Technical Report

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Fission gas release data for Ringhals PWRs

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Summary

Fission gas release fractions (FGR) have been calculated for two of the Swedish pressurized water reactors, Ringhals units 2 and 4. The calculations were made by AREVA based on power histories provided by Vattenfall Nuclear Fuel.

Maximum FGR values of about 15% and mean values around 7–8%, were calculated for Ringhals 2 and Ringhals 4 after power uprate. For Ringhals 4 before power uprate the FGR was considerably lower.

Contents

1 Definitions

AGORA-5A	Fuel type for 15×15 Pressurized water reactors from AREVA.
AGORA-7H	Fuel type for 17×17 Pressurized water reactors from AREVA.
BU	Burnup.
FGR	Fission Gas Release fraction, the proportion of produced fission gas that is released from the fuel pellet.
IRF	Instant Release Fraction, the proportion of certain fission products that is released instantly in contact with water.
SKB	Svensk Kärnbränslehantering AB.
VNF	Vattenfall Nuclear Fuel AB.

2 Introduction

SKB is currently making investigations needed to license the new final repository for spent nuclear fuel, SR-Site. For these analyses it is necessary to know how much of the fission products that will be released instantly if the fuel ever gets in contact with water, the so called Instant Release Fraction (IRF). There is not much data available for IRF but it has been shown that the IRF is proportional to the fission gas release fraction (FGR). The FGR can be measured, and more importantly it can be predicted with quite good accuracy by fuel rod calculations.

Vattenfall Nuclear Fuel (VNF) has been asked to provide calculated data for FGR for the Swedish pressurized water reactors. It was decided that it was sufficient to investigate one reactor with 15×15 fuel, which is Ringhals 2, and one reactor with 17×17 fuel, in which case Ringhals 4 was chosen since it will be operated at a higher power than Ringhals 3. This report presents data calculated for two equilibrium cores with high enrichment, one in Ringhals 2 and one in Ringhals 4 after power uprate to 3,292 MW_{th}. For comparison, data for the present cycles of the same reactors (cycle 33 for Ringhals 2 and cycle 26 for Ringhals 4) were calculated as well. The data were generated in collaboration with the fuel supplier AREVA.

3 Method

The fission gas release is calculated by AREVA based on fuel rod power histories provided by VNF. The fuel rod power histories are calculated using a neutronics code and then individual values for power, burnup and neutron fluence are collected for each rod at five different burnups for each cycle the fuel rod has been loaded in the core. These values are used by AREVA as input for best estimate calculations of the fission gas release using a fuel rod code.

3.1 Codes used

For all neutronic calculations VNF uses the CMS code package from Studsvik Scandpower. For fuel assembly multi-group two-dimensional calculations, CASMO-4 was used and for three dimensional core calculation, SIMULATE-3 was used. For the equilibrium cycle for Ringhals 2 AREVA performed the neutronics calculations with their own code package, CASCADE.

For the fuel rod calculations AREVA's fuel rod code CARO-E3 was used. The AREVA NP fission gas release database for UO_2 PWR fuel has been continuously enhanced due to the recent advances achieved in highly demanding fuel management schemes with respect to enrichment, burnup and/or high power level. Thus, the AREVA NP database comprises a variety of crucial features, i.e:

- enrichment up to 5%,
- high burnup (up to 100 MWd/kg(HM)),
- high power level over the whole burnup range.

This database was used to validate the latest version of the AREVA NP GmbH fuel rod code CARO-E3. Thus, it is a state-of-the-art code concerning the impact of high power and/or high burnup on fuel rod design. In particular, the mechanistic fission gas release model was upgraded to describe fuel rods under demanding uprated power conditions. In conclusion, CARO-E3 is very well qualified to calculate the fission gas release of fuel rods inserted in the current cycles as well as in future fuel management scenarios (e.g. GREAT, FREJ) of the Ringhals plants.

3.2 Cores investigated

3.2.1 Equilibrium cores

In an equilibrium core the same amount of fuel is loaded in the same loading pattern each cycle. This means that each batch is identical and the burnup distribution is the same for each cycle, e.g. the burnup distribution of the fuel burnt for three cycles is the same as it was one cycle earlier for the fuel now burnt for four cycles.

An equilibrium core loaded with AGORA-5A fuel from AREVA with enrichment 4.55 w/o ^{235}U was used as a generic case for Ringhals 2. It is an equilibrium core with 5 cycles and reaches a batch average burnup of 60 MWd/kgU and a maximum fuel rod burnup of 70 MWd/kgU. This can be expected to be limiting for the foreseeable future.

For Ringhals 4, which is planned to uprate its power to 118% or 3,292 MW_{th} in 2011, an equilibrium core at the new power rate was used. It uses 4 cycles of AGORA-7H with an enrichment of 4.95 w/o ^{235}U. This core will also reach a batch average burnup of 60 MWd/kgU and a maximum fuel rod average burnup of 70 MWd/kgU.

3.2.2 Reference cores

For reference, fission gas release data for the present cycle of each reactor were also calculated. The core for Ringhals 2 cycle 33 was mostly loaded with fuel with an enrichment of 4.10 w/o ^{235}U. The fuel that was loaded for its fourth or fifth cycle had, however, an enrichment of 3.95 w/o ^{235}U.

The core for Ringhals 4 cycle 26 was loaded with fuel with enrichment 3.95 w/o ^{235}U. The cycle is operating at the nominal power level 2,775 MW.

In all cores about 1–3% of the fuel rods contain burnable absorber in the form of Gd_2O_3 and have an enrichment level of about 70% of the enrichment of the pure UO_2-rods.

Table 3-1. The different cores used in the investigation.

Reactor		Thermal Power (MW)	Mean LHGR (W/cm)	Enrichment (w/o ^{235}U)	Max rod burnup (MWd/kgU)
Ringhals 2	Equilibrium	2,652	220.5	4.55	69.9
	Cycle 33	2,652	220.5	3.95–4.10	59.7
Ringhals 4	Equilibrium	3,292	211.5	4.95	70.8
	Cycle 26	2,775	178.3	3.95	56.3

4 Results

4.1 Equilibrium core for Ringhals 2

For the equilibrium cycle of Ringhals 2 a maximum FGR of as much as almost 12% is reached already after 2 cycles at a burnup of approximately 35 MWd/kgU. After that the maximum FGR does not increase much, the maximum value is about 15%. The mean value increases slightly from about 5% after 2 cycles to about 8% after 3, 4 and 5 cycles. See Table 4-1 and Figure 4-1.

Table 4-1. Fission gas release and burnup for the different batches at the end of the equilibrium cycle for Ringhals 2.

	2 cycles		3 cycles		4 cycles		5 cycles	
	BU [MWd/kgU]	FGR [%]	BU [MWd/kgU]	FGR [%]	BU [MWd/kgU]	FGR [%]	BU [MWd/kgU]	FGR [%]
mean	31.1	5.2	45.0	7.6	55.0	8.3	59.4	8.0
max	35.8	11.7	50.3	13.8	62.2	15.0	69.9	14.1

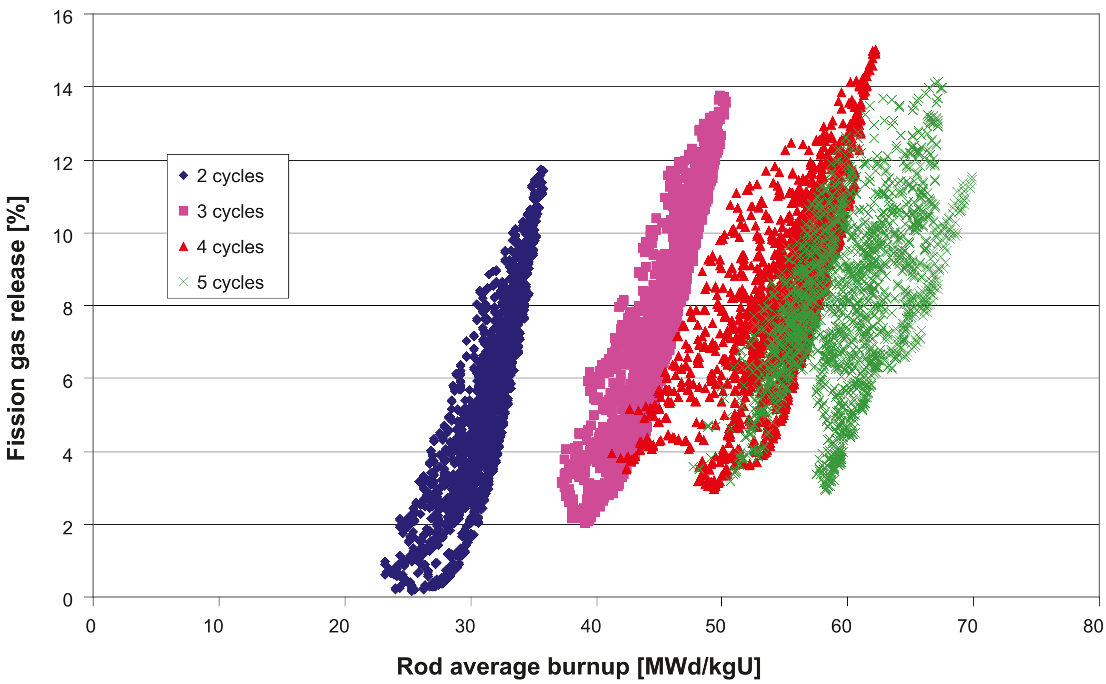

__Figure 4-1.__ Fission gas release as function of burnup for the different batches at the end of the equilibrium cycle for Ringhals 2.

4.2 Equilibrium core for Ringhals 4

For the equilibrium cycle of Ringhals 4 a maximum FGR of about 9% is reached after 2 cycles at a burnup of approximately 43 MWd/kgU. After that the maximum FGR increases slightly for each additional cycle, the maximum value is about 15%. The mean value increases slightly from about 4% after 2 cycles to about 7% after 4 cycles. See Table 4-2 and Figure 4-2.

Table 4-2. Fission gas release and burnup for the different batches at the end of the equilibrium cycle for Ringhals 4.

	2 cycles		3 cycles		4 cycles	
	BU [MWd/kgU]	FGR [%]	BU [MWd/kgU]	FGR [%]	BU [MWd/kgU]	FGR [%]
mean	37.5	3.7	52.6	6.4	59.8	6.7
max	42.6	9.3	59.0	12.5	70.8	15.4

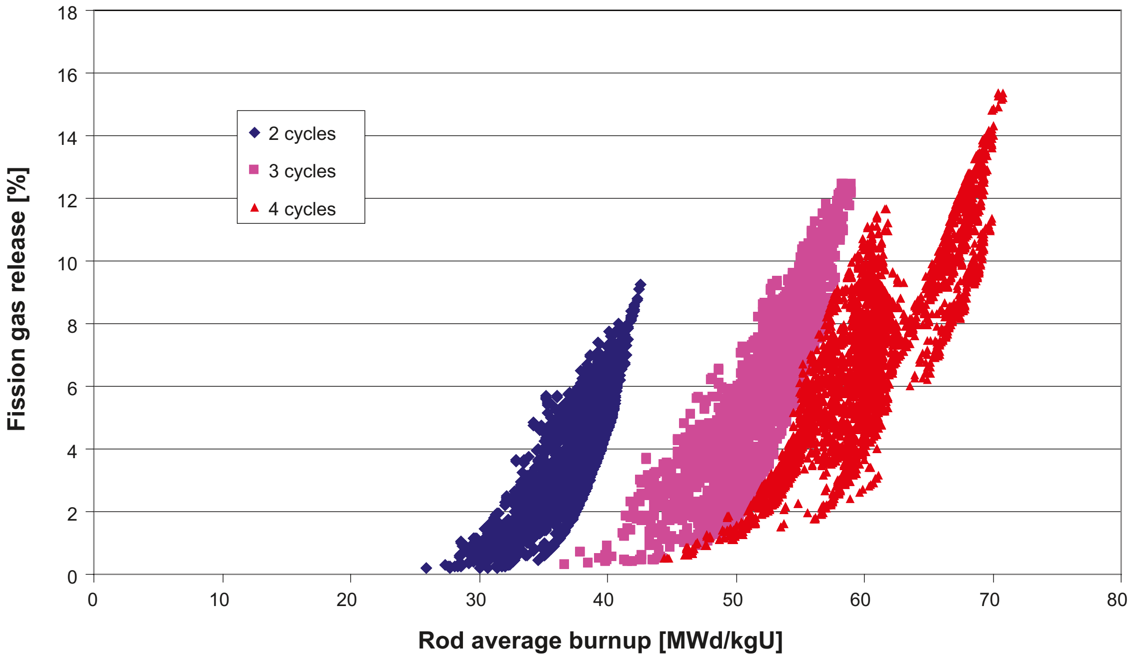

***Figure 4-2.** Fission gas release as function of burnup for the different batches at the end of the equilibrium cycle for Ringhals 4.*

4.3 Cycle 33 of Ringhals 2

For the core loaded for cycle 33 of Ringhals 2 the maximum value of about 10% FGR is reached already after 2 cycles and stays constant. The assemblies that were loaded for a fifth cycle probably did not have limiting power histories since they have quite low FGR. This is because only the assemblies with a lower burnup (and thus lower lifetime averaged power and FGR) were reloaded for a 5th cycle. The average value of FGR is about 4–5% for all batches. See Table 4-3 and Figure 4-3.

Table 4-3. Fission gas release and burnup for the different batches at the end of the cycle 33 for Ringhals 2.

	2 cycles		3 cycles		4 cycles		5 cycles	
	BU [MWd/kgU]	FGR [%]	BU [MWd/kgU]	FGR [%]	BU [MWd/kgU]	FGR [%]	BU [MWd/kgU]	FGR [%]
mean	27.9	3.4	41.4	4.7	50.8	4.9	48.4	2.2
max	36.2	10.1	46.9	10.1	59.7	10.1	54.7	5.4

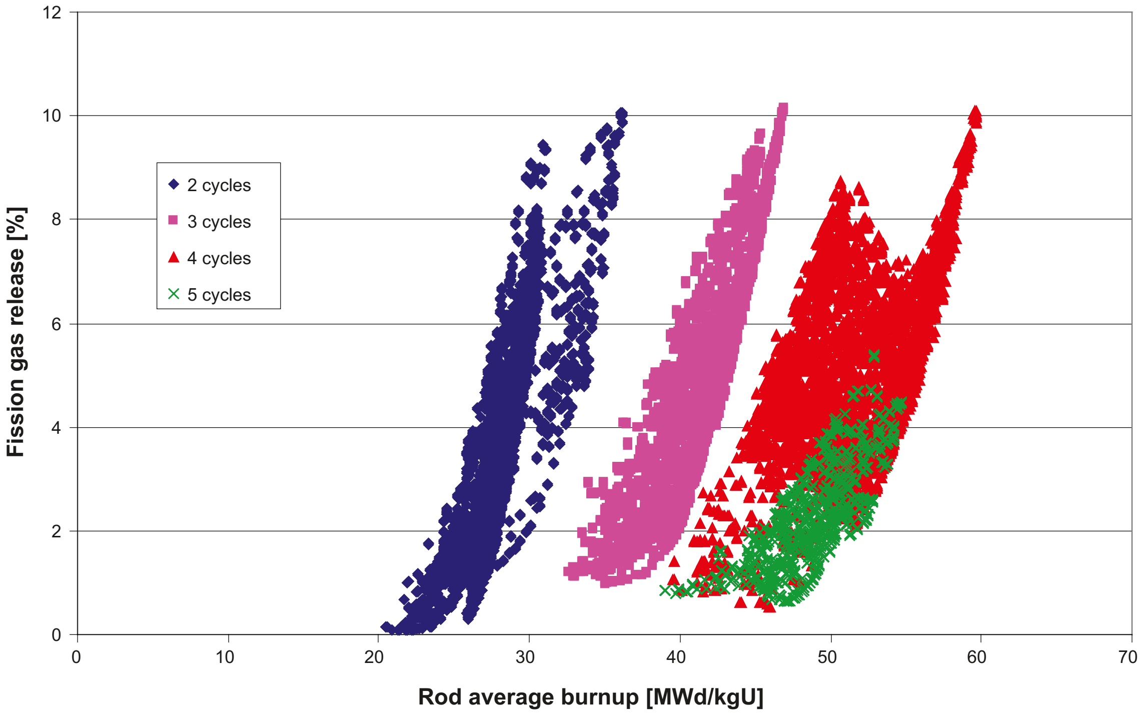

Figure 4-3. *Fission gas release as function of burnup for the different batches at the end of the cycle 33 of Ringhals 2.*

4.4 Cycle 26 of Ringhals 4

For the core loaded for cycle 26 of Ringhals 4 the maximum value of FGR is only about 2%. The core has been operated at a lower power than the equilibrium cycle and with a lower enrichment, which makes the FGR stay low. See Table 4-4 and Figure 4-4.

Table 4-4. Fission gas release and burnup for the different batches at the end of the cycle 26 for Ringhals 4.

	2 cycles		3 cycles		4 cycles		5 cycles	
	BU [MWd/kgU]	FGR [%]	BU [MWd/kgU]	FGR [%]	BU [MWd/kgU]	FGR [%]	BU [MWd/kgU]	FGR [%]
mean	28.0	0.2	41.0	0.5	45.8	0.6	52.4	1.3
max	32.8	1.1	44.8	1.2	54.6	2.4	56.3	2.3

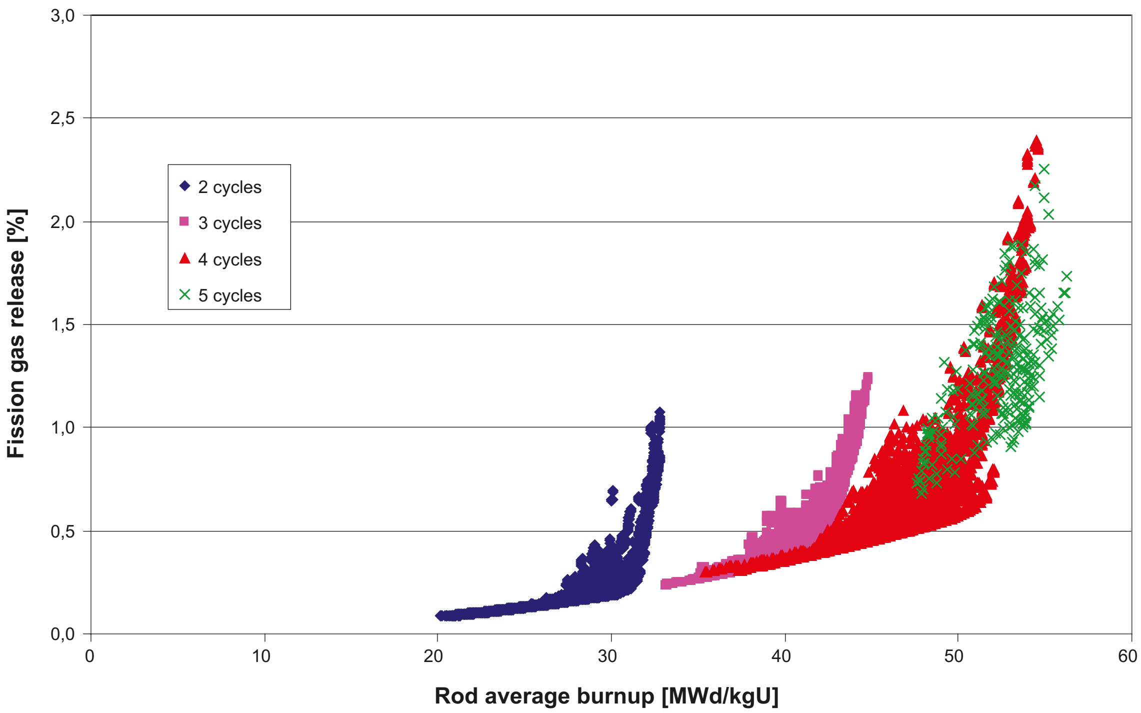

Figure 4-4. *Fission gas release as function of burnup for the different batches at the end of the cycle 26 of Ringhals 4.*

5 Conclusions

The maximum value for FGR for the equilibrium cycles of Ringhals 2 and 4 is about 15%. The mean value at final burnup is about 7–8%. For the actual core loaded cycle 33 of Ringhals 2 the values are only slightly lower while for the actual core loaded cycle 26 of Ringhals 4 they are much lower, less than 20% of the values for the equilibrium cycle.

This is because the fission gas release mainly depends on the linear power of the rod. For Ringhals 2 the average linear heat generation rate (LHGR) is 220.5 W/cm and for Ringhals 4 it is 178.3 W/cm now and will increase to 211.5 W/cm after the power uprate. The reason Ringhals 2 has a higher linear heat generation rate is that the power is distributed over fewer fuel rods. Ringhals 3 is also gradually uprating its power, from 178.3 W/cm until 2005 to 202.5 W/cm in 2009.

The enrichment only has an indirect influence on the fission gas release, with higher enrichment more reactivity remains at high burnup, which enables a higher rod power and hence higher FGR. Since the FGR depends on rod power so strongly, the FGR for the assemblies loaded for their last cycles may have a decreasing FGR since they are usually loaded in positions in the periphery of the core with low power density. Essentially no further gas is released in the last cycle, while the amount of generated fission gas in the pellets continues to increase so the FGR fraction decreases.

6 Background material

Fission Gas Release Data from Ringhals 2 and Ringhals 4 for Studies of Final Storage of Spent Fuel, AREVA report A1C-1335799-0.

Granskning av CARO-E3 för PWR, D Schrire, Vattenfall Nuclear Fuel report 1000045585/01.

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