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MAPLE Research Reactor Safety Margins Uncertainty Assessment Methodology

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1. Introduction

The MAPLE (Multipurpose Applied Physics Lattice Experiment) reactor is a low pressure, low temperature, open-tank-in-pool type research reactor that operates at a power level of 5 to 35 MW_{th} (refer to Figure 1). The compact light water cooled and moderated core uses proliferation resistant, low enriched silicide fuel. This rod-type fuel generates high fluxes of fast neutrons in the core and thermalized neutrons in the surrounding heavy water reflector tank. The MAPLE core is compact and under-moderated with the result that all temperature related reactivity coefficients are negative.

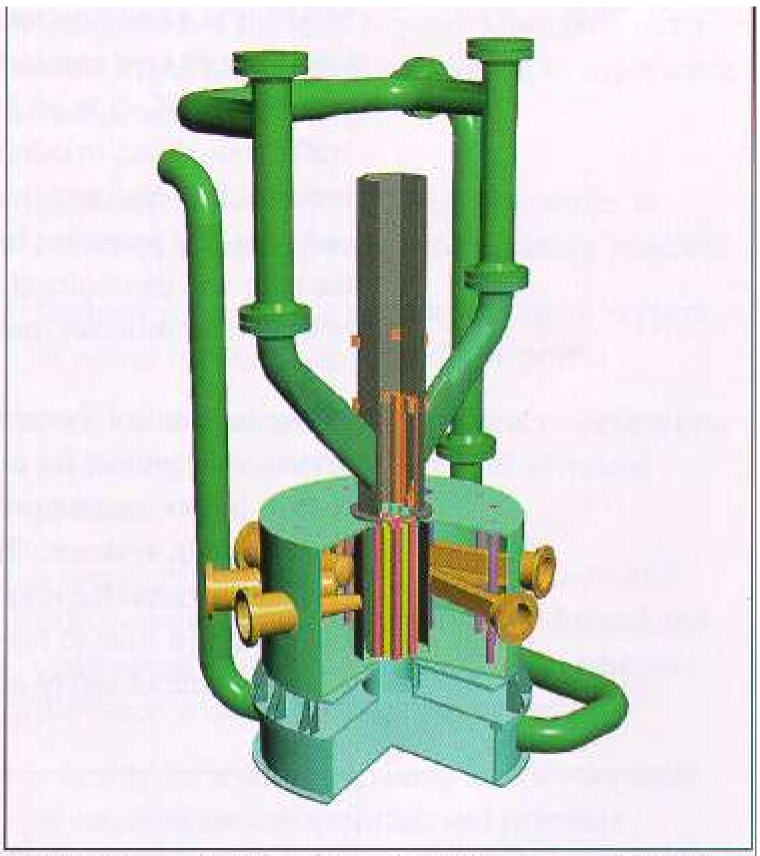

Figure 1 Multipurpose Applied Physics Lattice Experiment (MAPLE) Reactor

MAPLE is designed for ease of operation, maintenance, and to meet today's most demanding requirements for safety and licensing. The emphasis is on the use of passive safety systems and environmentally qualified components. Key safety features include two independent and diverse shutdown systems, two parallel and independent cooling loops, fail-safe operation, and a building design that incorporates the concepts of primary containment supported by secondary confinement.

Where possible, best estimate methods are used to assess safety margins associated with the operation of the MAPLE facility and, as such, an uncertainty assessment of the accuracy of those estimates is required. A full scope uncertainty assessment methodology has been developed [1] and applied to the limiting accident scenarios of the MAPLE facility.

Application of an uncertainty assessment methodology to MAPLE provides more realistic safety margins and illustrates the use of MAPLE as a vehicle for teaching, training, and development of essential nuclear expertise and licensing methods.

Section 2 of this paper provides an overview of the structured uncertainty assessment methodology. Section 3 lists the limiting accident scenarios to which the methodology is applied. The safety analysis code suite is introduced in Section 4. Section 5 describes the process of ranking important phenomena and associated parameters. Sections 6 to 8 describe methods of combining uncertainties into an overall uncertainty whether using the analysis programs directly or surrogate empirical models. Section 9 provides an example of an application to the limiting Loss of Regulation accident scenario.

2. Uncertainty Assessment Methodology

Any safety analysis relies on the use of computer codes, physical models, correlations and engineering judgment. Previous approaches to safety analysis include Risk Assessment, as part of waste storage assessments, Probabilistic Safety Analysis, as part of overall plant design and safety review for severe accidents and beyond-design basis events, and Deterministic Safety Analysis, to define plant operating limits for specified transients.

Each approach requires validated methods, which we define as the tools and techniques having specified statements of applicability and accuracy for the specific application, for the selected plant, and for the transient under examination. Validation exercises therefore produce quantified statements of the ranges and associated uncertainties for a specific application and qualify the method for the intended use. Therefore, the statement of accuracy for a particular method is inherently and intimately linked to the chosen safety analysis application.

The uncertainty assessment methodology described in this paper was adapted from OECD/CSNI recommendations and experience with the US NRC's CSAU[1] method, and consists of the following steps:

- identification of a limiting accident scenario;
- identification of the acceptance criteria to be met;
- identification of the margin parameters to be used to assess acceptance;
- working back through the analysis to determine the important phenomena and key parameters that have a significant impact on the value of the margin parameters;
- selection of a suite of computer programs to model the identified phenomena;
- identification of data sets that can be used to validate the selected computer programs;
- validation of the computer programs to provide a statement of accuracy for the conditions / geometries of the intended facility;

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1 Code Scaling Uncertainty and Applicability (NUREG/CR-5249)

- identification of all the sources of uncertainty that have a significant impact on the value of the margin parameters; and
- propagating the identified uncertainties through the safety analysis to provide an overall uncertainty assessment for the margin parameters.

Since the validation is for specified transients and operating states, the validation must be performed for relevant conditions and designs. This leads directly to the concept of phenomena based validation "matrices' where the method is tested against the ability to predict experimental data, known analytical solutions, or other (numerical and physical) benchmarks.

The output of the validation exercise is a statement of code accuracy and its associated uncertainty for the specified use, including the uncertainties in the ranges of the physical variables and the consequences of the various approximations that may be employed.

To conduct a safety analysis, it is necessary to consider the uncertainties in the safety analysis itself, which includes not only the modeling of the important phenomena but also the representations of the physical plant, equipment, and supporting experiments.

2.1 Computer Code Validation

The code validation process adopted by the Canadian nuclear industry is based on the five step process illustrated in Figure 2. The first two steps, formation of a Technical Basis Document (TBD) and a Validation Matrix, are generic. The last three steps, establishing a Validation Plan, performing Validation Exercises, and providing a summary Validation Manual, are code version specific.

The TBD identifies safety concerns and accident scenarios. Each accident scenario is subdivided into phases as different phenomena are dominant during different phases of a transient. Within each accident phase, the phenomena are ranked as to primary or secondary importance similar to the Phenomena Importance Ranking Table (PIRT) concept used in the CSAU methodology. However, the PIRT concept has been extended to rank the important parameters as well. This final step is necessary as uncertainties are evaluated for parameters. The assessment process is made representative and manageable by reducing the number of phenomena / parameters considered to include only the important ones.

The Validation Matrix identifies data sets that can be used for code validation purposes and cross references these with the governing phenomena identified in the TBD.

The Validation Plan describes how the Validation Matrix information is going to be used to estimate the systematic simulation uncertainty in important output parameters for a selected code version for selected accident scenarios. The Validation Exercises record the assessment process and results. The summary Validation Manual provides evidence for the accident scenarios and parameter ranges for which validation has been completed, and the range of uncertainty in important output parameters.

Development of the TBD and Validation Matrices for all safety analysis disciplines has been done as part of an Industry-wide initiative, the Industry Validation Matrices (IVM) [2] including small reactors. As AECL and the Canadian utilities have differing codes suites for safety analysis, another initiative, the Industry Standard Toolset (IST), is attempting to reduce the number of code versions requiring validation by selecting, for each discipline, a single code version or combining the functionality of similar computer programs.

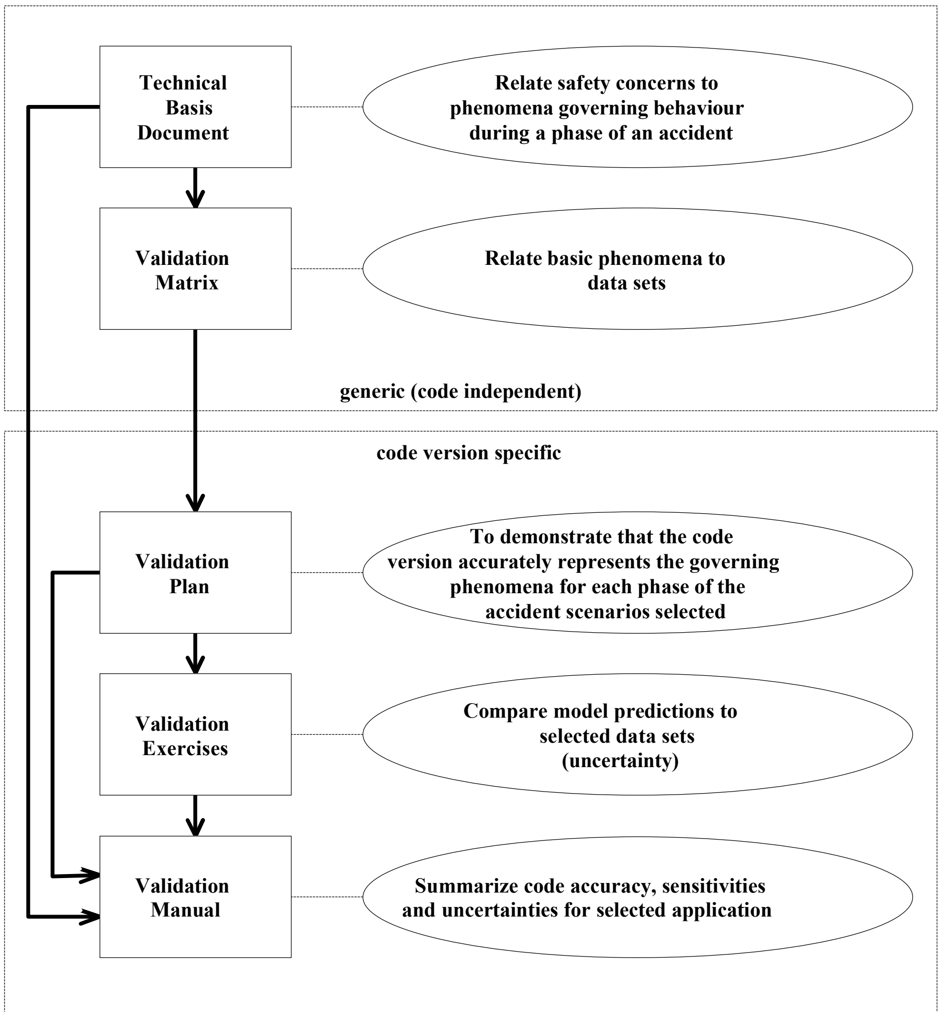

Figure 2 **The five steps involved in computer code validation.**

The exact version of each analysis code have been identified and placed under configuration management and change control. Software quality assurance (SQA) complies with the Canadian Standard N286.7.

By attempting to minimize the number of methods available and in active use, the cost of safety analysis and software maintenance is reduced. The important technical plus is that different plants and transients are analyzed by different people using similar methods. These methods therefore represent the "best estimate" codes and methods available for current use in safety analysis.

2.2 Structured Approach to Combining Sources of Uncertainty

The analysis of reactor safety margins utilizing a specific best estimate safety method or code suite proceeds with an integrated three step process, preceded by a statement of the selection of the method (illustrated in Figure 3). The three steps are [2]:

1. Establishment of Code Uncertainty (CUA): Uncertainty associated with models / correlations, the solution scheme, model options, unmodeled processes, data libraries and/or deficiencies of the computer program.
2. Assessment of the Representation Uncertainty (RUA): Uncertainty in representing / idealizing the real plant such as initial conditions, boundary conditions, plant state, nodalization, scaling (including 3D effects), fabrication tolerances and / or analysis assumptions.
3. Definition of the Plant Uncertainty (PUA): Uncertainty in measuring / monitoring the real plant such as reference plant parameters, instrument error, setpoints, instrument response, design allowances and/or availability requirements.

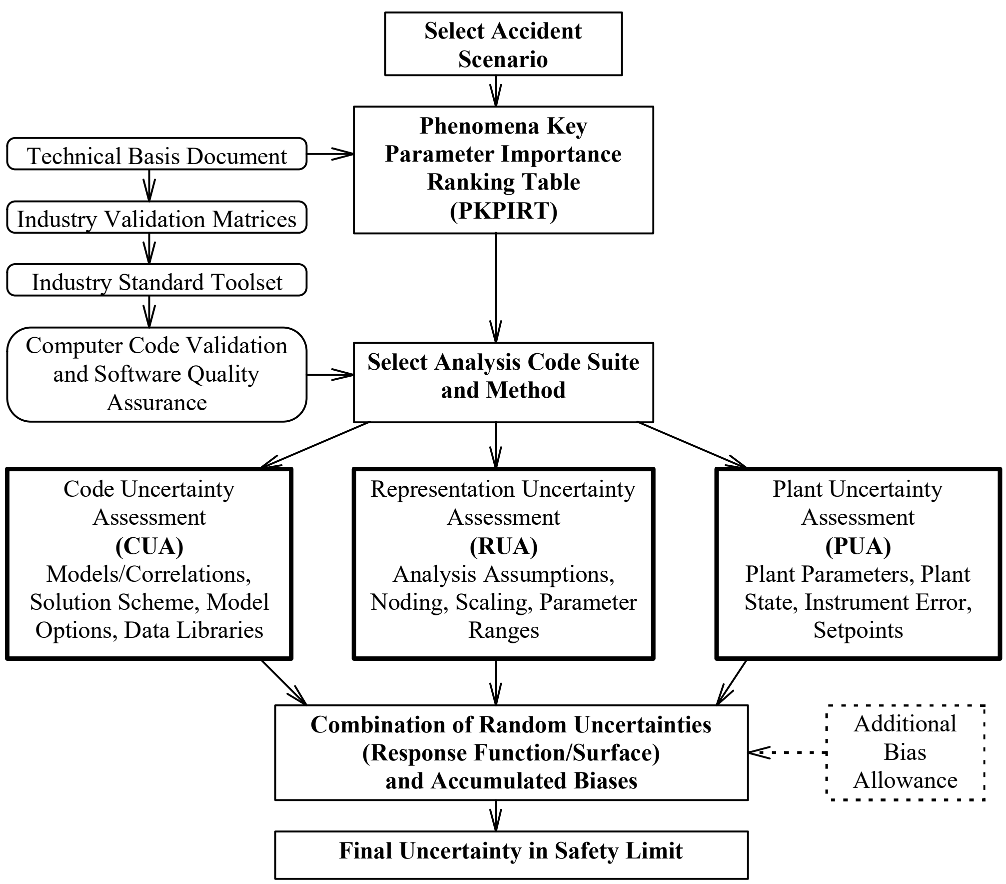

Figure 3 Information / process flow within the structured uncertainty assessment.

The sources of uncertainty should be tabulated and categorized with respect to CUA, RUA and PUA to ensure all important sources of uncertainty are considered. For the MAPLE uncertainty assessment, the format shown in Table 1 was found to be convenient for this purpose.

Table 1: Tabulation of Uncertainty Components

Source of Uncertainty	Uncertainty Component	
	Systematic	Random

Where the limits to the uncertainty are known but the shape of the distribution is not (e.g., tolerance interval), a uniform distribution (i.e., all values within the range equally probable) is assumed.

3. Limiting Accident Scenarios

The objective of the MAPLE assessment is to demonstrate that, for all design basis events, there are adequate margins to the derived acceptance criteria considering the overall uncertainties. From the internationally recognized design basis accidents, the limiting design basis accident scenarios assessed for the MAPLE facility include:

- Single Channel Flow Blockage (SCFB);
- Loss of Flow (LOF);
- Loss of Regulation (LOR); and
- Assessment of Stable Shutdown Margin (SDM).

The LOR scenario is limited by reflector downgrading. In the MAPLE reactor, the control ion chambers and gamma detectors are located outboard of the heavy water reflector. Downgrading of the heavy water reflector with light water masks the neutron and gamma fluxes to the detectors.

4. MAPLE Safety Analysis Code Suite

The safety analysis code suite consists of:

- a system thermal hydraulics computer program, CATHENA [3];
- a core physics computer program, 3DDT [4];
- a lattice physics computer program, WIMS-AECL [5];
- a neutron / photon transport computer program, MCNP [6];
- a burnup / depletion computer program, ORIGEN-S [7];
- a dose / shielding computer program, QAD-CGGP-A [8]; and
- a dose / atmospheric dispersion computer program, PEAR [9].

5. Importance Ranking of Phenomena and Key Parameters

Figure 4 illustrates the safety analysis code suite and the flow of information through the analysis. The acceptance parameters are dose to the public, on-site personnel, and Operators. If no fuel failures occur (i.e., no fission products are released), the derived acceptance parameter is the Critical Power Ratio (CPR) for the fuel channel.

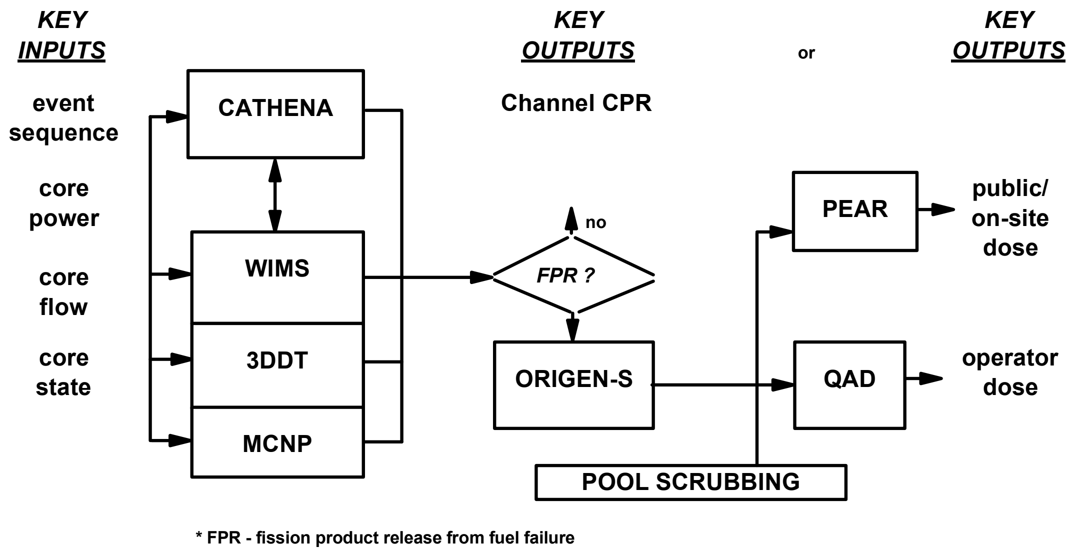

Figure 4 MAPLE Safety Analysis Code Suite

If the CPR remains above unity, fuel failure is precluded. The computer programs involved in the margin assessment are CATHENA, 3DDT/WIMS-AECL and MCNP.

If the CPR falls below unity, fuel burnout cannot be precluded, and fuel failure / fission product release is assumed. The computer programs involved in this assessment are ORIGEN-S, QAD-CGGP-A and PEAR. Pool scrubbing is an efficient means of slowing the transport and providing attenuation of fission products from the pool and has been modeled by both the AEA Technologies' FACSIMILE code and an independent model.

Table 2 indicates, for each computer program, the output parameters that have a significant impact on the value of the acceptance or margin parameter. A more specific breakdown by accident scenario for the reactor physics computer programs is shown in Table 3.

Table 2: Key Output Parameters from each Computer Program

Computer Program	Key Output Parameters
WIMS-AECL / 3DDT	Power distribution; k-effective; reactivity change
MCNP	Pin power distribution; gamma flux at detectors
CATHENA	Critical channel power for burnout
ORIGEN-S	Total nuclide inventories; radiation source term
QAD-CGGP-A	Gamma-ray dose rates
PEAR	Public dose

Table 3: Key Output Parameters from Reactor Physics Codes

Parameter	WIMS-AECL / 3DDT				MCNP			
limiting scenario	SCFB	LOF	LOR	SDM	SCFB	LOF	LOR	SDM
Channel power		✓	✓					
k-effective				✓				
Reactivity coefficients		✓						
Burnup distribution				✓				
Assembly reactivity		✓	✓	✓				
Pin powers						✓	✓	
Detector fluxes							✓	

Table 4 is a guide to assessing the relative importance or ranking of an output parameter (Y) based on changes in a key input or model parameter (X) using the product of the sensitivity, φY/φX, and the uncertainty, ⇔X.

Table 4: Importance Ranking of Key Input and Model Parameters

Sensitivity φY/φX	Uncertainty ⇔X	Importance Ranking [(φY/φX) ⇔X]
High	High	High
High	Low	Scenario dependent
Low	High	
Low	Low	Low
Parameter set at limiting or conservative value		Removed from uncertainty assessment

In creating a Phenomena Key Parameter Importance Ranking Table (PKPIRT), use of the numerical value of $[(φY/φX) ⇔X]^2$ would be appropriate for ranking purposes as it is indicative of the relative contribution to the overall uncertainty.

Table 5 illustrates the PKPIRT established for the LOR limiting scenario. Where a parameter has been set at a conservative value, it is removed from the uncertainty assessment and is not regarded as key. The identifiers shown with square braces are the phenomenon identifiers established for the Industry Validation Matrix initiative [2].

6. Combined Uncertainty Methodology

Whether a computer program is being used directly (designated Type 1) or an empirical model is being used (designated Type 2), the process of evaluating a combined uncertainty of the CUA, RUA, and PUA uncertainties is the same. For each of the key input or model parameters, a value is randomly sampled from the distribution of their values. The outcome of a single simulation with this input set creates one value for the selected key output parameter. By repeating this process many times, a distribution of values can be developed for the selected output parameter. This output distribution can be statistically analyzed to determine mean values and confidence levels.

Once the sources of uncertainty have been tabulated and the necessary response surfaces created, the assessment of overall uncertainty is relatively straight forward. A PC-based tool, SAM (for safety analysis method) has been developed to facilitate this assessment. SAM performs the sampling of a given set of input functions to generate an output distribution function for the combination of variations in these inputs. The output distribution is shown to be relatively insensitive to the random kernel used (e.g. EXCEL).

Table 5: PKPIRT for the Limiting LOR Scenario

Limiting Accident Scenario:	**Loss of Regulation (Reflector Downgrading) (LOR)**					
Margin Parameter:	**Minimum channel CPR**					
		Ranking				
Analysis Input Parameter	**Phenomenon Governed by Parameter**	WIMS/3DDT	MCNP	Point kinetics & Gamma dosimetry	Is parameter conservative ?	Is parameter key ?
Reflector downgrade (wt% H2O)	[PH14] Flux/power distn. in space & time	H	H		yes	
Channel power homogenization	[PH14] Flux/power distn. in space & time	H			yes	
Core configuration and total power	[PH14] Flux/power distn. in space & time	H	H		yes	
Channel power grouping	[PH14] Flux/power distn. in space & time	L				
Fuel burnup	[PH14] Flux/power distn. in space & time		M			yes
Fuel density	[PH14] Flux/power distn. in space & time		M			yes
Coolant temperature	[PH2] Coolant temp. change induced react.		L			
Critical channel power	[TH9] CHF/dryout & post-dryout heat trans.			H	yes	
Flux detector masking factor	[PH13] Flux detector response			H		yes
Shutdown system actuation delay	[PH11] Device movement induced react.			H	yes	
Peak-to-average pin power ratio	[PH14] Flux/power distn. in space & time			H		yes
Relative core power vs CAR position	[PH11] Device movement induced react.			H		yes
CAR withdrawal rate	[PH11] Device movement induced react.			H	yes	
Scattering correction to masking factors	[PH13] Flux detector response			M		yes
Absorber position	[PH11] Device movement induced react.			M		yes
PCS flow rate	[TH9] CHF/dryout & post-dryout heat trans.			M	yes	

CAR - Control Absorber Rod
PCS - Primary Cooling System

Table 8 in Section 9 lists the input file used with SAM for minimum CPR assessment for the limiting LOR scenario. The first block of data [i.e., @fixed] represents constants used in the assessment as coefficients, biases, etc. The second block of data [i.e., @inputs] defines the parameter, distribution type (N for Normal, U for uniform), mean, and standard deviation or range for parameters (refer to Section 2.2) that are to be randomly sampled during the assessment. The third block of data [i.e., @functions] gives the response surfaces generated for the assessment.

The response surfaces can be a series-parallel network that represents the safety analysis (i.e., a response surface can have inputs and other outputs as parameters). To assess the uncertainties in the outputs using the response functions, 10,000 simulations, or whatever number of simulations is needed to demonstrate convergence (i.e., less than x % change in the fit for times n more samples), are performed with inputs randomly sampled for each simulation. For each output parameter, minimum and maximum values are recorded and a 100 bin histogram is created. At the end of the process, means, standard deviations, 95% confidence level for values greater than or equal to, and 95% confidence level for values less than or equal to are evaluated.

7. Calibration for Type 2 Uncertainty Combination Using Empirical Models

In the absence of prior knowledge, for a process having *m* potential controlling factors, we would have to conduct experiments to explore every combination of those factors. In the worst case, where the output of the process depends on every parameter and on every possible combination of parameters equally, it would require 2^m experiments or computer simulations to assess the importance of each factor and the interaction between factors.

Fortunately, real processes do not behave in such a perverse manner. Typically a main effect and up to *k*-1 factor interactions can be estimated with approximately 2^k experiments. If the response is non-linear in some parameters, more simulations may be needed. Conversely, if *k* is relatively large (say more than 40), the behaviour of the process may be dominated by a small number of parameters, and fewer than *k* experiments may suffice. Where the expected number of factors is too large, the problem can be made more tractable by using prior knowledge to eliminate factors of little importance (refer to Section 5).

The phenomena represented in the MAPLE reactor safety analysis are sufficiently well understood that high quality mathematical models and computer codes are available. Many experiments have been performed over several decades to determine main effects and their interactions. The result of this effort is used to eliminate factors having negligible effect on the value of the key output parameter before extensive uncertainty assessment is initiated. The intial ranking of the factors (or key parameters) is based on experimental evidence, prior analysis experience, and consensus expert opinion.

If empirical models are used, the calibration cases required for fitting the model should be formally selected based on design of experiment methods to ensure that as much information on main effects and interaction effects is captured with the fewest number of calibration cases [3, 4]. Note that the calibration case results are obtained using the analysis code suite components.

7.1 Factorial Design

A full factorial design would require a calibration case for every combination of key input or model parameters (i.e., factors). To capture the variation of the underlying analysis within a small region of interest about the base or reference case, at least two values (or levels) of each parameter would be used. As the number of calibration cases increases as 2^k, where k is the number of parameters, such an approach is only practical for small values of k.

7.2 Latin Hypercube Design

Latin hypercube sampling is a technique to use when many levels are required and the full factorial design must be sampled extremely sparsely. Other designs requiring only a small number of simulations are also available (e.g., Koshal, Plackett/Burman [10]). In the Latin hypercube design, the range of values for each factor are subdivided into ranges of equal probability.

An example of a two-factor, three-level design illustrates the process (refer to Figure 5). First select a square (e.g, Ac) and block off the remainder of the associated row and column. From the remaining squares, select a square (e.g., Ba) and block of the remainder of its row and column. Continue until all squares are selected or blocked.

Care must be exercised by the analyst in using this design as it is possible to pick only diagonal elements and thus provide little information on interaction terms. Also, when extended to several factors, a "uniform" distribution of calibration cases within the parameter space is difficult to guarantee. However, the design is useful for scoping studies.

	Factor 1		
	A	B	C
a	-	x	-
b	-	-	x
c	x	-	-

Figure 5 Latin hypercube design for 2 factors and 3 levels.

7.3 Fractional Factorial Latin Hypercube Design

Andres [11] suggests a more optimal design, the fractional factorial Latin hypercube (FFLH) design, and has developed a FORTRAN program, SAMPLE2, to generate the design for the user. FFLH has all the advantages (and disadvantages) of the Latin hypercube design (estimates means with good efficiency, full domain of each parameter, excellent asymptotic properties) and the fractional factorial design (estimate main effects and interactions).

The FFLH design constrains the Latin hypercube design selected to achieve the factor interaction structure of the fractional factorial design. The FFLH design ensures a uniform distribution of calibration cases within the parameter space being investigated.

8. Creating An Empirical Model

Creating an empirical model or response surface is a curve or surface fitting exercise. Empirical model fitting should use phenomenologically correct expressions if possible or a general polynomial of high enough order to capture the main effects and interaction effects. Response surfaces are deliberately kept as simple as possible while retaining the required physical accuracy. One method of performing the regression analysis is to:

- run a linear regression analysis of the chosen polynomial for the main effects (*i.e.,* the main parameters). Using analysis of variance (ANOVA) results, remove main parameters that are shown to be statistically unimportant.
- add terms representing the square of the remaining main parameters. Using ANOVA results, remove squared terms that are shown to be statistically unimportant.
- add cross-product terms of the remaining main parameters. Using ANOVA results, remove cross-product terms that are shown to be statistically unimportant.

The process can be continued by adding higher-order terms until the least squares regression indicates that a good fit has been obtained. Commercial software is available to automate the multiple regression process (e.g., EXCEL, Systat).

9. Application to the Loss of Regulation Scenario

Note that this example is for illustration purposes only, chosen to illustrate the elements and their combination, including unrepresented effects. The values shown are representative of a limiting channel.

The limiting Loss of Regulation (LOR) accident for the MAPLE reactor is a slow LOR initiated at startup when the reflector is downgraded to 20 wt% H_2O - an analysis downgrading limiting assumption. In reality, sustained reactor operation is not possible above 20 wt% H_2O downgrading; startup is not possible above 2 wt% H_2O downgrading. The derived safety target is no systematic fuel failures, which can be assured if the CPR value for the fuel assembly does not fall below 1.0

Allowing for the CUA, RUA and PUA uncertainty components, the predicted minimum CPR value for the fuel assembly must be greater than or equal to 1.31 to meet the acceptance criterion at the 95% confidence level (refer to Section 9.3).

Determination of the minimum value of CPR requires the following steps:

1. The reactivity worth of the CARs as a function of CAR position is generated with 3DDT.
2. A neutron kinetics utility, PKSTART, is used to generate relative core power as a function of time (or CAR position as the CAR withdrawal rate was 1.0 $mmIs^{-1}$).
3. The CAR position is set at the elevation for full power
4. Increment CAR position.
5. Evaluate core power and channel power from nominal core power/channel power ratio.
6. Allow for core peaking on channel power.
7. Establish masked gamma detector reading including allowance for delayed gammas.
8. If the masked gamma reading does not agree with the 124% FP (full power) setpoint then return to step 4.
9. Add allowance to channel power for 1 s delay time between trip initiation and actuation.
10. Evaluate CPR for the fuel assembly.

9.1 Sources of Uncertainty

The sources of uncertainty for the LOR scenario are shown in Table 6. The random components are quoted as one standard deviation for a normal or gaussian distribution or, as low/high values for a uniform distribution.

Table 6: Sources of Uncertainty for the Loss of Regulation Event

Source of Uncertainty	Uncertainty Value	
	Systematic	Random
CAR position		-1 mm , +1 mm
Response function for relative core power	0	0.01757
Response function for unmasked gamma signal	0	0.017425
Critical channel power	+16.4%	14%
Core power assumption	-9.1%	4.55%
Core peak power	-3.6%	0
Core flow assumption	+10.1%	5.05%
Safety system actuation delay	-3%	9.6%
Masking in excess of 2 wt% H_2O	-32%	0
Scattering correction to masking factors	+4.8%	0
Uncertainty in assembly power:		
- from burnup uncertainty	-0.17%	2.4%
- from fuel density uncertainty	2.2%	2.1%

9.2 Estimates of Simulation Error (CUA Offset)

Key inputs to this analysis are the core power distribution and gamma distributions from MCNP. Validation exercises give the offset in core power distribution for the beginning-of-cycle equilibrium core as -0.15% with a standard deviation of 2.49%. The same reference gives the offset in predicted gamma signal masking factors as -2.08% with a standard deviation of 24.11%.

9.3 Combination of Uncertainties

The margin parameter for LOR due to reflector downgrading is the critical channel power ratio, CPR.

The response function for relative core power (P) versus CAR position (z) is given by the expression:

$$P = (a + bz^{1.5})^2$$

where $a = -3.5801892$
$b = 3.28863 \times 10^{-4}$
with a standard error of 0.01757.

The response function for the unmasked gamma signal (S) versus CAR position (z) is given by the expression:

$$S = (a + bz^2)^2$$

where $a = -2.1339565$
$b = 9.28862 \times 10^{-6}$
with a standard error of 0.017425.

Using these empirical response functions with the analysis values, for a masked gamma signal of 124% full power, the CAR position is 613.6 mm for a relative core power of 2.012. The maximum assembly power is thus 254.7 kWx(2.012)x(1.03)x(1.036) or 546.8 kW where the last two terms in brackets represent an allowance for safety system actuation delay and peak core power uncertainty respectively. The minimum CPR indicated is 937.3/546.8 or 1.71.

Minimum assembly CPR for a masked gamma signal of 124% full power is subject to the uncertainties shown in Table 7 under safety analysis limit assumptions.

Table 7: Sources of Uncertainty Under Safety Analysis Assumptions

Source of Uncertainty	Uncertainty Value	
	Systematic	Random
CAR position	0	-1 mm , +1 mm
Masking factor simulation offset	0	24.11%
Light water scattering effect on masking	0	0
Response function for relative core power	0	0.01757
Response function for unmasked gamma	0	0.017425
Critical channel power	0	14%
Core peak power	+3.6%	0
Safety system actuation delay	3%	0
Uncertainty in assembly power: - from burnup uncertainty - from fuel density uncertainty	 -0.17% 2.2%	 2.4% 2.1%

The uncertainties listed in Table 7 contribute a combined uncertainty of 30.2% at the 95% confidence level (refer to SAM input file in Table 8). The indicated minimum CPR of 1.71 is sufficiently above 1.302 (i.e., applying the uncertainty to the acceptance criteria of 1.0) that adequate margin is available allowing for these uncertainties.

Figure 6 provides a histogram and a cumulative distribution for the CPR margin parameter. The input data is taken from Table 8. The histogram for the output parameter is well behaved and approximates a normal distribution with mean 1.68 and a standard deviation of 0.242.

Table 8: SAM Input for Loss of Regulation (Reflector Downgrading) Under Safety Analysis Conditions

```
LOR due to Reflector Downgrading: startup with 20 wt% H2O
@fixed
CARpos,613.6                ' CAR position (mm)
n1,1.5                      ' response function coefficients
n2,2.
a1,-3.5801892
b1,3.28863e-4
a2,-2.1339565
b2,9.28862e-6
bupowb,-0.0017              ' burnup / power bias
denpowb,0.022               ' fuel density / power bias
SS,1.03                     ' SS actuation delay
```

```
Peak,1.036                    ' peak power correction factor
CP,254.7                      ' hottest cluster power (kW)
CCP,937.3                     ' critical cluster power (kW)
@inputs
mask1,N,1.,.1705              ' gamma masking factor for 0.2 wt%
mask2,N,.6651,.1705           ' gamma masking factor for 20 wt%
posua,U,-1.,1.                ' uncertainty in CAR position (mm)
bupowr,N,0.0,0.024            ' burnup / power random
denpowr,N,0.0,0.021           ' fuel / density / power random
rcpua,N,0.0,0.01757           ' relative core power vs CAR function
mgua,N,0.0,0.017425           ' masked gamma vs CAR function
CCPua,N,1.,.14                ' uncertainty in CCP
@functions
Y1=(a1+b1*Y3^n1)^n2+rcpua     ' relative core power vs CAR position
Y2=(a2+b2*Y3^n2)^n2+mgua      ' unmasked gamma signal vs CAR position
Y3=CARpos+posua               ' CAR position (mm)
gam=Y2*mask2/mask1            ' masked gamma signal
fuel=un+bupowb+bupowr+denpowb+denpowr
Cpow=CP*Y1*SS*Peak*fuel       ' hottest cluster power
CPR=(CCP*CCPua)/Cpow          ' CPR for cluster
@end
```

As a conservative assumption, scattering by light water for the 20 wt% downgrading limiting scenario had been omitted in the safety analysis. The validation exercise for masked gamma signal indicates that this correction would increase the masked gamma signal by 4.8%. However, the masking factor is under-predicted by 2.1% (see Section 9.2) yielding a net offset of 6.9% in the predicted masked gamma signal at this level of downgrading. The CAR position for an unmasked gamma signal of 124% full power would then become 607.8 mm at a relative core power of 1.816 instead of 2.012. This position adjustment would increase the predicted minimum CPR to (1.71x2.012/1.995) or 1.89.

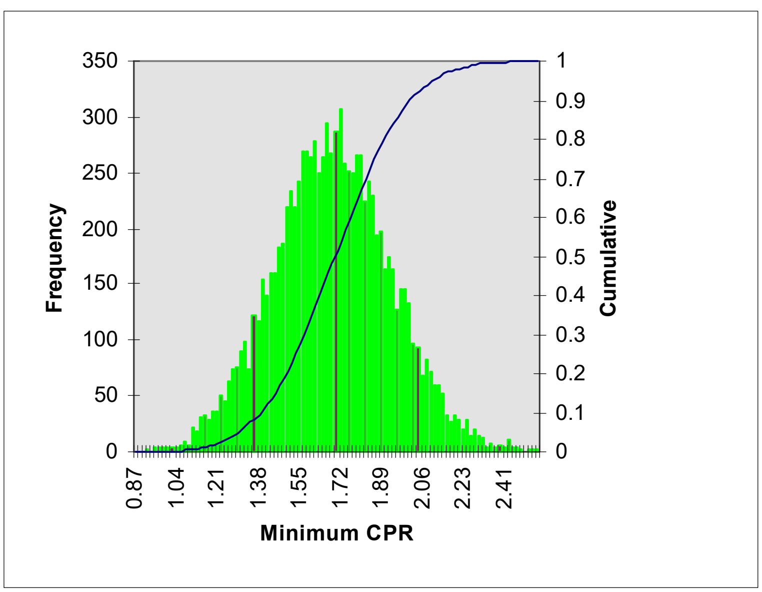

Figure 6 Distribution of Minimum CPR for Limiting LOR Scenario

9.4 Best Estimate Analysis

If the analysis assumption biases listed in Table 6 are removed in the analysis of this limiting scenario, the results would be more representative of a design centered analysis. When these bias adjustments are made, the predicted value of the minimum CPR becomes 2.54.

10. Summary

The structured method of uncertainty assessment presented in this paper adopts a systematic approach that:

- treats the safety analysis in an integrated manner;
- focuses on the governing phenomena and key parameters;
- combines uncertainty sources based on system response;
- accounts for interactions between phenomena; and
- provides a statement of the accuracy and confidence limits for safety margins.

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