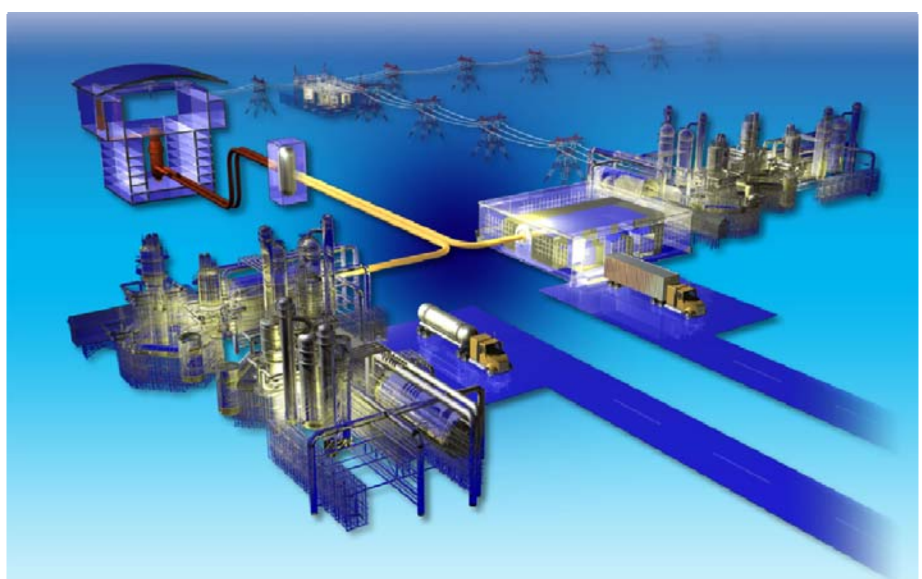
INL/EXT-10-19023

Use of SUSA in Uncertainty and Sensitivity Analysis for INL VHTR Coupled Codes

Gerhard Strydom

June 2010



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Next Generation Nuclear Plant Project
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Next Generation Nuclear Plant Project

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Approved by:

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ABSTRACT

The need for a defendable and systematic uncertainty and sensitivity approach that conforms to the Code Scaling, Applicability, and Uncertainty (CSAU) process, and that could be used for a wide variety of software codes, was defined in 2008.The Gesellschaft für Anlagen und Reaktorsicherheit (GRS) company of Germany has developed one type of CSAU approach that is particularly well suited for legacy coupled core analysis codes, and a trial version of their commercial software product Software for Uncertainty and Sensitivity Analyses (SUSA) was acquired on May 12, 2010. This interim milestone report provides an overview of the current status of the implementation and testing of SUSA at Idaho National Laboratory by the Very High Temperature Reactor Project Office.

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ACRONYMS

CDF	cumulative distribution function
CIAU	capability of internal assessment of uncertainty
CSAU	Code Scaling, Applicability, and Uncertainty
DLOFC	depressurized loss of forced cooling
FOM	Figure of Merit
GRS	Gesellschaft für Anlagen und Reaktorsicherheit
LWR	light water reactor
PBMR	pebble bed modular reactor
PDF	probability density functions
RIT	reactor inlet temperature
SUSA	Software for Uncertainty and Sensitivity Analyses

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1. INTRODUCTION

Title 10 Part 50 (10 CFR 50.46) of the United States Code of Federal Regulations first allowed *Best Estimate* calculations rather than conservative code models of safety parameters in nuclear power plants in the 1980s, stipulating, however, that uncertainties be identified and quantified. Since then, various approaches to uncertainty analysis have been developed, accepted, and used for some light water reactor (LWR) severe accidents. The simulation of the equilibrium neutronic and thermal-hydraulic characteristics of a reactor necessarily requires the application of a coupled-code system such as PEBBED or CYNOD to capture all the relevant physics. Propagating the uncertainty in various input parameters, models, and assumptions through to the output figures of merit (for example fuel temperature) is a process that is still under development in many countries.

2. OVERVIEW OF GENERAL UNCERTAINTY ANALYSIS IN COUPLED CODE SIMULATIONS

Code uncertainty is the uncertainty in the ability of a computer software product, coupled with a specific model, to accurately describe the actual physical system of interest. The computer model is an integration of the mathematical model, the numerical techniques used to solve those equations, and the representation of the physical model by the input geometry and material specifications. Each element contributes to the uncertainty in the output Figure of Merit (FOM).

The mathematical model consists of one or more governing equations that describe the balance between the creation, destruction, and flow of some quantity of interest (e.g., heat, coolant mass, or neutron flux) within a homogeneous control volume. It also consists of one or more subgrid equations that relate these gross phenomena to more complex physics that are neglected at the scale of the homogeneous control volume (e.g., neutron streaming between pebbles, heat conduction from the kernels to the pebble surface, etc.). The uncertainty associated with the mathematical model can be estimated by comparing the results with those generated using a different model that captures these phenomena more accurately or uses different governing equations or subgrid relations.

A further complication is that very few computer codes solve the analytic form of its governing equations. Instead, the differential operators in these equations are expanded as a truncated series and cast as a set of difference equations solved over a discrete mesh. If the equations are well-posed, the solution is unique and refining the mesh reduces the error between the solutions of the discretized equation and the original differential equation. Unfortunately, unlimited mesh refinement is not possible on a digital computer and one must tolerate some truncation error. Furthermore, in many complex fluid system simulation codes, the combination of governing equations and subgrid correlations yields ill-posed systems of differential equations that do not converge to the analytical solution upon refinement of the mesh. These errors can be shown to be minimal in codes like PEBBED and CYNOD, provided that the physical system is within the original range of applicability of the code. Nonetheless, in order to estimate the uncertainty introduced by the numerical approximations implemented in the code, direct comparisons to higher fidelity models can be performed.

Another important source of uncertainty is that the input model is a simplification of the actual physical geometry. For example, the distribution of pebbles in the core is neither regular nor uniform but to model it as anything else is computationally prohibitive. Complex geometrical detail in some of the prismatic designs can likewise be very difficult, if not impossible, to model accurately. In such cases, high fidelity models of only the core features in question can be constructed with reasonable boundary conditions provided by the larger core or system model. The results, in terms of the desired FOM, can be compared with its lower fidelity counterparts with uncertainty values derived from the differences.

The fourth major source of input uncertainty is the material properties. For core analysis, these include thermal properties such as conductivity and heat capacity, fluid properties such as density and viscosity, and neutronic properties such as cross sections. Knowledge of these parameters for each material of interest may be limited in the range of conditions found in a new type of reactor. Such uncertainty can be reduced through material testing and measurement, but the amount of testing is often limited by cost and schedule constraints and must be propagated through the calculations. In some cases, the natural variability of a given parameter under even the best experimental conditions may be large enough to inject uncertainty that cannot be ignored. Finally, when modeling of an actual operating reactor is considered, it is well known that the operational conditions (power level, inlet temperature, measured mass flow rates) can also have associated uncertainty ranges.

(Note that the sources of uncertainty discussed up to now are distinct from errors in the code and model that usually arise from developer/user errors. These factors are usually addressed as part of the software and model *verification* process).

Of the four types of uncertainty sources indicated here, the uncertainties in material properties can usually be addressed by relatively simple manipulation of the corresponding values in the input decks, and geometry simplifications can be benchmarked against higher fidelity codes. In contrast, variations in mathematical models and solver techniques are much more challenging, and in most cases not yet attempted in industry. Developments in uncertainty methodology are therefore currently focused on model and material input data uncertainties.

- Two major approaches are under development to perform this manipulation in a statistically rigorous manner. They differ mainly by the way they propagate uncertainties as described by Salah, et al. (2006) and are as follows: Statistical methods (input uncertainty propagation) include:
  - Use of a reduced number of uncertain input parameters
  - Assign subjective probability ranges and distributions to these parameters
  - Propagate the uncertainty through the core models to determine statistical properties of the FOM
- Deterministic methods (output uncertainty propagation) include:
  - Use of a relevant set of experimental data to establish a database of uncertain data for a large number of input parameters
  - Create hypercubes characterizing physical parameters for a wide variety of conditions, transients, etc.
  - Derive error bands enveloping the output FOM.

D'Auria developed the Capability of Internal Assessment of Uncertainty (CIAU) process as one type of deterministic uncertainty analysis. Statistical methods is well represented by the Code Scaling, Applicability, and Uncertainty (CSAU) approach (Langebusch et al 2005). The CSAU method has been accepted by the NRC and has been used for some Boiling Water Reactor Loss of Coolant Accident analyses. The GRS company (Gesellschaft für Anlagen und Reaktorsicherheit) of Germany has developed software that applies CSAU in a way that is particularly well suited for legacy coupled core analysis codes. A trial version of their commercial software product is described in this report. SUSA (Software for Uncertainty and Sensitivity Analyses)

Both methods have advantages and drawbacks, as shown in Table 1. Typically, because of the deterministic method requirement to have a large and comprehensive experimental database available, LWR and boiling water reactor uncertainty studies can use this method. However, in the high temperature reactor domain, only very limited experimental and operational data exists, and the use of statistical uncertainty methods is the only viable approach.

Table 1. Comparison between statistical and deterministic uncertainty assessment methodologies.

Method	Advantage	Disadvantage
Statistical	• Possible to use reduced number of code calculations, independent of number of uncertain inputs • Provides well proven statistical data properties on output	• Subjective selection of uncertain input parameters • Subjective selection of uncertainty distribution types and ranges
Deterministic	• Requires only a single calculation to provide continuous error bands for any output variable of interest	• Requires a relevant experimental/ operational data base to construct hypercubes • Contributors to uncertainty error bands not distinguishable

3. FEATURES OF THE GRS STATISTICAL UNCERTAINTY METHOD AND SUSA

The first step in the GRS method is to select the set of uncertain input parameters that will be used to evaluate the desired FOM. This step also involves the evaluation of the code's (e.g., PEBBED or CYNOD) applicability to a selected plant scenario. The Phenomena Identification and Ranking Table process is applied to identify and rank all the relevant phenomena utilizing expert judgment. The most important phenomena are identified and listed as "highly ranked" phenomena, based on an examination of experimental data and code predictions of the scenario under investigation. Only parameters important for the highly ranked phenomena are selected for consideration as uncertain input parameters. The selection is based on a judgment of its influence on the output parameters.

Information from the manufacture of nuclear power plant components as well as from experiments and previous calculations are used to define the mean value and probability distribution or standard deviation of uncertain parameters. Uniform and normal distributions are used in the absence of more knowledge about the input parameters. Once these distributions and dependencies have been established, the analyst can:

- Generate a random sample of size N (N <100 for typical 95/95 statistics- see below) for the input parameters from its probability distributions by a Monte Carlo module contained in the SUSA package.
- Perform the corresponding N simulations with the codes. Each simulation generates one possible solution of the model. All solutions together represent a sample from the unknown probability distribution of the model results.
- Calculate quantitative uncertainty statements, e.g., 5% and 95% quantiles or two-sided statistical tolerance limits like upper and lower limit values with 90% coverage and 95% confidence.

- Calculate quantitative sensitivity measures to identify those uncertain parameters that contribute most to the uncertainty of the results.

The number of code calculations is determined by the requirement to estimate a tolerance and confidence interval for the quantity of interest. Wilks' formulae (Wilks 1941) are used to determine the number of calculations required to obtain the desired uncertainty bands:

$$1 - a^n \geq b \tag{1}$$

$$(1 - a^n) - n(1 - a)a^{n-1} \geq b \tag{2}$$

Equations (1) and (2) are used for one-sided and two-sided statistical tolerance intervals, where (b × 100) is the confidence level (%) that the maximum code result will not be exceeded with the probability (a × 100 [%]) (percentile) of the corresponding output distribution, and n the number of calculations required. For example, for a 95% probability that the peak fuel temperature lies below the maximum value of the (unknown) peak fuel temperature distribution, and given with a confidence level of 95%, a total of n=93 calculations need to be performed. Put another way; the one sided 95th percentile value of the (unknown) peak fuel temperature distribution is obtained with a confidence level of 95% by selecting n=59, and the same number of runs would be needed for the 5% percentile. If both percentiles are required, 93 runs would be required.

It is important to note that the GRS Method does not generate the distributions of output parameters. Rather, it yields two-sided limit values (coverage) with a user-specified confidence. For example, a SUSA application may lead to the statement "*the analysis indicates with 95% confidence that 95% of the peak fuel temperature falls between 1,500 and 1,600^{o}C*." It also ranks the input parameters according to the effect that its uncertainties have on the uncertainty in the output parameter.

In summary, SUSA is a program that performs a statistical analysis of uncertainty in the output of nuclear systems codes. Among its functions, SUSA:

- Generates sets of input parameters given user-supplied distributions and input variable dependencies. The number of sets is a function of the confidence required in the uncertainty of the specified putput parameters.
- Can be programmed to write system code input decks for these parameters sets.
- Can be programmed to execute the corresponding models using appropriate calls to the system code.
- Performs a statistical analysis of the specified output parameters, correlates the uncertainty in the output to each of the input variables, and ranks the importance of each input variable to the output uncertainty.

The main advantage of the SUSA software is that is allows a core analyst to apply the sophisticated statistical techniques required of the GRS method without actually having to code them. Because no code modifications are required, the method is entirely suitable for use with existing and legacy codes.

4. SUSA INSTALLATION TEST CASE

The SUSA software was acquired and installed on INL computers. A tutorial and a number of test cases are supplied with the software to ensure that the software can run accurately on the customer's systems. These tests were performed successfully in support of the NGNP milestone and also as part of a longer term demonstration of SUSA's capabilities using the PEBBED code. The longer term project is as follows.

1. Obtain and install SUSA.

2. Perform tutorial test cases and verify installation *(milestone achieved)*
3. Define and execute an INL-specific test case: use the PEBBED code to calculate the pebble bed modular reactor (PBMR) 400 Exercise 2 benchmark steady state and depressurized loss of forced cooling (DLOFC) transient.
4. Use SUSA to vary two input variables (reactor power and reactor inlet gas temperature) and generate the statistical input data variations needed to produce a 95/95 statement for the peak fuel temperature as the FOM.
5. Perform the required 93 PEBBED runs.
6. Post-process the 93 peak fuel temperatures with SUSA to obtain the 95/95 values.

Completion of the first two objectives meet the milestone of acquiring and testing the SUSA software. **Error! Reference source not found.Error! Reference source not found.** provides an overview of the test platform and software details utilized for this study.

Table 2. Test platform and SUSA code details.

Description	Platform/code details	Remarks
Hardware	DELL laptop, Intel duo CPU @ 2.66 GHz, 3.5GB RAM .	
Operating system	Windows XP Professional, version 2002, Service pack 3.	
SUSA software	Version 3.6.	There is no indication in the code release documentation that the SUSA "evaluation" or "trial" version released to INL actually differs from the "commercial" version 3.6. All the available functionalities described in the commercial code's user manual are active for testing.
Additional required software (1)	SUSA uses a macro GUI through MS Excel, and both 2007 and 2003 versions are supported. 2007 Versions do however need additional .dll patches from the Microsoft site.	For this report, MS Excel 2003 Professional build (11.8320.38221) SP3 was used.
Additional required software (2)	SUSA provides a FORTRAN 90 "wrapper" or shell as part of the software package. This shell enables internal calls to the user code, which can then be complied as a single executable. A FORTRAN compiler is then required. No FOTRAN prescriptions are provided from SUSA's side, but it is known that GRS use COMPAQ Visual FORTRAN version 6.6 for their	The internal coupling (i.e. calling PEBBED internally with SUSA controlling the serial runs) was not yet attempted at INL. The "off-line" method (see Figure 5) was used for this study. Tests are currently underway to couple SUSA and PEBBED in the way suggested by GRS, using the Standard COMPAQ Visual FORTRAN complier, version 6.6a.

	development testing.	

Figure 1 thru Figure 4 illustrate the results of one of the tutorial test problems delivered with the software. The plots indicate the distribution of the output and the Lilliefors Test results used to determine if the distribution exhibits normal or log-normal properties. It can be seen that a log-normal nature is much more likely (significance factor 0.85) compared with a factor of 0.0 for the normal distribution. From this process, the 5th and 95th percentile values are obtained with 95% confidence, as shown in Figure 4 (with pink markers on the x-axis).

```
 94     188     94.00 %-QUANTILE =     6.8031E-05
 95     190     95.00 %-QUANTILE =     7.2357E-05
 96     192     96.00 %-QUANTILE =     7.3013E-05
 97     194     97.00 %-QUANTILE =     7.5278E-05
 98     196     98.00 %-QUANTILE =     8.4244E-05
 99     198     99.00 %-QUANTILE =     8.4790E-05
                         MAXIMUM =     8.9924E-05

         SAMPLE MEAN               =    2.3595E-05
         SAMPLE STANDARD DEVIATION =    2.0730E-05

RESULTS OF THE LILLIEFORS TEST FOR  N O R M A L I T Y
FOR CONSEQUENCE NO.    1
*****************************************************
                    SAMPLE SIZE =   200
                    SAMPLE MEAN =   2.3595E-05
      SAMPLE STANDARD DEVIATION =   2.0730E-05

 LILLIEFORS D-STATISTICS =   1.8434E-01
 BOUNDS FOR THE CORRESP. LEVEL OF SIGNIFICANCE =  0.00  0.01

RESULTS OF THE LILLIEFORS TEST FOR  L O G - N O R M A L I T Y
FOR CONSEQUENCE NO.    1
*************************************************************
                    SAMPLE SIZE =   200
                SAMPLE LOG-MEAN =  -1.1028E+01
  SAMPLE LOG-STANDARD DEVIATION =   9.0741E-01

 LILLIEFORS D-STATISTICS =   3.3080E-02
 BOUNDS FOR THE CORRESP. LEVEL OF SIGNIFICANCE =  0.85  0.86

RESULTS OF THE LILLIEFORS TEST FOR  E X P O N E N T I A L I T Y
FOR CONSEQUENCE NO.    1
***************************************************************
                    SAMPLE SIZE =   200
                    SAMPLE MEAN =   2.3595E-05
      SAMPLE STANDARD DEVIATION =   2.0730E-05
                  SAMPLE LAMBDA =   4.2381E+04

 LILLIEFORS D-STATISTICS =   1.0480E-01
 BOUNDS FOR THE CORRESP. LEVEL OF SIGNIFICANCE =  0.00  0.01
```

Figure 1. Screen shot of SUSA post-processing output, indicating mean, sigma, and statistical fitness results for the SCALAR test case.

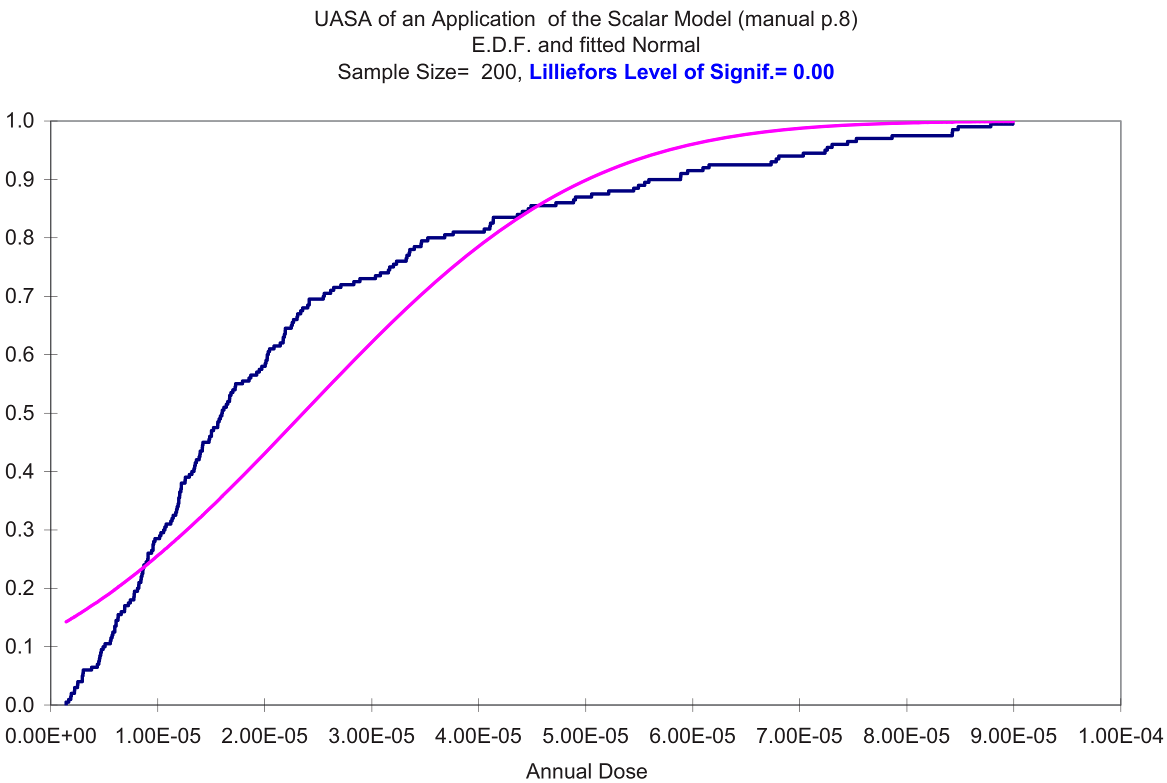


Figure 2. Lilliefors test results for the SCALAR example and a fitted normal distribution.

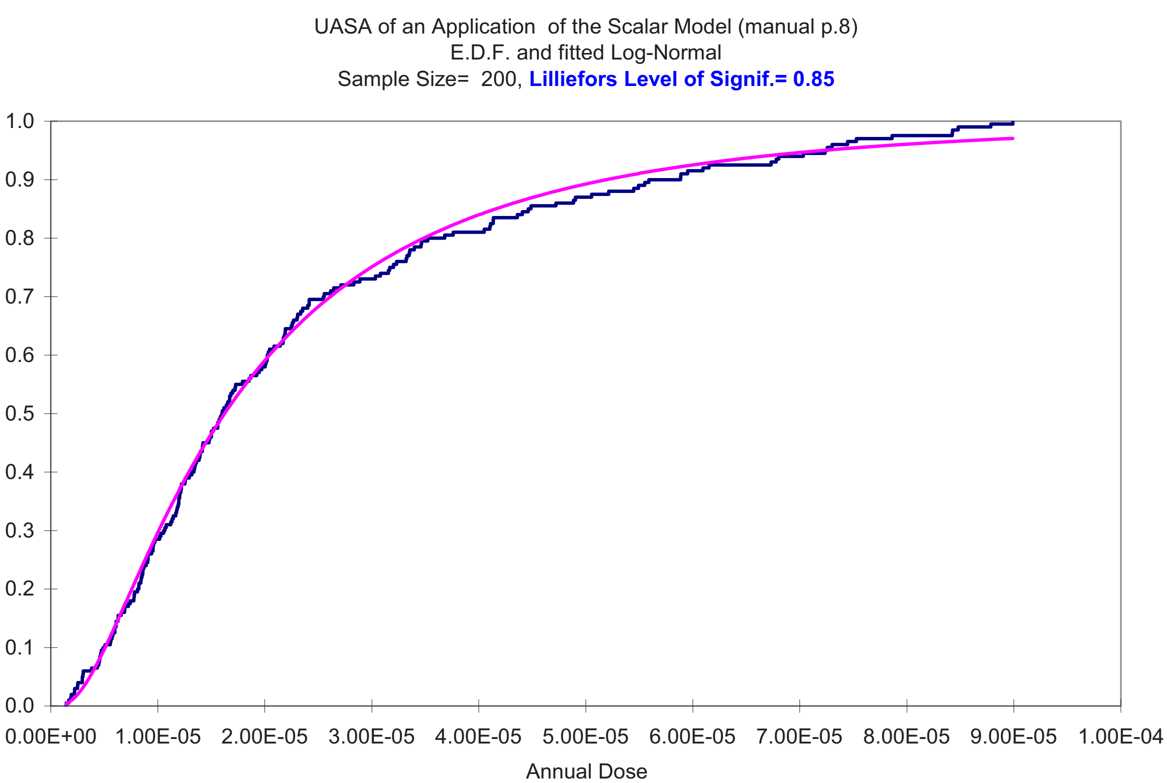


Figure 3. Lilliefors test results for the SCALAR example and a fitted log-normal distribution.

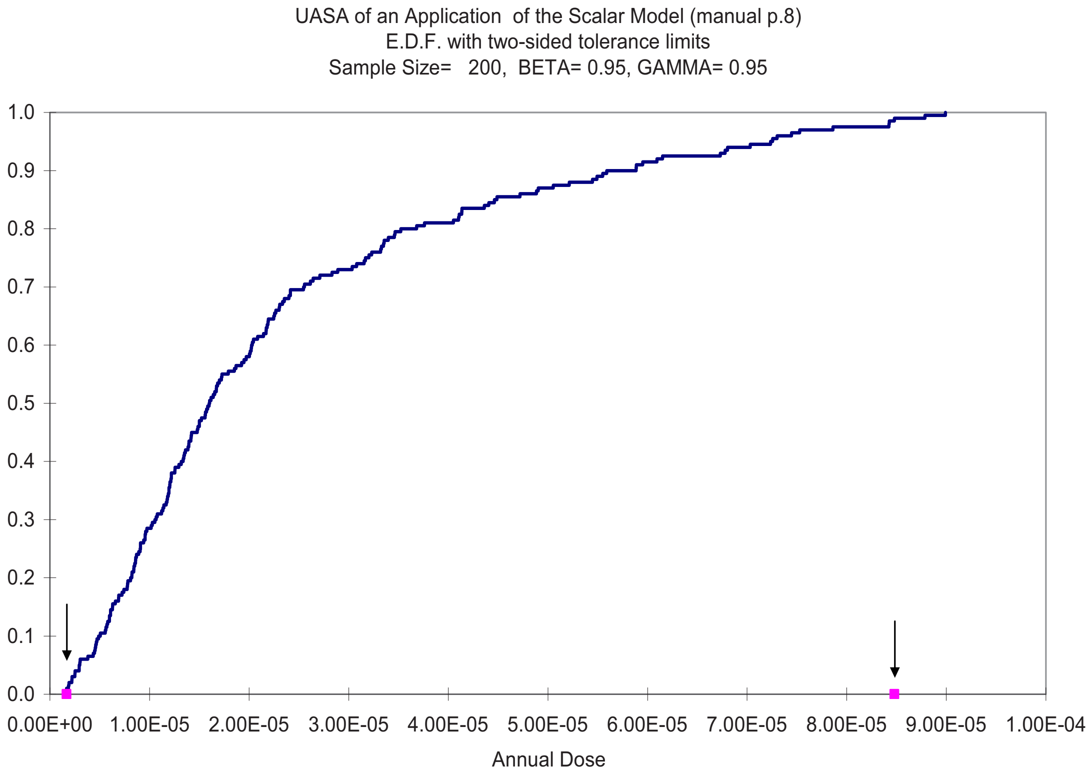


Figure 4. 5th and 95th percentile values of the output distribution, with 95% confidence.

5. SUSA TEST CASE: PEBBED DLOFC

To date, Objective 3 has been completed and Objective 4 has been started with 10 of the planned 93 PEBBED DLOFC cases completed. Further investigations of the coupling of SUSA and PEBBED will be performed using SUSA's provided FOTRAN shell.

To illustrate the use of the software, Figure 5 presents a simplified flow diagram of the methodology followed for the PBMR 400 Exercise 2 benchmark test case.

As a simple illustration of SUSA's capabilities, two scalar (noncorrelation dependent) parameters were selected: the total reactor power (MW) and the inlet gas temperature (°C). The distribution types and nominal 5and 95% values (slightly less than 3 sigma values) for these parameters are indicated in Table 3. The actual values used are not very significant at this stage, but the ranges are loosely based on studies performed for the PBMR design.

This information is entered into the SUSA code using a GUI operating out of Microsoft Excel. A screenshot of the GUI dialogue at this point in the information flow is shown in Figure 6.

The Latin Hypercube method, which is one of the random generator methods available in SUSA, was used to generate the required 93 random values for each parameter shown in Figure 7. The resulting sigma values, probability density functions (PDFs), and cumulative distribution functions (CDFs) for both parameters are shown in Figure 8 thru Figure 10, respectively. These visual representations are provided as useful cross-checks to the user to ensure that the requested information was provided accurately (e.g., it can be seen that the tails of the power PDF tapers off to zero, close to the requested 360 and 440 MW).

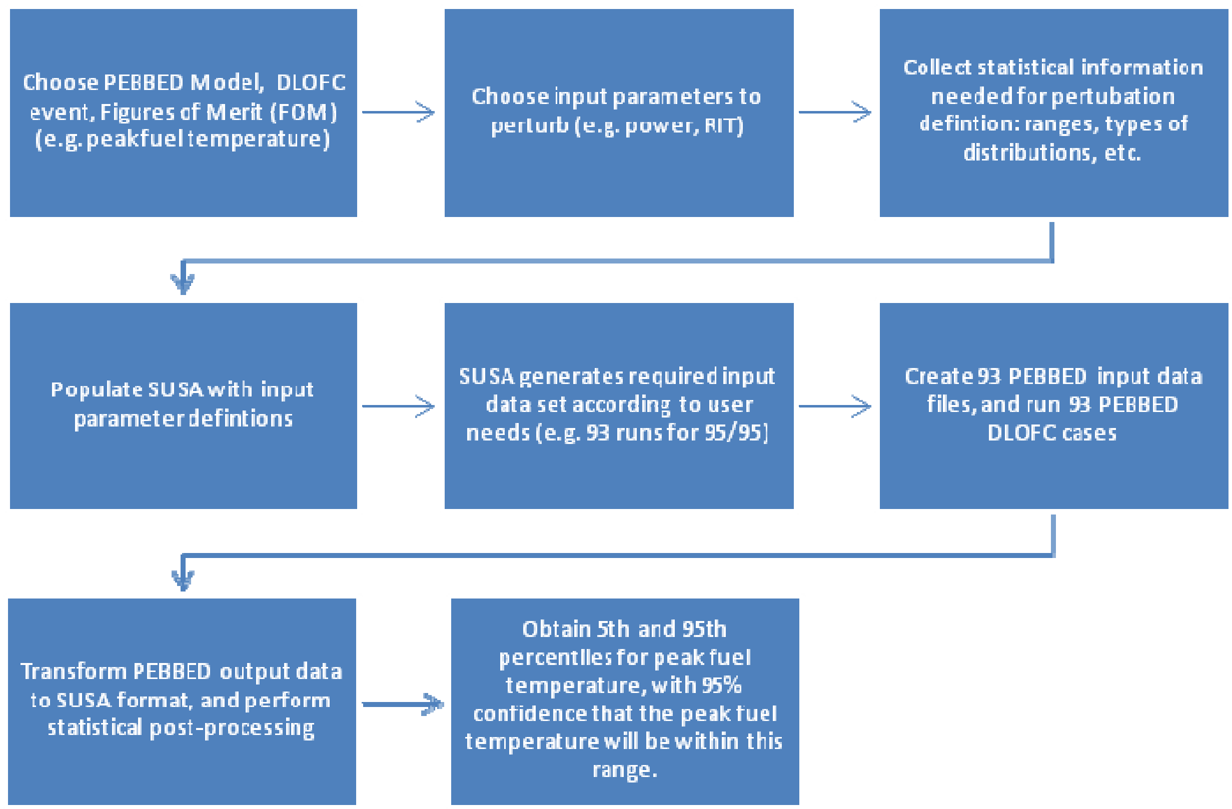


Figure 5. Example of the GRS method to the PEBBED calculation of the PBMR 400 Exercise 2 benchmark.

Table 3. Input uncertainty parameters.

Parameter	**Nominal, 5 and 95% values**	**PDF Type**
Reactor power (MW)	400, 360, 440	Normal
Inlet gas temperature (°C)	500, 480, 520	Normal

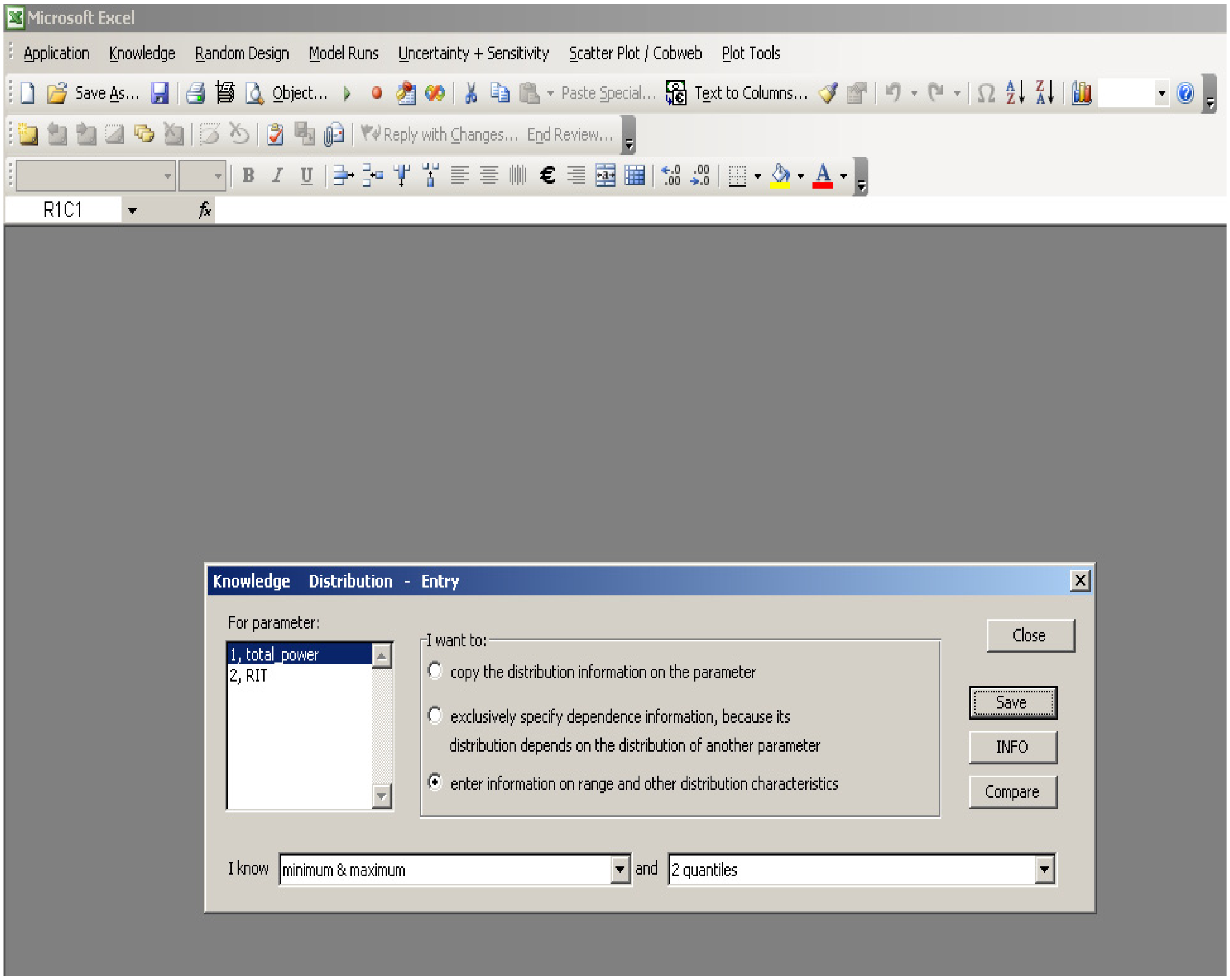


Figure 6. Screen shot of SUSA EXCEL interface—distribution information entry screen shown for parameter "Total Power."

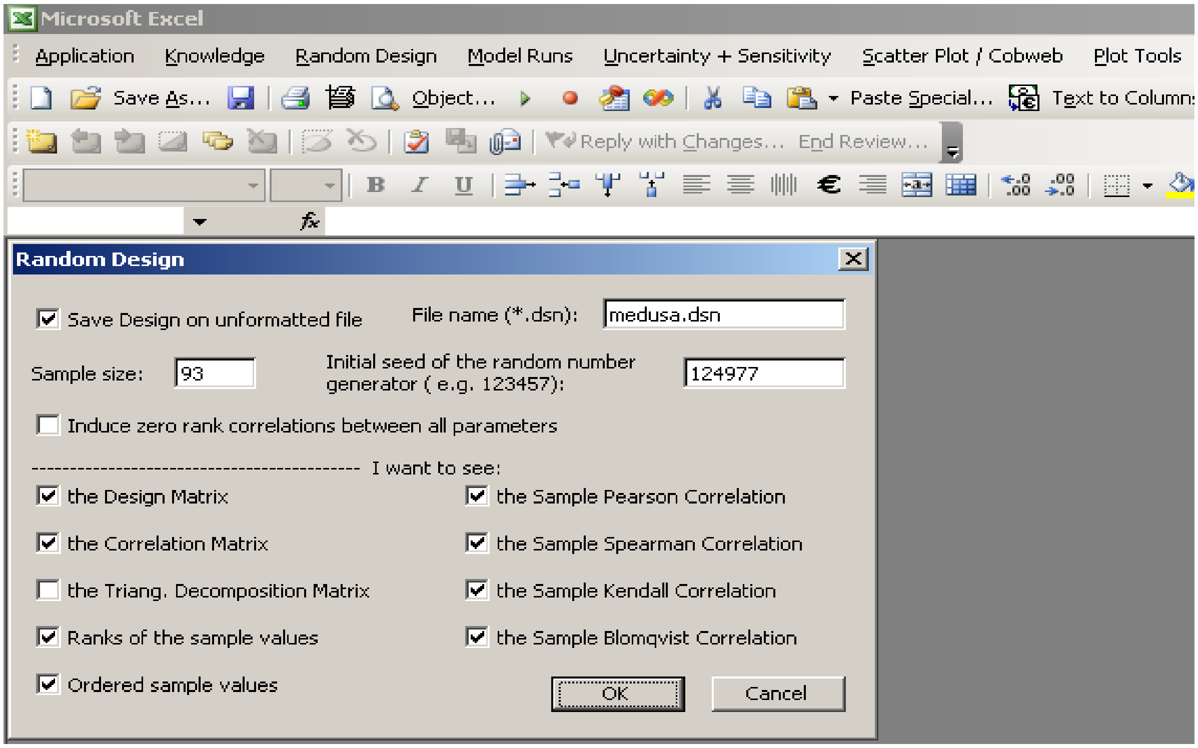
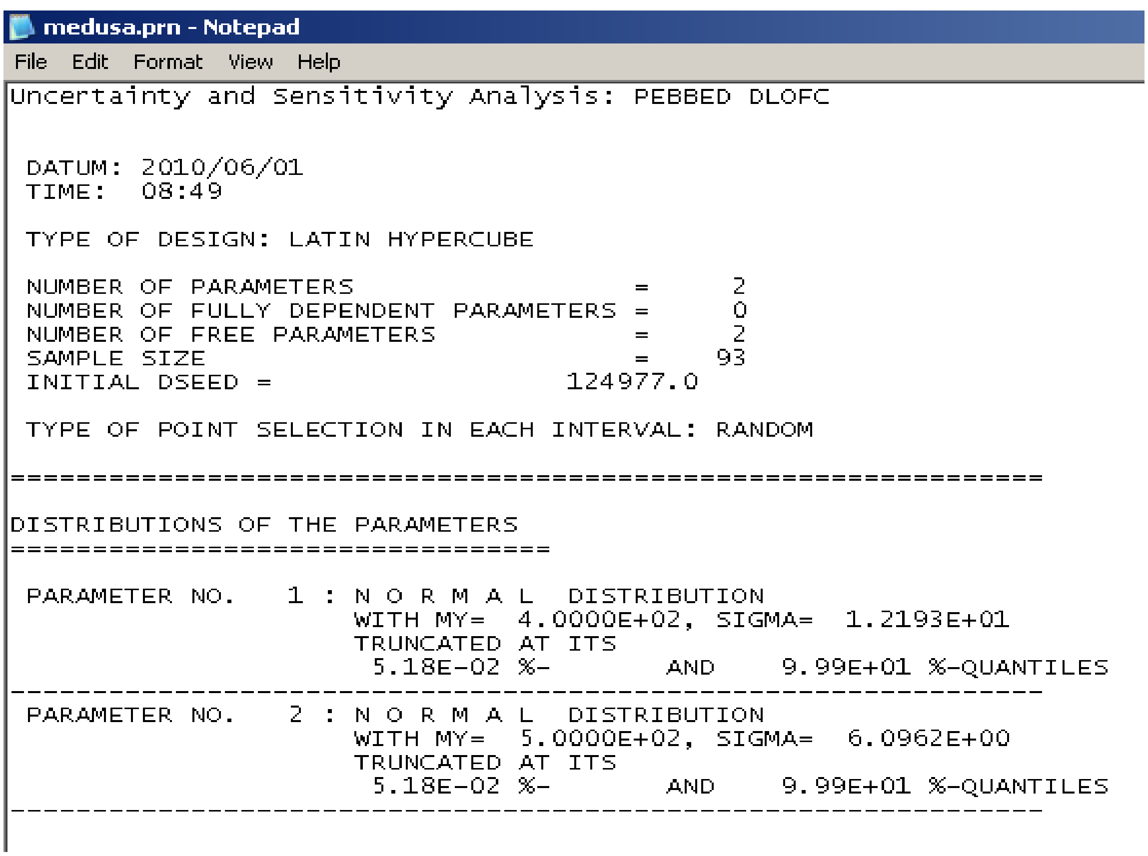


Figure 7. Screen shot of the SUSA random generator GUI dialogue.




```
Uncertainty and Sensitivity Analysis: PEBBED DLOFC


 DATUM: 2010/06/01
 TIME:  08:49

 TYPE OF DESIGN: LATIN HYPERCUBE

 NUMBER OF PARAMETERS                  =      2
 NUMBER OF FULLY DEPENDENT PARAMETERS  =      0
 NUMBER OF FREE PARAMETERS             =      2
 SAMPLE SIZE                           =     93
 INITIAL DSEED =                  124977.0

 TYPE OF POINT SELECTION IN EACH INTERVAL: RANDOM

===============================================================

DISTRIBUTIONS OF THE PARAMETERS
=================================

 PARAMETER NO.   1 : N O R M A L  DISTRIBUTION
                     WITH MY=  4.0000E+02, SIGMA=  1.2193E+01
                     TRUNCATED AT ITS
                      5.18E-02 %-      AND    9.99E+01 %-QUANTILES
---------------------------------------------------------------
 PARAMETER NO.   2 : N O R M A L  DISTRIBUTION
                     WITH MY=  5.0000E+02, SIGMA=  6.0962E+00
                     TRUNCATED AT ITS
                      5.18E-02 %-      AND    9.99E+01 %-QUANTILES
---------------------------------------------------------------
```

Figure 8. Screen shot of the SUSA medusa.prn output file.

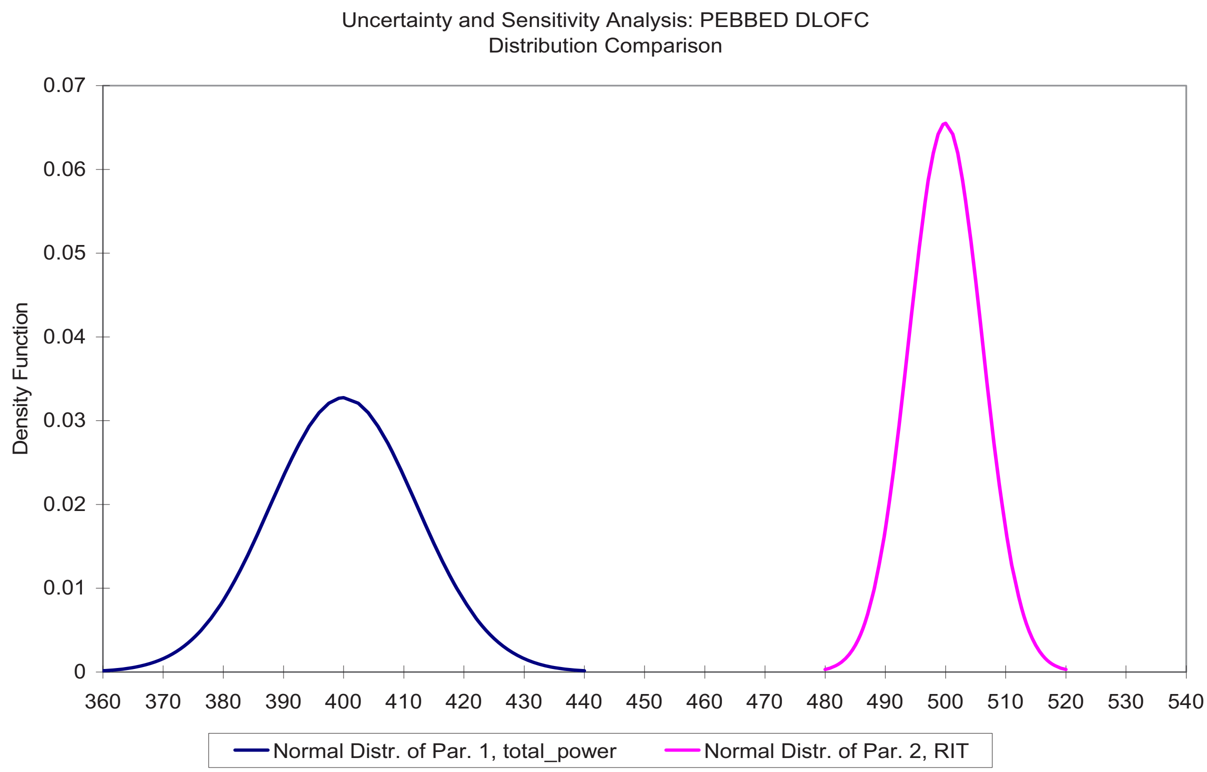


Figure 9. PDFs for the total power and reactor inlet temperature (RIT).

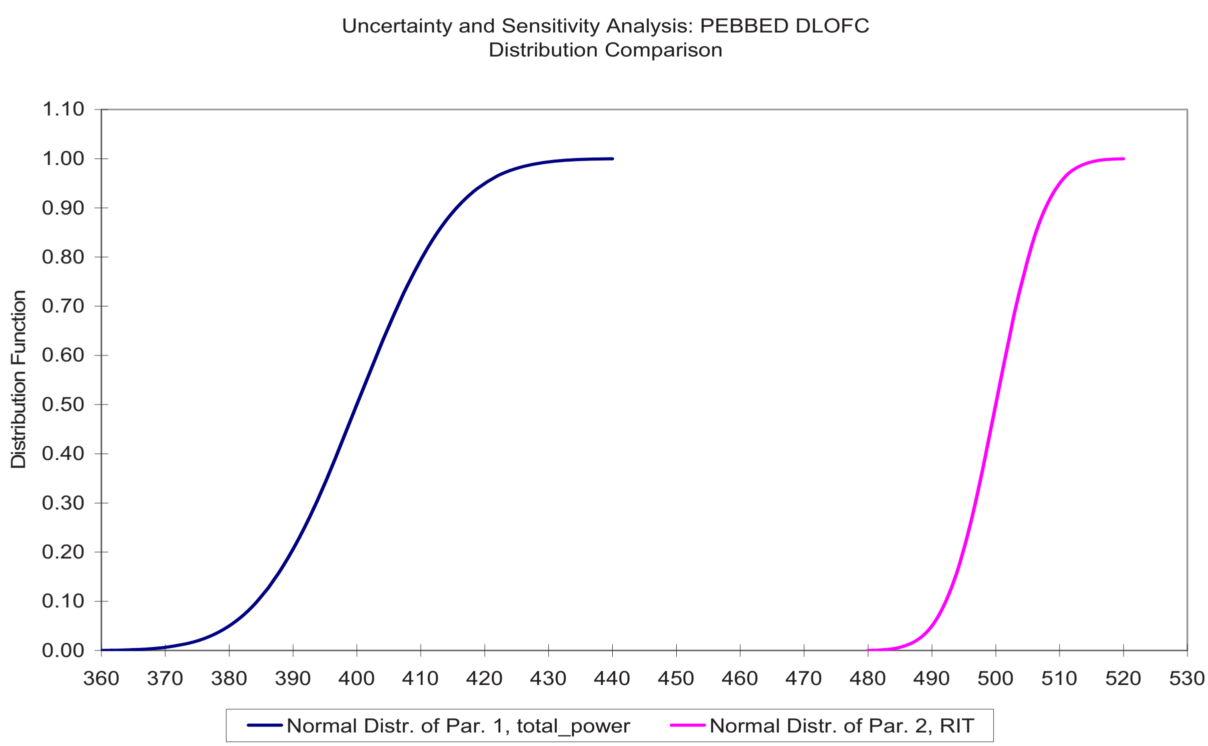


Figure 10. CDFs for the total power and RIT.

During the next step of the procedure, 10 of the 93 SUSA-generated data sets (shown as bolded text in Table 4) were used to produce the PEBBED transient DLOFC results presented in Figure 11 and Figure 12. It can be seen in Table 4 that the peak fuel temperatures vary between 1,620 and 1,725°C, a spread of ~105°C, or 6.4%. Note that these 10 samples are only a small subset of the true distribution that will be obtained when an infinite number of runs are performed, and that the upper result (case 10) in no way represents the limiting value.

Table 4. PEBBED input data for the 93 runs.

SUSA run #	Power (MW)	RIT (Celcius)	SUSA run #	Power (MW)	RIT (Celcius)
1	**397.5**	**497.2**	47	410.6	512.1
2	**419.9**	**502.8**	48	399.5	495.6
3	**419.4**	**506.5**	49	402.8	505.1
4	**396.6**	**498.2**	50	388.6	507.7
5	**381.4**	**514.1**	51	409.7	504.0
6	**380.0**	**504.7**	52	398.8	509.9
7	**389.5**	**494.5**	53	392.3	503.4
8	**409.1**	**502.6**	54	397.9	493.0
9	**400.1**	**508.1**	55	402.2	496.3
10	**424.6**	**505.3**	56	391.8	491.2
11	413.1	499.6	57	417.6	509.2
12	412.5	489.3	58	393.8	495.0
13	394.3	500.5	59	406.6	494.0
14	406.2	502.3	60	413.2	496.9
15	414.6	509.8	61	411.4	504.9
16	403.3	502.3	62	388.1	505.9
17	397.8	492.4	63	414.5	496.1
18	400.2	497.2	64	387.7	490.5
19	405.5	503.7	65	405.9	499.3
20	395.8	501.6	66	395.3	495.4
21	401.0	498.8	67	400.7	498.7
22	408.3	493.5	68	401.9	501.1
23	396.4	507.0	69	404.2	501.0
24	373.0	494.2	70	393.6	497.8
25	382.9	500.3	71	387.3	497.6
26	401.6	502.1	72	403.6	489.9
27	392.9	500.8	73	397.2	503.8
28	407.8	500.7	74	385.7	509.5
29	407.1	503.1	75	382.0	508.4
30	394.5	484.3	76	391.2	491.5
31	403.0	488.0	77	393.1	499.0
32	401.2	501.3	78	411.7	487.2

SUSA run #	Power (MW)	RIT (Celcius)	SUSA run #	Power (MW)	RIT (Celcius)
33	394.8	507.5	79	391.5	497.5
34	389.0	493.3	80	404.8	499.4
35	414.3	506.2	81	415.2	502.7
36	383.7	500.1	82	416.6	501.4
37	372.1	495.8	83	390.3	494.8
38	410.2	498.3	84	425.0	492.8
39	398.3	496.5	85	384.3	503.5
40	378.7	513.4	86	434.5	498.0
41	403.9	498.5	87	399.5	504.4
42	409.5	510.8	88	417.0	499.5
43	385.6	496.8	89	421.0	499.9
44	408.7	501.8	90	405.2	504.3
45	390.5	505.7	91	398.9	495.9
46	395.9	492.1	92	407.3	500.0
			93	376.1	494.4

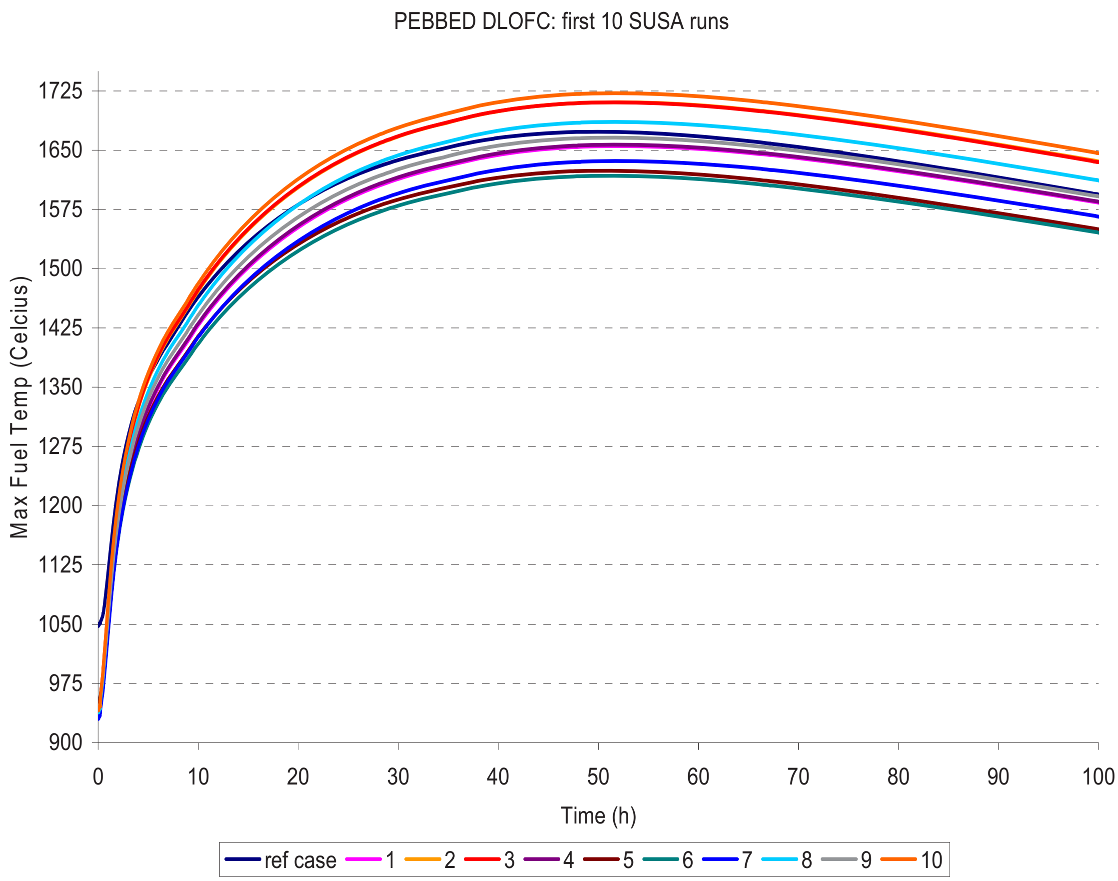


Figure 11. The first 10 PEBBED DLOFC results, based on the input in Table 3.

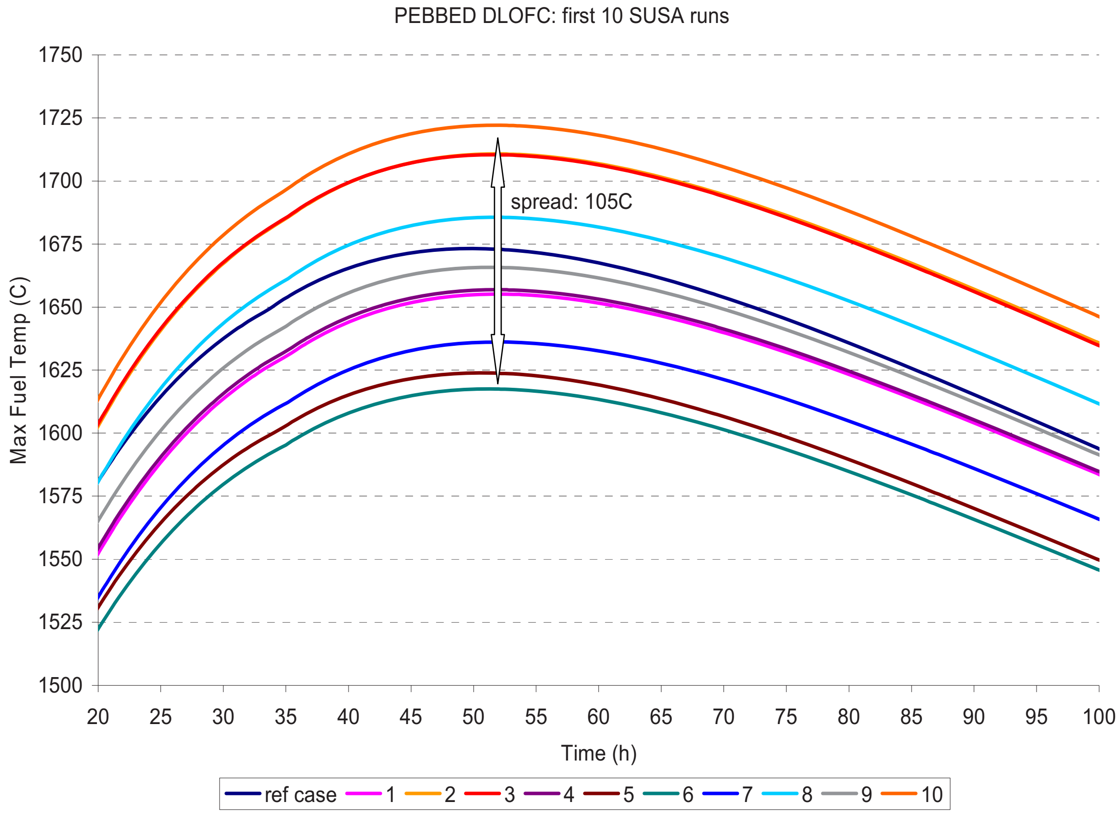


Figure 12. Detail of the first 10 PEBBED DLOFC results between 20–100 hours.

The PEBBED data in Figure 11 can also be represented as the number of times that each peak fuel temperature occurred in a specific temperature interval. Figure 13 shows such a histogram example, where five intervals from 1,600 to 1,750°C were selected. Data in this format is usually expressed in a normalized manner, so Figure 14 is a typical starting point for SUSA when the post-processing statistical analysis is performed.

In the final step, as shown earlier in Figure 1 to Figure 4 for the "Scalar" test case, SUSA performs a wide variety of statistical correlation "fitness" tests to determine the properties of the unknown statistical distribution for the peak fuel temperature. (It will always remain unknown, since SUSA does not attempt to build up a PDF/CDF of the final function). The final required data points can then be obtained from the process, i.e. the 5th and 95th percentile values, given with 95% confidence.

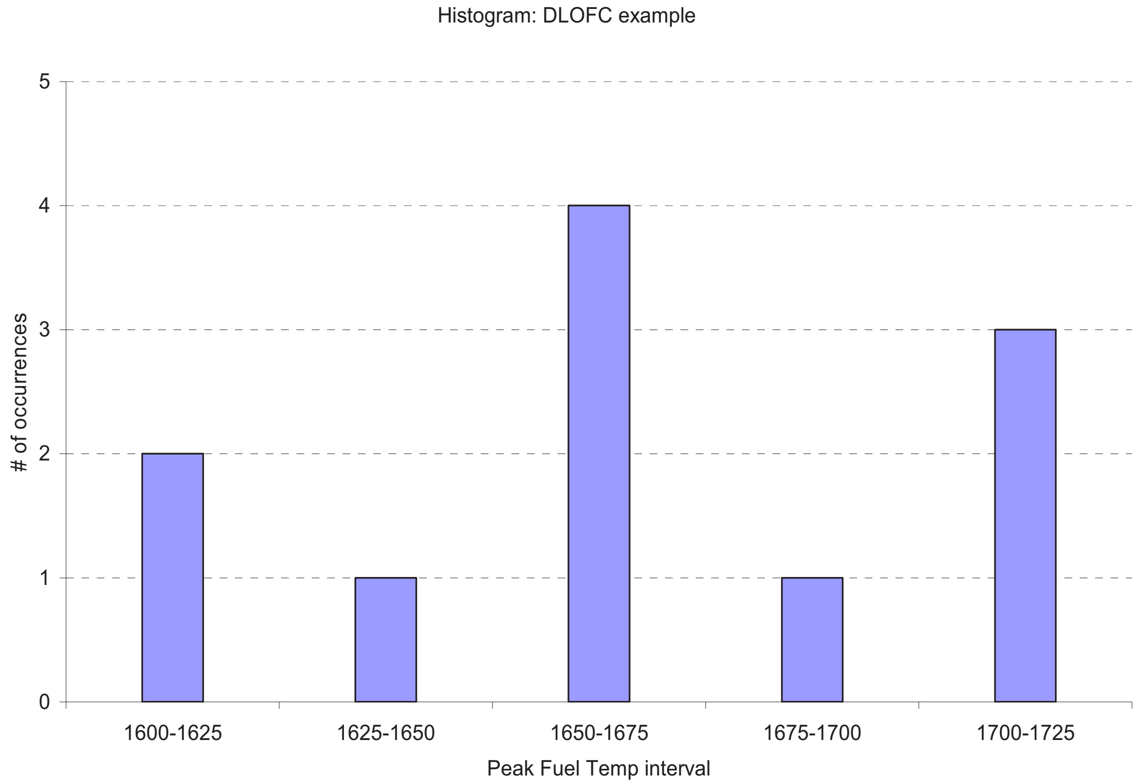


Figure 13. Histogram of the first 10 PEBBED DLOFC results.

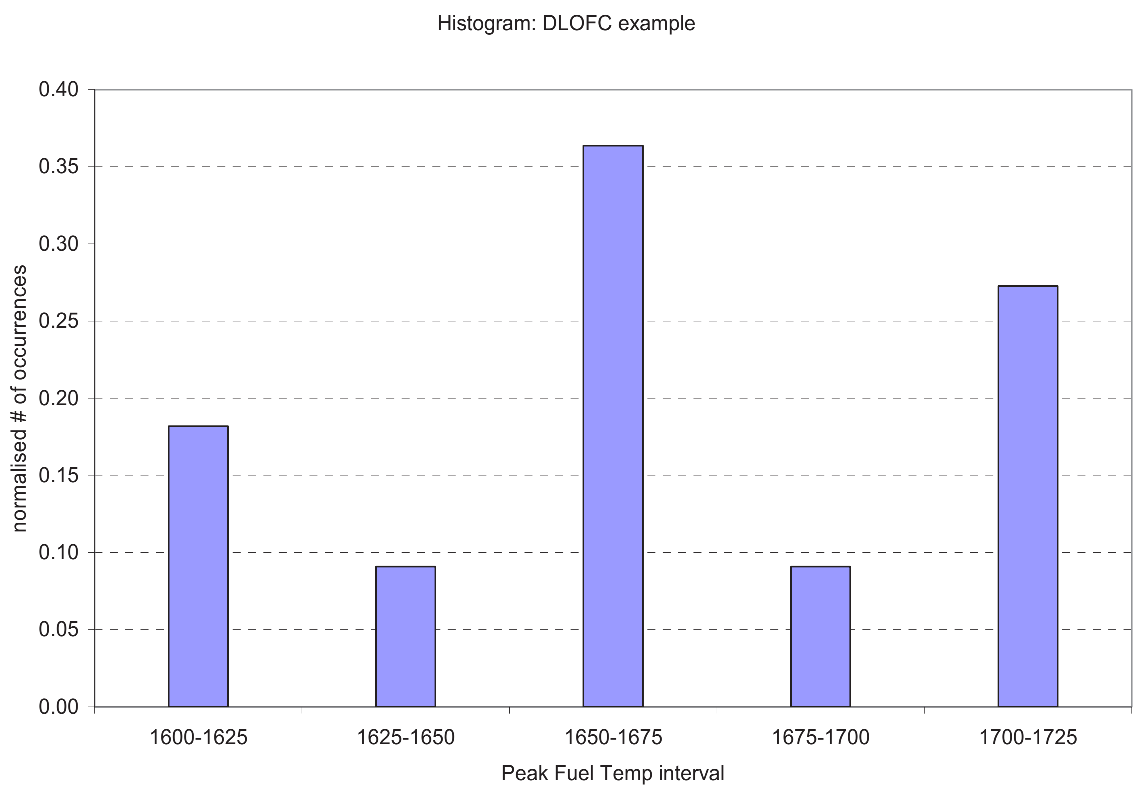


Figure 14. Normalized histogram of the first 10 PEBBED DLOFC results.

6. CONCLUSIONS

A status overview of the SUSA implementation project was provided. The code has been acquired and successfully installed. The test problems were executed, indicating that the software is compatible with INL computer systems and software.

Initial results were generated for a sensitivity analysis of the peak DLOFC test of the PBMR 400 using PEBBED and THERMIX-KONVEK. A more comprehensive uncertainty analysis is outlined in the next section but this preliminary testing indicates that the SUSA software will perform as intended. It also indicates the ease with which the interface can be constructed between SUSA and a complex reactor analysis code like PEBBED.

Future investigations will include the following:

- Submit all 93 PEBBED DLOFC cases to SUSA for 95/95 uncertainty and sensitivity analyses.
- Investigate fully coupled SUSA-PEBBED interface as a more practical option for higher number of runs.
- Clarify approach on complex nonscalar uncertainties: bypass flows, core thermal dispersion, radial/axial power peaking, Control Rod worths, etc.

A specific issue of interest will be the propagation of the uncertainties in the neutronic data (cross sections) from the basic nuclear ENDF libraries to the PEBBED steady state. Special neutronics-only test cases will be used to isolate the effect of XS uncertainties.

7. REFERENCES

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