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Calculation of Mixed Core Safety Limit Minimum Critical Power Ratio

Westinghouse

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Calculation of Mixed Core Safety Limit Minimum Critical Power Ratio

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LIST OF ACRONYMS AND TERMS

2D	Two-Dimensional
3D	Three-Dimensional
ADAMS	Agency-wide Documents Access and Management System
AOO	Anticipated Operating Occurrence
BFBT	NUPEC BWR Full-size Fine-mesh Bundle Test
BWR	Boiling Water Reactors
CHFR	Critical Heat Flux Ratio
CPR	Critical Power Ratio
DNB	Departure from Nucleate Boiling
DNBR	DNB Ratio
FRIGG	Westinghouse BWR test loop in Västerås, Sweden
LAR	License Amendment Request
Legacy Fuel	Fuel assembly types from vendors other than Westinghouse.
MCPR	Minimum CPR
McSLAP	Monte Carlo Safety Limit Analyzer Program
NRC	Nuclear Regulatory Commission
OLMCPR	Operating Limit Minimum CPR
Q_{cor}	Predicted critical power of the optimized correlation
Q_{leg}	Legacy fuel critical power
Q_{mea}	Measured critical power from FRIGG test loop
Q_{mef}	Predicted critical power of the VIPRE-W/MEFISTO training database
RAI	Request for Additional Information
SER	Safety Evaluation Report
SLMCPR	Safety Limit Minimum CPR
Training Data	Data generated by VIPRE-W/MEFISTO for re-optimizing a CPR correlation

1 INTRODUCTION

The Westinghouse Electric Company methodology for the calculation of Safety Limit Minimum Critical Power Ratio (SLMCPR) of Boiling Water Reactors (BWRs) was reviewed and approved by the NRC in Reference 1. The approved methodology employs [ ]^{a,c} evaluation of the SLMCPR. The SLMCPR is for use in assessing margin to given fuel dryout safety criteria. In U.S. licensing applications, according to Reference 10, the following are two acceptable criteria for evaluating the SLMCPR:

A. For departure from nucleate boiling ratio (DNBR), CHFR or CPR correlations, there should be a 95-percent probability at the 95-percent confidence level that the hot rod in the core does not experience a DNB or boiling transition condition during normal operation or AOOs.
B. The limiting (minimum) value of DNBR, CHFR, or CPR correlations is to be established such that at least 99.9 percent of the fuel rods in the core will not experience a DNB or boiling transition during normal operation or AOOs.

This document provides improvements to the mixed core treatment for use with the approved SLMCPR methodology. In this document, the term "mixed core" refers to a core containing fuel types from multiple fuel vendors. Example applications of the improved mixed core treatment are presented. This document also supplies additional detail and further validation of the approved SLMCPR methodology and its implementation. This information is provided in order to establish a more detailed reference regarding the SLMCPR calculation which may aid in the review of future SLMCPR-related licensing applications (e.g., License Amendment Requests for Technical Specification changes to SLMCPR values).

1.1 PURPOSE

Westinghouse recognizes, based on the NRC's request for additional information during the latest Licensing Amendment Request for transition to Westinghouse's fuel, that the information provided in Reference 1 needs to be completed or clarified regarding the SLMCPR methodology.

This document is intended as an enhancement to the mixed core SLMCPR calculation process described in Reference 1. The purpose is to improve the mixed core treatment, to reaffirm applicability of the Westinghouse SLMCPR calculation method to all boiling water reactors, and to provide an important reference that will better facilitate straightforward efforts in future licensing applications regarding SLMCPR.

The improved CPR treatment of cores which contain a mix of fuel types from different vendors is established in order to facilitate a more consistent application of the Reference 1 SLMCPR methodology. The improvement consists of an approach for calculating [

]^{a,c} By evaluating the actual mixed core condition in the SLMCPR calculation, effects of the mixed core conditions including feedback to fresh fuel CPR distributions are better captured. The improvement more clearly establishes SLMCPR values which capture all relevant CPR uncertainties, and therefore [

]^{a,c}

In addition to improvements in mixed core treatment, greater detail and background information to the NRC-approved methodology is presented, as well as SLMCPR results to validate that the methodology is implemented correctly. The [

]^{a,c} Additional details and validations regarding the approved SLMCPR calculation are presented in Appendices A and B in order to eliminate ambiguities and to establish applicability to all BWRs.

1.2 SLMCPR LICENSING BACKGROUND

The Monte Carlo safety limit calculation process used by Westinghouse in U.S. applications was approved in Reference 1 and has been implemented over the past two decades for a variety of BWR plants in the U.S. and in Europe. The special treatment of mixed core conditions used in these applications [

]^{a,c}

1.3 NRC REVIEW SCOPE AND LIMITS OF APPLICABILITY

The basic Westinghouse NRC-approved SLMCPR methodology remains unchanged as described by Reference 1. The SLMCPR methodology of Reference 1 is applicable to BWR reactors only with the appropriate conditions and/or limitations as specified by its safety evaluation report. Condition/Limitation 7 from Reference 1 is specifically directed to mixed core CPR calculations and is provided as follows:

7. The ABB/CE methodology for determining the operating limit maximum [sic] *critical power ratio (OLMCPR) for non-ABB/CE fuel as described in CENPD-300-P and additional submittals is acceptable only when each licensee application of the methodology identifies the value of the conservative adder to the OLMCPR. The correlation applied to the experimental data to determine the value of the adder must be shown to meet the 95/95 statistical criteria. In addition, the licensee's submittal must include the justification for the adder and reference the appropriate supporting documentation.*

By applying an improved mixed core treatment as described in this supplement document, [

]^{a,c}

This document describes a generic process for treating the mixed core condition and establishing [ ]^{a,c} from other vendors. Fuel assembly types from vendors other than Westinghouse are referred to as "legacy fuel" in this document. The mechanistic dryout prediction tool VIPRE-W/MEFISTO described in Appendix C is used as an example for establishing [ ]^{a,c} The generic process is explained in Section 3 using SVEA-96 Optima3 and the D5 CPR correlation as an example. Different scenarios of mixed core application are considered in Appendix D. They differ by the amount of information available for the legacy fuel in terms of a CPR database and are meant to describe the span of applications of the improved mixed core treatment. The data and results in Appendix D also represent examples of the information that would be provided in a LAR supporting a typical fuel transition.

In order to examine the extent of potential error introduced [ ]^{a,c}

The increased uncertainty, as compared to what is normally obtained for an NRC-licensed CPR correlation, accounts for [ ]^{a,c} in the legacy fuel as well as for the uncertainties in [ ]^{a,c} data. Other components to the legacy fuel CPR such as fuel geometry, power peaking, and basic thermal hydraulics are assumed to be available from the vendor and modeled in the core simulator in a manner similar to Westinghouse fuel.

In a more typical case in which the available CPR database is considered extensive but not complete (Scenario 2), the added information of the CPR database may be used to further validate and improve the accuracy of the re-optimized CPR correlation and R-factor and thereby reduce [ ]^{a,c} by the process described. A detailed example of such application is given in Section D.2. This scenario is considered to be the most frequently encountered.

In case a complete CPR database is available (Scenario 3), reference is given to the generic approach of developing a CPR correlation in Reference 4.

VIPRE-W/MEFISTO is an internal code package in Westinghouse and is used to [ ]^{a,c} The VIPRE-W/MEFISTO code package is not approved for use as a stand-alone substitution of a CPR correlation. [ ]^{a,c} The CPR predictions of VIPRE-W/MEFISTO have been extensively validated as described in References 5-7. NRC approval is meant to be limited to the calculation method and is not meant to include generic approval for VIPRE-W/MEFISTO since, in principle, the calculation process described may be applied with any dryout prediction tool or method, given the appropriate justification of uncertainties for the use the generated training data are determined and provided to the NRC.

The use of an extreme error value for the case of Scenario 1, or any reduction in [

]^{a,c} through the use of additional information according to Scenarios 2 or 3 will be justified as part of a license amendment request with a fuel product transition. While the process is described using an example with the SVEA-96 Optima3 D5 correlation, the mixed core approach in this report is not limited to use with the D5 correlation and it could conceivably be applied also with previous and future NRC-licensed CPR correlations and fuel products. [

]^{a,c}

Each fuel type in a mixed core may have a unique CPR correlation associated with it. The CPR correlations should be consistently applied in both the SLMCPR calculation and reload transient analyses which determine the OLMCPR value. A re-optimized CPR correlation is only necessary in cases where proprietary restrictions do not allow for the direct use of a previously approved CPR correlation for a legacy fuel product. Therefore, the use of a re-optimized CPR correlation is normally limited to the reload licensing analysis and SLMCPR determination for each cycle of mixed core operation, as well as core design and scoping calculations.

[

]^{a,c}

In summary, Westinghouse seeks NRC review and approval of an improved methodology for developing a conservative mixed core SLMCPR which addresses legacy fuel CPR uncertainties such that [

]^{a,c}

1.4 MONTE CARLO METHOD SUMMARY

The rod power distributions, bundle power distributions, and bundle and rod CPR distributions used in the SLMCPR Monte Carlo calculations are created with NRC-approved 2D lattice and 3D nodal codes (e.g., PHOENIX and POLCA, Reference 8). The NRC-approved SLMCPR methodology description is given in Section 5.3.2.2 of Reference 1, and further elaborated through the RAI Questions F11-F13 in Appendix F of Reference 1. The rod, bundle power, and CPR distributions are administrated in the SLMCPR calculation by a suite of Westinghouse internal codes referred to as the Monte Carlo Safety Limit Analyzer Program (McSLAP). This suite of administrative data codes has historically been applied in all Westinghouse SLMCPR Monte Carlo calculations.

The McSLAP administrative code suite is used to determine the appropriate SLMCPR value based on [ ]^{a,c} CPR uncertainty as specified in Reference 1. CPR uncertainties are discussed in Appendix A.

The following basic steps are involved in the Monte Carlo SLMCPR calculation:

- Identify the input variables which significantly affect the calculated CPR values, establish [ ]^{a,c}
- Generate [ ]^{a,c}
- For each [ ]^{a,c}
- Perform [ ]^{a,c}

The main advantages [ ]^{a,c}

The approved Monte Carlo method as implemented by the McSLAP administrative code suite has been used in multiple U.S. and European applications and has been extensively validated against analytical (deterministic) methods. In order to provide confidence in the implementation, additional details of the method relative to those provided in Reference 1 as well as a comparison to deterministic results have been included in Appendix B.

1.5 SUMMARY OF CHANGES TO THE MIXED CORE TREATMENT

In accordance with the approved methodology in Reference 1, an effective CPR correlation is established for the legacy fuel through [

]^{a,c} The CPR results in licensing analyses for the legacy fuel are then calculated using this re-optimized correlation. However, because only [

]^{a,c}

To address unknown information about the legacy fuel, the mixed core treatment presented in Reference 1 applies [

]^{a,c}

The intent of the SLMCPR value is to address CPR calculation uncertainty, so that reload licensing and core monitoring applications may evaluate margin to dryout directly. Rather than to calculate [

]^{a,c} in the same manner as a core comprised of only Westinghouse fuel types. The process of [

]^{a,c} are eliminated in this improved approach.

To support the improved mixed core approach, a mechanistic dryout prediction tool (e.g., VIPRE-W/MEFISTO described in Appendix C and in References 5-7) is used to [

]^{a,c}

This process is detailed in Section 3 and Appendix D, and is closely linked with the process that has been applied for establishing CPR correlation data and uncertainties in Westinghouse fuel, (e.g., D5 correlation in Reference 4).

[

]^{a,c}

[

]^{a,c}

2 MIXED CORE SLMCPR BACKGROUND

Special considerations are needed for fuel cycles during the transition process from one fuel vendor to another. For a transition cycle with a mixed core condition, the legacy fuel can be incorporated in the SLMCPR calculation in the same manner as for the fresh fuel with its own uncertainty inputs given that they are known and that a representative CPR correlation is available. While typically the licensed CPR correlation is provided to a nuclear utility for core monitoring applications, it may not be available to a competing fuel vendor for the core design and licensing applications. Therefore in such cases a CPR correlation must be established for the legacy fuel, which is done by [

]^{a,c}

For SLMCPR calculations with legacy fuel, the [

]^{a,c} Because individual rod CPR distribution data may not be available, an explicit SLMCPR calculation was avoided in the historical mixed core approach of Reference 1. The background for this historical mixed core approach is explained in detail below.

<u>Background of Historical Mixed Core Approach</u>

The historical Westinghouse mixed core approach described in Reference 1 is considered simplistic and [

]^{a,c}

In order to address [

]^{a,c}

[

]^{a,c}

3 IMPROVED MIXED CORE CPR TREATMENT

An approach is developed whereby a more realistic mixed core SLMCPR calculation may be performed in a straightforward manner. This process serves as an alternative approach to Reference 1 which applies [

]^{a,c}

An NRC-approved CPR correlation and associated approved R-factor model are [

]^{a,c}

By use of the re-optimized CPR correlation and R-factor model, together with relative rod powers predicted by an NRC-approved lattice code (e.g., PHOENIX) and information from an NRC-approved 3D nodal code (e.g., POLCA), both the [

]^{a,c} which addresses the increased uncertainties in the re-optimized CPR correlation and R-factor model. Furthermore, as for the Westinghouse fuel, the uncertainties in [

]^{a,c} are included as separate components in the SLMCPR calculation. By establishing legacy fuel CPR results and incorporating the appropriate increased CPR uncertainties, the mixed core SLMCPR calculation can be performed in a straightforward manner.

3.1 MODELING WITH SUB-CHANNEL FILM-FLOW ANALYSIS CODE

To model the legacy fuel neutronically, geometrical and mechanical design data are provided in addition to the nuclear data supplied by the legacy fuel vendor or through the utility customer. This data is used to perform the reload licensing analyses as described in Reference 1. Therefore, the relevant cross sectional geometry data for a sub-channel film-flow analysis are known, i.e., rod diameters, rod positions, and coordinates for the wall boundaries of the outer channel and any internal water channels.

Figure 3-1 illustrates the flow of a sub-channel film-flow calculation with VIPRE-W/MEFISTO for a SVEA sub-bundle. In this case, the coolant volume is divided into [

]^{a,c} More details on the VIPRE-W and MEFISTO methods and calculation process are given in Appendix C and References 5-7.

[ ] a,c

Figure 3-1. Illustration of a sub-channel film-flow calculation with VIPRE-W/MEFISTO

With VIPRE-W/MEFISTO, the effects of partial length fuel rods can be [

]^{a,c}

In the MEFISTO code, the [

]^{a,c}

For legacy fuel in which the [

]^{a,c}

3.2 ESTABLISHING TRAINING DATA FOR RE-OPTIMIZING CPR CORRELATION AND R-FACTOR MODEL

[ ]^{a,c} the process of generating training data for re-optimizing an NRC-approved CPR correlation and associated R-factor model includes the following steps:

[

]^{a,c}

[

]^{a,c}

3.3 RE-OPTIMIZING COEFFICIENTS OF A CPR CORRELATION AND AN R-FACTOR MODEL

Given a set of training data developed according to the process described in Section 3.2, [

]^{a,c} This optimization process involves the following additional steps:

[

]^{a,c}

3.4 FURTHER OPTIMIZATION AND VALIDATION OF THE RE-OPTIMIZED CPR CORRELATION AGAINST A LEGACY FUEL CPR DATABASE

In case additional information is available in terms of a CPR database for the legacy fuel, the
[

]^{a,c} An example application of this type is given in Appendix D, Section D.2.

4 REFERENCES

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2. Memo from Benjamin T. Parks to Gregory Cranston, Staff Position Regarding the use of Methods Described in ABB/Westinghouse Topical Report CENPD-300-P-A, "Reference Safety Report for Boiling Water Reactor Reload Fuel," For Safety Limit Minimum Critical Power Ratio Determinations, August 2008, ADAMS ACCESSION # ML082261478.

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10. U.S. NRC Standard Review Plan, NUREG-0800 - Chapter 4, Section 4.4, Revision 2, Thermal and Hydraulic Design, March 2007.

APPENDIX A: UNCERTAINTIES AFFECTING CPR

In this section, the types of stochastic variables that can be included in the treatment of CPR uncertainty are described. Table A-1 provides only an example of uncertainties for a typical SLMCPR application and could be modified depending on fuel product (for example, uncertainty in [ ]^{a,c} may be unique to only a fuel design with water cross). In the Westinghouse SLMCPR methodology, stochastic variables are treated [ ]^{a,c} For the sake of description, the variables can be grouped into different levels: core, fuel assembly, and fuel rod.

In the [ ]^{a,c} In the majority of cases, the manufacturing processes for the fuel and plant data measurements may be [ ]^{a,c} So far in the application of the SLMCPR methodology there has been [ ]^{a,c}

Table A-1. Example of input variables considered for CPR uncertainty evaluation in the SLMCPR methodology

[ ]^{a,c}

A discussion of typical uncertainties given in Table A-1 follows:

[

]^{a,c}

[ ]^{a,c}

Figure A-1. Orientations of channel bow as randomly sampled in McSLAP

McSLAP calculates [ ]^{a,c}

Uncertainty Contributions

The contributions to the SLMCPR by some of the uncertainties from a typical application are presented in Figure A-2. While the individual contributions to SLMCPR can vary with the uncertainties and responses for the particular reactor or cycle evaluated, it may be generally concluded that the uncertainties in [ ]^{a,c} have the main influence over the SLMCPR result, followed by the uncertainty in [ ]^{a,c} It is important to keep in perspective that in most applications the remaining uncertainties will have only a minor influence over the SLMCPR result.

a,c

Figure A-2. Significance of the CPR uncertainty contributions to SLMCPR from a typical calculation

Observations in Mixed Core SLMCPR Behavior

In protecting against dryout in pressurization transients, BWRs typically become most limiting [

]^{a,c}

For each particular cycle application, the level of sophistication warranted for legacy fuel CPR in licensing calculations may depend upon the ability of the burned fuel to have meaningful contribution to core minimum CPR or SLMCPR results. It is important to note that in many applications [

]^{a,c}

As an improvement to the original mixed core SLMCPR approach given in Reference 1, an approach to calculation of mixed core SLMCPR is developed and discussed. It should be noted that in transition cores of mixed fuel loadings, many reactors are operated in a manner that [

]^{a,c} In cases which apply less conservative treatments than those presented, cycle-specific justifications would be established and supplied as part of fuel transition license amendment requests as appropriate.

a,c

Figure A-3. Example impact of high uncertainties to legacy fuel rod CPR in a 12-month cycle

a,c

Figure A-4. Example impact of high uncertainties to legacy fuel rod CPR in a 24-month cycle

APPENDIX B: MONTE CARLO SLMCPR CALCULATION PROCESS BACKGROUND

The SLMCPR calculation process used in implementing the methodology given in Reference 1 and described in its RAI responses is further elaborated in this section, followed by a validation against deterministic methods. This appendix is provided only as further detail of the approved calculation process and does not include any updates or changes relative to previous NRC-approved SLCMPR calculations performed and applied in the U.S. An example of a typical calculation process for SLMCPR is shown visually in Figure B-5 which illustrates a combination of the use of cycle-specific [

]^{a,c}

B.1 NOMINAL CPR DISTRIBUTION

A nominal core state for safety limit analysis is characterized by a core-wide rod CPR distribution at a given time in the fuel cycle. This information is obtained by [

]^{a,c}

The 3D calculations are based on the reference core loading pattern depletion used for the licensing analysis described by Reference 1. For SLMCPR evaluation, [

]^{a,c}

Increasing the number of rods that are near the core minimum CPR in the initial condition (i.e., flattening the core CPR distribution) will [

]^{a,c}

The actual operating limit CPR may not be known at the time of the SLMCPR calculation, therefore [

]^{a,c}

B.2 CPR RESPONSE FUNCTIONS

[

]^{a,c}

B.2.1 Example of Response Function

[

]^{a,c}

[

]^{a,c}

B.2.2 Channel Bow Response Functions

The SLMCPR channel bow response model is unique relative to the other uncertainty inputs and can be summarized as follows:

- [

]^{a,c}

[

]^{a,c}

B.3 MONTE CARLO CALCULATION PROCESS

[

]^{a,c}

[ ]a,c

Figure B-1. Fuel rod CPR histogram example

B.4 METHOD VALIDATION

[

]^{a,c}

a,c

Figure B-2. Comparison of a linear assembly response in the SLMCPR method to a simplified deterministic result

[

]^{a,c}

a,c

Figure B-3. Comparison of a realistic implementation of the SLMCPR method to a simplified deterministic result

[

]^{a,c}

[

]^{a,c}

a,c

Figure B-4. Example of CPR response from assembly power changes

[

]^{a,c}

a,c

Figure B-5. Overview of SLMCPR calculation process

APPENDIX C: VIPRE-W/MEFISTO

Westinghouse has developed the MEFISTO film flow analysis code with the aim to mechanistically predict the boiling transition phenomena in a BWR fuel bundle under both steady-state and transient conditions. For the evaluation of SLMCPR with the Westinghouse methodology, only steady-state CPR predictions are of interest. The primary purpose of the MEFISTO code is to predict the 1-dimensional multi-film flow evolution on the surfaces of all fuel rods, and in particular the disappearance of the film and hence the onset of dryout. The three processes of film entrainment, film evaporation and drop deposition governing the mass balance of the liquid film are shown schematically in Figure C-1. A detailed description of the MEFISTO film flow model for steady-state conditions is provided in Reference 5.

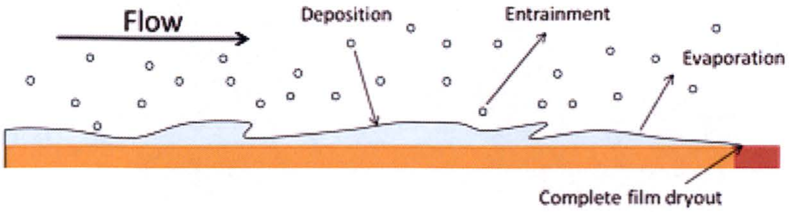


Figure C-1. Film dryout phenomenon on BWR fuel rod

All necessary geometrical complexities are considered explicitly by the MEFISTO code: sub-channels of coolant volume delimited by rod-to-rod gaps and surfaces of heated fuel rods and/or cold channel walls, part-length fuel rods, spacer grids, etc. To demonstrate the meaning of "sub-channels," Figure C-2 shows a cross-section view of the SVEA-96 Optima2 and Optima3 sub-bundle geometry. The sub-channels are numbered from 1 to 35 and fuel rods are numbered from 1 to 24. In the example, rods 1, 20, and 24 are part-length rods of either one-third (Rod 1) or two-third (Rods 20 and 24) of the full heated length.

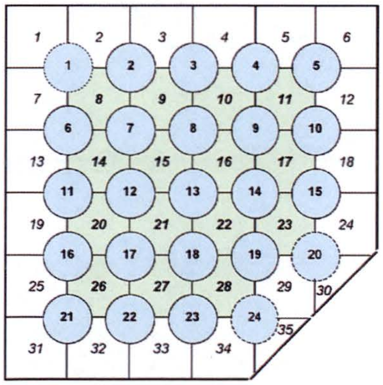


Figure C-2. Example of sub-channels (1-35) for a SVEA-96 sub-bundle

The MEFISTO code was developed based on two main simplification principles: (1) the sub-channel cross-flow information is pre-calculated by a sub-channel analysis code and (2) the film flow analysis is performed in decoupled sub-channels. This simplified and computationally efficient approach relies on the observation that a complex three-field sub-channel analysis is not required to accurately calculate the coupled one-dimensional two-phase (liquid/steam) flow and enthalpy distributions within each sub-channel of a fuel bundle. It follows that only a one-way coupling from any relevant two-phase sub-channel analysis driver code to a film model is necessary and, hence, the film flow analysis can be performed as a separate post-processing step. The VIPRE-W code (Reference 7) was selected to carry out the sub-channel analysis and the MEFISTO code was developed to carry out the film modeling.

The MEFISTO code consistently incorporates the sub-channel cross-flows into the film model and complex technical features, such as part-length fuel rods and spacer grids, are handled by mechanistic or semi-mechanistic models. The 1-dimensional three-field mass balance equations in every sub-channel are hence decoupled from each other and resolved as simple (multi-wall) tubes (with additional sink/source terms to account for the cross flows via mass balance) without feedback to the other sub-channel solutions. The approach provides detailed multi-film flow solutions for any BWR fuel bundle with high axial resolution, while enhancing flexibility, improving robustness and reducing the computational time by an order of magnitude as compared to standard three-field sub-channel analysis.

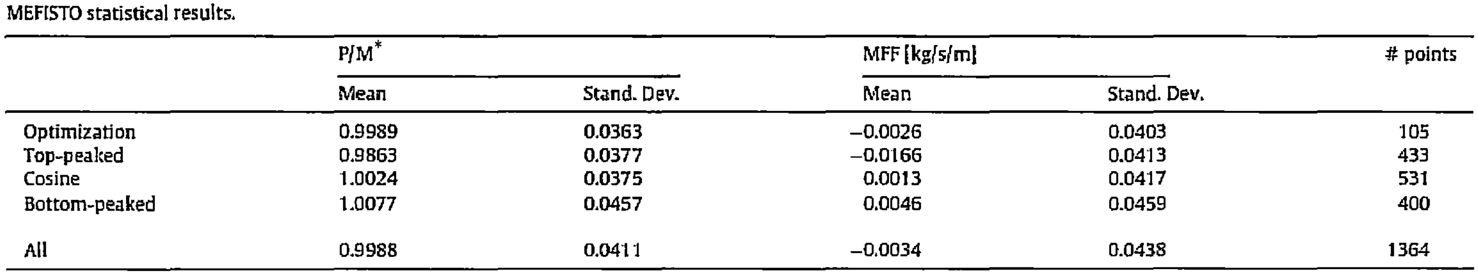
MEFISTO Model Calibration and Validation Results

The spacer grid effects are included as an axially varying enhancement of the drop deposition rate due to turbulence downstream of the grid. The resulting enhancement factor is considered as a multiplier in the standard deposition rate model. Thus, the spacer grid model contains one empirical parameter for each sub-channel which depends on the local geometrical characteristics of the spacer grid, in particular the mixing vane design.

When MEFISTO is adapted to a particular fuel bundle design, such as the SVEA-96 Optima3 sub-bundle, the effects of the spacer grids on downstream drop deposition are calibrated against critical power data by adjusting the drop deposition enhancement factor for each sub-channel. For SVEA-96 Optima3, this calibration was done using only a small subset of the FRIGG data for one particular axial power profile, the cosine profile. Only about 7% of the entire FRIGG Optima3 database was used for calibration. The capability of MEFISTO to extrapolate beyond the small calibration dataset, and in particular to other axial power profiles, was then validated using the bottom- and top-peaked data series. When replacing the cosine axial power distribution with the bottom-peaked (top-peaked) distribution, the measured critical power increases (decreases) by approximately 10% (Reference 4). In spite of these relatively large changes in critical power, the mean errors (biases) in the predictions by MEFISTO for the bottom- and top-peaked power shapes were only about 1% and the standard deviation less than 4%. The validation results of MEFISTO for CPR predictions in SVEA-96 Optima3 are summarized in Table C-1.

The MEFISTO code has been extensively validated against many experimental dryout databases, both from the FRIGG loop and external databases (e.g., BFBT in Reference 9). A summary of the validation results are given in Reference 6. The code has demonstrated notable capabilities of predicting dryout power (CPR) and dryout location (both axial and radial), as well as extrapolating outside the calibration database.

Table C-1. Validation results of MEFISTO for SVEA-96 Optima3 (Table 1 from Reference 5).



MEFISTO statistical results.

	P/M*		MFF [kg/s/m]		# points
	Mean	Stand. Dev.	Mean	Stand. Dev.	
Optimization	0.9989	0.0363	−0.0026	0.0403	105
Top-peaked	0.9863	0.0377	−0.0166	0.0413	433
Cosine	1.0024	0.0375	0.0013	0.0417	531
Bottom-peaked	1.0077	0.0457	0.0046	0.0459	400
All	0.9988	0.0411	−0.0034	0.0438	1364

*"P/M" refers to the predicted over measured critical powers

APPENDIX D: APPLICATION EXAMPLES OF IMPROVED MIXED CORE CPR TREATMENT

In this appendix three conceptually different scenarios of application of the improved mixed core CPR treatment described in Section 3 are considered and demonstrated by examples. The scenarios differ by the amount of information available from the legacy fuel vendor in terms of a CPR database. The CPR database [

]^{a,c}

Scenario 1: The CPR database is limited.
In this case the operating conditions do not span the operating regime for the legacy fuel. For example, there may be no CPR data for off-nominal mass flux, pressure and sub-cooling conditions. The amount of information may be limited to just a few (less than 10) data points such that a meaningful statistical comparison with [

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Scenario 2: The CPR database is extensive, but not complete.
The operating conditions span large parts of the operating regime, to an extent sufficient for further validation and possibly further optimization of the CPR correlation. [

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Scenario 3: The CPR database is complete.
This means that the CPR database is covering all relevant operating conditions and is detailed enough to enable a [

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D.1 SCENARIO 1: LIMITED CPR DATABASE.

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Table D-1. Optimized radial power distribution for cosine axial power profile

[ ] a,c

Table D-2. Examples of peaked radial power distributions based on the optimized radial power distribution of Table D-1

[ ] a,c

a,c

Figure D-1. Training data: sub-bundle critical power versus mass flux

a,c

Figure D-2. Training data: sub-bundle critical power versus pressure

a,c

Figure D-3. Training data: sub-bundle critical power versus sub-cooling

a,c

Figure D-4. Training data: sub-bundle critical power versus I_2-variable

a,c

Figure D-5. Training data: sub-bundle critical power versus R-factor

a,c

Figure D-6. Histogram of prediction errors for re-optimized CPR correlation and R-factor model when compared against *training database*

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a,c

Figure D-7: Histogram of prediction errors for re-optimized CPR correlation and R-factor model when compared against *dryout measurement database*

Table D-3. Standard deviation error and mean error in predictions of re-optimized CPR correlation and R-factor model when compared against *training database*

a,c

Table D-4. Standard deviation error and mean error in predictions of re-optimized CPR correlation and R-factor model when compared against *dryout measurement database*

a,c

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D.2 SCENARIO 2: EXTENSIVE BUT INCOMPLETE CPR DATA

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a,c

Figure D-8. Hypothetical CPR database: critical power versus mass flux

a,c

Figure D-9. Hypothetical CPR database: critical power versus pressure

a,c

Figure D-10. Hypothetical CPR database: critical power versus sub-cooling

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Figure D-11. Hypothetical CPR database: critical power versus I_2-variable

[ ] a,c

Figure D-12. Hypothetical CPR database: critical power versus R-factor

a,c

Figure D-13. Histogram of prediction errors for re-optimized CPR correlation and R-factor model when compared against *hypothetical legacy fuel CPR database*

a,c

Figure D-14. Histogram of prediction errors for re-optimized CPR correlation and R-factor model when *further optimized* and compared against *hypothetical legacy fuel CPR database*

Table D-5. Standard deviation error and mean error in predictions of re-optimized CPR correlation and R-factor model when compared against *hypothetical legacy fuel CPR database*

[ ]^{a,c}

Table D-6. Standard deviation error and mean error in predictions of re-optimized CPR correlation and R-factor model when *further optimized* and compared against *hypothetical legacy fuel CPR database*

[ ]^{a,c}