Integrated Uncertainty Analysis using RELAP/SCDAPSIM/MOD4.0

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ABSTRACT

The RELAP/SCDAPSIM/MOD4.0 code, designed to predict the behavior of reactor systems during normal and accident conditions, is being developed as part of an international nuclear technology Software Development and Training Program (SDTP). RELAP/SCDAPSIM/MOD4.0, which is the first version of RELAP5 completely rewritten to FORTRAN 90/95/2000 standards, uses the publicly available RELAP5 and SCDAP models in combination with (a) advanced programming and numerical techniques, (b) advanced SDTP-member-developed models for LWR, HWR, and research reactor analysis, and (c) a variety of other member-developed computational packages. One such computational package is an integrated uncertainty analysis package being developed jointly by the Technical University of Catalunya (UPC) and Innovative Systems Software (ISS).

The integrated uncertainty analysis approach used in the package uses the following steps:

1. Selection of the plant;
2. Selection of the scenario;
3. Selection of the safety criteria;
4. Identification and ranking of the relevant phenomena based on the safety criteria;
5. Selection of the appropriate code parameters to represent those phenomena;
6. Association of uncertainty by means of Probability Distribution Functions (PDFs) for each selected parameter;
7. Random sampling of the selected parameters according to its PDF and performing multiple computer runs to obtain uncertainty bands with a certain *percentile* and *confidence level*;
8. Processing the results of the multiple computer runs to estimate the uncertainty bands for the computed quantities associated with the selected safety criteria.

The first four steps are performed by the user prior to the RELAP/SCDAPSIM/MOD4.0 analysis. The remaining steps are included with the MOD4.0 integrated uncertainty analysis (IUA) package.

This paper briefly describes the integrated uncertainty analysis package including (a) the features of the package, (b) the implementation of the package into RELAP/SCDAPSIM/MOD4.0, and (c) the application of the package for a representative LB-LOCA calculation for a typical PWR.

KEYWORDS

Thermal hydraulics, Uncertainty analysis, LB-LOCA

1. INTRODUCTION

The present paper describes the uncertainty analysis of a Large Break Loss-Of-Coolant-Accident (LB-LOCA) scenario using the RELAP/SCDAPSIM/MOD4.0 code [1]. The work described in this paper is an application of a new capability implemented in RELAP/SCDAPSIM/MOD4 which allows the automatic execution of an uncertainty analysis. The improved code is suitable for any application based on a probabilistic methodology. In this case, the presented application uses a BEPU type methodology, developed by the UPC with the technical cooperation and sponsorship of the Spanish regulatory body (CSN).

The paper is divided into five main sections. The first section is a general introduction to the work. The second section outlines the main features of the BEPU methodologies and of the uncertainty methodology used in this work. The third section describes the uncertainty package implemented in RELAP5/SCDAP/MOD4.0. The fourth section goes into the detail of the methodology applied to the LB-LOCA scenario. The last section summarizes the conclusions of the exercise.

2. BEPU METHODOLOGIES

The use of best estimate codes in accident analysis for licensing applications typically requires an uncertainty evaluation. The contributors to the uncertainty results can be divided into code specific (e.g. numerical methods, physical models), plant specific data (e.g. tolerance of plant parameters), and user specific (e.g. inadequate assumptions, or the documentation used). The objective of uncertainty methodologies is to evaluate the behavior of safety related parameters by giving a range of values where an event is likely to happen rather than a single one.

The current approaches for BEPU methodologies can be divided into two main groups:

- Extrapolation of accuracy.
- Propagation of uncertainty.

The uncertainty methodology applied is based on the probabilistic approach of the "propagation of uncertainty" type proposed by GRS [2], a combination of the earlier CSAU methodology [3] with the use of Wilks' formula [4]. The early steps of the methodology are devoted to ensure the capability of the code and the nodalization developed for the analysis. The steps dealing with the propagation of uncertainties, closely related to the architecture of the developed uncertainty tool, are listed below:

1. Selection of the plant;
2. Selection of the scenario;
3. Selection of the safety criteria;
4. Identification and ranking of the relevant phenomena based on the safety criteria;
5. Selection of the appropriate code parameters to represent those phenomena;
6. Association of the Probability Density Functions (PDFs) for each selected parameter;
7. Random sampling of the selected parameters according to its PDF. Performing multiple computer runs to obtain the uncertainty bands with a certain percentile and

confidence level. The number is determined by the Wilks' formula [4] and only depends on the percentile and the confidence level of the desired uncertainty bands (and not on the number of input parameters);

8. Processing the results of the multiple computer runs to estimate the uncertainty bands for the computed quantities associated with the selected safety criteria.

As a conclusion to the uncertainty evaluation, sensitivity studies are usually performed to evaluate the selection of the input uncertainties: the sensitivity coefficients measure the influence of variations in the input parameters on the output response.

3. UNCERTAINTY PACKAGE

The application of the uncertainty package integrated into RELAP/SCDAPSIM/MOD4.0 [1] is divided into three phases, closely related to the methodology steps. Each of the phases requires an input file with a specific suffix, and a command line specifying one of the three phases (see Fig.1). The three phases, setup, simulation and post-processing are described as follows.

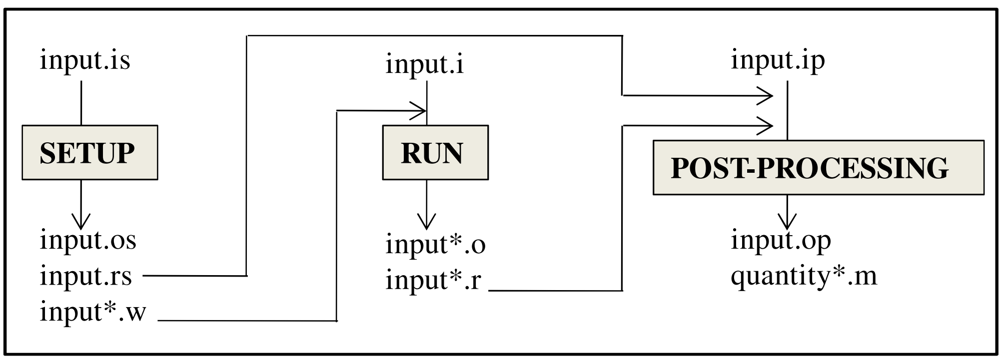

Figure 1. Uncertainty package phases and files.

3.1. First phase: Setup

The *setup phase* generates the required number of weight files containing the multipliers used for the uncertainty association. The execution of the setup phase requires an input deck file containing information related to:

- Number of uncertainty runs needed.
- Uncertainty data for input treatable parameters.
- Uncertainty data for source code coefficients.
- Base input deck.

The user may introduce Wilks' related data so that the code will compute the required number of runs. The required information is the values for:

- Percentile (<1).
- Confidence level (<1).
- Order for Wilks' formula application (1, 2...).

First two numbers describe the characteristics of the uncertainty bands to be obtained. The written percentile is the amount of the population contained between the uncertainty bounds with the desired confidence level. The two bounds, obtained at the end of the process, after going through the 3 phases, are called Unilateral Tolerance Levels. (The Unilateral Tolerance

Level means that the *percentile* and *confidence level* apply for the upper bound, and *(1-percentile)* and the *confidence level* apply for the lower bound, separately.) The order of the Wilks' formula is expected to increase the required code runs but will also obtain a more accurate estimation of the uncertainty bounds.

The number of code runs can either be computed by the code or be fixed by the user. In the latter case the code will not use the information related to Wilks' formula and will only print the information in an output file as additional information. An additional feature is the implementation of start and end numbers for a code run, which allows the continuation of previous work or the correction of any failure without starting a new process.

The package also includes the possibility of adding extra runs (which might be useful to extend the range of the analysis), setting a maximum or minimum number of runs (when the user is not sure of the number of runs computed by the code) and the introduction of the seed to start the random generating process. The next seed to be used is also written in the output print file generated in this phase and might be useful when desiring to continue previous work. These features permit the user to adapt to the specific methodology.

Uncertainty parameters are of two types: the "input treatable parameters" and the "source code coefficients". The first type can be modified using the cards of a standard RELAP5 input deck with the information required for the setup phase being RELAP5 card and word numbers. The second type of parameters are inserted through a minor modification to the RELAP source code. The parameters that could be modified through "source code coefficients" when this analysis was performed were:

- Interfacial heat transfer coefficients.
- Heat transfer coefficients.
- Critical Heat Flux.
- Gap thermal conductivity from the gap conductance model. In this correlation the user may apply different multipliers to different ranges of temperature, or a single multiplier for the whole temperature range.
- Viscosity.
- Thermal conductivity.
- Surface tension.

Other "source code coefficient" parameters can be added as needed.

The only additional input information required for the integrated analysis analysis for a given input model is the list of uncertainty parameters to be used and the PDF's associated with those parameters. For instance when a Normal Distribution is desired, the code requires the mean and the standard deviation, when a Uniform distribution is desired the maximum and minimum values are required. Up to now, 4 distribution types are available:

- Normal distribution.
- Uniform distribution.
- Log-normal distribution.
- Trapezoidal distribution.

The user can specify whether the code should compute the weight on an entered data basis or, instead, write a number – what we can call a bias – which will be used by the code for all the uncertainty runs. When sampling the values according to a normal distribution no truncation is applied.

The information needed for the input parameters is divided into two sets, the first only being related to the uncertainty distribution features and second involving cards within the input deck that can be modified. The first set requires the entry of the distribution type and the corresponding characteristic parameters. The second set requires the card numbers, the word to be modified and allows the following options:

- Use of different or equal weights for parameters with the same distribution function.
- User entered bias, instead of the computed weight.
- Normalization to the base case value. When this flag is activated, the code computes the sum of the base case values for the marked parameters and renormalizes the modified values to sum up to the same base case quantity.
- Maximum of 1 for the modified value. This feature might be useful when dealing with decay power tables with nominal power as common multiplier factor for each value.

The setup phase checks the consistency of the uncertainty data entered with the reference input deck. As a result of the setup phase three different types of files will be generated:

- Weight files: The computed or user input number of runs is used to generate the same number of weight files, which contain the multipliers to be used for each uncertainty run;
- Output print file: Contains Wilks' formula related data and the list of the uncertainty multipliers to be used when running each uncertainty code calculation;
- Restart file: contains Wilks' related information (percentile, confidence level, order of Wilks' formula application, estimated number of runs and total number of runs including requested extra runs) to be used in the post-processing phase, when building the uncertainty bounds.

3.2. Second phase: Simulation

The *simulation phase* consists of the performance of all uncertainty runs.

The files needed for the process are the base case input deck and the uncertainty weight files generated in the previous phase. Except for the reference case, each uncertainty run reads its corresponding weight file generated by the setup phase for that run.

The package allows the uncertainty runs to be restarted from a restart-plot file containing previous results.

3.3. Third phase: Post Processing

The last phase, post-processing phase, uses data coming from the previous phases to build the uncertainty bands for the desired output parameters.

In the post-processing input file, the user specifies the run numbers to be used for the statistical treatment. This allows the user to exclude selected runs if desired and to vary the number of calculations involved in the construction of uncertainty bands.

The code will use the Wilks' specified order (setup phase) and the time-dependent quantities from each restart plot file. For a specific quantity, the code will order the quantity from the minimum value (order 1) to the maximum value (order N, where N is the number of calculations) at each time step. The number of resulting curves will be the same as the number of the calculations but now each curve corresponds to a rank rather than to a simulation.

Depending upon the specified order, the code will use the first and last (N) orders (1st order), second and N-1 order (2nd order), and so on.

By means of minor edits, the user introduces the quantities for which the uncertainty bands are to be obtained. After running this phase, the code will produce graphs containing the time history for the:

- Upper and lower uncertainty bands, according to Wilks' information introduced in setup phase, and built according to order statistics.
- Base case value.
- Difference between upper and lower values at each time step.

The post-processing phase also generates EXCEL compatible files with the sorted values for each required quantity in the input file. From these files, scalar quantities such as time of core quench or peak cladding temperature can be obtained with little effort.

4. APPLICATION TO A LB-LOCA

A first application of the package has been performed on a simulated LB-LOCA scenario in a typical NPP. The simulated NPP is a 3000 MWth PWR of Westinghouse design. It has a 3-loop configuration with the pressurizer connected to the third loop. HPIS and LPIS pumps inject into the cold legs. Accumulators are connected to each cold leg and have independent lines. SGs are of the U-tube type.

4.1. Input deck

The input deck models the three loops separately (see Fig.2). The downcomer is modeled by three annulus components, one per loop. The three downcomers are connected by crossflow junctions, except at the entrance to avoid excessive bypass flow to the broken cold leg.

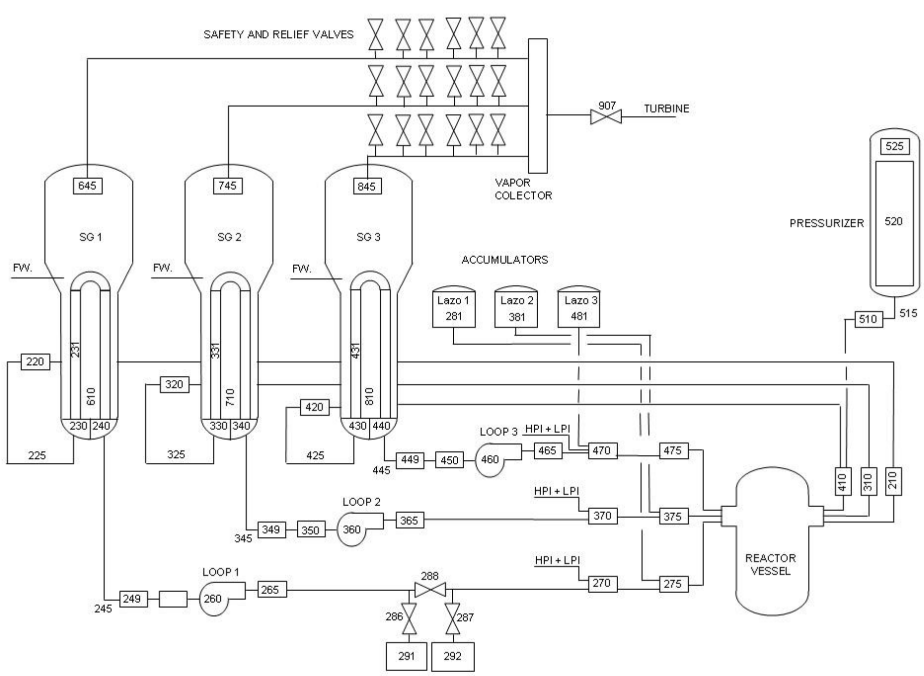

Figure 2 NPP nodalization for a LB-LOCA simulation

The core is modeled using two pipes connected at each level by crossflow junctions (see Fig.3). Heat structures simulating the fuel are of 3 types:

- Average rods, associated to the peripheral channel.
- Average hot rods, associated to the hot channel.
- A single hot rod, associated to the hot channel.

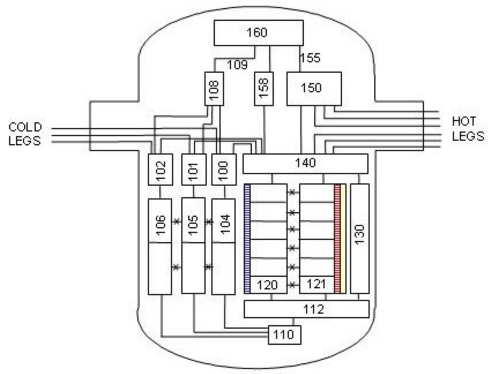

Figure 3 Reactor pressure vessel nodalization

The safety injection system is connected to cold legs. Each loop has an accumulator and LPIS.

4.2. Scenario features

A double ended guillotine break is simulated in the cold leg, close to the vessel connection. The reactor is at rated power when the pipe rupture takes place. The break initiates after 1000 seconds of steady state and is modeled by means of two trip valves connected to time dependent volumes simulating containment conditions (see Fig.2). Time dependent volume conditions are set by time dependent pressure tables.

Imposed events:

- Beginning of the transient at t_{break} = 1000s by opening break valves.
- Scram at t_{break}. A table with multipliers to nominal power is used for power after scram (residual and fission products heat).
- Pumps trip at t_{break}. Pump velocity after the break is input by a time-velocity table: two different tables are built, one for the broken and the other for the intact loops.
- MFW stops at t_{break} + 20 seconds.
- Steam lines are isolated at t_{break} + 10 seconds.
- No AFW simulated.
- No HPIS simulated.

LPIS behavior is controlled by a pressure-flow table.

4.3. Base case results

The characteristic periods for the LB-LOCA scenario, based on trends in changes in the liquid inventories of the vessel, the core, and the lower plenum are:

- Blowdown, which begins with the break initiation and ends when accumulator injection initiates in the intact loops;
- Refill, which begins with accumulator injection and ends when the mixture level in the

lower plenum reaches the core inlet;
- Reflood, which starts when the liquid mass in the core starts to increase and ends when the whole core is quenched and submerged again.

The blowdown period lasts for 12 seconds, at that time accumulators in the intact loops start injecting and the refill phase begins. At 18.5 seconds after the break, the primary pressure falls below the low pressure set point (1.8 MPa) and the three LPIS start injecting. The refill phase lasts roughly 18 seconds. At the end of the refill phase the core inlet is filled again with liquid (see Figures 5 and 6). Core quenching occurs approximately 450 seconds after initiation of the break.

Concerning the maximum cladding temperature time trend (see Figure 5), the first peak cladding temperature, the so-called blowdown peak, is produced during the fast depressurization (see Figure 4) following the opening of the valves. The blowdown peak has a value of 1106 K and occurs 7.5 seconds after initiation of the break. The second peak cladding temperature, the so-called reflood peak, has a value of 1237 K and occurs 205 seconds after initiation of the transient. This reference calculation has been performed with the purpose of showing the performance of the uncertainty package capabilities.

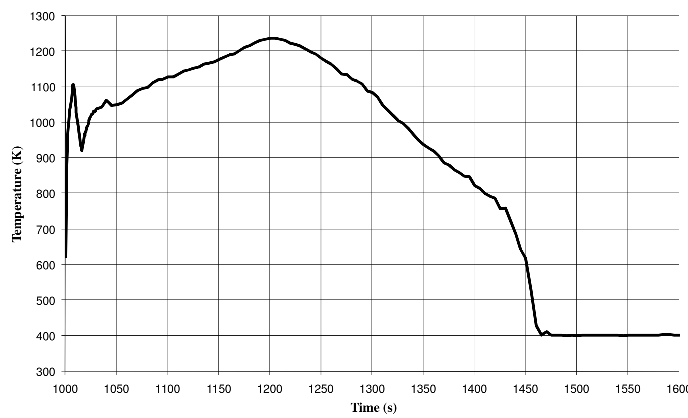

Figure 4 Maximum cladding temperature

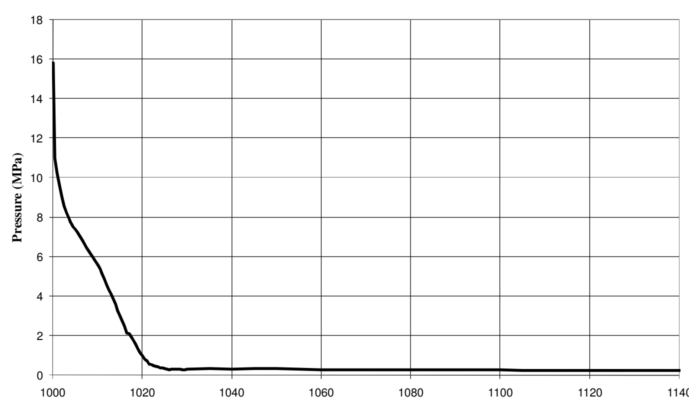

Figure 5 Primary pressure

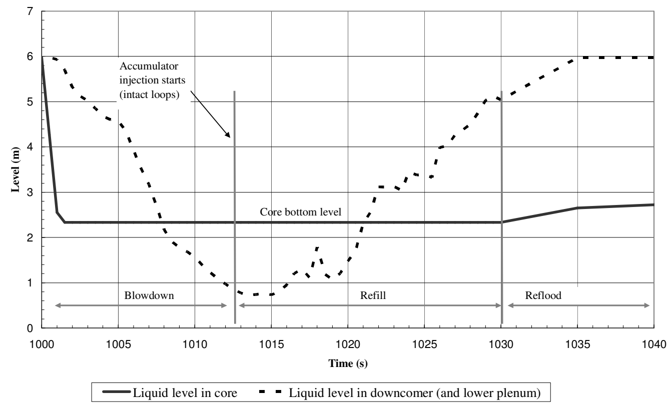

Figure 6 Calculated core and lower plenum levels, defining blowdown, refill and reflood phases

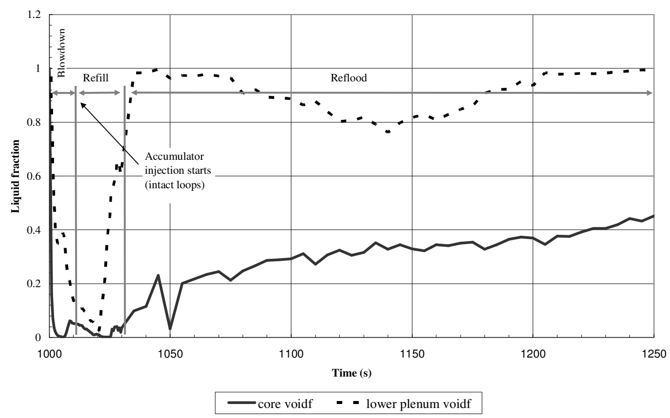

Figure 7 Calculated liquid fractions in core and lower plenum showing blowdown, refill and reflood phases

4.4. LB-LOCA Uncertainty Analysis: Setup

The analysis was performed at Wilks' third order with a percentile and a confidence level of 0.95 each. Thus, 124 calculations were needed. No extra code runs were performed. Following the recommendations of BEMUSE project [5] all calculations should be successful runs or corrected in case of run failures. Nevertheless, application of the formula at the third order would permit two run failures since they could be discarded by considering conservatively their results and associating the maximum or the second maximum value of the quantity (order N-1 and order N). If extra runs are needed the uncertainty package allows the user to build a new uncertainty run from the last seed used in the analysis.

Forty four input quantities were selected for the uncertainty analysis. Two tables were used to describe the uncertainty input parameters. Table 1 refers to input treatable parameters and contains 20 parameters. These parameters refer to initial plant conditions and material properties. Table 2 refers to the internal multipliers built-in the code correlations and sums up to 24 multipliers. These parameters are code correlations to the simulated physical phenomena related to wall heat transfer in the core and interfacial heat transfer between the liquid and vapor phases.

The set of uncertainty parameters were selected on the basis of previous uncertainty analyses such as Phase V of BEMUSE [6], PIRT documentation [7] and expert judgment [8].

Table 1 Input treatable parameters

	Phenomena	Description	SPDF	Comments
01	Fuel thermal behavior.	Initial core power	Normal	-
02		Power after scram	Normal	-
03		Peaking factor	Normal	Hot rod axial power.
04		Fuel thermal conductivity	Normal	$T \leq 2000.K$
05			Normal	$T > 2000.K$
06		Fuel volumetric specific heat	Normal	$T \leq 1800.K$
07			Normal	$T > 1800.K$
08	Pump behavior	Rotation speed after break	Normal	Intact loops
09			Normal	Broken loop
10	Data related to injections.	Accumulator pressure	Normal	3 accumulators.
11		Friction form loss in accumulator line	Log-normal	3 accumulators.
12		Accumulator liquid temperature	Normal	3 accumulators.
13		Flow characteristic of LPIS	Normal	3 LPIS.
14	Pressurizer.	Initial pressurizer pressure	Normal	-
15		Friction form loss in the surge line	Log-normal	-
16	CCFL.	Gas intercept in Wallis correlation.	Uniform	Upper core tie plate.
17	Flow rate at the break.	Containment pressure	Uniform	Time-pressure tables (both sides of the break).
18		Break discharge coefficients.	Uniform	Subcooled flow.
19			Uniform	Two phase flow.
20	Pressure drops.	Core form loss coefficients.	Uniform	Core pipes

Table 2 Source code coefficients

	Phenomena	Description	SPDF	Comments
01	Fuel thermal behavior.	Gap conductivity	Uniform	Gap conductance model.
02	Interfacial Heat Transfer	Bubbly flow regime	Uniform	Heat transfer to liquid.
03			Uniform	Heat transfer to vapor
04		Slug flow regime	Uniform	Heat transfer to liquid.
05			Uniform	Heat transfer to vapor
06		Annular mist flow regime	Uniform	Heat transfer to liquid.
07			Uniform	Heat transfer to vapor
08		Mist pre-CHF flow regime	Uniform	Heat transfer to liquid.
09			Uniform	Heat transfer to vapor
10		Mist flow regime	Uniform	Heat transfer to liquid.
11			Uniform	Heat transfer to vapor
12		Mist post-CHF flow regime	Uniform	Heat transfer to liquid.
13			Uniform	Heat transfer to vapor
14		Horizontal stratified flow regime	Uniform	Heat transfer to liquid.
15			Uniform	Heat transfer to vapor
16	Wall heat transfer for bundle geometry.	Single phase liquid	Uniform	(Mode 2)
17		Single phase gas	Uniform	(Mode 9)
18		Nucleate boiling	Uniform	Subcooled regime (Mode 3)
19			Trapezoidal	Saturated regime (Mode 4)
20		Transition boiling	Trapezoidal	Subcooled regime (Mode 5)
21			Trapezoidal	Saturated regime (Mode 6)
22		Film boiling	Trapezoidal	Subcooled regime (Mode 7)
23			Trapezoidal	Saturated regime (Mode 8)
24	CHF	Groenveld look up table	Log-normal	Multiplier to table.

The four available distribution functions were used for the exercise.

Specific features available in the uncertainty package were used for the following parameters:

- Normalization feature was used for the peaking factor in hot rod: the axial power profile of hot rod in hot channel was modified in the three nodes with higher weighting factor, the normalization flag was applied to the whole profile so that the resulting sum wouldn't exceed the base case sum.
- The power after scram was modified by adding a multiplier to the values of the reference case, which are a fraction of the initial power. This multiplier only affects to values for time ≥ 0.3 s, that is once the scram occurs. According to BEMUSE phase V procedures [6], a maximum of 1.0 was required for the new multiplier so that the resulting curve wouldn't exceed the initial power.

4.5. LB-LOCA Uncertainty Analysis: Simulation and Post Processing

The simulation included the base case and 124 runs. The post processing generates for each desired output quantity a graph as a function of time with the base case time trend, the upper and the lower uncertainty limits, and the variation between the upper and lower limits. Maximum cladding temperature and the primary pressure were selected for the post processing in this example. The post processing also generates EXCEL compatible files for each of the desired output quantities. These files contain the values sorted according to their rank (magnitude). The desired unilateral tolerance limits can be constructed by taking into account the Wilks' order of application. The uncertainty bands for the maximum cladding temperature and the primary pressure are depicted in Figure 8 and Figure 9 together with the reference case time trend.

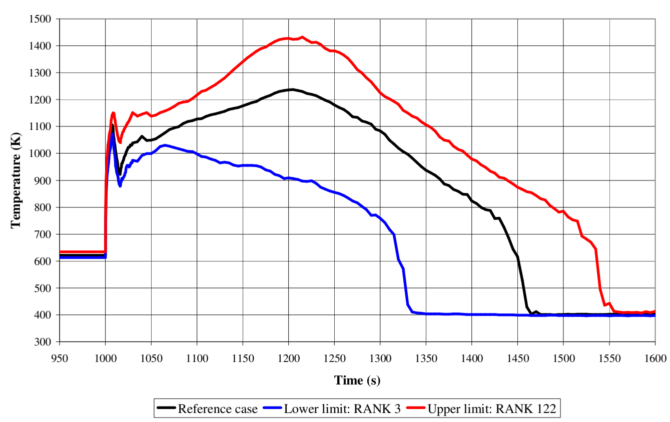

Figure 8 Maximum cladding temperature uncertainty bands

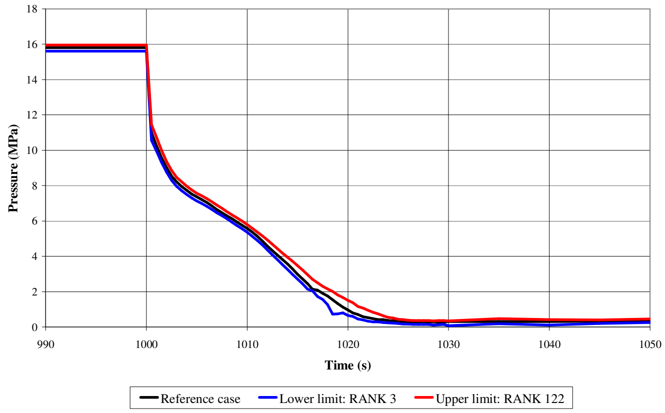

Figure 9 Primary pressure uncertainty bands

The results from the 124 calculations, required for the third order Wilks analysis, also can be used to evaluate the influence of sample selection as well as the order of the analysis. For example, the influence of the sample selection can be evaluated by comparing the uncertainty bands resulting from a first order Wilks analysis derived from the first set of 59 calculations with the ones from the second set of 59 calculations. The results for the maximum cladding temperature time trend are depicted in Figure 10. Each set of calculations was generated by varying the same uncertainty parameters with the same subjective probability functions using two different sampling sets of random numbers. An example of the evaluation of the influence of the order of the analysis is given in Table 3. In this case, the results of the first, second, and third order analysis can be compared along with influence of sample selection for the first order.

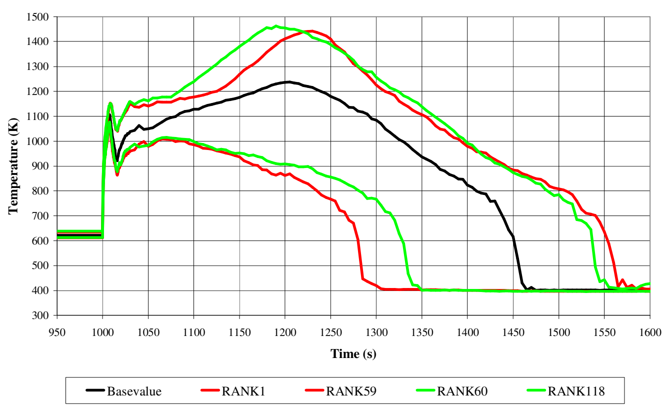

Figure 10 Sample size effect on uncertainty bands

Table 3 Maximum peak cladding temperature. Comparison

Temperature is in K.	Lower limit 5/95	Reference Case (RC)	Upper limit 95/95	Band width	Upper limit – RC
1st order (run numbers 1 to 59)	1086	1237	1441	356	204
1st order (run numbers 60 to 118)	1079		1462	383	225
2nd order (run numbers 1 to 93)	1084		1441	358	204
3rd order (run numbers 1 to 124)	1086		1441	356	204

Since the purpose of the work is not a safety analysis, any comments regarding the results should be carefully evaluated. However, the following comments would apply to this example.

- Maximum cladding temperature:
  - The resulting upper uncertainty limit falls below the safety criterion for the maximum peak cladding temperature of 1478 K (2200 ^{0}F).
  - The maximum band width (about 730 K) occurs near the time the reference case's core has been completely reflooded.

- Primary pressure:
  - The uncertainty band is rather small, which has been a characteristic of results produced by analogous probabilistic BEPU methodologies [5].
  - Maximum uncertainty band is 1.3 MPa and occurs 18.5 seconds after break initiation. This is the time when the LPIS starts injecting in the reference case.

5. CONCLUSIONS

A package to perform integrated uncertainty analyses has been developed and integrated into RELAP/SCDAPSIM/MOD4.0. The integrated tool allows performing different steps of a probabilistic BEPU methodology with mimimal changes to a standard RELAP input input model and standard RELAP5 model source coding. Statistical and thermal hydraulic simulation steps have been successfully combined in a very "user friendly" way.

An application of the uncertainty package has been performed with successful results for a Large Break LOCA scenario.

NOMENCLATURE

AFW: Auxiliary Feed Water.
BEMUSE: Best Estimate Methods Uncertainty and Sensitivity Evaluation.
BEPU: Best Estimated Plus Uncertainty.
CCFL: Counter Current Flow Limitation.
CHF: Critical Heat Flux.
CSN: Spanish regulatory body.
HPIS: High Pressure Injection System
ISS: Innovative System Software.
LB-LOCA: Large Break Loss of Coolant Accident.
LPIS: Low Pressure Injection System.
MFW: Main Feed Water.
NPP: Nuclear Power Plant.
PDF: Probability Density Function.
PIRT: Phenomena Identification and Ranking Table.
PWR: Pressurized Water Reactor.
SG: Steam Generator.
SPDF: Subjective Probability Density Function.
UA: uncertainty analysis.
UPC: Technical University of Catalonia

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