

Statistical analysis of plant data for revision of operating rules minimizing risk of PCI failure in BWRs

Master of Science Thesis in the Master Degree Programme, Nuclear Engineering

ALBORZ AZADRAD

Department of Applied Physics
Division of Nuclear Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2013
CTH-NT-281

ISSN 1653-4662

CTH-NT-281

Statistical Analysis of Plant Data for Revision of Operating Rules Minimizing Risk of PCI Failure in BWRs

ALBORZ AZADRAD

Department of Applied Physics
Division of Nuclear Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2013

Statistical analysis of plant data for revision of operating rules
minimizing risk of PCI failure in BWRs
ALBORZ AZADRAD

© ALBORZ AZADRAD, 2013

Master's Thesis
CTH-NT-281
ISSN 1653-4662
Department of Applied Physics
Division of Nuclear Engineering
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover (left to right):
UO₂ fuel pellet, fuel rod, SVEA96 Optima2 fuel assembly and
BWR75 reactor pressure vessel with internals.

Chalmers Reproservice
Göteborg, Sweden 2013

Statistical analysis of plant data for revision of operating rules minimizing risk of PCI failure in BWRs

Master's Thesis in the Master Degree Program Nuclear Engineering

ALBORZ AZADRAD

Department of Applied Physics

Division of Nuclear Engineering

Chalmers University of Technology

ABSTRACT

Nuclear power reactors are responsible for producing electricity; the electricity comes from a generator, driven by turbines that receive their power from expanding steam forcing its way through the turbine blades. The steam in turn comes from a cylindrically shaped vessel that houses thousands of rods containing a uranium compound that through a process called nuclear fission generate heat which in turn boils the water. Power is controlled by control rods that slide between the rod bundles, an insertion result in a power decrease and vice versa. During power increases there is a risk the fuel rods crack and release radioactive material in the steam cycle. Fuel related failures that lead to such events are called PCI (pellet-cladding interaction) failure

Data from past operation experience, both from commercial operation and from power ramp tests, have been collected and analyzed, in order to evaluate the probability of PCI failures. The parameters that have been analyzed are the maximum power level (LHGR) and power steps for each pin node during a cycle or during a power ramp test. This information has then been graphically presented together with some operating restrictions (the TMOL curve and the current PCI threshold curve).

Based on this information, a statistical analysis has been performed assessing the PCI failure probability as function of the power step. The derived probabilities are highly determined by the results from the power ramp tests.

It should be noted that the PCI failure probability is estimated not only to be dependent on the magnitude of the power step, but also on the burnup level and the starting power level at which the power step has been taken, as well as the possible occurrence of pellet and cladding defects. These dependencies, not evaluated in this study, are recommended to be treated in future analyses.

Keywords: PCI, Westinghouse, Statistics, Nuclear, Pellet, BWR, Liner, Probability, Failure, Cladding

This page intentionally left blank.

Contents

1	INTRODUCTION	1
2	THE PCI FAILURE PHENOMENON	2
2.1	Stress corrosion cracking	2
2.2	Hydrogen embrittlement strain failure	2
2.3	Delayed hydride cracking	2
3	THEORY	2
3.1	Introduction	2
3.1	Current operating rules	3
3.2	Conditioning/Deconditioning model	3
4	METHOD	7
4.1	Software	7
4.1.1	POLCA7	7
4.1.2	CORE MASTER 2	7
4.2	Data extraction	7
4.3	Scripts used	8
4.3.1	Description of core scanner and output files	8
4.3.1.1	Pinlhgr-max.txt	9
4.3.1.2	Steps-max.txt	10
4.3.1.3	Histogram.txt	10
4.3.1.4	LHGR-max.txt	10
4.3.2	Burnup plotter	10
4.3.3	Splitting of ramp segments	10
5	RESULTS	11
5.1	Experience from standard operation	11
5.2	Experience from ramp experiments	14
5.3	Comparison with current rules	16
6	STATISTICAL ASSESSMENT	16
6.1	Registered data	16
6.2	Methodology	18
6.3	Fitting of a normal distribution	20
7	CONCLUSION	22
8	REFERENCES	23
APPENDIX A POLCA7 CODE MAP		
APPENDIX B BURNUP DEPENDENCE PLOTS FOR ALL REACTORS		
APPENDIX C SCRIPTS USED		

ABBREVIATIONS

BWR	Boiling Water Reactor
CM2	Core Master 2
CHF	Critical Heat Flux
DHC	Delayed Hydride Cracking
FMCRD	Fine Motion Control Rod Drive
GUI	Graphical user interface
HESF	Hydrogen Embrittlement Strain Failure
LHGR	Linear Heat Generation Rate
LWR	Light Water Reactor
MC	Main Circulation
MLE	Maximum Likelihood Estimation
MPS	Missing Pellet Surface
NDE	Non Destructive Examination
NSSS	Nuclear Steam Supply System
PCI	Pellet Cladding Interaction
PCMI	Pellet Cladding Mechanical Interaction
PWR	Pressurized Water Reactor
R2	Studsvik research reactor
SCC	Stress Corrosion Cracking
TCL	Tool Command Language
TMOL	Thermal Mechanical Operating Limit
VVER	Russian type PWR

Preface

The basis for this master's thesis originated from the employer and was presented to the division of nuclear engineering at Chalmers University of Technology for approval. It is in Westinghouse belief that the findings in this master's thesis will be of benefit when presenting power manoeuvring guidelines in the future.

Westinghouse Electric Sweden AB, earlier ASEA Atom and later ABB Atom is a company responsible for constructing nine nuclear power plants in Sweden and two in Finland of the type boiling water reactor (BWR). The company has four offices in Sweden of which three are in Västerås and one in Täby outside of Stockholm. One of them is a modern nuclear fuel factory responsible for manufacturing fuel assemblies for BWR, PWR and VVER and also manufactures control rods for BWRs.

The second is the main office where its Sweden Fuel Engineering branch resides; it is here calculations are performed to assess the various areas of a nuclear power plant. Core physicists, method developers, fuel rod designers, software designers, project managers, materials specialists and many more disciplines can be found here.

The third is the light water reactor (LWR) Services centre that also houses the thermal-hydraulic test loops FRIGG and ODEN where fuel manufacturers can simulate the thermal conditions in a nuclear reactor by using electrically heated rods in one fuel assembly. It is used extensively to perform critical heat flux (CHF) measurements for avoidance of the dryout phenomenon; a condition in which no liquid water is in contact with the fuel rod.

The fourth office, situated in Täby is responsible for supplying the power industry with non destructive examination (NDE) equipment and services which are useful during servicing and revision.

Due to the confidential agreements between Westinghouse and its customers some part of the thesis has been redacted or obscured. This is applied to figures as well in order to protect trade secrets.

Acknowledgements

I wish to express my very great appreciation to my supervisor Per Seltborg for his valuable and constructive suggestions during the thesis work as well to my other supervisors Mats Thunman and Sven-Birger Johannesson for their experience and educating me on the computer programs used by Westinghouse.

My special thanks are extended to the staff of Sweden Fuel Engineering at Westinghouse Electric Sweden AB.

I would also like to thank Christophe Demaziere, professor at the division of nuclear engineering at Chalmers and examiner of this thesis for sharing his extensive knowledge in reactor physics and aiding me in the formal parts. Credit is also given to master's programme director Anders Nordlund whose courses made well prepared for the various tasks in this report. During the work I have been provided with resources and knowledge from Westinghouse Electric Sweden AB.



1 INTRODUCTION

In the 1970's, LWRs were prone to fuel-related failures of leaking fuel rods from PCI failures. The earliest remedy consisted of ramp experiments that assessed the thermo-mechanical properties of the cladding. They were backed by a set of operating rules specified by the manufacturer. These remedies were extended to liners, a coating inside the cladding to dampen the effects from pellets exerting pressure in it. After introduction of liner fuel the next step was to change the lattice of the fuel assembly; increasing the number of fuel rods but in smaller diameter and keeping the liner. With each design update, associated ramp tests were made but the operating rules have remained mostly the same since their inception.

All of these remedies except the liner had the specific purpose of lowering the linear heat generation rate (LHGR), as it has a direct impact on the PCI risk. The fuel temperature is related to LHGR and due to the poor thermal conductivity of uranium dioxide, the centerline LHGR can reach a high value and consequently also the fuel temperature. Controlling the LHGR is the key to minimize damages to the cladding; such events are known as PCI failures. A PCI failure causes an activity release in the primary systems in a LWR leading to delays when revision/refueling of the reactor takes place. PCI failures were tolerated decades ago but today utilities avoid them as much as possible.

It is generally known that the greatest risk of PCI failure occurs when an increase of power is made and so far the rules have been the accepted standard in avoiding PCI failure. When it comes to fuel manufactured by Westinghouse, there has been no PCI failures detected for 8x8 and 10x10 liner fuel.

However, these rules are currently being reevaluated. This report is part of a larger project that aims to increase the general understanding of the PCI phenomenon and to reevaluate the operating recommendations for avoiding PCI failures. The current study has primarily focused on analyzing past operation experience, both from commercial operation and from power ramp tests. Collecting these data is the first step in order to check if any violations of the rules have been made and to examine the operating range. This has been made using the Westinghouse nodal code POLCA7 together with a number of complementary scripts written in Matlab.

The second step is to statistically evaluate the data in order to derive a relationship between LHGR and PCI failure probability. This has been done using Excel and Matlab. PCI is also an issue in PWR but this report is only focused on BWRs. Through modifications of the software, it is anticipated that this will pave way for a new PCI methodology that is scientifically more robust than the current methodology.

2 THE PCI FAILURE PHENOMENON

A PCI failure can occur in numerous ways but three distinct failure modes has been identified and it is from these modes computational models has been developed. A short description of them is given below and the interested reader is referred to [1].

2.1 STRESS CORROSION CRACKING

Stress corrosion cracking (SCC) is associated with the aggressive fission products that are formed inside the pellet. They react with the cladding and form compounds that lower the mechanical performance. SCC can be split into pellet-cladding-mechanical-interaction (PCMI) and iodine corrosion. PCMI is the physical exertion of the pellet on the inside surface of the cladding and iodine corrosion is the occurrence when iodine formed from fission reacts with the cladding material and forms compounds that weakens cladding integrity.

2.2 HYDROGEN EMBRITTLEMENT STRAIN FAILURE

Hydrogen embrittlement strain failure (HESF) originates in neutron radiation and hydrogen uptake. The degree of their impact occurs at different time of life for the cladding. Radiation hardening reaches its peak value early and hydrogen embrittlement occurs when enough hydrogen is present that hydride compounds form.

2.3 DELAYED HYDRIDE CRACKING

In delayed hydride cracking (DHC), cracks outside the cladding mantle serve as nucleation points for PCI failure. As time progresses the cracks grow larger and eventually perforation is attained.

There is always some hydrogen dissolved in the cladding and it diffuses towards spots with low temperature, i.e. the outer cladding surface. Small cracks from the manufacturing process serve as nucleation points for hydride compounds. These hydrides have a lower density and thus occupy more space, putting stress on the crack. This failure mode is dominating for high burnup fuel as it takes long time for the hydrogen to concentrate.

This failure mode differs from the preceding significantly, as DHC initiates from the outside. Hence, the liner provides no protection against it.

3 THEORY

3.1 INTRODUCTION

Initially there is a gap between the fuel pellets and the cladding about 75 μm wide. As the fuel is put into operation, being depleted and heated up, it expands, thus decreasing the gap and eventually closing it. The force from the expanding pellet exerts a pressure inside the cladding mantle and can rupture it if the expansion is fast enough. The general phenomenon of fuel interacting with the cladding is called pellet cladding interaction (PCI) and when causing a leak of fission products from a crack, it is called a PCI failure.

There are many factors that affect the risk of PCI failure; temperature and burnup being the ones with the greatest impact. A temperature increase, which is induced by a power ramp

leads to thermal expansion of the fuel pellets. The longer time the fuel is being depleted the more fission products are formed inside the fuel rods. The effect of thermal expansion is instantaneous whereas the effect of burn-up is a much slower process.

Contact between the fuel pellets and the cladding will occur at some point during the lifetime of a fuel rod but even after the gap has closed the stresses are manageable due to the fact that the cladding is not rigid and possesses some ductility. After a power increase the cladding stress increases instantaneously but the elastic nature of the cladding allows it to conform to the larger pellet geometry leading to a reduced level of stress in the cladding as stress equilibrium is being reached. The reduction of stress as time progresses is increased by the liner that acts as support inside the cladding. This phenomenon is called conditioning.

However, when a power reduction is performed, the temperature is decreased and causes the pellet to shrink. The cladding will shrink too but at a slower rate than the pellet thus causing the gap to re-open (assuming the rate of the power reduction is fast enough). The clad stress will instantaneously be reduced and slowly approach a new equilibrium level as the burnup increases. This phenomenon is called deconditioning.

The thermal and burnup effects can be added up, yielding equation 3-1, a simplified model governing the pellet radius:

$$\frac{dr}{dt} = dE \times k_E(t) + \frac{dT}{dt} \times k_T(t) \quad \text{for } t > 0 \quad 3-1$$

where,

k_E = Burnup expansion coefficient
 k_T = Thermal expansion coefficient
 T = Temperature (K)

E = Burnup (MWd/kg U)
 r = Radius (m)
 t =Time (h)

3.1 CURRENT OPERATING RULES

The current regulations to avoid PCI failure can be divided into local rules and global recommendations. The global recommendations concerns core operation and are a transformation of the local rules to reflect the PCI failure mechanisms [2]. Some of them are given below for Westinghouse fuel:

- A conditioning ramp rate, either continuous 0.25 kW/m/h or in equivalent steps of 1.5 kW/m every 6 hours when operating above the PCI threshold. This is a local rule.
- Conditioning should be applied from about 90% core power during first start-up. This is a global recommendation.

3.2 CONDITIONING/DECONDITIONING MODEL

All materials are elastic when put under stress below a material specific level, which means that a deformation is not permanent. To account for this reversibility when speaking of PCI, a suitable conditioning model must be used. The current model used in POLCA7 is based on the old recommendations described above and has been slightly altered in this study.

The relation between the gap closure and the burnup has been established using Westinghouse's fuel performance code STAV7 (version 7.3.3). At a certain burnup of a fuel rod segment, there is an LHGR that closes the gap. This LHGR decreases as time progresses due to the effect of burnup growth. Figure 1 shows this for SVEA64 8x8 and SVEA96 10x10 fuels. The gap closure line can be linearly approximated and is set in the limit editor in CM2 as the PCI threshold. Throughout this report, the gap closure has been set as the PCI threshold in POLCA7. Figure 1 has been made by holding a constant LHGR for a single fuel rod, the burnup that correspond to a closed gap has been recorded and repeated for several different LHGRs.

The other way to generate a gap closure curve is to perform power ramps at different burnup values to see which LHGR steps that close the gap. The gap closure is weakly dependent on the path reaching it but it has been assumed independent in this study. "Path" refers to the order of gap closing operations; it can be

RAMP + WAIT + RAMP → GAP CLOSED
or
WAIT + RAMP + WAIT → GAP CLOSED
or
WAIT + RAMP + RAMP → GAP CLOSED
etc.

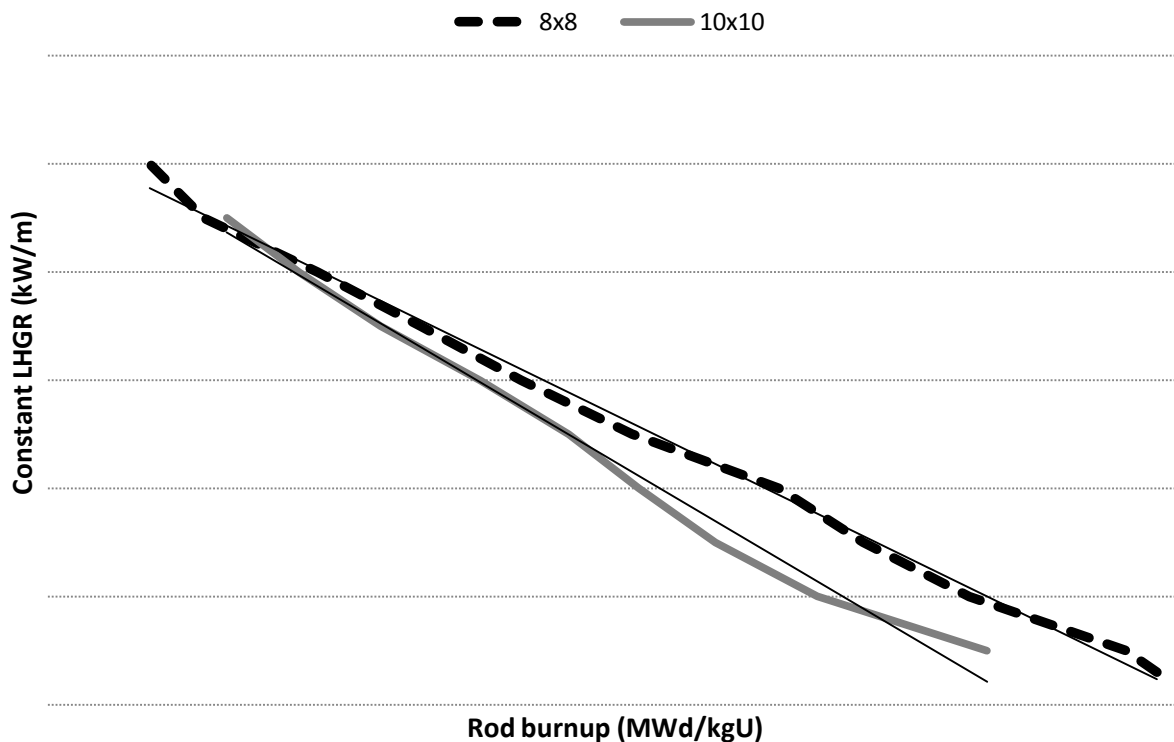


Figure 1. Gap closure for 8x8 and 10x10 Westinghouse liner fuel as a function of burnup.

After the gap has closed, any power step above it conditions the cladding. The current conditioning model used in POLCA7 states that when a power increase is made, the catch-up of the conditioned power (CONDPR) to the new level is linear. However, when viewed on a

mechanistic level, the hoop stress of the cladding decreases exponentially to the new level; according to recent results provided by STAV7 (version 7.3.1) analyses. In this report, this exponential behaviour of the clad stress has been implemented into POLCA7 by allocating an exponential behaviour to the CONDPR.

The linear conditioning model given in equation 3-2 states:

$$\Delta_t = L - C_t = \Delta_0(1 - \lambda_{cond}\Delta t) \quad \text{with} \quad C_t \leq L \quad 3-2$$

where,

Δ_t =Difference at time t

C_t = Conditioned LHGR at time t

Δt = time between step

L =Linear Heat Generation Rate

λ_{cond} = Conditioning rate

Δ_0 =Difference at time 0

It is assumed that the conditioning rate of LHGR should follow with the same exponential shape as the stress would have. Figure 2 shows the two models when an increase in LHGR is made. The rate of increase for the linear model is dependent on a constant, λ_{cond} , and it is unique to the fuel assembly used [3]. The conditioning model used in this study has its time constant taken from Westinghouse study for PCI for PWRs [4]. It should be mentioned that the time-constant, τ , is also dependent on the assembly type and a generic value (140 hours) has been chosen here. The figure shows that if a power step of 20 kW/m is made, the current model would have taken 80 hours to catch-up whereas the proposed model only reaches about 9 kW/m after 80 hours (due to the large time-constant).

The applied conditioning model given in equation 3-3 can now be written as:

$$\Delta_t = L - C_t = \Delta_0(1 - e^{-\Delta t / \tau}) \quad \text{with} \quad C_t \leq L \quad 3-3$$

where,

Δ_t =Difference at time t

C_t = Conditioned LHGR at time t

Δt = Time between step

L = Linear Heat Generation Rate

τ = Conditioning time-constant

Δ_0 =Difference at time 0

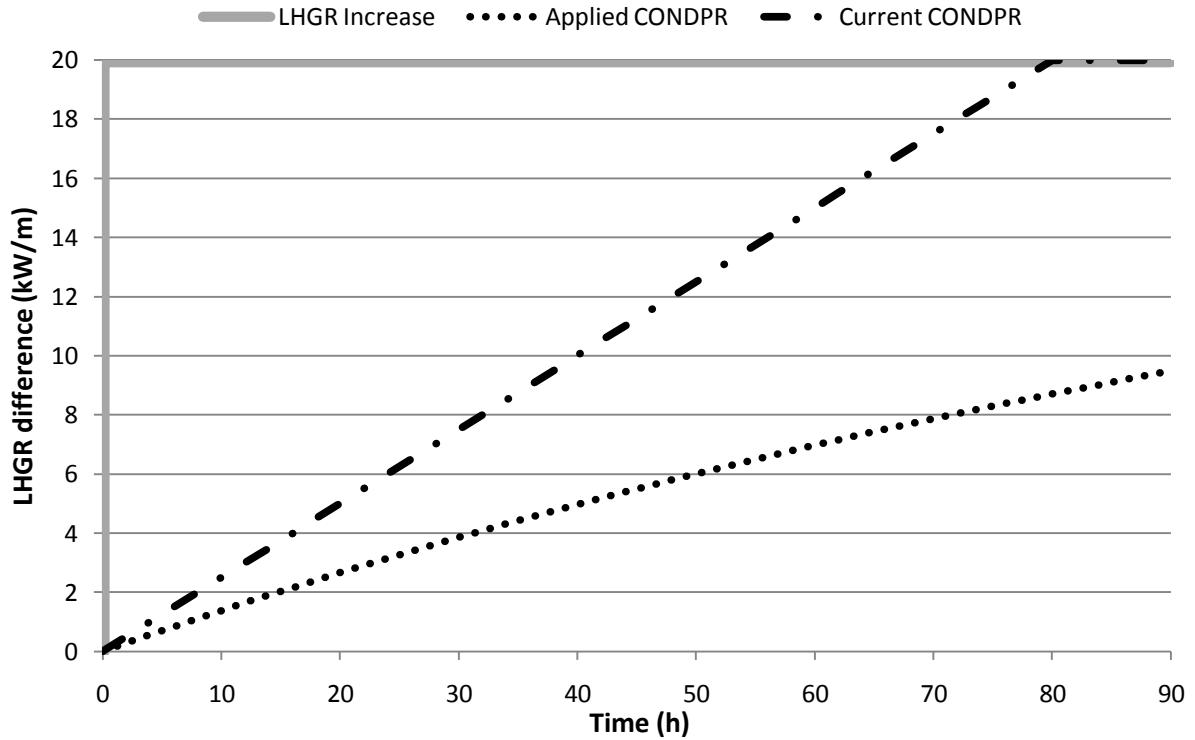


Figure 2. Difference between exponential and linear conditioning model when a LHGR increase of 20 kW/m is made. The time-constant for the conditioning model used here is set to 140 h.

When the LHGR decreases, the cladding stress also decreases. Deconditioning is mainly dependent on burnup rather than on the time. The proposed conditioning/deconditioning model has been employed in a test version of POLCA7 used in this study.

When the LHGR decreases, the cladding stress also decreases. The ability of the cladding to withstand the mechanical interaction of the previous, higher, LHGR level will gradually be lost after LHGR reduction, this process is called deconditioning. Deconditioning is mainly dependent on burnup rather than on time. The proposed conditioning/deconditioning model has been employed in a test version of POLCA7 used in this study. The applied deconditioning constant is set to 3.0 MWd/kgU.

Even though it is not evident that PCI data from a PWR based PCI model can be used for a BWR model, it is a good first approximation and provides a foundation for a new conditioning model that is more concurrent with reality. The main differences between BWRs and PWRs here are the operating pressure and the absence of void in PWRs. The difference of power steps between a PWR and a BWR is also small at large LHGR steps and such power steps are only noticeable when the power is increased with control rods.

4 METHOD

4.1 SOFTWARE

4.1.1 POLCA7

POLCA7 is a 3D core simulator from Westinghouse that models both thermal-hydraulics and neutron kinetics at stationary conditions. It consists of three main parts; an input file describing the simulated model, a processor that carries out the calculations and an output file where the results are printed out. POLCA7 has been used in this report to recalculate process data provided by the utilities. A map showing the calculations and corresponding codes/libraries is found in Appendix A POLCA7 code map. The version used in this study is 4.15.1 with a special PCI module.

4.1.2 CORE MASTER 2

CM2 is a computational supervisory tool that is coupled to POLCA7. It can handle input files and displays the results in text form via its built-in report generator or using the graphical user interface (GUI). Reactor core databases are very large and CM2 allows a quick overview with its OAK core exploring tool. OAK stores the reactor data in cycles. A reactor cycle is the time the reactor is in operation and is often 12 or 24 months. Each cycle is divided into a number of time-steps (typically about ~150 h long). In this study, the time-steps of most interest have been further divided into smaller time steps (~4 h). This division is performed with a script and allows capturing actual LHGR behaviour when control rod withdrawals are performed. The division is of even more interest when analyzing utilities lacking fine motion control rod drive (FMCRD) as large LHGR steps can be encountered.

CM2 has been used extensively in this report to make sure the data computed in POLCA7 are in agreement with the extracted data. It is also used to change input files and limit files. Scripting is performed with a programming language called Tool Command Language (TCL). The CM2 used in this report is a special version named 3.10.0-T3_pci.

4.2 DATA EXTRACTION

With the input processor of POLCA7, the most appropriate distributions were identified and with CoreInt the relevant commands for data extraction were identified [5][6]. The CoreInt is the interface between TCL and the OAK core objects. Core objects are used in CM2 to store distributions, those used as input and those generated by the 3D-simulator POLCA7. The ASYTYP distribution was useful in filtering out the competitor fuel some reactors in this report used. The POLCA7 distributions are summarized in Table 1 followed by an explanation of the variables. Complexity refers to the order of magnitude from largest to smallest (Core> Fuel assembly> Fuel rod> Pin-node> Pellet).

Distribution	Description	Formula	Unit	Complexity
PCILHGR	Contains data on the axial power per unit length	$LHGR = \frac{(1 - \gamma_{tot}) \pi_v h_x^2}{N_f} Q_{rel} \cdot p$	kW/m	Available on pin-node level
CONDPR	Contains data on LHGR history	Details in section 3.2	kW/m	Available on pin-node level
PINBUR PCIPIBU	Contains data on burnup	$\Delta E_n = \frac{l}{m_{fuel}} \int_0^t LHGR dt$	MWd/kg U	Available on pin-node level
ASYTYP	Contains data on fuel assembly model number	Not applicable	String	Available on pin-node level
ASYAGE	Contains data on fuel assembly age	Not applicable	Integer	Available on assembly level
$\Delta LHGR$	Power step or LHGR step	PCILHGR(t)- CONDPR(t)	kW/m	Available on pin-node level

Table 1. Summary of distributions used. PCIPIBU is the same as PINBUR but with data stored in the same order as other PCI distributions.

where,

γ_{tot} = Fraction of fission power dissipating to the coolant through radiation

π_v = Nominal volumetric power density

h_x = Node width

N_f = Number of fuel pins per node

ΔE_n = Burnup

l = Length of active fuel stack

m_{fuel} = Mass uranium

Q_{rel} = Relative core power

p = Relative pin stub power

t = Time

4.3 SCRIPTS USED

A brief description of the applied programs will follow together with a pictorial illustration of the algorithm. The codes are found in Appendix C.

4.3.1 Description of core scanner and output files

Using CoreInt, a script has been written that extracts the data stored in CM2. Each core from OAK is opened, read from and closed. The data is acquired at POLCA7s' smallest computational level, i.e. a pin-node. The script is named core scanner since it scans the core, pin by pin. No discrimination is made of the pin constituents, everything is extracted, i.e. water channels and empty pins. This scanning is repeated until the script reaches the end of a reactor cycle. As the distributions are collected, four output ASCII files are generated that are

described below. The only thing required by the user is to set the OAK path, start/end core and a suitable label for the output files.

A power step is defined as the difference between PCILHGR and CONDPR. The script is written in TCL programming language.

4.3.1.1 Pinlhgr-max.txt

The maximum power step over each pin node is collected and stored in a text-file called pinlhgr. As the power step is taken it stores them in an imaginary core for each core that has been scanned. The end result is a condensed core where each pin-node only has one data point with all distributions, i.e. first the power step is taken then the rest of the distributions of that step are saved. The order of the burnup steps is not important since the core scanner script has a condition that compares the sizes of the power steps before it is collected. An example of how the algorithm works is shown below:

Imagine a two-dimensional core viewed from the top having a total of 24 fuel assemblies in symmetric geometry. To simplify, only a few cores of small dimension are demonstrated, and the example shows the algorithm on a fuel assembly level. An image showing this configuration is Figure 3.

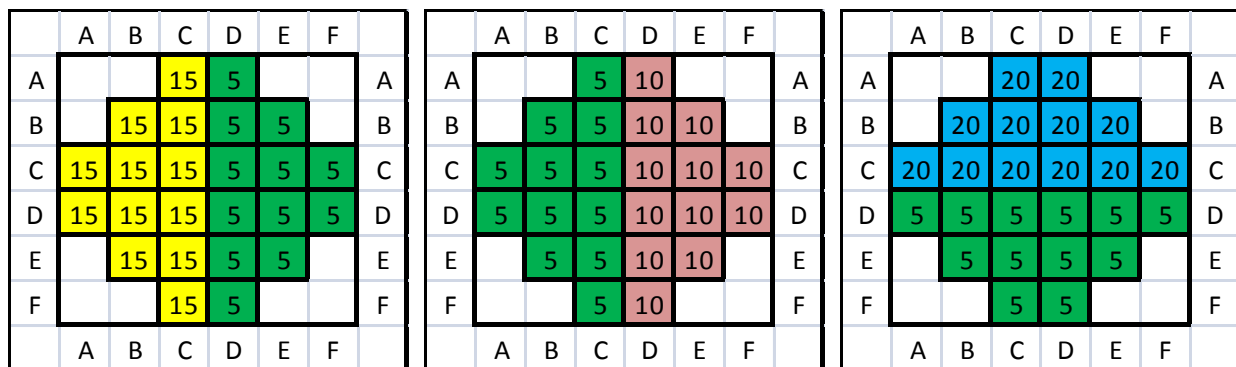


Figure 3. Sequence of burnup steps (units in kW/m).

The result is shown in Figure 4 when the conditions have been fulfilled:

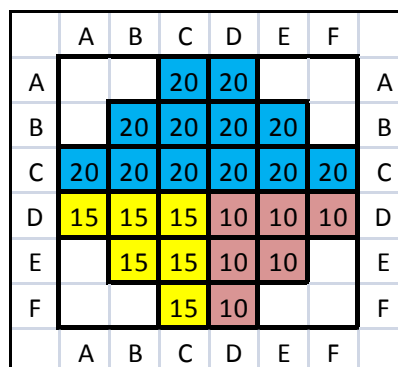


Figure 4. Graphic end result of the core scanning script, a condensed core. Units in kW/m.

The higher power steps “replace” the ones in the upper half of the core from the previous cores since they are the ones that are of interest and can cause PCI failure. Note that none of the low power steps came with the condensed core.

The actual data in CM2 adds more complexity than what the example above describes. The number of cores is larger, is performed in three dimensions and for pin-nodes within fuel assemblies. The total number of compared pin-nodes is in the range of 1-1.7 million.

4.3.1.2 Steps-max.txt

Here, all power steps for each core are stored along with pin coordinates, time in cycle and other distributions leading to a very large file as a pin node in the same location can be saved several times.

4.3.1.3 Histogram.txt

This file contains the number of pin-nodes that has experienced a power step within a specified interval. The user chooses bin size, start LHGR step and end LHGR step.

4.3.1.4 LHGR-max.txt

This file is the same as pinlhgr-max.txt with the exception that the maximum PCILHGR for the cycle is stored and not the step.

4.3.2 Burnup plotter

It is desirable to see at what stage of the fuel segments life a power step has been made and a script has been written that simplifies this task. The script begins with reading from the pinlhgr-max.txt file and assigns the distributions as vectors for easier handling. This script is written in Matlab.

4.3.3 Splitting of ramp segments

In Westinghouse’s extensive ramp test database, eight cases were found for 10x10 fuels, of which six of them had sufficient data for use in this script. The ramp test data in its current form are given as input files for STAV7. Since the number of ramp test nodes is not equivalent to number of pellets inside a fuel segment, the pellet positions must be calculated using their geometrical information from the ramp test database. This splitting is undertaken in order to make the statistical inclusion of ramp data mathematically and physically correct, more information about this can be found in Section 6.2.

The script begins with reading an Excel file containing all the experiments, one sheet at a time. The length of the ramp segment is divided by the fuel pellet height to get the number of pellets and the number is rounded up since the ramp experiments are not performed using partial pellets. To ease calculations, each pellet is assumed to have a uniform power profile within the pellet. In mathematical terms, the power profile for a pellet is applied to a point and this point is situated in the middle. This midpoint is interpolated using two points from the input file for STAV 7, one point below the pellet and one above it.

Figure 5 shows an example of the axial power profile from the ramp splitter as a stem/leaf-plot. Star markers are positions of the input points and circular markers are the positions of the pellets.

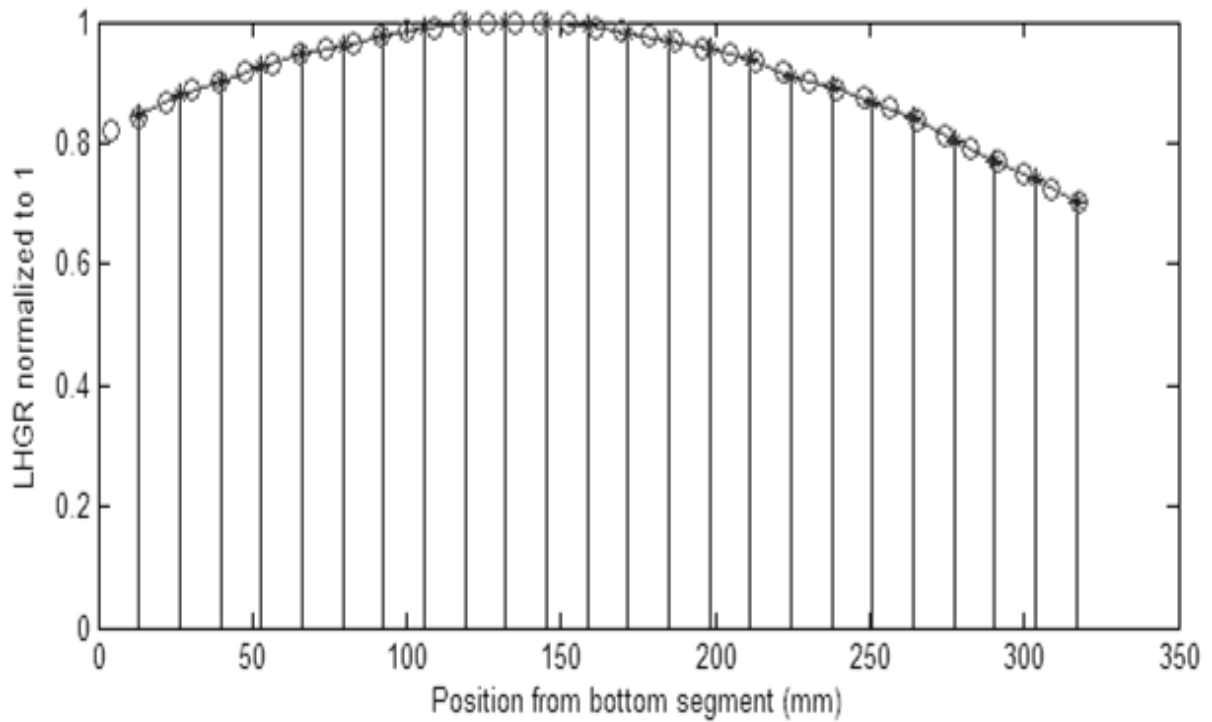


Figure 5. Example of a ramp test power profile, EXP2677 refers to the experiment ID-number. Note the extrapolated pellet in the beginning of the profile.

5 RESULTS

5.1 EXPERIENCE FROM STANDARD OPERATION

To comprehend the vast amount of data generated by the scripts described in the previous section, a series of plots has been made that reflects the fuel behaviour as a function of some parameters. Table 2 is a summary of the reactors analyzed.

Reactor	Manufacturer	Highest LHGR step (kW/m)	Power (MW _e)
X-1	ASEA-Atom	10.7	<1000
Y-1	General Electric	10.1	<1000
Z-1	General Electric	14.2	<1000
X-2	General Electric	15.3	>1000
Y-2	ASEA-Atom	15.7	>1000
Z-2	ASEA-Atom	14.1	<1000

Table 2. Summary of reactors analyzed and their fundamental properties. The manufacturer column refers to the fabricator of the NSSS not the fuel.

When plotting the power step against burnup in Figure 6, one can see when the power steps were made, the magnitude and start/end points. Each step is unique and can be identified by its coordinates, as the bottom corresponds to the CONDPR distribution and the top corresponds to the PCILHGR distribution. The PCIIBU/PINBUR distribution is used to

connect all the distributions. As an example, the data for Z-1 is shown in Figure 6 together with several lines. A brief description of them is given below:

Blue line: Gap closure curve. Below this line the gap is still open and the steps appearing here are of no interest for this study. Its derivation is described in Section 3.2.

Green line: This is the old PCI threshold curve for SVEA-96 Optima2. It has been calculated using STAV7 (version 7.3.3). It is power steps made above this line that must be limited according to the local rules (as described in the first bullet in Section 3.1). However, in this report, the PCI threshold in POLCA7 is enforced after the gap has closed.

Pink dashed line: TMOL curve for SVEA-96 Optima2. When designing a new core prior to refuelling, power utilities normally impose an additional design margin. This design margin varies from a few percent up to about 15%. This line can be interpreted as a never-to-exceed limit.

The large number of power steps makes it impossible to distinguish them visually in the plot but can be easily found using the Matlab script. None of the power steps were above the TMOL curve and this can be seen in the figure as all the power steps are below it.

The plot is generated by using the pinlhgr-max.txt output file from the core scanner.

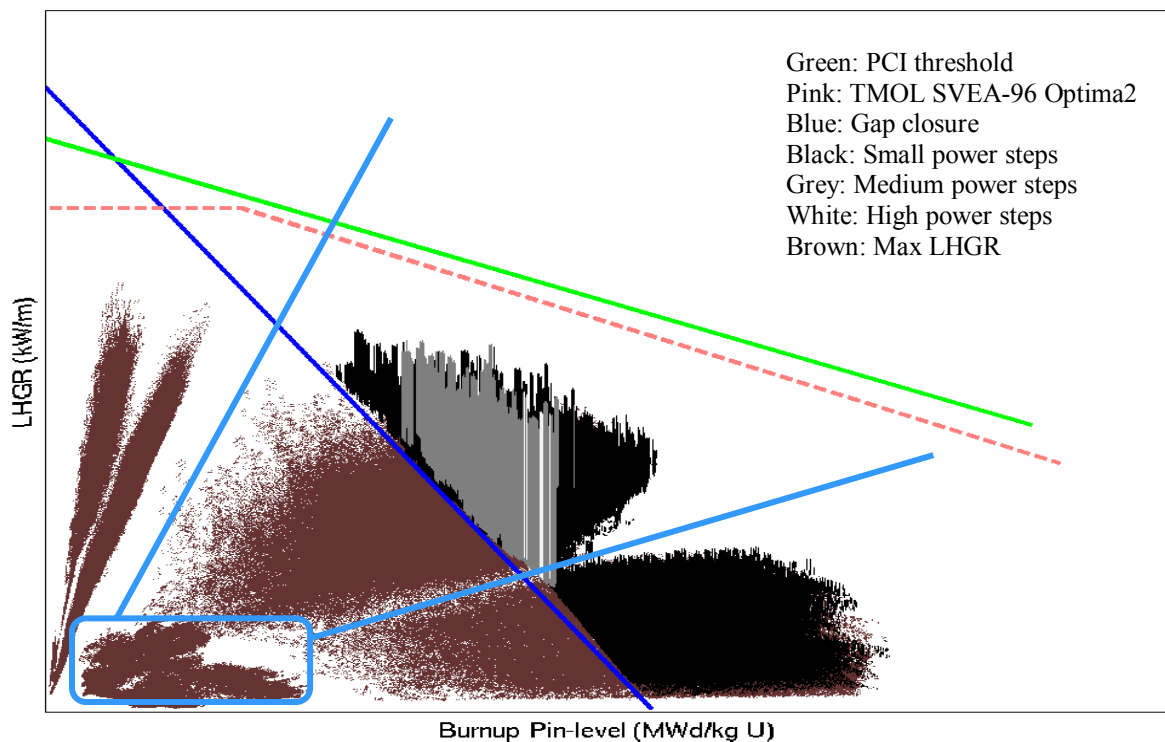


Figure 6. Maximum LHGR and maximum LHGR steps for each pin node collected for Z-1. Rays from origin separate fuel generations and the area inside the rectangle represents the fuel blanket region.

The plot is interesting as the power steps first appear at a burnup of 20 MWd/kg U and not earlier. The reason for this can be explained by looking at the PCILHGR distribution that has the highest LHGR. Here, they appear as brown dots forming a “cloud” by using the LHGR-

max.txt output file from the core scanning script. By plotting it, the complete historical operating region of a reactor can be established.

For clarity, rays from origin and a rectangle have been added in Figure 6. Beginning from the left, the first fuel region can be seen when only PCILHGR is added because the power steps lie below the gap closure curve thus not appearing. This region corresponds to fresh fuel. The lack of power steps is expected in this area since the threshold for collecting power steps was set to the gap closure. The second fuel region is situated between the two rays but outside the rectangle in the figure. Most of the registered power steps are found here as the gap has closed and the location of the fuel assemblies are in the centre of the core so relatively high power steps should be expected. This corresponds to fuel that is one cycle old. The third fuel region lies below the second region and the power steps are small since it is general practice to move high-depleted fuel to the rim of the core to act as a mantle. The different fuel regions were identified using the ASYAGE distribution applied on a pin level.

The area inside the rectangle comprises the blanket regions which are the nodes in the top and bottom section of the core that have a lower enrichment of ^{235}U . Since Z-1 uses 24 month cycles, the separation of the fuel regions is clear.

When applying this method to all analyzed reactors and combining them to one plot, Figure 7 shows the result. This figure is similar to Figure 6.

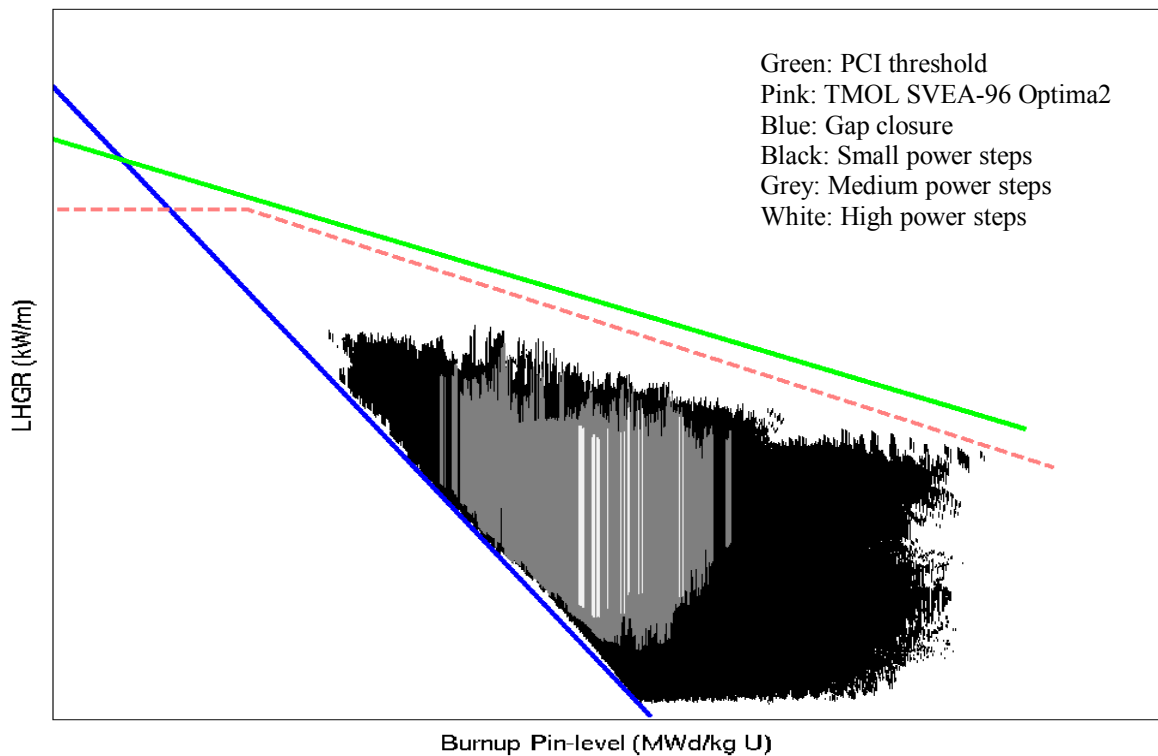


Figure 7. Maximum LHGR steps for each pin node collected for all of the analyzed plants.

Considering the core scanner script described in Section 4.3.1, it only saves the maximum power step for each node and stores them in an imaginary core. This means that if a power step early in the cycle (i.e. low burnup) for a specific pin-node is recorded and then has a

higher power step later in the cycle, then the value of the previous step is discarded and replaced by the new one.

One could dispute whether to use the steps-max.txt output file from the core scanner that records all power steps for all time-steps but the amount of data is many times larger and the software capabilities today prevents the use of it.

Another reason why no steps were encountered at low burnup lies in the definition of a power step which was PCILHGR subtracted by CONDPR; if PCILHGR lies below the gap closure curve, this would correspond to a negative power step. A negative power step has no impact on the risk of PCI failure since this means that the gap is still open and has room for the pellet to expand further.

Large power steps are not encountered even though the PCILHGR distribution lies closer to TMOL at BOC and not closer to the gap closure; the explanation for that is found in the abbreviation of LHGR; linear HEAT generation rate. High LHGR is synonymous with high temperature and uranium dioxide has a low thermal conductivity. The gap itself is filled with helium gas with an even lower thermal conductivity relative to uranium dioxide.

This causes the overall heat transfer to be low and if one would attempt to compensate for the heat loss when the gap is present with a high LHGR; there is a risk fission gases will be released when the very hot pellet makes contact with the relatively cool cladding and melting it. Another reason is the fact that the gap closure was calculated recently and the operating rules were not drafted with it at that time.

5.2 EXPERIENCE FROM RAMP EXPERIMENTS

A ramp test is a destructive testing method with the purpose of assessing the material and operational limits for nuclear fuel. A typical test is preceded by irradiating a fresh fuel assembly in a commercial power reactor for a few cycles. Then, a rod segment is taken from the fuel assembly and inserted in a test reactor where it is pre-conditioned for 10-12 hours.

The experiment begins by rapidly increasing the power (ramping) in increments with a holding time between each ramp until the final LHGR level is reached. The controlled environment given by the research reactor and higher neutron flux allows the rod segments to reach higher power levels than a regular power reactor would provide. After the ramp test, regardless of the result of it, a thorough examination of the segment is undertaken.

The identified ramp experiments performed for Westinghouse 10x10 liner fuel together with some relevant data are summarized in Table 3. The availability of a power profile allows for more data in the statistical analysis. For more information about the ramp experiments, the interested reader is referred to [7][8][9][10].

Studsvik experiment ID	Peak LHGR (kW/m)	Outcome of experiment	Available power profile?
2380	39.5 (45)	Rod failed	No
2685	41	Rod survived	Yes
2653	42	Rod survived	No
2679	45	Rod survived	Yes
2678	52	Rod survived	Yes
2677	42.5 (52)	Rod failed	Yes
2667	56.7	Rod survived	Yes
2671	57.7	Rod survived	Yes

Table 3. Ramp experiments for Westinghouse 10x10 liner fuel. Values in parentheses designate original target for LHGR peak.

The whole experimental procedure is exemplified in Figure 8. This type of ramp test is of stair-case model, the LHGR is increased in step increments with a holding time between. CONDPR in this experiment was 12 kW/m and the LHGR at the end of the experiment is 42.5 kW/m. This gives a maximum LHGR step of 30.5 kW/m.

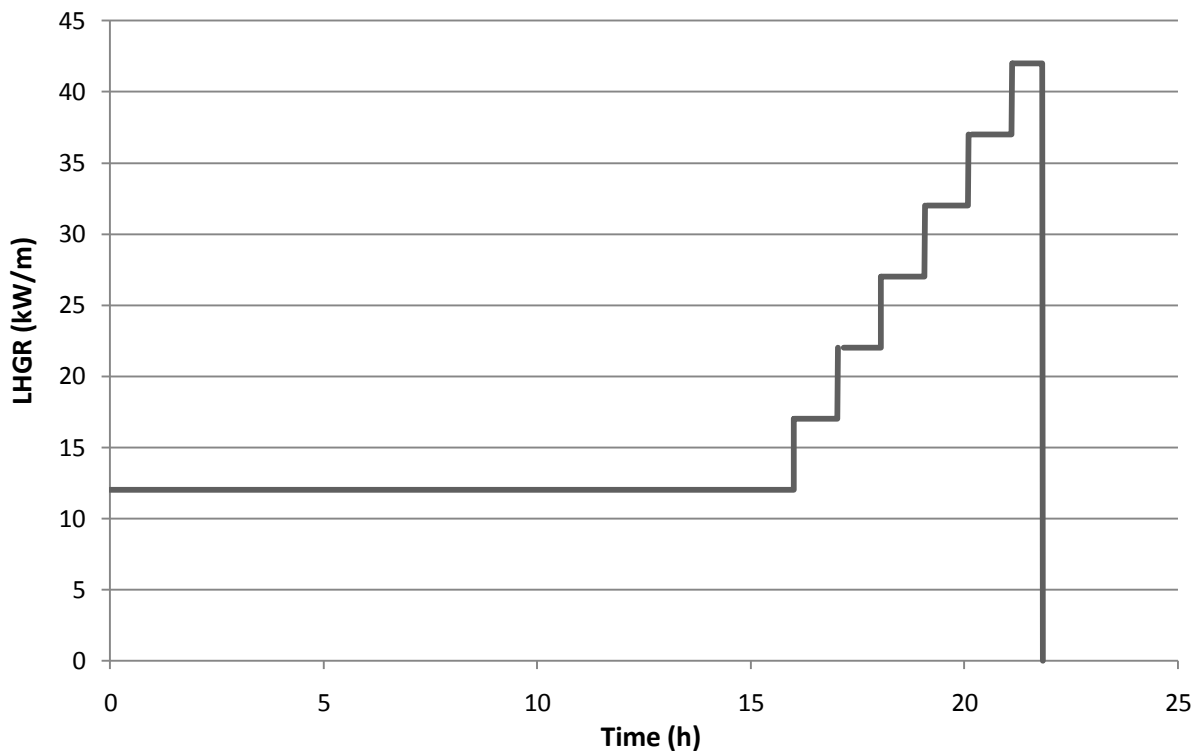


Figure 8. LHGR level as function of time for ramp experiment EXP2677. Note the relatively long pre-conditioning before the experiment starts.

Ramp tests are time consuming and expensive, part of it due to the extensive procedure of the post-experiment analysis with highly active material. They are typically performed on a few rod segments that have a length of about 1/10th compared to a full length rod. The reactor used for the Westinghouse ramp tests analyzed here is the R2 research reactor (decommissioned 2005) at the Studsvik site.

In Figure 9, the LHGR steps of the analyzed ramp tests are plotted in analogy with Figure 6. The ramp experiments where the rods survived are represented by light-blue vertical lines and the rods that cracked by red vertical lines. The starting point of the ramp is the conditioned power level and the end point is the peak LHGR. Hence, the difference gives the size of the step. The segment average burnup has been used which is the burnup of the section used in the ramp test (slightly higher than the rod average burnup).

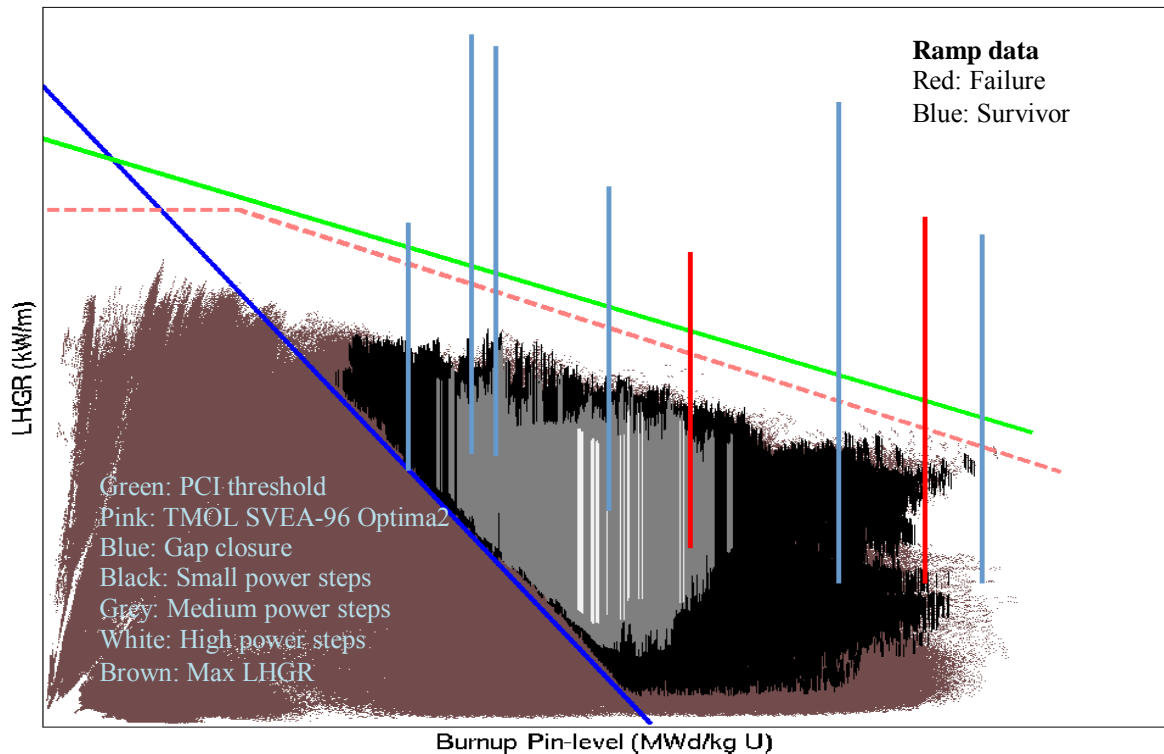


Figure 9. Maximum LHGR and LHGR steps from both the commercial operation and the power ramp tests.

5.3 COMPARISON WITH CURRENT RULES

Of the rules mentioned in Section 3.1, the most important is the first one regulating the rate of power increase above the PCI threshold. This rule has been enforced and it can be seen in two ways. When the online version of POLCA7 is run at a nuclear power plant, a PCI-tracking is performed that discovers if violations to this or any other rule is made. The distribution in POLCA7 is called PCIVOL but since this is based on power steps exceeding 1.5 kW/m, the distribution has been of little interest. The other way is to observe the power steps in Figure 7; if they appear above the TMOL curve, a violation has occurred.

6 STATISTICAL ASSESSMENT

6.1 REGISTERED DATA

Figure 10 shows the distribution of LHGR steps ordered into “bins” that covers the whole spectrum of power steps experienced in standard operation. The reason for this is explained in section 6.2. The level of detail is equivalent to the bin size which has been set to 0.1 kW/m. X-1 data are not included in the plot since the fuel analyzed was the older SVEA 64 8x8 with liner, and as a consequence the X-1 data have also been removed in the statistical analysis.

The interested reader is referred to Appendix B for the individual treatment of X-1. This exclusion is necessary to be consistent with the other reactors that use the more modern 10x10 fuel with liner. The highest power step from a power reactor came from Y-2 and was 15.7 kW/m.

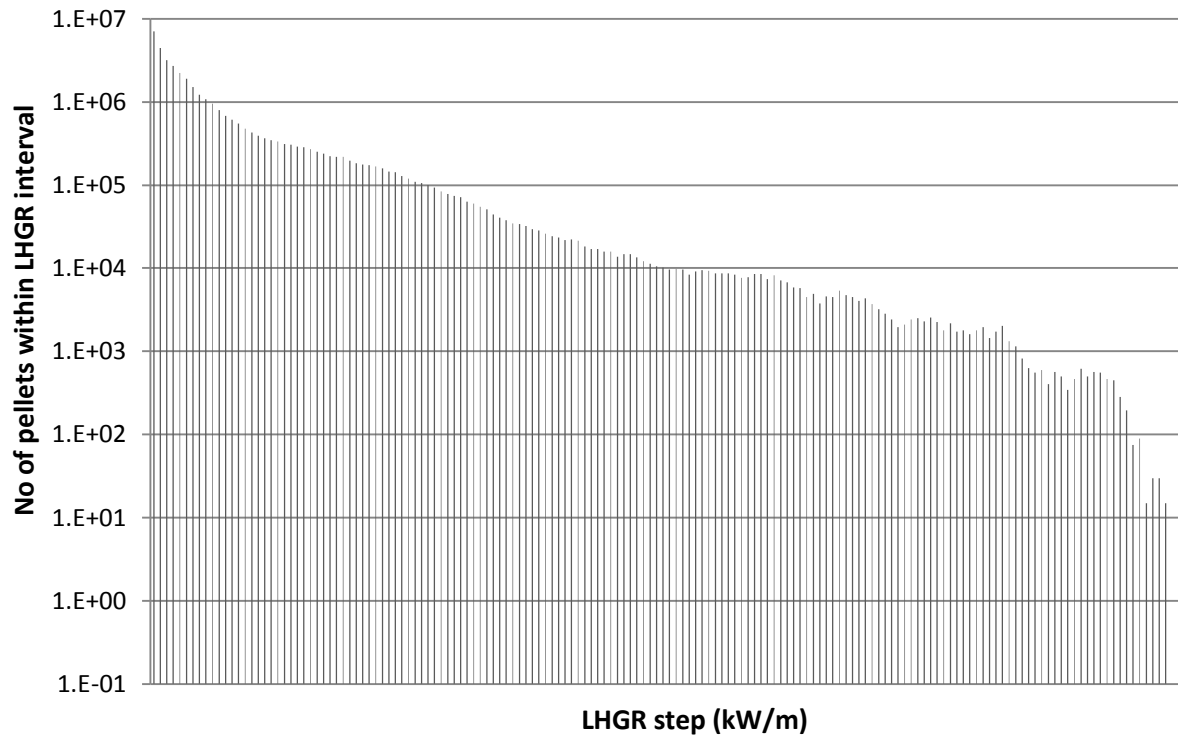


Figure 10. Number of pellets exposed to LHGR steps divided into small intervals registered for all of the analyzed reactors (note the logarithmic vertical axis).

The distributions including also the ramp experiments are shown in Figure 11. The highest registered power step was 40 kW/m for a ramp test.

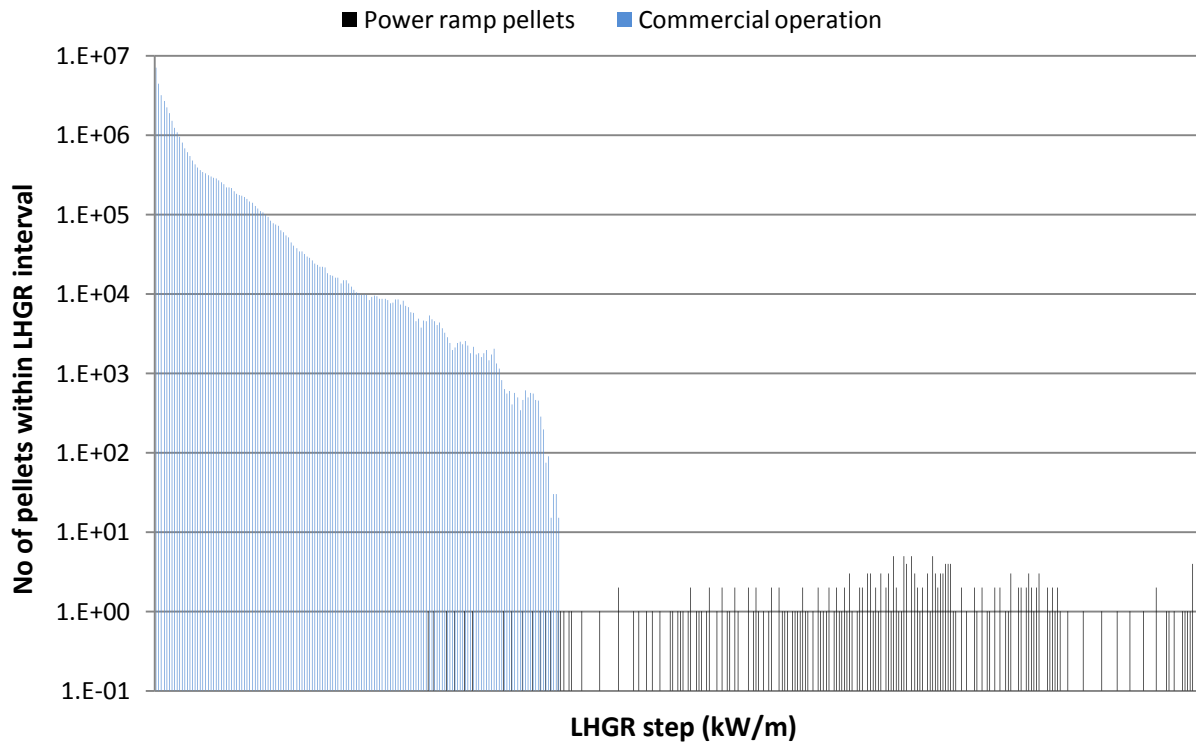


Figure 11. Number of pellets exposed to LHGR steps divided into small intervals registered for both the commercial operation and the power ramp tests (note the logarithmic vertical axis).

6.2 METHODOLOGY

In order to predict the probability of PCI failure as a function of LHGR step (above conditioned level), a relation must be established. When the fuel rod experiences a power increase during normal operation, one of two possible outcomes may occur. Either the rod survives or it cracks. The events are mutually exclusive meaning that the set of possible outcomes are only two and they can't be simultaneous. An event in this context is defined as *an increase in LHGR*. A statistical model suitable for these types of calculation is the binomial distribution, as it fulfils the required conditions above set for an event. Within a specified LHGR interval, there are a number of pellets that have experienced a particular LHGR. The difficulty lies in forecasting the LHGR that leads to PCI failure since there are no cases of PCI failure from liner fuel manufactured by Westinghouse. Nevertheless, a significance level has been applied, here denoted by α . The significance level is a measure of how much the results are affected by randomness. The end result is a probability that will *not* lead to a PCI failure.

In order to perform the statistical analysis, an extension of the binomial distribution has been selected: the Clopper-Pearson method [11]. It has the following useful properties such as:

- Valid for small samples
- Valid for non-failure cases

Despite the useful characteristics of the Clopper-Pearson method, some assumptions have been made prior to its implementation. For instance, the missing pellet surface (MPS), a manufacturing flaw, is not taken into account when calculating the probabilities (it is assumed to be included since no failures have been found). The second assumption is that every LHGR bin contains a number of pellets experiences and they are independent of each other (adjacent pellets in a fuel rod have no impact on one another).

The third assumption is that the individual pellet axial levels of a fuel rod can be treated separately. This is based on the assumption that a PCI failure is induced by one single pellet and, hence, all the other pellet segments of the fuel rod have actually survived. This assumption is true in particular if the PCI failure has been induced by an MPS. The validity of this assumption is at present not obvious.

For the non-failed cases, the Clopper-Pearson formula in equation 6-1 is simplified to:

$$P_{nf} = \alpha^{1/k} \quad 6-1$$

where,

P_{nf} = Probability of no failure k = number of pellets within a LHGR bin
 α = Significance level

When the failed cases are included on the other hand, the complete Clopper-Pearson formula given in equation 6-2 and 6-3 is written as:

$$\text{Lower } P_{nf} = B\left(\frac{\alpha}{2}, x, k - x + 1\right) \quad (\text{Pnf equals 0 if } x = 0 \text{ i.e. no intact clad segments}) \quad 6-2$$

$$\text{Upper } P_{nf} = B\left(1 - \frac{\alpha}{2}, x + 1, k - x\right) \quad (\text{Pnf equals 1 if } k = x \text{ i.e. no failed clad segments}) \quad 6-3$$

where,

B = Inverted Beta distribution P_{nf} = Probability of no failure
 k = total number of clad segments within a Δ LHGR bin α = Significance level
 x = number of intact clad segments within a Δ LHGR bin

In this study, the significance level in all figures has been set to 5%.

The practical implementation of the inverted beta distribution is performed in Excel using the statistical function BETAINV [12]. Figure 12 shows a probability chart for all reactor data, including from ramp tests. Two data series can be seen: “Individual” is calculated by treating the number of pellets within the bins individually, this gives the scattered graph.

“Cumulative” is calculated by a right-hand summation of the pellets within the bins. As an example, at a power step of 20 kW/m, all the affected pellets above this level are accumulated. This is performed to reflect the fact that a pellet having survived a certain power step has also survived the lower levels. This relation can be further expressed as $P_{nf, \text{High}} < P_{nf, \text{Low}}$.

Low.

As long as there are no or only a few failures (i.e. the data set contains only survivors), this is a conservative approach not assessing the actual probability of a failure or a non-failure. The derived probability of a non-failure is directly dependent only on the number of collected events and will in principle be continuously increasing as long as more data are collected (assuming no failures appear). In order to assess the actual probability with some confidence, a significant number of failure events need to be collected and included in the data set (to be applied with the complete Clopper Pearson equation).

For the power ramp tests of the Westinghouse 10x10 liner fuel, two of them had cracks at about 25 kW/m and 30 kW/m. In analogy with how the non-failures were accumulated for lower power steps, the failures have been accumulated for higher power steps. Hence, assuming a failure at a certain LHGR step, it is implied that this would have been a failure also for all LHGR steps higher than this. In this case, this means that all LHGR steps above the first failure has a failure count of one and all LHGR steps above the second failure has a failure count of two. This assumption is valid as the number of PCI failures keep increasing until a certain power step where all rods fail.

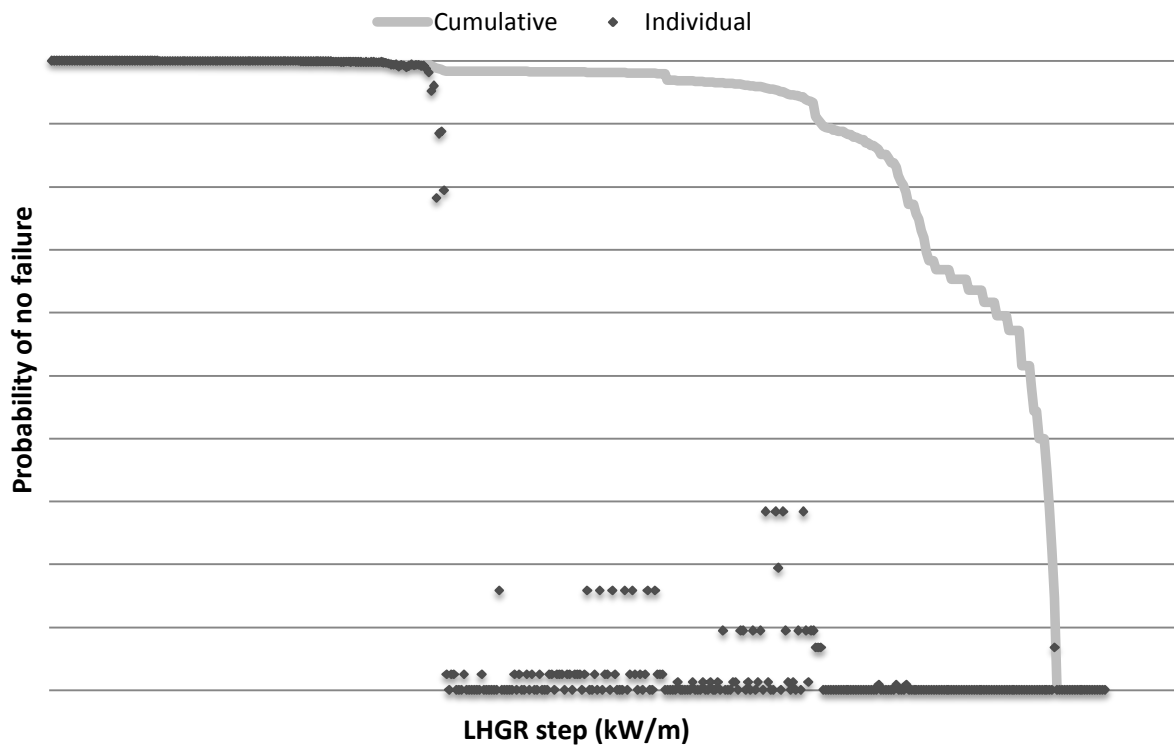


Figure 12. Probability of no PCI failure as a function of LHGR step, including data from both commercial operation and power ramp tests. The dots represent the probability for each individual LHGR step bin whereas the black line represents the accumulated probability.

6.3 FITTING OF A NORMAL DISTRIBUTION

The shape of the probability curve in Figure 12 exhibits a non-realistic behavior and the sharp reduction in number of pellets in Figure 11 that starts at about 15 kW/m implies that the curve should have a different shape to better reflect the reality. Any distribution of a random variable assumes the shape of a Gaussian curve if the number of samples is high and one attempt to capture it would be to fit a cumulative normal distribution curve to the derived

data. In Figure 13, the normal distribution fitted to the accumulated probabilities derived directly from the collected operation experience data is given.

The fitting was performed using the Excel statistical function NORMDIST to acquire the cumulative normal distribution. The area generated between the two curves was minimized by varying the mean and the standard deviation using maximum likelihood estimation (MLE). The mean and standard deviation obtained from this minimization were 37.12 and 3.71 respectively. The fitted normal distribution lies above the calculated probability for all points in the interval 0-32 kW/m.

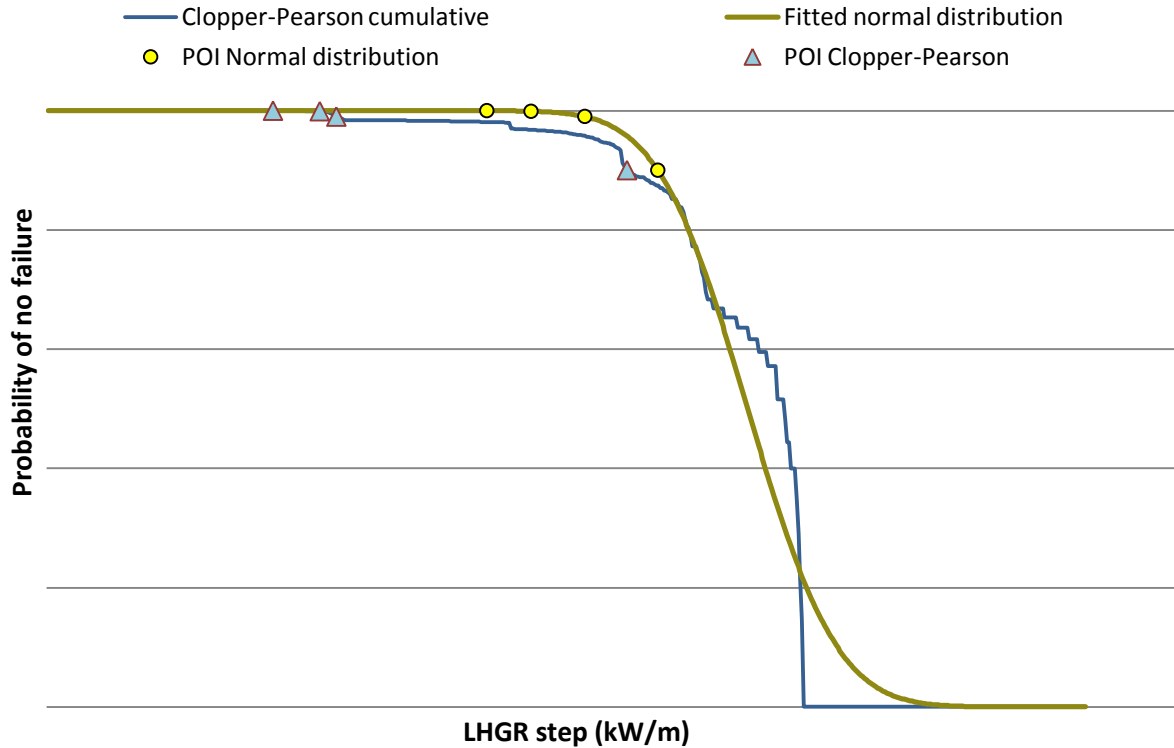


Figure 13. Probability of no PCI failure as a function of LHGR step, derived directly from past operation experience (using the Clopper-Pearson formula) as well as from a normal distribution fitted that data. The LHGR steps corresponding to some different probabilities are also plotted.

In Table 4, the LHGR step corresponding to some different probabilities are listed, both for the probability curve derived directly from past operation experience (using the Clopper-Pearson formula) and for the fitted normal distribution. It should be noted that the respective LHGR steps are much higher for high probabilities (~99% and above) whereas they are relatively similar for lower probabilities.

As an example for clarification of what the probabilities derived in this study really means, certain values of the significance level (e.g. $\alpha=5\%$) and the probability of no failure (e.g. 99%) are assumed. Then, according to the fitted normal distribution as listed in Table 4, it can be stated that there is a 95% ($1-\alpha$) probability that an LHGR step of 28.5 kW/m has a 99% chance of not failing.

Probability of no failure	LHGR step (kW/m)	
	Calculated with Clopper-Pearson	Fitted normal distribution
99.99%	12.0	23.3
99.9%	14.5	25.6
99%	15.3	28.5
90%	30.7	32.4

Table 4. LHGR step corresponding to some different probabilities of no PCI failure, derived directly from past operation experience (using the Clopper-Pearson formula) as well as from the normal distribution fitted to that data.

7 CONCLUSION

Data from past operation experience, both from commercial operation and from power ramp tests, have been collected and analyzed, in order to evaluate the probability of PCI failures. The parameters that have been analyzed are the maximum LHGR and LHGR steps for each pin node during a cycle or during a power ramp test. This information has then been graphically presented together with some operating restrictions (the TMOL curve and the old PCI threshold curve). It can be concluded from this that the old PCI threshold was never exceeded during those cycles analyzed within this study.

Thereafter, the collected power steps have been evaluated statistically, by assessing the probability of no failures as function of LHGR step, assuming that the outcome of a power step (either failure or no failure) can be represented by a binomial distribution and applying the Clopper-Pearson method. In order to better represent the true behavior of the PCI failure probability, a normal distribution has in the final step been fitted to the data.

It should be noted that assuming that the PCI failure probability is only dependent on the magnitude of the LHGR step is a relatively rough approximation. In reality, there are some effects that also need to be taken into account in order to better represent the true behavior, such as the dependency on the burnup level at which the power step is taken and the starting level of the power step. Furthermore, the effect of the possibility of pellet and cladding defects is neither treated in this analysis.

8 REFERENCES

- [1] Bolander, M. (2012) *Nuclear Fuel Pellet Cladding Interaction Failure Modeling*. Uppsala Sweden: Uppsala University (M.Sc thesis from the faculty of Science and Technology)
- [2] Westinghouse Electric Sweden report (redacted title)
- [3] Westinghouse Electric Sweden report (redacted title)
- [4] Beard, C.L. et. al. (2011) *Development of Westinghouse PCI Model and Evaluation of PCI Aspects of the AP1000® Plant Under MSHIM Core Control Strategy*. USA (NRFE-10-129, rev 0)
- [5] Lindahl, S-Ö. (2013) *POLIN - Input processor of POLCA7*. Västerås Sweden. (BR 95-924, rev 33)
- [6] Pedemonte, E. (2013) *Core Master 2 – CoreInt, Programmer's Guide*. Västerås Sweden. (BCM 98-121, rev 6)
- [7] Engman, Ulf et. al. (2005) *Power ramp test of SCIP rod KKL-2*. Studsvik Sweden. (N-05/134)
- [8] Engman, Ulf. (2003). *Power ramp test of two rods with advanced pellets from Barsebäck 2*. Studsvik Sweden. (N(R)-03/037)
- [9] Karlsson, J.K.H. (2007). *B64, Special cold ramp test of rod 2653*. Studsvik Sweden. (N-05/174)
- [10] Engman, Ulf. (2004). *Power ramp test of a BWR-Westinghouse rod from KKL*. Studsvik Sweden. (N-04/105)
- [11] Webb, D.B. (2011) *A Comparison of Various Methods Used to Determine the Sample Size Requirements for Meeting a 90/90 Reliability Specification*. Maryland USA. (ARL-TR-5468).
- [12] Medical Device and Diagnostic Industry (MDDI). *New Interval Offers Confidence—Without Limits*. <http://www.mddionline.com/article/new-interval-offers-confidence-without-limits> [2013-08-21]



Report

[REDACTED]

Appendix A Page 1 of 1

APPENDIX A POLCA7 CODE MAP

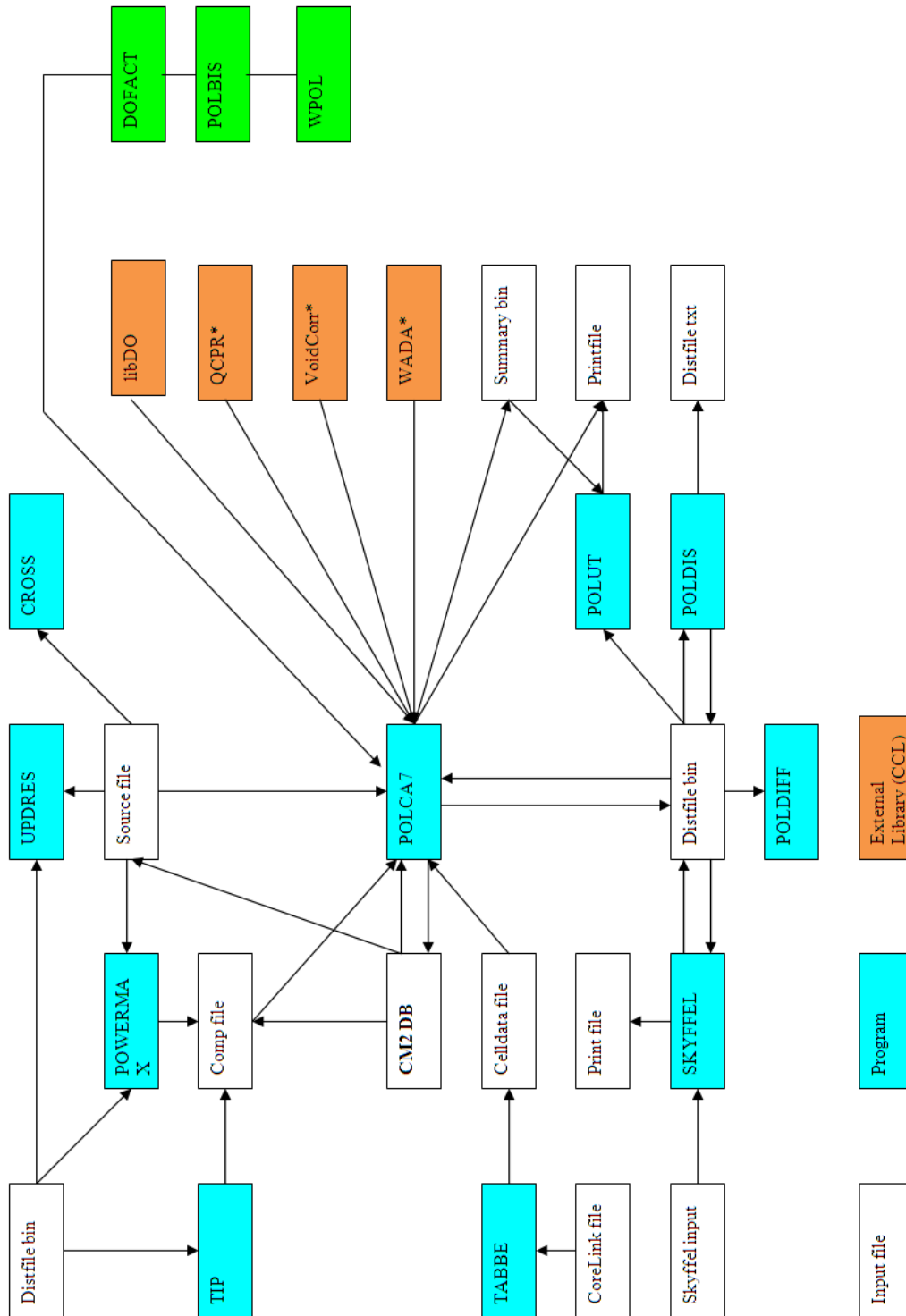


Figure 14. POLCA7 code map



Report

[REDACTED]

Appendix B Page 1 of 6

APPENDIX B BURNUP DEPENDENCE PLOTS FOR ALL REACTORS

In this section the burnup dependence plots for all reactors are individually displayed. One plot for each reactor ordered in low, medium and high in step size depending on colour. Due to ecological concerns the figures in this appendix has been printed in greyscale. The legend however is the same as in Figure 6.

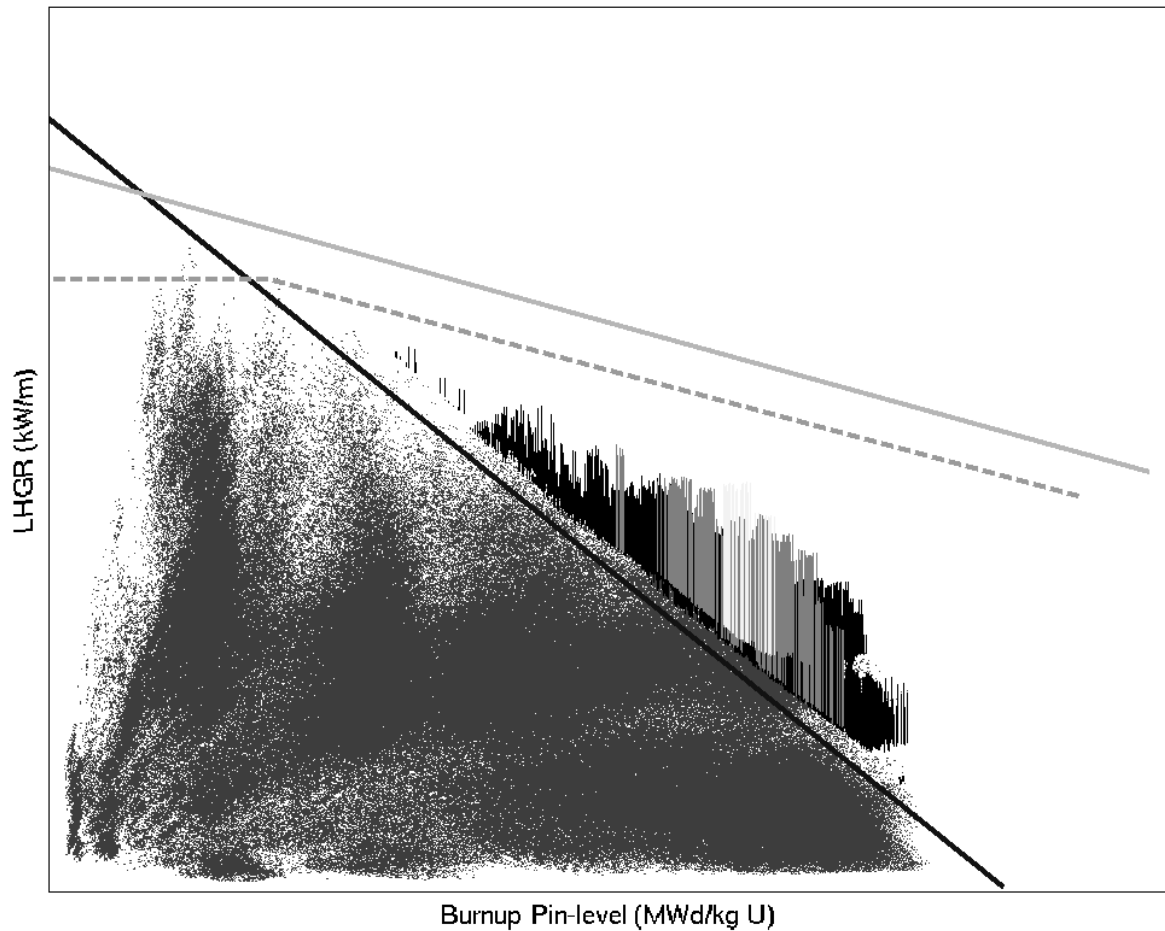


Figure 15. Maximum LHGR and maximum LHGR steps for each pin node collected for X-1

**Report**

[REDACTED]

Appendix B Page 2 of 6

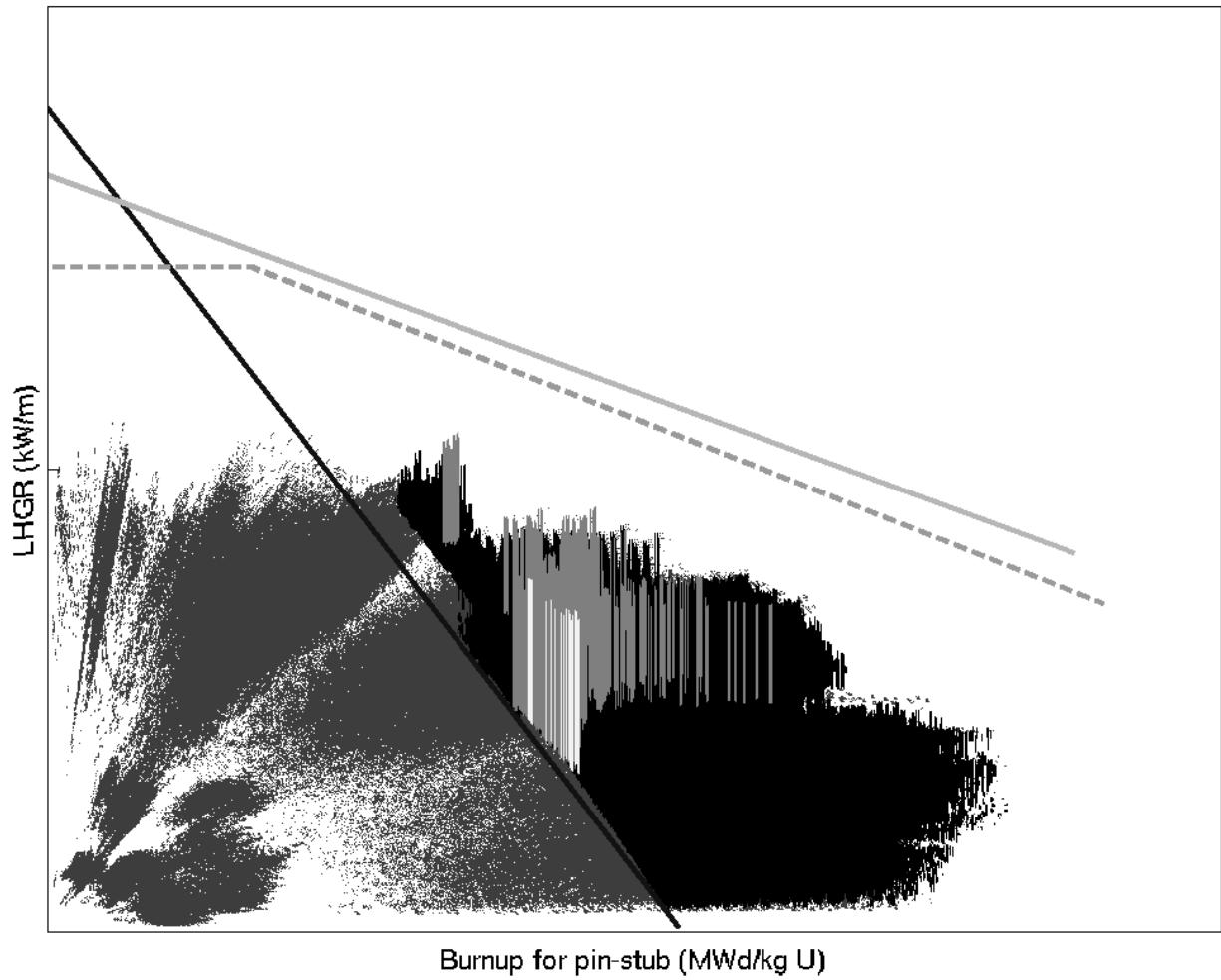


Figure 16. Maximum LHGR and maximum LHGR steps for each pin node collected for Y-1



Report

[REDACTED]

Appendix B Page 3 of 6

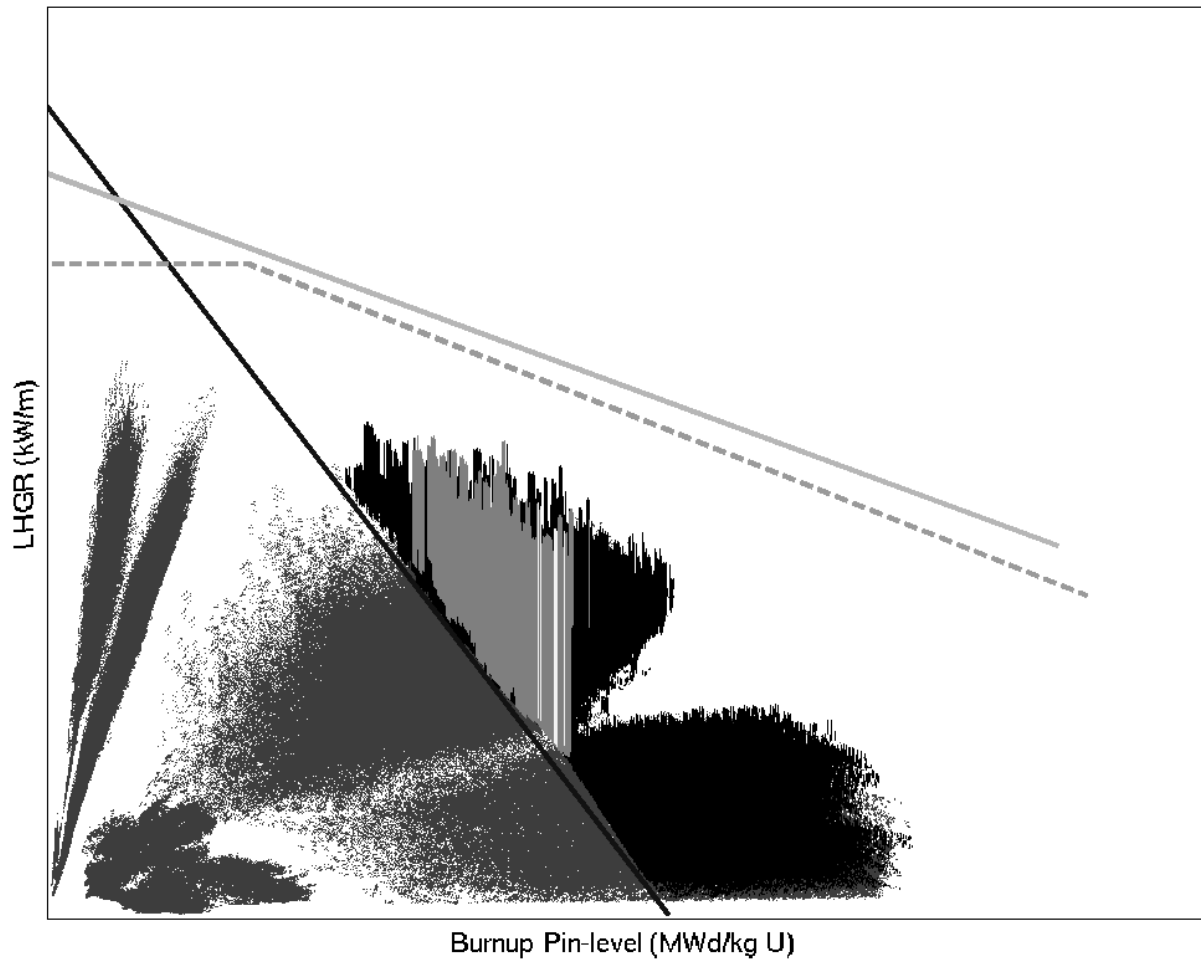


Figure 17. Maximum LHGR and maximum LHGR steps for each pin node collected for Z-1



Report

[REDACTED]

Appendix B Page 4 of 6

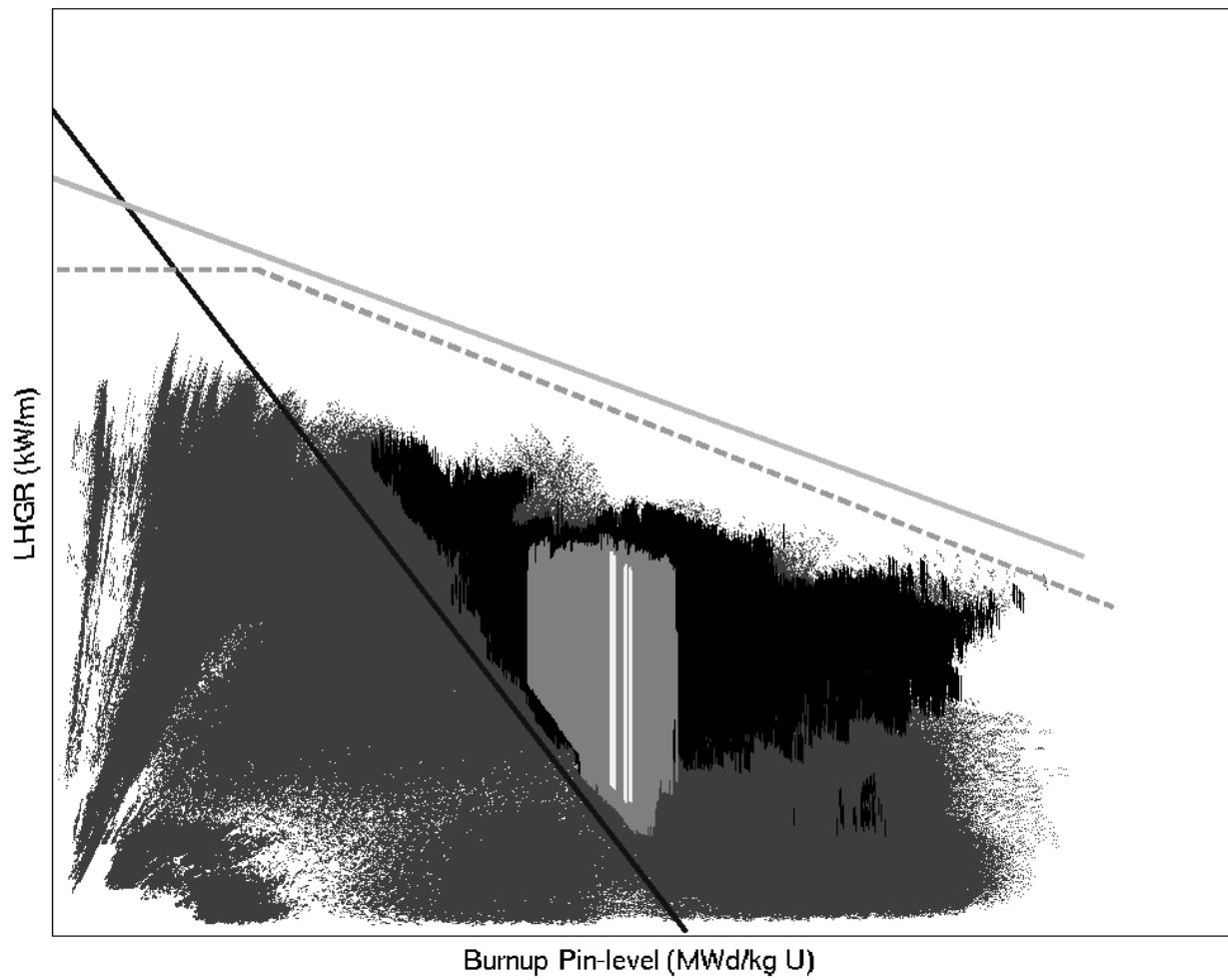


Figure 18. Maximum LHGR and maximum LHGR steps for each pin node collected for X-2.



Report

[REDACTED]

Appendix B Page 5 of 6

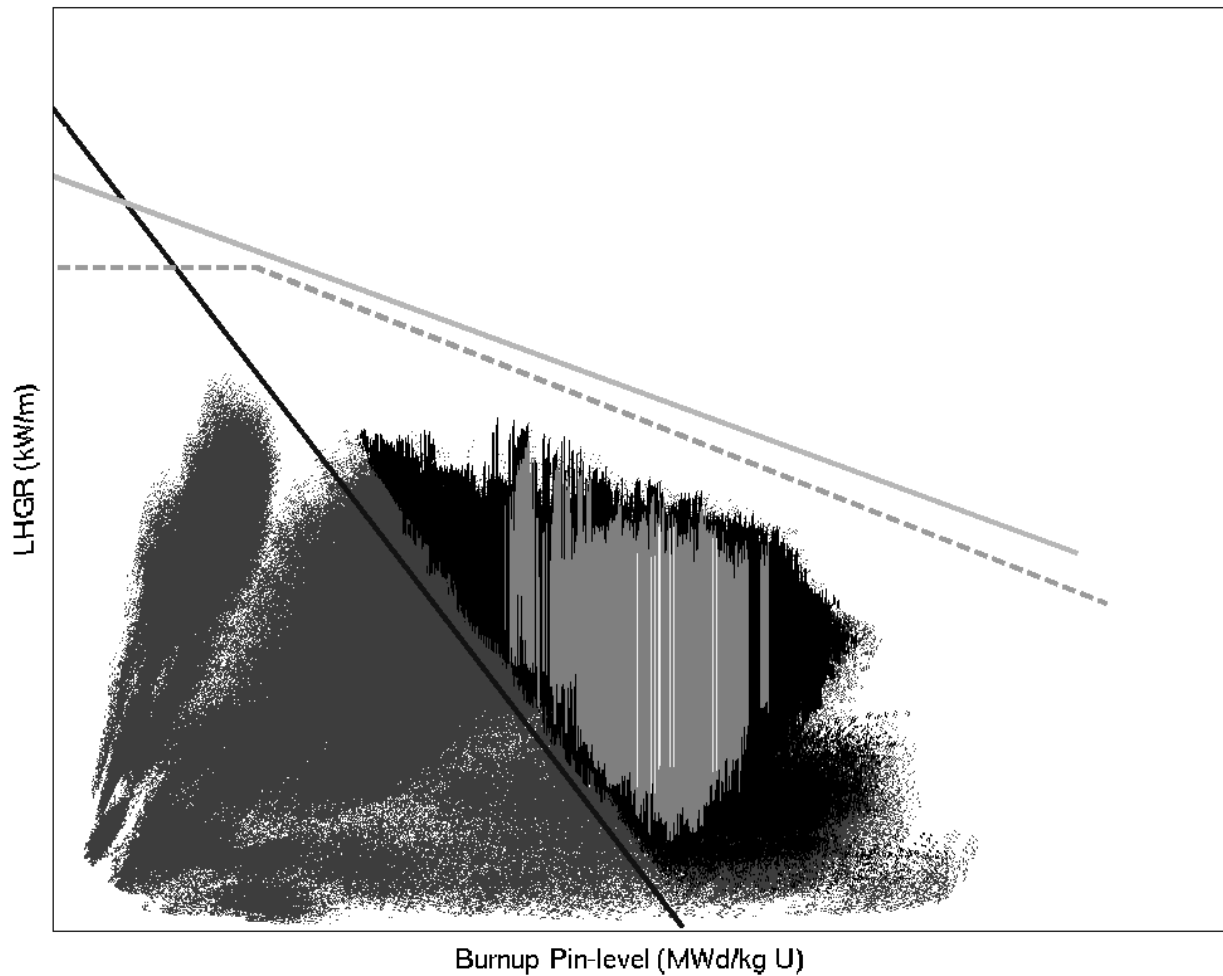


Figure 19. Maximum LHGR and maximum LHGR steps for each pin node collected for Y-₂

**Report**

[REDACTED]

Appendix B Page 6 of 6

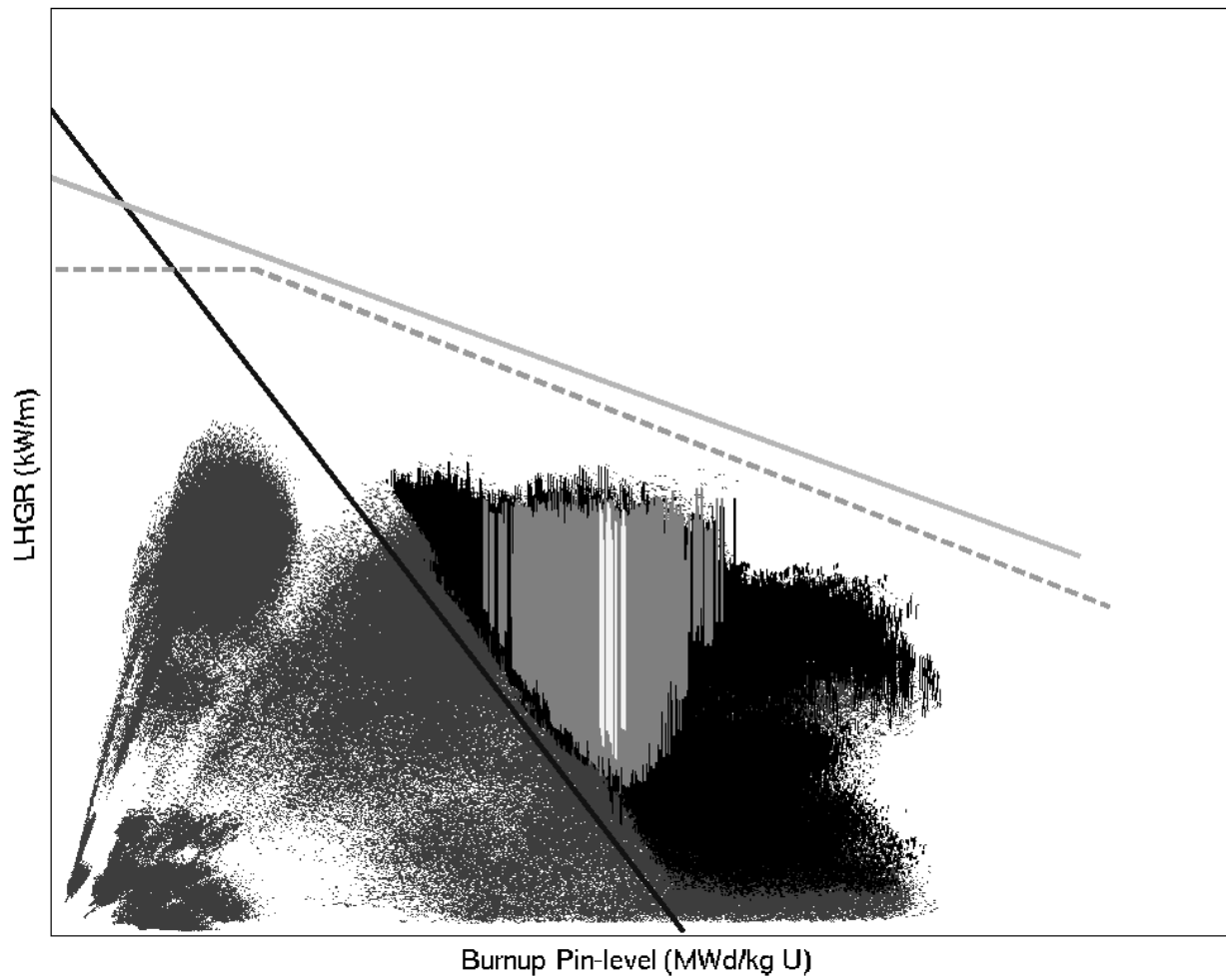


Figure 20. Maximum LHGR and maximum LHGR steps for each pin node collected for Z-2

**Report**

[REDACTED]

Appendix C Page 1 of 13

APPENDIX C SCRIPTS USED**Core scanner input code**

```
#!/bin/sh
SPATH=burnup_stat_Swed.tcl

echo Processing distr @Reactor

#Input timestep start and end
FIRST=19
LAST=138

#Input filters
STEPFILT=0
HIGHFILT=0

UTFIL=PINLHGR-max.txt
echo "Database:" $DBNAME > $UTFIL

STEPFIL=steps-max.txt
HISTFIL=histogram.txt

#Database path
CPATH=/ (REACTOR NAME) : (CYCLE ID) : (FORCE START)

echo $CPATH
cm2 bgint -v 3.10.0-T3_pci $SPATH $CPATH PCILHGR MAXPRINT $STEPFIL $FIRST
$LAST $HISTFIL $STEPFILT $HIGHFILT>>$UTFIL

echo ----- >>
$UTFIL
```

**Report**

[REDACTED]

Appendix C Page 2 of 13

Core scanner processor code

```

# histogram
#   Return histogram information from a list of numbers
#
# Arguments:
#   limits   Upper limits for the buckets (in increasing order)
#   values   List of values to be examined
#
# Results:
#   List of number of values in each bucket (length is one more than
#   the number of limits)
#
#
proc histogram {limits values} {

    if { [llength $limits] < 1 } {
        return -code error -errorcode ARG -errorinfo {No limits given} {No
limits given}
    }

    set limits [lsort -real -increasing $limits]

    for { set index 0 } { $index <= [llength $limits] } { incr index } {
        set buckets($index) 0
    }
    set last [llength $limits]

    foreach value $values {
        if { $value == {} } {
            continue
        }

        set index 0
        set found 0
        foreach limit $limits {
            if { $value <= $limit } {
                set found 1
                incr buckets($index)
                break
            }
            incr index
        }

        if { $found == 0 } {
            incr buckets($last)
        }
    }

    set result {}
    for { set index 0 } { $index <= $last } { incr index } {
        lappend result $buckets($index)
    }

    return $result
}

```

```

    }

# ----- end proc

set cpath [lindex $argv 0]
set distname [lindex $argv 1]
set pflag [lindex $argv 2]
set stepfil [lindex $argv 3]
set first [lindex $argv 4]
set last [lindex $argv 5]

set histogram [lindex $argv 6]
set stepfilt [lindex $argv 7]
set highfilt [lindex $argv 8]

set start 0
set terminate "end"

if {$stepfilt != ""} {set stepfilt 0}
if {$highfilt != ""} {set highfilt 0}

if {$first != ""} {set start $first}
if {$last != ""} {set terminate $last}

set xmax 0
set ymax 0
set imax 0
set jmax 0
set corecount 0

set mod ""
set modtyp ""
set symmetry "full"

puts "stepfil= $stepfil"
set sfil [open $stepfil w]

set dbid [oak open]
set cycle_id [Cycle open $cpath]

set branch [Cycle branch $cycle_id]
puts "Data from branch, [lindex $branch 0]"
set ncore [llength $branch]
puts "ncore=,$ncore"
puts "maxstep      COLUMN      ROW  PC,PR  NODE      Delta   (kW/m) "

foreach core [lrange $branch $start $terminate] {
set shortcore [oak compresspath $dbid $core]

set core_id [Core open $core]
set corecount [expr $corecount+1]
set maxstep -100000
set xmax 0
set ymax 0
set imax 0
set jmax 0

```

**Report**

[REDACTED]

Appendix C Page 4 of 13

```

set coregeom [Core geometry $score_id -symmetry $symmetry]

set index1 [lindex $coregeom 4]
llength $coregeom
set nrow [lindex $coregeom 2]

for {set m 0} {$m<$nrow} {incr m} {

    set sindex [lindex [lindex $index1 $m] 0]
    set s2index [lindex [lindex $index1 $m] 1]

    for {set kh $sindex} {$kh <= $s2index} {incr kh} {

        set raden [expr $m+1]

        set x [expr $m+1]
        set y $kh
        #-----
        -----

        set okflag [Core pindist $score_id $distname $x $y distarr $modtyp
$mod]

        set okflag [Core pindist $score_id CONDPR $x $y condarr $modtyp $mod]

        set okflag [Core pindist $score_id PCIPIBU $x $y burnarr $modtyp $mod]

        set okflag [Core dist $score_id ASYTYP $symmetry -varname gearr]

        set okflag [Core dist $score_id ASYAGE $symmetry -varname agearr]

        #set okflag [Core value $score_id ASYID $x $y gearr $modtyp $mod]

        set nmax [array size distarr]
        set arrindx [array names distarr]
        set assembly [array names gearr]
        set assemblage [array names agearr]

        #-----
        -----

        foreach i [lsort -dictionary $arrindx] {

            set arrrad $distarr($i)
            set conrad $condarr($i)
            set pinburn $burnarr($i)

            set irad [llength $arrrad]

            for {set j 0} {$j < $irad} {incr j 1} {

                set step [expr [lindex $arrrad $j]-[lindex $conrad $j] ]
                set max_cond [lindex $conrad $j]
                set max_lhgr [lindex $arrrad $j]

```

**Report**

[REDACTED]

Appendix C Page 5 of 13

```

set pinb [lindex $pinburn $j]

#find max step for each specific core
if {$step>$maxstep} {
set maxmaxcore $shortcore
set maxstep $step
set xmax $x
set ymax $y
set imax $i
set jmax $j
}

# Find max step in each pin-node for all cores in branch (first time pick
all values then for case 2 and onwards change if step is larger)
if {$corecount==1} {
set maxs($x,$y,$i,$j) $step
set maxscond($x,$y,$i,$j) $max_cond
set maxslhgr($x,$y,$i,$j) $max_lhgr
set maxsburn($x,$y,$i,$j) $pinb
set whatasy($x,$y,$i,$j) $gearr($x,$y)
set whatage($x,$y,$i,$j) $agearr($x,$y)
set maxcore($x,$y,$i,$j) $shortcore
set xmaxall($x,$y,$i,$j) $x
set ymaxall($x,$y,$i,$j) $y
set imaxall($x,$y,$i,$j) $i
set jmaxall($x,$y,$i,$j) $j
} else {
if {$step>$maxs($x,$y,$i,$j)} {
set maxs($x,$y,$i,$j) $step
set maxscond($x,$y,$i,$j) $max_cond
set maxslhgr($x,$y,$i,$j) $max_lhgr
set maxsburn($x,$y,$i,$j) $pinb
set whatasy($x,$y,$i,$j) $gearr($x,$y)
set whatage($x,$y,$i,$j) $agearr($x,$y)
set maxcore($x,$y,$i,$j) $shortcore
set xmaxall($x,$y,$i,$j) $x
set ymaxall($x,$y,$i,$j) $y
set imaxall($x,$y,$i,$j) $i
set jmaxall($x,$y,$i,$j) $j
}
}

if {$pflag=="FULLPRINT"} { puts "$x $y $i $j [lindex $arrrrad $j]
[lindex $conrad $j] $step $pinb"
if {$step>$stepfilt && [lindex $arrrrad $j]>$highfilt} {
puts $sfil "filtsteps $x $y $i $j [lindex $arrrrad
$j] [lindex $conrad $j] $step $pinb"
}
}
}
}

```

**Report**

[REDACTED]

Appendix C Page 6 of 13

```

puts "maxstep $maxmaxcore, $whatasy($xmax,$ymax,$imax,$jmax),
Cycle$whatage($xmax,$ymax,$imax,$jmax),      $xmax,      $ymax,      $imax,
$jmax,      $maxstep"
#set GZ [expr ($maxsburn($x,$y,$i,$j))*XX+XX]

    Core close $score_id
}

    puts "\nMaxsteps over all cores for each pin-node"
    puts "Time,          AGE, COL, ROW,  PC,PR   NODE,      LHGR,      CONDPR,
        DELTA,          BURNUP"
    for {set m 0} {$m<($nrow)} {incr m} {
        set sindex [lindex [lindex $index1 $m] 0]
        set s2index [lindex [lindex $index1 $m] 1]

        for {set kh $sindex} {$kh <= $s2index} {incr kh} {
            set x [expr $m+1]
            set y $kh
            foreach i [lsort -dictionary $arrindx] {
                set arrrad $distarr($i)
                set irad [llength $arrrad]
                for {set j 0} {$j < $irad} {incr j 1} {
                    lappend steplist $maxs($x,$y,$i,$j)
                    $maxslhgr($x,$y,$i,$j), $maxscond($x,$y,$i,$j),
$maxs($x,$y,$i,$j), $maxsburn($x,$y,$i,$j)"
                    if {$pflag == "MAXPRINT"} {puts "$maxcore($x,$y,$i,$j),      $x,
$y,  $i,      $j,      $maxslhgr($x,$y,$i,$j), $maxscond($x,$y,$i,$j),
$maxs($x,$y,$i,$j), $maxsburn($x,$y,$i,$j)" }
                }
            }
        }
    }

    set limmit 0
    set dlim 0.1
    set nbin XX
    for {set k 1} {$k<=$nbin} {incr k} {
        set limmit [expr $limmit+$dlim]
        lappend hlimits $limmit
    }

    set histogrammet [histogram $hlimits $steplist ]
    histogram $hlimits $steplist
    set histfil [open $histogram w]
    puts $histfil "binlimits= $hlimits"
    puts $histfil "histogram= $histogrammet"
    #puts $histfil "Asytyp= $assembly"

    puts "Write ok"
    close $histfil
    close $sfil
    Cycle close $cycle_id
    oak close $dbid

```

**Report**

[REDACTED]

Appendix C Page 7 of 13

Core scanner sample output

Maxsteps over all cores for each pin-node

Time,	COL,	ROW,	PC,PR	NODE,	LHGR,	CONDPR,	DELTA,	BURNUP
/Z-2:c29:4226, 10.654865			1,	11, 1,1,	0,	0.538757,	40.460487,	-39.92173,
/Z-2:c29:4226, 28.759645			1,	11, 1,1,	1,	1.160179,	18.251234,	-17.091055,
/Z-2:c29:4226, 37.336033			1,	11, 1,1,	2,	1.319107,	7.727972,	-6.408865,
/Z-2:c29:4226, 41.372841			1,	11, 1,1,	3,	1.405241,	2.774529,	-1.369288,
/Z-2:c29:3051, 43.231255			1,	11, 1,1,	4,	1.453583,	1.430466,	0.023117,
/Z-2:c29:3051, 43.544292			1,	11, 1,1,	5,	1.543423,	1.525135,	0.018288,
/Z-2:c29:3051, 44.019966			1,	11, 1,1,	6,	1.655393,	1.643553,	0.01184,
/Z-2:c29:3219, 44.361553			1,	11, 1,1,	7,	1.772415,	1.766735,	0.00568,
/Z-2:c29:3386, 44.103355			1,	11, 1,1,	8,	1.879621,	1.879079,	0.000542,
/Z-2:c29:3554, 44.558773			1,	11, 1,1,	9,	2.003755,	2.015560,	-0.011805,

**Report**

[REDACTED]

Appendix C Page 8 of 13

Burnup plotter code

```

clc

clear all
tic

load 'STORERAMP_F.mat'
%-----
Steplimit=XX
%-----
%Stepmax=XX

%for Steplimit=Steplimit:1:Stepmax
%-----
tic
X0=0;
Y0=XX;
X1=XXX
Y1=XX;
SlopeXX;

load 'PINBURN.mat'

n_ok=1;
n_bad=1;

whatindex=find(Steplimit>=PINBURN(:,8));
PINBURN(whatindex,:)=[];

SPINBURN=sortrows(PINBURN,8);
COL=SPINBURN(:,1);
ROW=SPINBURN(:,2);
PINCOL=SPINBURN(:,3);
PINROW=SPINBURN(:,4);
NODE=SPINBURN(:,5);
LHGR=SPINBURN(:,6);
CONDPR=SPINBURN(:,7);
DELTA=SPINBURN(:,8);
BURNUP=SPINBURN(:,9);
GZ=SPINBURN(:,9)*Slope+Y0;

s=length(LHGR)
%clear PINBURN

whitebg([0.85 0.85 0.85]);

% JUSTLHGRX-2=plot(MAXLHGRX-2(:,2),MAXLHGRX-2(:,1));
% set(JUSTLHGRX-2,'color',[0.45 0.3 0.3],'linestyle','.', 'markersize',1);
% hold on

%line below for gap closure (blue)
hb=plot([X0, X1],[Y0 , Y1]);
set(hb,'linewidth',2)
hold on

```

**Report**

[REDACTED]

Appendix C Page 9 of 13

```

%Line below for OLD PCI Threshold (green)
threshold=plot([X, XX],[XX,XX],'color',[0 1 0])
set(threshold,'linewidth',2)
hold on

%---TMOL Curve (pink)-----
TMOL1=plot([X, XX, XX],[XX, XX, XX]);
set(TMOL1,'color',[1 0.5 0.5],'linestyle','--','linewidth',2);
hold on

%-----
hold on

%Loop below for all the "good values"
%-----

for k=1:s;
    if LHGR(k)>=GZ(k);

        OK=plot([BURNUP(k), BURNUP(k)], [CONDPR(k), LHGR(k)]);
        set(OK,'color',[0.0 0.0 0.0],'linestyle','-');
        %set(OK,'color',[1 1 1].*(Steplimit/Stepmax),'linestyle','-
        ', 'linewidth',2);
        hold on

        %Show_ok=[LHGR(k) GZ(k) LHGR(k)-GZ(k) BURNUP(k)];
        %Store_ok(n_ok,:)=Show_ok;
        count_ok=n_ok;
        n_ok=n_ok+1;
        end

        hold on

        k=k+1;
    end
    hold on
    %-----
    %Loop below for all the "bad values"

    for r=1:s;

        if LHGR(r)<GZ(r);
            hold on

            %Show_bad=[COL(r) ROW(r) PINCOL(r) PINROW(r) NODE(r) LHGR(r)
            GZ(r) LHGR(r)-GZ(r) BURNUP(r) CONDPR(r)];
            %Store_bad(n_bad,:)=Show_bad;
            count_bad=n_bad;
            n_bad=n_bad+1;
            BAD=plot([BURNUP(r), BURNUP(r)], [CONDPR(r), LHGR(r)], 'r');
            hold on

```

**Report**

[REDACTED]

Appendix C Page 10 of 13

```

        % (Show_bad(1,4), Show_bad(1,5), 'y');
        %hold on
        end

        r=r+1;
    end

    %---Plot the yellow boundary lines (upper and lower included)-----
    %plot([BURNUP(1),Store_bad(1,4) ],[GZ(1),Store_bad(1,1) ]);
    %hold on
    %plot([BURNUP(1),Store_bad(1,4) ],[GZ(1),Store_bad(1,5) ]);

    %-----
    hold on
    %---Plot the last point and last line-----
    % plot(Store_bad(:,4),Store_bad(:,5), 'y')
    % hold on
    % plot(Store_bad(:,4),Store_bad(:,1), 'y')
    % hold on
    % plot([Show_bad(1,4), X1], [Show_bad(1,1),Y1 ], 'y')
    % hold on
    % plot([Show_bad(1,4), X1], [Show_bad(1,5),Y1 ], 'y')
    %-----
    %---For survived ramp experiments
    for e=1:6
        RAMP=plot([STORERAMP_F(e,1), STORERAMP_F(e,1)], [STORERAMP_F(e,2),
        STORERAMP_F(e,3)]);
        set(RAMP, 'color', [0.4 0.6 0.8], 'linestyle', '-', 'linewidth', 2);
        hold on
    end
    %---For failed ramp experiments

    for e=7:8
        RAMP=plot([STORERAMP_F(e,1), STORERAMP_F(e,1)], [STORERAMP_F(e,2),
        STORERAMP_F(e,3)]);
        set(RAMP, 'color', [1 0.0 0.0], 'linestyle', '-', 'linewidth', 2);
        hold on
    end

    xlabel('Burnup Pin-level (MWd/kg U)');
    ylabel('LHGR (kW/m)');
    %title(['Burnup dependence shown for ramp experiments']);
    %title(['Burnup dependence shown for steps more than or equal to ',
    num2str(Steplimit) , ' kW/m for all reactors']);

    hold on

    %saveas(hb, ['burndiff_', num2str(Steplimit)]');
    saveas(hb, ['Betadiff_ALL_', num2str(Steplimit), '.bmp'])
    %print(hb, ['Betadiff_X-2_', num2str(Steplimit), '.bmp'], 'rnumber', A4)
    %Steplimit=Steplimit+1;
    %hgsave(hb, ['Betadiff_X-2_', num2str(Steplimit)])

    toc
    %end

```

**Report**

[REDACTED]

Appendix C Page 11 of 13

Ramp splitter processor

```

clc
clear all
clear all
clf
n=0
k_store=1

% This script takes the power profile of a ramp segment and chops it into
pellet segments.
% It then interpolates linearly between two power points and saves to a new
matrix called
% Store_ok.

%--Excel Data extraction-----
sheetstart= 3
sheetend=3
for sheetnumber=sheetstart:1:sheetend

[type, sheet] = xlsfinfo('ramp_defrag.xls')
hawt=sprintf('%s',sheet{sheetnumber})
INDATA=xlsread('ramp_defrag',hawt)

s=length(INDATA) % Number of nodes from teh ramp test

POWERSEG=INDATA(:,1)
POWERPROF=INDATA(:,4)

SEG=max(POWERSEG) %Length of segment
lkuts=INDATA(4,5) %Length of pellet in mm
nkuts=ceil(SEG/lkuts)
LHGR_max=INDATA(1,5) %Peak power for this particular experiment
CONDPR_max=INDATA(2,5) %Conditioning that corresponds to the maximum LHGR
BURNUP_max=INDATA(3,5) %Burnup that corresponds to the rod
clear INDATA
RAMPSTAT=[]
RAMPMAX=[]
all=[]
%Power profile plot-----

%acnos=subplot(2,1,1)
acnos=stem(POWERSEG,POWERPROF,'-*')
hold on
plot(POWERSEG,POWERPROF,'-r')
hold on

xlabel('Position from bottom segment (mm)');
ylabel('LHGR normalized to 1');
title(['Axial power profile for ramp experiment ',
sprintf('%s',sheet{sheetnumber})]);

%subplot(2,1,2)

```

**Report**

[REDACTED]

Appendix C Page 12 of 13

```

%plot(POWERSEG,0.5,'*r')
%hold on
% for n=1:nkuts
%     plot([n,n]*lkuts,[0,1],'k')
%
%     hold on
%     n=n+1;
% end
% xlabel('Position from bottom segment (mm)');
% title(['Position of nodes in pellet']);

clear n

%Calculation and plot of interpolated data-----

for k=1:nkuts-1
    dim=(k*lkuts-lkuts/2);

    lowerindx=find(dim>=POWERSEG);

    if isempty(lowerindx)==true;
        lowerindx=1;
    end
    lowerindx=lowerindx(end);

    upperindx= lowerindx+1;

    x0=POWERSEG(lowerindx);
    x1=POWERSEG(upperindx);
    y0=POWERPROF(lowerindx);
    y1=POWERPROF(upperindx);

    slope=(y1-y0)/(x1-x0);
    intersect=y0-slope*x0;
    yint=slope*dim+intersect;
    Show_ok=[k yint];
    Store_ok(k_store,:)=Show_ok;
    k_store=k_store+1;
    k=k+1;
end

%Adding the final element-----
dimfinal=(k*lkuts-lkuts/2)
slopefinal=(y1-y0)/(x1-x0);
intersectfinal=y0-slopefinal*x0;
yint_final=slopefinal*dimfinal+intersectfinal;

Show_end=[k yint_final]
Store_ok(k_store,:)=Show_end;

%subplot(2,1,1)
plot(Store_ok(:,1)*lkuts-lkuts/2,Store_ok(:,2),'mo')

```

**Report**

[REDACTED]

Appendix C Page 13 of 13

```

CONDPR=Store_ok(:,2)*CONDPR_max;
LHGR=Store_ok(:,2)*LHGR_max;
DELTA= LHGR-CONDPR;
BURNUP=ones(size(LHGR))*BURNUP_max;
EXPR=[Store_ok(:,1) LHGR CONDPR DELTA BURNUP]
save(hawt)
dlmwrite(['PELLET',hawt,'.txt'],EXPR)
dlmwrite(['NODE',hawt,'.txt'], [POWERSEG POWERPROF])
Store_ok
%legend('Ramp nodes','Ramp shape','Pellet midpont')

saveas(acnos,['RAMP PLOT ',num2str(sheetnumber),'.bmp'])
%clf

RAMPSTAT=[RAMPSTAT DELTA]
%RAMPMAX=cat(1,[sheet(sheetnumber) LHGR_max CONDPR_max BURNUP_max])
SHOWRAMP=[ LHGR_max CONDPR_max BURNUP_max]
STORERAMP(sheetnumber,:)=SHOWRAMP

%RAMPMAX=vertcat([hawt,LHGR_max,CONDPR_max,BURNUP_max])
%clear DELTA hawt LHGR_max CONDPR_max BURNUP_max
%RAMPSTAT=append([],DELTA)
%RAMPMAX=append(hawt,LHGR_max,CONDPR_max,BURNUP_max)

sheetstart=sheetstart+1
%clf
end
%save(STORERAMP.mat,STORERAMP)
%dlmwrite('RAMPSTAT.txt',RAMPSTAT)

```