POOLSIDE INSPECTIONS AT LOVIISA NPP

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ABSTRACT

The two VVER-440 units at Loviisa Nuclear Power Plant are operated by Fortum. The operating license for both units has been renewed for a 50-year lifetime, Loviisa-1 to 2027 and Loviisa-2 to 2030. The fuel reliability experience of Loviisa NPP has been very good and the fuel failure rates have been very low. Systematic inspection of spent fuel assemblies, and especially all failed assemblies, are carried through in order to improve fuel reliability and operational safety. In this paper we present a summary of the current Loviisa NPP poolside inspection programs and methods used to verify the fuel performance, licence new fuel types and assure the safety of the spent fuel in the long term interim wet storage. Also, some results of the poolside inspections are presented.

1. Introduction

The Loviisa NPP with two Russian-design VVER-440 pressurised water reactors started operation in 1977. At Loviisa NPP, a poolside inspection equipment (ATULA) was developed in the mid-80’s and has been extensively used for inspections of irradiated fuel, but in 90's and 00's ATULA was used in licensing new advanced fuel types also. In the recent years ATULA has been mainly used for post-irradiation and long-term storage surveillance of spent nuclear fuel as well as inspecting failed fuel assemblies in order to find causes and remedies for the occurrences. As to fuel failures, recent statistics show excellent performance - Units 1 and 2 combined, there has been only five fuel failures during the last 20 years of operation.

During the long outages that occur biennially, but only every fourth years for a unit, some of the control rod absorbers and the pressure vessel shielding elements are inspected with ATULA also. The absorber inspections are related to the lifetime extension program of the absorbers. The surveillance program of the shielding elements that protect the pressure vessel from radiation damage has no other purpose than to regularly inspect the shielding elements for possible damages and deformations.

In addition to the non-destructive examinations carried out at the NPP, destructive hot cell examinations are used gather additional information and to verify the poolside inspection results. In 2003, three TVEL fuel rods were shipped to Studsvik, Sweden. The examinations and the subsequent in-pile testing of the fuel within the OECD Halden Reactor Project were part of a burnup extension project that included a change from the 3-batch loading to 4-year fuel cycle. In order to achieve burnup extension and 4-year fuel cycle, the Finnish Radiation and Nuclear Safety Authority (STUK) required experimental evidence for both normal operation and abnormal conditions. Currently Studsvik is performing hot cell examinations to five Loviisa NPP fuel rods, that were shipped to Sweden in January 2018. The objective of these inspections is to perform regular post-irradiation surveillance, but also to gather information that is needed when the final disposal of the spent fuel is prepared.

Currently Loviisa NPP has only one fuel vendor, JSC TVEL, but also BNFL/Westinghouse fuel has supplied total 7 reloads in the 00's. At the moment, a transition from regular TVEL GEN-II assemblies to GEN-II assemblies with modified spacer grids is currently ongoing on both units. The first assemblies with this feature were the 12 Lead Test Assemblies (LTA) loaded to Loviisa-1 reactor in 2012. Before the loading of LTAs, a dummy assembly with rods containing steel bars instead of the fuel pellets was inspected in 2012 after one reactor cycle. Furthermore, the same dummy assembly was inspected again after two reactor cycles. The first LTA was inspected in March 2016 after three irradiation cycles. Another LTA is scheduled to be inspected during 2018 after four irradiation cycles.

Other recent poolside inspections include the inspection of the first four cycles old high burnup TVEL GEN-II assembly (without modified spacer grids) during spring 2015. Also in spring 2015, a leaking GEN-II fuel assembly that failed during its first cycle in Loviisa-2 in December 2012 was inspected. Later on some follow-up inspections were done to it and one other assembly that was next to the leaker during the 2012-2013 irradiation cycle, because foreign material was found inside the failed assembly. Same material was found from the adjacent assembly also. The first TVEL GEN-II fuel follower assembly was inspected after three irradiation cycles in 2017. In January 2018, some remeasurements were done to the rods sent to the hot cell inspections at Studsvik.

1.1 Loviisa NPP reactor core and assemblies

The standard GEN-II VVER-440 fuel assembly has 126 fuel rods in hexagonal formation with a fuel rod pitch of 12.3 mm. Unlike in many PWR designs, the fuel bundle is surrounded by a shroud tube channel, which also gives structural stability for the assembly. Both Loviisa reactors have 276 fixed fuel assemblies together with 36 shielding elements placed in the perimeter of the core. The 37 control rods (CR) are of flux trap type and have fuel follower assemblies connected beneath them so that in normal operation the CR's are completely withdrawn from the core. The TVEL fuel uses Zr-Nb alloys (Zr1%Nb 'E110' alloy for the rod cladding) as structural material. The BNFL/Westinghouse fuel used Zircaloy-4 and the different materials gave rise to some differences in structural behaviour as far as irradiation growth and clad creep are concerned, but the overall performance differences are small.

2. Scope of inspections programs

The fuel operation and post-irradiation surveillance programs are required by the Finnish Radiation and Nuclear Safety Authority (STUK). Loviisa NPP poolside inspection programs fulfil the authority requirements ([1], [2]) and are complemented by Loviisa NPP own needs. Currently there are four separate poolside inspection programs:

- Verification of safe fuel operation
- Spent fuel condition monitoring during long-term storage
- Lifetime extension program for the control rod absorbers
- Inspection program for pressure vessel shielding elements

The verification of safe fuel operation program consists of different inspection campaigns based on the changes made in fuel manufacturing or operating conditions. The program also includes the inspections of the leaking fuel assemblies in order to identify the root cause for the leakage if possible. Furthermore, some of the irradiated assemblies are routinely inspected post-irradiation to verify the stable fuel behaviour. The number of inspections within the program changes yearly. During major changes in fuel design, there can be numerous pre- and post-irradiation inspections, but if there are no design changes or new leaking assemblies, only one or more routine inspections are performed that year.

Loviisa NPP stores all spent nuclear fuel in wet condition in storage pools. The leaking and non-leaking assemblies are stored identically. At the moment the spent fuel condition monitoring program contains six assemblies selected to present different materials and operational histories. More assemblies can be added to the control group if e.g. a new material is taken into use. Each assembly is inspected roughly every ten years and because the purpose is to evenly distribute the inspection throughout the years, currently one of the inspections is made every second or third year.

The purpose of the lifetime extension program for the control rod absorber elements is to extend the operational lifetime of the absorbers from 20 to 30 years and the program originally included the oldest six absorbers from both units. The oldest absorbers go to their 30th and last cycle this year. The inspections are done biennially, but only every four years for a unit when the unit is in its long outage. In addition to the 12 absorbers, one 27 cycles old absorber is planned to be cut open during 2018 in order to directly inspect the lowermost boron insert of the absorber. The condition of the lowermost boron insert together with the wear of the control surfaces are the limiting factors for the service life of the absorbers.

The inspection program for the pressure vessel shielding elements is related to the change in shielding element design. The head piece of the original shielding element has six pins with fixed springs that prevent the floating of the shielding element. The lifetime of these fixed springs, 8 years, sets the lifetime of the shielding elements also. The new design replaced the pins and fixed springs with replaceable spring packages. The nominal lifetime of the new shielding elements is 24 years and the spring packages are changed twice during that time, after 8 and 16 years of use. The new shielding elements were taken into use in 2005 in Loviisa-1 and 2006 in Loviisa-2. The inspection program includes four shielding elements from both units and the inspections are done biennially, but only every four years for a unit when the unit is in its long outage. The scope of the inspections varies from inspection to inspection. Based on the current operational experience, it is expected that the extent and amount of inspections can be significantly reduced during the last 8 years of shielding element lifetime.

3. Scope of examinations

The ATULA equipment is currently installed in one of the storage pools of the spent fuel storage building and it has a platform with one socket where an assembly (fixed assembly, fuel follower assembly, absorber element, or shielding element) can be mounted. Once installed into the socket, the assembly can be rotated around its vertical axis and also moved vertically together with the platform. Different tools and devices can be attached to a manipulator arm, which is attached to another platform. The manipulator arm can be moved horizontally in two directions and the platform allows vertical movement independently of the other platform holding the assembly. The visual inspections are carried out using a periscope to which a photo or video camera can be attached. The following inspection techniques and measurements are available:

- Assembly dimensions (assembly length, bow, bow direction, twist and distance across flats)
- Fuel rod length (in assembly indirectly or manually for detached rods)
- Visual inspection of the assembly, fuel rod bundle and detached fuel rods
- Removal and replacement of the shroud tube and top nozzle, including driving and locking the screws fixing the joint
- Rod diameter measurement while the rods are in the rod bundle (excluding areas behind the grids)
- Detachment and reinsertion of the fuel rods, handling of the fuel rods using a rod gripper
- Profilometry and spiral profilometry of the detached fuel rods
- Fuel pellet-cladding gap of the detached rod by a squeezing technique
- Gamma spectrometry measurements including axial scanning and fission gas release estimates (based on Kr-85 measurement from the plenum area)
- Spring force measurements (for the spring packages of the shielding elements)
- Sample collection by scraping or cutting

Since the water-side corrosion is typically very low in VVER-440 and the oxide layer has been earlier verified to be 4-6 microns after 3 to 4 cycles of irradiation for E110 cladding material and up to about 20 microns for Zircaloy-4, oxide layer thickness measurements are not routinely done at Loviisa NPP. Because of this, ATULA has no instrument to directly measure the oxide layer thickness. If the oxide layer is considered to be abnormally thick during the visual inspection, a separate inspection of the oxide layer thickness is arranged (purchased).

The scope of examinations within a campaign depends on the inspection program to which the campaign belongs. If the intent is to verify safe fuel operation, most of the available measurements are used to evaluate the performance of a fuel assembly. Sometimes the scope of examinations can be very narrow and specific, for example when the mixing vanes were added to the TVEL GEN-II spacer grids. In the long-term storage program, only the visual examination of the shroud tube and rod bundle is performed, and the appearance of the assembly is compared to the previous examination. For the absorber elements, in addition to the visual inspection, the shape of the absorber is measured, especially the area of the lowermost boron insert. Also the wear of the guide grooves and holes are measured from the tail and head piece, respectively. For the shielding elements, one inspection campaign contains the visual inspection, the shape measurements and spring force measurements. The spring force measurements of the head piece spring packages can be left out from the campaign when sufficient operational experience and measurements have been gathered to verify the relaxation rate of the springs.

4. Recent results from the Loviisa NPP poolside inspections

4.1 Absorber element inspections

The service life of the absorber element of the control assembly was originally four years in Loviisa NPP. Starting from 1993, the absorber service life has been extended several times, first to ten years, then to twenty years and in 2009, the authorities gave permission for thirty years' service life. The wear measurements are required for the absorbers older than ten years. The current limit, thirty years, requires that the absorbers are operated for maximum six years in controlling positions and in addition to the wear measurements, the shape of the shroud tube is controlled by visual inspections and measurements. Loviisa NPP has performed absorber measurements in 1993, 1994, 1996 and biennially from 2000 onwards. Both units had six absorbers in the inspection program originally, but now one of Loviisa-1 absorbers has been removed from the reactor and it will be inspected destructively during 2018. The latest measurements were done during Loviisa-1 outage in 2016. The next measurements will be done during 2019 after the absorbers in the inspection program have reached the current lifetime limit, 30 years. The results presented in this paper are an update to the results presented in [3].

Fig. 1 shows the location of the lowermost boron insert, the guide holes and the guide grooves that are critical for the service life of an absorber. These locations are inspected during every inspection campaign. The continued use of an absorber is approved, if there is no risk that the absorber will exceed its mechanical specifications during the next three years of operation. The assessment is done by extrapolating the measured values using the maximum measured wear rates. No swelling of the lowermost boron insert has been detected and thus extrapolation is not used for the deformation values.

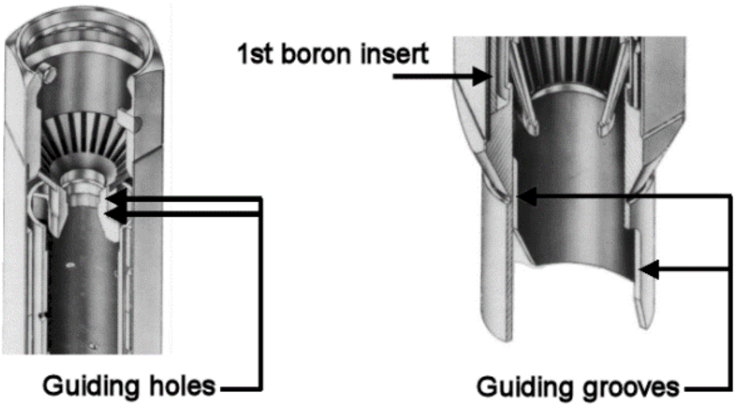

Fig 1. Critical surfaces and structures of a VVER-440 absorber element.

Fig. 2 shows the combined guide hole measurement results of Loviisa-1 and Loviisa-2 absorbers from inspection campaigns since 1989. Although the both guide holes (diameters 42 and 46 mm) are measured, only the results from 42 mm hole are used as a criterion for continued use. This is because the structure of the control rod mechanism is such, that when the 42 mm hole eventually starts to wear, the 46 mm guide hole cannot wear at any different rate from that point forward. Since the guide hole measurements are done manually using a dial gauge, each measurement is repeated twice, and the diameter is measured from three points, each point roughly 120 degrees apart from each other. Furthermore, each guide hole is measured by at least two persons. Based on the linear estimate (Fig. 2), the 42 mm diameter guide hole has not worn at all.

Fig. 3 shows the combined guide groove measurement results of Loviisa-1 and Loviisa-2 absorbers from inspection campaigns since 1989. The two guide grooves at the absorber tailpiece control how much it is possible for the absorber to turn around its vertical axis. If the absorber turns vertically more than few degrees, it will touch the adjacent fuel assemblies and there is a risk that the control rod mechanism doesn't work properly. Luckily the groove surface with least wear controls the amount the absorber is able to turn and thus we can measure only the change in the guide groove width. This is easier and more conservative measurement than measuring the wear of each contact point between guide grooves and fuel follower element lifting pins. Based on the linear estimate (Fig. 3), the guide groove wear can be expected to start to limit the service life only after 51 years of use.

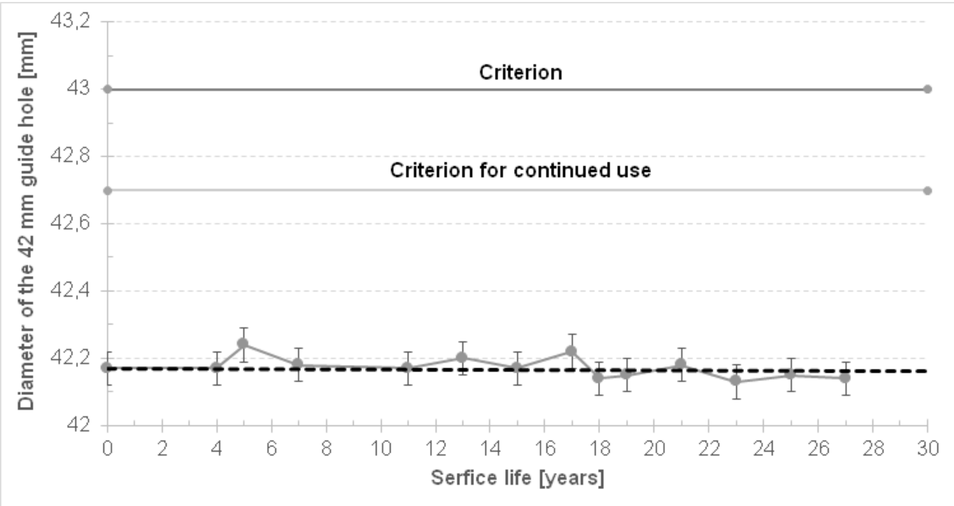

Fig. 2. Combined Loviisa-1 and -2 results of absorber inspection campaigns 1993-2016.

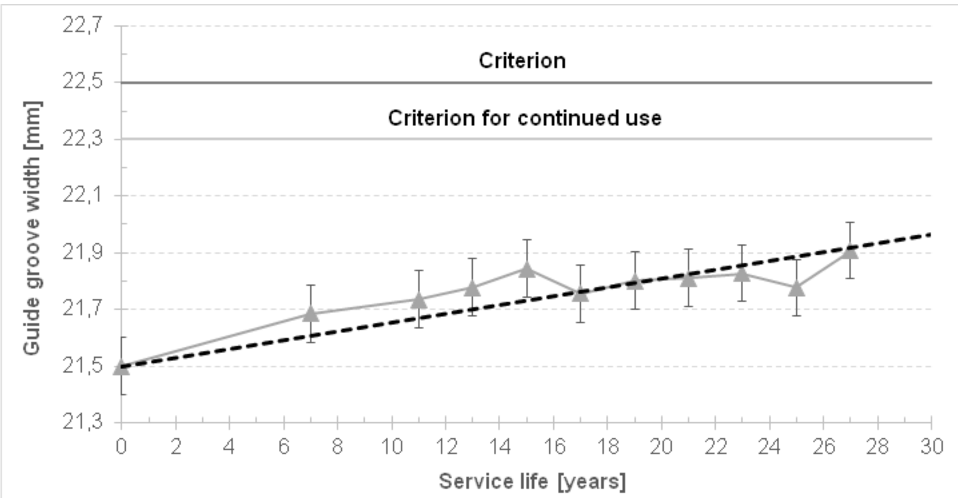

Fig. 3. Maximum wear of Loviisa-1 and -2 absorber tailpiece guide grooves.

Based on the measurement results described above, thirty years of service life can be easily achieved. However, the poolside inspections do not directly measure the possible swelling of the lowermost boron insert and it is also unclear how much the boron concentration has changed during the years. For these reasons and to confirm previous measurements and calculations, Fortum has decided to disassemble one 27 cycles irradiated absorber and deliver its lowermost boron insert to hot cell examinations. The results from the destructive inspection are expected to be available during 2019.

4.2 Shielding element inspections

The shielding elements are used to protect the reactor pressure vessel from excessive radiation damage. Since the elements are made of steel and periodically moved from one side of the reactor to the opposite side to equalize the possible radiation induced changes, no significant shape changes or other damages are expected to occur during their nominal 24 years lifetime. However, in 2005 when these new shielding elements with changeable spring packages were introduced, the design was completely new and thus an inspection program was set up to gather operational experience and to control the performance of the shielding elements and their spring packages. The continued use of a shielding element is approved, if there are no significant visual damages, the shape of the element is within specifications and each spring package exceeds the minimum spring force limit. If a spring package fails to exceed the limit, it will be exchanged.

The eight shielding elements (four per unit) in the inspection program have all been inspected twice during their operational life (Loviisa-1: 2008 and 2012, Loviisa-2: 2010 and 2014). The spring packages have been changed once (Loviisa-1: 2012, Loviisa-2: 2014). Originally it was expected, that the spring force measurements could have been left out from the inspection program after the 2014 measurements based on operational experience, but since it was necessary to make some design changes to the spring packages and the original spring design was not feasible anymore, the spring force measurements are continued in the future also. The results have been presented previously in [3].

Fig. 4 shows a comparison of the 2010 and 2014 spring force measurement results for the four Loviisa-2 shielding elements in the inspection program. The graph includes the new (unused) spare spring packages also. The spare packages were used to replace the old packages that had reached their service life limit, eight years. The error bars in the 2010 data are much larger, because the measurements were done using different (old) measuring device. Based on Fig. 3 it is clear that 0, 4 and 8 cycles irradiated spring packages all perform similarly from the spring force point of view. However, during the test run it can be seen, that the used spring packages do not move as smoothly as the new ones.

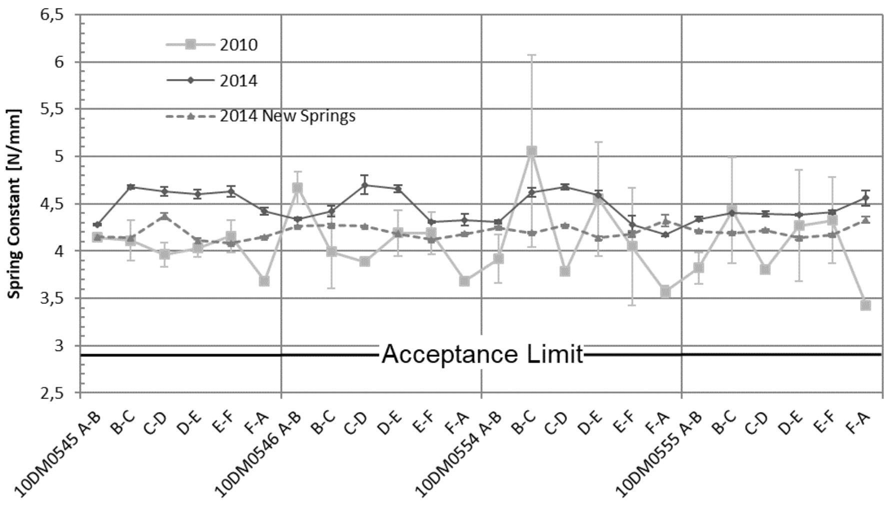

Fig. 4. Results of the spring constant measurements of four Loviisa-2 shielding elements

4.3 Inspections related to verification of safe fuel operation

Last ten years have been an active period for the safe fuel operation program. The introduction of TVEL GEN-II assemblies and the switch from 3-cycle to 4-cycle operation have both required a lot of inspection campaign. Luckily there has been only three leaking assemblies during this period, so this has balanced the work load. The largest of the campaigns during this period has been the inspection of the first four cycles old TVEL GEN-II assembly; most of the inspection methods described in section 3 were used in evaluation. The assembly with the highest burnup in its batch was selected for the inspection.

The individual campaigns related to the TVEL GEN-II spacer grid design change have been quite small and mostly limited to visual inspection of the grid-to-rod contact points, but number of campaigns is large. In total five campaigns are required completely verify the design change, which of three has been already done. The fourth inspection will be the last Loviisa-1 LTA to be inspected after four irradiation cycles. The fifth and the last inspection will be done to an assembly that has been irradiated four cycles in Loviisa-2 reactor. Loviisa-2 has slightly higher primary coolant flow rate than Loviisa-1 and this may affect the performance of the spacer grids.

The safe fuel operation program will continue to be active even after the current design changes have been fully verified, because there are plans to introduce a new fuel type with increased uranium capacity and an optimised water-uranium balance compared to the assemblies currently used at the Loviisa NPP. The results presented in this paper are an update to the results presented in [3] and contain measurement data previously presented in several conferences and seminars, e.g. [4] and [5].

Typical measurement campaign is started by measuring the assembly dimensions. Fig. 5 demonstrates the measured irradiation growth occurring in Loviisa NPP fuel assemblies. Since the assemblies are only a bit over 3 meters in length, the assembly bow and twist are minimal. A typical assembly bow is 1-2 mm and twist less than a degree.

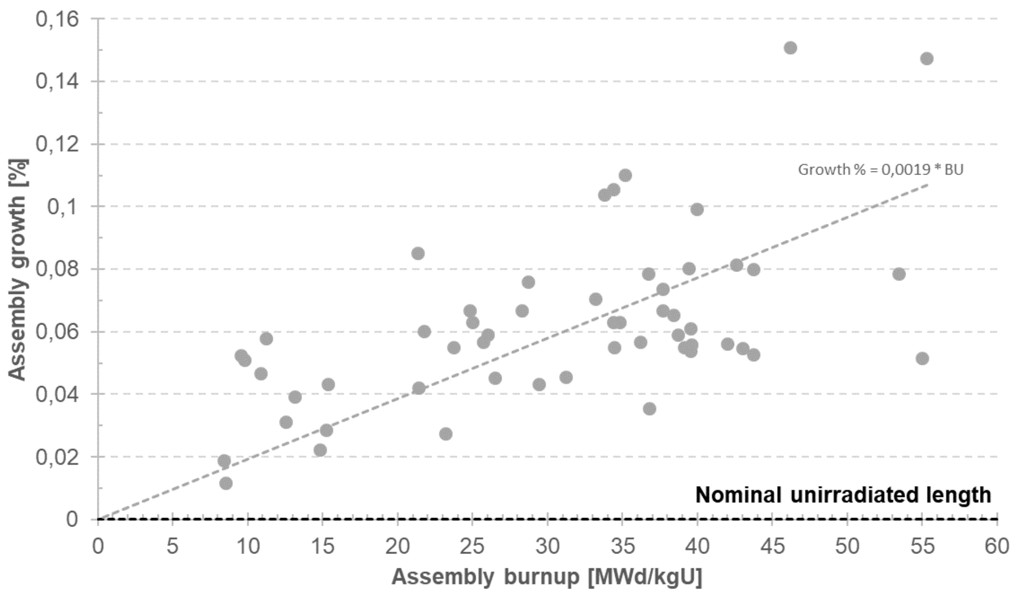

Fig. 5. Assembly irradiation growth relative to the nominal unirradiated length.

After the assembly measurements and visual inspection, the assembly is dismantled by removing the shroud tube and top nozzle. After this the visual inspection can be carried out to the rod bundle and spacer grids.

When the rod bundle inspections are done, single rods are then removed one by one from the assembly and inspected individually. Fig. 6 demonstrates the rod irradiation growth occurring in different fuel types used in Loviisa NPP. The results include both E110 and Zircaloy-4 cladding. In addition to the rod length measurements, rod profilometry and gamma measurements are done to the detached rods. Fission gas releases (FGR) are estimated from the gamma measurements using modified (VTT) version of the LADAKH code [6]. Fig. 7 contains recent FGR estimates and also the results from the Studsvik 2003 direct measurements (by puncturing). Studsvik 2018 results are not yet available.

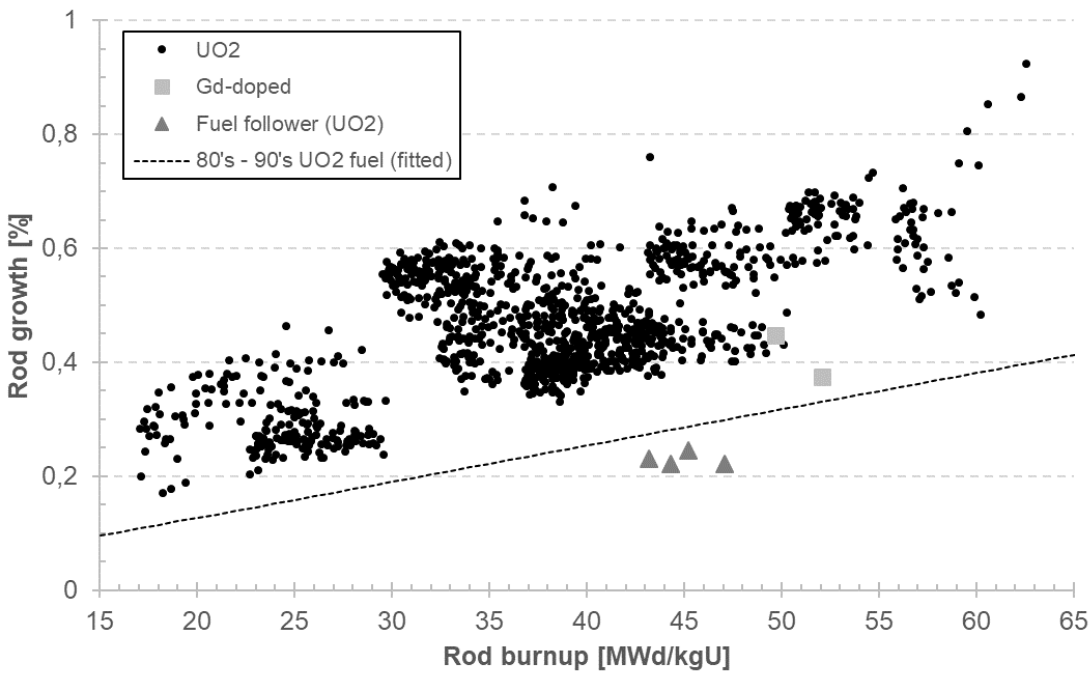

Fig. 6. Rod irradiation growth relative to the nominal unirradiated length.

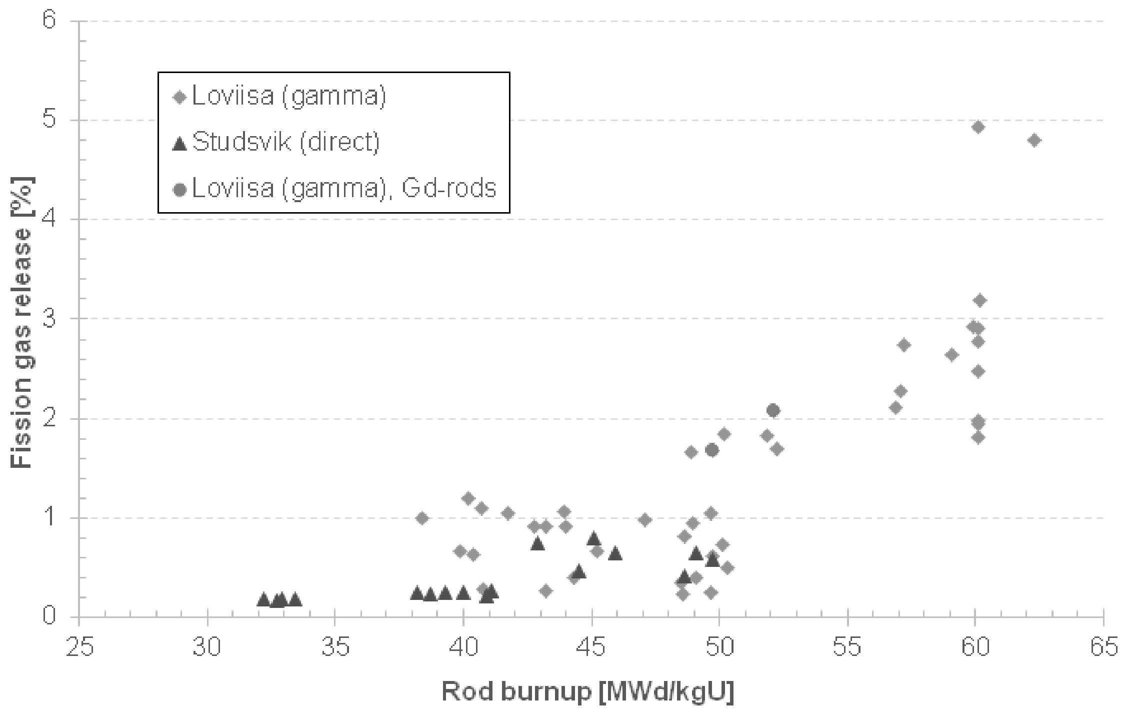

Fig. 7. Fission gas release based on Loviisa NPP estimates and Studsvik measurements.

4.4 Spent fuel condition monitoring during long-term storage

The spent fuel condition monitoring program during long-term storage was implemented in its current form in 2005. Since then all fuel assemblies (6 pcs) included in the program has been inspected at least once. As expected, no significant changes in the assemblies have been found. In fact, most if not all changes were related to the repeated removal and installation of the shroud tube which causes new handling scratches every time the assembly is inspected. On the other hand, these new bright post-irradiation scratches help the inspection work since changes in their brightness are easiest to notice.

5. Discussion

The poolside inspections form an important part of the nuclear fuel related activities of Loviisa NPP. Only through post-irradiation poolside inspections it is possible to assess the true reliability of the assemblies and factors that affect the reliability. Based on findings from the poolside inspections performed at Loviisa NPP, several reliability improvements have been made to the fuel throughout the years. In addition, several other design changes have been verified by the poolside inspections. The systematic inspections of the spent fuel assemblies, and especially all failed assemblies, is a good practice that is employed in Finland and the advantages of this practice are clear. This practice should be taken into wider use in other countries also.

Based on the recent poolside inspection campaigns, the performance of Loviisa NPP fuel has been excellent and the implementation of the design changes have proceeded smoothly. The results from the Studsvik 2018 hot cell measurements are expected to be available during 2019 and provide useful information to both verify and calibrate Loviisa NPP poolside inspection results.

The use of the poolside inspection platform ATULA at Loviisa NPP continues actively until and beyond the shutdown of the units until all spent fuel has been removed from Loviisa NPP and transported to the final disposal site in Olkiluoto. Suppporting information will be gathered from hot cell inspections and possible experimental in-pile and out-of-pile testing of fuel materials.

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