Technical Report

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Distribution of fission gas release in 10x10 fuel

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September 2009

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Abstract

This report presents the distribution of best-estimate fission gas release for six different cores in three reactors. The evaluations have been performed for three cores with a batch average burnup of ~60 MWd/kgU and three other cores with a batch average burnup of ~45 MWd/kgU. The thermal reactor power for the cores varies between 1,375 MW and 3,900 MW.

The calculations have been performed using an equilibrium cycle for each considered case. The evaluated fuel is Westinghouse SVEA-96 Optima2. The fission gas release is modeled with the Westinghouse fuel performance code STAV7.3.

Contents

Abbreviations

ENSI	Eidgenössisches Nuklearsicherheitsinspektorat.
EOL	End of Life.
FGR	Fission Gas Release.
IRF	Instant Release Fraction.
LHGR	Linear Heat Generation Rate.
SKB	Svensk Kärnbränslehantering AB.
SSM	Strålsäkerhetsmyndigheten.

1 Background

Svensk Kärnbränslehantering AB (SKB) is currently making investigations needed to license the new final repository for spent nuclear fuel. For these analyses it is necessary to know how much of the fission products that will be released instantly if the irradiated fuel ever gets in contact with water, the 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 (FGR), therefore, it is important to know the FGR for all rods the after the last cycle. In this report the best-estimate FGR from six equilibrium cycles (Table 1-1) will be presented.

The six equilibrium cycles represent cores with different thermal reactor power and batch average burnup.

The two last lines in Table 1-1 represent the same reactor with different power upratings, 109% and 129%.

Table 1-1 Cases treated in this report.

Reactor	Thermal reactor power [MW]	Batch average burnup ~45	[MWd/kgU] ~60
Kernkraftwerk Leibstadt (KKL)	3,600		Case 1
Oskarshamn 1 (O1)	1,375	Case 6	Case 3
Oskarshamn 3 (O3)	3,292 (3,020×109%)	Case 4	Case 2
Oskarshamn 3 (O3)	~3,900 (3,020×129%)	Case 5	

2 Method

The existing symmetries for the cores have been used to simplify the calculations, i.e. for case 1 a quarter of a core has been evaluated and for case 2, 4 and 5 half a core has been evaluated. For case 6 there is no symmetry.

Best-estimate Fission Gas Release (FGR) has been calculated for all rods. Histograms and basic statistics for the FGR have been calculated for each case. Also the FGR at the end of each cycle is presented.

3 Assembly And Core Design

All assemblies are SVEA-96 Optima2. The input data used can be found in the background material (see p. 27). All calculations are performed with nominal input.

Power histories for each case can be found in Appendix B. The rods with highest and lowest FGR at end of irradiation are plotted together with some power histories with an average FGR.

The cycles are described in separate reports; see Background material. The cores have equilibrium cycles. An equilibrium cycle is reached when, for a single fuel design, the same loading pattern, core operating parameters, control rod sequence and cycle length is repeated over a period of several cycles.

4 Code

The calculations are performed with the Westinghouse fuel performance code STAV7.3. The code has been verified against poolside and hot cell measurements on fuel irradiated in both commercial and test reactors. The database used for calibration of the code covers rod burnups of over 70 MWd/kgU. The correlation between best-estimate FGR calculated by STAV7.3 and measured values on rods irradiated in KKL and O3 are depicted in Figure 4-1. It can be seen that the best-estimate calculations bound about 60% of the total FGR data points.

Figure 4-2 presents the best-estimate calculated FGR minus the measured data as a function of rod average burnup. It can be seen that the majority of calculated – measured FGR are bounded within ± ~2% along the larger interval of burnups.

From the validation performed in previous Westinghouse reports (see Background material), it can be concluded that the FGR calculations using STAV7.3 are adequate for fuel rod performance and licensing analysis.

The STAV code has been approved to be used for fuel rod design calculations by the Swedish authority Strålsäkerhetsmyndigheten (SSM) and the Swiss authority Eidgenössisches Nuklearsicherheitsinspektorat (ENSI), among others.

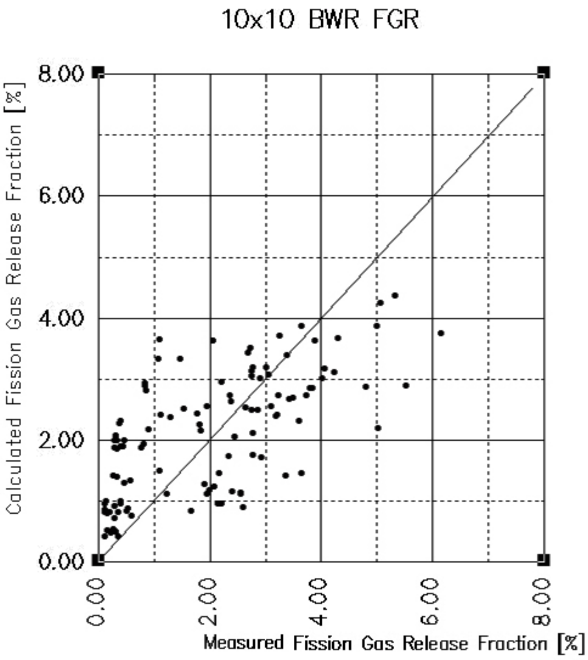

Figure 4-1. Best-estimate FGR calculated by STAV7.3 vs. measured values for 10×10 rods irradiated in O3 and KKL.

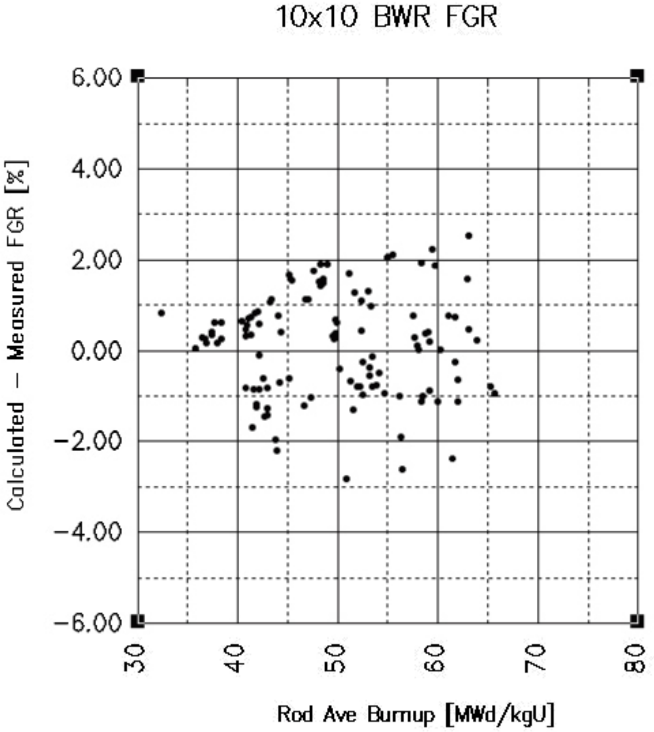

Figure 4-2. *The best-estimate calculated by STAV7.3 minus measured FGR as a function of burnup for 10×10 rods irradiated in O3 and KKL.*

5 Results

5.1 Summary Of The Results

The best-estimate FGR is calculated per rod for all rods in each of the six cores. Table 5-1 and Figure 5-1 give the average and standard deviation for the relative fission gas release at end of irradiation for each core. In Appendix A the FGR is given in moles for helium, krypton and xenon. The helium derives both from the helium used when pressurizing the rods and from helium released during irradiation.

It should be noted that the distribution of the fission gas release within a core is not normally distributed. In a fuel assembly, the edge rods and the part length rods in the middle often form a second population.

Table 5-1. Relative fission gas release fraction [–] per rod at the end of irradiation for the different cores.

	Power [MW]	Burnup [MWd/kgU]	Average	Standard dev.
Case 1	3,600	~60	0.0453	0.0163
Case 2	3,292	~60	0.0447	0.0135
Case 3	1,375	~60	0.0344	0.0082
Case 4	3,292	~45	0.0195	0.0049
Case 5	3,900	~45	0.0236	0.0116
Case 6	1,375	~45	0.0155	0.0033

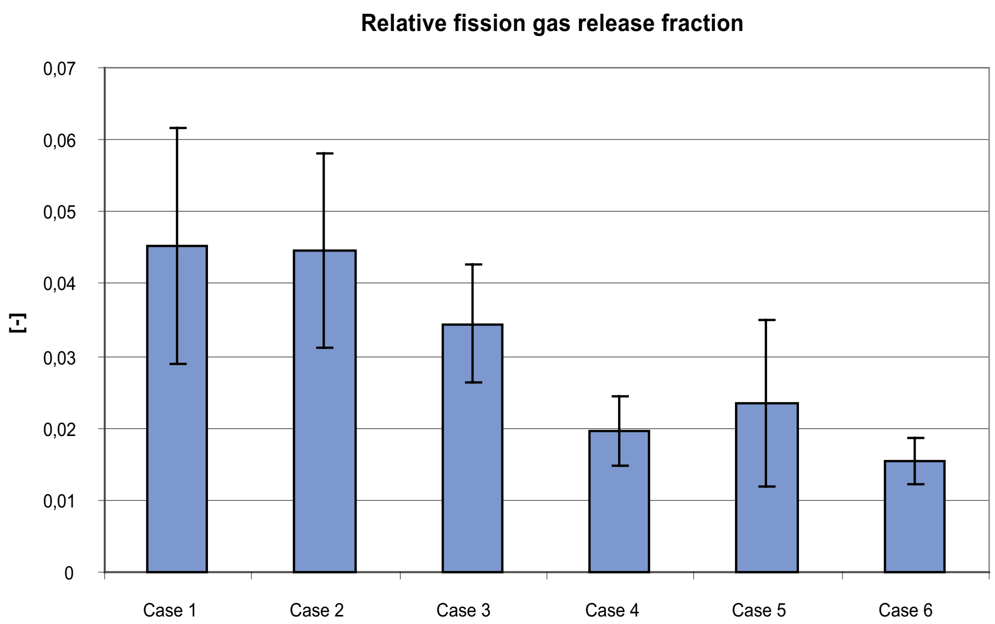

__Figure 5-1.__ Relative fission gas release fraction per rod at the end of irradiation. The error bars are ± one standard deviation.

5.2 Case 1 – 3,600 MW, ~60 MWD/KGU

This section gives the result from the best-estimate calculations of FGR for case 1, see Table 1-1. The histogram in Figure 5-2 shows the distribution of fission gas release fraction at the end of the last cycle. The rods have received full burnup after 5 or 6 cycles and will hence be removed from the core. In Figure 5-3 and Table 5-2 the FGR at the end of each cycle is presented. Since some assemblies reach discharge burnup after 5 cycles and some after 6 cycles the results for discharged rods from cycle 5 and 6 are also given together. In Appendix A the FGR in moles for helium, krypton and xenon is depicted.

Table 5-2. Relative fission gas release fraction [–] at the end of each cycle for case 1.

	Average Burnup [MWd/kgU]	Average	Standard dev.
Cycle 1	13.4	0.00588	0.00986
Cycle 2	26.2	0.00945	0.0128
Cycle 3	39.0	0.0225	0.0170
Cycle 4	51.0	0.0376	0.0150
Cycle 5	58.0	0.0433	0.0150
Cycle 6	60.6	0.0463	0.0161
Cycle 5+6 (discharged rods)	59.8	0.0453	0.0163

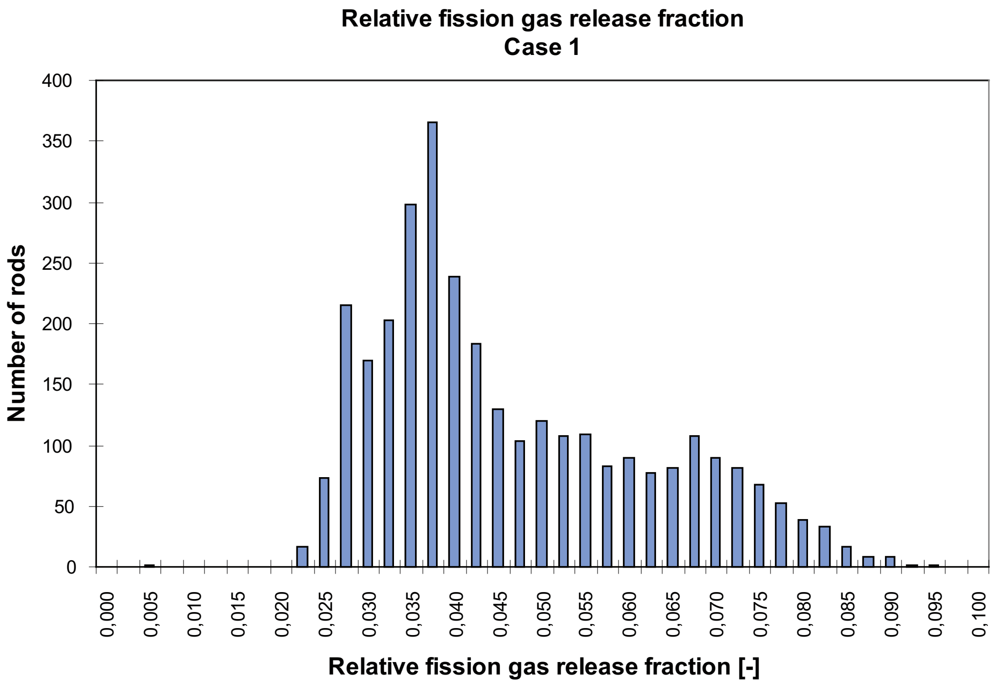

Figure 5-2. *Relative fission gas release fraction for irradiated fuel leaving the core, i.e. all rods from cycle 6 and some from cycle 5, for case 1, 3,600 MW, ~60 MWd/kgU.*

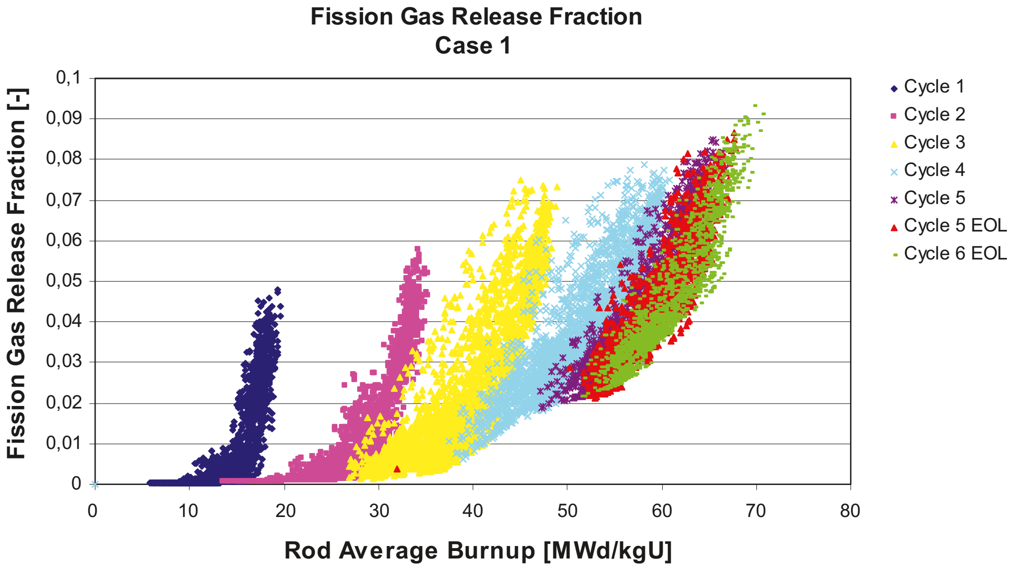

Figure 5-3. *The relative fission gas release fraction at the end of each cycle for case 1, 3,600 MW, ~60 MWd/kgU. The rods at end of irradiation are labeled EOL (end of life).*

5.3 Case 2 – 3,292 MW, ~60 MWd/kgU

This section gives the result from the best-estimate calculations of FGR for case 2, see Table 1-1. The histogram in Figure 5-4 shows the distribution of the fission gas release fraction at the end of the last cycle for case 2.The rods have received full burnup after 5-7 cycles and will hence be removed from the core. In Figure 5-5 and Table 5-3 the FGR at the end of each cycle is presented. Since assemblies reach discharge burnup after 5, 6 or 7 cycles, the results for discharged rods from all three cycles are also given together. In Appendix A the FGR in moles for helium, krypton and xenon is depicted.

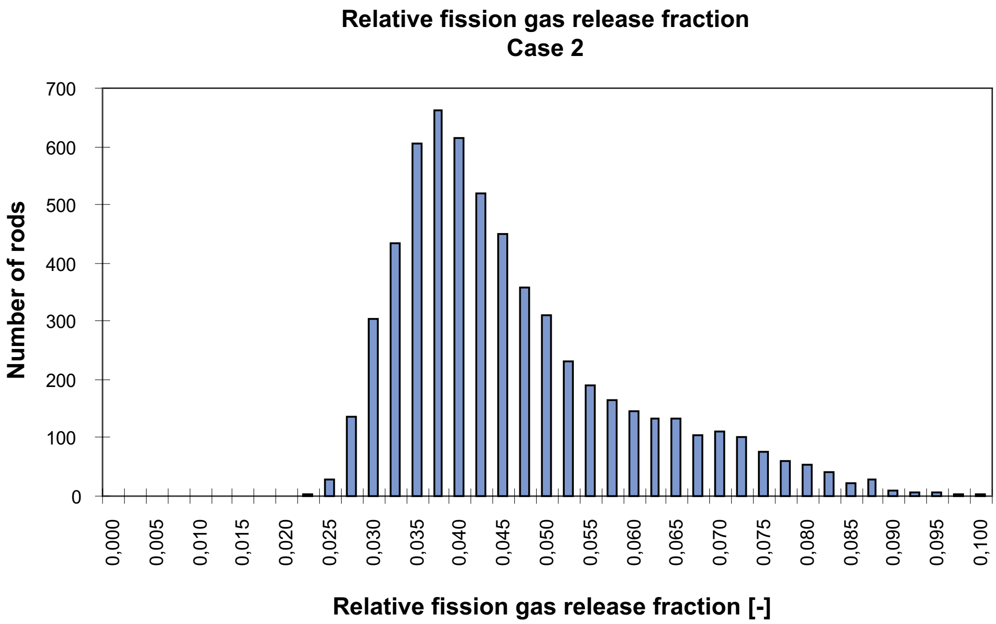

Figure 5-4. *Relative fission gas release fraction for irradiated fuel leaving the core, i.e. all rods from cycle 7 and some from cycle 5 and 6, for case 2, 3,292 MW, ~60 MWd/kgU.*

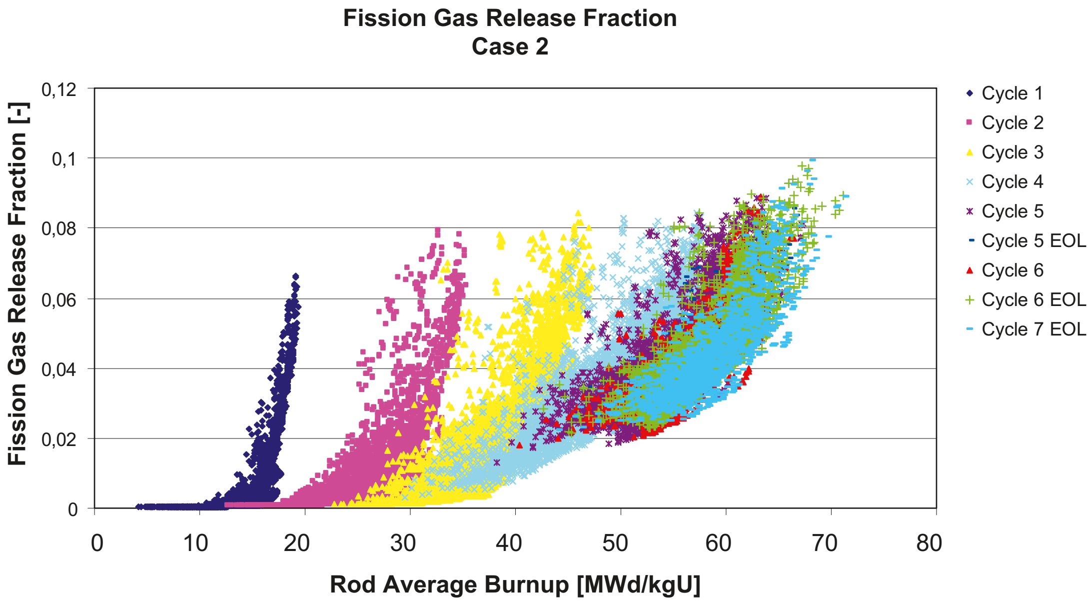

Figure 5-5. *The relative fission gas release fraction at the end of each cycle for case 2, 3,292 MW, ~60 MWd/kgU. The rods at end of irradiation are labeled EOL.*

Table 5-3. Relative fission gas release fraction [–] at the end of each cycle for case 2.

	Average Burnup [MWd/kgU]	Average	Standard dev.
Cycle 1	13.3	0.00432	0.00922
Cycle 2	25.5	0.00916	0.0128
Cycle 3	37.0	0.0195	0.0160
Cycle 4	47.4	0.0343	0.0143
Cycle 5	54.5	0.0411	0.0129
Cycle 6	56.1	0.0424	0.0129
Cycle 7	58.6	0.0443	0.0132
Cycle 5-7 (discharged rods)	58.0	0.0447	0.0135

5.4 Case 3 – 1,375 MW, ~60 MWd/kgU

This section gives the result from the best-estimate calculations of FGR for case 3, see Table 1-1. The histogram in Figure 5-6 shows the distribution of fission gas release fraction at the end of the last cycle for case 3. The rods have received full burnup after 9-11 cycles and will hence be removed from the core. In Figure 5-7 and Table 5-4 the FGR at the end of each cycle is given. Since assemblies reach discharge burnup after 9, 10 or 11 cycles the results for discharged rods from cycle 9-11 are also given together. In Appendix A the FGR in moles for helium, krypton and xenon is depicted.

The FGR for this case is lower than case 1 and case 2, mainly due to lower temperature, see also section 5.7.

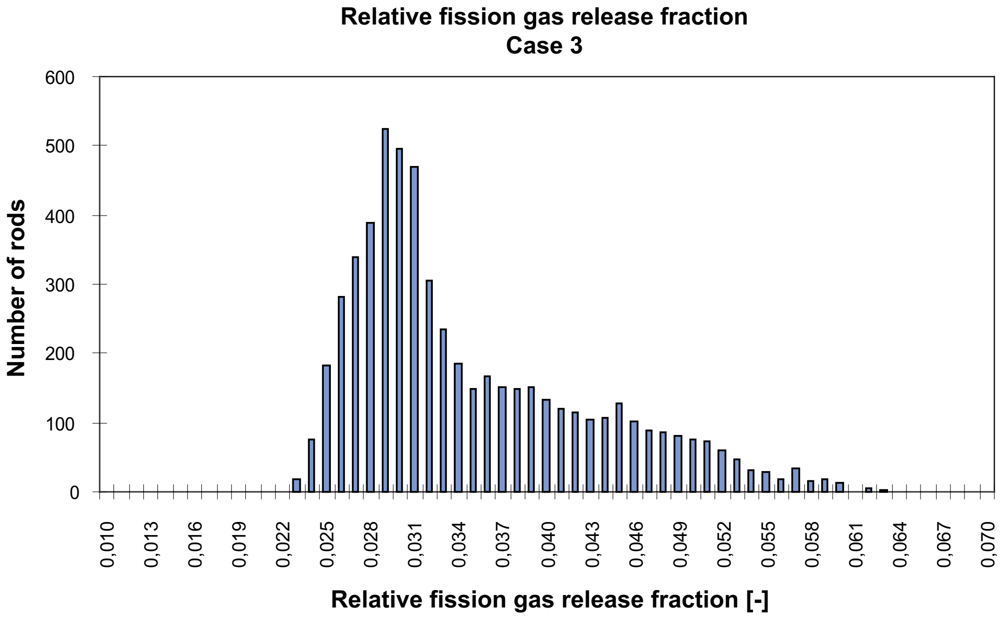

Figure 5-6. *Relative fission gas release fraction for irradiated fuel leaving the core, i.e. all rods from cycle 11 and some from cycle 9 and 10, for case 3, 1375 MW, ~60 MWd/kgU.*

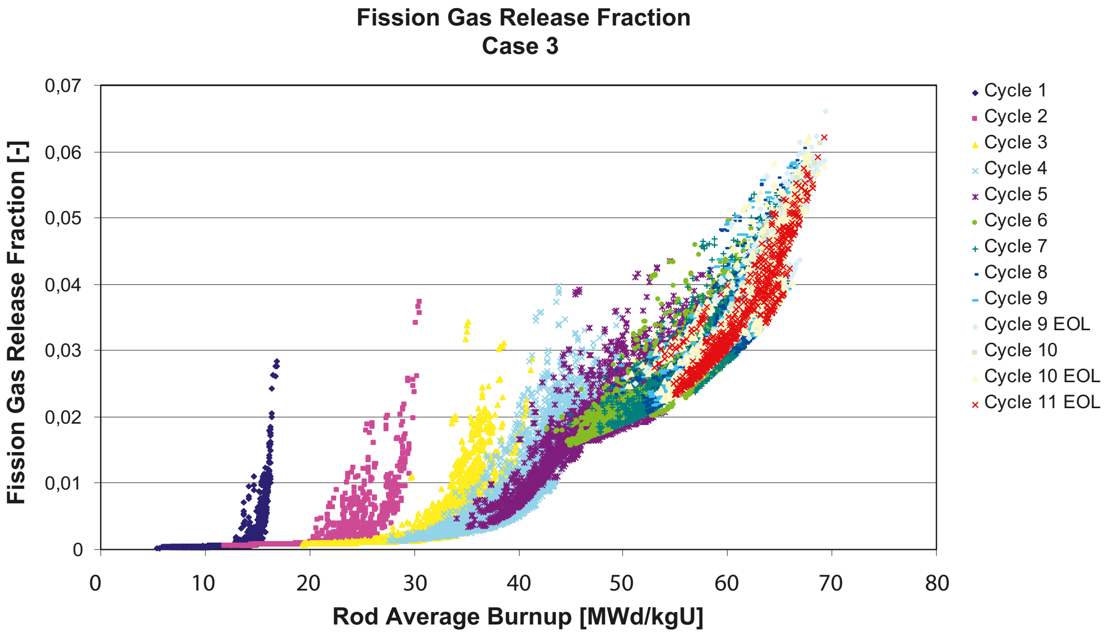

Figure 5-7. *The relative fission gas release fraction at the end of each cycle for case 3, 1375 MW, ~60 MWd/kgU. The rods at end of irradiation are labeled EOL.*

Table 5-4. Relative fission gas release fraction [–] at the end of each cycle for case 3.

	Average Burnup [MWd/kgU]	Average	Standard dev.
Cycle 1	11.5	0.000857	0.00178
Cycle 2	20.2	0.00139	0.00229
Cycle 3	29.8	0.00306	0.00363
Cycle 4	38.3	0.00792	0.00653
Cycle 5	46.9	0.0183	0.00641
Cycle 6	54.0	0.0254	0.00602
Cycle 7	57.1	0.0292	0.00698
Cycle 8	59.1	0.0322	0.00770
Cycle 9	59.9	0.0335	0.00804
Cycle 10	60.3	0.0343	0.00813
Cycle 11	60.5	0.0343	0.00787
Cycle 9-11 (discharged rods)	60.4	0.0344	0.00820

5.5 Case 4 – 3292 MW, ~45 MWd/kgU

This section gives the result from the best-estimate calculations of FGR for case 4, see Table 1-1. The histogram in Figure 5-8 shows the distribution of fission gas release fraction at the end of the last cycle for case 4. The rods have received full burnup after 4, 5 or 6 cycles and will hence be removed from the core. In Figure 5-9 and Table 5-5 the FGR at the end of each cycle is presented. Since assemblies reach discharge burnup after 4, 5 or 6 cycles the results for discharged rods from cycle 4, 5 and 6 are also given together. In Appendix A the FGR in moles for helium, krypton and xenon is depicted.

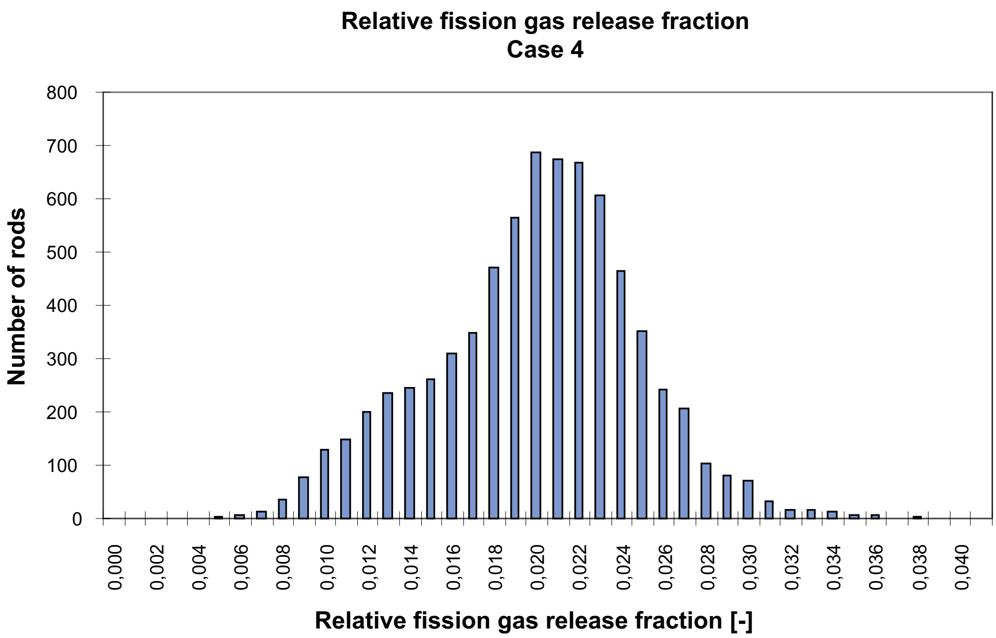

Figure 5-8. *Relative fission gas release fraction for irradiated fuel leaving the core, i.e. all rods from cycle 6 and some from cycle 4 and 5, for case 4, 3,292 MW, ~45 MWd/kgU.*

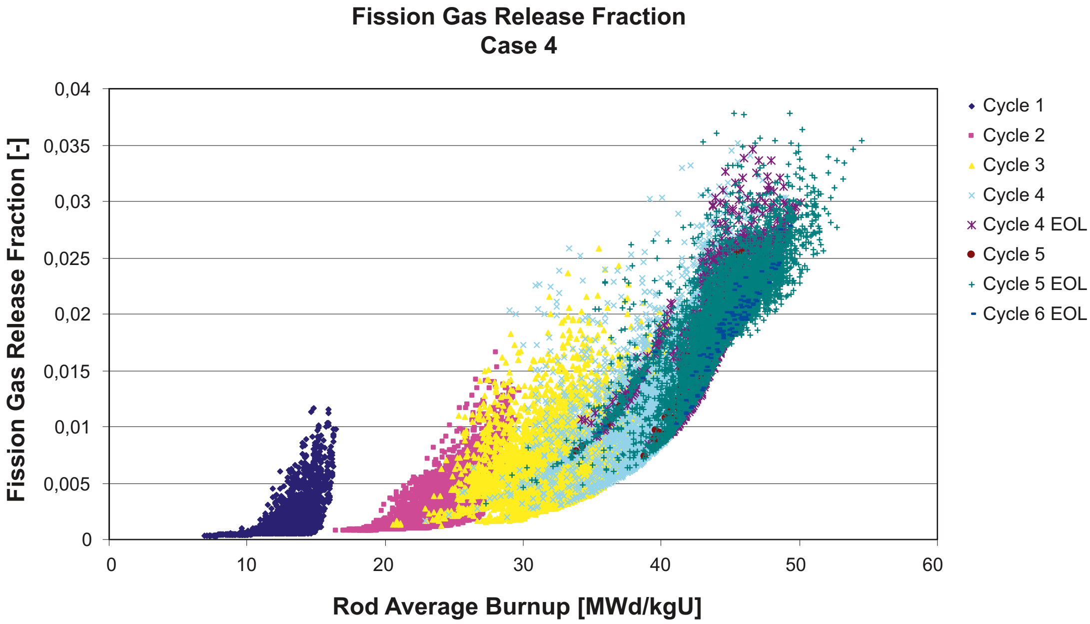

Figure 5-9. *The relative fission gas release fraction at the end of each cycle for case 4, 3,292 MW, ~45 MWd/kgU. The rods at end of irradiation are labeled EOL.*

Table 5-5. Relative fission gas release fraction [–] at the end of each cycle for case 4.

	Average Burnup [MWd/kgU]	Average	Standard dev.
Cycle 1	12.4	0.00120	0.00134
Cycle 2	23.8	0.00287	0.00215
Cycle 3	33.7	0.00740	0.00336
Cycle 4	40.7	0.0152	0.00567
Cycle 5	44.2	0.0192	0.00501
Cycle 6*	44.6	0.0186	0.00372
Cycle 4-6 (discharged rods)	44.3	0.0195	0.0049

*Only one assembly is irradiated for 6 cycles.

5.6 Case 5 – 3,900 MW, ~45 MWd/kgU

This section gives the result from the best-estimate calculations of FGR for case 5, see Table 1-1. The histogram in Figure 5-10 shows the distribution of fission gas release fraction at the end of the last cycle for case 5. The rods have received full burnup after 4 or 5 cycles and will hence be removed from the core. In Figure 5-11 and Table 5-6 the FGR at the end of each cycle is given. Since some assemblies reach discharge burnup after 4 cycles and some after 5 cycles the results for discharged rods from cycle 4 and 5 are also given together. In Appendix A the FGR in moles for helium, krypton and xenon is depicted.

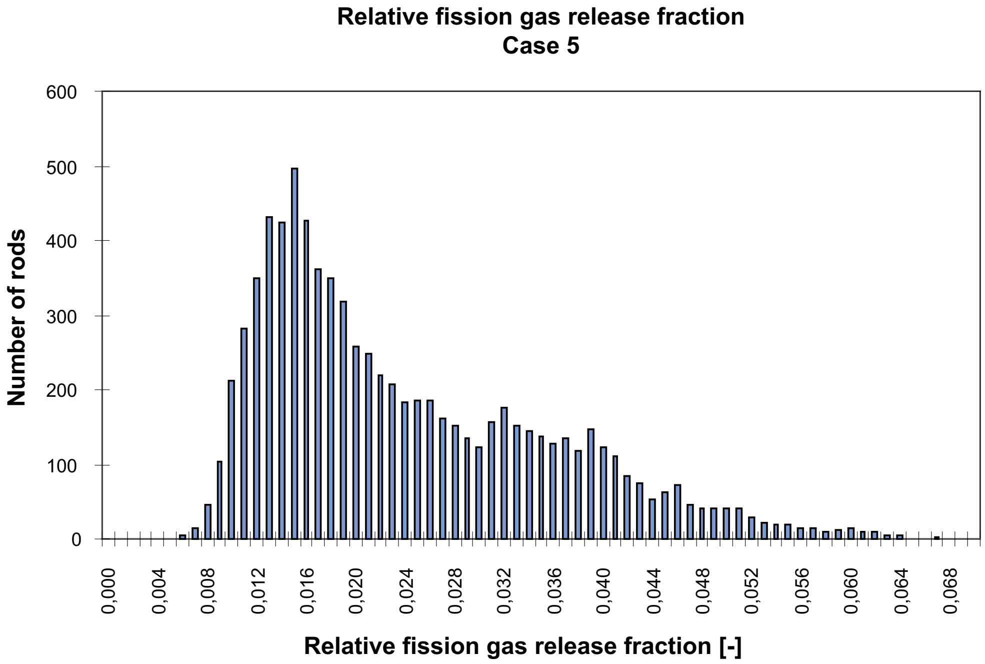

Figure 5-10. Relative fission gas release fraction for irradiated fuel leaving the core, i.e. all rods from cycle 5 and some from cycle 4, for case 5, 3,900 MW, ~45 MWd/kgU.

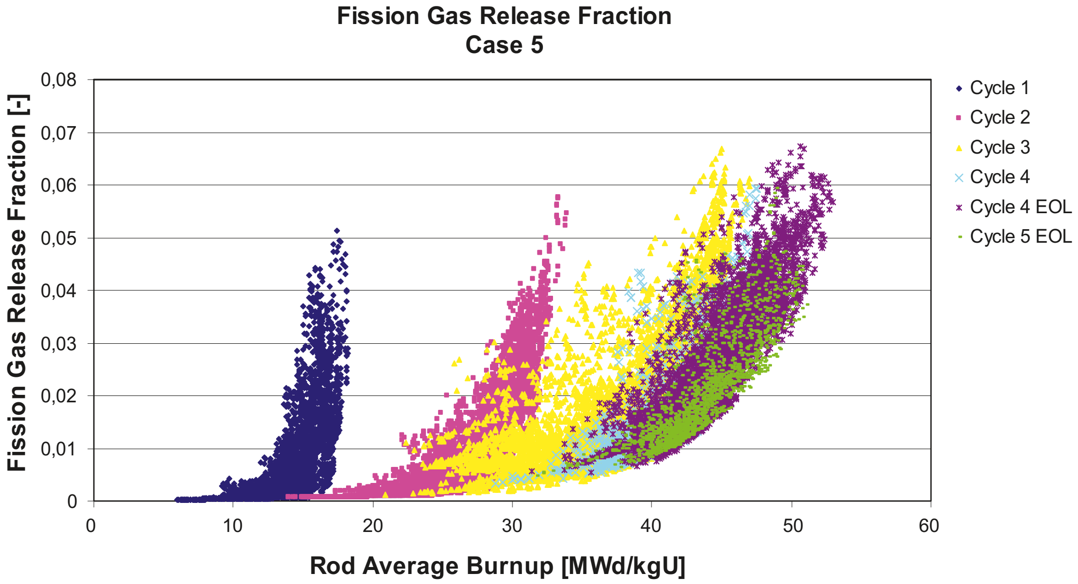

Figure 5-11. The relative fission gas release fraction at the end of each cycle for case 5, 3,900 MW, ~45 MWd/kgU. The rods at end of irradiation are labeled EOL.

Table 5-6. Relative fission gas release fraction [–] at the end of each cycle for case 5.

	Average Burnup [MWd/kgU]	Average	Standard dev.
Cycle 1	13.1	0.00446	0.00745
Cycle 2	25.5	0.00767	0.00820
Cycle 3	37.0	0.0155	0.00928
Cycle 4	43.1	0.0226	0.0117
Cycle 5*	43.5	0.0207	0.0100
Cycle 4+5 (discharged rods)	43.9	0.0236	0.0116

*18 assemblies out of 85 run for 5 cycles.

5.7 Case 6 – 1,375 MW, ~45 MWd/kgU

This section gives the result from the best-estimate calculations of FGR for case 6, see Table 1-1. This core has the lowest FGR of the six cores. The histogram in Figure 5-12 shows the distribution of fission gas release fraction at the end of the last cycle for case 6. The rods have received full burnup after 7, 8 or 9 cycles and will hence be removed from the core. In Figure 5-13 and Table 5-7 the FGR at the end of each cycle is presented. Since assemblies reach discharge burnup after 7, 8 or 9 cycles the results for discharged rods from cycle 7–9 are also given together. In Appendix A the FGR in moles for helium, krypton and xenon is depicted.

The FGR consists of two mechanisms; one part that is athermal FGR that is primarily fission rate dependent, and one part that is thermal FGR. There is a temperature threshold, the so called Vitanza curve /13/, below which there is no thermal FGR. For case 6 the pellet centerline temperature is always well below this curve, hence the FGR for case 6 is almost only athermal FGR with low spread.

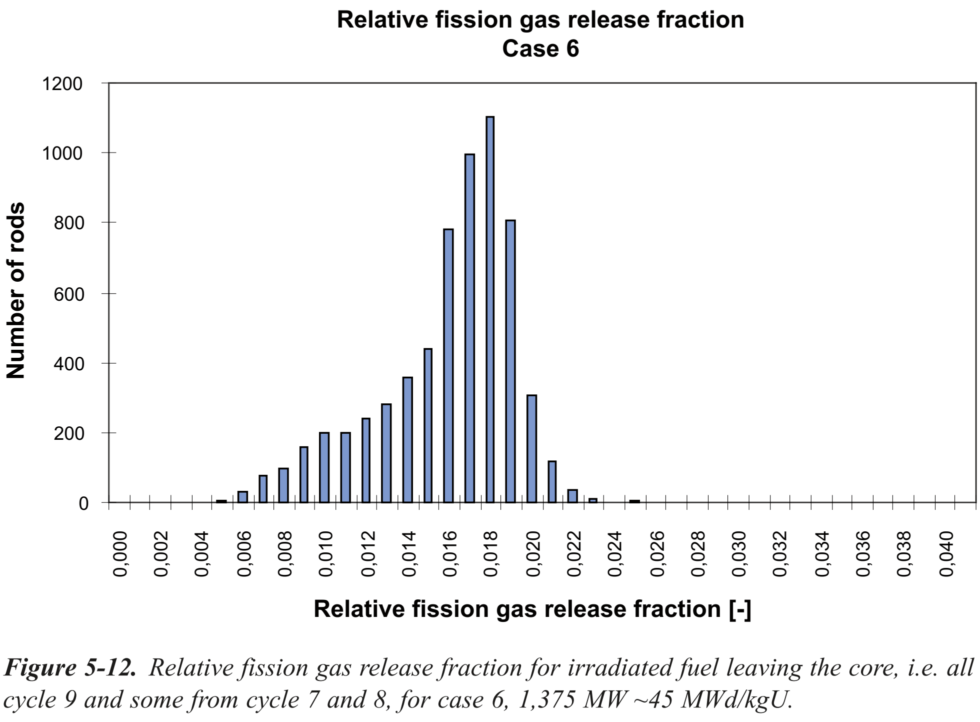

Figure 5-12. *Relative fission gas release fraction for irradiated fuel leaving the core, i.e. all rods from cycle 9 and some from cycle 7 and 8, for case 6, 1,375 MW ~45 MWd/kgU.*

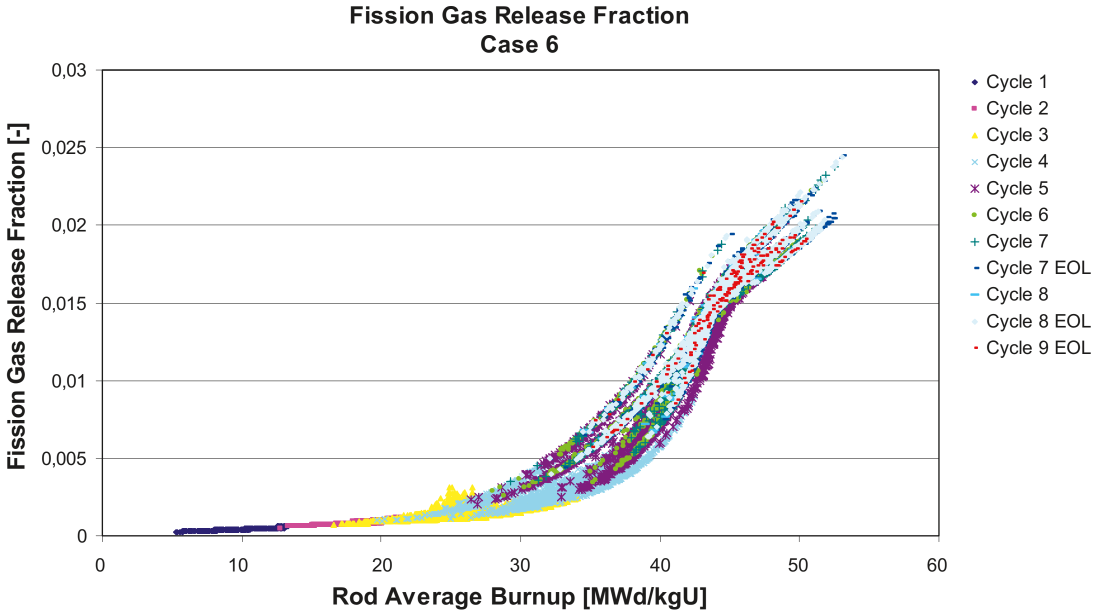

Figure 5-13. *The relative fission gas release fraction at the end of each cycle for case 6, 1,375 MW, ~45 MWd/kgU. The rods at end of irradiation are labeled EOL.*

Table 5-7. Relative fission gas release fraction [–] at the end of each cycle for case 6.

	Average Burnup [MWd/kgU]	Average	Standard dev.
Cycle 1	9.9	0.000431	0.0000636
Cycle 2	19.0	0.000827	0.0000897
Cycle 3	26.7	0.00147	0.000335
Cycle 4	33.8	0.00343	0.00120
Cycle 5	40.3	0.00932	0.00346
Cycle 6	43.0	0.0131	0.00363
Cycle 7	44.5	0.0150	0.00341
Cycle 8	44.8	0.0154	0.00344
Cycle 9	44.7	0.0153	0.00350
Cycle 7-9 (discharged rods)	44.9	0.0155	0.0033

6 Conclusions

- The first conclusion from those calculations is that a higher burnup gives higher FGR.
- The second conclusion is that the pellet temperature, (and LHGR), has a large impact on FGR. Case 6 and case 3 that run at lower temperature have lower FGR.
- The FGR has in none of these cases a normal distribution. In a fuel assembly, the rods at the edges and the 2/3 length rods in the middle close to the water cross[1] often form a second population in the histograms. This second population can have both higher and lower FGR than the main population.

[1] The water cross is the open area in the middle of the assembly through which the water flows.

7 Background material

R Faxén, 2002. Westinghouse Atom Report BTA 01-159, rev 1. KKL SVEA-96 Optima2 reloads. Fuel Rod Design.

J Eriksson, 2007. Westinghouse Report BTM 07-1225, rev 0. Oskarshamn 3 PULS SVEA-96 Optima2 med aktiv längd 3.68 m och SVEA-96 Optima3 med aktiv längd 3.69m.

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C Halling, 2009. Westinghouse Report BTF 08-1505, rev 0. SVEA96 Optima2 equilibrium cycle, Case 1 - KKL at 60 MWd/kgU.

C Halling, 2009. Westinghouse Report BTF 08-1506, rev 0. SVEA96 Optima2 equilibrium cycle, Case 2 - O3 (109% power) at 60MWd/kgU.

C Halling, 2009. Westinghouse Report BTF 08-1507, rev 0. SVEA96 Optima2 equilibrium cycle, Case 3 - O1 at 60 MWd/kgU.

C Halling, 2009. Westinghouse Report BTF 08-1508, rev 0. SVEA96 Optima2 equilibrium cycle, Case 4 - O3 (109% power) at 45 MWd/kgU.

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A Massih, Z Weiss. ABB Atom Report BU 97-091, rev 2. STAV7 Model Description.

G Zhou, R Faxén. Westinghouse Report BTU 05-008, rev 0. STAV7 High Burnup Update and Verification

G Zhou. Westinghouse Report BTU 08-0223, rev 0. BWR Cladding Corrosion and Hydrogen Pickup Models Update and Verification in STAV7.3.2

D Sheppard, C Vitanza, 1979. Fission gas release from LWR fuel during steady state and transient conditions. Paper to be Presented at the Enlarged Halden Programme Group Meeting.Hankø, Norway, 17th-22nd June, 1979. OECD Halden Reactor Project.

Appendix A

Results of release of fission gas in moles

Helium is released during irradiation, but the main part is helium used for prepressurizing the rods. This explains why the graphs, for instance Figure A-2, show three groups, one for each rod length as the rods of different length have different plenum volumes. The different amount of helium for the different cases in Figure A-1 is due to the filling pressure that is 0.4 MPa for case 3 and 6 and 0.8 MPa for all other cases. The amount of helium deriving from fission gas release is approximately the same as the amount of krypton and therefore the expected standard deviation, as a measure of uncertainty, for helium and krypton should be the same. That is not the case in Table A-1 and that is due to the fact that all three rod lengths are included and the part length rods, with a different amount of helium from the prepressurizing, have a large impact on the standard deviation. For instance, for case 4, the standard deviation has been calculated for only the full length rods and that resulted in a standard deviation of $5.987 \cdot 10^{-5}$ for krypton and $5.997 \cdot 10^{-5}$ for helium. Hence the difference in standard deviation for helium and krypton in Table A-1 is a result from the prepressurizing, not from the fission gas release.

Table A-1. Moles of fission gas release per rod for the different cores.

	Helium [moles]		Krypton [moles]		Xenon [moles]	
	Average	**Standard dev.**	**Average**	**Standard dev.**	**Average**	**Standard dev.**
Case 1	0.00793	0.00144	0.000687	0.000318	0.00618	0.00286
Case 2	0.00726	0.00107	0.000635	0.000247	0.00571	0.00222
Case 3	0.00345	0.000458	0.000498	0.000172	0.00448	0.00155
Case 4	0.00684	0.00101	0.000217	0.0000777	0.00195	0.000699
Case 5	0.00688	0.000982	0.000253	0.000130	0.00228	0.00117
Case 6	0.00311	0.000383	0.000167	0.0000497	0.00151	0.000447

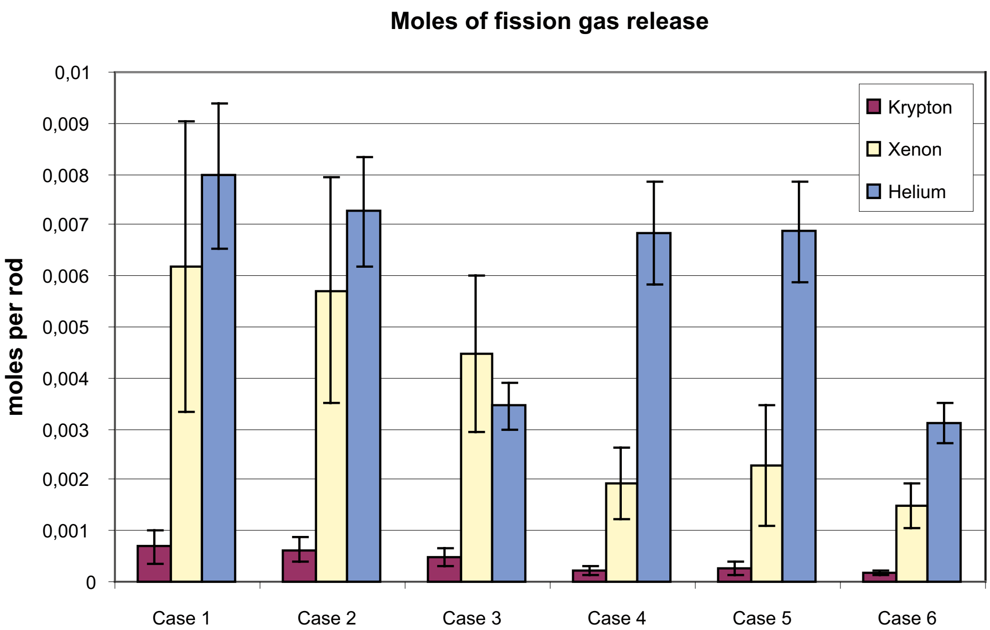

Figure A-1. *Fission gas release per rod in moles. The error bars are ± one standard deviation.*

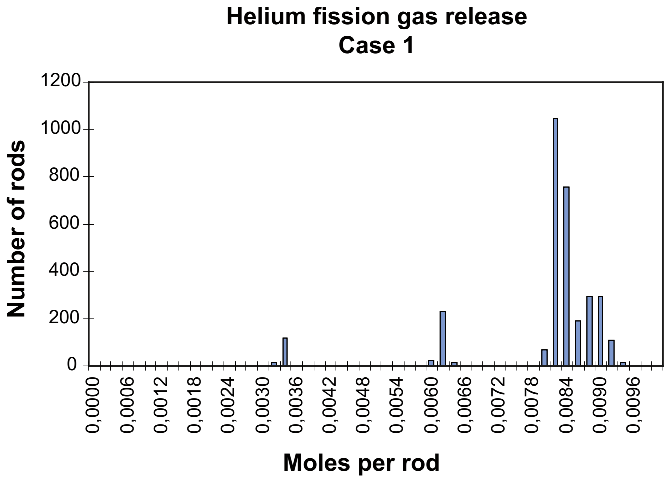

Figure A-2. Release of the fission gas helium in moles for case 1.

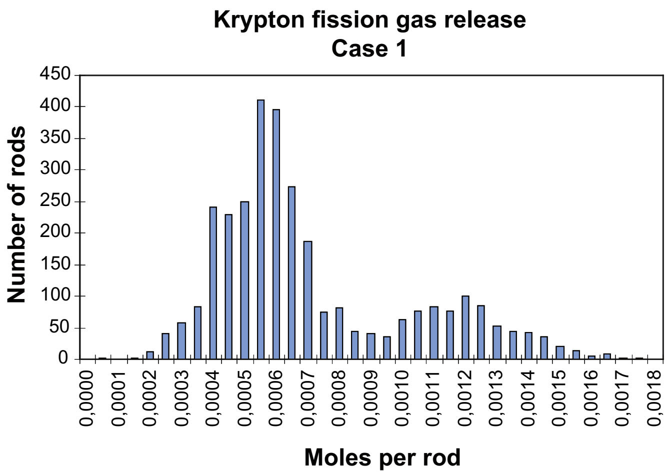

Figure A-3. Release of the fission gas krypton in moles for case 1.

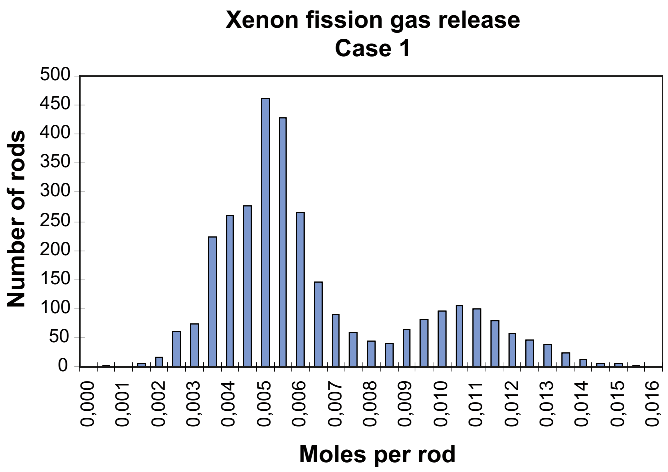

Figure A-4. Release of the fission gas xenon in moles for case 1.

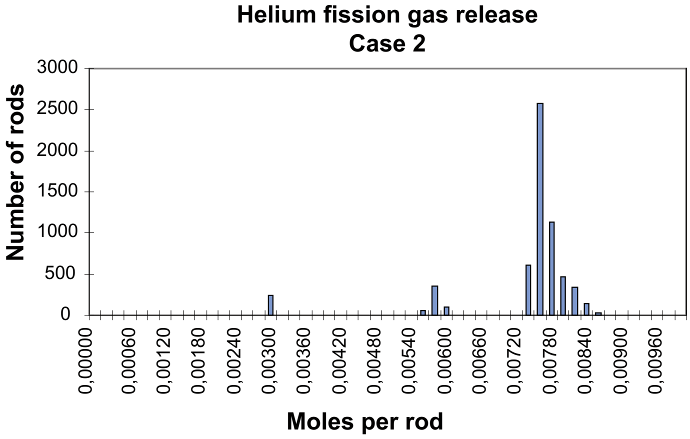

Figure A-5. *Release of the fission gas helium for case 2.*

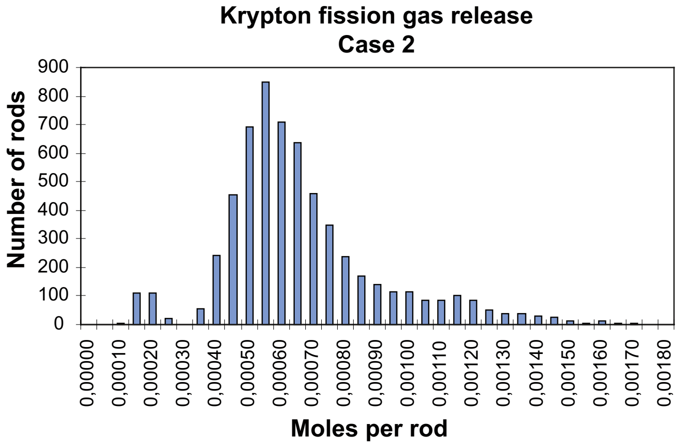

Figure A-6. *Release of the fission gas krypton for case 2.*

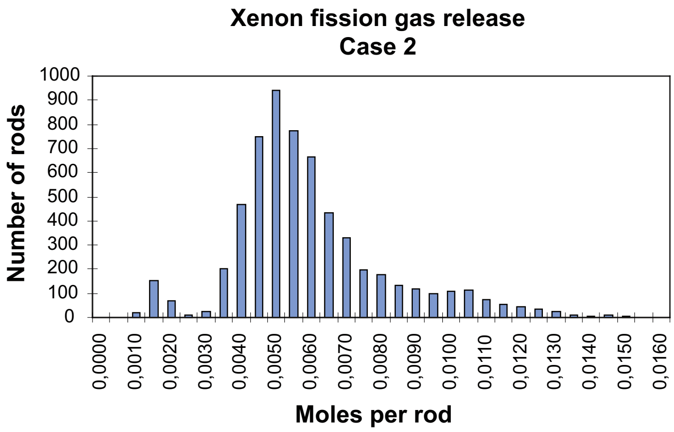

Figure A-7. *Release of the fission gas xenon for case 2.*

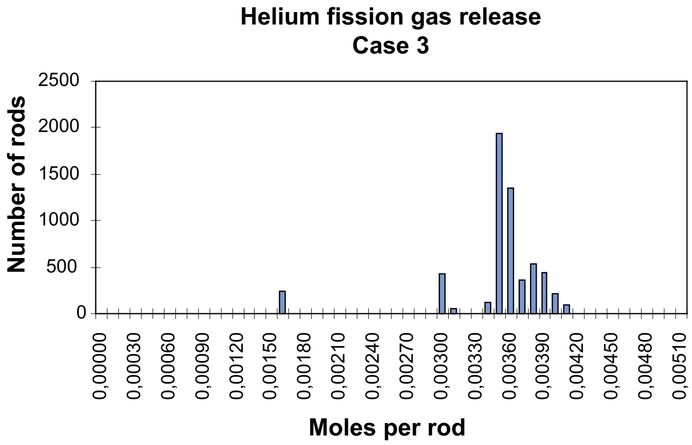

Figure A-8. *Release of the fission gas helium for case 3.*

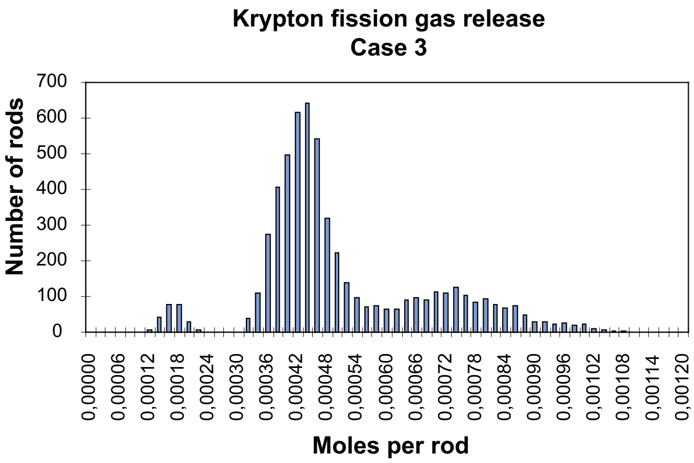

Figure A-9. *Release of the fission gas krypton for case 3.*

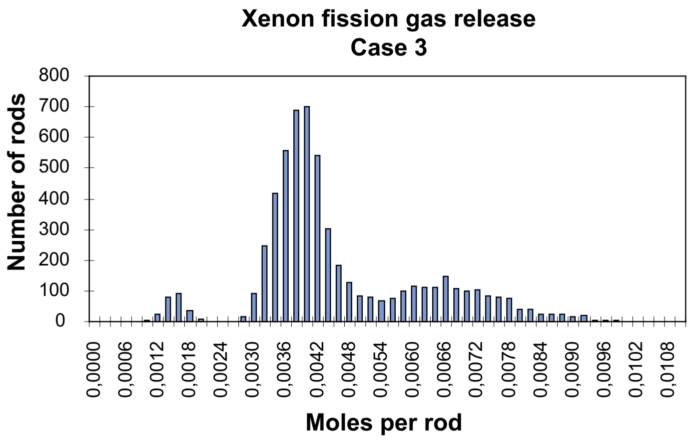

Figure A-10. *Release of the fission gas xenon for case 3.*

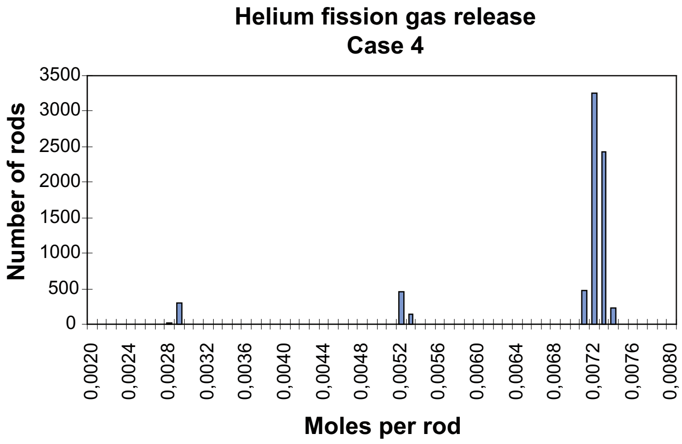

Figure A-11. Release of the fission gas helium for case 4.

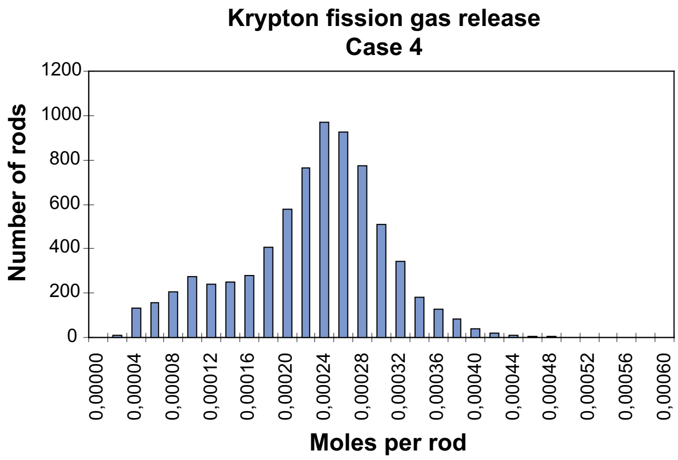

Figure A-12. Release of the fission gas krypton for case 4.

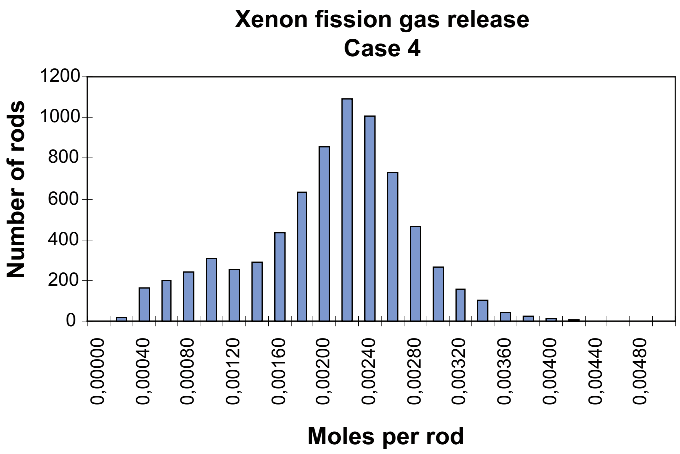

Figure A-13. Release of the fission gas xenon for case 4.

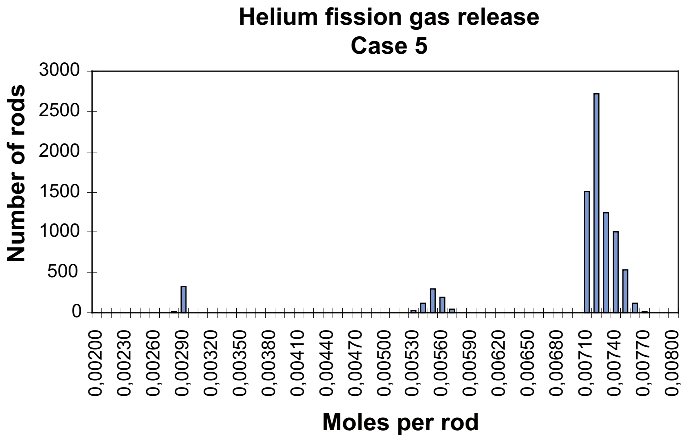

Figure A-14. *Release of the fission gas helium for case 5.*

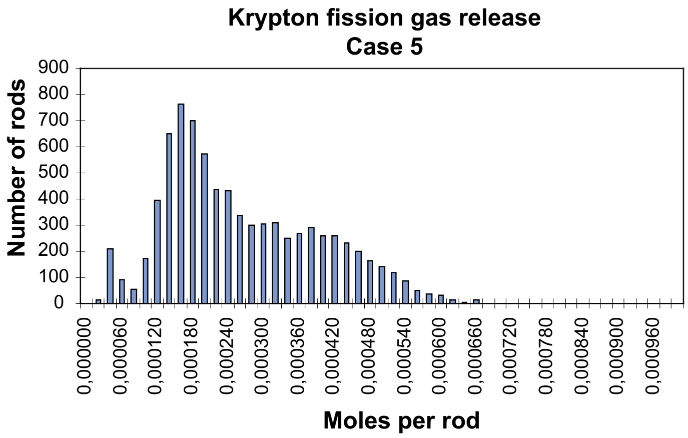

Figure A-15. *Release of the fission gas krypton for case 5.*

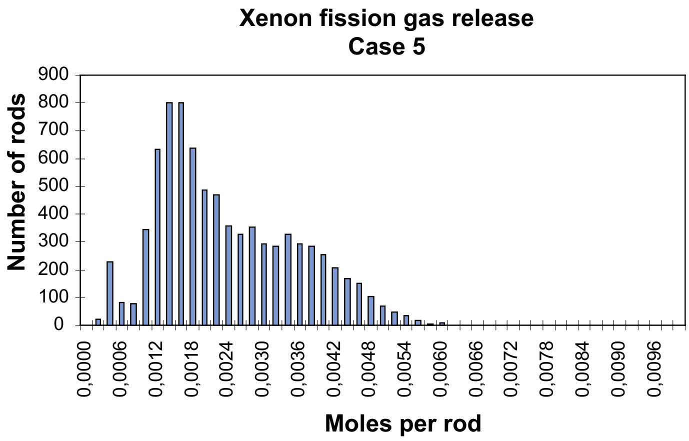

Figure A-16. *Release of the fission gas xenon for case 5.*

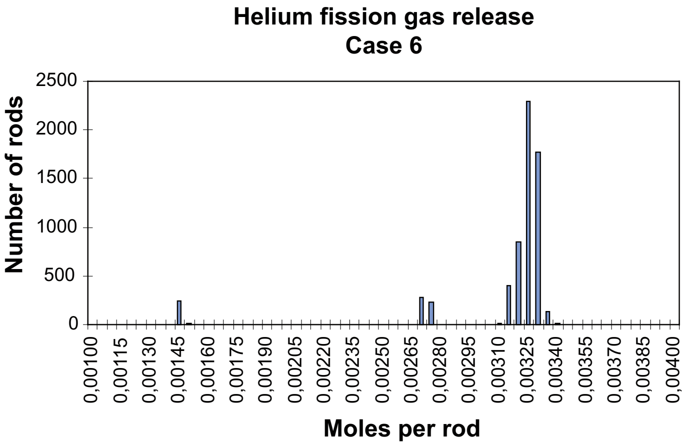

Figure A-17. *Release of the fission gas helium for case 6.*

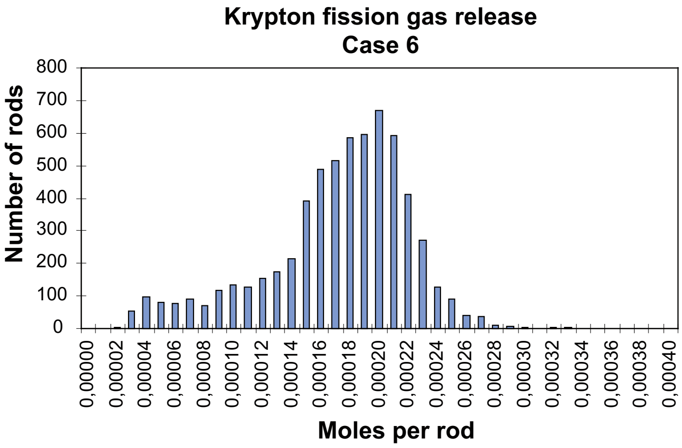

Figure A-18. *Release of the fission gas krypton for case 6.*

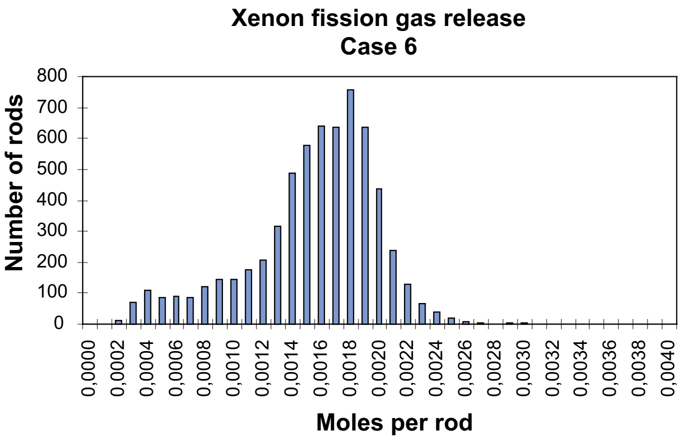

Figure A-19. *Release of the xenon gas helium for case 6.*

Power histories

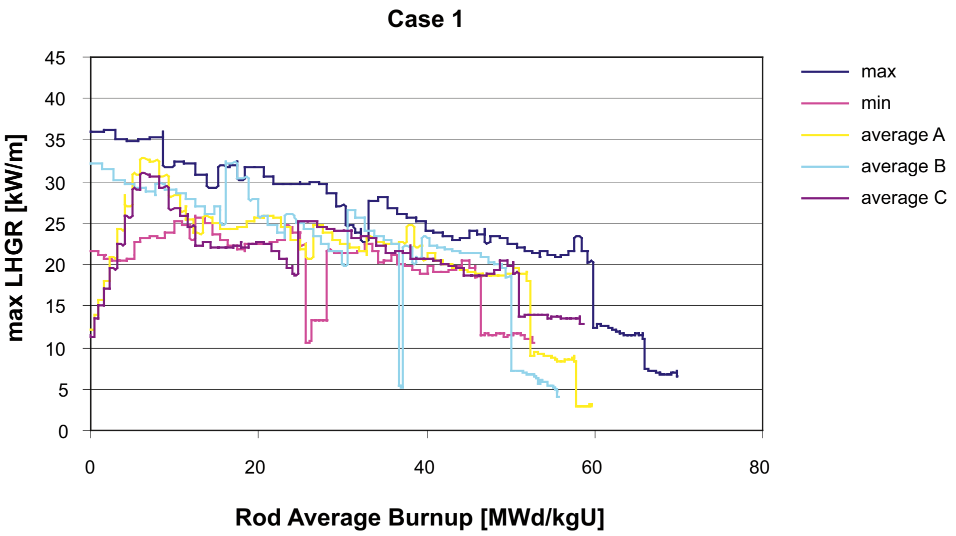

Figure B-1. Power histories for case 1. Max and min refers to the power histories with highest and lowest FGR at the end of irradiation. Average A, B and C are power histories with an average FGR at the end of irradiation.

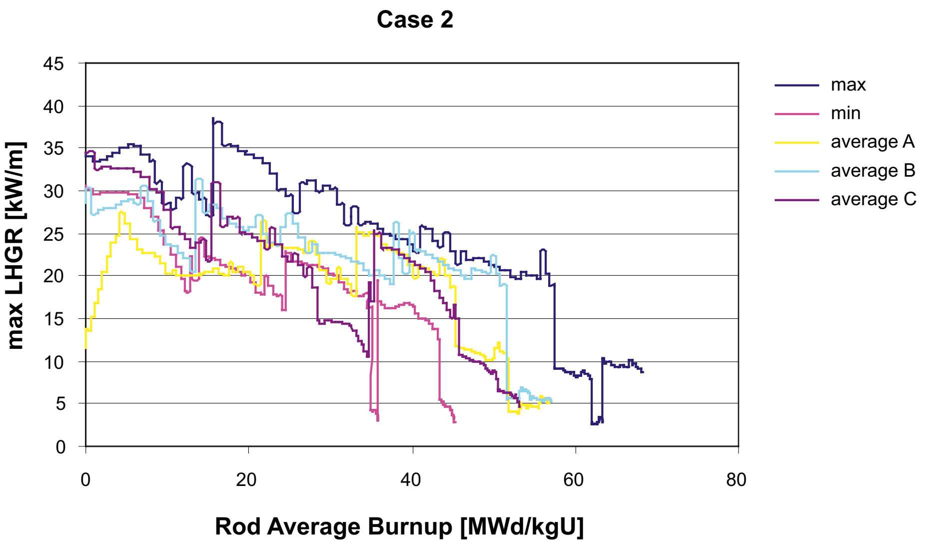

Figure B-2. Power histories for case 2. Max and min refers to the power histories with highest and lowest FGR at the end of irradiation. Average A, B and C are power histories with an average FGR at the end of irradiation.

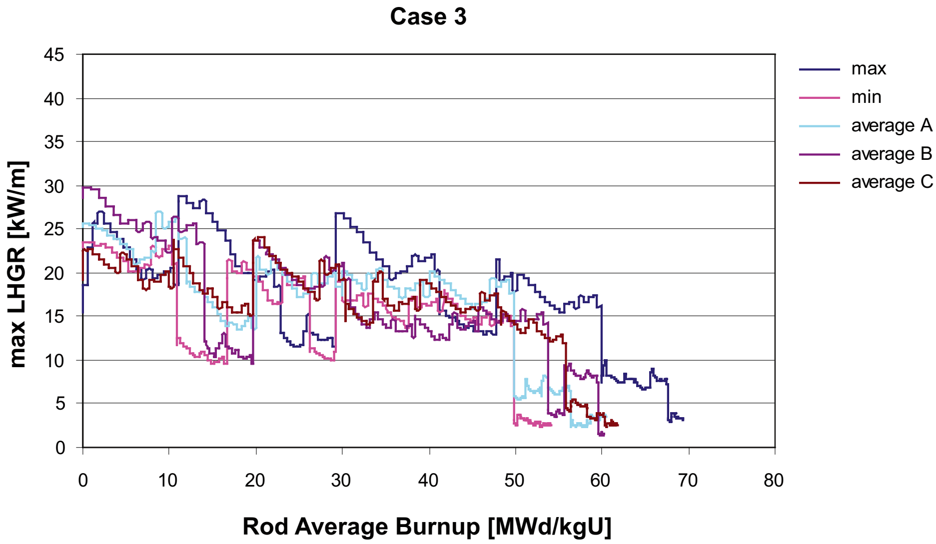

Figure B-3. *Power histories for case 3. Max and min refers to the power histories with highest and lowest FGR at the end of irradiation. Average A, B and C are power histories with an average FGR at the end of irradiation.*

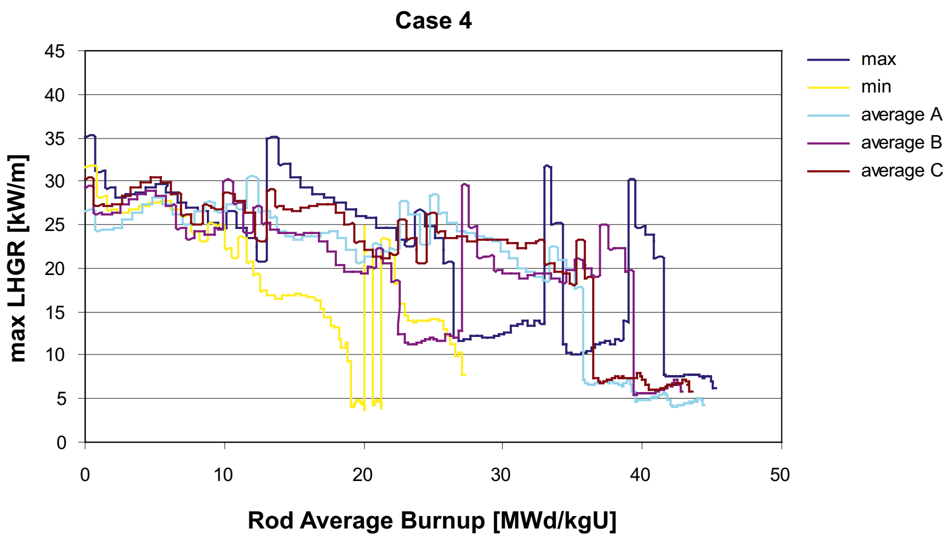

Figure B-4. *Power histories for case 4. Max and min refers to the power histories with highest and lowest FGR at the end of irradiation. Average A, B and C are power histories with an average FGR at the end of irradiation.*

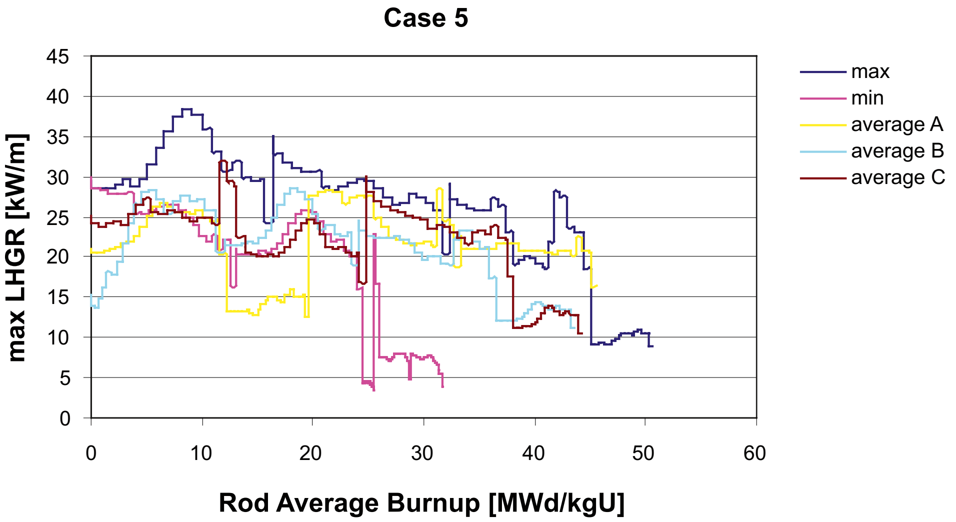

Figure B-5. Power histories for case 5. Max and min refers to the power histories with highest and lowest FGR at the end of irradiation. Average A, B and C are power histories with an average FGR at the end of irradiation.

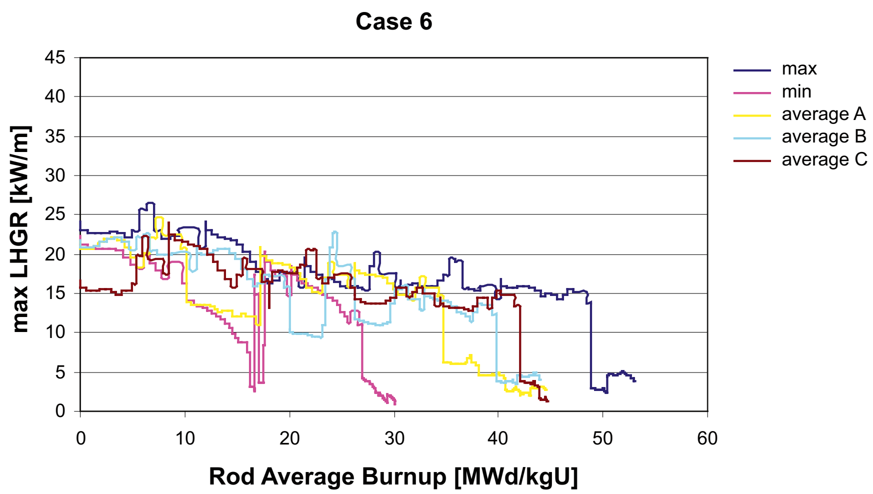

Figure B-6. Power histories for case 6. Max and min refers to the power histories with highest and lowest FGR at the end of irradiation. Average A, B and C are power histories with an average FGR at the end of irradiation.

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