Fuel Reliability Experience in Finland

L. Kekkonen

Fortum Power and Heat Ltd, Espoo, Finland

Abstract

Four nuclear reactors have operated in Finland now for 35-38 years. The two VVER-440 units at Loviisa Nuclear Power Plant are operated by Fortum and two BWR's in Olkiluoto are operated by Teollisuuden Voima Oyj (TVO).

The fuel reliability experience of the four reactors operating currently in Finland has been very good and the fuel failure rates have been very low. Systematic inspection of spent fuel assemblies, and especially all failed assemblies, is a good practice that is employed in Finland in order to improve fuel reliability and operational safety. Investigation of the root cause of fuel failures is important in developing ways to prevent similar failures in the future.

The operational and fuel reliability experience at the Loviisa Nuclear Power Plant has been reported also earlier in the international seminars on WWER Fuel Performance, Modelling and Experimental Support. In this paper the information on fuel reliability experience at Loviisa NPP is updated and also a short summary of the fuel reliability experience at Olkiluoto NPP is given.

Keywords: VVER-440, fuel reliability, operational experience, poolside inspections, fuel failure identification.

1. Introduction

The two VVER-440 units at the Loviisa nuclear power plant (NPP) have been in operation since 1977 and 1980. The load factors of all units have been very high and the fuel reliability experience has also been excellent. During the total of 71 operational cycles until the refuelling outages in 2014 the number of leaking assemblies adds up to 34. This corresponds to an average fuel failure rate of 3x10-5 per year with one failed rod per assembly.

The operational and fuel reliability experience at the Loviisa NPP has been reported also earlier in the International Conference on WWER Fuel Performance, Modelling and Experimental Support (e.g. [1],[2],[3],[4]). This paper updates the information on fuel reliability experience at Loviisa NPP and a short summary of the fuel reliability experience at Olkiluoto NPP is also given. In addition, other on-going nuclear projects in Finland are shortly described.

2. Nuclear Power in Finland

There are two operating nuclear power plants in Finland, Loviisa NPP and Olkiluoto NPP. Both plants have two operating units, Loviisa-1 (LO1) and Loviisa-2 (LO2), and Olkiluoto-1 (OL1) and Olkiluoto-2 (OL2). The two reactors at Loviisa NPP are VVER-440 type V213 and they are operated by Fortum. The two units at Olkiluoto are both BWR reactors and operated by Teollisuuden Voima Oyj (TVO). A third unit at Olkiluoto, Olkiluoto-3 (OL3), is under construction. Olkiluoto-3 will be European Pressurised Reactor (EPR) by AREVA Siemens Consortium. The basic data for these reactors are given in Table 1.

A new nuclear unit, Hanhikivi-1 (FH1), is planned to be built at a new site in Pyhäjoki by a new nuclear power company Fennovoima. The decision-in-principle for the new reactor was received from the Ministry of the Employment and the Economy (MEE) in 2010 and the construction license was applied for in the end of June 2015. The reactor would be a generation 3+ VVER-1200 reactor AES-2006 and it will be supplied by JSC Rusatom Overseas. Fortum participates in the project with a share of 6.6 % of the power plant.

Also TVO received, at the same time with Fennovoima, in 2010 a decision-in-principle for building their fourth reactor at the Olkiluoto site. In June 2015 TVO decided not to apply for the construction license for Olkiluoto-4 during the period of validity of the decision-of-principle, which expired at the end of June 2015. This decision was taken due to the delay of the Olkiluoto-3 project.

In addition to the commercial nuclear power plants, a research reactor has been operated in Espoo since 1962. The reactor was built for research and education purposes and later on it was modified for isotope production and radiotherapy. Now VTT Technical Research Centre of Finland Ltd is preparing for shutdown of the first nuclear reactor in Finland, because it has become unprofitable. In February 2015 VTT got the approval statement for an environmental impact assessment of decommissioning and dismantling of the

Table 1. Nuclear reactors in Finland

Name of NPP	Unit No. / Reactor type	Operator	Start of operation	Net output MWe	Load factors 2014, %	
					cumulative	in 2014
Loviisa	1 / VVER	Fortum	1977	496	87.3	92.5
	2 / VVER	Fortum	1980	496	89.4	89.3
Olkiluoto	1 / BWR	TVO	1978	880	92.5	94.5
	2 / BWR	TVO	1980	880	93.5	97.4
	3 / EPR	TVO	2018*	1600	-	-
Hanhikivi	1 / VVER	Fennovoima	2024*	1200	-	-

* Present plan

reactor and government's authorisation for decommissioning the reactor will be applied for in 2016. The primary plan for disposal of the nuclear fuel is to send it back to the USA where the reactor and the fuel were purchased from. The low- and intermediate-level waste from dismantling of the reactor will be stored and disposed of in co-operation with Fortum and TVO. [5]

3. Fuel Designs and Fuel Performance

3.1. Loviisa NPP

3.1.1. Fuel designs

For the Loviisa NPP there is currently only one fuel supplier, JSC TVEL (TVEL). TVEL has supplied fuel for the Loviisa plant continuously from the start of operation in 1977.

BNFL/Westinghouse has supplied seven fuel reloads for Loviisa-1 reactor in 2001 - 2007. The reloads were preceded by five Lead Test Assemblies (LTAs), which were irradiated in the Loviisa-2 reactor between 1998 and 2003 up to 5 cycles. The last BNFL fuel assemblies were unloaded from Loviisa-1 reactor in 2012.

Evolutionary changes have been introduced to TVEL's fuel design since the beginning of operation. The biggest design change has been introducing the so-called 2nd generation VVER-440 fuel. This design change comprised of improvements in both fuel economy and structural stability. The first reloads of 2nd generation fuel were loaded into Loviisa-1 and Loviisa-2 in 2009 and 2010, respectively. Simultaneously with introducing the 2nd generation fuel the loading scheme at Loviisa NPP has been switched from 3-batch loading to 4-batch loading, thus the first 2nd generation fuel assemblies have been unloaded from Loviisa-1 in 2013 and from Loviisa-2 in 2014.

The objectives of the design changes have been either to improve fuel performance or to facilitate manufacturing. Sometimes the need for the changes in order to improve the fuel performance has resulted from Fortum's fuel performance surveillance activities, but mostly the initiative for design changes has come from TVEL or from the fuel manufacturer JSC Mashinostroitelny Zavod (MSZ). However, a regular exchange of information on operational experience between TVEL and Fortum (and other users) has affected also the improvements initiated by TVEL. Especially the poolside inspections performed by Fortum at Loviisa NPP have been very useful in finding out root causes for some shortcomings in the fuel design. The latest design change initiated by Fortum has beenintroducing mixing vanes in spacer grids of the 2nd generation fuel assemblies in order to improve fuel economy.

The major design changes of the Loviisa fuel are listed in Table 2. The reasons for the changes in the design can be divided into three categories: improvement of the fuel thermo-mechanical performance, improvement of the fuel economy, and facilitating the inspection and possible repair of the fuel during and after the irradiation.

3.1.2. Burnup

The average discharge burnup has developed from the 30 MWd/kgU in the beginning of operation to the present 45 MWd/kgU. The limit for the assembly maximum discharge burnup was increased in 2011 up to 57 MWd/kgU.

3.1.3. Fuel failures

Both at Loviisa and Olkiluoto NPP's the I-131 activity concentration of the coolant water is followed as fuel integrity indicator. The number of failed fuel rods is also estimated from the activity measure-

Table 2. **Major changes in VVER-440 fuel supplied to Loviisa NPP by TVEL**

No.	Time of introduction	Design change	Objective
1	1984	Allowance for fuel rod elongation increased from 8 to 25 mm	To ensure sufficient room for fuel rod elongation to avoid rod bowing
2	1988	Introduction of pressed and chamfered fuel pellets (instead of extruded)	To reduce PCMI
3	1988	Increase of initial rod He pressure from 1 to 6 bar	To reduce cladding creep-down and to minimize end-of-life rod internal pressure of the hottest rods
4	1992	Removal of rigid fixing of the upper grid to the top nozzle	To avoid axial compression and subsequent bowing of fuel rods in case of rod jamming to the upper grid
5	1994	Change of spacer grid material from stainless steel to Zr1%Nb (E110)	To improve neutron economy. May have improved the performance of the grid-to-rod connection
6	1998	Introduction of de-mountable fixed fuel assembly structure (de-mountable shroud tube and fuel rods) in 6 Lead Assemblies	To facilitate the inspection of the fuel assemblies
7	1998	Decrease of the shroud tube thickness from 2 mm to 1,5 mm	To improve neutron economy
8	1998	Change in the fixing of the spacer grids to the central tube to allow limited axial movement of the spacer grids during operation	To avoid the consequences of potential jamming of the rods in the spacer grids
9	2002	Demountable fuel assembly (shroud tube) in all fixed fuel assemblies of the reload.	To facilitate the inspection of the fuel assemblies
10	2008	Introduction of 2nd generation fuel - demountable shroud tube and fuel rods both in the fixed fuel assemblies and in the fuel followers - reinforced skeleton - increase of U-mass by 5 % - burnable poison (Gd) - Hf-plates in the fuel follower shroud tube above the fuel column	To facilitate the inspection (and repair?) of the fuel assemblies To improve the overall mechanical and economic performance of the fuel
11	2011	Introduction of mixing vanes in spacer grids	To improve coolant mixing leading to improved safety and economy

ments. In Loviisa there are fuel failure limits determined during operation without leaking fuel rods for both I-131 and Xe-133 activities:

- ^{131}I < 2.2 E2 kBq/m^3 and
- ^{133}Xe < 7.4 E3 kBq/m^3.

If the above mentioned limits are exceeded, the I-131 / I-133 and Xe-133 / Xe-135 ratios are used in the leak analysis so that there are no leaking fuel rods if:

- ^{131}I / 133I < 0.1,
- ^{133}Xe / 135Xe < 0.3 and
- ^{131}I < 5.0E4 kBq/m^3.

In case of a small leak the reactor operation is continued until the end of the irradiation cycle and the core is sipped during the first annual outage following the failure detection. However, if the activity analysis shows that there is a large leak or several failed fuel rods, the reactor will be shut down immediately. Earlier the failed fuel assemblies were identified by in-core sipping performed by Fortum, but from 2013 the in-core sipping has been replaced by in-mast sipping carried out in co-operation with Westinghouse.

Cumulative fuel assembly failure rate in Loviisa NPP is $4.3 \cdot 10^{-3}$ (quantity of failed assemblies per all irradiated assemblies). This corresponds to a fuel rod failure rate of $3.4 \cdot 10^{-5}$, assuming that there is only one failed rod per failed assembly, which has been the case in the vast majority of the cases according to the pool-side examination results of the discharged assemblies and the

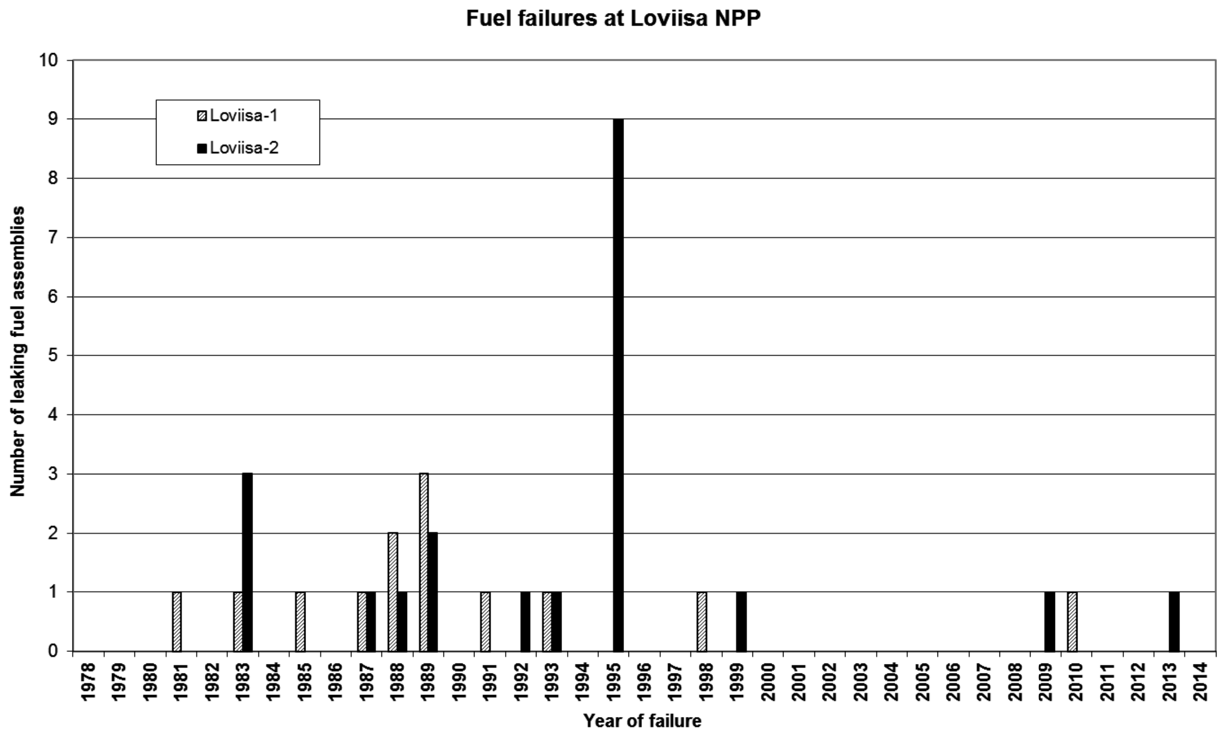

Figure 1. Number of failed fuel assemblies at Loviisa nuclear power plant

estimates based on the coolant activity measurements during irradiation. The number of failed fuel assemblies during the operational life of Loviisa-1 and Loviisa-2 is given in Figure 1.

In Finland the Nuclear Safety Authority (STUK) requires that the nuclear power utilities shall make an effort to identify the causes of any fuel failure. Very often a visual inspection is sufficient to reveal the failure cause, but at least at Loviisa NPP also other inspections and measurements are usually done for the failed fuel assembles using a poolside inspection equipment (for more information on the poolside inspections, see [6]). However, in most cases the leaking rod cannot be found in the visual inspection or the immediate failure cause cannot be judged from the findings.

When the failure cause has been identified, the primary reason for most of the fuel failures in Loviisa has been fuel to spacer grid fretting. A crud deposit incident at Loviisa-2 in 1994 was also followed by grid-to-rod fretting failures caused by crud induced vibrations. The root cause for the grid-to-rod fretting was believed to be the spacer grid design and/or material, which were changed in 1994. This can be considered as the main reason for the drastic reduction in fuel failures since 1999 when the last batches with the spacer grids of the old design were unloaded from the Loviisa reactors. The root causes of the recent fuel failures can be regarded as individual occurrences and are not expected to recur with the fuel design currently in use at Loviisa NPP. The only 2nd generation fuel assembly failure at Loviisa NPP thus far was found to be caused by foreign material. A rough estimation of the causes behind fuel failures at Loviisa NPP is given in Figure 2.

The inspections carried out at Loviisa NPP have also resulted in some design changes to avoid future fuel failures. Examples of these are:

- In the early days of Loviisa NPP operation, fuel inspections using a simple underwater camera revealed that the axial allowance for the fuel rod growth was insufficient. As a result, the upper grid structure was changed in 1984 to allow the axial rod growth for all foreseeable operation of the VVER-440 reactors (item 1 in Table 2).
- In late 80'ies the poolside inspections at Loviisa NPP revealed that some of the upper spacer grids were deformed and partially broken. It was concluded that the root cause was the fact that the fuel rods were not able to slide through the upper grid. Since the upper grid was fixed to the top nozzle of the assembly, the elongation of the rods during irradiation caused forces to the upper spacer grids and consequently deformed or broke them. As result, the upper grid was no longer fixed to

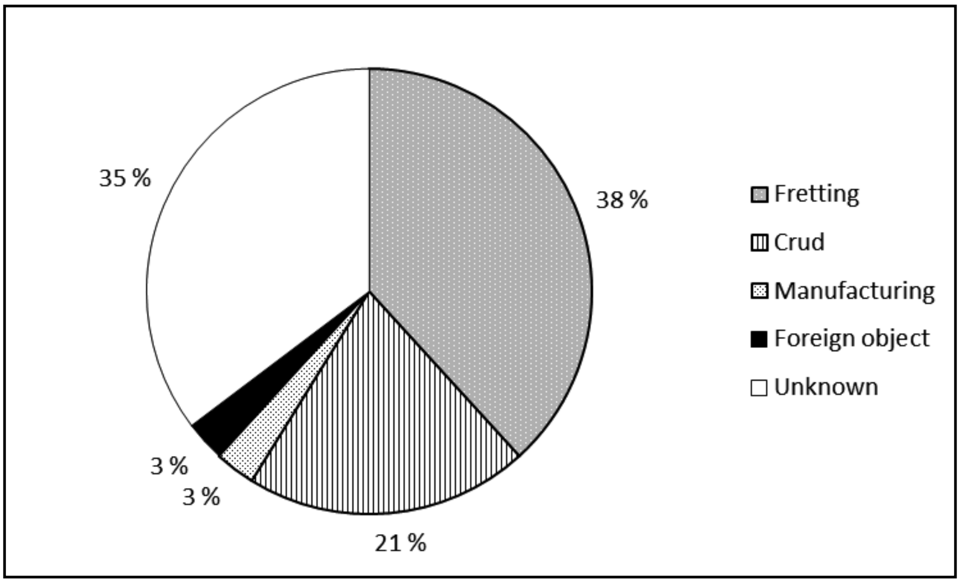

Figure 2. Fuel failure causes at Loviisa NPP

the top nozzle but only to the instrument tube with allowance to axial movement (item 4 of Table 2).

- Visual inspection of two fuel assemblies in 1997 revealed inadvertent axial movement of some of the spacer grids. Further investigations involving eddy current measurements of the spacer grid axial locations of 136 fixed fuel assemblies and fuel followers revealed four additional assemblies with moving grids [7]. It was established that the root cause for the moving grids was essentially the same as in the previous example: The fuel rods did not slide through the spacer grids when they elongated during operation but stuck to them. As a result the central bush fixing the grids to the instrument tube was broken and the grids were able to move upwards driven by the coolant flow. The corrective action was to change the fixing of the central bush to the instrument tube to allow for the some axial movement of the grid (item 8 of Table 2).

3.2. Olkiluoto NPP

The reactor cores of Olkiluoto-1 and Olkiluoto-2 comprise 500 fuel assemblies. The reactors operate at annual cycles. Modernisations of the turbines and renewal of some other components as well as optimisations of core loadings have lead to 880 MW electric power with the reload sizes of about 110 assemblies per unit.

3.2.1. Fuel designs

TVO has operating experience of fuel delivered by Westinghouse Electric Sweden AB (earlier ABB Atom), GENUSA and AREVA NP (earlier Siemens). The newest fuel delivery contracts for 2016 - 2019 are with Areva and Westinghouse Electric Sweden. Under these contracts Areva will supply ATRIUM 10XM assemblies for Olkiluoto-1 and Westinghouse will deliver SVEA-96 Optima 3 fuel assemblies for Olkiluoto-2. It is foreseen that the fuel design delivered by Areva to Olkiluoto-1 will be upgraded to ATRIUM 11 during the contract period. [8]

3.2.2. Burnup

Similar to Loviisa NPP, the fuel burnup of Olkiluoto reactors has gradually increased. Average discharge batch burnup has increased, similar to Loviisa, from the initial 30 MWd/kgU up to 45 MWd/kgU. The current maximum assembly burnup is limited to 50 MWd/kgU.

3.2.3. Fuel failures

The cumulative fuel rod failure rate in Olkiluoto NPP is currently 5·10-5. The number of discharged failed fuel assemblies in Olkiluoto-1 and Olkiluoto-2 reactors in 1980-2014 is given in Figure 3. It can be seen that also at Olkiluoto NPP the amount of fuel failures has decreased from the 1990s, but there has been several fuel leaks at Olkiluoto-2 also in the 2000s.

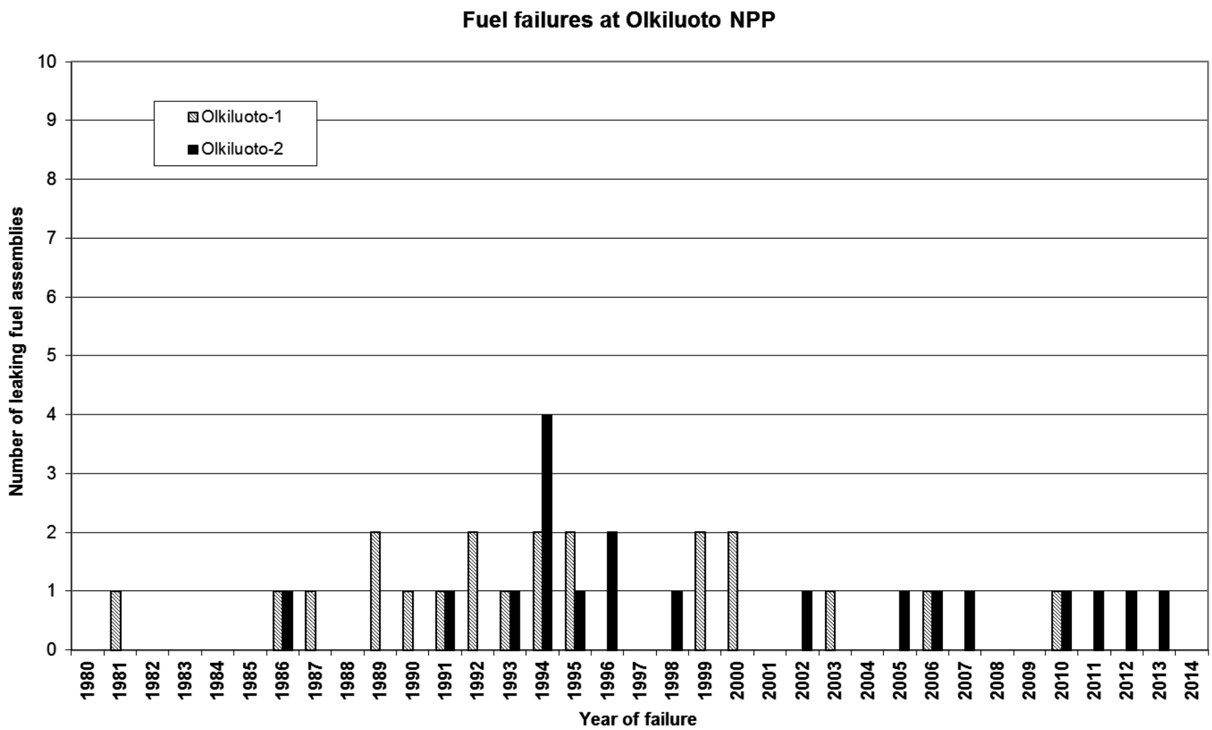

Figure 3. Number of failed fuel assemblies at Olkiluoto nuclear power plant. [3],[9]

The main cause of failure at Olkiluoto has been found to be small foreign objects that have ended up in the reactor during maintenance operations. New foreign object sieves have been adopted at Olkiluoto-2 in order to reduce the amount of loose objects and thus minimising the fuel failures. [9]

4. Summary

The four operating nuclear units in Finland have now operated approximately 35 years. The overall operational experience has been excellent with high load factors and low fuel failure rates. At Loviisa NPP the longest period without leaking fuel assemblies in either of the two units has been nine years, from 2000 to 2008.

All failed fuel assemblies, but also other spent fuel assemblies are systematically inspected to improve fuel reliability and operational safety. Investigating the failure cause is important when trying to prevent such failures in the future. In order to maintain, improve and confirm the fuel reliability and safe operation, poolside inspections are made in Loviisa also for intact fuel assemblies on a regular basis, especially when fuel design or operational parameters are changed. The main motivation for the regular inspections is finding possible defects that could lead to a fuel failure already before they occur during operation. This is also based on the requirements by the Finnish Radiation and Nuclear Safety Authority (STUK) and therefore similar inspections are done also at the Olkiluoto NPP, where two BWR units are currently in operation. As a result of these actions of active monitoring and improvement of fuel integrity, the fuel reliability has been at high level at both operating NPP's in Finland.

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