Integrated Uncertainty Analysis using RELAP/SCDAPSIM/MOD4.0

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Abstract

The RELAP/SCDAPSIM/MOD4.0 code, designed to predict the behaviour of reactor systems during normal and accident conditions, is being developed as part of the international SCDAP Development and Training Program (SDTP). RELAP/SCDAPSIM/MOD4.0, which is the first version of RELAP5 completely rewritten to FORTRAN 90/95 standards, uses 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 and Innovative Systems Software.

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

1. Selection of the scenario
2. Selection of the safety criterion
3. Identification and ranking of the important phenomena
4. Selection of appropriate RELAP5 parameters to represent those phenomena
5. Association of the appropriate Probability Distribution Functions (PDF) for each selected parameter
6. Random sampling of the selected parameters according to its PDF and performing a number of computer runs to obtain the uncertainty bands with a certain *percentile* and *confidence level*
7. Processing the results of the multiple computer runs to estimate the uncertainty bands for computed quantities associated with the selected safety criterion.

The first three steps would be performed by the user prior to the RELAP/SCDAPSIM/MOD3.4 analysis while the remaining steps are included with the MOD4.0 integrated uncertainty analysis (IUA) package. The user would then select the appropriate RELAP parameters including both input quantities and source code quantities that are to be perturbed, define the appropriate PDFs, and then select the appropriate percentile and confidence level (typically using the default Wilks' formula) and start sampling computer runs. Using the base input model, the code automatically perturbs the selected parameters for each computer run and generates the necessary output files for the post-processing run. The post-processing run builds the uncertainty bands of the desired output parameters, plots the desired output parameters with uncertainty bands, and sorts their values according to its ranks. The values sorted in ranks are generated in EXCEL-compatible files that can be edited for further data analysis.

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 LBLOCA calculation for a typical PWR.

Keywords

Thermal Hydraulics, Uncertainty Analysis, LBLOCA

1. INTRODUCTION

Best Estimate plus Uncertainty (BEPU) methods are nowadays broadly used worldwide. Engineering organizations devoted to perform calculations for licensing Nuclear Power Plants are the most significant end users of such methodologies. Although different methods are available, most of them are based on propagation of input uncertainties. These are usually statistical methods using Wilks' formula to determine the number of calculations needed to produce a certain uncertainty band around the established reference case.

The Technical University of Catalonia is by now completing its own development in the field of BEPU methodology. The predecessor of this method has been used in the OECD BEMUSE programme, which is a comparative exercise of different BEPU methods. BEMUSE has provided an opportunity to gain insights on the existing approaches, and also on different codes and different techniques devoted to solve a common problem.

To perform an uncertainty analysis, as explained below, different steps have to be defined and followed and the most significant of them are connected to the selected thermal hydraulic code and processing of the results produced.

The main goal of this paper is to describe and use a computational package that integrates uncertainty analysis and thermal hydraulic calculation. The package has been developed jointly by Innovative Systems Software and the Technical University of Catalunya.

Uncertainty methodology followed by the package is of the type of input uncertainty propagation. These methodologies associate uncertainty to a number of input parameters and by running massive calculations and using statistic statements obtain uncertainty bands for the desired output parameters.

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

1- Selection of the scenario.
2- Selection of the safety criteria.
3- Identification and ranking of the relevant phenomena based on the safety criteria.
4- Selection of the appropriate RELAP5 parameters to represent those phenomena.
5- Association of Probability Density Functions (PDFs) for each selected parameter.
6- Random sampling of the selected parameters according to its PDF. Performing a number of computer runs to obtain the uncertainty bands with a certain percentile and confidence level.
7- Processing the results of the multiple computer runs to estimate the uncertainty bands for computed quantities associated with the selected safety criteria.

Steps 4 to 7 are covered by the package.

The package has a robust skeleton; although it is known to the developers that some further work is needed to improve and allow a wider range of the capabilities.

2. PACKAGE DESCRIPTION

The package is integrated in RELAP/SCDAPSIM/MOD3.4 and 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. The three steps, setup, simulation and post-processing are described in what follows.

2.1 First phase: setup

The first one, *setup phase*, covers steps 4 and 5 of the methodology and generates the required number of weight files containing the multipliers used for uncertainty association (up to now, uncertainty is associated only by means of multipliers). An input deck file with specific suffix ".is" is required.

Information held in it is related to:

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

A proper command line executes Relap5 in this setup mode. 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 of Wilks' formula application (1, 2...).

First two numbers describe the uncertainty bands to be obtained. The written percentile is the amount of population contained in between the uncertainty bounds with the written confidence level. The two bounds obtained at the end of the whole process, after going through the 3 phases, are called Unilateral Tolerance Levels, which means that *percentile* and *confidence level* apply for the upper bound, and *(1-percentile)* and *confidence level* apply for the second bound, separately. The order of Wilks' formula is expected to increase the required code runs but also to obtain a more accurate estimation of the uncertainty bounds.

The number of code runs can also be fixed by the user, then the code will not use the information related to Wilks' formula and will only print it in an output file as additional information. Code also permits to give start and end numbers of code runs (which allows the continuation of previous work or the correction of any failure without starting a new process).

The package also gives the possibility of adding extra runs (which might be useful for possible code failures), setting maximum and minimum number of runs (when not being sure about what will be the computed number by the code) and the introduction of the seed to start the random generating process. 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 last features permit the user to adapt to the specific methodology.

The package also allows the user to modify the built-in PDFs for the code correlations. Up to now, correlations available for uncertainty association are:

- Interphase heat transfer coefficients. (flow type related)
- Heat transfer coefficients.
- Critical Heat Flux (only for PG correlations and lookup table method)
- Gap thermal conductivity from gap conductance model. In this correlation the user my associate different multipliers to different ranges of temperature. A single multiplier for the whole temperature range is also allowed.
- Viscosity.
- Thermal conductivity.
- Surface tension.

The required information is the type of PDF and characteristic parameters. For instance when Normal Distribution is desired, the code requires the mean and the standard deviation, when Uniform distribution, maximum and minimum values are required. Up to now 4 types of distribution are available:

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

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

The information for input parameters is divided into two sets, first one being only related to uncertainty distribution features and second one involving cards within the input deck to be modified. First set requires the entry of the distribution type and the corresponding characteristic parameters. 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 associated.
- User entered bias, instead of computed weight.
- Normalization to the base case value. When the flag is activated, the code computes the sum of the base case value 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 also checks consistency of uncertainty data entered with the reference input deck. As a result of the setup phase different types of files will be generated:

- Weight files: The computed or user input number of runs is used to generate the same amount 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, to be used in the post-processing phase, when building the uncertainty bounds.

2.2 Second phase: simulation

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

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

The package also allows the simulation runs to be restarted from a restart-plot file containing steady-state results.

2.3 Third phase: post processing

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

In post-processing input file, the user specifies the run numbers to be used for the statistical treatment. This allows avoidance the use of failed codes and to vary the number of calculations involved in the uncertainty bands construction.

The code will use Wilks' specified order (setup phase) and time-dependent quantities from each restart plot file. For a specific quantity, the code will order from the minor value (order 1) to the maximum value (order N, where N is the number of calculations) at each time step, the resulting curves will be the same as the number of the calculations but will not step each other since they have been ordered in increasing order. Depending upon the specified order, the code will use the first and last (N) orders (1^{st} order), second and N-1 order (2^{nd} order), and so on.

By means of minor edits, the user introduces the quantities for which the 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 of 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.

3 APPLICATION OF THE PACKAGE: LBLOCA IN A SPANISH NPP

A first application of the package has been performed on a LBLOCA scenario simulated in a typical NPP. Simulated NPP is a 2940 MWth PWR of Westinghouse design. It has a 3-loop configuration with the pressurizer connected to the third loop. HPIS and LPIS pumps inject in cold legs. Accumulators are connected to each cold leg and have independent lines. SGs are of U-tube type.

3.1 Input deck

The input deck simulates the three loops separately.
The downcomer is simulated by three annulus components, one per loop. The three downcomers are connected by crossflow junctions, except for the entrance to avoid excessive bypass to the broken cold leg.

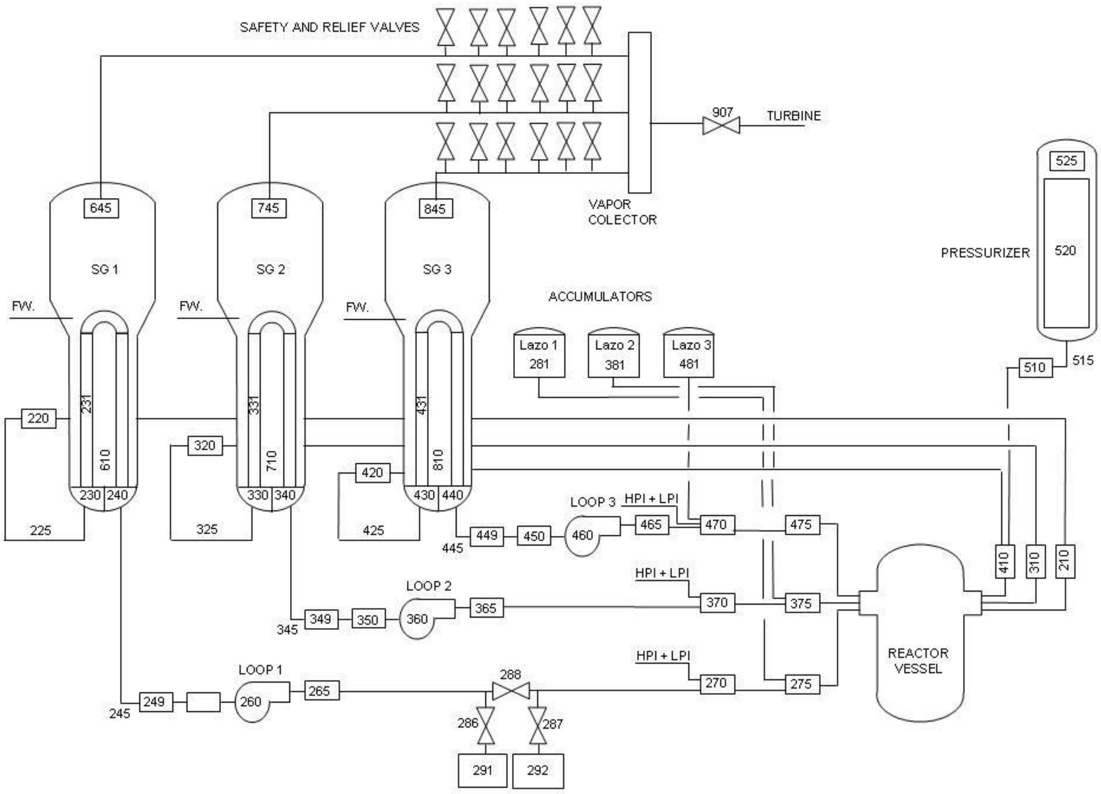

Fig. 1 NPP nodalization for a LBLOCA

The core is simulated with two pipes connected at each level by crossflow junctions. Heat structures simulating the fuel are of 3 types (see Fig.2):

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

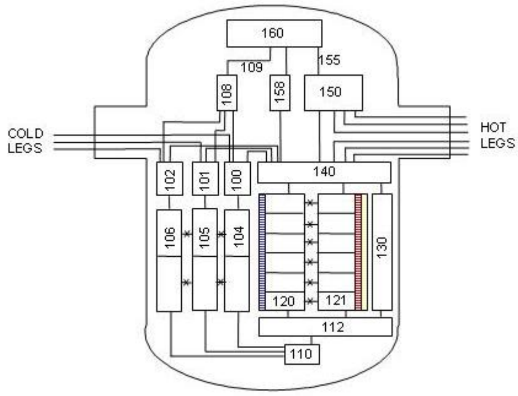

Fig. 2 Reactor vessel nodalization

Safety injection is connected to cold legs. Each loop has an accumulator and LPIS (see Fig.1).

3.2 Transient features

A double ended guillotine break is simulated in the cold leg, close to the vessel connection. The reactor is at full power when the pipe rupture takes place.
The break takes place after 1000 seconds of steady state. The break is simulated by means of two trip valves connected to time dependent volumes simulating containment conditions (see Fig.1). Time dependent volume conditions are set by time pressure tables.

Imposed events:

- Beginning of the transient at t_{break} = 1000s by opening break valves.
- Scram at t_{break}.
- Pumps trip at t_{break}.
- MFW stops at t_{break} + 20 seconds.
- Steam lines are isolated at t_{break} + 10 seconds.
- No AFW simulated.
- No HPIS simulated.
-

Pump velocity after the break is input by a time-velocity table, 2 different tables are built, one for the broken and another one for intact loops.
A table with multipliers to nominal power is used for power after scram (residual and fission products heat)
LPIS behaviour is ruled by a pressure flow table.

3.3 Base case results

The characteristic periods of the LBLOCA scenario based on trends of 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 the accumulator injection initiates in the intact loops
- Refill, which begins with the 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 is of 13 seconds, at that time accumulators in the intact loops start injecting. At 19 seconds after the break LPIS of the three loops start injecting. Refill phase, started 13 seconds after the break, lasts a period of about 26 seconds, when core inlet is filled again with liquid phase. Core quenching occurrence is at about 460 seconds after break initiation.
First peak cladding temperature, reached during first depressurization after valves opening, has a value of 1102. Second peak cladding temperature is 1177 K, reached in reflood phase, 173 seconds after the

initiation of the transient.

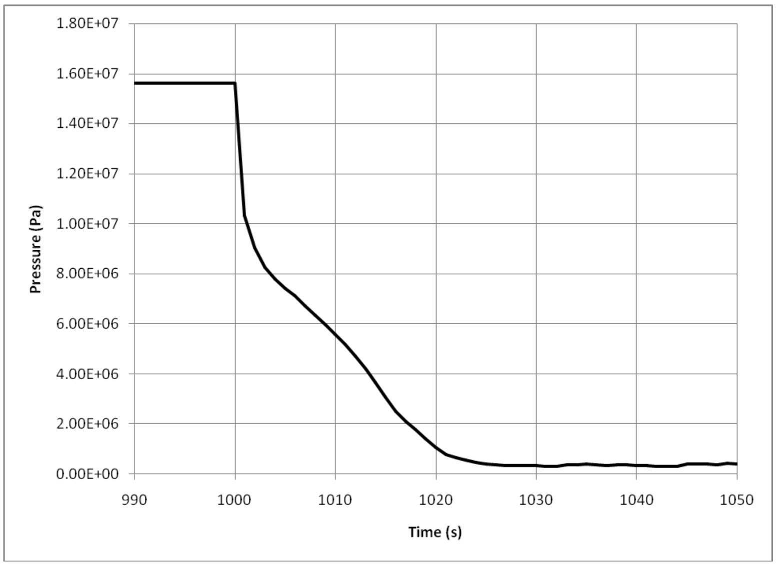

Fig. 3 Base case - Primary pressure

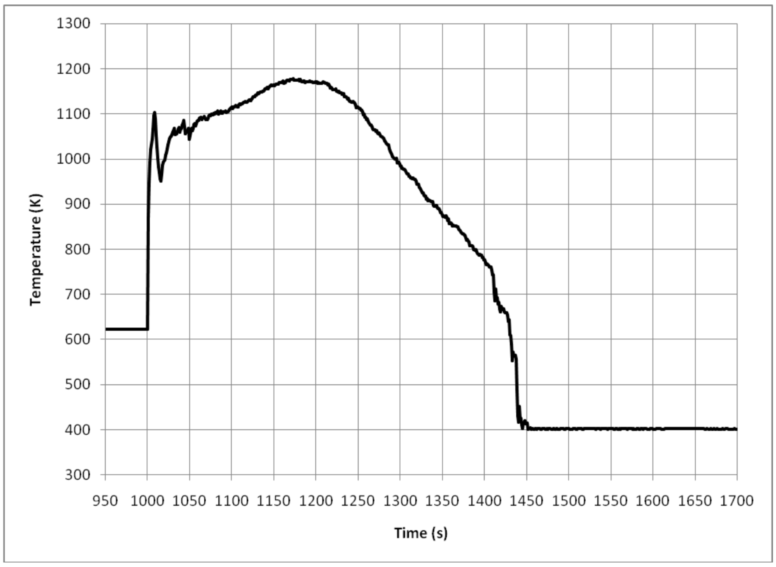

Fig. 4 Base case - Maximum cladding temperature

3.4 Setup phase – Determination of code runs and uncertainty parameters

The analysis was performed at Wilks' first order, with a percentile and confidence level of 0.95 each. Thus 59 code runs are needed. In addition, 11 extra code runs were requested in the setup file to take into account possible failures. The total number of weight files generated by the package is 70.

A total number of 29 input quantities were selected for the uncertainty analysis. Two tables are used for the description of the uncertainty input parameters. First one (see Table 1) refers to input treatable parameters and contains 22 parameters suitable to modification by means of input deck cards. Second one (see Table 2) refers to internal multipliers built in code correlations and sums up to 7 multipliers.

The list of the input uncertainty quantities was built by means of PIRT (Ref.3) and expert judgment (Ref.4 and Ref.5). The uncertainty PDFs were associated according to technical data and expert judgment.

Num.	Phenomena	Description	PDF	Parameter
01	Fuel thermal behaviour.	Initial core power	Normal distr.	Multiplier to base case value.
02		Power after scram	Normal distr.	Multiplier to power after scram table.
03		Peaking factor.	Normal distr.	Hot rod axial power shape.
04		Fuel thermal conductivity	Normal distr.	Property table. T ≤ 2000. K
05			Normal distr.	Property table. T > 2000. K
06		Fuel volumetric specific heat	Normal distr.	Property table. T ≤ 1800. K
07			Normal distr.	Property table. T > 1800. K
08	Pump behaviour.	Rotation speed after break.	Normal distr.	Intact loops table.
09			Normal distr.	Broken loop table.
10	Data related to injections.	Accumulator pressure.	Normal distr.	3 accumulators.
11		Friction form loss in accumulator line.	Log-normal distr.	3 accumulators.
12		Accumulator liquid temperature.	Normal distr.	3 accumulators.
13		Flow characteristic of LPIS.	Normal distr.	3 LPIS.
14	Pressurizer.	Initial pressurizer pressure.	Normal distr.	Pressurizer control component.
15		Friction form loss in the surge line.	Log-normal distr.	Pressurizer surge line.
16	Initial conditions: Primary system.	Initial intact loop mass flow rate.	Normal distr.	Initial (steady-state) pumps' velocity.
17	CCFL.	Gas intercept in Wallis correlation.	Uniform distr.	Upper core tie plate.
18	Flow rate at the break.	Containment pressure	Uniform distr.	Time-pressure tables (both sides of the break).
19		Break discharge coefficients.	Uniform distr.	Subcooled flow.
20			Uniform distr.	Two phase flow.
21	Critical heat flux.	Local boiling factor.	Uniform distr.	Fuel heat structures.
22	Pressure drops.	Core form loss coefficients.	Uniform distr.	Core pipes (inner and outer channels).

Table 1. Input treatable parameters

List of distribution used and their characteristic parameters:
- Uniform distribution: [minimum value, maximum value]
- Normal distribution: [mean-1.96 sd, mean+1.96 sd] where sd – standard deviation
- Log-normal distribution: mean, sd of the normal distribution, the code takes the exponential of the obtained multiplier for the normal distribution.
- Trapezoidal distribution: [lower left, left, right, upper right]

Normalization feature has been 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 weigh factor, the normalization flag was applied to the whole profile so that the resulting sum wouldn't exceed the base case sum.

A maximum of 1.0 was required for the power after scram multiplier so that the resulting curve wouldn't exceed the nominal power.

As stated above, built-in correlations have a unique value of 1. for multipliers (except for PG-CHF correlations). Table below lists the PDFs associated to 7 quantities suitable for uncertainty association.

First one is gap conductivity for gap conductance model (activated in the three heat structures simulating the fuel), the other 6 are related to wall to fluid heat mode transfers for bundle geometry without cross flow (number 110).

Num.	Phenomena	Description	PDF	Parameter
23	Fuel thermal behaviour.	Gap conductivity.	Uniform distr.	Gap conductance model. Fuel HSs.
24	Heat transfer.	Subcooled nucleate boiling.	Uniform distr.	Mode 3. Bundle geometry (110)
25		Saturated nucleate boiling.	Trapezoidal distr.	Mode 4. Bundle geometry (110)
26		Subcooled transition boiling.	Trapezoidal distr.	Mode 5. Bundle geometry (110)
27		Saturated transition boiling.	Trapezoidal distr.	Mode 6. Bundle geometry (110)
28		Subcooled film boiling.	Trapezoidal distr.	Mode 7. Bundle geometry (110)
29		Saturated film boiling.	Trapezoidal distr.	Mode 8. Bundle geometry (110)

Table 2. Source code quantities.

3.5 Simulation phase

A batch file was prepared to run the base case (run number 0) and the 70 runs.
There were 10 code failures, 3 of them could be solved. The 63 successful cases are sufficient code runs to apply Wilks' formula with confidence level ≥ 0.95.

3.6 Post processing phase

A post processing file was used to select the successful code runs and the output parameters for the uncertainty analysis. A total number of 63 code runs were used for the uncertainty bands.

For the present application, the selected output quantities for the uncertainty study were the maximum cladding temperature and the primary pressure.

A graphic for each specified output quantity is generated after running the post processing phase. The graphic contains the base case time trend, the upper and the lower uncertainty bands, and the difference between the two bounds.

An EXCEL compatible file is generated for each of the requested quantities when executing post processing phase. These files contain the values sorted according to its rank (magnitude). Fig.5 and Fig.6 are obtained from each of these files generated after running post processing phase by using EXCEL. In each graphic there are depicted the base case time trend, the upper uncertainty bound and the lower uncertainty bound.

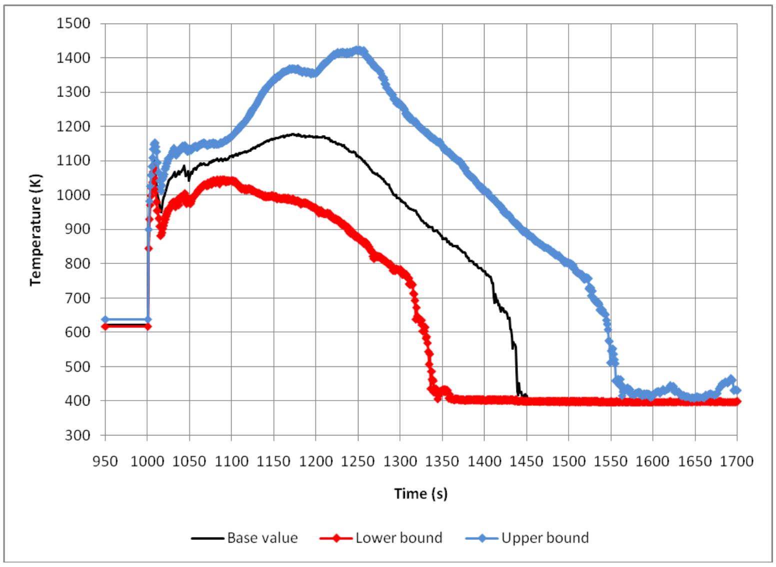

Fig. 5 Uncertainty bands - Maximum cladding temperature

Peak cladding temperature, computed from maximum cladding temperature file, has a value of 1424 K and is produced at 252 seconds after the break.

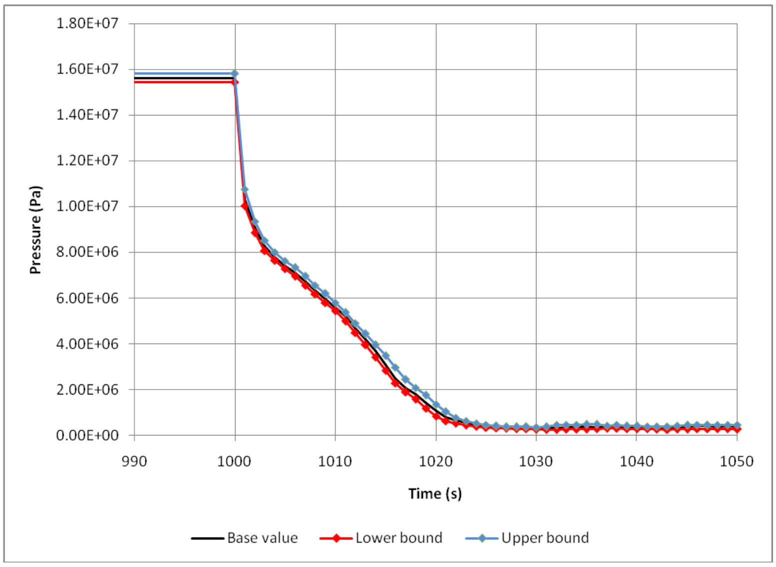

Fig. 6 Uncertainty bands - Primary pressure

4 CONCLUSION

A package to compute integrated uncertainty analyses has been developed and integrated to RELAP/SCDAPSIM/MOD4.0. The integrated tool allows performing different steps of the BEPU methodology minimizing data transfer and thus avoiding some error sources. Statistical and thermal hydraulic simulation steps have been successfully combined.

A first application of this uncertainty package has been performed with successful results for a Large Break LOCA scenario. The order of magnitude of the uncertainty bands obtained for the maximum cladding temperature and for the primary pressure is reasonable. The general results of study are close to those of recent international comparative exercises.

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.
HPIS: High Pressure Injection System.
HS: Heat Structure.
LBLOCA: 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: Pressurised Water Reactor.
SG: Steam Generator.

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