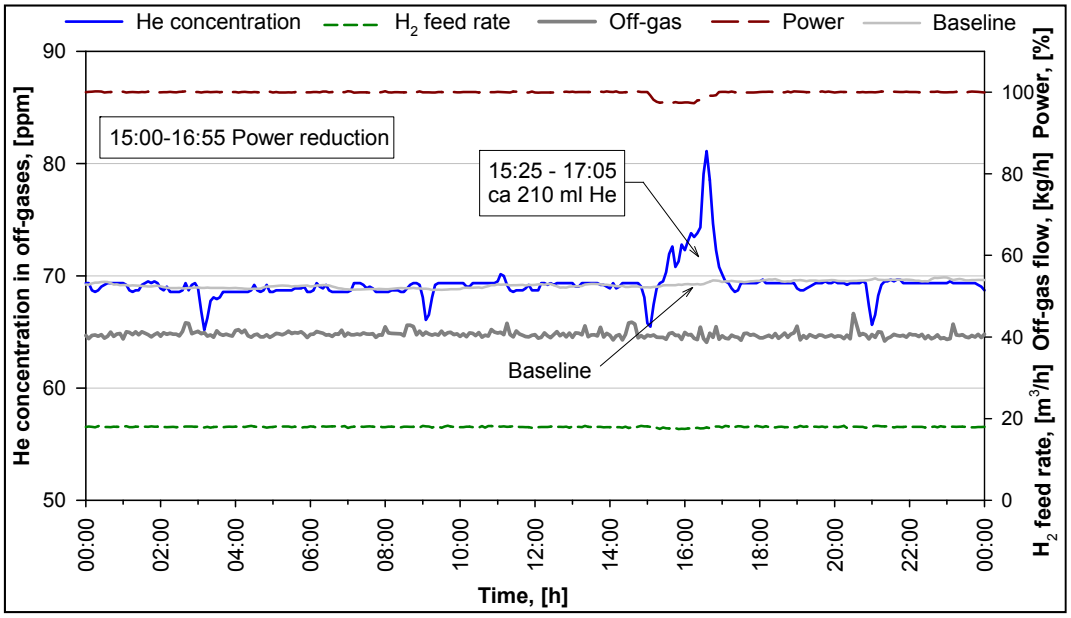

Figure 26. Helium concentration increase due to power reduction.

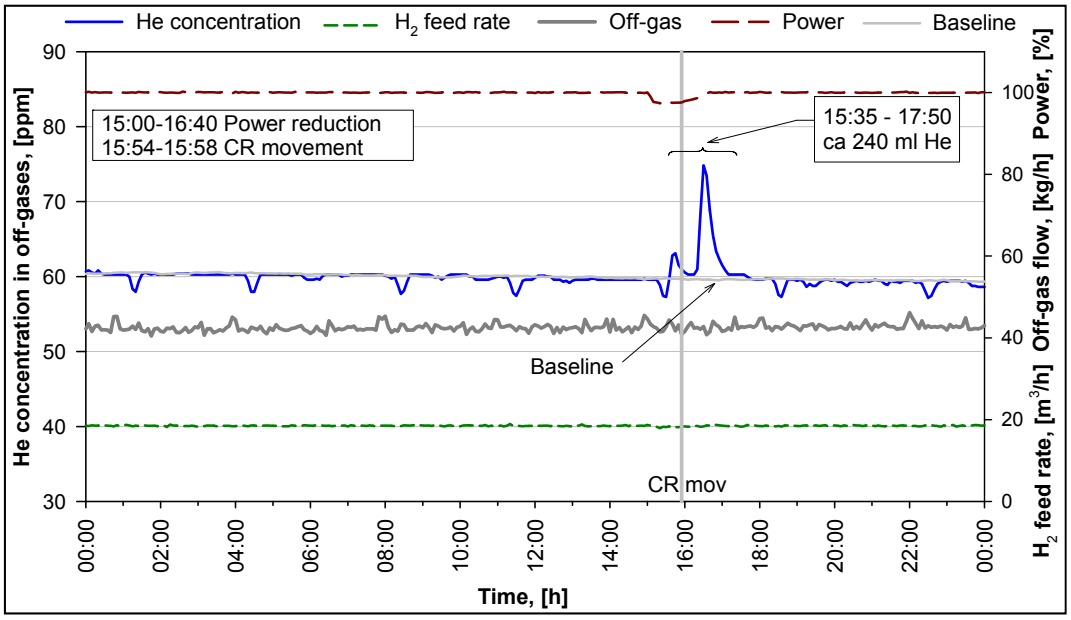

Figure 27. Helium concentration increase due to power reduction and control rod movements.

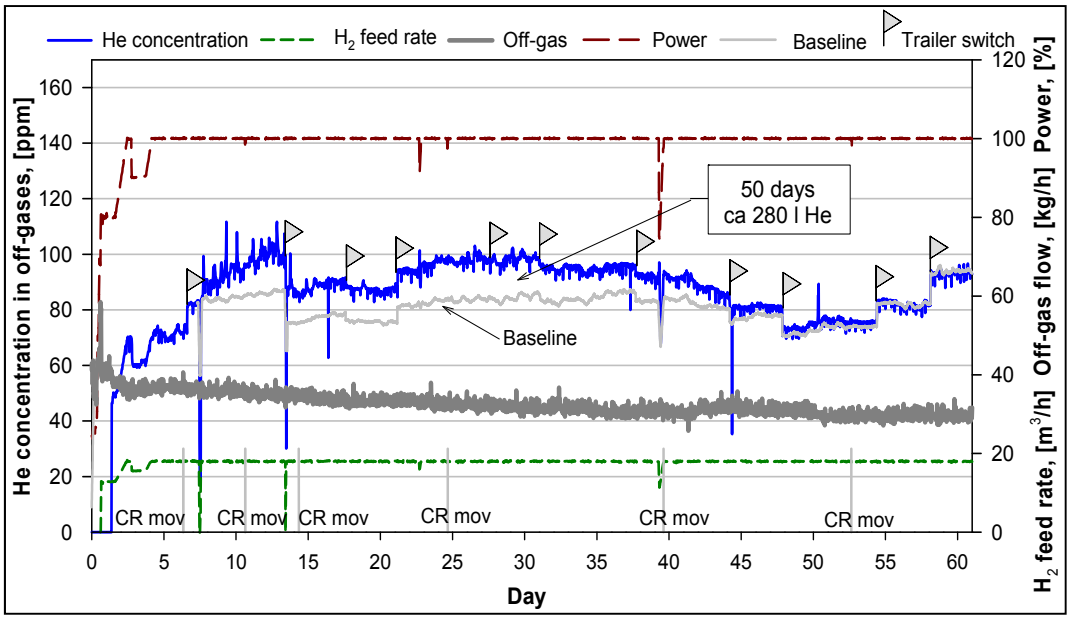

Figure 28. Helium concentration increase over a two months period after the start-up.

7.2.3 Experiments with helium injections

At KKL, two experiments with helium injections were performed, that are described in detail in Paper VI. During the first experiment helium was injected into the container, usually used for manual grab samples, in order to study the influence of the delay line on the helium measurements and the shape of the signal. In another experiment, conducted at KKL, helium was injected into the feed water line using the dosage line for platinum injections during OLNC, where the gas was transported to the feed water line and subsequently to the reactor by deionized water with low flow rate. In addition to the investigation of the ability for measuring helium released from a fuel failure, the behavior and spreading of the gas passing through the delay system before it reached the measuring point were studied along with the recovery rate of injected to the detected helium amount.

Helium injections in the off-gas grab sampling point

The aim of the experiment at KKL was to examine the possibility of measuring the helium amounts that would correspond to a release from a fuel rod failure, evaluate the influence of the delay line on the helium measurements and to study the spreading of helium when it is transported through large systems before reaching the sampling point. The evaluation of the influence of the delay line and the choice of an optimal measuring point for helium sampling was performed by using the same injected helium measured at two different sampling points, before and after the in delay line.

Helium volumes of 20 cm^3 and 40 cm^3 (i.e. 1/4 and 1/2 of helium volume in a fuel rod at STP) were injected with a syringe into a small container with a volume of about 750 cm^3, where grab samples are normally taken. Because of the under pressure in the line

(P_{abs} ≈ 230-250 mbar), the gas was sucked in and transported to the collecting pipe for non condensable gases of the condenser, thereafter passing through ejector, recombiner and gas cooler before reaching the measuring point. The helium was injected in series of three for each amount. First the system was switched to perform direct measurements, i.e. measure before the delay line. When an increase was registered and the measured signal decreased back to the baseline level, the sampling was switched in order to detect the same injection of helium after the delay line. The measurements were performed with a frequency of 5 seconds for improved resolution of the experimental results. Results of the experiment are shown in Figure 29 and can be viewed in a Table 2 in Paper VI.

As can be seen in Figure 29, the measured values due to the injections of 20 cm^3 and 40 cm^3 could be fully observed in both cases, when measuring before and after the delay system. The peaks measured before the delay system (1BF – 6 BF) were higher and narrower while the peaks measured after the delay line (1AF – 6AF) were, as expected, much lower and more spread in time.

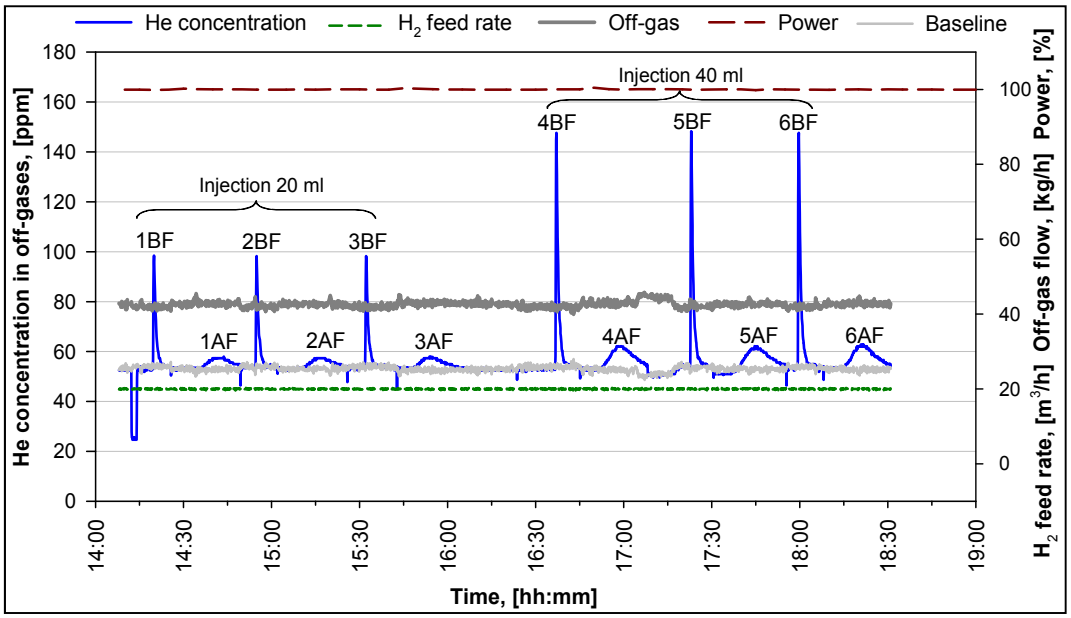

Figure 29. He measurements during He injections into the off-gas grab sampling point at KKL.

The detector response was observed already 60-75 seconds after the injection, when measuring before the delay system, while when measuring after the delay line, the increase was registered after about 18 minutes. The duration of the peaks also showed an influence of the delay line on the gas transport and subsequently on the duration of peaks, as the duration of peaks increased with almost 11 minutes for each case. The thorough analysis of the detector response, the delay time estimation and duration of the peaks can be seen in Paper VI.

The amount of measured helium was 25-40% higher than injected, when measuring both before and after the delay, as can be seen in Table 2 in PaperVI. These results are of course unexpected, as recovery rates lower than 100 % is expected particularly in case of delay mode measurements. The experiment showed that injected amounts of 20 and 40 ml helium injections were detected as well-defined peaks with good reproducibility. The heights of the peaks, from the measurements before and after the delay line, showed very little discrepancy. The influence of the delay system on helium measurements was shown in the spreading of the gas and the heights of the peaks, which is analyzed in Paper VI.

The helium detection system has shown very good efficiency in detecting small variations in helium concentrations in the off-gases. Thus, in case of a fuel failure, where the leakage would correspond to the injected amounts, i.e. 20 ml and 40 ml, there is a fair possibility that a primary fuel failure would be detected with this system. However, additional experiments with helium injection into the feed water were needed in order to examine the influence of the reactor, turbine and condenser on the gas transport before any conclusions about the detection of helium from a fuel failure could s be drawn.

Helium injections into the feed water

The aim of the experiment was to simulate a fuel failure by injecting helium in the feed water, let it pass through the reactor core and subsequent systems, and finally measure the helium increase with a helium leak detector. The point for injection was chosen in close vicinity to the reactor core, which is normally used for platinum injections during OLNC. Because of the implementation of the HWC and OLNC at KKL, injection of helium followed by high pressured nitrogen, was ruled out in order to prevent a radiation increase due to activation of additional nitrogen because of the HWC.

The loop for helium injection was constructed with suitable Swagelock valves and a metallic tube with diameter of 4 mm, as shown in Figure 30 and Figure 31. A sensitive fine scaled manometer and a helium tube were also attached to the equipment. The volume of the loop of 29-30 ml was established by filling the loop with water and weighing the collected water afterwards. A constructed loop was then tested to withstand pressure of 100 bar and connected to the valves (V4) and (V5) of the platinum injection line, as shown in Figure 31. The details of experimental equipment and platinum line can be seen in Paper VI, where the sequence of the experiment and uncertainties during the performance are discussed.

During the experiment, the loop (L1) was filled with helium, thereafter deionized water entered the loop and compressed the injected helium. When the valve (V5) was opened, the helium from the loop was pushed through the platinum injection line into the feed water pipe. After each injection, the water from the loop was collected through the drain for control of the volume carried out following weighing. Several injections were made in this manner, where the loop (L1) was pressurized with helium three times to 2 bar; one injection was made with helium of 4 bar, and, finally, three additional helium volumes of 8 bar absolute pressure were injected.

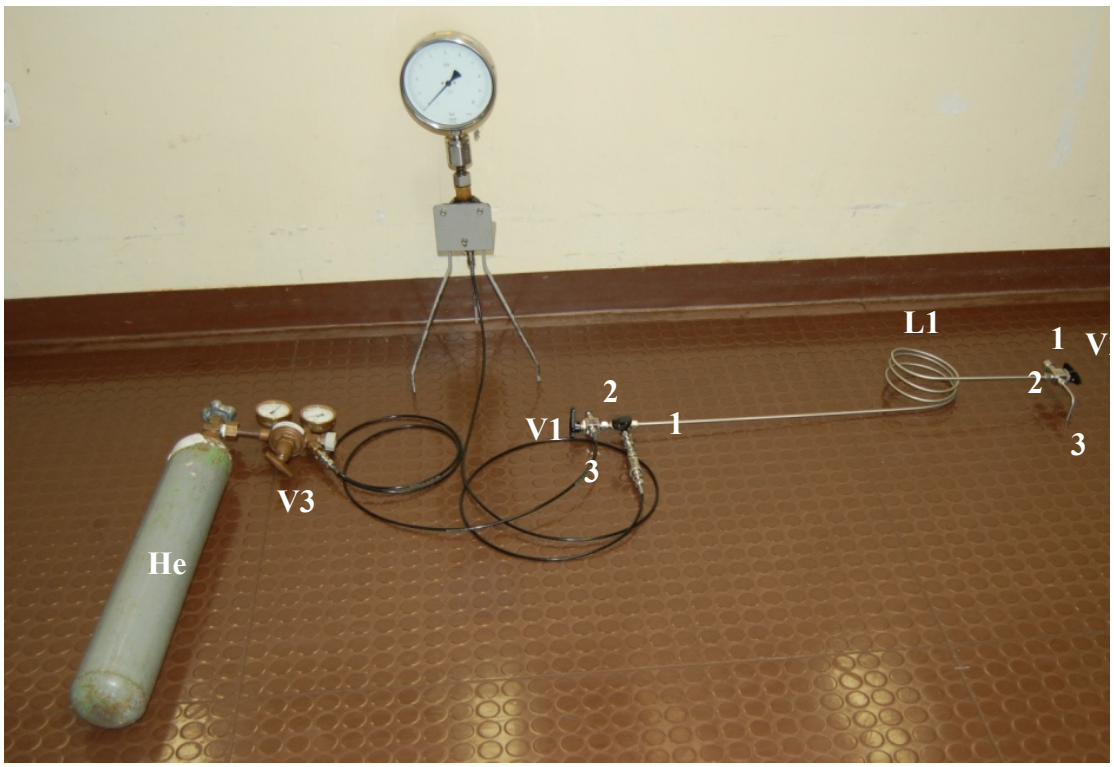

Figure 30. The loop constructed for injection of helium into the feed water at KKL.

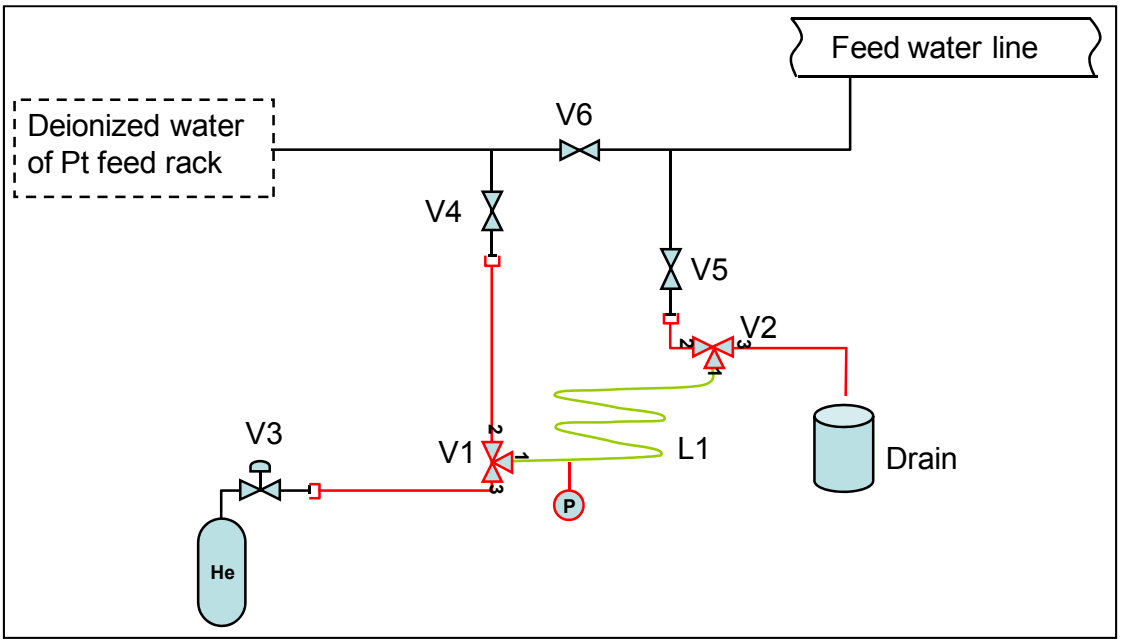

Figure 31. Schematic experimental set up for injection of helium into the feed water at KKL.

During the experiment, the sampling was performed with the frequency of 5 seconds in the direct measuring mode, i.e. measuring before the delay line. The time of the injections was registered by a stop clock for establishing the time from the injection to the increase of the signal registered by the helium measuring system. The graphical representation of the experimental results is illustrated in Figure 32. In Paper VI diagrams for selected time periods for the helium injections along with the summary of the results in Table 3 are presented.

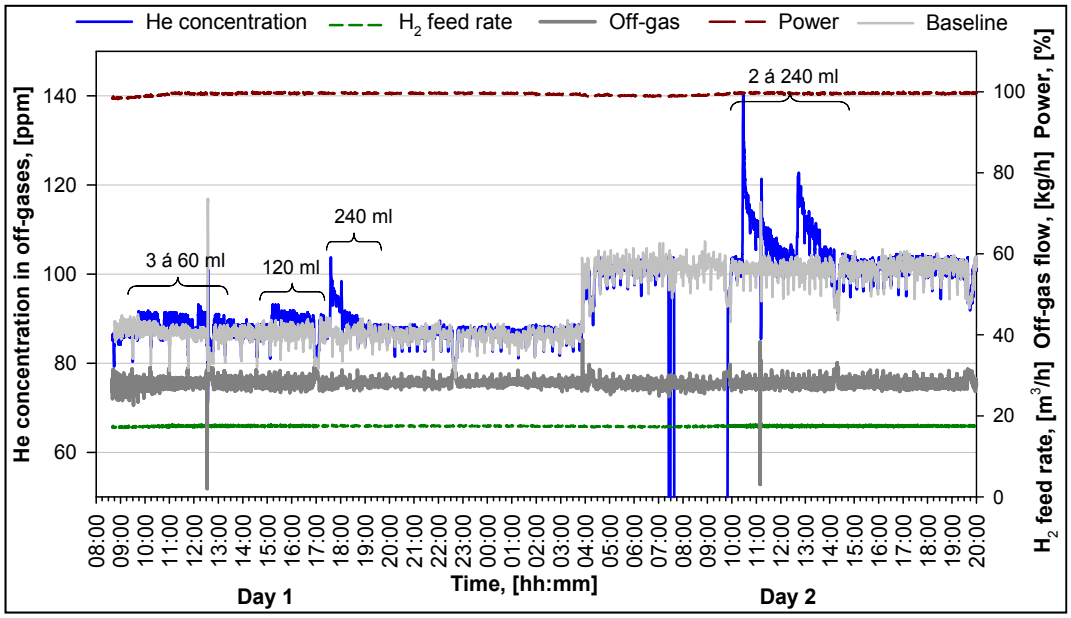

Figure 32. He measurements during to He injections into the feed water at KKL.

During the first day of the experiment, the increase of the signal was observed 9-10 minutes after the time of each injection, while on the second day of the experiment the response time shortened to 6-7 minutes. As can be read in Paper VI, it was established that the injected gas should be transported to the feed water pipe in about 3.5 minutes seconds, not taking into account the additional time caused by gas passing through check valves and possible time delays due to curvature of the line. In addition, there are also some uncertainties in the length and diameter of the line, which might influence the gas transportation time.

The duration of the increase was surprisingly prolonged, where the shape of the peak was considerably spread in time: about 1 hour for the smallest injections and more than 2 hours for larger amounts of the injected helium. Such spreading of the signal could suggest that the injected helium was not transported to the feed water and subsequent systems as one cohesive gas bubble, but was delayed somewhere in the bending or by the check valves connecting the platinum injection line to the feed water pipe. The parts of the gas bubble were then slowly washed out with the flowing by water. In addition, there might have been some dissolution of

helium in the water. Although helium has very low solubility in water, the solubility considerably increases with the pressure [31].

The recovery rate, i.e. the ratio of measured to injected amounts, of some injections was higher than 100%, although in some cases it was only 80 % of the injected amount. This suggested that not all of the helium followed to the feed water pipe, but some helium stuck somewhere as a gas pocket and was released later on. The sum of the measured amounts is 1.1 factor larger than the injected amounts, as can be seen in Paper VI. A similar phenomenon was observed earlier during injections into the grab sampling point at KKL, where the factor was 1.3. To obtain conversion equation Eq. (11) only one rough calibration was performed. To get a better correlation, a calibration with a series of standard calibration gases has to be conducted. So far mainly the release trend was watched and a rough estimation of the helium amount was calculated.

Chapter 8

EXPERIENCES OF MEASUREMENTS FROM FORSMARK

In this chapter a brief summary of papers VI and VII are given. The chapter includes a section on calibration of the detector and the conversion formula. The experiences from helium measurements at Forsmark 3, where the helium measuring system was installed to improve fuel failure detection, are also descrived. More detailed evaluation of the experiences is given in Paper VI. Additionally, an experiment where helium was injected into the feed water system is also presented, although a complete description of these experiments can be found in paper VI.

8.1 Calibration of helium detector

The calibration of the helium detector can be performed in two different ways: internal and external calibration. An internal calibration can be carried out by means of a built-in test leak. An external calibration can be performed by using a test leak attached to the inlet port [25]. It is recommended by a detector vendor to recalibrate every calibrated leak at regular intervals to validate its value [30].

8.1.1 Internal calibration

The Adixen ASM 142 helium leak detector used at Forsmark 3 is equipped with a built-in internal calibration leak of the order of 1 x 10^{-7} mbar l/s. An internal calibration of the detector at Forsmark is automatically activated during the start up of the detector. It is however, recommended to perform the internal calibration on a regular basis to verify a proper operation of the detector, particularly at heavy use. Yet, to perform a calibration, the measuring mode has to be interrupted, which will cause discontinuity of measurements.

8.1.2 Calibration and conversion equation

Before installing the detector and connecting it to the off-gas system of the reactor, the calibration of the helium leak detector with the gas separation cell including PTFE membrane was performed at standard pressure. The objective of this calibration was to obtain a relation in the form of a conversion formula between the detector signal (mbar l/s) and the helium concentration in the off-gases (ppm). The calibration was performed with four predetermined helium concentrations: 50 ppm, 500 ppm, 5000 ppm and 50 000 ppm = 5 %, delivered by the AGA Company in the mini flasks pressurized to 10 bar.

After performing a tightness test of the gas separation cell, gas of each concentration was injected several times. In order to provide a gas flow through the gas separation cell, a hose pump was connected to one of the openings on the upper part of the gas separator. Thereafter the gas was injected into the other opening. This resulted in a steady flow of gas through the cell and improved the reproducibility of the signal.

The detector signal is linearly proportional to the helium concentration of the gas sample. The helium concentration of the gas samples used for calibration differed from each other by a factor of 10, i.e. 50 ppm, 500 ppm, 5000 ppm and 50000 ppm. A factor of 10 was also registered in the detector signal which is illustrated in Figure 33. A linear dependence between average values of the detector signal and helium concentration was obtained by list square fit approximation, see Eq. (16).

$$\boldsymbol{c(He_{OG}) = \frac{P_{cal}}{P_{sampl.line}}\ 1.4 \cdot 10^{9} \cdot LR(He)}, \qquad \textbf{(16)}$$

where

$c(He_{OG})$ – concentration of He in the off-gases, (ppm),
$P_{cal}(= 1000\ mbar)$ – pressure at the calibration of the detector, (mbar),
$P_{sampl.line}$ – pressure in the sampling line, (mbar),
$LR(He)$ – measured He leak rate, (mbar l/s).

8.2 Helium measurements during operation

The installed helium measuring system at Forsmark is mainly focusing on improving the detection of fuel failures, as was described in Sec. 5.3.2. After that all the control rods at Forsmark 3 have been replaced in recent years due to design construction issues, no control rod failure has been detected in the core, based on measurements of helium in the off-gases and tritium in the reactor coolant.

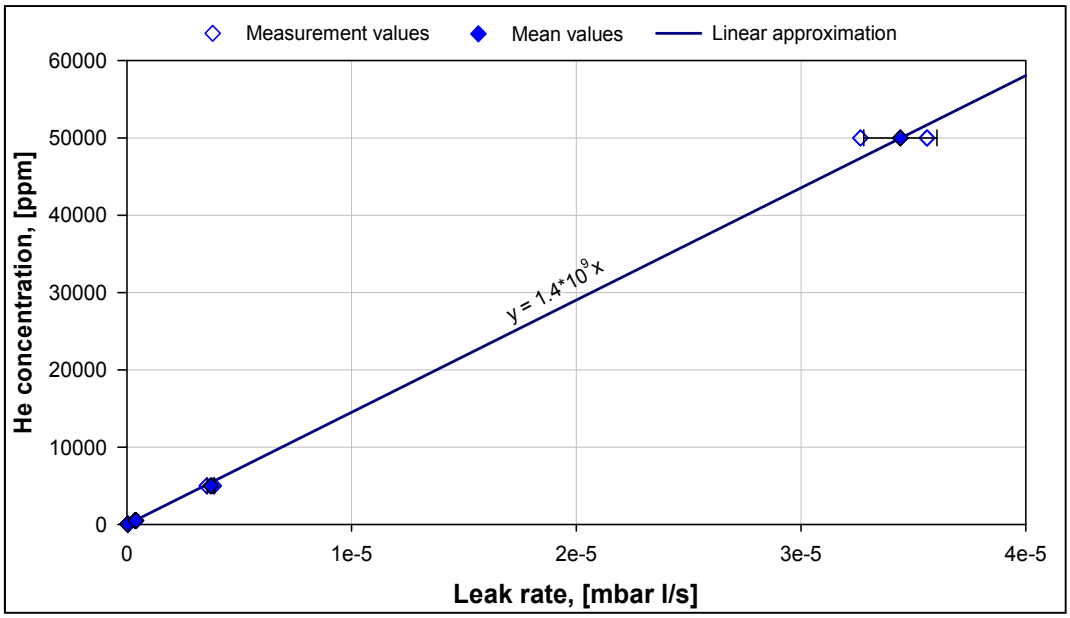

Figure 33. Linear dependence between concentration and leak rate.

8.2.1 Method for analysis of the measured data

The estimation of the helium amount released from the core follows the same approach as at KKL. However, in case of Forsmark, the background concentration is not affected in the same way. The background level is low and stable and can be assumed to be a straight line, which simplifies the calculation. Thus, Eq. (15) introduced in Sec. 7.2.1 can also be applied for the calculations of the released helium amount at Forsmark. Under stable conditions the background level can be taken as the last value before the detected increase, but if the baseline is unstable, an average value over a certain period should be taken.

8.2.2 Analysis of the measurements and interpretation

While a primary 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 they will not have enough time to decay before reaching the measuring point in the off-gas system. Due to the short half-life of Xe-138 ($t_{1/2}$=14 min.), an increase of that nuclide usually suggests that there is a release from an open fuel failure or from washout of fissile material from an existing failure. At Forsmark 3, there were periods with a measured increase helium concentration, suggesting a possible release of helium in the core after the installation of the helium measuring system. During one month, an increase of the helium detector signal was detected twice. The first increase was registered for more than two hours with about 70 ml helium released, as shown in Figure 34.

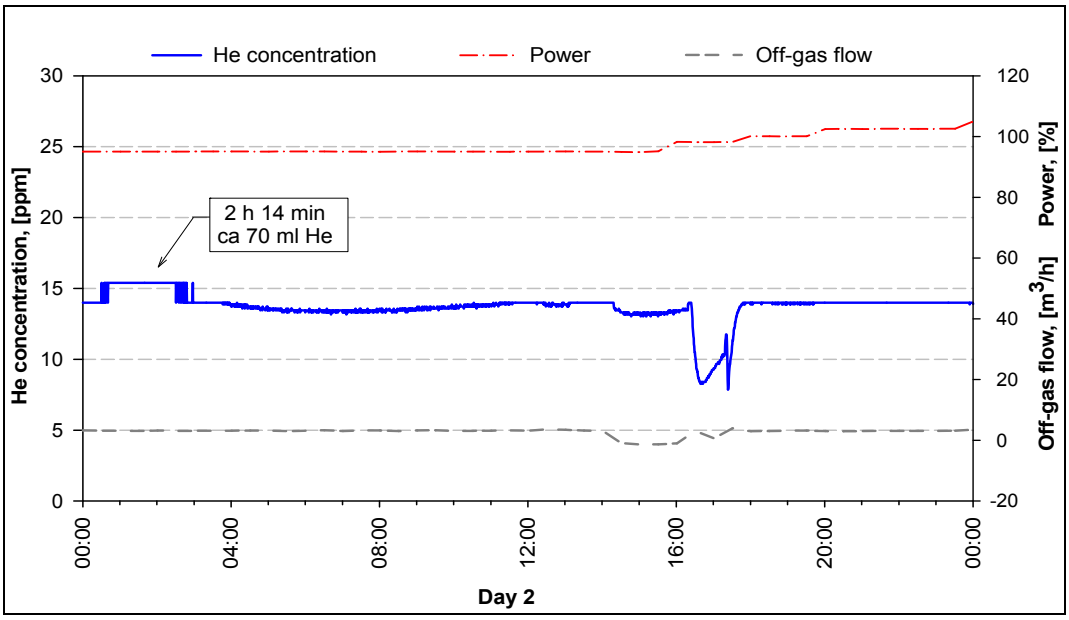

Figure 34. Increase of He concentration at F3.

A few hours later, a slight increase in activity was detected (primarily Xe-138), as shown in Figure 35. It is however, not entirely 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 very small and the activity release was close to the detection limit.

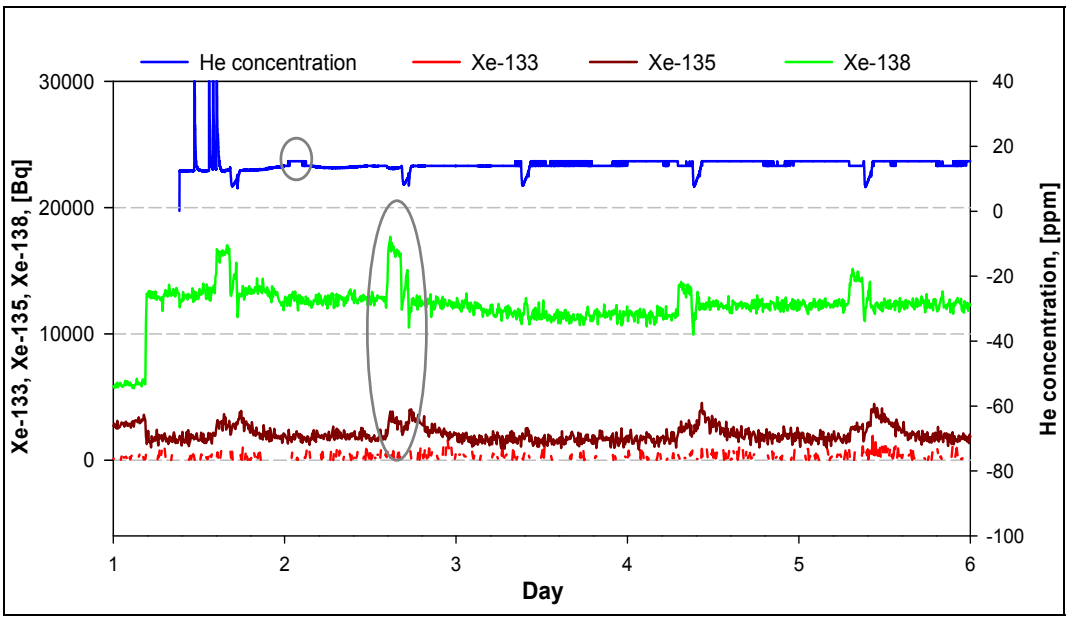

Figure 35. He concentration and activity measurements at F3.

Furthermore, 22 days after the first increase, there was another brief increase in the helium signal, with a duration of 20 minutes and the released amount of helium was estimated to about 10 ml, which is shown in Figure 36. At the same time an increase of gamma emitting

noble gases was detected, as can be seen in Figure 37. The measured increase of both the helium concentration and the concentrations of the active fission gases indicates a fuel failure. Most likely, these releases were from the same failure. At first most of the helium in a fuel rod leaked out due to the first penetration of the fuel cladding, and three weeks later, a small amount (approximately 10 ml) of the remaining helium was released. Afterwards, a gradual increase of Xe-133 activity was observed, which can also be seen in Figure 37.

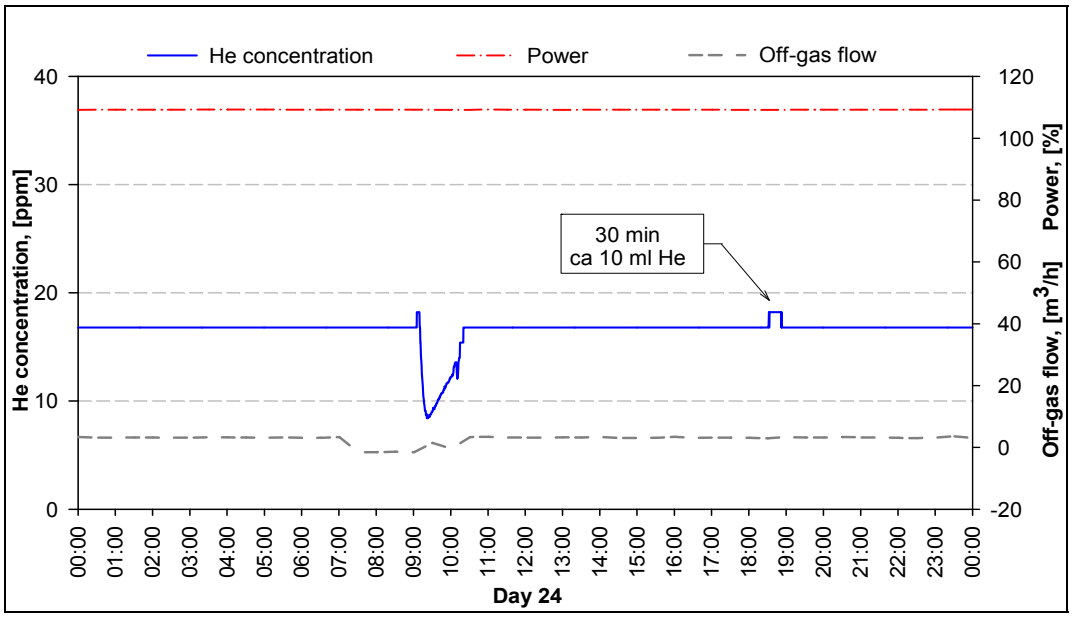

Figure 36. Increase of He concentration at F3.

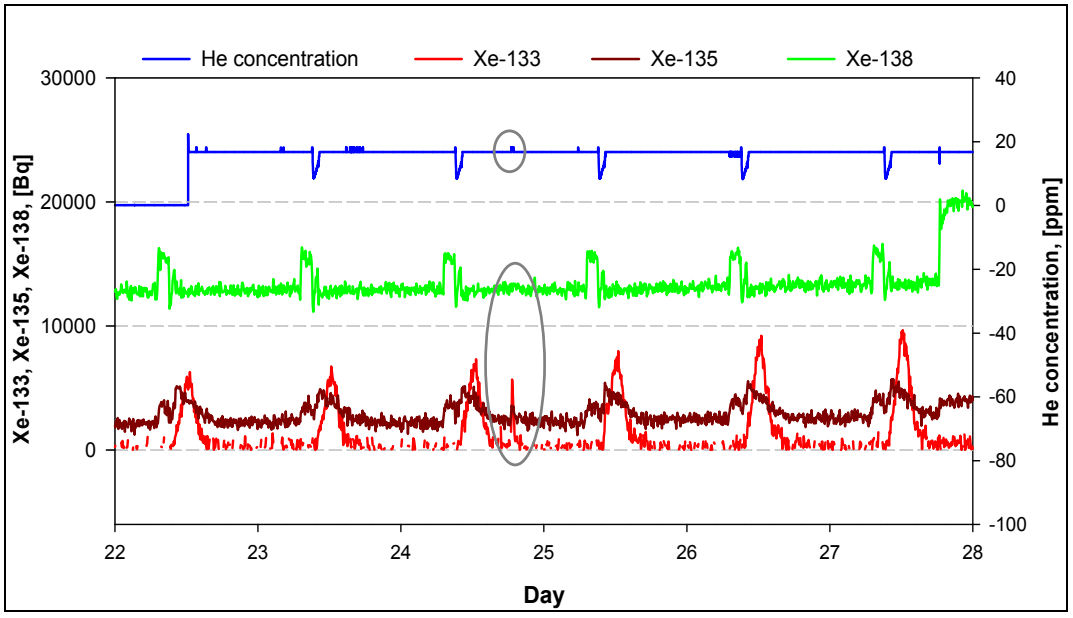

Figure 37. He concentration and activity measurements at F3.

Several months later, another increase of the helium concentration in the off-gases was detected, as shown in Figure 38. The duration of this increase was almost 2.5 hours and the helium amount determined during the increase was about 70 ml. Simultaneously, an increase of noble gas activity was measured, in particular of the long-lived isotopes Xe-133 and Xe-135, see Figure 39. This might be an indication that an additional failure occurred in the core.

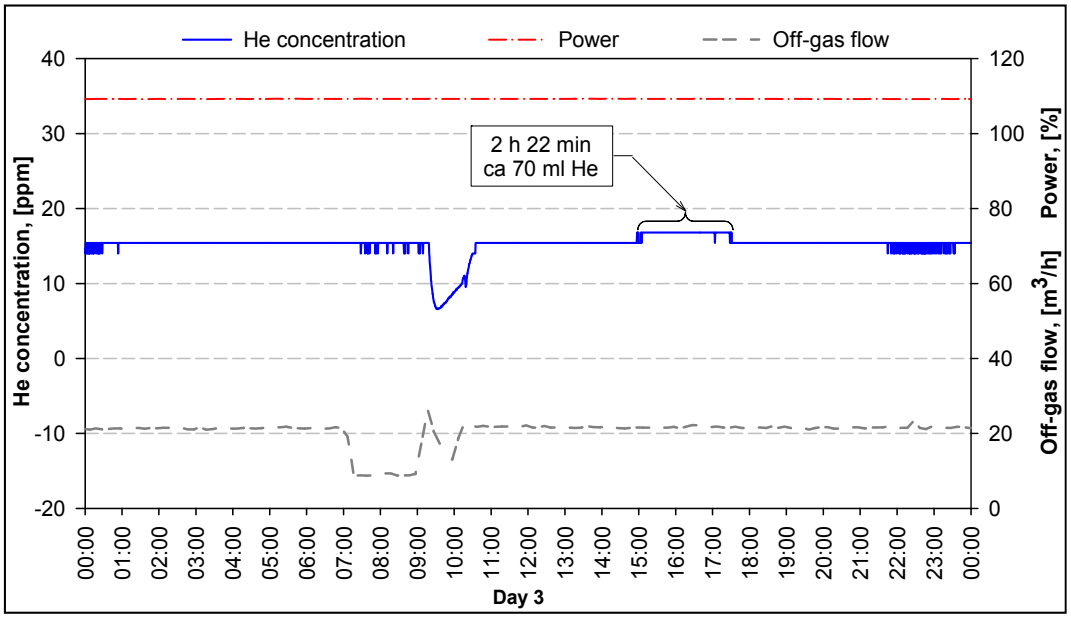

Figure 38. Increase of He concentration at F3.

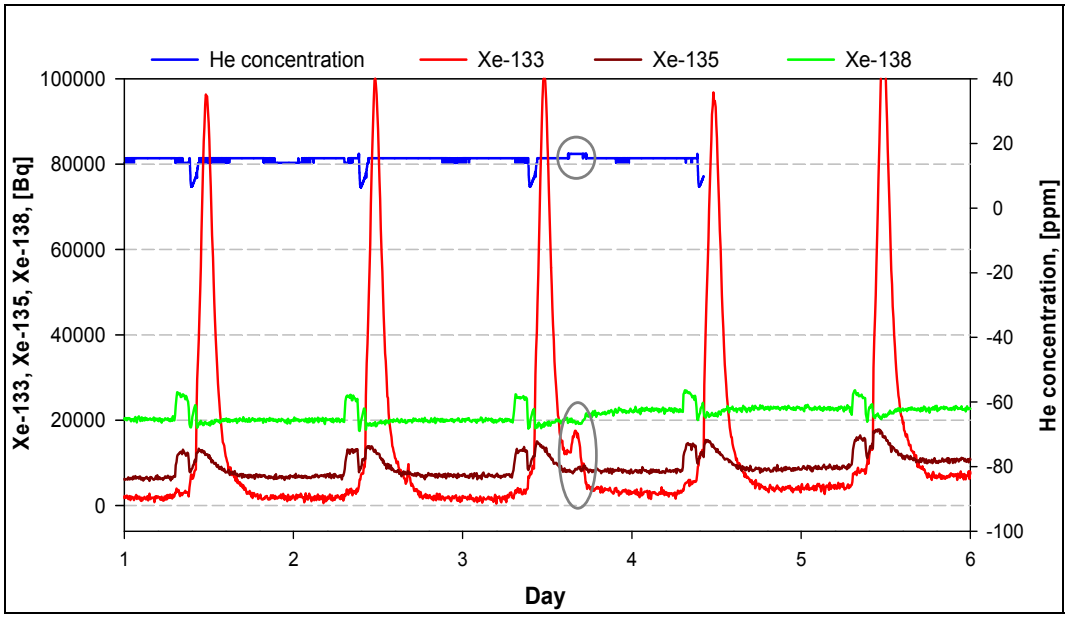

Figure 39. He concentration and activity measurements at F3.

The experiences of our measurements at Forsmark have shown that the helium measuring system, installed in the off-gases in connection to the system for nuclide specific measurements of gamma emitting noble gases, is helpful when detecting fuel failures. However, neither system has been able to detect all the failed fuel, identified later by sipping during outage. One possible reason to why all the failed fuel rods have not been identified by the helium measurements could be periods of discontinuity of measured data. Furthermore, there were significant disturbance of the helium 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 helium signal. Finally, each fuel failure is unique with different size and severity of the penetration and will therefore cause different release rates, which also needs to be studied further.

The obtained results show that the on-line helium measuring system is able to detect helium released from fuel failures. Even though the detection needs to be optimized, it has already been shown to provide a valuable support to the nuclide specific measurements of gamma emitting noble gases, for detection of fuel failures. Yet, more experience of measurements is needed to be able to imrove the system and to verify the ability to detect fuel failures using helium measurements.

8.2.3 Experiment with helium injections

An experiment at Forsmark 3 NPP was performed to ensure the ability of the helium measuring system, installed in the off-gas system, to detect helium that would correspond to a release from a fuel failure. The experiment and the obtained results are described in detail in Paper VI. In addition, the delay time and the spreading profile of the helium when the gas passes through different systems (reactor, turbine, condenser, ejector, recombiner, gas cooler, etc.) before reaching the detector were studied and presented in Paper IV.

Helium injections into the feed water

During the experiment, 80 ml and 40 ml of helium, i.e. amount of helium in an intact fuel rod or half of that amount, were injected followed by nitrogen of high pressure, which pressed helium into the feed water line leading to the reactor. Such rate of injection would correspond to an instantaneous release of all or half of the helium gas contained in a fuel rod.

The injections with helium were made in a point, which is usually used for taking feed water grab samples, in close vicinity to the reactor core. The details regarding the feed water sampling line can be found in Paper VI.

The pressure in the feed water pipe is at least the pressure in the reactor, e.g. 70 bar. In order to surpass the pressure in the feed water pipe and enable injection of the gas into the feed water, a dosing loop that would withstand high pressure was constructed using suitable Swagelok valves, as shown in Figure 40. A schematic set up of the experimental equipment and its connection to the injection point is shown in Figure 41. The volume of the loop (5) was determined to be 18 ml by weighing the empty loop and compare it to the weight of the

loop filled with deionized water. During the experiment, the loop (5) was filled with helium to a pressure of 4.5 bars which corresponds to 80 ml helium at standard pressure and room temperature considering the loop's volume. Dosage of 80 ml helium was repeated twice, after that the helium amount was decreased by a factor of two, and two additional injections of helium were performed. The details of the experiment and the sequence of the execution can be seen in Paper VI**.** The exact time of the injections was registered in order to determine the delay time of the gas when being transported from the dosing point through the reactor, turbine, condenser, ejector, recombiner, gas cooler before it reached the point of measurement where the helium detector registered the increased signal. The frequency of sampling by the helium measuring system was switched to 10 seconds to achieve good resolution of the signal. Results of the experiment are shown in Figure 42, the summary of the results is presented in Table 1 in Paper VI.

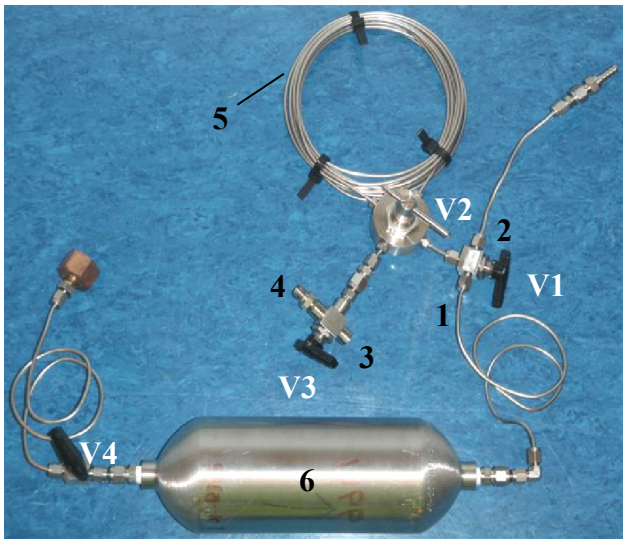

Figure 40. Dosing loop for helium injections into the feed water at F3.

V1: three way valve for nitrogen (1) and helium (2) injections;
V2: four way valve for switching the dosing loop for helium containment (5);
V3: three way valve for the connection to the drain to the sewer (3) and to the dosing point (4);
V4: three way valve for nitrogen injections to the gas container (6).

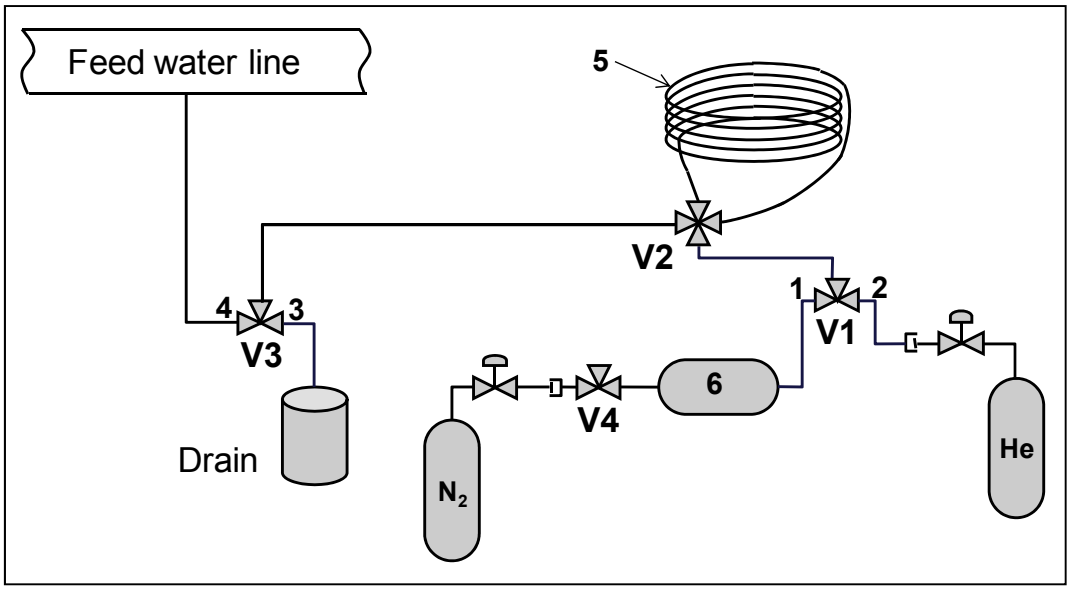

Figure 41. Schematic experimental set up for injection of helium into the feed water at F3.

All four injections resulted in narrow and well defined peaks of the helium concentration in the off-gas system, with minimal spreading of the gas, as can be seen in Figure 42. As described earlier, each injection of helium was followed by a large amount of nitrogen of high pressure which led to a very rapid helium injection in the feed water. The delay time from the helium injections to the initial helium signal increases in the gas sampling point, was determined to be 5-8 minutes. The thorough analysis of the detector response and delay time estimation is described in Paper IV and Paper VI.

All four peaks in the helium concentration signal have similar shape, as can be seen in Figure 42, showing only minor spreading of the gas when being transported from the dosing point to the sampling point. When the first increase of the helium concentration was detected, the signal increased rapidly and reached its maximum within 2-4 minutes. During the following 17-20 minutes, the signal decreased to less than 5% of its height. However, it took another 20 minutes for the signal to decrease to the original background level.

The experiment at Forsmark 3 confirmed the ability to detect a primary fuel failure by a helium measuring system under the assumption that most of the helium contained in a fuel rod would be released within a reasonable short time period. However, the helium release rate from a fuel failure is unsure and further studies on this topic should be performed before any final conclusions are made. The experiment also showed that the described helium detection system is useful for estimation of the delay time for gases transported from the core to the gas sampling point in the off-gas system, as well as for studies of the gas spreading during the transport from the core to the sampling point.

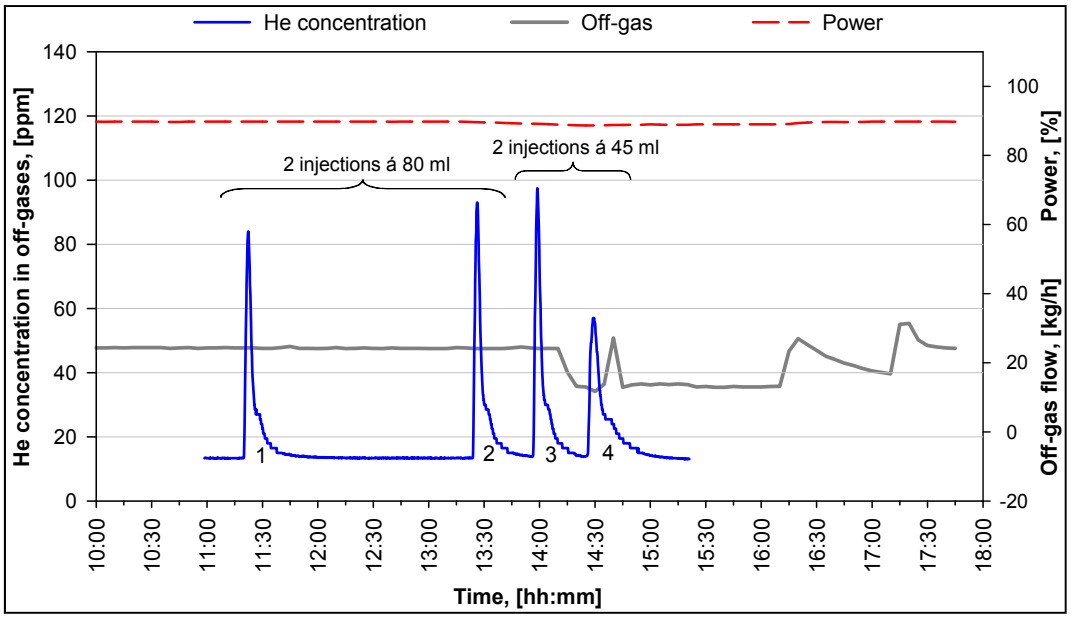

Figure 42. Results of the experiment with helium injections into the feed water at F3.

Chapter 9

SUMMARY

The main goal of this work was to investigate whether a system for on-line measurements of helium concentration, installed in the connection to an on-line nuclide specific gamma emitting noble gas measuring system, in the off-gases of a BWR would be useful for detection of fuel and control rod failures. To study the ability of such an on-line helium detector system, demo systems were installed in the off-gas systems at KKL in Switzerland and at Forsmark 3 in Sweden. The outcome if this work is summarized in Papers I-VII.

An on-line measuring system which combines monitoring of helium and nuclide specific gamma emitting noble gases in the off-as system is a robust and reliable method for detection of fuel and control rod failures, as presented in Papers I and II, since fuel rods contain both helium and gamma emitting noble gases, while control rods only contain helium. Such a system gives fast response and a prompt detection of both the helium gas and the noble gases that leak out into the coolant and are subsequently transported to a sampling point.

The efficiency of the helium detector system for the surveillance of control rod integrity in the core has been confirmed by experiences from measurements at KKL, as described in Paper V, where the main purpose of the system has been the detection of control rod failures using continuous helium monitoring. Control rod failures at KKL have been identified and followed by the on-line helium detector system. Since 2012 the helium measurement system is part of the process control and is also part of the KKL core supervision system, which includes monitoring of thermal operation parameter of the reactor core and relevant chemical parameters of the reactor water. In addition, an equation determining the baseline of the helium in the core is developed, which would enable a prompt and automatic calculation of the released amounts of helium, once the equation is incorporated in the supervision system.

At Forsmark, the main focus has been to evaluate the ability of the helium detector system to detect fuel failures. The experiences from the measurements performed during this project have shown good efficiency of the system and helium release from fuel failures have been detected, which is described in Paper VII. To verify the ability to detect even minor helium leaks, experiments with helium injections, described in Paper VI, were conducted at both

NPPs. These experiments assured the ability of the system to detect even small amounts of helium passing through the reactor core and the subsequent systems before reaching the sampling point in the off-gas system. In addition, as described in Paper VI, experiments at Forsmark 3 were performed to study the gas spreading when the helium were transported through the reactor systems, and to determine the delay time from the reactor core to the sampling point. This information is of great importance when performing a PST.

However, when evaluating the measured results, a number of factors that can influence the measurements have to be taken into consideration. These factors are discussed in Paper III.

Furthermore, although the helium measuring system is simple, user friendly, robust and cheap, it needs a periodic maintenance, with service of the detector recommended once per year. In addition to the periodic internal calibration, a calibration with sources of predetermined helium concentration should be performed at least once per year, to verify the conversion equation used to convert the detector leak signal mbar l/s to concentration in ppm.

Chapter 10

FUTURE WORK

To optimize the evaluation of the helium measurements and to simplify the analysis, the measured data should be automatically normalized and stored together with normalized values of the noble fission gases from the nuclide specific measurements of the off-gases. Data from the core supervision system, e.g. reactor power level, off-gas flow rate, control rod movements, hydrogen injection (if it is applied), etc. should also be stored, together with data on temperature and pressure in the sampling line. All these data should then be easily displayed using the same software in a combined system to make it easy to correlate changes in the concentration levels of helium and noble fission gases to each other and to reactor operational changes. The use of such a measuring system would be even more beneficial if the data could be stored automatically and be accessible from any computer at the NPP, as it is realized at KKL where the helium measurements are implemented into the core supervision system.

An on-line helium measuring system could also be useful for location of leaking control rods in the core. The location of fuel failures during operation of a BWR can be identified by performing a PST. A PST is usually implemented as a support to the sipping procedure, which is performed during the outage. During a PST, measurements of the helium concentration in the off-gases could be performed in parallel with measurements of gamma emitting nuclides. This could show the location of leaking control rods at the same time as the location of failed fuel rods are found without any additional costs or inspections.

The helium measuring system could also be used for tightness control of the condenser during start-up of the reactor. If the system would be permanently installed and automatically controlled, it would reduce both measurements uncertainties and extra costs.

Another matter that needs to be improved is the accuracy of the control rod depletion estimation, used in a model the estimation of helium in a void volume of a control rod. When estimating the amount of helium in the void volume of a control rod, an average depletion of the whole control rod, which is often used today, might be misleading. As the helium release from the B_4C in the control rod is dependent on the ^{10}B depletion, segmented control rod

depletion or even node depletion should also be analyzed. When analyzing the helium release from Marathon control rods, knowledge of the ^{10}B depletion, instead of the normally used ^{10}B equivalent depletion, would give much more accurate results since ^{10}B equivalent depletion includes depletion of hafnium which gives no contribution to the helium amount in a control rod.

The model that was used to predict the amount of helium in a control rod depending on its depletion in this project could not be fully benchmarked as no reliable post-irradiation measurements of the helium inventory in a control rod were available to the authors. A high accuracy of the estimation of the helium amount in a control rod might anyway not be essential due to the uncertainties of the helium measurements, and since each failure is very individual and will therefore cause a different helium release profile.

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