







Development of sensitivity and uncertainty analysis tool for reactor dynamics codes

Authors: Elina Syrjälähti

Confidentiality: Public

Report's title	
Development of sensitivity and uncertainty analysis tool for reactor dynamics codes	
Customer, contact person, address	Order reference
SAFIR2010 Research Programme (VYR,VTT)	
Project name	Project number/Short name
TRICOT, Tridimensional core transient analysis methods	13228
Author(s)	Pages
Elina Syrjälähti	15
Keywords	Report identification code
Sensitivity and uncertainty analysis, reactor dynamics	VTT-R-00843-08
<p>Summary</p> <p>This report describes the work done in the subtask of the SAFIR2010/TRICOT project. The work with the sensitivity and uncertainty analysis of the reactor dynamic codes has been started in SAFIR research programme. In 2005, the first version of the sensitivity and uncertainty analysis tool was developed. That tool was designed for the management of large amount of HEXTRAN/SMABRE calculations, and it was possible to calculate also some statistical sensitivity measures.</p> <p>In 2007, that work has been continued. The tool has been further developed so, that it can be used also for TRAB-3D/SMABRE calculations. DNB calculation with TRAB-CORE code has also been included to the tool. Several modifications have improved usability of the tool and have made it more versatile for the management of large amount of reactor dynamics calculations.</p> <p>The tool has been tested with HEXTRAN/SMABRE, TRAB-3D/SMABRE and TRAB-CORE calculations. Some results of the test calculations are in this report.</p>	
Confidentiality	Public
Espoo 24.1.2008	
Signatures	Signatures
	
Elina Syrjälähti	Antti Daavittila
Project Manager	Team Leader
Signatures	Signatures
	
Timo Vanttola	Timo Vanttola
Technology Manager	Technology Manager
VTT's contact address	
Distribution (customer and VTT)	
SAFIR2010 Reference group 3	
VTT: Daavittila, Hämäläinen, Pusa, Rätty, Seppälä, Syrjälähti	
<p><i>The use of the name of the VTT Technical Research Centre of Finland (VTT) in advertising or publication in part of this report is only permissible with written authorisation from the VTT Technical Research Centre of Finland.</i></p>	

Contents

1	Introduction	3
2	Changes in the tool	3
2.1	Result management	4
3	User's manual	4
4	Example cases	7
5	Further development	14
6	Summary	15
	References	15

1 Introduction

Previously, each computer run with VTT's reactor dynamic codes HEXTRAN and TRAB-3D has been made separately. Thus variation calculations have demanded lot of work. In 2005, a new sensitivity and uncertainty analysis tool was developed for HEXTRAN/SMABRE [1]. With that tool, it was possible to perform several calculations at a time, and also calculate some statistical sensitivity measures.

In 2007, development of the tool has been continued. Possibility to perform DNB calculations with the TRAB-CORE for each 3D variation calculation has been added to the procedure. Analyses can be made now also for the TRAB-3D/SMABRE calculations. User interface and post-processing of results have been improved.

In the connection of this project, also some changes have been made to the reactor dynamic codes TRAB-3D and HEXTRAN. These changes have been documented in separate report [3].

2 Changes in the tool

The sensitivity and uncertainty analysis tool has been improved so that it is now possible to perform analysis also for the TRAB3D/SMABRE calculations. Earlier version of the tool was tailored for the HEXTRAN/SMABRE calculations.

DNB-calculation has been included to the tool. After each 3D-calculation it is possible to perform TRAB-CORE calculation for each channel, whose axial node power distribution has been printed out to file **_nodesl.dat*. It is possible to perform some variation calculations also in TRAB-CORE calculations. The same tool can be used for TRAB-CORE calculations also in the case that 3D-calculations have been made separately without the help of this tool.

If some dynamics code calculations fail, failed cases can be skipped when sensitivity values are calculated or results are plotted. When tolerance limits are determined, 95 % coverage and 95% probability level are used. If the number of calculated cases is not enough for 95% coverage, the tool uses all available cases and calculates coverage value that can be achieved with that number of cases. However, if some cases have failed and thus are dropped off from sensitivity measures, it is reasonable to find out the reason for failed calculations. Sensitivity measures and tolerance limits can become distorted, if conditions in failed cases have been so difficult, that solution is not found. However, often reason for failed TRAB-3D and HEXTRAN calculations may lie in input or output reading, not in the solution.

User interface and internal logic of the tool have been modified during implementation of above mentioned changes and testing.

2.1 Result management

Results of all SMABRE and TRAB3D or HEXTRAN calculations are saved to the directory *./Irunx*, where *x* is number of variation run and *./* refers to the working directory. User can define, how many variation runs will be made. Typical amount is 100, if one wants to achieve reasonable probability level and coverage for two-sided tolerance intervals.

If DNB-calculation is performed, results of hot channel calculations are saved to directories *Irunx/HCvari*y, where *y* is number of hot channel variation calculation.

Figures from 3D-calculations are saved to the directory *./Plot*. If sensitivity measures are calculated, results are saved to the directory *./Results*.

Results of the hot channel calculations are not plotted automatically due to huge amount of calculated cases. In each directory *Irunx/HCvari*y is file *minmax.txt*, that includes minimum and maximum values of selected time-dependent FUNTIM output variable [2]. File includes information, in which channel minimum or maximum value is achieved and time of that extreme value.

When all calculations have been performed, the tool goes through the all output files *Irunx/HCvari*y/*minmax.txt* and searches extreme values from these files. Results are written to the file *./minmax_slave.txt*. This file may help to find cases that are worth of deeper study.

3 User's manual

All input-files that user have to prepare before using the tool, have to be located in the directory *./Input*. The tool *sensla.pl* makes all other files that are mentioned in this report.

For 3D-calculations there should be following files:

- SMABRE input *smabre_*.dat*
- SMABRE restart-file *restart.dat* for the coupled calculation
- TRAB-3D input *tr3d_*.dat* or HEXTRAN-input *hext_*.dat*
- Material file *tr3d.mat* or *hext.mat*
- *hydrchannels.dat* that includes TRAB-3D or HEXTRAN hydraulic channel numeration. "Cut and paste" from input file record 5.8.3 is easiest way to make that file.
- *smch.dat* that includes data which trab3d/HEXTRAN hydraulic channels belong to which SMABRE channel. Syntax of the file is:

smabre	first_tr3d/hextran_channel	last_tr3d_hextran_channel
xx	yy	zz
xx2	yy2	zz2

Syntax of this file will be modified in future to avoid errors in more complicated cases.

- Distribution data for variation runs in file *xdist.dat*. Instructions for that file are in report [1].

- *filet.f* for the post-processing of SMABRE results.

For DNB calculations following files are needed:

- TRAB-CORE input *trab_*.inp*.
- For TRAB-CORE variations file *slavevar.dat*. If each channel is calculated only once after each 3d-calculation, this file is not needed.
- file *nodesl0.f* for the modification of axial distributions.

It is possible to skip some phases of the analysis, for example if DNB calculation is not needed, or if some phase of analysis needs to be repeated for example due to the failed computer runs.

Because the whole analysis demands plenty of computer time and disk space, it is reasonable to perform some test calculations before the whole analysis is started, for example so that tool prepares all files but does not perform TRAB3D or HEXTRAN –calculation. One test calculation can easily be carried out by using command files **.bat*, that are saved to the directory *./Files.*. When separate cases are recalculated or one wants to investigate results more closely, it is worth of noticing that *sensla.pl* will remove or compress (with zip) some input- and output files. List of deleted and compressed files is written in the file *./removed_files.txt*. If one wants to calculate all cases so that for example modified SMABRE input file will not be deleted, it is possible to modify the script *sensla.pl*. Deleting of files is made with the command *unlink*.

It is also possible to recalculate sensitivity measures and plot results so that failed calculations are dropped off. If *sensla.pl* is interrupted during the calculations, it is possible to continue by executing script again and by giving a number of run from which calculation is continued. In that case, it is necessary to check that file links that are created for HEXTRAN, TRAB-3D and SMABRE calculations have been deleted. Otherwise dynamic code calculations may fail.

The script is executed by typing the name of the script: *~rea/ua/Srun/sensla.pl*. At first, the script asks information for supervising the analysis. When file names are asked, user should give only part of the name marked with *, not the whole file name. All of the following questions are not made every time. For example if hot channel calculations are not performed (answer to the question 13 is n), file names for TRAB-CORE calculations are not asked. Default value in yes/no questions is no.

1. Make analysis for 3D-calculations (y/n)
n if only hot channel calculations are performed. In that case, following question is number 13.
y otherwise.
2. TRAB-3D/SMABRE (t) or HEXTRAN/SMABRE (h)?
3. Name of the SMABRE input file, *smabre_*.dat*, *?
4. Name of the 3D-input?
TRAB3D-input *tr3d_*.dat* or HEXTRAN input *hext_*.dat*.
sensla.pl uses same extension also for output files of separate SMABRE calculations that are performed before coupled calculation.
5. Name of the TRASMA-output, **_irunx_tr3d.lis*, **_irunx_smabre.f03* etc ?
or in HEXTRAN/SMABRE calculations:

- Name of the HEXSMA-output, **_irun_hextra.lis*, **_irun_smabre.f03* etc. ?
6. Number of 3D-calculations?
 7. Generate data (y/n)?
The script generates new parameter values, if answer is y. If file *dvar.dat* exists, it is possible to use that existing file. Choose n especially if you want to calculate sensitivity measures or plot results from earlier dynamic code calculations. If answer is y, old *dvar.dat* is deleted and it is no more possible to calculate correlation coefficients from results of old 3D-calculation even if those 3D-results exist. Tolerance limits can still be calculated.
 8. Run 3D-code (y/n) ?
y if SMABRE and TRAB3D/SMABRE or HEXTRAN/SMABRE calculations are performed. Otherwise input files and *.bat files are prepared, but dynamic calculations are not performed. Answer n for example if you want to check before starting 100 time-consuming calculations that script *sensla.pl* writes input files properly, or if you want to calculate sensitivity measures and plot results of earlier calculations.
 9. Continue from calculations number *?
If answer to the question 7 was n (= earlier input parameters) and to the question 8 y, it is possible to start calculation from later than run number one. This may be useful if execution of script has been interrupted and you don't want to recalculate several time-consuming reactor dynamic calculations. Default value is 1 = all cases are recalculated.
 10. Calculate sensitivity measures (y/n)
If y, tolerance limits, correlation coefficients etc. are calculated.
 11. List numbers of cases that will be skipped (separated by space)?
If sensitivity measures are calculated for old 3D results (Answers to the question 10 was y and to the question 8 n), it possible to skip some calculations if for example some 3D-calculation has been failed.
 12. Plot (y/n)?
 13. Perform hot channel calculations (y/n)
If answer is n, rest of the questions are skipped and *sensla.pl* can start analysis.
 14. nodesl-data from TRAB-3D(t) or HEXTRAN(h) ?
This question is made, if 3D analysis is skipped (answer to the question 1 was n).
 15. Give name of the 3D-output, *Irun?/*_irun?_nodesl.dat*
This question is made, if answer to the question 1 was n and 3D-calculations have not been made.
*nodesl.dat files should be in directories *./Irun?*, where ? is number starting from 1.
 16. Give number of 3D-core output sets, for which hot channel calculation is made.
This question is made, if answer to the question 1 was n.
 17. Give name of the file that includes LOAD-cards
This question is made, if answer to the question 1 was n.
TRAB-3D of HEXTRAN input file or other file that includes LOAD cards. File should be in same directory *./Irun?* than corresponding *nodesl.dat file.
 18. Give name of the TRABCO input file *trab_*.inp*, *?
 19. Perform TRABCO-calculation (y) or only write input and bat files (n)?

It is possible to vary input parameters also in hot channel calculations. For those variations, user has to give values for varied parameters. Data should be in file *Input/slavevar.dat*. This file is not needed, if variation calculations are not performed and each channel is calculated after each 3D-calculation only once. As in the 3D input files, also in the input file *./Input/trab_*.inp* varied parameters are replaced by string XXXDVAR?X, where ? is number of varied parameter. If the TRABCO input file includes same parameters than 3D-input, varied value is used also in hot channel calculations. Thus if in 3D-calculations $n1$ parameters were varied, numbers from 1 to $n1$ are reserved, and hot channel variations are numbered starting from $n1+1$.

At the moment list of the studied TRAB-CORE output variables is given inside the script *sensla.pl*. (array @outputvar). In the future, this feature will be modified so that variables are selected via input.

Modification of the tool is easy. The tool is written with Perl. The script *sensla.pl* or its subroutines can be modified with a text editor and the modified tool can be used immediately after modification by typing name of the script. Perl programs do not demand separate compilation before execution.

4 Example cases

The tool was tested with the HEXTRAN/SMABRE and TRAB-3D/SMABRE. In this report no deeper analysis is made for used models and transients, because purpose is only to demonstrate use of the improved sensitivity analysis tool. For the same reason DNB-calculation is performed also for the turbine trip transient, where DNB calculation is not necessary.

With the TRAB-3D/SMABRE code, a control rod ejection of PWR was calculated. 100 cases were calculated, but in 7 cases coupled calculation failed. Thus 93 cases were used for results. In each case, TRAB-CORE calculation was performed for 23 core channels.

Varied parameters were mainly from the SMABRE input:

1. Primary pressure, uniform distribution, width of the range 0.45 MPa
2. Heat transfer in gas gap, uniform distribution, range 99-101% from best-estimate value
3. Secondary pressure, uniform distribution, width of the range 0.15 MPa
4. Water level in steam generator, uniform distribution, width of the range 0.7 m
5. Heat transfer area of steam generator tubes, two possible values. Value describes how many steam generator tubes have been plugged. Discrete distribution was used due to testing of different type of distributions.

In TRAB-CORE calculation additional variations were not made. Possibility to variations was tested with such input variables as the end time of simulation.

SMABRE has non-iterative solution method and thus stationary state is searched by running SMABRE code alone before coupled calculation. In all cases calculation starts from same state at time $t=-100s$. During first 100s SMABRE runs towards stationary state that corresponds to the input data. Coupled calculation starts at $t=0s$ and control rod ejection is initiated at $t=3.0s$.

Most varied parameters were in SMABRE input. Thus already initial state of TRAB-3D/SMABRE calculation depends strongly on varied parameters. For that reason connecting subroutines of TRAB-3D/SMABRE and HEXTRAN/SMABRE codes were modified so that some of the steady state data is transferred from SMABRE to TRAB-3D inside the code [3]. Thus some parameters in TRAB-3D and HEXTRAN input files have no meaning. These parameters are PINLET and POUTLT in record 1.8.9, WATERF, STEAMF, WENTH and SENTH in record 1.8.10 and PSYS00, WMM00 and QH00 in record 6.2.1. Transient at the beginning of the coupled calculation (Figure 1) may be an indication that still more data have to be transferred from SMABRE to TRAB-3D already before steady state calculation. It can be seen, that plugged tubes in steam generator have largest effect even to steady state conditions in primary circuit. For example cold leg temperature curves can be divided to two groups according to the shape of the curve (Figure 2). Steady state parameters have most effect on coolant temperature in primary circuit (Figure 7). Transient itself have minor effect compared to the effect of initial values. The same can be seen also in other result variables as in pressurizer level (Figure 3) and also in fission power (Figure 6). Summary of the TRAB-CORE calculations is in Table 1.

RELATIVE FISSION POWER

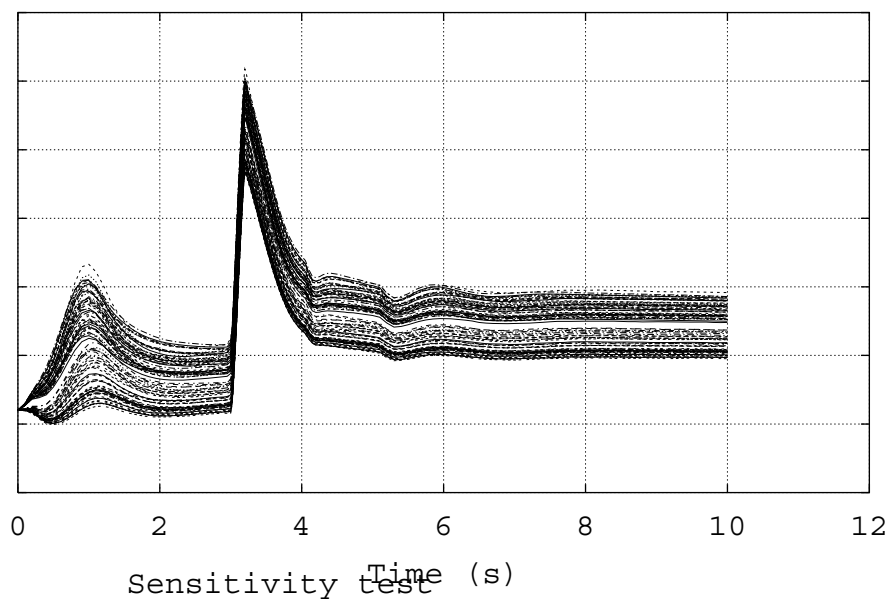


Figure 1: Relative fission power in all calculated cases in CRE transient.

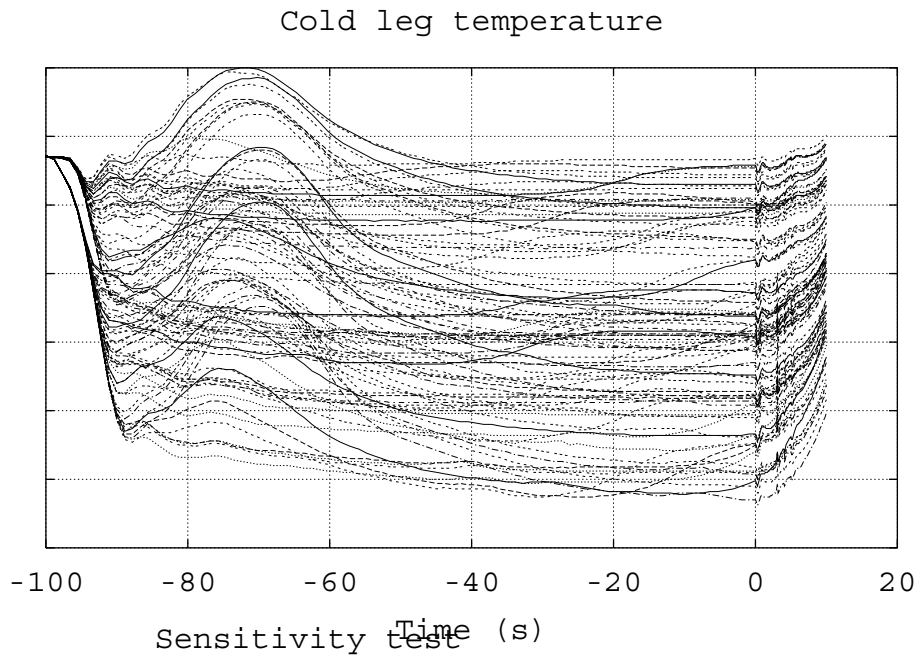


Figure 2: Cold leg temperature in CRE transient

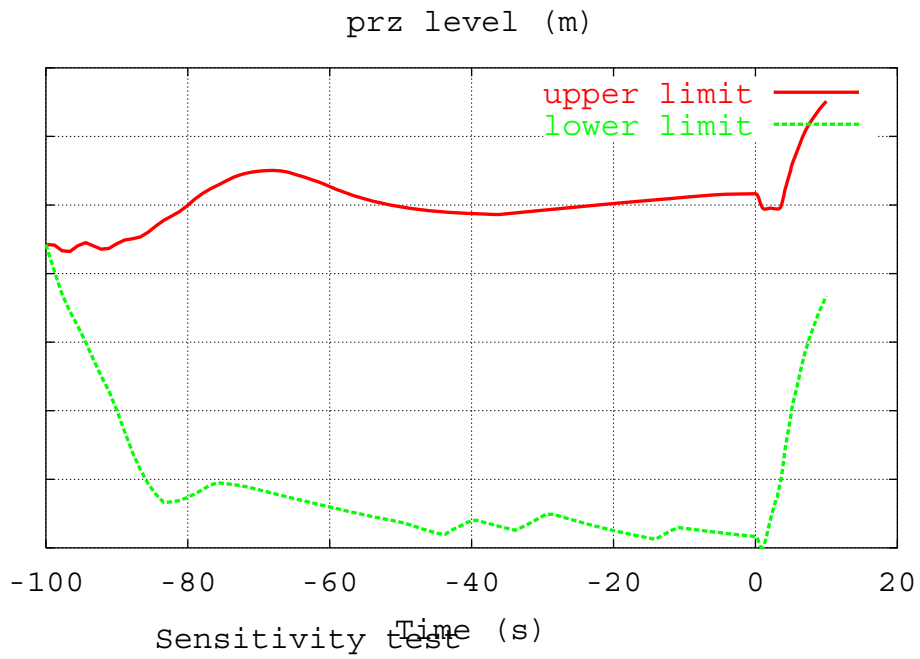


Figure 3: Tolerance interval for pressurizer level in CRE transient.

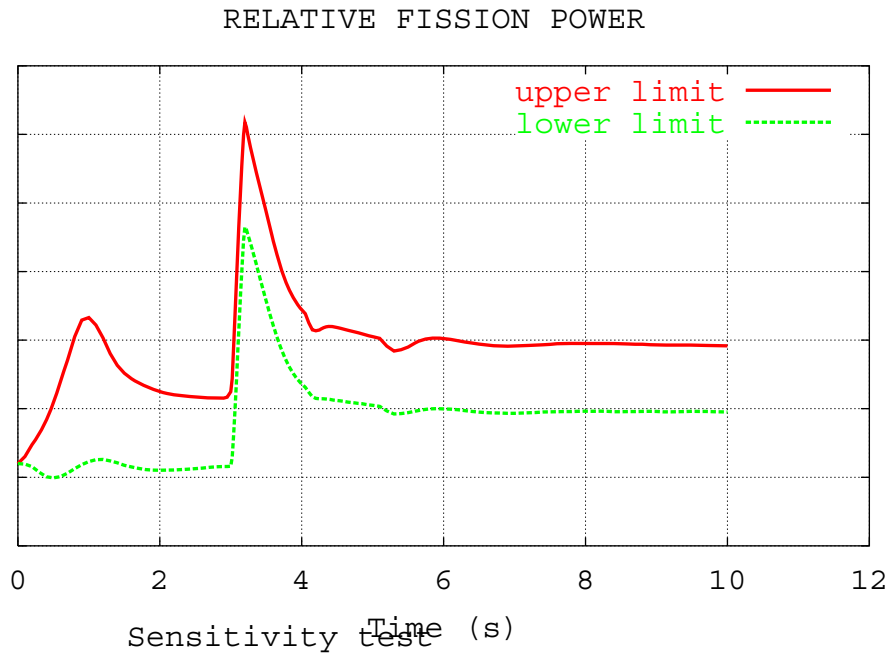


Figure 4: Tolerance interval for relative fission power in CRE transient.

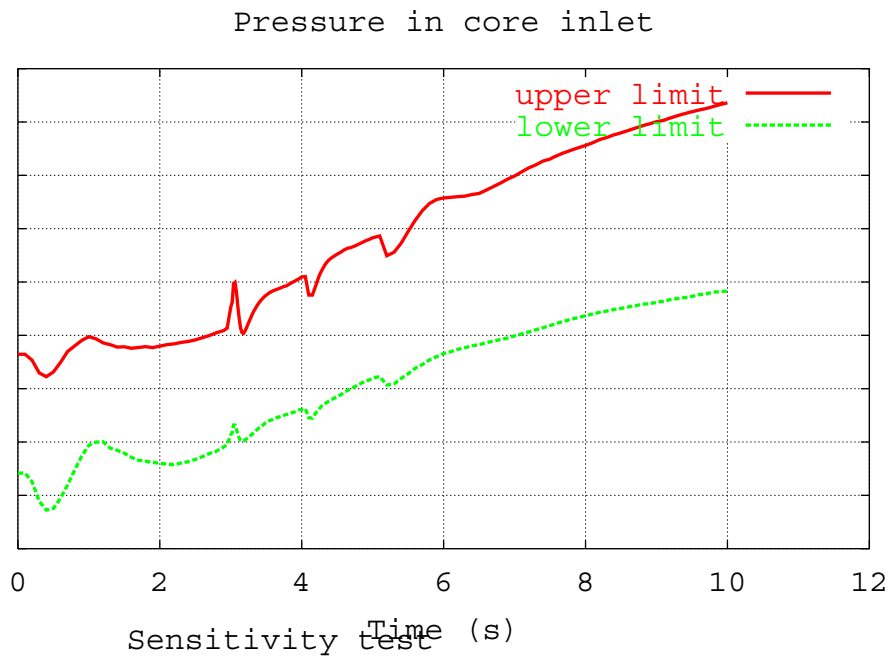


Figure 5: Tolerance interval for core inlet pressure in CRE transient.

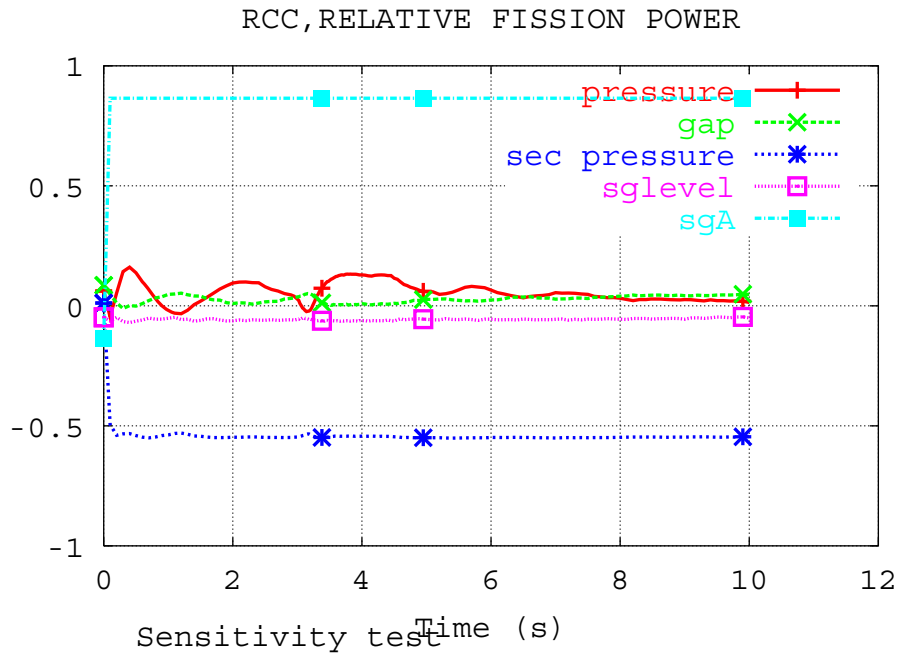


Figure 6: Rank correlation coefficient for fission power in CRE transient.

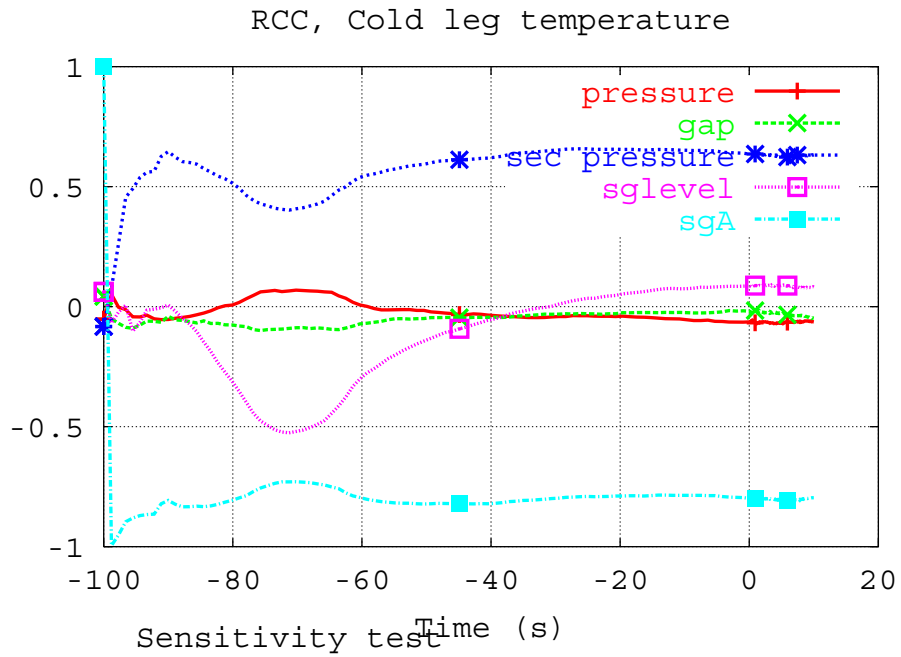


Figure 7: Rank correlation coefficient for cold leg temperature in CRE transient

Table 1: Summary from TRAB-CORE calculations, 23 channels, and 93 TRAB3D/SMABRE calculations.

min/max	variable	value	irun	time	channel
MIN	AVER.POWER_IN_FUEL_(MW/M3)_max	x1	39	3.2	14
MAX	AVER.POWER_IN_FUEL_(MW/M3)_max	x2	33	3.2	14
MIN	AVER.POWER_IN_FUEL_(MW/M3)_max_2nd	x3	39	3.2	11
MAX	AVER.POWER_IN_FUEL_(MW/M3)_max_2nd	x4	33	3.2	11
MIN	AVER.POWER_TO_COOLANT_(MW/M3)_max	x5	39	10	16
MAX	AVER.POWER_TO_COOLANT_(MW/M3)_max	x6	35	10	16
MIN	AVER.POWER_TO_COOLANT_(MW/M3)_max_2nd	x7	39	10	10
MAX	AVER.POWER_TO_COOLANT_(MW/M3)_max_2nd	x8	35	10	10
MIN	AVERAGE_FISS.POWER_(MW/M3)_max	x9	39	3.2	14
MAX	AVERAGE_FISS.POWER_(MW/M3)_max	x10	33	3.2	14
MIN	AVERAGE_FISS.POWER_(MW/M3)_max_2nd	x11	39	3.2	11
MAX	AVERAGE_FISS.POWER_(MW/M3)_max_2nd	x12	33	3.2	11
MIN	AX.MAX.OF_MEAN_TEMP._IN_FUEL(C)_max	x13	39	10	17
MAX	AX.MAX.OF_MEAN_TEMP._IN_FUEL(C)_max	x14	33	10	17
MIN	AX.MAX.OF_MEAN_TEMP._IN_FUEL(C)_max_2nd	x15	39	10	16
MAX	AX.MAX.OF_MEAN_TEMP._IN_FUEL(C)_max_2nd	x16	33	10	16
MIN	DNBM_GIDROPRES_(BEZRUKOV)_min	x17	33	4.1	4
MAX	DNBM_GIDROPRES_(BEZRUKOV)_min	x18	39	4.1	4
MIN	DNBM_GIDROPRES_(BEZRUKOV)_min_2nd	x19	33	4.5	16
MAX	DNBM_GIDROPRES_(BEZRUKOV)_min_2nd	x20	39	4.5	16
MIN	DNBM_SMOLIN_BUNDLE_min	x21	33	4.1	4
MAX	DNBM_SMOLIN_BUNDLE_min	x22	39	4.1	4
MIN	DNBM_SMOLIN_BUNDLE_min_2nd	x23	33	9.9	16
MAX	DNBM_SMOLIN_BUNDLE_min_2nd	x24	39	10	16
MIN	MAX_TEMP_OF_FUEL_(C)_max	x25	39	10	17
MAX	MAX_TEMP_OF_FUEL_(C)_max	x26	33	10	17
MIN	MAX_TEMP_OF_FUEL_(C)_max_2nd	x27	39	10	16
MAX	MAX_TEMP_OF_FUEL_(C)_max_2nd	x28	33	10	16
MIN	MAX_TEMP_ON_CLAD_SURF_(C)_max	x29	66	10	16
MAX	MAX_TEMP_ON_CLAD_SURF_(C)_max	x30	83	10	16
MIN	MAX_TEMP_ON_CLAD_SURF_(C)_max_2nd	x31	66	10	10
MAX	MAX_TEMP_ON_CLAD_SURF_(C)_max_2nd	x32	83	10	10
MIN	MAXIMUM_HEAT_FLUX_(W/CM2)_max	x33	39	10	16
MAX	MAXIMUM_HEAT_FLUX_(W/CM2)_max	x34	33	9.9	16
MIN	MAXIMUM_HEAT_FLUX_(W/CM2)_max_2nd	x35	39	10	10

New version of the tool was tested with HEXTRAN-SMABRE by using VVER-440 turbine trip transient. Varied parameters were same as in report [1]. 100 cases were calculated, and the TRAB-CORE calculations were performed for the 7 core channels in each case.

Due to the changes in initialization of HEXTRAN steady state [3], deviation of several result variables is less than in older calculations [1]. More data is now transferred from SMABRE to HEXTRAN inside the code before HEXTRAN steady state calculation.

Minimum values of relative fission power during transient are now approximately 45 % (Figure 8), when in older calculations minimum value was in two cases less

than 30 %. The range of cold leg temperature at the end of the calculations is now from 260 °C to 266 °C (Figure 9). In the earlier calculations range was from 253 °C to 266 °C. The effect of modified data transfer can be seen especially in Figure 10. In earlier calculations mass flow varied already at steady state from 8200 kg/s to 8500 kg/s. Now range is from 8120 kg/s to 8134 kg/s. The proportion of core by-pass flow was varied from 3% to 12 % of total mass flow. In earlier calculations the effect of that flow was not properly taken into account in HEXTRAN steady state initialization. In normal HEXTRAN/SMABRE analysis initialization has been made by hand to the HEXTRAN input file, but in statistical calculations data has to be transferred inside the code.

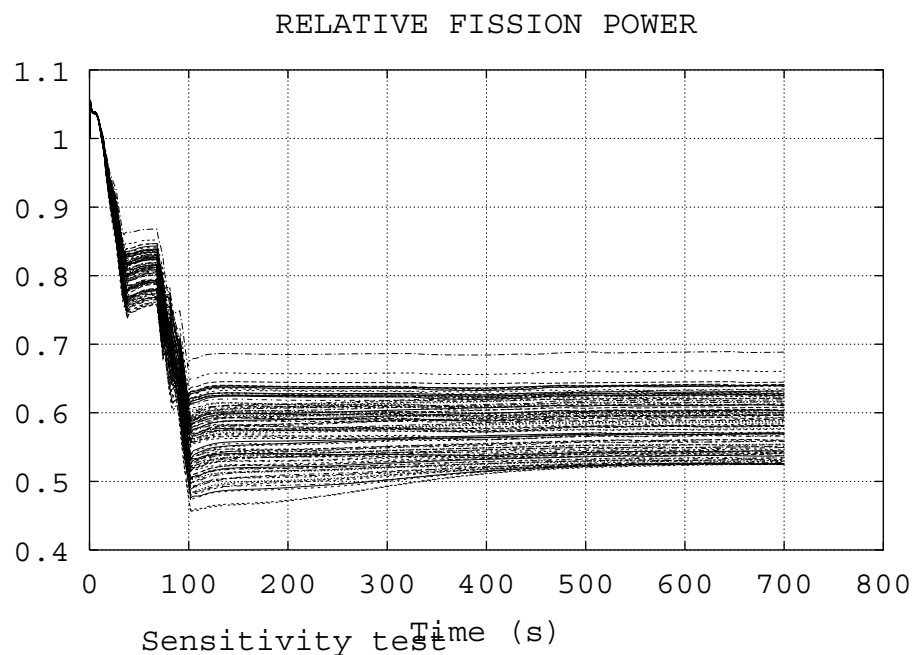


Figure 8: Relative fission power in turbine trip.

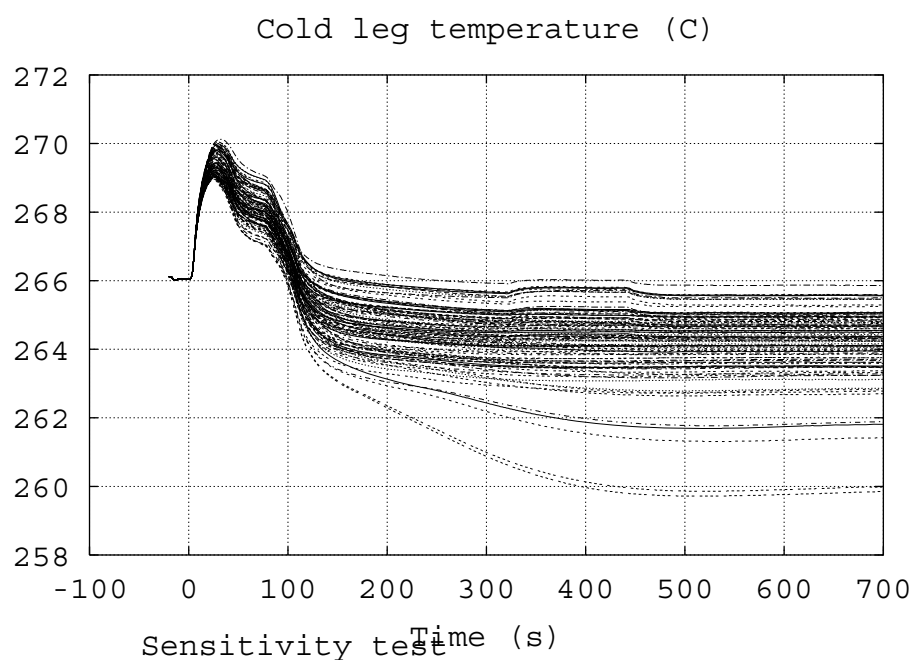


Figure 9: Cold leg Temperature in turbine trip.

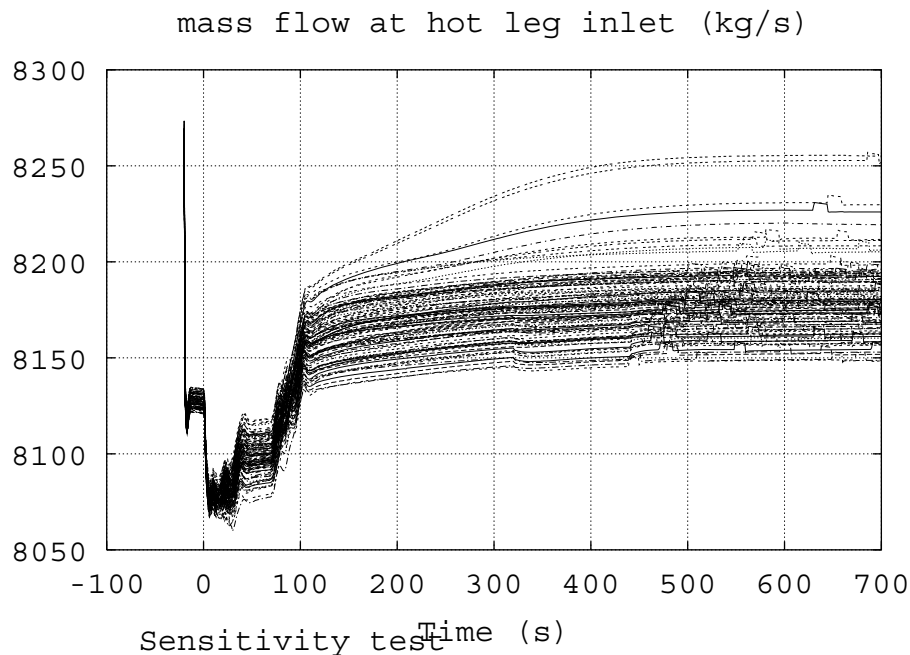


Figure 10: Mass flow at hot leg inlet in turbine trip.

5 Further development

Next step in the development of the tool is to find out, how to combine reactor dynamic calculations to fuel rod analysis. Some methods for uncertainty analysis of fuel rod analysis have been developed during last few years at VTT, but in those demo cases APROS calculations were used as boundary conditions for transient data [4,5]. Because input decks of reactor dynamic codes are in text file format, large amount of variation calculations are easier to perform than with APROS using graphical user interface. Thus data for statistical fuel rod analysis can be more comprehensive.

Usability of sensitivity and analysis tool may demand some modifications. Especially the processing of the SMABRE results demands some changes, because modification of subprogram *filet.f* by hand might be laborious. One possibility is to calculate sensitivity measures for all time-dependent variables in SMABRE output file *.f07 as is made for FUNTIM output variables of HEXTRAN and TRAB-3D, but also in that case some auxiliary subroutine is needed, because *.f07 is in binary format.

Now only two-sided tolerance limits are calculated. If fulfilment of acceptance criteria is sufficient result, one-sided tolerance limits may give enough information. Calculation of one-sided tolerance intervals can be added to the *sensla.pl* easily. Advantage of one-sided tolerance intervals is that fewer cases are needed to achieve same coverage and probability level. With $\beta=0.95$ and $\gamma=0.95$ only 59 cases are needed instead of 93, that is needed for two-sided tolerance intervals.

In statistical fuel rod analysis method that was demonstrated in the report [5], input data was divided to six groups. For that kind of use it would be useful to calculate some quantiles from 3D results. For example with 10-quantiles data could be divided to 10 groups so that each group includes same amount of cases. That kind of addition to the tool would be quite straightforward.

6 Summary

This report describes the work done in the subtask of the SAFIR2010/TRICOT project. The work with the sensitivity and uncertainty analysis of the reactor dynamic codes has been started in SAFIR research programme. In 2005, the first version of the sensitivity and uncertainty analysis tool was developed. That tool was designed for the management of large amount of HEXTRAN/SMABRE calculations, and it was possible to calculate also some statistical sensitivity measures.

In 2007, that work has been continued. The tool has been further developed so, that it can be used also for TRAB-3D/SMABRE calculations. DNB calculation with TRAB-CORE code has also been included to the tool. Several modifications have improved usability of the tool and have made it more versatile for the management of large amount of reactor dynamics calculations.

The tool has been tested with HEXTRAN/SMABRE, TRAB-3D/SMABRE and TRAB-CORE calculations. Some results of the test calculations are in this report.

Development of the sensitivity analysis methods will be continued in 2008. One important aim is to find out how to combine the sensitivity and uncertainty analysis of reactor dynamic codes and fuel rod analysis.

References

- [1] Syrjälähti Elina, New sensitivity analysis tool for the reactor dynamic codes. Espoo 2005. Technical Research Centre of Finland. Project Report PRO1/1016/05,
- [2] Rätty Hanna, Users's manual for reactor dynamics codes TRAB-3D and HEXTRAN. Espoo 2007. Technical Research Centre of Finland. Research report VTT-R-04724-07.
- [3] Syrjälähti Elina & Rätty Hanna, Updatings of reactor dynamic codes in 2007. Espoo 2008. Technical Research Centre of Finland. Research Report VTT-R-00979-08
- [4] Rintala Jukka, Polttoaineaurioiden määrän tilastollinen arviointi. Espoo 2007. Technical Research Centre of Finland. Research Report VTT-R-08163-06.
- [5] Rintala Jukka, Probabilistic analyses for fuel rod behaviour: demonstration. Espoo 2007. Technical Research Centre of Finland. Research report VTT-R-