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RANKING OF INPUT PARAMETERS IMPORTANCE FOR BWR STABILITY BASED ON RINGHALS-1

Ivan Gajev and Tomasz Kozlowski
Division of Nuclear Power Safety, Royal Institute of Technology
Alba Nova University Centrum, Roslagstullbacken 21, SE 106 91 Stockholm, Sweden
Tel: +46 (0) 8 5537 8845, Fax: + 46 (0) 8 5537 8830, Email: gajev@safety.sci.kth.se

Yunlin Xu and Thomas Downar
Department of Nuclear Engineering and Radiological Sciences
University of Michigan
Ann Arbor, MI 48104

ABSTRACT

Unstable behavior of Boiling Water Reactors (BWRs) is known to occur during operation at certain power and flow conditions. Uncertainty calculations for BWR stability, based on the Wilks' formula, have been already done for the Ringhals-1 benchmark. In this work, these calculations have been used to identify and rank the most important parameters affecting the stability of the Ringhals-1 plant. The ranking has been done in two different ways and a comparison of these two methods has been demonstrated. Results show that the methods provide different, but meaningful evaluations of the ranking.

Key Words: Ranking, BWR Stability, Sensitivity.

1. INTRODUCTION

Best Estimate codes are used for licensing but with conservative approaches. It is claimed that the uncertainties are covered in the conservatism of the calculation. Many Nuclear Power Plants are applying for power up-rates and life extension, therefore evaluation of the uncertainties could help increase performance, while staying below the limit of the safety margin [1]. It is known that under certain conditions, BWR reactors are likely to undergo power oscillations, and the only solution is to SCRAM the reactor, which would negatively impact the plant availability and therefore its economic performance.

The measure for stability is usually the Decay Ratio and the Natural Frequency of Oscillation of the reactor power. The Ringhals-1 OECD Stability Benchmark was used in this work, primarily because of the large database of available data and the lack of scaling effect. The measurements are provided for four cycles, with 8 to 11 points per cycle, for a total of 37 points at different power, flow conditions and core configuration, including uncertainties for the evaluation of the Decay Ratio.

The uncertainty in a coupled code calculation arises from the inaccuracies of the simulation tools and the inaccuracies in the basic data used in the models. The uncertainties in Initial and

Boundary Conditions, Reactor Plant Operating Parameters, Material Properties, Models, Scaling Effect, and Numerical Parameters (Nodalization, etc.) introduce errors in the calculation and proper uncertainty evaluation is necessary.

The Propagation of Input Errors (PIE) method [2] is an uncertainty method which represents statistical variation of the input parameters, together with their uncertainties, in order to reveal the propagation of errors through the code. The method relies on a real code calculation, but instead of calculating certain parameters with discrete values, it assumes the given parameter as a probability distribution by performing the calculation a number of times. This approach allows evaluation of correlation coefficients between the uncertain parameters and the target output parameter, which can be used to determine the most influential parameters. The drawback of this method is that all uncertain parameters have to be identified and probability density functions must be assigned to them, which sometimes have to be an engineering judgment. Another issue is that the error propagates through the code which itself is not a perfect tool.

Depending on the requirements of the confidence interval, one can estimate how many calculations are needed in order to obtain the desired results. The minimum number of runs needed to cover the 95%/95% coverage/confidence estimation, which is taken as the best-estimate prediction requirement by the U.S. NRC, corresponds to a set of 93 runs [2].

2. RANKING METHODOLOGIES

Having the uncertainty calculation results, it is important to understand how the different parameters affect the stability of the BWR system. The paper illustrates an effort to rank the importance of parameters on the BWR stability. The parameters have been identified and used in an uncertainty calculation, based on the Wilks' formula approach, also known as the Propagation of Input Errors (PIE) method. Two methodologies have been used to rank the parameters, the first one is based on performing Sensitivity Calculations, and the second one is based on the Spearman Rank Correlation.

2.1 Ranking using Sensitivity Calculations.

The first procedure is simply execution of sensitivity calculations for each parameter separately, according to its Probability Density Function. In this method, only 2 runs per parameters are executed – one with the lowest value the parameter can have, and one with the highest value the parameter can have. In this case, it is assumed that each parameter has a linear behavior and the relations between the different parameters are neglected.

The advantage of this procedure is that it is not very time consuming and the ranking can be performed for all parameters. The drawback is that, combined influence of two or more parameters cannot be detected. Another issue is that only linear dependence can be detected between the input and the output parameters, and this is not always the case.

2.2 Ranking using the Spearman Correlation.

The Second methodology comes directly from the implementation of the uncertainty method. It is based on the Spearman Rank Correlation Coefficient from the PIE calculation.

The Spearman rank correlation coefficient between the output parameter and the input parameter value can be used to identify the most influential parameters. This coefficient provides a quantitative indication if the considered parameter (and its uncertainty, represented by its PDF) has a significant impact on the output parameter (stability of the reactor). The criterion for “importance” consists of the so called critical value of the Spearman correlation coefficient. If the absolute value of the estimated rank is higher than the critical value, then this parameter is determined to have a statistically significant impact on the result. Otherwise, the parameter will be considered to have low or no importance. The critical values r_s for the Spearman rank correlation coefficient are evaluated using the formula (1) [3].

$$r_s = \pm \frac{z}{\sqrt{n-1}} \tag{1}$$

For the confidence interval of 95%, z=1.96 and n is the number of runs (93 in this case) [3]. Therefore, the Critical Values, for the Spearman rank correlation coefficient for 93 runs are $r_s=\pm 0.2$.

The methodology consists of 2 stages. The first stage is obtaining Spearman Correlation coefficients from the PIE calculation. When the most influential parameter has been identified (i.e. the one with the highest Spearman Rank), it is being removed from the uncertainty calculation and the PIE calculation is run again to find out the next most influential parameter. This procedure can be repeated until all remaining parameters are below the critical value and in this case a clear ranking of all them can be drawn. The drawback is that this method is very time consuming.

3. BWR STABILITY TEST CASE

The Ringhals-1 OECD Stability Benchmark was used in this work, primarily because of the large database of available data, and the lack of scaling effect. The measurements for the DR and the FR are provided for four cycles, with 8 to 11 points per cycle, for a total of 37 points at different power and flow conditions. In addition to the measurements, the uncertainty of the evaluation of the Decay Ratio is also provided in the benchmark. However, this is the error due to the evaluation method only and it does not include the measurement error [4]. In this work, ranking will be provided only for 4 points of Cycle 14 – Points 06, 08, 09, and 10.

The time domain coupled code TRACE/PARCS was used to simulate the desired stability scenario. The TRACE/PARCS model consists of Reactor Pressure Vessel, Fuel Bundles, Steam Separators, Steam Lines, Recirculation Loop, and a Feed Water Pipe. Nodalization diagram is shown on Figure 1. In addition to the thermal-hydraulic model, a neutronics feedback is given by the PARCS code. The stability parameters Decay Ratio and Natural Frequency (DR and FR) are evaluated using the DRARMAX program, which is an ARMA-based method, developed at Purdue University [5], [6], [7].

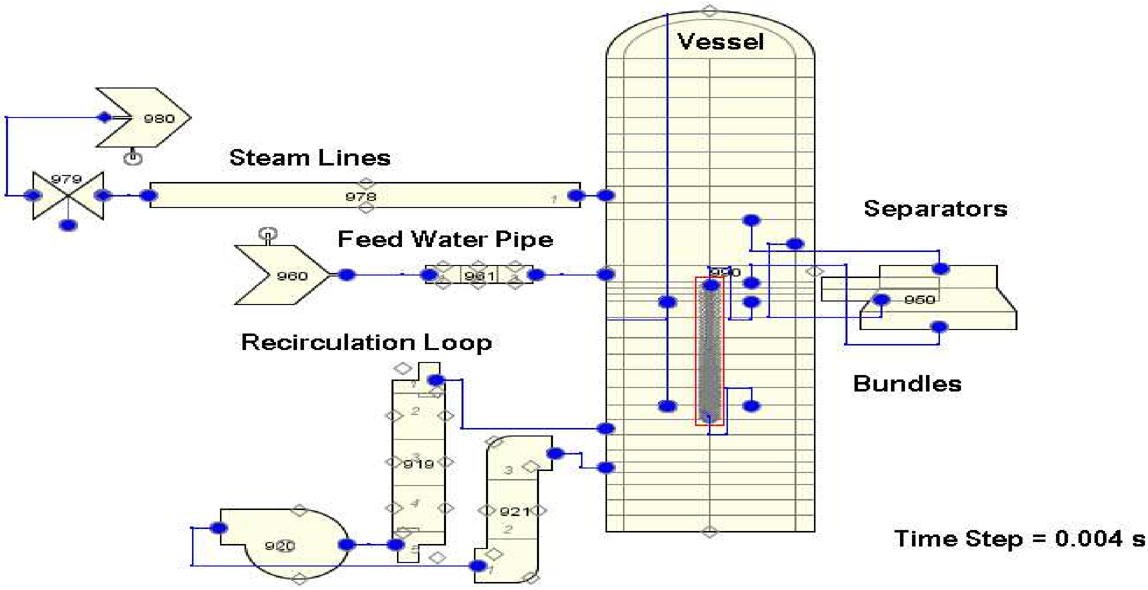

Figure 1 Initial Nodalization Scheme

In work [8], the model was proven to be space-time converged, and base case and PIE results were obtained, as presented in Figure 2. The measured errors are provided in the benchmark, which are attributable to the method used to evaluate the Decay Ratios from the power signal of the Ringhals-1 reactor [4]. The calculated errors are coming from the implementation of the PIE method. For the given points (06, 08, 09, and 10), one can notice that all points are very close to the measurement, for both the stability parameters – DR and FR.

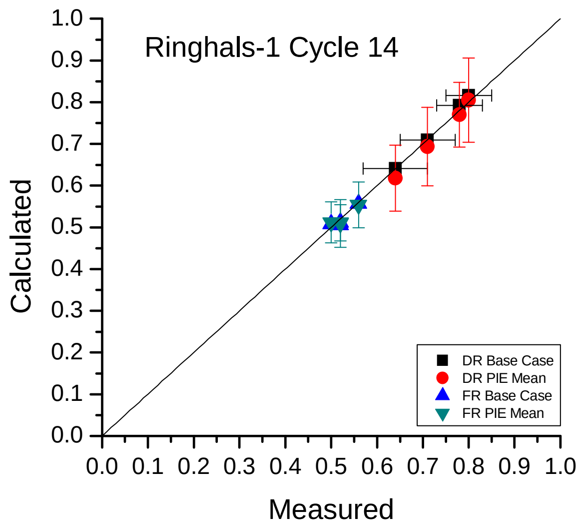

Figure 2 Results from the base cases and PIE Calculation. Cycle 14, points 06, 08, 09, and 10.

The input parameters, used in the PIE calculation, Figure 2 [8], are presented in Table I for Neutronic parameters and Table II for Thermal-Hydraulic parameters. Those parameters are to be ranked in this paper according to their influence on the Decay Ratio.

Table I Uncertain Neutronic Parameters

Parameter	*1-σ Uncertainty*	*Type of Distribution*	*Reference*
Cross Section Parameters			
$\Sigma_{transport}$	*2.5%*	*Uniform*	*[9], page 731*
$\Sigma_{fission}$	*2.5%*	*Uniform*	*[9], page 731*
$\Sigma_{absorption}$	*2.5%*	*Uniform*	*[9], page 731*
$\upsilon\Sigma_{fission}$	*2.5%*	*Uniform*	*[9], page 731*
$\Sigma_{scattering}$	*7.5%*	*Uniform*	*[9], page 731*
$\kappa\Sigma_{fission}$	*2.5%*	*Uniform*	*Same as* $\Sigma_{fission}$
Assembly Discontinuity Factor	*2.5%*	*Uniform*	*Same as* $\Sigma_{fission}$
Exposure Parameters			
Burn Up	*±3.825%*	*Uniform*	*[10], page 82*
Moderator Density History	*±1.9125%*	*Uniform*	*Half the Burn Up*
Control Rods History	*±1.9125%*	*Uniform*	*Half the Burn Up*
Kinetic Parameters			
λ – Prompt Neutron Generation Time	*0.6%*	*Uniform*	*[11], page 280*
β – Delayed Neutron Fraction	*0.7%*	*Uniform*	*[11], page 280*
Inverse Neutron Group Speed	*0.7%*	*Uniform*	*Same as β*
Fission Yield	*0.7%*	*Uniform*	*[9], page 704*
Poison Related Parameters			
Xenon Concentration	*±15%*	*Uniform*	*[12], page 43*
$\Sigma^{abs}{}_{Xe}$	*5%*	*Uniform*	*Double the* $\Sigma_{absorption}$

The cross-section parameters uncertainties have been approximated using [9], results of the target accuracy study for cross-sections of a PWR reactor. In this work, this was used as an approximation of the BWR cross-sections uncertainty. It should be noted that the uncertainties stated in this work are rather illustrative than precise.

Table II Uncertain Thermal-Hydraulic Parameters

Parameter	*1-σ Uncertainty*	*Type of Distribution*	*Reference*
Main T/H Parameters			
Power	*0.75%*	*Normal*	*[13], page 21*
Core Total Mass Flow	*0.5%*	*Uniform*	*[13], page 21*
Inlet Sub Cooling	*0.5K*	*Normal*	*[13], page 21*
Vessel Related Parameters			
Inlet Orifice of the Core	*5%*	*Uniform*	*Own Judgment*
Steam Lines Roughness	*30%*	*Normal**	*[14], page 3.32*
Separators Roughness	*30%*	*Normal**	*[14], page 3.32*
Chimney Length	*0.01m*	*Uniform*	*[15], page 13*
Down Comer Water Level	*0.025m*	*Uniform*	*[15], page 13*
Carry Under	*33%*	*Uniform*	*[16], page 11*
Steam Dome Pressure	*0.05%*	*Uniform*	*[15], page 13*
Bundle Related Parameters			
Spacers Friction	*5%*	*Uniform*	*Own Judgment*
Gas Gap Heat Transfer Coefficient	*35%*	*Uniform*	*[17], page 85*
Bundle Wall Roughness	*30%*	*Normal**	*[14], page 3.32*
Bundle Leak Path Loss Coefficient	*5%*	*Uniform*	*Own Judgment*
Bundle Flow Area	*0.5%*	*Uniform*	*[15], page 13*
Bundle Hydraulic Diameter	*0.5%*	*Uniform*	*Own Judgment*
Fuel Related Parameters			
Fuel Thermal Conductivity	*10%*	*Uniform*	*[18], page 51*
Fuel Heat Capacity	*1%*	*Uniform*	*[18], page 43*
Clad Thermal Conductivity	*6.25%*	*Uniform*	*[18], page 43*
Clad Heat Capacity	*3%*	*Uniform*	*[18], page 43*
Closure Models Parameters			
Annular Wall Drag Coefficient	*5%*	*Uniform*	*Own Judgment*
Bubbly Slug Wall Drag Coefficient	*5%*	*Uniform*	*Own Judgment*
Total Interfacial Friction Coefficient	*5%*	*Uniform*	*Own Judgment*
k-Factor for an Abrupt Constriction or Expansion	*5%*	*Uniform*	*Our Judgment*
Total Interfacial Heat Transfer Coefficient	*5%*	*Uniform*	*Own Judgment*

** The distribution was approximated with Normal.*

4. RESULTS

The first ranking consists of sensitivity calculations which were executed assuming linear dependence between the input and the output parameter, and so in this case, only 2 runs per parameter were executed. Results are presented in Appendix A where the length of the bars represent the amount of Decay Ratio “decrease” or “increase” from the mean value for each parameter. The absolute difference of the DR in the two runs were calculated and averaged over the four points of Cycle 14. The final sensitivity ranking is presented in Table III, column 2.

The second method is based on removal of the most influential parameter from the PIE calculation, one by one, until the parameters are below the critical value. In this work, the procedure was repeated 10 times due to the long calculation time needed. Parameters have been tested for influence on the Decay Ratio only. Since the removal sequence differs for each point, each parameter has been assigned a rank (the iteration in which it has been removed in the current point). For example, the first parameter that has been removed gets a rank of 1; the second parameter gets the rank of 2, and so on. If a parameter exists only in 1 point then for the other points it gets a rank of 11, because the number of iterations is 10. That way, parameters with lower rank are more. Then, the ranks for all parameters have been added and the PIE ranking is presented in Table III, column 3.

Table III Ranking Table of Parameters Affecting the Decay Ratio.

No.	Sensitivity Ranking	Spearman Ranking
	Parameter	Parameter
1.	Bundle Wall Roughness	**Bubbly Slug Wall Drag Coefficient**
2.	$\Sigma_{scattering}$	**Fuel Thermal Conductivity**
3.	Gas Gap Heat Transfer Coefficient	**Total Interfacial Drag Coefficient**
4.	**Bubbly Slug Wall Drag Coefficient**	**Annular Wall Drag Coefficient**
5.	$\Sigma_{absorption}$	**Power**
6.	**Fuel Thermal Conductivity**	**Inlet Sub Cooling**
7.	Inlet Orifice of the Core	**Fuel Heat Capacity**
8.	**Inlet Sub Cooling**	**Carry Under**
9.	$\upsilon\Sigma_{fission}$	Gas Gap Heat Transfer Coefficient
10.	**Power**	Inverse Neutron Group Speed
11.	**Total Interfacial Drag Coefficient**	Bundle Wall Roughness
12.	**Annular Wall Drag Coefficient**	β – Delayed Neutron Fraction
13.	Burn up	$\Sigma_{fission}$
14.	Xenon Concentration	Inlet Orifice of the Core
15.	β – Delayed Neutron Fraction	$\upsilon\Sigma_{fission}$

It is noticeable that the two rankings differ. Explanation of this phenomenon is how each parameter is being modified. Some parameters have been modified according to their PDF for each (Thermal-Hydraulic or Neutronic) node with a different random number. This should be the case for all parameters, but due to limitations in the representation of the parameter in the code input, some parameters have been changed with the same random number for every node (Bold parameters in Table III). In these cases (Bubbly Slug Wall Drag Coefficient, Fuel Thermal

Conductivity) the same random number for each node has been propagated through the code during the current run.

When a parameter is being calculated using the Sensitivity method – each node is modified with the minimum or maximum value of the parameter’s PDF. In the PIE method, non-bold parameters (different random number for each node) overall value is not as spread as in the Sensitivity method, and this decreases their influence. That is why, in the second method (Spearman Ranking) the first 8 parameters are bold (same random number for each node) and the rest are non-bold parameters (different random number for each node), while in the case of the Sensitivity Ranking – they are mixed. One can notice that the first six bold parameters (same random number for each node) somehow match with both rankings (if one excludes the non-bold parameters in the Sensitivity Ranking).

5. CONCLUSION

The Ringhals-1 TRACE/PARCS space-time converged model has been used in uncertainty analysis for BWR Stability in previous work [8]. In this current paper, an effort has been done to rank the input uncertainty parameters according to their influence on the Stability (Decay Ratio). Two different methodologies have been used for the ranking, one based on sensitivity calculations with minimum and maximum values, and another one based on the Spearman Rank Correlation extraction from the uncertainty calculation.

Results show that the two rankings are not equivalent, but due to the nature of the parameters and the ranking methodologies, it is reasonable. It should be noted that, for extraction of output uncertainty one should use the PIE method with a different modification of parameters for each node. However, for ranking of parameters affecting the output, one should modify the parameters with the same random number for each node. In this case one would be able to extract the ranking, but not the output uncertainty.

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Appendix A. Decay Ratio change from the two sensitivity calculations

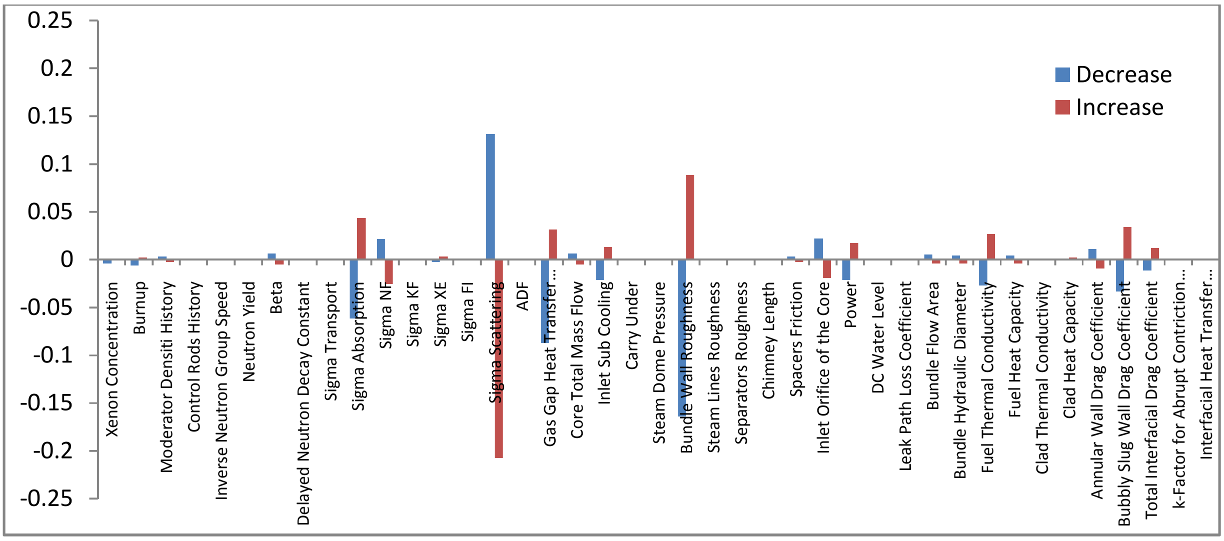

Figure 3 Cycle 14 Point 06

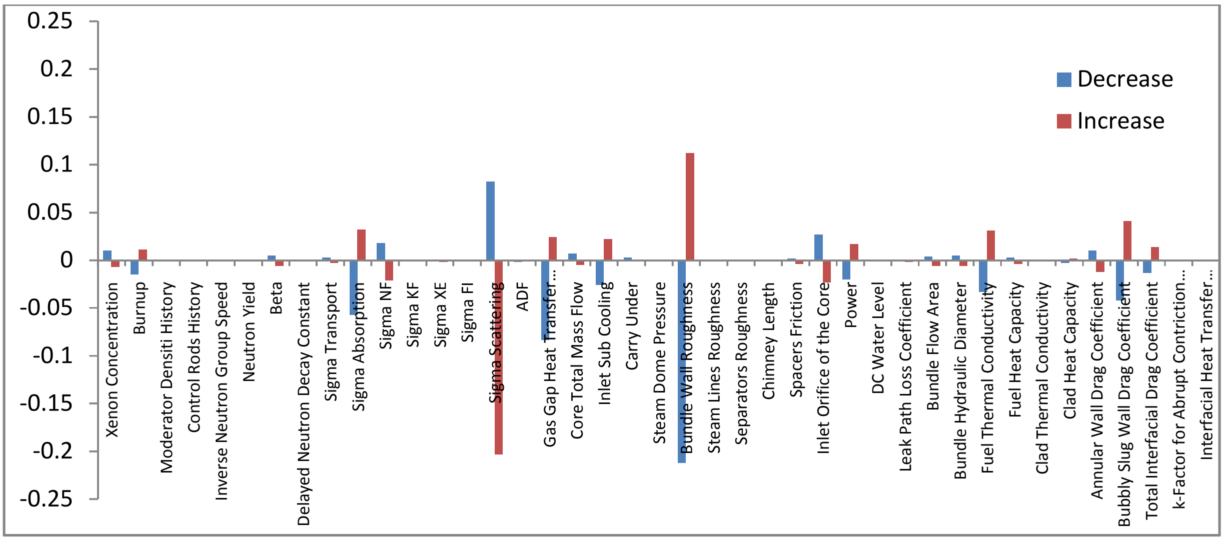

Figure 4 Cycle 14 Point 08

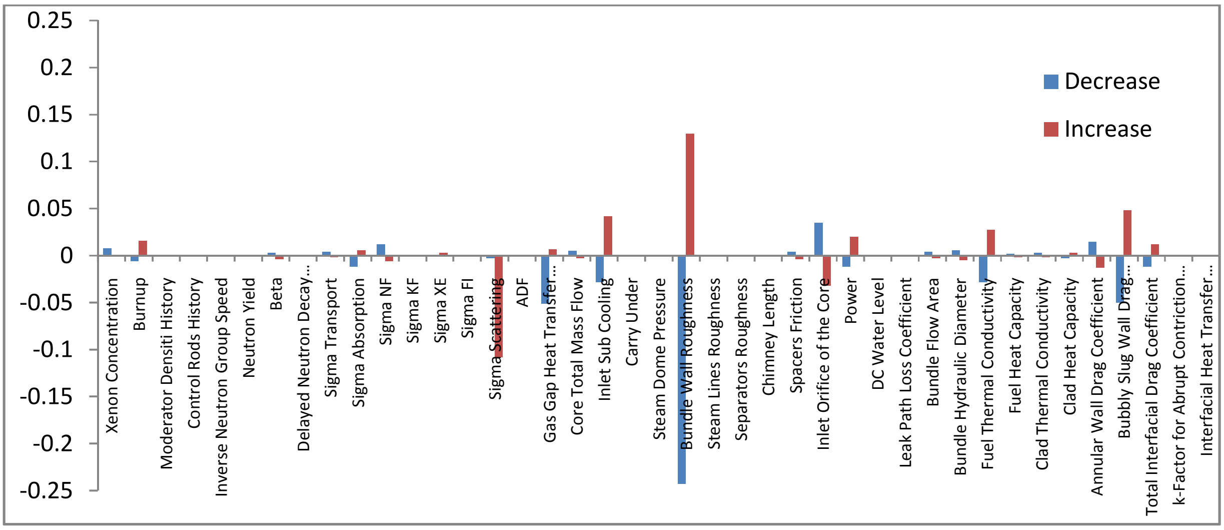

Figure 5 Cycle 14 Point 09

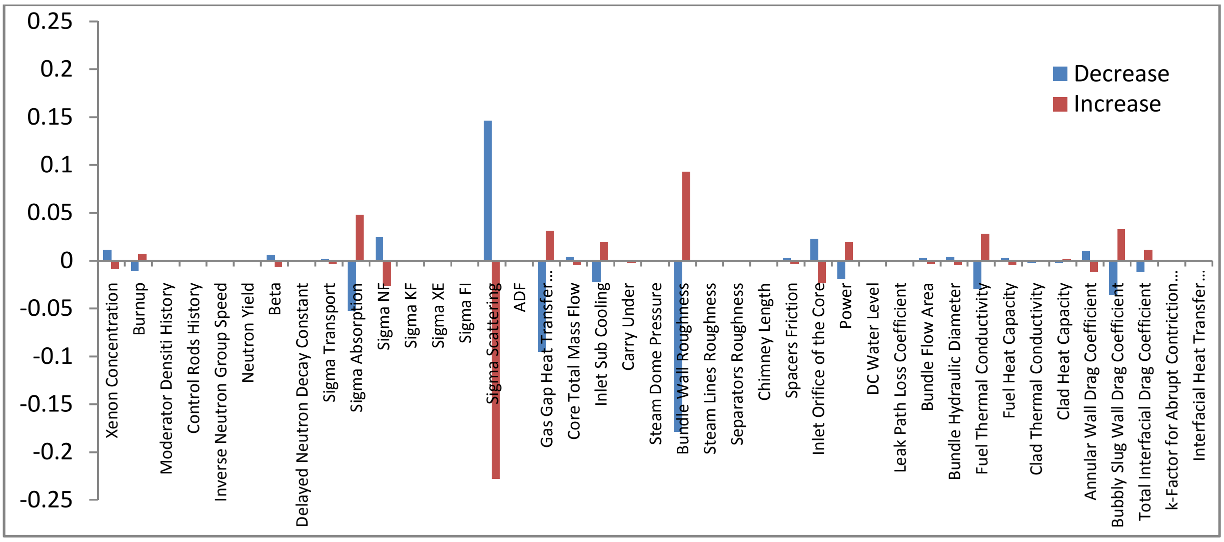

Figure 6 Cycle 14 Point 10