Uncertainty Analyses for LB loca in VVER-440/213

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ABSTRACT: The paper describes the project recently initiated at the Nuclear Regulatory Authority of the Slovak Republic (ÚJD SR) to introduce the application of the best estimate methodology with the evaluation of uncertainty (BE+U) in the licensing process. The project is included into the long-term bilateral cooperation between the ÚJD SR and Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) in the area of nuclear safety of Russian designed WWER-440 reactors under the financial support of the German Ministry of Economy and Labor and presently partially also of Ministry of Environment. Within this cooperation GRS provides ÚJD SR with the state-of-the-art computer codes and serves as technical advisor. The initial phases of the BE+U project comprise of the methodology transfer and pilot application of the methodology to a selected scenario, which is the LB LOCA. In the following text the current situation in the area of safety analysis in Slovakia is described, the conservative and BE+U methodologies are briefly characterized and compared and the main goals and phases of the project are defined. Finally, recent results of the LB LOCA calculation and future plans are discussed.

1 CURRENT PRACTICE

According to the regulations, for each nuclear installation within the country safety analysis report (SAR) has to be submitted to the national regulator for revision and this document has to be accepted by the regulator to issue the license for operation. Typically the largest part of the SAR is devoted to the safety analyses, which demonstrate (by the computer simulation) the capacity of the nuclear facility to cope with unexpected events, failures, defects, accidents etc.
To perform the safety analysis clear and rigor state-of-the-art methodology has to be approved and well-defined guidelines should be available. Recently the use of best estimate codes is highly recommended along with applying conservative input data and initial and boundary assumptions, or best estimate initial and boundary conditions - in that case with the evaluation of the uncertainty.

2 METHODOLOGIES IN THE SAFETY ANALYSES

2.1 Conservative approach

Nowadays, the conservative approach is typically understood (e.g. in Slovakia or Germany) as the application of the best estimate code together with conservative input data and initial and boundary conditions, which means the initial plant parameters, availability of safety and control components and systems and operator action are selected over the nominal values in the way to aggravate the course of the event. This methodology is widely applied in the licensing calculations around the world since long, which means that a significantly large amount of knowledge, experience and practical recommendations are available to the code users.

2.2 Best estimate approach with the evaluation of uncertainty

On the other hand BE+U approach is characterized by applying the best estimate codes and realistic input data along with the nominal (or "best-estimate") initial and boundary conditions, which means the initial facility parameters are defined at their nominal values; availability of safety and control components and systems are still assumed in a conservative way. But, the introduction of the nominal values implies the evaluation of uncertainty. The major sources of uncertainty in the area of safety analysis are represented by the uncertainty of the code (associated with the code models and correlations, solution scheme, model options, data libraries or deficiencies of the code), representation uncertainties (accuracy of the complex facility geometry, 3D effects, scaling, control and system simplifications) and plant data uncertainties (unavailability of some plant parameters, instrument errors and uncertainty in instrument response). There are several methods for the application of the BE+U approach, however the common feature is that they all highly depend upon the extensive experimental database, from which uncertainties can be derived. The comprehensive description and comparison of some of BE+U methods can be found e.g. in OECD/NEA report on the uncertainty study [1]. In the project mentioned in the following sections the GRS method is applied. In this method all identified uncertain parameters are varied simultaneously for each code calculation. The number of calculations depends on the required probability content and confidence level of the statistical tolerance limits based on the Wilk's formula (e.g. for two-sided statistical tolerance limit with 95% confidence level and 95% probability at least 93 runs have to be performed). The method allows for the evaluation of the sensitivity measures of the importance of parameter uncertainties for the uncertainties of the results giving the ranking of input parameters. The method is supported by the software system named SUSA (Software System for Uncertainty and Sensitivity Analysis) providing the user with the easy and automated way to perform the uncertainty calculations. The detailed description of the GRS method is given in [2] and SUSA description can be found in [3].

2.3 Conservative vs. BE+U approach

Among the others, major advantage of the BE+U methodology, at least from the regulator point of view, is the quantification of the safety margin between the realistic value of the calculated parameters and the defined safety limits. Applying the conservative approach analysis is able to show that the facility's parameters are below the safety limits, but without knowing exactly how far. Except that, BE+U provides the analyst with several statistical tools to get more detailed evaluation of the calculated results and, thus possibly resolves some hidden issues and phenomena, which could be omitted by the traditional conservative methodology. On the other side the data needed to perform the BE+U analysis are far more complex than in the traditional conservative approach and for some kind of events the required information might not even be available.

3 BE+U PROJECT

The project oriented on the application of the BE+U methodology is a part of the long-term cooperation between ÚJD SR and GRS. The bilateral cooperation was initiated back in 1997 under the financial support of the German Ministry for Education and is focused on the transfer of the knowledge along with the corresponding software in the area of the nuclear safety. Namely in the area of the thermal-hydraulic analyses the project started with the basic training and application of ATHLET computer code. Under the guidance of GRS this code has been used for the simulation of several operational events, integral tests and SAR review calculations [4]. Lately based on the mutual interest the cooperation has been extended also on the BE+U applications.

3.1 Main goals and phases of the project

Major goal of the project is the introduction of the BE+U methodology at the Regulatory Authority and later, based on the results achieved in the initial phases of the project, possible application of BE+U approach in the licensing calculations in Slovakia. Practical use of the BE+U methodology will hopefully lead to an increased confidence in the calculated results from the safety analysis.
The whole project is divided into the following five phases:
Introduction of the GRS method by means of the training courses by the method developer GRS,
Pilot application of the GRS method to the large break loss of coolant accident (LB LOCA) scenario for VVER-440 reactors,
ATHLET computer code simulation of the SPE-3 test (3rd standard problem exercise of a leak of the coolant from the primary to secondary circuit - PRISE) on the PMK-NVH facility and compilation of the list of uncertainties for this kind of accidents by comparing the calculated results with the experimental data,
Simulation of PRISE accident in VVER-440 reactors with the BE+U approach while benefiting from the knowledge and experience gained in phase 3,
Evaluation of the project results and discussion about the further practical application of the BE+U methodology, mainly in licensing calculations.

3.2 LB LOCA calculation

Upon the completion of the initial phase of the project a first application of the GRS method has been started. LB LOCA was selected to be simulated due to the following reasons:
Relatively large experience with the simulation of these accidents at ÚJD SR,
Dynamic course of the event with quick occurrence of all major phenomena allowing for a short calculation time ad thus reducing the necessary allocation of computational time,
Availability of information from a similar calculation for a German PWR types of reactors performed by GRS.

On the other hand, one drawback of selecting the LB LOCA event is that there are practically no experimental data for VVER types of reactors and therefore the selection of the uncertain parameters is partly based on engineering judgment and some kind of extrapolation from the existing database of experiments.

3.2.1 Definition of the scenario

The definition of the simulated event was based on the general rules for applying the BE+U approach [5, 6] taking into account the results of the VVER-440/213 LB LOCA sensitivity studies [7]. According to these studies the most adverse situation is the instantaneous double-ended guillotine break of the inseparable part of the cold leg. Primary loop with the connection to one LPIS is typically chosen for the location of the break because a significant part of the water inventory from ECCS is directly lost through the break. Where possible the nominal initial parameters are used for the calculation to comply with the BE approach.

3.2.2 Definition of the uncertain parameters and input deck preparation

The definition of the uncertain parameters for the LB LOCA simulation is the most predominant part of the analysis. The master list containing 56 uncertain parameters was taken from the GRS study on the PWR LB LOCA [8]. This list was carefully examined and redefined to fit the VVER-440 particularities. Finally 50 parameters, listed in Table 1, have been approved – 38 of them representing code/model uncertainties, 2 representation uncertainties and 10 plant data uncertainties.

Table 1 List of uncertain parameters for LB LOCA

No.	Parameter	Description	Nominal Value	Range		Distribution
				Min	Max	
1	TURB	Turbulence factor for evaporation in critical break flow	20	1.0	50.0	Log-normal μ=2.29 σ=0.65 shift=1.0 truncated over [0.0,50.0]
2	FD	Weisbach-Darcy wall friction coefficient	0.03	0.02	0.04	Triangular
3	OHWFC	Correction factor for single phase forced convection to water (Dittus-Boelter)	1	0.85	1.15	Uniform
4	OHWNC	Correction factor for single phase natural convection to water (Mc Adams)	1	0.85	1.15	Uniform
5	IHTC30	Selection of correlation (parameter 6)	2	1 or 2		Discrete 50%-50%
6	OHVFC	Correction factor for single phase forced convection to steam (Dittus-Boelter II, 50%)	1.0	0.8	1.2	Uniform
		Correction factor for single phase forced convection to steam (McEligot, 50%)	1.0	0.85	1.25	Uniform
7	IHTCI0	Selection of correlation (parameter 8)	1	1 or 2		Discrete 50%-50%
8	OHWFB	Correction factor for film boiling, modified Douglas-Rohsenow correlation (50%)	1.0	0.65	1.3	Uniform
		Correction factor for film boiling, Condie-Bengston IV (50%)	1.0	0.75	1.25	Polygonal 0.75-0.8-1.2-1.25
9	ICHFI0	Selection of the correlation for parameter 10	0	0	6	Discrete (two values 0, 6)

10	OTRNB	Correction factor for CHF, min. value (50%) Correction factor for CHF, Gidropress cor. (50%)	1.0 1.0	0.7 0.8	1.3 1.2	Uniform Uniform
11	OHWNB	Correction factor for nucleate boiling (modified Chen correlation)	1.0	0.8	1.2	Uniform
12	OHWPB	Correction factor for pool film boiling at natural convection (Bromley correlation)	1.0	0.75	1.25	Uniform
13	OTMFB	Correction factor for minimum film boiling temperature (Groeneveld-Stewart correlation)	1.0	0.9	1.30	Uniform
14	CQHTWT	HTC of rewetted side, upper quench front	5xE5 W/ m^2K	2xE4	1xE6	Log-uniform
15	CQHTWB	HTC of the rewetted side, bottom quench front	5xE5 W/ m^2K	1xE5	1xE6	Log-uniform
16	ZBO	Number of bubbles per unit volume(m^{-3})	5xE9 $1/m^3$	10xE8		Log-triangular
17	ZT	Number of droplets per volume(m^{-3})	5xE9 $1/m^3$	10xE8		Log-triangular
18	OMTCON	Correction factor for direct condensation	1.0	0.5	2.0	Histogram 0.5-1.0-2.0/ 50%-50%
19	ITMPO	Selection of wall friction model, ITMPO=1: Use of input wall friction, ITMPO=2: Wall friction calculated using wall roughness	1	1 or 2		Discrete 50%-50%
20	ALAMO	Pipe wall friction (if option ITMPO=1)	0.03	0.02	0.04	Triangular
21	ALAMO	Rod bundle wall friction (if option ITMPO=1)	0.03	0.02	0.04	Triangular
22	ROUO	Pipe wall roughness (ITPMO=2)	-	6.3xE-6		Polygonal 6.3E-6-8.0E-6-10.0E-6-12.5E-6
23	ROUO	Rod bundle wall roughness (if option ITMPO=2)	-	1.5xE-6	2.0xE-5	Polygonal 1.5E-6-5.0E-6-1.0E-6-2.0E-5
24	OFI2	Correction factor for two-phase multiplier in vertical pipe, Martinelli-Nelson correlation with constant friction factor(ITMPO=1)	1.0	0.2	2.0	Log-normal μ=-0.247, σ=0.339
25	OFI2H	Correction factor for two-phase multiplier in horizontal pipe, Martinelli-Nelson correlation with calculated friction using wall roughness(ITMPO=2)	1.0	0.1	2.0	Log-normal μ=-0.545, σ=0.411
26	ZFFJO/ ZFBJO	Correction factor for form loss coefficient at upper reactor plate (nom. value	1.0	0.5	2.0	Histogram 0.5-1.0-2.0/ 50%-50%
27	OIHST	Correction factor for interfacial shear in stratified and wavy horizontal pipe flow	1.0	0.2	2.0	Histogram 0.2-1.0-2.0
28	OIBSB	Correction factor for interfacial shear in bubbly, slug and churn turbulent horizontal pipe flow	1.0	0.35	3.5	Histogram 0.35-1.0-3.5/50%-50%
29	OIHT1	Correction factor for critical velocity of transition from stratified to slug flow in horizontal pipes	1.0	1.0	3.0	Uniform
30	OIHDI	Correction factor for critical velocity of transition from non-dispersed to dispersed droplet flow in horizontal pipes	1.0	1.0	2.0	Uniform
31	OIVPI	Correction factor for interfacial shear in non-dispersed vertical pipe flow	1.0	0.35	2.5	Histogram 0.35-1.0-2.5/50%-50%
32	OIBUN	Correction factor for interfacial shear in non-dispersed vertical bundle flow	0.84	0.01	2.5	Histogram 0.01-0.84-2.5/50%-50%
33	OIANU	Correction factor for interfacial shear in non-dispersed vertical downcomer flow	1.0	0.05	3.0	Histogram 0.05-1.0-3.0/50%-50%
34	OENBU	Correction factor for critical velocity of transition from non-dispersed to dispersed droplet flow in vertical bundle	1.0	1.0	3.0	Uniform

35	OIVTP	Correction factor for critical velocity of transition form non-dispersed to dispersed droplet flow in vertical pipe and downcomer	1.0	1.0	1.5	Uniform
36	OIVDI	Correction factor for interfacial shear in dispersed vertical droplet pipe flow	1.0	0.8	1.2	Uniform
37	OIHDI	Correction factor for interfacial shear in dispersed horizontal droplet pipe flow	1.0	0.8	1.2	Uniform
38	OFRIC	Coefficient k of fraction of water and steam to wall friction, correction of standard distribution	0.0	-3.2	4.0	Uniform
39	CSA	Bypass flow cross section in reactor core	1.0	0.96	1.02	Uniform
40	YHS	Two-phase multiplier for head	Table	Table	Table	Uniform
41	YTS	Two-phase multiplier for torque	Table	Table	Table	Uniform
42	QROD00	Correction factor for the reactor power (1375MW)	1.0	0.96	1.04	Uniform
43	RPODC	Correction factor for decay heat	1.0	0.9	1.1	Uniform
44	QROD00	Correction factor for hot assembly (nom. value 3.94 MW)	1.3	1.0	1.51	Uniform
45	QROD00	Correction factor for hot pin (nom. value 31268.48 W)	1.4	1.0	1.74	Uniform
46	GAP10	Gap width between fuel and clad – nominal values	1.9xE-4	1.6xE-4	2.5xE-4	Uniform
47	WLFM					Uniform
48	HAT	Temperature of HA Water	50°C	20°C	60°C	Uniform
49	EPS	Convergence criterion	10xE-3	10xE-4	10xE-2	Log-triangular
50	CLIMA	Correction factor for lowest local absolute error of void fraction	1.0	0.2	2.0	Uniform

Table 2 lists the summary of the main initial conditions of the unit – the third column of the table indicates whether the individual parameter was identified as uncertain or not. Availability of the systems and components have been considered according the current practice – the safety systems have been assumed to be in operation and control systems have been assumed to be in operation only if their action aggravates the course of the event [9]. Also the single failure was taken into account – the failure of one electrical grid has been considered resulting in loss of one ECCS train (HPIS and LPIS).

For the calculation an input deck describing the unit with the VVER-440/213 reactor developed at UJD SR was used. This input deck was slightly modified to comply with the BE+U methodology and to simulate the LB LOCA event.

Table 2 Main initial conditions of the unit

Parameter	Unit	Nominal value	Uncertain (Y/N)
Reactor power	MW	1,375.0	Y
Primary pressure (core outlet)	MPa	12.26	N
PRZ level	m	5.96	N
Mass flow in core	kg/s	9,306	Y
Core inlet temperature	°C	267.0	N
HA pressure	MPa	5.8	N
HA coolant volume	m^3	45.0	N
HA coolant temperature	°C	40.0	Y
MSH pressure	MPa	4.51	N
SG water level	m	2.105	N
FW mass flow	kg/s	125.0	N
FW temperature	°C	222.1	N
Decay heat	-	ANS-79	Y

3.2.3 Analysis of the calculated results

93 input decks with varied uncertain parameters and 93 runs have been performed using the automated features of SUSA software to fulfill the Wilk's formula for 95% confidence level and 95% probability. Figure 1 presents all 93 achieved results for the maximum cladding temperature. The maximum value was reached in the first run – 1,043°C in 158 second of the calculation (for the illustration in the SAR for V-2 NPP [7] the maximum calculated cladding temperature peak reached 940°C). These time histories of the maximum cladding temperature have been statistically evaluated resulting in the 95%-95% two-sided tolerance limits (upper and lower bound) - in other words at any point of time, at least 95% of the combined influence of all considered uncertainties on the calculated results is between the presented upper-lower range, at a confidence level of at least 95%.

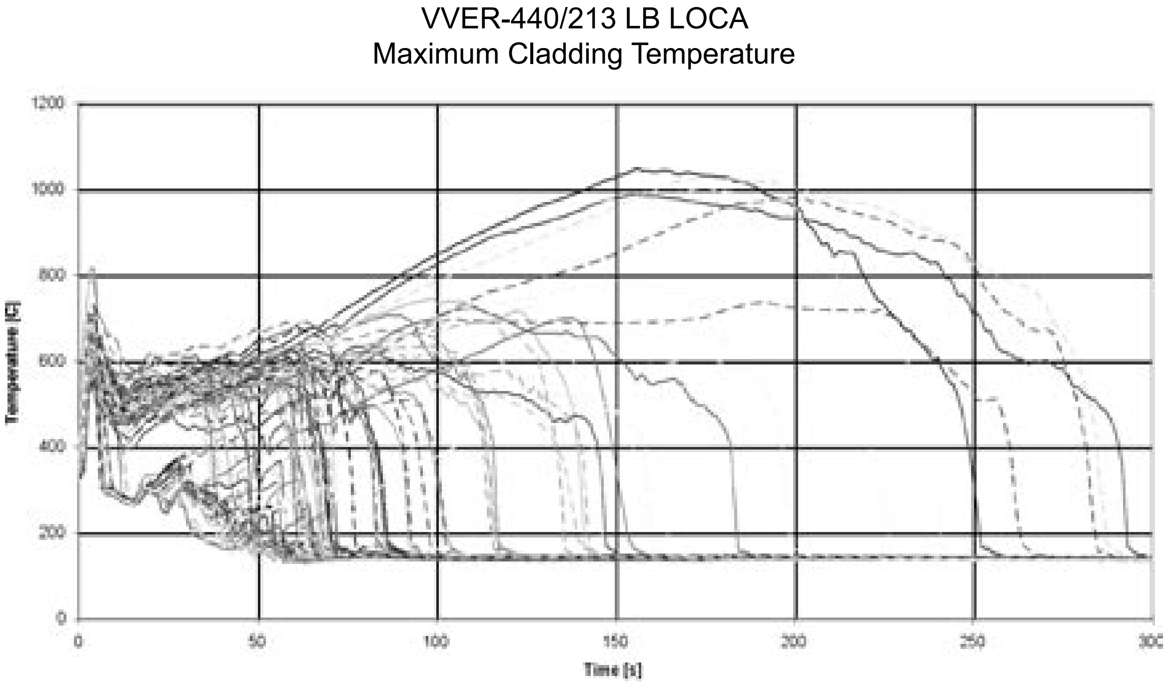

Figure 1: Time histories of maximum cladding temperatures - 93 runs

Together with this tolerance range the reference calculation (e.g. when all uncertain parameters are replaced by their nominal or best-estimate values) is depicted – see Figure 2.

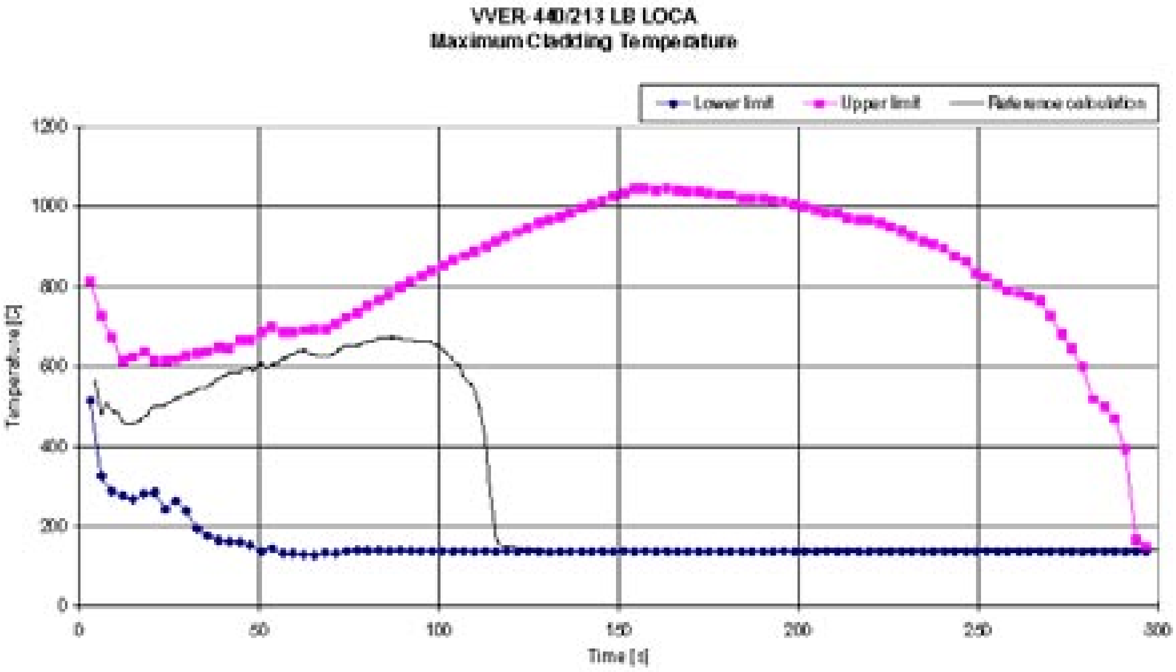

Figure 2. Reference calculation and two-sided tolerance limits for LB LOCA

Figure 3 shows the global sensitivity measures using the Rank regression coefficient indicating the influence of the uncertainty in input parameters on the maximum cladding temperature. The absolute value of each parameter represents its contribution to the uncertainty of the respective parameter (e.g. peak cladding temperature) and its sign indicates positive or negative relation (e.g. positive sign means increasing input uncertainty values tends to increasing peak cladding temperature and vice versa). Thus, conclusion from this picture is, that the most contributing uncertain parameters with respect to the peak cladding temperature are hot pin correction factor for the maximum power and temperature of the water in hydroaccumulators (positive relation) and nucleate boiling factor for Chen correlation and correction factor for single phase natural convection to water for Mc Adams correlation (negative relation). Now a more detailed look at the uncertain parameters has to be done using the SUSA statistical tools to derive some reasonable conclusions about the influence of the uncertain parameters during the course of the event. This evaluation may show where the individual parameters are most important and possibly how to improve the knowledge about the calculated event.

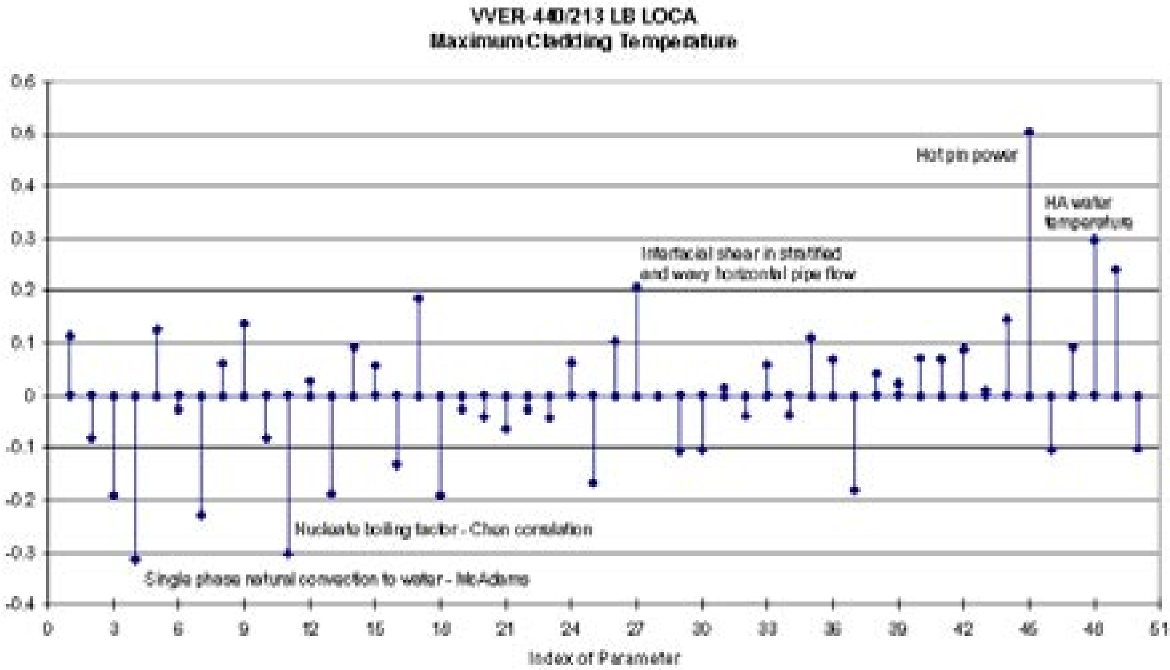

Figure 3. Standardized regression coefficients - Spearman's correlation

3.3 PRISE calculation

After finishing the LB LOCA evaluation the simulation of the PRISE (primary to secondary leak) event is planned. In the first step the SPE-3 (hot collector lift up) from PMK-NVH will be recalculated using the ATHLET computer code and the achieved results will be compared to the experimental data. Based on this simulation a list of uncertain parameters will be generated and will serve as the initial list of uncertain parameters for the PRISE event calculation for VVER-440/213 type of reactor.

4 CONCLUSIONS

Up to now the first phase of the project is completed, the regulatory staff is trained to use the GRS method and necessary software was installed and tested. The second and third phases have been initiated almost simultaneously. The input decks representing the VVER-440 reactor and the PMK-NVH facility are compiled. The list of uncertain parameters for the LB LOCA scenario has been defined and the event has been running using the ATHLET computer code and SUSA software. The achieved results have been discussed with GRS experts and are under the detailed evaluation. The similar process is planned for the PRISE event. At the end an overall evaluation of the project will be done and the possibility of the introduction of the BE+U methodology in the licensing process will be considered.

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