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Full-core uncertainty analysis of nuclear fuel behavior

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ABSTRACT

Fuel performance analysis can be used to show compliance with regulatory criteria, such as criteria related to fuel melting, rod internal pressure and cladding stresses and strains. A nuclear reactor core contains typically tens of thousands fuel rods in hundreds of fuel assemblies, and each rod experiences different generated power and coolant conditions during its irradiation. Therefore fuel performance analysis must be performed on each rod separately, resulting in tens of thousands of simulation runs.

Additionally, the manufacturing parameters of the fuel rods, fuel performance code model parameters and even the determined power are fundamentally uncertain: they are not single, exact values but rather their true nature can be approximated with statistical distributions. Therefore also the results are distributions of values and not exact. Parameters of these distributions must be compared to regulatory criteria, and as a conservative approach some limiting values can be established which can be used to show whether a regulatory criteria is exceeded or not. A method widely in use in the nuclear industry is based on order statistics, and can be used to show that the 0.95-content tolerance interval with 95 % probability does not exceed the examined criterion.

In this work a method applicable for full-core fuel performance analysis is demonstrated with a calculation of a PWR 17x17 assembly. Fuel performance parameters such as maximum temperature, pressure and cladding stress are investigated.

1 INTRODUCTION

The YVL guides allow the use of statistical methods to show compliance with regulatory criteria. Specifically, YVL B.3 allows that uncertainty analysis on deterministic models can be used to show that there is a 95 % probability that an examined safety parameter does not exceed a limiting criterion with 95 % confidence [1]. This requires the determination of the effect of uncertainty in the input parameters on the output parameters of the model. This paper presents a method for performing uncertainty analysis that is applicable for full-core fuel behavior. The method is an extension to work performed with uncertainty analysis of fuel assembly mean fission gas release for spent fuel disposal studies [2]. A single assembly is used as an example to demonstrate the capabilities of the method.

2 METHODOLOGY

2.1 Fuel behavior analysis

Fuel performance analyses in this work were performed with the VTT-modified ENIGMA fuel performance code [3,4].

The input files for VTT-ENIGMA was generated by a statistical script by Ikonen [5]. The script samples code input parameters from their distributions and creates input files with the varied parameters.

2.2 Uncertainty analysis

Wilks [6] showed that the coverage of a distribution is independent of the underlying distribution, and his results can be used to find tolerance intervals of distributions in a nonparametric manner. When concerned whether a parameter exceeds a limiting value or not, the upper tolerance interval of the parameter can be used as a measure that a certain proportion of a distribution remains below the value of the interval with a certain degree of confidence. The upper tolerance interval U of a single parameter is defined as

$$P\left(\int_{-\infty}^{U} f(x)dx \geq \gamma\right) \geq \beta, \qquad (1)$$

where f(x) is the probability density function of the variable x, γ is the probability content covered by the interval and β is the confidence. Wilks derived the minimum amount of samples required for a certain order statistic, the observations of the variable x arranged in order by their magnitude, to be greater or equal than the tolerance limit U. For one considered output parameter, this number of samples, N, is found from the formula

$$\beta = 1 - \gamma^N. \tag{2}$$

In this case, the largest (Nth) value is the upper tolerance intercal. Different formulae can be found for cases when for example (N-1)th value is desired to be greater or equal to the tolerance interval. Formula for the Nth value is said to be the first-order formula, whereas for the (N-1)th value it is said to be second-order and so on.

However, for multiple output parameters, the joint distribution of the output parameters, g(x), must be used, and a tolerance region can be defined by several tolerance intervals $U_1,\ldots,U_n$:

$$P\left(\int_{-\infty}^{U_1} \ldots \int_{-\infty}^{U_n} g(x_1, \ldots, x_n) dx_1 \ldots dx_n \geq \gamma\right) \geq \beta, \tag{3}$$

Pal and Makai [7] show that this probability is also independent of the joint distribution function, and the number of samples can be obtained from

$$\beta = I(\gamma; s_1 - n + 1, N - s_1 + n), \tag{4}$$

where I(x; a, b) is the normalized incomplete beta function, s_1 the order statistic required to be greater or equal to the tolerance interval and n the number of output parameters. The normalized incomplete beta function is defined as

$$I(x; a, b) = \frac{B(x; a, b)}{B(1; a, b)}, \tag{5}$$

where B(x;a,b) is the incomplete beta function, defined as the integral

$$B(x; a, b) = \int_0^x t^{a-1}(1-t)^{b-1} dt, \tag{6}$$

which yields the complete beta function by setting x=1. In table 1, values of N are shown for numbers of output parameters and order of the formula in Eq. (4) varying from 1 to 10.

In the case of maximum temperature, maximum internal pressure and maximum cladding hoop stress we have three output parameters, we set n = 3 and s_1 = N for the first-order formula, resulting in N = 124.

		Number of outputs									
		1	2	3	4	5	6	7	8	9	10
Order	1	59	93	124	153	181	208	234	260	286	311
	2	93	124	153	181	208	234	260	286	311	336
	3	124	153	181	208	234	260	286	311	336	361
	4	153	181	208	234	260	286	311	336	361	386
	5	181	208	234	260	286	311	336	361	386	410
	6	208	234	260	286	311	336	361	386	410	434
	7	234	260	286	311	336	361	386	410	434	458
	8	260	286	311	336	361	386	410	434	458	482
	9	286	311	336	361	386	410	434	458	482	506
	10	311	336	361	386	410	434	458	482	506	530

Table 1: Number of required samples with different order of the Wilks' formula and a different number of outputs.

2.3 Example data

Data used in this work is based on the case US PWR 16x16 from the OECD/NEA International Fuel Performance Experiments database [8]. Power histories were available for 9 rods, and 236 power histories corresponding to a full assembly were generated from the original data by multiplying the 9 available power histories randomly with multipliers in the range of 0.8 to 1.2. Fuel rod manufacturing parameters from the IFPE database were used along with realistic parameter distributions.

Each manufacturing parameter distribution was assumed to be normal, and the varied input parameters were pellet radius, cladding inner and outer radii, pellet density and grain size, plenum length and fill gas pressure. In addition, ENIGMA model parameters affecting the fission gas release, pellet thermal conductivity, cladding creep and pellet thermal expansion models were varied according to their respective distributions.

3 RESULTS

3.1 Uncertainty analysis

Some results from the example uncertainty analysis are presented in figures 1 through 4 regarding maximum fuel temperature, maximum rod internal pressure and maximum cladding hoop stress. A single value from each fuel performance simulation is extracted regarding each parameter, and this is the highest value at any point of the simulation.

In the figures, the distribution of the medians of these maximum values across all the simulation runs for each rod are shown along with the distribution of the tolerance interval calculated for each rod. As expected from and required by the definition of the tolerance interval, the tolerance interval distribution is situated at higher values than the median.

In figure 1, the maximum calculated temperatures are shown. The requirement from YVL B.4 [9] for fuel temperature is that the fuel rod is not allowed to melt, so the upper tolerance interval values for all rods in this assembly can be said to fulfil that criterion by a large margin, as uranium oxide melting temperature is over 3000 K.

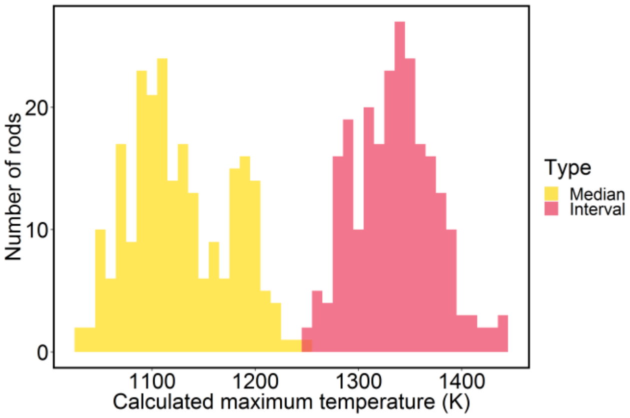

Figure 1: Uncertainty analysis results regarding maximum calculated temperature. Median refers to the distribution of the medians of the values calculated across all simulation runs, and Interval refers to the tolerance interval distribution.

The maximum rod internal pressure results are shown in figure 2. The results show different behavior compared to, for example, the temperature results, as the spread of the tolerance interval values is much wider than that of the median values.

This is attributed to the behavior of fission gas release, shown in figure 3. The distribution of calculated fission gas releases typically have a heavy tail, which results in comparatively high maximum fission gas releases compared to the median. This directly affects the internal pressure results. The maximum values regarding fission gas release do not correspond to the upper tolerance interval of fission gas release, as at the outset the analysis of three parameters was selected and the simulations were run a sufficient number of times for the simultaneous analysis of three output parameters. However, the fission gas release distribution can be studied to understand the behavior of the internal pressure results.

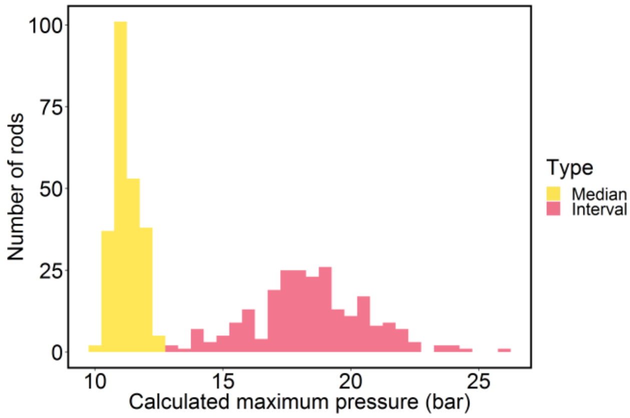

Figure 2: Uncertainty analysis results regarding maximum calculated rod internal pressure. Notation as in figure 1.

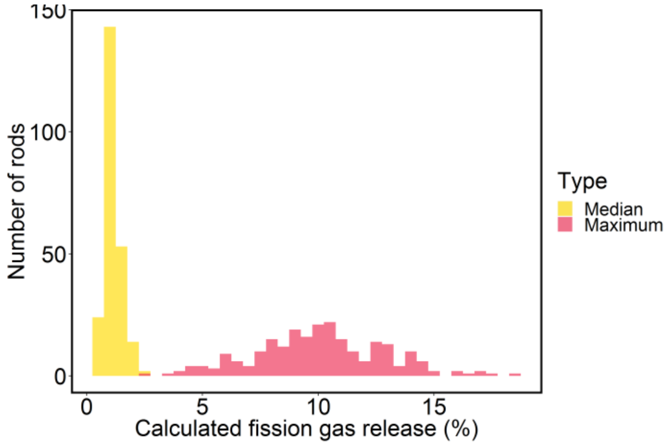

Figure 3: Uncertainty analysis results regarding fission gas release. In this case, the distribution shown in red is not the tolerance interval distribution, but the maximum value distribution, as described in the text.

The maximum cladding hoop stress results are shown in figure 4. The resulting distribution of median values shows a small range of values occurring most of the time, with the rest having more scatter. The most prevalent values occur around 20

MPa. The upper tolerance interval distribution is more symmetric, centering around 85-90 MPa. These values are much lower than the yield stress of Zircaloy, and as such are very acceptable.

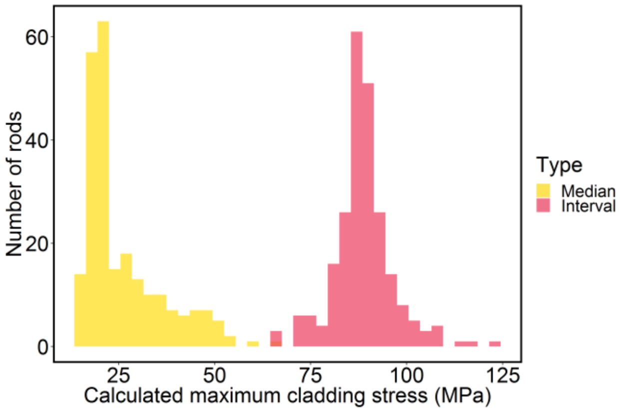

Figure 4: Uncertainty analysis results regarding maximum calculated cladding hoop stress. Notation as in figure 1.

3.2 Running time

The running time of the number simulations with the parameters described here, three output parameters and 236 rods, is about 30 CPU-hours, and the method is very parallelizable as each rod can be calculated independent of the others. Such a running time makes it reasonable to use this method for full-core fuel behavior analysis, where typically the calculation of a few hundred fuel assemblies is required.

4 CONCLUSIONS

An uncertainty analysis method and related tools applicable for full-core fuel behavior analysis has been developed at VTT. The method was demonstrated with a single assembly, but can also be efficiently applied to full-core calculations.

ACKNOWLEDGEMENTS

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