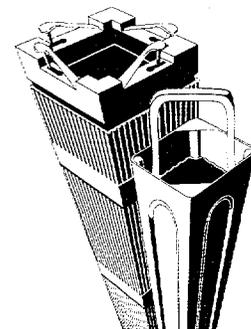


# SIEMENS

EMF-2209(NP)(A)  
Revision 1

## SPCB Critical Power Correlation

July 2000



Siemens Power Corporation  

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Nuclear Division

Siemens Power Corporation

ISSUED IN SPC ON-LINE  
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DATE: 7/17/00

EMF-2209(NP)  
Revision 1

Issue Date:

### SPCB Critical Power Correlation

Prepared: *R B Macduff*  
R. B. Macduff, Staff Engineer  
Safety Analysis Methods

17 Mar 2000  
Date

Prepared: *T.H. Keheley*  
T. H. Keheley, Staff Engineer  
Safety Analysis Methods

\_\_\_\_\_  
Date

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SPCB Critical Power Correlation

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Regulatory Affairs



UNITED STATES  
NUCLEAR REGULATORY COMMISSION

WASHINGTON, D.C. 20555-0001

July 3, 2000

Mr. James F. Mallay  
Director, Nuclear Regulatory Affairs  
Siemens Power Corporation  
2101 Horn Rapids Road  
Richland, WA 99352

SUBJECT: ACCEPTANCE FOR REFERENCING OF LICENSING TOPICAL REPORT  
EMF-2209(P) REVISION 1, "SPCB CRITICAL POWER CORRELATION"  
(TAC NO. MA6639)

Dear Mr. Mallay:

Revision 0 of the subject topical report was submitted by the Siemens Power Corporation (SPC) by letter dated September 24, 1999, and Revision 1 was submitted by letter dated April 20, 2000. This topical report describes the analyses conducted by SPC pertaining to the application of the SPCB critical power correlation to the ATRIUM-9B and to the ATRIUM-10 fuel designs. The ATRIUM-9B fuel design is a 9x9 square array, while the ATRIUM-10 fuel design is a 10x10 square array. Both fuel designs are fixed at axial locations by ULTRAFLOW spacers and use an internal square water canister, replacing a 3x3 array of rods. The ATRIUM-9B fuel assembly contains 72 full-length rods (no part-length rods) and the ATRIUM-10 fuel assembly is made up of 83 full-length rods and 8 part-length rods.

The SPCB correlation uses planar average values of coolant mass velocity, enthalpy, and pressure to predict planar average critical heat flux. Although SPCB is a generic correlation (applicable to both ATRIUM-9B and ATRIUM-10), it is very similar to the original ANFB-10 correlation that is currently used to predict critical heat flux for the ATRIUM-10 fuel assemblies.

The staff, after their review, determined the topical report to be acceptable for referencing and conveyed the acceptance along with the safety evaluation (SE) to you by letter dated May 17, 2000. However, in the May 17 letter and accompanying SE, the revision number of Topical Report EMF-2209(P) was referenced as 0. By this letter and the enclosed SE, the revision number is corrected to 1 and additional minor corrections have been made to the SE.

Pursuant to 10 CFR 2.790, we have determined that the enclosed SE does not contain proprietary information. However, we will delay placing the SE in the public document room for a period of ten (10) working days from the date of this letter to provide you with the opportunity to comment on the proprietary aspects only. If you believe that any information in the enclosure is proprietary, please identify such information line by line and define the basis pursuant to the criteria of 10 CFR 2.790.

The staff will not repeat its review and acceptance of the matters described in the report, when the report appears as a reference in license applications, except to assure that the material presented is applicable to the specific plant involved. Our acceptance applies only to the matters described in the report.

Mr. James F. Mallay

- 2 -

July 3, 2000

In accordance with the procedures established in NUREG-0390, the NRC requests that SPC publish accepted versions of the report, including the safety evaluation, in the proprietary and non-proprietary forms within 3 months of receipt of this letter. The accepted versions shall incorporate this letter and the enclosed evaluation between the title page and the abstract. The accepted versions shall include a "-A" (designating accepted) following the report identification symbol. The accepted versions shall also incorporate all communications between SPC and the staff during this review.

Should our criteria or regulations change so that our conclusions as to the acceptability of the report are no longer valid, SPC and the licensees referencing the topical report will be expected to revise and resubmit their respective documentation, or to submit justification for the continued effective applicability of the topical report without revision of their respective documentation.

Sincerely,

A handwritten signature in black ink, appearing to read "S. Richards", with a large, sweeping flourish extending to the right.

Stuart A. Richards, Director  
Project Directorate IV and Decommissioning  
Division of Licensing Project Management  
Office of Nuclear Reactor Regulation

Project No. 702

Enclosure: Safety Evaluation



UNITED STATES  
NUCLEAR REGULATORY COMMISSION  
WASHINGTON, D.C. 20555-0001

SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT EMF-2209(P), REVISION 1,

"SPCB CRITICAL POWER CORRELATION"

SIEMENS POWER CORPORATION

1.0 BACKGROUND

EMF-2209(P) describes the methodology behind the application of the SPCB correlation to the SPC's ATRIUM-9B and ATRIUM-10 fuel designs (References 1 and 2). EMF-2209(P) provides test data taken specifically at the Siemens test facility at Karlstein, Germany, in support of the application of the SPCB correlation to the ATRIUM-9B and ATRIUM-10 fuel designs and to the determination of the associated correlation, "Additive Constants." The ATRIUM-9B fuel has no part-length rods, but the ATRIUM-10 fuel does.

The additive constants are determined in accordance with the NRC-approved procedure described in References 3 and 4. The uncertainties associated with these additive constants are then used in the approved SPC safety limit methodology for boiling water reactor (BWR) fuel designs. The approved methodology is used to ensure that less than 0.1 percent of the fuel rods are in boiling transition during steady-state operation and during anticipated operational occurrences, in accordance with General Design Criterion 10 and Section 4.4 of the Standard Review Plan.

The SPCB correlation is new but similar to the ANFB-10 correlation, described in References 3 and 5. However, the definitions of the associated parameters (inlet sub-coolant, pressure, and mass flow) as described in Reference 3 are not changed for the application of the new SPCB to the SPC ATRIUM-9B and ATRIUM-10 fuel designs. The technical analysis of the SPCB correlation and its exclusive application to the ATRIUM-9B and ATRIUM-10 fuel designs is presented below.

2.0 TECHNICAL EVALUATION

The SPCB correlation is a new correlation designed and developed to address the critical power behavior of the SPC ATRIUM-9B and ATRIUM-10 fuel designs. The SPCB correlation is designed for application in steady-state, transient, and loss-of-coolant accident critical heat flux (CHF) calculations for the ATRIUM-9B and ATRIUM-10 fuel designs.

The SPCB correlation was developed to predict assembly critical power for the ATRIUM-9B and ATRIUM-10 fuel designs. The correlation was developed to predict the limiting rod in a bundle and account for local spacer effects and bundle geometry on critical power by a set of constants, typically referred to as "Additive Constants," one constant for each rod in the bundle. Each individual fuel design requires a unique set of additive constants.

The SPCB correlation is an empirically derived expression that is a complex function of the input parameters: local coolant enthalpy, mass flow, and pressure. These input parameters cover the ranges of pressure, mass velocity, and inlet cooling, consistent with expected operating and accident conditions. The correlation is based on local coolant conditions predicted from uniform and non-uniform axial power distribution test data. The correlation includes correction factors to account for geometry and non-uniform axial power distributions that deviate from the test data conditions.

Low-flow and high-flow behavior of the correlation are captured by refining the parameters in the correlation equations (Reference 1). These parameters address the impacts of the variations in the local enthalpy from the planar average enthalpy. One of these parameters is the F-effective, which characterizes the fuel rod local behavior, such as enthalpy rise, and which also factors additive constants into the calculations. The additive constants account for the fuel bundle geometry and spacer effects on the critical power behavior of the bundle (References 3 and 4).

## 2.1 SPCB Database and Test Strategy

The SPCB database consists of data taken at the SPC test facility at Karlstein, Germany. The test setup comprises electrically heated bundles that are physically the same as the ATRIUM-9B and the ATRIUM-10 fuel assemblies. The tests are designed to reproduce the local conditions typically present in a BWR fuel assembly and support the full range of applicability for the SPCB correlation.

Different test programs were developed to accumulate a database representative of the appropriate statistical requirements for the ATRIUM-9B and the ATRIUM-10 fuel designs. The tests selected and the number of points required were dictated by the requirements of the statistical design of experiment SDE (References 6 and 7). This approach ensures that an adequate number of tests are performed and that sufficient data are gathered to perform appropriate simulation of the behavior of the ATRIUM-9B and the ATRIUM-10 fuel designs.

Both steady-state and transient tests were performed as part of the validation of the SPCB correlation. In each case, the tests were designed to include test runs with peaked rods located adjacent to the internal water channel.

The database comprises more than 2500 data points taken in a large number of tests performed at the SPC test facility. The database consists of upskew, downskew, and cosine axial power shapes accounting for adjacent rod positions, rods on the interior of an assembly, and rods adjacent to the water canister (channel), a feature unique to the ATRIUM fuel design.

The local power peaking patterns were selected to determine the effects of the upskew axial power profiles as compared to the cosine power profiles in several regions of the test bundle. Local power peaking data were also collected at the corners, the peripheral rows, as well as around the internal water canister to ensure complete understanding of the fuel CHF behavior, particularly in these regions.

The internal water canister is a major and unique characteristic of the SPC's ATRIUM fuel design. It replaces a 3x3 matrix of fuel rods. The rectangular canister is designed so that the subchannels around it are regular in size, typical of those addressed by the original base ANFB correlation. The test matrixes of the ATRIUM-9B and the ATRIUM-10 fuel designs used at the SPC test facility included tests to confirm the behavior of the fuel surrounding the internal water canister. Neither the ATRIUM-9B nor the ATRIUM-10 fuel design showed any abnormal behavior around the internal water canister.

## 2.2 Description of the Additive Constants

Correlation parameters such as F-effective ( $F_{EFF}$ ) account for the local peaking factor effect on the bundle critical power.  $F_{EFF}$  is constructed in two parts. One part depends solely on the peaking factors of the rod of interest and its immediate neighbors ( $F_{EFF0}$ ); the other part, termed the "additive constant," accounts for other local effects, such as bundle geometry and spacer effects. These spacer and bundle geometry effects influence the critical power behavior of the bundle. Therefore, an offset term is applied to each rod in the bundle, subject to the rod's position in the bundle. This offset term is called the "additive constant." The additive constant can be considered as a flow/enthalpy redistribution characteristic of a particular lattice/spacer design, so the additive constants are unique to a particular fuel design. They are explicitly determined for each lattice/spacer design configuration and are utilized in design calculations for the corresponding fuel bundle (Reference 3).

The additive constants are derived from the critical power tests for the ATRIUM-10 fuel and the ATRIUM-9B fuel separately. Specifically, the additive constants are derived from about 80 percent of the data for each fuel. The data includes sufficient radial peaking distributions, sufficient axial shapes, and a representative density of flows and pressures.

## 3.0 STATISTICAL ASPECTS OF THE SPCB CORRELATION

The statistical aspects of the SPCB correlation consist of applying appropriate statistical techniques (References 6 and 7) to the SPCB database. These techniques involve the evaluation of distribution characteristics, figures of critical power ratios (CPRs) with respect to each characteristic within the correlation, descriptive statistics for subgroups of data, descriptive statistics for additive constants and additive constants uncertainty, and conservatism of the SPCB critical power correlation. A good correlation would place the CPR near 1.00 (unity), with a very small associated uncertainty.

The correlation study examined the CPR in a series of tests. A total of 12 tests were performed: 7 tests pertained to the ATRIUM-9B and 5 tests pertained to the ATRIUM-10 fuel designs. For the ATRIUM-9B fuel, three of the seven tests were conducted with a chopped cosine shaped axial power profile, one test with a downskew power profile, and two tests with an upskew power profile. For the ATRIUM-10 fuel, three of the five tests were conducted with a chopped cosine shaped axial power profile, one of the five tests with a downskew power profile, and one test with an upskew power profile. Each test was repeated many times ("runs"). The input variables into each run entered the experimental design at different levels to reflect a diversified operating environment, resulting in a database containing in excess of 2500 data points. Twenty percent of this data was used to validate the correlation, while the remaining 80 percent was used to develop the SPCB correlation.

The multiplicity of runs within each test was required in order to involve various levels of input factors (inlet flow, inlet sub-cooling, and pressure). For most of the runs, these factors were selected at random, following standard statistical procedures (References 6 and 7). For dryout testing, additional runs were made following a two-level, three-factor factorial design to ensure that the entire range of interest (including "corner to corner") was represented.

Review of SPC calculations shows that the average CPR appears to be very near 1.0. That ratio is retained without any apparent trend across inlet mass velocity (Mlb/hr-ft<sup>2</sup>), enthalpy (Btu/lbm), pressure (psia), the best estimate of the  $F_{EFF}$ , or the axial offset. The overall CPR mean for the ATRIUM-9B 1629 data points was calculated to be 0.996, and the CPR mean for the ATRIUM-10 1028 data points was calculated to be 0.996.

To evaluate the quality of the correlation, the staff independently calculated a CPR 95/95 upper tolerance limit (References 8 and 9) for each test, for each profile, and for the entire set of runs. The staff 95/95 calculation was compared to SPC's 95/95 calculation. Apart from rounding errors and conservative table interpolations, the staff's calculation was in total agreement with SPC's calculation. This limit is interpreted to mean that one is 95 percent sure that at least 95 percent of the population of runs yields a CPR value no higher than 1.022 for ATRIUM-9B and a value of 1.034 for ATRIUM-10. SPC's calculations also show that for any test or grouping of tests, the percentage of runs that fall below their associated tolerance limits is at least 95.7 percent for ATRIUM-9B and 96.8 percent for ATRIUM-10.

The submittal contains charts and tables reflecting CPR behavior across different mass velocity (Mlb/hr-ft<sup>2</sup>) for individual tests. Although some tests show higher CPR values associated with high mass velocity, the reverse is true for other tests, and no dependency between CPR and mass velocity is apparent.

Another objective of SPC's study that involves statistical consideration is the determination of the additive constant for both fuel types. The additive constant is a statistical adjustment to the measure of the  $F_{EFF}$  to account for the effect of the rod's geometric position within the assembly. This adjustment has two components: a calculated additive constant and a measure of uncertainty associated with the calculation. In the development of the additive constants, SPC uses only the cosine profile data. However, the measure of the associated uncertainty is calculated from the entire database, containing cosine, upskew, and downskew test data.

The main contributors to this uncertainty are two sources of variability: "within test variability" and "between test variability." The within test variability is given as a weighted average in which the weighting factors are the number of runs per test. The between test variability is given as a weighted average of the difference between the  $F_{EFF}$  for a rod in a test bundle and the average  $F_{EFF}$  for the test bundle. The weighting factors are the number of boiling transitions for a rod in the test bundle. The square root of the sum of the squares (the two sources of variability) give the measure of variability associated with the calculation of the additive constant. In-depth review of the statistical section of the submittal leads the staff to concur with the statistical methods used and the results obtained by the vendor.

#### 4.0 SPCB CORRELATION BEHAVIOR

The SPCB correlation was tested to ensure smooth functions and no significant discontinuities in its behavior over the entire range of operability of the fuel. Flow, enthalpy, and pressure-dependent functions within the correlation, such as the "Tong Factor" correction for both fuels, was investigated for its behavior over the entire applicable range of the fuels. A number of tests were conducted to determine the sensitivity of the major functions within the SPCB correlation to flow, inlet subcooling, pressure variation,  $F_{EFF}$ , and axial power shape.

Review of the data, figures, and tables indicates that the SPCB correlation behaves well over the applicable range of the fuel.

#### 5.0 SPCB CORRELATION VALIDATION

SPC performed several tests to validate the behavior of the SPCB correlation in steady-state and transient events. The validation database consisted of 20 percent of the total steady-state data points that were not included in the correlation database. The remaining 80 percent of the database (the so-called verification set) was used to develop the correlation. In addition, data were collected from tests conducted on an ATRIUM-10P assembly that contained more part-length fuel rods than are usually found in a typical ATRIUM-10 assembly. These tests were conducted to demonstrate the ability of the SPCB correlation to capture the effects of the part-length rods, as well as the correlation agreement with the data. The predicted SPCB correlation between critical power versus the measured critical power for these tests showed very good agreement.

Two sets of transient tests were performed as part of the validation process. Both tests were designed to peak rods around the internal water canister. The difference between the two tests is that the first test had rods with a chopped cosine-shaped axial power profile and the second had rods with an upskew axial power shape. Another purpose of the tests was to validate the concept that the additive constants can be derived from steady-state tests and applied to other axial shapes under transient conditions.

The transient tests performed were the simulated load rejection with no bypass (LRNB) events that consisted of power, pressure ramps, and flow decay. Power forcing functions were programmed to produce transient heat flux on the surface of the rod typical of an LRNB event. Parameters monitored during the tests were power, inlet flow, system pressure, inlet temperatures, and cladding temperatures.

The transient thermal-hydraulic code, XCOBRA-T (References 10 and 11), was used to predict the test results using the SPCB steady-state critical power correlation. XCOBRA-T calculates the fluid conditions at a specified time step. The CHF is calculated at each axial position and time step, then compared to the corresponding measured rod heat flux at the surface of the rod. The ratio of the calculated heat flux to the measured rod heat flux is defined to be the critical heat flux ratio (CHFR). When this ratio is unity, it is referred to as the minimum critical heat flux ratio (MCHFR), and it signifies "boiling transition" in a transient event. Comparison of measured and calculated time-to-boiling transitions for cosine and upskew transient tests shows that the XCOBRA-T calculated time-to-boiling transition values are conservative when

compared to actual boiling transition time. This validation confirms the use of the steady-state SPCB correlation and the associated additive constants in evaluating transient events.

## 6.0 LOCAL PEAKING FACTORS

Although local peaking factors may be exceeded in controlled bundles, these bundles by definition are not limiting bundles, consequently, they do not factor in the calculation of the minimum critical power ratio (MCPR) safety limit. If, however, in the process of calculating the MCPR safety limit, the local peaking factor of 1.5 is exceeded, an additional additive constant uncertainty is applied on a rod-by-rod basis in accordance with Table 3.15 of Reference 1. These conditions have been agreed upon by both the NRC staff and SPC (Reference 12).

## 7.0 NON-CONFORMANCE ISSUES

The submittal, as documented in Reference 1, is SPC's corrective action in response to Part 2 of notice of Nonconformance 99900081/97-01, as stated in Attachment II of SPC's letter to the NRC, dated February 24, 1998 (Reference 13). The Nonconformance stated that: SPC failed to develop an adequate number of tests points and failed to test an adequate range of conditions to justify the uncertainty values for the "additive constants" used in determining the safety limit minimum critical power ratio (SLMCPR) for the ATRIUM-9B fuel design. This statement implies that SPC should have used larger uncertainty values in the SLMCPR determinations in order to reflect the full operability range of the ATRIUM-9B fuel design. In addition, because the results of the ANFB correlation are used as inputs to the safety limit methodology, this has immediate implications regarding the SLMCPR and the operating limit minimum critical power ratio (OLMCPR) of the Commonwealth Edison Company plants (Quad Cities Unit 2, Cycle 15, Dresden Unit 2, Cycle 15, and LaSalle County Unit 2, Cycle 8) and the Washington Public Power Supply System (Washington Nuclear Unit 2, Cycle 13) loaded with ATRIUM-9B fuel.

In response to this notice of Nonconformance, SPC developed and implemented interim methodologies (ANF-1125, Appendixes D and E) (References 14 and 15), while performing additional dryout testing of the ATRIUM-9B design to obtain additional data to cover the extended range of thermal-hydraulic parameters for the ATRIUM-9B fuel design.

The NRC staff contends that with the submittal of EMF-2209(P), the vendor (SPC) has provided the additional data necessary for the SPCB critical power correlation to provide a rigorous treatment over the entire operating range of the ATRIUM-9B fuel. Thus, with the submittal of EMF-2209(P), all problems identified in the inspection report (Nonconformance 99900081/97-01, Part 2) related to the dryout methodology for ATRIUM-9B fuel have been addressed.

## 8.0 TECHNOLOGY TRANSFER

SPC described the technology transfer program (Reference 16) which the licensees must successfully complete in order to perform their own thermal-hydraulic calculations using the SPCB correlation and the XCOBRA-T code in support of reload analyses. The overall process consists of training, benchmarking, and change control. In addition, SPC described the process for a licensee to implement the new correlation (SPCB). This process includes performance of

an independent benchmarking calculation by SPC for comparison to the licensee-generated results to verify that the new CHF correlation is properly applied. The staff has reviewed the process and find it acceptable because training, bench-marking, and change control have been adequately addressed.

## 9.0 CONCLUSION

The staff has reviewed the analyses in Topical Report EMF-2209(P), Revision 1, "SPCB Critical Power Correlation," and concludes that on the basis of its findings presented above, Topical Report EMF-2209(P) is acceptable for licensing applications, in accordance with SPC's agreement, subject to the following conditions:

1. The SPCB correlation (as described in this submittal, Reference 1) is applicable to SPC ATRIUM-9B and ATRIUM-10 fuel designs, with a local peaking factor no greater than 1.5.
2. If, however, in the process of calculating the MCPR safety limit, the local peaking factor of 1.5 is exceeded, an additional uncertainty of 0.026 for ATRIUM-9B and 0.021 for ATRIUM-10 will be imposed on a rod-by-rod basis.
3. The SPCB correlation range of applicability is as follows:

Pressure (psia)	571.4 to 1432.2
Inlet Mass Velocity (Mlb/hr-ft <sup>2</sup> )	0.087 to 1.5
Inlet Subcooling (Btu/lbm)	5.55 to 148.67
Design Local Peaking	1.5
Tested Local Peaking	1.45

4. Technology transfer will be accomplished only through the process described in Reference 16, which includes the performance of an independent bench-marking calculation by SPC for comparison to the licensee-generated results to verify that the new CHF correlation (SPCB) is properly applied for the first application by the licensee.

## 10.0 REFERENCES

1. Letter from H. D. Curet, SPC, to the U.S. Nuclear Regulatory Commission, submitting Topical Report EMF-2209(P), Revision 0, September 24, 1999.
2. Letter from J. F. Mallay to the U.S. Nuclear Regulatory Commission, "Request for Additional Information (RAI) to Topical Report EMF-2209(P), 'SPCB Critical Power Correlation,'" Revision 0, March 20, 2000.
3. Letter from R. A. Copeland, SPC, Transmittal of (A) Version of ANF-1125(P) to the U.S. Nuclear Regulatory Commission, April 27, 1990.

4. Letter from H. D. Curet, SPC, to the U.S. Nuclear Regulatory Commission, submitting Topical Report EMF-1997(P), Revision 0, October 30, 1997, and Letter from H. D. Curet, submitting Topical Report EMF-1997(P), Supplement 1, Revision 0, January 29, 1998.
5. Letter from J. F. Mallay to the U.S. Nuclear Regulatory Commission, "Request for Additional Information (RAI) to Topical Report EMF-1997(P), 'ANFB-10 Critical Power Correlation,'" Revision 0, May 7, 1998.
6. "Statistical Methods for Nuclear Material Management," NUREG/CR-4604, PNL-5849, December 1988.
7. G. J. Hahn and S. S. Shapiro, "Statistical Models in Engineering," Wiley, 1967.
8. H. W. Lilliefors, "On the Kolmogorov Test for Normality with Mean and Variance Unknown," Journal of American Statistical Association, Vol. 62, June 1967.
9. R. E. Odeh and D. B. Owen, "Tables for Normal Tolerance Limits," Table 1, Marcel Dekker, Ink, 1990.
10. "XCOBRA-T: A Computer Code for BWR Transient Thermal-Hydraulic Core Analysis," XN-NF-84-105(P)(A), Volume 1, Supplements 1 and 2, Exxon Nuclear Company, Richland, WA 99352, February 1987.
11. "XCOBRA-T: A Computer Code for BWR Transient Thermal-Hydraulic Core Analysis, Void Fraction Model Comparison to Experimental Data," XN-NF-84-105(P)(A), Volume 1, Supplement 4, Advanced Nuclear Fuels Corporation, Richland, WA 99352, February 1987.
12. Letter from J. F. Mallay to the U.S. Nuclear Regulatory Commission, "SER Conditions for EMF-2209(P) Revision 1, SPCB Critical Power Correlation," April 20, 2000.
13. Letter, Samuel J. Collins, NRC, to David G. McLees, SPC, "Demand for Information and Notice of Nonconformance (Inspection Report 99900081/97-01)," EA97-495, dated October 27, 1997.
14. Letter from Don Curet, SPC, to the U.S. Nuclear Regulatory Commission, Requesting Review of ANFB Critical Power Correlation Uncertainty for Limited Data Sets, ANFB-1125(P), Supplement 1, Appendix D, April 18, 1997.
15. Letter from J. F. Mallay to the U.S. Nuclear Regulatory Commission, "Request for Review of ANFB Critical Power Correlation Determination of ATRIUM-9B Additive Constant Uncertainties, ANFB-1125(P), Supplement 1, Revision 0, August 11, 1998.
16. Letter from J. F. Mallay to the U.S. Nuclear Regulatory Commission, "SER Conditions for EMF-2209(P) Revision 1, SPCB Critical Power Correlation," April 24, 2000.

Principal Contributor: A. Attard

Date: July 3, 2000



UNITED STATES  
NUCLEAR REGULATORY COMMISSION

WASHINGTON, D.C. 20555-0001

May 17, 2000

Mr. James F. Mallay  
Director, Nuclear Regulatory Affairs  
Siemens Power Corporation  
2101 Horn Rapids Road  
Richland, WA 99352

SUBJECT: ACCEPTANCE FOR REFERENCING OF LICENSING TOPICAL REPORT  
EMF-2209(P) REVISION 0, "SPCB CRITICAL POWER CORRELATION"  
(TAC NO. MA6639)

Dear Mr. Mallay:

The subject topical report was submitted by the Siemens Power Corporation (SPC) by letter dated September 24, 1999. This topical report describes the analyses conducted by SPC pertaining to the application of the SPCB critical power correlation to the ATRIUM-9B and to the ATRIUM-10 fuel designs. The ATRIUM-9B fuel design is a 9x9 square array, while the ATRIUM-10 fuel design is a 10x10 square array. Both fuel designs are fixed at axial locations by ULTRAFLOW spacers and use an internal square water canister, replacing a 3x3 array of rods. The ATRIUM-9B fuel assembly contains 72 full-length rods (no part-length rods), and the ATRIUM-10 fuel assembly is made up of 83 full-length rods and 8 part-length rods.

The SPCB correlation uses planar average values of coolant mass velocity, enthalpy, and pressure to predict planar average critical heat flux. Although SPCB is a generic correlation (applicable to both ATRIUM-9B and ATRIUM-10), it is very similar to the original ANFB-10 correlation that is currently used to predict critical heat flux for the ATRIUM-10 fuel assemblies.

The staff has reviewed the topical report and the additional information and finds that the topical report is acceptable for referencing. Our safety evaluation (SE) is provided in Enclosure 1.

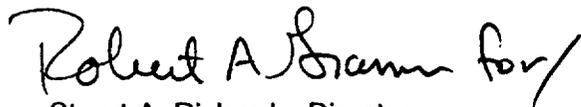
Pursuant to 10 CFR 2.790, we have determined that the enclosed SE does not contain proprietary information. However, we will delay placing the SE in the public document room for a period of ten (10) working days from the date of this letter to provide you with the opportunity to comment on the proprietary aspects only. If you believe that any information in the enclosure is proprietary, please identify such information line by line and define the basis pursuant to the criteria of 10 CFR 2.790.

The staff will not repeat its review and acceptance of the matters described in the report, when the report appears as a reference in license applications, except to assure that the material presented is applicable to specific plant involved. Our acceptance applies only to the matters described in the report.

In accordance with the procedures established in NUREG-0390, the NRC requests that SPC publish accepted versions of the report, including the safety evaluation, in the proprietary and non-proprietary forms within 3 months of receipt of this letter. The accepted versions shall incorporate this letter and the enclosed evaluation between the title page and the abstract. The accepted versions shall include a "-A" (designating accepted) following the report identification symbol. The accepted versions shall also incorporate all communications between SPC and the staff during this review.

Should our criteria or regulations change so that our conclusions as to the acceptability of the report are no longer valid, SPC and the licensees referencing the topical report will be expected to revise and resubmit their respective documentation, or to submit justification for the continued effective applicability of the topical report without revision of their respective documentation.

Sincerely,

A handwritten signature in black ink, appearing to read "Robert A. Richards for".

Stuart A. Richards, Director  
Project Directorate IV and Decommissioning  
Division of Licensing Project management  
Office of Nuclear Reactor Regulation

Project No. 702

Enclosure: Safety Evaluation



UNITED STATES  
NUCLEAR REGULATORY COMMISSION  
WASHINGTON, D.C. 20555-0001

SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION RELATING  
TO TOPICAL REPORT EMF-2209(P), REVISION 0,  
"SPCB CRITICAL POWER CORRELATION  
SIEMENS POWER CORPORATION  
TAC NO. MA6639

## 1.0 BACKGROUND

EMF-2209(P) describes the methodology behind the application of the SPCB correlation to the SPC's ATRIUM-9B and ATRIUM-10 fuel designs, (Refs. 1 and 2). EMF-2209(P) provides test data taken specifically at the Siemens test facility at Karlstein, Germany, in support of the application of the SPCB correlation to the ATRIUM-9B and ATRIUM-10 fuel designs and to the determination of the associated correlation, "Additive Constants." The ATRIUM-9B fuel has no part-length rods, but the ATRIUM-10 fuel does.

The additive constants are determined in accordance with the NRC-approved procedure described in References 3 and 4. The uncertainties associated with these additive constants are then used in the approved SPC safety limit methodology for boiling water reactor (BWR) fuel designs. The approved methodology is used to ensure that less than 0.1 percent of the fuel rods are in boiling transition during steady-state operation and during anticipated operational occurrences, in accordance with the General Design Criterion 10 and the Standard Review Plan, Section 4.4.

The SPCB correlation is new but similar to the ANFB-10 correlation, described in References 3 and 5. However, the definitions of the associated parameters (inlet sub-coolant, pressure, and mass flow) as described in Reference 3 are not changed for the application of the new SPCB to the SPC ATRIUM-9B and ATRIUM-10 fuel designs. The technical analysis of the SPCB correlation and its exclusive application to the ATRIUM-9B and ATRIUM-10 fuel designs is presented below.

## 2.0 TECHNICAL EVALUATION

The SPCB correlation is a new correlation designed and developed to address the critical power behavior of the SPC ATRIUM-9B and ATRIUM-10 fuel designs. The SPCB correlation is designed for application in steady-state, transient, and Loss of Coolant Accident critical heat flux (CHF) calculations for the ATRIUM-9B and ATRIUM-10 fuel designs.

The SPCB correlation was developed to predict assembly critical power for the ATRIUM-9B and ATRIUM-10 fuel designs. The correlation was developed to predict the limiting rod in a bundle

Enclosure

and account for local spacer effects and bundle geometry on critical power by a set of constants, typically referred to as "Additive Constants," one constant for each rod in the bundle. Each individual fuel design requires a unique set of additive constants.

The SPCB correlation is an empirically derived expression that is a complex function of the input parameters: local coolant enthalpy, mass flow, and pressure. These input parameters cover the ranges of pressure, mass velocity, and inlet cooling, consistent with expected operating and accident conditions. The correlation is based on local coolant conditions predicted from uniform and non-uniform axial power distribution test data. The correlation includes correction factors to account for geometry and non-uniform axial power distributions that deviate from the test data conditions.

Low-flow and high-flow behavior of the correlation are captured by refining the parameters in the correlation equations (Ref. 1). These parameters address the impacts of the variations in the local enthalpy from the planar average enthalpy. One of these parameters is the F-effective, which characterizes the fuel rod local behavior, such as enthalpy rise, and which also factors additive constants into the calculations. The additive constants account for the fuel bundle geometry and spacer effects on the critical power behavior of the bundle (Refs. 3 and 4).

## 2.1 SPCB Database and Test Strategy

The SPCB database consists of data taken at the SPC test facility at Karlstein, Germany. The test setup comprises electrically heated bundles that are physically the same as the ATRIUM-9B and the ATRIUM-10 fuel assemblies. The tests are designed to reproduce the local conditions typically present in a BWR fuel assembly and support the full range of applicability for the SPCB correlation.

Different test programs were developed to accumulate a database representative of the appropriate statistical requirements for the ATRIUM-9B and the ATRIUM-10 fuel designs. The tests selected and the number of points required were dictated by the requirements of the statistical design of experiment SDE (Refs. 6 and 7). This approach ensures that an adequate number of tests are performed and that sufficient data are gathered to perform appropriate simulation of the behavior of the ATRIUM-9B and the ATRIUM-10 fuel designs.

Both steady-state and transient tests were performed as part of the validation of the SPCB correlation. In each case, the tests were designed to include test runs with peaked rods located adjacent to the internal water channel.

The database comprises more than 2500 data points taken in a large number of tests performed at the SPC test facility. The database consists of upskew, downskew, and cosine axial power shapes accounting for adjacent rod positions, rods on the interior of an assembly, and rods adjacent to the water canister (channel), a feature unique to the ATRIUM fuel design.

The local power peaking patterns were selected to determine the effects of the upskew axial power profiles as compared to the cosine power profiles in several regions of the test bundle. Local power peaking data were also collected at the corners, the peripheral rows, as well as around the internal water canister to ensure complete understanding of the fuel CHF behavior, particularly in these regions.

The internal water canister is a major and unique characteristic of the SPC's ATRIUM fuel design. It replaces a 3X3 matrix of fuel rods. The rectangular canister is designed so that the subchannels around it are regular in size, typical of those addressed by the original base ANFB correlation. The test matrixes of the ATRIUM-9B and the ATRIUM-10 fuel designs used at the SPC test facility included tests to confirm the behavior of the fuel surrounding the internal water canister. Neither the ATRIUM-9B nor the ATRIUM-10 fuel design showed any abnormal behavior around the internal water canister.

## 2.2 Description of the Additive Constants

Correlation parameters such as F-effective ( $F_{EFF}$ ) account for the local peaking factor effect on the bundle critical power.  $F_{EFF}$  is constructed in two parts. One part depends solely on the peaking factors of the rod of interest and its immediate neighbors ( $F_{EFF0}$ ); the other part, termed the "additive constant," accounts for other local effects, such as bundle geometry and spacer effects. These spacer and bundle geometry effects influence the critical power behavior of the bundle. Therefore, an offset term is applied to each rod in the bundle, subject to the rod's position in the bundle. This offset term is called the "additive constant." The additive constant can be considered as a flow/enthalpy redistribution characteristic of a particular lattice/spacer design. So the additive constants are unique to a particular fuel design. They are explicitly determined for each lattice/spacer design configuration and are utilized in design calculations for the corresponding fuel bundle (Ref. 3).

To assert the ability of the correlation to predict steady-state as well as transient upskew and downskew axial power shape, only the cosine test data were used in the determination of the additive constants, thus validating the use of the additive constants in steady-state and transient calculations. The additive constants are experimentally determined from a large data bank representative of the power profile expected during the operational range of the ATRIUM-9B and the ATRIUM-10 fuel designs.

## 3.0 STATISTICAL ASPECTS OF THE SPCB CORRELATION

The statistical aspects of the SPCB correlation consist of applying appropriate statistical techniques (Refs. 6 and 7) to the SPCB database. These techniques involve the evaluation of distribution characteristics, figures of critical power ratios (CPRs) with respect to each characteristic within the correlation, descriptive statistics for subgroups of data, descriptive statistics for additive constants and additive constants uncertainty, and conservatism of the SPCB critical power correlation. A good correlation would place the CPR near 1.00 (unity), with a very small associated uncertainty.

The correlation study examined the CPR in a series of tests. A total of 12 tests were performed: 7 tests pertained to the ATRIUM-9B and 5 tests pertained to the ATRIUM-10 fuel designs. For the ATRIUM-9B fuel, three of the seven tests were conducted with a chopped cosine shaped axial power profile, one test with a downskew power profile, and two tests with an upskew power profile. For the ATRIUM-10 fuel, three of the five tests were conducted with a chopped cosine shaped axial power profile, one of the five tests with a downskew power profile, and one test with an upskew power profile. Each test was repeated many times ("runs"). The input variables into each run entered the experimental design at different levels to reflect a diversified operating environment, resulting in a database containing in excess of 2500 data points. Twenty percent of this data was used to validate the correlation, while the remaining 80 percent was used to develop the SPCB correlation.

The multiplicity of runs within each test was required in order to involve various levels of input factors (inlet flow, inlet sub-cooling, and pressure). For most of the runs, these factors were selected at random, following standard statistical procedures (Refs. 6 and 7). For dryout testing, additional runs were made following a two-level, three-factor factorial design to ensure that the entire range of interest (including "corner to corner") was represented.

Review of SPC calculations shows that the average CPR appears to be very near 1.0. That ratio is retained without any apparent trend across inlet mass velocity (Mlb/hr-ft<sup>2</sup>), enthalpy (Btu/lbm), pressure (psia), the best estimate of the  $F_{EFF}$ , or the axial offset. The overall CPR mean for the ATRIUM-9B 1629 data points was calculated to be 0.996, and the CPR mean for the ATRIUM-10 1028 data points was calculated to be 0.996.

To evaluate the quality of the correlation, the staff independently calculated a CPR 95/95 upper tolerance limit (Refs. 8 and 9) for each test, for each profile, and for the entire set of runs. The staff 95/95 calculation was compared to SPC's 95/95 calculation. Apart from rounding errors and conservative table interpolations, the staff's calculation was in total agreement with SPC's calculation. This limit is interpreted to mean that one is 95 percent sure that at least 95 percent of the population of runs yields a CPR value no higher than 1.022 for ATRIUM-9B and a value of 1.034 for ATRIUM-10. SPC's calculations also show that for any test or grouping of tests, the percentage of runs that fall below their associated tolerance limits is at least 95.7 percent for ATRIUM-9B and 96.8 percent for ATRIUM-10.

The submittal contains charts and tables reflecting CPR behavior across different mass velocity (Mlb/hr-ft<sup>2</sup>) for individual tests. Although some tests show higher CPR values associated with high mass velocity, the reverse is true for other tests, and no dependency between CPR and mass velocity is apparent.

Another objective of SPC's study that involves statistical consideration is the determination of the additive constant for both fuel types. The additive constant is a statistical adjustment to the measure of the  $F_{EFF}$  to account for the effect of the rod's geometric position within the assembly. This adjustment has two components: a calculated additive constant and a measure of uncertainty associated with the calculation. In the development of the additive constants, SPC uses only the cosine profile data. However, the measure of the associated uncertainty is calculated from the entire database, containing cosine, upskew, and downskew test data.

The main contributors to this uncertainty are two sources of variability: "within test variability" and "between test variability." The within test variability is given as a weighted average in which the weighting factors are the number of runs per test. The between test variability is given as a weighted average of the difference between the  $F_{EFF}$  for a rod in a test bundle and the average  $F_{EFF}$  for the test bundle. The weighting factors are the number of boiling transitions for a rod in the test bundle. The square root of the sum of the squares (the two sources of variability) give the measure of variability associated with the calculation of the additive constant. In-depth review of the statistical section of the submittal leads the staff to concur with the statistical methods used and the results obtained by the vendor.

#### 4.0 SPCB CORRELATION BEHAVIOR

The SPCB correlation was tested to ensure smooth functions and no significant discontinuities in its behavior over the entire range of operability of the fuel. Flow, enthalpy, and pressure-dependent functions within the correlation, such as the "Tong Factor" correction for both fuels, was investigated for its behavior over the entire applicable range of the fuels. A number of tests were conducted to determine the sensitivity of the major functions within the SPCB correlation to flow, inlet subcooling, pressure variation,  $F_{EFF}$ , and axial power shape.

Review of the data, figures, and tables indicates that the SPCB correlation behaves well over the applicable range of the fuel.

#### 5.0 SPCB CORRELATION VALIDATION

SPC performed several tests to validate the behavior of the SPCB correlation in steady-state and transient events. The validation database consisted of 20 percent of the total steady-state data points that were not included in the correlation database. The remaining 80 percent of the database (the so-called verification set) was used to develop the correlation. In addition, data were collected from tests conducted on an ATRIUM-10P assembly that contained more part-length fuel rods than are usually found in a typical ATRIUM-10 assembly. These tests were conducted to demonstrate the ability of the SPCB correlation to capture the effects of the part-length rods, as well as the correlation agreement with the data. The predicted SPCB correlation between critical power versus the measured critical power for these tests showed very good agreement.

Two sets of transient tests were performed as part of the validation process. Both tests were designed to peak rods around the internal water canister. The difference between the two tests is that the first test had rods with a chopped cosine-shaped axial power profile and the second had rods with an upskew axial power shape. Another purpose of the tests was to validate the concept that the additive constants can be derived from steady-state cosine tests and applied to other axial shapes under transient conditions.

The transient tests performed were the simulated load rejection with no bypass (LRNB) events that consisted of power, pressure ramps, and flow decay. Power forcing functions were programmed to produce transient heat flux on the surface of the rod typical of an LRNB event. Parameters monitored during the tests were power, inlet flow, system pressure, inlet temperatures, and cladding temperatures.

The transient thermal-hydraulic code, XCOBRA-T (Refs. 10 and 11), was used to predict the test results using the SPCB steady-state critical power correlation. XCOBRA-T calculates the fluid conditions at a specified time step. The CHF is calculated at each axial position and time step, then compared to the corresponding measured rod heat flux at the surface of the rod. The ratio of the calculated heat flux to the measured rod heat flux is defined to be the critical heat flux ratio (CHFR). When this ratio is unity, it is referred to as the minimum critical heat flux ratio (MCHFR), and it signifies "boiling transition" in a transient event. Comparison of measured and calculated time-to-boiling transitions for cosine and upskew transient tests shows that the XCOBRA-T calculated time-to-boiling transition values are conservative when compared to actual boiling transition time. This validation confirms the use of the steady-state SPCB correlation and the associated additive constants in evaluating transient events.

## 6.0 LOCAL PEAKING FACTORS

Although local peaking factors may be exceeded in controlled bundles, these bundles by definition are not limiting bundles, consequently, they do not factor in the calculation of the minimum critical power ratio (MCPR) safety limit. If, however, in the process of calculating the MCPR safety limit, the local peaking factor of 1.5 is exceeded, an additional additive constant uncertainty is applied on a rod-by-rod basis in accordance with Table 3.15 of Reference 1. These conditions have been agreed upon by both the NRC staff and SPC, (Ref. 12).

## 7.0 NON CONFORMANCE ISSUES

The submittal, as documented in Reference 1, is SPC's corrective action in response to Part 2 of notice of Nonconformance 99900081/97-01, as stated in Attachment II of SPC's letter to the NRC, dated February 24, 1998 (Ref. 13). The Nonconformance stated that: SPC failed to develop an adequate number of tests points and failed to test an adequate range of conditions to justify the uncertainty values for the "additive constants" used in determining the safety limit minimum critical power ratio (SLMCPR) for the ATRIUM-9B fuel design. This statement implies that SPC should have used larger uncertainty values in the SLMCPR determinations in order to reflect the full operability range of the ATRIUM-9B fuel design. In addition, because the results of the ANFB correlation are used as inputs to the safety limit methodology, this has immediate implications regarding the SLMCPR and the operating limit minimum critical power ratio (OLMCPR) of the Commonwealth Edison Company plants (Quad Cities Unit 2, Cycle 15, Dresden Unit 2, Cycle 15, and LaSalle County Unit 2, Cycle 8) and the Washington Public Power Supply System (Washington Nuclear Unit 2, Cycle 13) loaded with ATRIUM-9B fuel.

In response to this notice of Nonconformance, SPC developed and implemented interim methodologies (ANF-1125, Appendixes D and E) (Refs. 14 and 15), while performing additional dryout testing of the ATRIUM-9B design to obtain additional data to cover the extended range of thermal-hydraulic parameters for the ATRIUM-9B fuel design.

The NRC staff contends that with the submittal of EMF-2209(P), the vendor (SPC) has provided the additional data necessary for the SPCB critical power correlation to provide a rigorous treatment over the entire operating range of the ATRIUM-9B fuel. Thus, with the submittal of EMF-2209(P), all problems identified in the inspection report (Nonconformance 99900081/97-01, Part 2) related to the dryout methodology for ATRIUM-9B fuel have been addressed.

## 8.0 TECHNOLOGY TRANSFER

SPC described the technology transfer program (Ref. 16) which the licensees must successfully complete in order to perform their own thermal-hydraulic calculations using the SPCB correlation and the XCOBRA-T code in support of reload analyses. The overall process consists of training, benchmarking, and change control. In addition, SPC described the process for a licensee to implement the new correlation (SPCB). This process includes performance of an independent benchmarking calculation by SPC for comparison to the licensee-generated results to verify that the new CHF correlation is properly applied. The staff has reviewed the process and find it acceptable because training, bench-marking, and change control have been adequately addressed.

## 9.0 CONCLUSION

The staff has reviewed the analyses in Topical Report EMF-2209(P), Revision 0, "SPCB Critical Power Correlation," and concludes that on the basis of its findings (presented above), Topical Report EMF-2209(P) is acceptable for licensing applications, in accordance with SPC's agreement, subject to the following conditions:

1. The SPCB correlation (as described in this submittal, Reference 1) is applicable to SPC ATRIUM-9B and ATRIUM-10 fuel designs, with a local peaking factor no greater than 1.5.
2. If, however, in the process of calculating the MCPR safety limit, the local peaking factor of 1.5 is exceeded, an additional uncertainty of 0.026 for ATRIUM-9B and 0.021 for ATRIUM-10 will be imposed on a rod-by-rod basis.
3. The SPCB correlation range of applicability is as follows:

Pressure (psia)	571.4 to 1432.2
Inlet Mass Velocity (Mlb/hr-ft <sup>2</sup> )	0.087 to 1.5
Inlet Subcooling (Btu/lbm)	5.55 to 148.67
Design Local Peaking	1.5
Tested Local Peaking	1.45

4. Technology transfer will be accomplished only through the process described in Reference 16, which includes the performance of an independent bench-marking calculation by SPC for comparison to the licensee-generated results to verify that the new CHF correlation (SPCB) is properly applied for the first application by the licensee.

## 10.0 REFERENCES

1. Letter from H. D. Curet, of SPC to the U.S. Nuclear Regulatory Commission, submitting Topical Report EMF-2209(P), Revision 0, September 24, 1999.
2. Letter from J. F. Malley to the U.S. Nuclear Regulatory Commission, "Request for Additional Information (RAI) to Topical Report EMF-2209(P), "SPCB Critical Power Correlation," Revision 0, March 20, 2000.
3. Letter from R. A. Copeland, of SPC, Transmittal of (A) version of ANF-1125(P) to the U.S. Nuclear Regulatory Commission, April 27, 1990.
4. Letter from H. D. Curet, of SPC to the U.S. Nuclear Regulatory Commission, submitting Topical Report EMF-1997(P), Revision 0, October 30, 1997, and Letter from H. D. Curet, submitting Topical Report EMF-1997(P), Supplement 1, Revision 0, January 29, 1998.
5. Letter from J. F. Malley to the U.S. Nuclear Regulatory Commission, "Request for Additional Information (RAI) to Topical Report EMF-1997(P), ANFB-10 Critical Power Correlation," Revision 0, May 7, 1998.

6. "Statistical Methods for Nuclear Material Management," NUREG/CR-4604, PNL-5849, December 1988.
7. G. J. Hahn, and S. S. Shapiro, "Statistical Models in Engineering," Wiley, 1967.
8. H. W. Lilliefors, "On the Kolmogorov Test for Normality with Mean and Variance Unknown," Journal of American Statistical Association, Vol. 62, June 1967.
9. R. E. Odeh and D. B. Owen, "Tables for Normal Tolerance Limits," Table 1, Marcel Dekker, Inc, 1990.
10. "XCOBRA-T: A Computer Code for BWR Transient Thermal-Hydraulic Core Analysis," XN-NF-84-105(P)(A), Volume 1, Supplements 1 and 2, Exxon Nuclear Company, Richland, WA 99352, February 1987.
11. "XCOBRA-T: A Computer Code for BWR Transient Thermal-Hydraulic Core Analysis, Void Fraction Model Comparison to Experimental Data," XN-NF-84-105(P)(A), Volume 1, Supplement 4, Advanced Nuclear Fuels Corporation, Richland, WA 99352, February 1987.
12. Letter from J. F. Malley to the U.S. Nuclear Regulatory Commission, "SER conditions for EMF-2209(P) Revision 1, SPCB Critical Power Correlation," April 20, 2000.
13. Letter, Samuel J. Collins, of NRC to David G. McLees, of SPC "Demand for Information and Notice of Nonconformance (Inspection Report 99900081/97-01)," EA97-495, dated October 27, 1997.
14. Letter from Don Curet, of SPC to the U.S. Nuclear Regulatory Commission, requesting review of ANFB Critical Power Correlation Uncertainty for Limited data Sets, ANFB-1125(P), Supplement 1, Appendix D, April 18, 1997.
15. Letter from J. F. Malley, of SPC to the U.S. Nuclear Regulatory Commission, "Request for review of ANFB Critical Power Correlation Determination of ATRIUM-9B Additive Constant Uncertainties, ANFB-1125(P), Supplement 1, Revision 0, August 11, 1998.
16. Letter from J. F. Malley to the U.S. Nuclear Regulatory Commission, "SER conditions for EMF-2209(P) Revision 1, SPCB Critical Power Correlation," April 24, 2000.

Principal Contributor: A. Attard

Date: May 17, 2000

# SIEMENS

April 24, 2000  
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U.S. Nuclear Regulatory Commission  
Washington, D.C. 20555-0001

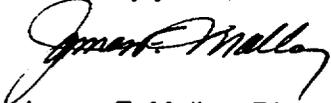
## **SER Condition for EMF-2209(P) Revision 1, "SPCB Critical Power Correlation"**

Ref.: 1. Generic Letter 83-11, Supplement 1, "Guidelines for Qualifying Licensees to Use Generically Approved Analysis Methods," June 24, 1999.

The NRC has proposed that a condition be included in the SER for EMF-2209(P), a topical report describing the SPCB critical power correlation. This condition addresses the transfer of the technology needed by a licensee to successfully execute methodology developed by Siemens Power Corporation (SPC) and approved by the NRC. To address this condition, SPC has developed Work Practice P104,135, "Guidelines to Qualify a Licensee to Use NRC Approved Analysis Methods." This work practice, as one of the work practices within EMF-1928(P), "Engineering Work Practices," addresses the processes SPC will follow to assist a licensee in meeting the guidelines of Generic Letter 83-11, Supplement 1 (Reference 1). This work practice provides a procedure to help ensure that licensees are adequately trained and are able to comply with the guidelines of Reference 1.

SPC has discussed this condition with the NRC and agrees it is acceptable and appropriate. In addition, SPC believes this work practice fully addresses the intent of the condition.

Very truly yours,



James F. Mallay, Director  
Regulatory Affairs

/arn

cc: A. C. Attard  
N. Kalyanam  
Project No. 702

## **Siemens Power Corporation**

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# SIEMENS

April 20, 2000  
NRC:00:023

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Washington, D.C. 20555-0001

## SER Conditions for EMF-2209(P) Revision 1, "SPCB Critical Power Correlation"

The NRC has proposed that three conditions be included in the SER for EMF-2209(P), a topical report describing the SPCB critical power correlation. These conditions are:

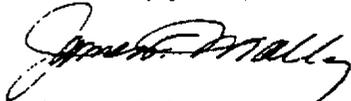
1. The SPCB correlation is applicable to Siemens Power Corporation ATRIUM<sup>\*</sup>-9B and ATRIUM-10 fuel designs with a local peaking factor no greater than 1.5.
2. If, in the process of calculating the MCPR safety limit, the local peaking factor exceeds 1.5, an additional uncertainty of 0.026 for ATRIUM-9B and 0.021 for ATRIUM-10 will be imposed on a rod by rod basis.
3. The range of applicability of the SPCB correlation shall be limited to:

Pressure (psia)	571.4 to 1432.2
Inlet mass velocity (Mlb/hr-ft <sup>2</sup> )	0.087 to 1.5
Inlet subcooling (Btu/lbm)	5.55 to 148.67

For clarification, it is noted that the values cited in the second condition are taken from Table 3.15 on page 3-39 of the topical report under "Incremental Uncertainty." The values in condition 3 are found in Table 1.1 on page 1-2. The peaking values in this table are addressed in condition 1.

Siemens Power Corporation has discussed these conditions with the NRC and agrees they are acceptable and appropriate.

Very truly yours,



James F. Mallay, Director  
Regulatory Affairs

/am

cc: A. C. Attard  
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Project No. 702

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\* ATRIUM is a trademark of Siemens.

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# SIEMENS

March 20, 2000  
NRC:00:019

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Washington, D.C. 20555-0001

## **Request for Additional Information to the Topical Report EMF-2209(P) Revision 0, "SPCB Critical Power Correlation"**

- Ref.: 1. Letter, N. Kalyanam (NRC) to James F. Mallay (SPC), "Request for Additional Information – Siemens Topical Report, EMF-2209(P) Revision 0, *SPCB Critical Power Correlation* (TAC No. MA6639)," February 22, 2000.
- Ref.: 2. Letter, James F. Mallay (SPC) to Document Control Desk (NRC), "Request for Review of EMF-2209(P) Revision 0, *SPCB Critical Power Correlation*," NRC:99:042, September 24, 1999.

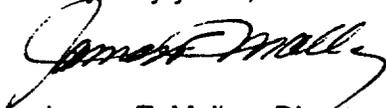
In Reference 1, the NRC requested additional information to facilitate the completion of its review of the Siemens Power Corporation topical report on the SPCB correlation (see Reference 2). Responses to this request are provided in two attachments: one proprietary and one nonproprietary.

These responses, along with several editorial corrections, have made it necessary to change numerous pages in the topical report. These changes have been incorporated in Revision 1 to the topical report and are described on page i, "Nature of Changes," in the report.

In addition to the attached responses, four copies of the proprietary version and two copies of the nonproprietary version of Revision 1 of the topical report are enclosed with this letter. When the revised report is found acceptable for referencing in license applications, SPC will publish the accepted versions of the report in accordance with the procedures established in NUREG-0390.

Siemens Power Corporation considers some of the information contained in the attachments and enclosures to this letter to be proprietary. This information has been noted by enclosing it within brackets. The affidavit provided with the original submittal of the reference topical report satisfies the requirements of 10 CFR 2.790(b) to support the withholding of this information from public disclosure.

Very truly yours,



James F. Mallay, Director  
Regulatory Affairs

cc: N. Kalyanam (3(P) and 1(NP); w/attachment)  
Project No. 702 (1(P) and 1(NP); w/attachment)

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## Responses to RAI Questions to EMF-2209

Q.	SPCB-Correlation Development RAIs.
1	<p><i>On page 1-2, second paragraph, it is stated that an additional [ ] validation data points were included to the [ ] validation data base for the purpose of validating the SPCB correlation. Were the [ ] data points obtained for a different fuel assembly? Please Clarify.</i></p> <p>Response: As shown on page 4-6 and 4-7 SPCB was validated with an alternate (different) fuel design comprised of 12 part-length rods and 79 full-length rods. This alternate fuel design is an ATRIUM-10 design with a spacer that is similar in design to the spacer used in the data base. The distinction of the alternate design is essentially the use of 12 rather than 8 part-length rods.</p>
2	<p><i>On page 1-2, third paragraph, please explain the need for additional uncertainty required for peaking factors greater than 1.5.</i></p> <p>Response: During the dryout testing some tests were performed where the high peaked rods were as high as about 1.45. Because of the trend of the data, one may safely extrapolate to a local peaking of 1.50 for design cases. However, during the safety limit analysis the local peaking may be perturbed so that a design local peaking may increase over the 1.50 limit. If that happens, the safety limit analysis will use the incremental uncertainties for the ATRIUM-9B and ATRIUM-10 designs provided in Table 3.15.</p>
3	<p><i>On page 2-4, first paragraph, it is stated that two coefficients are used, one for the mass velocity less than or equal to 0.37 and one for mass velocities greater than or equal to 0.42.</i></p> <p><i>a. What is the basis for these lower and upper limits?</i></p> <p><i>b. Provide technical justification for the interpolation between these bounds.</i></p> <p>Response: The behavior of critical power is observed to be strongly influenced by flow rate. The rod indicating boiling transition or dryout may change from a high powered rod to a lower powered rod as the flow rate changes. The intention of the correlation is to provide relationships that help describe the phenomena that are observed while maintaining acceptable uncertainty, no singularity, and well behaved transition between regions. The lower limit is based on providing a good fit of what is occurring at the low flows while the upper limit is based on providing a good fit of what is occurring at the higher flows.</p> <p>The fitting of the coefficients for the A and B functions was performed in the following manner:</p> <p>All of the correlation data for the ATRIUM-10 (774 data points) were evaluated to determine coefficients for A and B simultaneously. The result, when applied, provided good estimates for CPR especially for the low flow region. In order to provide improved estimates of CPR for higher flow regions, the data for high flow was correlated (696 data points) and an alternate set of coefficients was determined. In order to provide a smooth transition between the use of the two</p>

Q.	<p>SPCB-Correlation Development RAls.</p> <p>sets of coefficients, a region was established for which a linear interpolation process would be used. For example a value for the function of A would be determined at the mass velocity corresponding to the usage limit of 0.37 Mlb/hr-ft<sup>2</sup> using the low flow set of coefficients and A would be determined at the high mass velocity lower bound of 0.42 Mlb/hr-ft<sup>2</sup> using the high flow set of coefficients. Then a linear interpolation of A would be performed based on the two flows. Technically the issue is one of avoiding step changes in behavior.</p> <p>Note: Equation 2.7 on page 2.4 shows a double asterisk with the A3 coefficient. This is a typographical error and will be corrected to show a single asterisk in the final approved version of the document.</p>
4	<p><i>Tables 2.1 through Table 2.7 provide values for various coefficients, subject to lower and upper bounds. Is one to assume that different values for these coefficients are obtained by interpolation as in the case of Table 2.1?</i></p> <p>Response: Yes, for the case of flows falling between the various regions of the various tables, a linear interpolation is used to obtain a value of the overall coefficient for use in the correlation.</p>
5	<p><i>Chapter 2, in particular Sections 2.0 to 2.3, contains the mathematical development of the SPCB Correlation. As such it is imperative that one obtains a clear understanding of the various components (variables, parameters, etc.) and their respective use in the formulation of the correlation for the two different fuels. In reviewing Sections 2.0 to 2.3 it quickly became apparent that there are a number of junctions in the road, depending on whether one is addressing the ATRIUM-9B fuel or the ATRIUM-10 fuel. In order to expedite the review of this Topical Report, please provide a road map (Flow Chart/Event Tree) showing the clear and separate routes taken in developing the two forms of the SPCB correlation for each of the fuels in question.</i></p> <p>Response: A flow chart is shown in the attachment that depicts the separate routes taken in developing the two forms of the SPCB correlation for each of the fuel types in question. The notation G in the flow chart is interchangeable with <math>\bar{G}</math>.</p>
6	<p><i>On page 2-23 (Item 2, middle of page), please provide the reasoning for switching from a simple mean to a weighted mean. (Item 2 middle of the page.)</i></p> <p>Response: The use of a simple mean from a power weighted mean was introduced with the ANFB-10 correlation (Reference 2.1) and is retained for the SPCB critical power correlation. The Reference indicated on page 2.23 should be to Reference 2.2, the ANFB correlation.</p>
7	<p><i>Please provide additional information for Figure 2.3.</i></p> <p>Response: Figure 2.3 with a legend is provided in Revision 1 to EMF-2209(P).</p>
8	<p><i>On page 2-34, paragraph 2, reference is made to the "ANFB" limits. Should that be the "SPCB" limits?</i></p>

Q.	SPCB-Correlation Development RAIs.
	Response: Yes, the letters ANFB have been replaced with the letters SPCB in Revision 1 to EMF-2209(P).
9	<p><i>On page 2-35, Section 2.6.2.1, the high and low enthalpy limits addressed. What are the values of these limits?</i></p> <p>Response: The values of the limits are depicted in Table 1.2 on page 1-3.</p>
10	<p><i>On page 2-36, second paragraph, it is stated that "corresponding quality distributions are artificially increased." What are "quality distributions?"</i></p> <p>Response: For each nodal enthalpy, a thermodynamic quality can be determined. As quality is a parameter in the Hench-Levy correlation, then when incrementing the enthalpy, the quality is also incremented. As each node would have a different enthalpy, then within the assembly there would be a distribution of quality.</p>
11	<p><i>Is "inlet mass velocity" inter-changeable with "inlet mass flow rate?"</i></p> <p>Response: The correlation calculation relates only to inlet mass velocity (a mass flow rate per unit area). The correlation or physical behavior can be visually examined using either mass velocity or mass flow rate.</p>
12	<p><i>Figure 3.8 on page 3-15, the x-axis is labeled "Active flow." What is "Active Flow?"</i></p> <p>Response: The test assembly uses an electrically heated model of a fuel assembly. One of the differences between a test assembly and an assembly produced for in-reactor use is the test assembly does not typically allow flow through the water channel while an in-reactor fuel assembly would allow flow through the water channel. Thus the flow rate that is measured and delivered to the inlet of a test assembly is the flow rate that is present in the electrically heated region. Within an in-reactor fuel assembly, the flow that passes through the orifice is progressively decreased due to the need for flow in the bypass and the planned flow within the water rod or water channel structure. The flow adjacent to nuclear fuel rods is referred to as active flow to distinguish it from the total flow that might be delivered at the inlet of the assembly. This terminology was borrowed for use in the test assembly to aid the in-house engineer that is reading the document in understanding that the flow that was delivered in test is in-fact the flow that is in the region where the powered rods are located.</p>
13	<p><i>Does Figure 3.39 on page 3-41 include all the data for the ATRIUM-9B and that for the ATRIUM-10?</i></p> <p>Response: Yes, ATRIUM-9B and ATRIUM-10 validation and verification data are included. Figure 3.39 is an overlay of Figure 1.2 on Figure 1.1.</p>
14	<p><i>Page 4-9, Figure 4.7, please provide justification for the difference in magnitude at high inlet flow.</i></p> <p>Response: The principle reason for differences in magnitude of power at high inlet flow is due to the influence of axial power shape. Axial power shape (as might be visualized by the gradient of heat flux) has a strong influence at the high mass velocities. The fact that data is observed to behave in this manner results in the use</p>

Q.	SPCB-Correlation Development RAIs.
	of an upstream memory effect such as the Tong-Factor or the non-uniform axial correction factor of SPCB. At the lower mass velocities, the importance of heat flux increases and the axial shape is not as dominant.
15	<i>Page 4-9, the last sentence in the second paragraph states that Test 48.1 consists of transient data only. Does that mean that Test 29.5 consist of data other than transient data?</i>
	Response: Yes, as shown on page 3-32 Test assembly 29.5 was used for steady state critical power data and then was used for transient data. Test 48.1 was only used for transient data.
16	<i>In Section 5.3, the third paragraph brings up the subject of peaked rods going into dryout. For both fuel types, what procedure is used in determining which rods are peaked and which rods go into dryout.</i>
	Response: The first thing to consider when developing the planned peaking pattern for dryout testing is that the peaking pattern does not necessarily mimic a neutronic design. Instead, by peaking certain rods one may take advantage of the bundle symmetry and minimize the number of tests required. Rods are peaked in groups in an attempt to drive certain locations into dryout. Because of the methodology for determining additive constants, if a group of rods are peaked and only one rod goes into dryout, it is conservatively assumed that the other two rods went into dryout at the same power. If a rod location is not peaked at all during the dryout testing, then that position has its additive constant determined by assuming that it went into dryout during the test that had the highest peaking in this location.
17	<i>Page 5-11, last paragraph. Please provide additional discussion regarding as to why only two tests were needed to be performed on the ATRIUM-9B to demonstrate that the ATRIUM-10 additive constant methodology is applicable to the ATRIUM-9B fuel.</i>
	Response: The methodology for determining the effect of local peaking on additive constants was developed in ANF-1125, Supplement 1(P)(A). That methodology has remained the same for both ANFB-10 and SPCB. During the testing of the ATRIUM-10 bundle several tests were run to drive rods into dryout at different local peakings. The positions of these tests were in positions that represented each different bundle location; i.e., 3x3 corner, edge rods, interior, etc. The ATRIUM-9B bundle geometry is therefore represented in the ATRIUM-10 testing. Bear in mind also, that the additive constant methodology considers the effect of the rods surrounding the peaked rod of interest. Therefore, the methodology doesn't know whether the bundle is a 4x4, 5x5, 9x9, or 10x10 assembly.
18	<i>Page 5-12, in the last paragraph refers to "individual case." Is this same as "individual test?"</i>
	Response: The word "individual" is used three times in the document. One time it modifies "tests," a second time it modifies "rod," and the third time it modifies "case." The context for which it is used as a modifier to case would be this: each line in Table 5.5 would represent a different individual case.

Q.	SPCB-Correlation Development RAIs.																						
	Note: The reference to Table 5.9 on page 5-14 has been corrected to Table 5.5 in Revision 1 of EMF-2209(P).																						
Q	SPCB Statistical RAIs																						
1	<p><i>A general statement: Whenever presenting mean and standard deviation (such as in the bottom sentence of page 1-1) include the sample size and the associated tolerance limit.</i></p> <p>Response: See Tables 3.1, 4.1, 4.2, and 4.3 in Revision 1 of EMF-2209(P).</p>																						
2	<p><i>Page 1-2, Section 1.1. Provide statistical tests that compare the behavior (mean, variance) of the 1,876 correlation points to the [ ] validation points. Also, did the [ ] additional validation points differ in behavior from the [ ] validation points?</i></p> <p>Response: Statistical tests can be performed to compare the means and/or the variances between or among these data groups. Due to the large number of data, the statistical tests would be expected to show statistical difference. However, the nature of the difference would be of no practical significance. As can be observed, the standard deviation of the three groups are similar in magnitude and the mean values of the two groups of importance are less than unity.</p> <table border="1"> <thead> <tr> <th>Group</th> <th>Number</th> <th>Mean ECPR</th> <th>Standard Deviation</th> </tr> </thead> <tbody> <tr> <td>Verification</td> <td>1876</td> <td>0.992</td> <td>0.0204</td> </tr> <tr> <td>Validation</td> <td>781</td> <td>0.983</td> <td>0.0241</td> </tr> <tr> <td>Validation2</td> <td>316</td> <td>1.002</td> <td>0.0233</td> </tr> </tbody> </table> <p>Comparison of means:</p> $0.0204/\sqrt{(1876)} = 0.0005$ $0.0241/\sqrt{(781)} = 0.0009$ $0.0233/\sqrt{(316)} = 0.0013$ <p>Group</p> <table border="1"> <tbody> <tr> <td>Verification</td> <td><math>0.992 \pm 0.0005</math></td> </tr> <tr> <td>Validation</td> <td><math>0.983 \pm 0.0009</math></td> </tr> <tr> <td>Validation2</td> <td><math>1.002 \pm 0.0013</math></td> </tr> </tbody> </table> <p>This implies a slight statistical difference in the means of the groups, i.e., 0.01 difference between the Verification and the Validation group. However, there is not a practical difference.</p> <p>Comparison of variances:</p> <p>For example consider an F test between Verification and Validation Then</p> $F = (0.0241/0.0204)^2 = 1.396$ <p>Comparing this with an estimate from a table would suggest a slight statistical difference. However there is not a practical difference in as much as the overall statistics that are used in the analysis process specifically includes the effect of the differences within test and between tests.</p>	Group	Number	Mean ECPR	Standard Deviation	Verification	1876	0.992	0.0204	Validation	781	0.983	0.0241	Validation2	316	1.002	0.0233	Verification	$0.992 \pm 0.0005$	Validation	$0.983 \pm 0.0009$	Validation2	$1.002 \pm 0.0013$
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Q.	SPCB-Correlation Development RAIs.
3	<p><i>Page 1-2, Second paragraph. Text states that transient tests are performed on ATRIUM 10 (not mentioning ATRIUM 9-B). Page 3-36, second paragraph says that dryout tests were performed on the ATRIUM-9B and ATRIUM-10.</i></p> <p>Response: Distinction is made between transient test and quasi-steady state dryout tests. Quasi-steady state dryout tests maintain parameters such as flow, inlet subcooling, and pressure constant while slowly increasing power to attain a dryout condition. Transient tests are purposely varying power and flow in accord with a desired plan and detecting dryout. The ATRIUM-10 was selected for performing transient tests while both ATRIUM-9B and ATRIUM-10 assemblies are tested for steady state dryout.</p>
4	<p><i>Pages 2-4 thru 2-10 (Tables 2.1 thru 2.7). Is "G" in these tables the same as G bar (<math>\bar{G}</math>) given in, say, equation (2.7)?</i></p> <p>Response: Yes. Revision 1 to EMF-2209(P) has (<math>\bar{G}</math>) in these tables.</p>
5	<p><i>Page 2-6, Equation 2.12. The coefficient "f1" in equation 2.12 is not defined.</i></p> <p>Response: The definition of f1 shown on page 2-6 in the first line following Equation 2-11 is intended to be the same f1 as used in Equation 2-12. An explanatory note could be added to the text to indicate this common usage for the approved version.</p>
6	<p><i>Page 2-13, Equation 2.23. Identify/explain how the coefficients 0.624 and 0.314 were obtained.</i></p> <p>Response: Equation 2.23 remains identical to the formulation for FEFF presented in EMF-1997, "ANFB-10 Critical Power Correlation" and ANF-1125, Supplement 1, "ANFB Critical Power Correlation." The empirical formulation developed for the 1990 critical power correlation is used so as to minimize the review of some different or new formulation.</p>
7	<p><i>Page 2-26, Figure 2.3. Symbols (like X, square, and diamond) need a legend.</i></p> <p>Response: See response to question 7 of SPCB-Correlation Development RAIs.</p>
8	<p><i>Page 3-1, Table 3.1. Show how Sigma (given as 0.021) for ATRIUM-9B was derived.</i></p> <p>Response: The value of 0.021 for the ATRIUM-9B is obtained by applying the standard relationship for standard deviation such as found as equation 1.7 on page 9 or equation 1.9 on page 10 of NUREG/CR-4604 for the 1629 data of ATRIUM-9B tabulated in Section 5 of the topical report.</p>

Q.	SPCB-Correlation Development RAIs.
9	<p><i>Page 3-1, Table 3.1:</i></p> <ul style="list-style-type: none"> <li>• <i>Expand the table to include for each test the 95/95 upper tolerance limit for ECPR,</i></li> <li>• <i>maximum value obtained for the test,</i></li> <li>• <i>number of data points in the test that exceed the tolerance limit, and</i></li> <li>• <i>the percent number of points below the tolerance limit.</i></li> </ul> <p><i>Provide similar entries, separately for each fuel, and for all tests of the same profile.</i></p> <p>Suggestion: Follow the style of Table 4.1 for ANFB 10 that you provided in your May 26, 1998 communication to E.Y. Wang.</p> <p>Response: Tables 3.1, 4.1, 4.2, and 4.3 have been revised in Revision 1 of EMF-2209(P).</p>
10	<p><i>Page 3-2, Table 3.2. Show a complete table of the analysis of variance (ANOVA). Please provide separate analysis for each fuel type. Did any analysis detect significant test differences? Was the data tested for homogeneity of variances prior to constructing the ANOVA?</i></p> <p>Response: From a practical viewpoint, data from one test to another are expected to behave statistically differently. Thus, it is appropriate to combine those differences. The actual way these differences are combined for Safety Analysis is through uncertainty in Additive Constants. This Analysis of Variance is provided as supplementary information.</p> <p>The Analysis of Variance process used by SPC produces the information shown below. The input is the Table 3.1 entries by test section for the number of data points, the mean ECPR, and the standard deviation. The output is the information shown in Table 3.2. This table shows the result of the Analysis of Variance. This approach is used to separate the components of variance in order to estimate the population variance and the degrees of freedom. The variance model is:</p> $\sigma_{\text{TRUE}}^2 = \sigma_{\text{Between}}^2 - \frac{\sigma_{\text{WithinTest}}^2}{\text{ESS}}$ <p>where</p> <ul style="list-style-type: none"> <li><math>\sigma_{\text{TRUE}}^2</math> = True between mean variance</li> <li><math>\sigma_{\text{BETWEEN}}^2</math> = Total between test variance</li> <li><math>\sigma_{\text{WithinTest}}^2</math> = Within test variance</li> <li>ESS = Effective sample size</li> </ul> <p>The degrees of freedom are computed using Satterthwaite's formula.</p>

Q.	SPCB-Correlation Development RAIs.																																
10	<p>It is apparent from the data in Table 3.1 that the measurement variances are not from the same statistical populations. Most of the differences can be explained by differences in test equipment and particular test. Inclusion of all valid test data provides a more robust and conservative basis for the analysis that establishes the Safety Limit.</p> <p>As the purpose of the Analysis of Variance is to account for the differences of the data, tests for homogeneity of variances was not performed. The summary of information by design and overall is shown below:</p> <table border="1" data-bbox="293 646 1399 940"> <thead> <tr> <th>Parameter</th> <th>All Data</th> <th>ATRIUM-10</th> <th>ATRIUM-9B</th> </tr> </thead> <tbody> <tr> <td>Within Test Variance</td> <td>0.000349876</td> <td>0.000421355</td> <td>0.000305357</td> </tr> <tr> <td>Between Test Variance</td> <td>0.000133328</td> <td>0.0000742898</td> <td>0.0001763</td> </tr> <tr> <td>Weighted Mean ECPR</td> <td>0.99104</td> <td>0.99495</td> <td>0.98315</td> </tr> <tr> <td>Standard Deviation</td> <td>0.021982</td> <td>0.02226</td> <td>0.021946</td> </tr> <tr> <td>Population Variance</td> <td>0.0004832</td> <td>0.0004956</td> <td>0.0004817</td> </tr> <tr> <td>Equivalent Sample Size</td> <td>51</td> <td>44</td> <td>80</td> </tr> <tr> <td>Degrees of Freedom</td> <td>302</td> <td>439</td> <td>56</td> </tr> </tbody> </table> <p>(Satterthwaite)</p> <p>The correction to Table 3.2 is provided in Revision 1 of EMF-2209(P).</p>	Parameter	All Data	ATRIUM-10	ATRIUM-9B	Within Test Variance	0.000349876	0.000421355	0.000305357	Between Test Variance	0.000133328	0.0000742898	0.0001763	Weighted Mean ECPR	0.99104	0.99495	0.98315	Standard Deviation	0.021982	0.02226	0.021946	Population Variance	0.0004832	0.0004956	0.0004817	Equivalent Sample Size	51	44	80	Degrees of Freedom	302	439	56
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11	<p><i>Pages 3-2 and 3-3, equations for <math>m_2</math>, <math>m_3</math>, <math>m_4</math>, <math>\beta_1</math>, and <math>\beta_2</math>. What is the numeric value of "n" in each of these calculations?</i></p> <p>Response: All values of ECPR were used in the analysis. Thus, n=2657 Note: the following corrected values are shown below and will be included in the approved version of the document.</p> <p><math>m_2 = 0.000491</math>  <math>\sqrt{\beta_1} = 0.004488</math>      <math>\beta_2 = 2.83</math></p>																																
12	<p><i>Page 3-5, Paragraph 3.2. Justify the use of 1 percent as a level of significance for testing normality. What is the numerical value of Lillifor's statistic?</i></p> <p>Response: The numerical value of the Lillifor statistic is 0.0173. This compares with the 0.02 critical value for 1 percent and the 0.017 value for the 5 percent.</p> <p>The requirement for the data going into the Safety Analysis is that it be approximately normally distributed. The 1 percent level of significance assures this. A tighter level of significance such as 5 or 10 percent could be harmful in that valid data could be excluded.</p>																																
13	<p><i>Pages 3-4 thru 3-29, Figures 3.1 through 3.36. Indicate the sample size associated with each figure.</i></p> <p>Response: The figures were modified in Revision 1 of EMF-2209(P) as requested.</p>																																

Q.	SPCB-Correlation Development RAIs.
14	<p><i>Page 3-38, last paragraph. Indicate where the upper 95 percent confidence limits on the additive constants are implemented.</i></p> <p>Response: The implementation of the upper 95 percent confidence limit for an incremental additive constant uncertainty is presented in Table 3.15. The values of additive constant uncertainty and the corresponding incremental value for rods peaked more than 1.5 are implemented in the determination of the safety limit MCPR in the methodology contained in ANF-524 (P)(A), Revision 2, "Advanced Nuclear Fuels Corporation Critical Power Methodology for Boiling Water Reactors," November 1990.</p>
15	<p><i>Page 4-2, Tables 4.1, 4.2 and 4.3. Expand the tables as requested for Table 3.1.</i></p> <p>Response: Tables 3.1, 4.1, 4.2, and 4.3 have been revised in Revision 1 of EMF-2209(P).</p>
16	<p><i>Page 4-8, Figure 4-6 (and others): What do the different lines represent? Provide the necessary labels. Similarly, provide the necessary labels for Figures 5.7 thru 5.89.</i></p> <p>Response: The lines represent the SPCB correlation prediction of the data as a function of inlet subcooling. The separation among the lines is due to different flow families for the data.</p>
17	<p><i>Were there any outliers in the evaluation, and if so, what was their disposition?</i></p> <p>Response: In EMF-1997, the comment is made that runs 125.4 and 132.4 for test 29.2 are experimentally determined to be outliers. Several low flow points were excluded in EMF-1997 as being below the flow limit for applicability.</p> <p>Due to the refitting process of the "A" and "B" coefficients in EMF-2209, these points are included in the evaluation process. That is, the low flow points are in the domain of the correlation and retained and the two experimental outliers were retained. The inclusion of the outliers provides conservatively greater value of uncertainty.</p>









UNITED STATES  
NUCLEAR REGULATORY COMMISSION

WASHINGTON, D.C. 20555-0001

February 22, 2000

Mr. James F. Mallay  
Director, Nuclear Regulatory Affairs  
Siemens Power Corporation  
2101 Horn Rapids Road  
Richland, WA 99352

SUBJECT: REQUEST FOR ADDITIONAL INFORMATION ON SIEMENS TOPICAL  
REPORT, EMF-2209(P), REVISION 0, "SPCB CRITICAL POWER  
CORRELATION" (TAC NO. MA6639)

Dear Mr. Mallay:

By letter dated September 24, 1999, the Siemens Power Corporation (SPC) submitted Revision 0 to Topical Report EMF-2209(P), "SPCB Critical Power Correlation" for staff review. The staff has done a preliminary review and requests the following information identified in the enclosure.

The additional information was discussed with your staff and a mutually agreeable target date of 30 days from the date of this letter for your response was established. If circumstances result in the need to revise the target date, please call me at the earliest opportunity at 301-415-1480.

Sincerely,

N. Kalyanam, Project Manager, Section 1  
Project Directorate IV & Decommissioning  
Division of Licensing Project Management  
Office of Nuclear Reactor Regulation

Project No. 702

Enclosure: Request for Additional Information

## REQUEST FOR ADDITIONAL INFORMATION

### SIEMENS TOPICAL REPORT, EMF-2209(P)

### "SPEC CRITICAL POWER CORRELATION"

#### SPCB-Correlation Development

1. On page 1-2, second paragraph, it is stated that an additional 316 validation data points were included to the 781 validation data base for the purpose of validating the SPCB correlation. Were the 316 data points obtained for a different fuel assembly? Please clarify.
2. On page 1-2, third paragraph, please explain the need for additional uncertainty required for peaking factors greater than 1.5.
3. On page 2-4, first paragraph, it is stated that two coefficients are used, one for the mass velocity less than or equal to 0.37, and one for mass velocities greater than or equal to 0.42.
  - a. What is the basis for these lower and upper limits?
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6. On page 2-23 (item 2, middle of the page), please provide the reasoning for switching from a simple mean to a weighted mean.
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10. On page 2-36, second paragraph, it is stated that "corresponding quality distributions are artificially increased." What are "quality distributions"?
11. Is "inlet mass velocity" inter-changeable with "inlet mass flow rate" ?
12. Figure 3.8 on page 3-15. The x-axis is labeled "Active flow". What is "Active Flow"?
13. Does Figure 3.39 on page 3-41 include all the data for the ATRIUM-9B and that for the ATRIUM-10?
14. Page 4-9, Figure 4.7. Please provide justification for the difference in magnitude at high inlet flow.
15. Page 4-9, the last sentence in the second paragraph states that Test 48.1 consists of transient data only. Does that mean that Test 29.5 consist of data other than transient data?
16. In Section 5.3, the third paragraph brings up the subject of peaked rods going into dryout. For both fuel types, what procedure is used in determining which rods are peaked and which rods go into dryout.
17. Page 5-11, last paragraph. Please provide additional discussion regarding as to why only two tests were needed to be performed on the ATRIUM-9B to demonstrate that the ATRIUM-10 additive constant methodology is applicable to the ATRIUM-9B fuel.
18. Page 5-12, the last paragraph refers to "individual case." Is this same as "individual test?"

#### SPCB-Statistical RAIs

1. A general statement: Whenever presenting mean and standard deviation (such as in the bottom sentence of Page 1-1), include the sample size and the associated tolerance limit.
2. Page 1-2, Section 1.1. Provide statistical tests that compare the behavior (mean, variance) of the 1,876 correlation points to the 781 validation points. Also, did the 316 additional validation points differ in behavior from the 781 validation points?
3. Page 1-2, second paragraph. Text states that transient tests are performed on ATRIUM 10 (not mentioning ATRIUM-9B). Page 3-36, second paragraph says that dryout tests were performed on the ATRIUM-9B and ATRIUM-10.
4. Pages 2-4 thru 2-10 (Tables 2.1 thru 2.7). Is "G" in these tables the same as G bar given in, say, equation (2.7)?
5. Page 2-6, Equation 2.12. The coefficient "f1" in equation 2.12 is not defined.

6. Page 2-13, Equation 2.23. Identify/explain how the coefficients 0.624 and 0.314 were obtained.
7. Page 2-26, Figure 2.3. Symbols (like X, square, and diamond) need a legend.
8. Page 3-1, Table 3.1. Show how Sigma (given as 0.021) for ATRIUM-9B was derived.
9. Page 3-1, Table 3.1:
  - expand the table to include for each test the 95/95 upper tolerance limit for ECPR,
  - maximum value obtained for the test,
  - number of data points in the test that exceed the tolerance limit, and
  - the percent number of points below the tolerance limit.

Provide similar entries, separately for each fuel, and for all tests of the same profile.

Suggestion: Follow the style of Table 4.1 for ANFB 10 that you provided in your May 26, 1998 communication to E.Y. Wang.

10. Page 3-2, Table 3.2. Show a complete table of the analysis of variance (ANOVA). Please provide separate analysis for each fuel type. Did any analysis detect significant test differences? Was the data tested for homogeneity of variances prior to constructing the ANOVA?
11. Pages 3-2 and 3-3, equations for  $m_2$ ,  $m_3$ ,  $m_4$ ,  $\beta_1$ , and  $\beta_2$ : What is the numeric value of "n" in each of these calculations?
12. Page 3-5, paragraph 3.2. Justify the use of 1 percent as a level of significance for testing normality. What is the numerical value of Lillifor's statistic?
13. Pages 3-4 through 3-29, Figures 3.1 through 3.36. Indicate the sample size associated with each figure.
14. Page 3-38, last paragraph. Indicate where the upper 95 percent confidence limits on the additive constants are implemented.
15. Page 4-2, Tables 4.1 and 4.2. Expand the tables as requested for Table 3.1.
16. Page 4-8, Figure 4-6 (and others). What do the different lines represent? Provide the necessary labels. Similarly, provide the necessary labels for Figures 5.7 thru 5.89.
17. Were there any outliers in the evaluation, and if so, what was their disposition?

# SIEMENS

September 24, 1999  
NRC:99:042

Document Control Desk  
ATTN: Chief, Planning, Program and Management Support Branch  
U.S. Nuclear Regulatory Commission  
Washington, D.C. 20555-0001

## **Request for Review of EMF-2209(P) Revision 0, "SPCB Critical Power Correlation"**

Ref.: 1. ANF-1125(P)(A) and Supplements 1 and 2, "ANFB Critical Power Correlation," Advanced Nuclear Fuels Corporation, April 1990.

Ref.: 2. EMF-1997(P)(A) Revision 0, "ANFB-10 Critical Power Correlation," July 1998.

Fifteen proprietary and 12 nonproprietary copies of topical report EMF-2209(P) Revision 0, "SPCB Critical Power Correlation" are being submitted to the NRC for review and acceptance for referencing in licensing actions. (NOTE: Three proprietary copies and one nonproprietary copy have been sent directly to Mr. Nageswaran Kalyanam). This topical report presents an improved critical power correlation that was developed to eliminate deficiencies previously noted by the NRC in other SPC critical power correlations (Reference 1 and Reference 2).

Also enclosed are copies of the two references, which are extensively referred to in EMF-2209(P) Revision 0. These copies have been forwarded to Mr. Kalyanam and are provided for the convenience of the reviewer of the subject topical report.

SPC requests approval of this topical report by April 1, 2000, to permit the use of the correlation in support of licensing action on reload fuel. During a meeting with representatives of the Reactor Systems Branch in late August, they suggested that their review would be facilitated if SPC provided a discussion of the topical report. In response to this suggestion, we propose that a meeting be held at the NRC during the week of October 18. The individuals who developed the correlation would explain its unique characteristics, describe its verification and validation data base, and note its improvements over the current SPC critical power correlations.

Some of the information contained in the enclosed topical report is considered to be proprietary to Siemens Power Corporation. As required by 10 CFR 2.790(b), an affidavit is enclosed to support the withholding of this information from public disclosure.

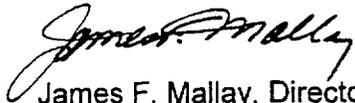
## **Siemens Power Corporation**

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The affidavits originally submitted for the enclosed copies of References 1 and 2 satisfy the requirements of 10 CFR 2.790(b) to support the withholding of this information from public disclosure.

Very truly yours,



James F. Mallay, Director  
Regulatory Affairs

cc: Mr. N. Kalyanam (w/Enclosures)  
Mr. J. L. Wermiel  
Project No. 702 (w/Enclosures)

EMF-2209(NP)(A)  
Revision 1

## SPCB Critical Power Correlation

March 2000

### Nature of Changes

Item	Page(s)	Description and Justification
1.	1-3	Deleted sentence below Table 1.2. <u>Justification:</u> Sentence determined to be unnecessary.
2.	2-4	Corrected A3** to A3* in Equation 2.7 and replaced G with $\bar{G}$ in Tables 2.1 and 2.2. <u>Justification:</u> Correction
3.	2-5 through 2-7	Replaced G with $\bar{G}$ in tables. <u>Justification:</u> Correction
4.	2-23	Corrected reference from Reference 2.1 to Reference 2.2. <u>Justification:</u> Correction
5.	2-26	Inserted legend for test pressures in revised Figure 2.3. <u>Justification:</u> Requested by NRC reviewer.
6.	2-34	Changed reference to ANFB to SPCB in last sentence of 2.6.1.2. <u>Justification:</u> Correction
7.	3-1 and 3-2	Inserted revised Tables 3.1 and 3.2 and changed note and title to Table 3.2. <u>Justification:</u> Requested by NRC reviewer.
8.	3-3	Inserted corrected numbers for $m_2$ , $\sqrt{\beta_1}$ , and $\beta_2$ . <u>Justification:</u> Correction
9.	3-4 through 3-29	Modified title of figures to include number of data. <u>Justification:</u> Requested by NRC reviewer.
10.	4-2	Inserted revised Tables 4.1 and 4.2 to expand the tabular information. <u>Justification:</u> Revised as requested by NRC reviewer.
11.	4-4	Revised Table 4.3 to expand tabular information and moved to page 4-5. <u>Justification:</u> Revised as requested by NRC reviewer.
12.	4-5 through 4-17	Changed pagination due to insertion of larger Table 4.3. <u>Justification:</u> Update
13.	5-14	Referenced Table 5.5 rather than Table 5.9. <u>Justification:</u> Correction

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## 1. Introduction and Summary

This document describes SPCB, Siemens Power Corporation's (SPC) critical power correlation for boiling water reactors (BWR). This correlation is designed for application to steady-state, transient, and Loss of Coolant Accident (LOCA) critical heat flux (CHF) predictions for ATRIUM™ -9B and ATRIUM-10 fuel designs.

With the introduction of advanced spacer designs it was determined that the ANFB (Reference 1.1) critical power correlation (CPR) required modification to properly account for the upstream effects of ULTRAFLOW™ spacers. ULTRAFLOW spacers have swirl vanes at the spacer internal strip intersections which impart a centrifugal force on the two phase mixture. This results in separation of vapor and liquid with the heavier water droplets being deposited on the rod surface, and the steam remaining in the subchannel. The ANFB correlation is comprised of two essential components. One component calculates critical heat flux for axially uniform power conditions. The second component adjusts the calculated heat flux for non-uniform axial conditions. While the correlation could have been modified by changing only the non-uniform axial power corrector, it would have resulted in an increase in the uncertainties associated with the correlation. Therefore, the constants for the correlation were modified to maintain a reasonably low standard deviation.

The SPCB correlation can be used to accurately predict assembly critical power for ATRIUM-9B and ATRIUM-10 fuel designs. The correlation allows accurate prediction of the limiting rod within a bundle and accounts for local spacer effects and bundle geometry on critical power by a set of constants, one constant for each rod in the bundle. These constants are called Additive Constants and are presented in Table 3.10 for the ATRIUM-9B and Table 3.11 for the ATRIUM-10 design. The critical power ratio distribution associated with SPCB is adequately represented with a normal curve using an overall mean of [

] for ATRIUM-9B and an overall mean of [ ] for ATRIUM-10.

---

\* ATRIUM and ULTRAFLOW are trademarks of Siemens.

1.1 **SPCB Data Base**

The SPCB data base is comprised of [ ] steady-state data points taken on [ ] different test assemblies. The axial power shapes of the tests were [ ] peak-to-average cosine and [ ] peak-to-average upskew and downskew. The data base was compiled from tests performed exclusively at the Siemens thermal hydraulic test facility at Karlstein, Germany.

During the correlation development, the data base was divided into a correlating (verification) set of data and a validation data set. Of the [ ] steady-state data points, [ ] were set aside for validation. In addition, another [ ] validation points taken from steady-state critical power tests not included in the data base were analyzed. Transient tests were performed on an ATRIUM-10 test assembly with both a cosine and upskew axial power distribution as part of the correlation validation.

The dryout tests were designed to represent the range of local conditions present in an operating BWR fuel assembly. The data base and correlation address the effects due to operating pressure, mass velocity, enthalpy, axial power profile, and local peaking distribution. Tables 1.1 represents the range of parameters tested. [

] Bounding

values for enthalpy are checked at the plane of boiling transition based on ranges shown in Table 1.2.

**Table 1.1 SPCB Range of Applicability**

Pressure (psia)	571.4 to 1432.2
Inlet Mass Velocity (Mlb/hr-ft <sup>2</sup> )	0.087 to 1.5
Inlet Subcooling (Btu/lbm)	5.55 to 148.67
Design Local Peaking	1.5
Tested Local Peaking	1.45

## 1.2 ***SPCB Comparison to the Data Base***

SPCB has been used to predict the critical power for each data point in the data base. The ratio of the predicted critical power to the measured critical power (Experimental Critical Power Ratio, ECPR) has been determined for each test point and the additional validation points and is used along with the standard deviation of the ECPR as the basis to determine the ability of the correlation to predict critical power. Comparisons of the predicted and measured critical power for both the ATRIUM-9B and the ATRIUM-10 are shown in Figures 1.1 and 1.2, respectively.



1.3 **References**

- 1.1 ANF-1125(P)(A) and Supplements 1 and 2, *ANFB Critical Power Correlation*, Advanced Nuclear Fuels Corporation, April 1990.

## 2. SPCB Correlation

A BWR fuel assembly operates into the annular flow regime. A liquid film on the rod and a steam-water mixture in the center region characterizes this regime. As the flow progresses upward the water film changes because of boiling off and the deposition of water droplets onto the liquid film. A rapid temperature excursion occurs when the liquid film goes to zero thickness. The loss of this liquid film is variously termed dryout, boiling transition, and critical heat flux (CHF).

The SPCB correlation is similar to the ANFB-10 Critical Power Correlation (Reference 2.1) and the ANFB Critical Power Correlation (Reference 2.2). All three correlations use empirical fits to the data that use planar average conditions to predict critical heat flux. The form of the correlations is that developed by Macbeth (Reference 2.3). This correlation form is developed by the transformation from the linear behavior of CHF with inlet subcooling to the linear behavior of CHF with local enthalpy. A plot of inlet subcooling versus critical heat flux (for example, see Figure 2.8) shows that critical heat flux varies linearly with inlet subcooling. For uniform heat flux (Base), this relationship can be expressed

$$q''_{\text{Base}} = A + B(h_{\text{in}}) \quad (2.1)$$

where A and B are functions of pressure and flow and  $h_{\text{in}}$  is the inlet subcooling. However, inlet enthalpy is not an appropriate parameter for a transient application, so the correlation must be converted for local conditions by application of a channel average heat balance. This results in the form

$$q''_{\text{Base}} = \frac{A - B(h_{\text{bt}})}{1 - \frac{B}{G}} \quad (2.2)$$

where G is the mass velocity and  $h_{\text{bt}}$  is the enthalpy at the plane of boiling transition. For the SPCB application another term, C, is added to  $h_{\text{bt}}$ . This parameter is specific to the fuel type being analyzed. Also non-uniform axial power corrector is used which is developed from the

Tong factor (Reference 2.3) used in the analysis of BWR core thermal-hydraulic behavior. This corrector is based on a mass balance on the liquid film and has the form

$$F = \frac{\Omega}{q''_{\ell_c} (1 - e^{-\Omega \ell_c})} \int_0^{\ell_c} [e^{-\Omega(\ell_c - Z)}] q''(Z) dZ \quad (2.3)$$

In this expression,  $\Omega$  is a function of mass velocity and heat flux gradient,  $q''(Z)$  is the axial heat flux,  $\ell_c$  is the axial plane of interest, and  $Z$  is the position on the fuel rod. [

]

Combining equations 2.2 and 2.3 results in the correlation for a non-uniform (NU) heat flux case,

$$q''_{\text{NU}} = \frac{q''_{\text{Base}}}{F} \quad (2.4)$$

This formulation is the basis for the SPCB correlation.

### 2.1 **SPCB Base Correlation**

Using the Macbeth form of the critical heat flux equation developed above, SPCB Correlation has the following form:



### 2.1.1 Functions of A and B

The terms A and B are applicable to both the ATRIUM-9B and ATRIUM-10. The functions A and B have the form







## 2.2 ***Non-Uniform Axial Heat Flux Factor***

The non-uniform axial power corrector (Tong et al., Reference 2.3) used in the ANFB critical power correlation (Reference 2.2) provides the basis of the non-uniform axial correction factor for SPCB. The non-uniform axial correction factor characteristic modified in SPCB is the empirical factor, " $\Omega$ " (Reference 2.4). In addition, a post-multiplier to the non-uniform axial factor is included to provide an adjustment to better address the impact of non-uniform axial shapes. This adjustment factor is appropriate for the steady-state and transient evaluation processes. [

]

The base non-uniform axial factor is given by:

$$F_{\text{Base}} = \frac{\Omega}{q''_{\ell_c} (1 - e^{-\Omega \ell_c})} \int_0^{\ell_c} \left[ e^{-\Omega(\ell_c - Z)} \right] q''(Z) dZ \quad (2.14)$$

where

- $q''(Z)$  = Axial heat flux
- $Z$  = Axial position on fuel rod
- $\Omega^a$  = Empirical factor (described below)
- $\ell_c$  = Axial position of plane of interest

### 2.2.1 Non-Uniform Factor Corrector

An additional correction is obtained by multiplying the base non-uniform axial factor,  $F_{\text{Base}}$ , by the following pressure, flow, and enthalpy gradient term.

[ ]

---

<sup>a</sup>  $\Omega$  is taken as the [ ]

<sup>b</sup> [ ]

<sup>c</sup> [ ]



---

a [

]

]



### 2.2.2 Gradient Function

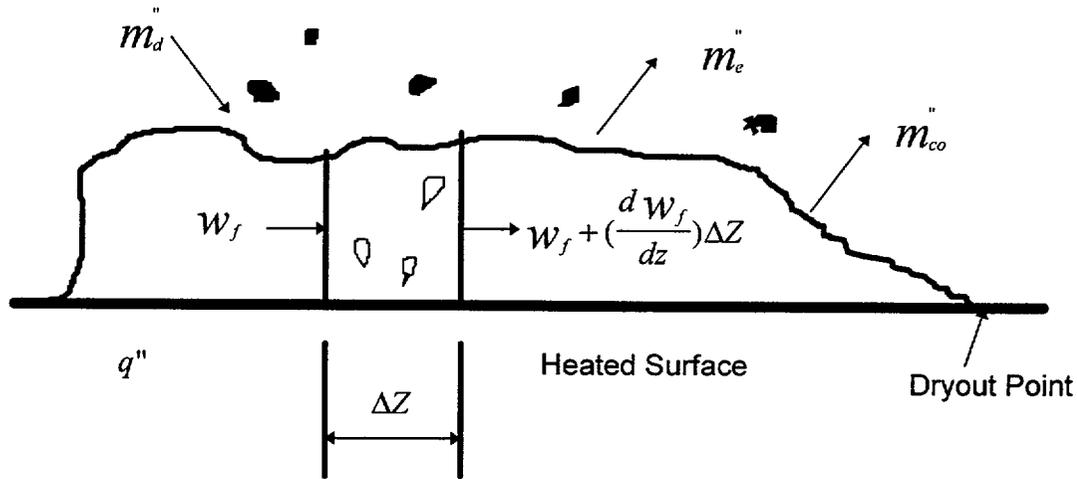
This section describes the GRAD1<sup>a</sup> term and how it is calculated and used in evaluating critical power. A gradient type of term was suggested as being important for dryout in References 2.4 and 2.5.

The influence of the axial heat flux shape is effected by the gradient of enthalpy at the location of interest. More specifically, for a steady-state configuration, the gradient of the axial heat flux shape represents the feature being modeled. Enthalpy is used to transform the heat flux shape gradient behavior to the fluid properties used to predict critical heat flux.

---

<sup>a</sup> [ ]

It is an experimentally determined fact that dryout normally occurs in a region of decreasing heat flux. This is shown by (see Reference 2.5)



- Let
- $w_f$  = liquid flow rate
  - $P_H$  = heated perimeter
  - $m_e''$  = liquid entrainment mass flux
  - $m_{co}''$  = liquid carryover mass flux
  - $m_d''$  = liquid disposition mass flux
  - $A_{x-s}$  = cross section flow area
  - $W_{le}$  = entrained liquid flow rate

$$w_f + \frac{dw_f}{dz} \Delta Z + \frac{P_H \Delta Z q''}{h_{fg}} + m_e'' P_H \Delta Z + m_{co}'' P_H \Delta Z - w_f - m_d'' P_H \Delta Z = 0$$

$$\frac{dw_f}{dz} = P_H \left( m_d'' - \frac{q''}{h_{fg}} - m_e'' - m_{co}'' \right)$$

$$w_f = GA_{x-s} (1 - \langle x \rangle) - W_{le}$$

(2.19)

If one assumes that the occurrence of dryout happens when the film flow gradient is zero, then

$$\begin{aligned} \frac{dw_f}{dZ} &= 0 \\ q_c'' &= h_{fg}(m_d'' - m_e'' - m_{co}'') \\ m_e'' &= m_{co}'' = 0 \\ q_c'' &= h_{fg}m_d'' \end{aligned} \tag{2.20}$$

Therefore, the spatial derivation of the flow gradient is:

$$\frac{d^2w_f}{dZ^2} = P_H \left( \frac{dm_d''}{dZ} - \frac{1}{h_{fg}} \frac{dq''}{dZ} \right) > 0 \tag{2.21}$$

Normally,  $\frac{dm_d''}{dZ} < 0$  as dryout is approached since the amount of liquid is decreasing.

Therefore,  $\frac{dq''}{dZ} < 0$  for upstream dryout to occur.

The correlation uses the gradient in the evaluation of the post-multiplier to the non-uniform axial factor, as expressed earlier. The value of gradient is determined for every node. The gradient is based on the Equation 2.22.

$$\text{Grad1} = f \left( \frac{\partial^2 h}{\partial z^2} \right) \tag{2.22}$$

where

h represents the enthalpy (Btu/lbm) at node j

z represents the axial elevation (ft) at node j

[

]

[

]

### 2.3 *Radial Heat Flux Distribution (Rod Centered Local Peaking Function)*

The function C in Equation 2.2 includes the parameter FEFF. The FEFF parameter characterizes the local peaking factor effect on the bundle critical power and is retained from Reference 2.1 and 2.2 and is defined in the same manner. This section describes how the FEFF calculation is applied to ATRIUM-10 and ATRIUM-9B fuel assemblies. The critical power varies inversely with FEFF. That is, as FEFF increases in value, the critical power decreases in value. FEFF has two parts. One part depends solely on the peaking factors of the rod of interest and its immediate neighbors. The other is termed an Additive Constant,  $\ell$ , which accounts for other local effects from spacing and geometry. The Additive Constant is determined from the experimental data. The definitions of FEFF and examples for several rod locations, including rods located adjacent to part-length rods as would be observed for ATRIUM-10 are discussed below.

The portion of FEFF that depends on local peaking distribution is termed FEFFO. FEFFO for the  $j^{\text{th}}$  rod is calculated from the equation

┌

└



### 2.3.1 FEFFO for Corner Rods

Corner rods in a lower lattice of an assembly are adjacent to three fueled rods. This is illustrated as



### 2.3.2 FEFFO for Side Rods

Side rods could be adjacent to fueled rods and are illustrated as

SPCB Critical Power Correlation

---



Similarly, with the unheated portion in a  $k$  position, Equation 2.26 becomes



### 2.3.3 FEFFO for Interior Rods

Interior rods in lower lattices of an ATRIUM-10 fuel assembly are adjacent to other heated rods. In the lattice that considers the plenum of the part-length rod, one rod position is treated as unheated. In the lattice above the top of the part-length rod, one rod position continues to be treated as unheated. Interior rods adjacent to the ATRIUM water canister are addressed in Section 2.3.4.

The rod configuration examined for an interior rod is illustrated as

$$\begin{array}{ccc}
 k & j & k \\
 j & i & j \\
 k & j & k
 \end{array}$$

The application of Equation 2.23 for rod  $i$  becomes





[

]

#### 2.3.4 FEFFO for Interior Rods Adjacent to the ATRIUM Water Canister

The essential character for rods adjacent to the ATRIUM water canister is similar to the character for rods adjacent to the side (Section 2.3.2). That is, fewer rods are taken into consideration in both the numerator and the denominator of Equation 2.14. For the lower lattice of the ATRIUM-10 design, rods in the middle of the channel see three  $j$  rods and two  $k$  rods, similar to the side rods described in Section 2.3.2. Interior rods adjacent to the middle rod see three  $j$  rods and three  $k$  rods, while rods on the corner of the ATRIUM water canister see four  $j$  rods and three  $k$  rods. The calculation for FEFFO corresponding to these three cases is

---

$$\begin{array}{ccc} j & i & j \\ k & j & k \end{array}$$







### 2.3.5 Weighting Factors

The weighting factors used in Equation 2.22 of Section 2.3 determined in the work reported in Reference 2.1 continue to be appropriate and have not been modified.

### 2.3.6 Bundle Geometry/Spacer Effects (Additive Constants)

Spacers and bundle geometry influence the critical power behavior of the bundle. [

] These

[ ] are termed the Additive Constants,  $\ell$ . Additive Constants can be considered as a flow/enthalpy redistribution characteristic for a given bundle or spacer design.



[

]

The described averaging process ensures that the ECPR (ratio of calculated critical power to measured critical power, sometimes abbreviated CPR) is always 1 for the set of experiments used to determine the Additive Constants.

Once values of  $FEFF(i)$  are available, critical power can be determined on a rod-specific basis. The critical bundle power is the critical power calculated based on the limiting rod  $FEFF$ . The averaging process for the Additive Constants can yield values of  $FEFFBT$  that are lower than the limiting  $FEFF$ . All rods with an  $FEFF(i)$  exceeding the  $FEFFBT$  are considered to be in boiling transition. The maximum  $FEFF$  value for an assembly is determined using the Additive Constants and local peaking of the assembly. This maximum  $FEFF$  may exceed the  $FEFFBT$  for some test sections. Using this maximum value of  $FEFF$  provides an appropriate view of the mean ECPR and standard deviation characteristic of the population. The observation that some assemblies will have some rod locations where actual  $FEFF$  exceeds  $FEFFBT$  provides for conservatism in the application of the SPCB correlation; i.e., more rods would be predicted to be in boiling transition.

#### 2.4 ***SPCB Correlation Behavior***

The SPCB critical power correlation was investigated functionally to ensure smooth functions and no discontinuities. Section 2.4.1 describes the functional behavior of the major

components of the correlation. The correlation was also investigated for its behavior over a wide range of conditions; this is described in Section 2.4.2.

#### 2.4.1 Functional Behavior of Major Functions Within SPCB

Functions A and B are smooth and have a weak dependence on pressure but a strong dependence on flow. Figure 2.1 and Figure 2.2 show the behavior of the A and B functions respectively. The symbols are based on pressures between 600 and 1400 psi.



Equation 2.1 shows that the function  $\left[ \left( 1 - \frac{B}{G} \right) \right]$  in the correlation. This term is always positive and does not cause any discontinuity. Figure 2.3 shows the behavior of this term. The symbols in Figure 2.3 account for a range of pressures (600 - 1400 psi). [

]

Note that functions A and B are similar to the functions A and B described in References 2.1 and 2.2.

#### 2.4.2 Overall Behavior of SPCB

The critical power calculated by the SPCB correlation behaves well throughout its range of validity. This section provides results of sensitivity studies for critical power with respect to flow, pressure, inlet subcooling, FEFF, and axial power shape.



### **Pressure**

Figures 2.6 and 2.7 show the behavior of SPCB with pressure. These figures show that pressure is only a minor contributor to critical power. The reduction in critical power with increasing pressure becomes significant at higher flow rates. [

]



### **Inlet Subcooling**

Figures 2.8 and 2.9 show the gain in critical power with increasing subcooling reduces with a reduction in flow rate. The figures show a nearly linear impact of inlet subcooling on critical power. [

]



**FEFF**

The effect of FEFF on critical power is shown in Figures 2.10 and 2.11. [

]



### Axial Power Profile

Figure 2.12 shows a sequence of simulated axial power profiles with peaks varying in both location and absolute magnitude. The corresponding changes in assembly critical power with respect to the variation in axial power shape are shown in Figures 2.13 and 2.14 for five different inlet flow rates. The sensitivity of critical power with respect to the variation of axial power profile is captured by the correlation through the non-uniform axial factor and through the gradient parameter. [

]

## 2.5 ***Additive Constants***

Additive Constants were determined using the procedure described in Section 2.3.6. These were determined for the ATRIUM-9B and for the ATRIUM-10 fuel assemblies. The verification data was used to determine the Additive Constants; the combined verification and validation data were used to determine the uncertainty of Additive Constants. The Additive Constants for

the ATRIUM-9B fuel assemblies are given in Table 3.10; those for the ATRIUM-10 are given in Table 3.11.

## 2.6 ***Correlation Range and Applicability***

Dryout tests are performed with electrically heated test assemblies. The test assemblies have controls for power, inlet flow, pressure, and inlet subcooling. The specified test parameters are flow, pressure, and subcooling. Determining the power at which dryout occurs is the desired test result. The conditions of the test are used to determine a dryout power. The calculated dryout power divided by the measured power defines the ECPR. In addition, the calculation determines fluid conditions at every location of the bundle.

### 2.6.1 Mass Velocity

The range of applicability for nodal mass velocity at the plane of boiling transition is presented in Table 1.2. [

]

#### 2.6.1.1 Steady-State Core Monitoring

##### High Mass Velocity Limit

If the nodal mass velocity exceeds the high mass velocity applicability limit, an overly optimistic critical heat flux for the node might be predicted because of using the correlation beyond its test range. To avoid this situation and to provide a conservative estimate of the bundle critical power ratio, assemblies with mass velocities greater than the high mass velocity limit are analyzed with the mass velocity conservatively reduced to the high mass velocity limit. This results in conservatively high enthalpy and quality distributions in the bundle and the use of the SPCB correlation within its range of applicability to produce a conservative CHF and bundle critical power ratio (CPR).

### Low Mass Velocity Limit

The critical power calculation is not performed for a bundle with a nodal mass velocity below the low mass velocity applicability limit. Appropriate messages are printed in calculational output.

#### 2.6.1.2 Transient $\Delta$ CPR Analysis

The  $\Delta$ CPR during a transient is the difference between the steady-state CPR before the transient and the minimum CPR during the transient. The transient calculation is performed with an initial assembly power that results in boiling transition (critical heat flux ratio = 1.0) at the worst point throughout the transient simulation. The computer program checks the coolant conditions at the time of boiling transition against the SPCB applicability limits.

### High Mass Velocity Limit

If the nodal mass velocity exceeds the high mass velocity limit at the worst point in the transient, CHF is calculated with both the actual nodal mass velocity, and again with the nodal mass velocity set to the critical power correlation high mass velocity limit. The transient CHF is determined from the more conservative of the two calculations.

### Low Mass Velocity Limit

If the nodal mass velocity is below the low mass velocity limit at the point of boiling transition, the transient CHF is determined from the Hench-Levy correlation (Reference 2.8).

#### 2.6.1.3 MCPR Safety Limit

### High Mass Velocity Limit

The same logic that is applied in the steady-state core monitoring is used for the minimum critical heat flux ratio (MCHFR) node in the MCPR safety limit calculation. The difference is that the resultant lower CHF is used to determine the number of rods in boiling transition rather than the bundle CPR.

### Low Mass Velocity Limit

If the MCHFR nodal mass velocity is below the low mass velocity limit, every rod in the bundle is assumed to be in boiling transition.

### 2.6.2 Enthalpy

The range of applicability for nodal enthalpy at the plane of boiling transition is presented in Table 1.2 as a function of nodal mass velocity. These ranges represent the boiling transition enthalpies envelope observed during SPC testing. Because the boiling transition enthalpy is a primary hydraulic parameter that characterizes the bundle CHF performance for the current hydraulic conditions and the neutronic power distribution within the bundle, specific checks are made within the SPC methodology for exceeding these limits.

#### 2.6.2.1 Steady-state Core Monitoring

### High Enthalpy Limit

If the boiling transition nodal enthalpy exceeds the high enthalpy applicability limit, dryout is assumed to occur when the bundle power is elevated to produce the boiling transition nodal enthalpy equal to the high enthalpy applicability limit. Even though the SPCB correlation used at the high enthalpy applicability limit would predict margin to dryout, no credit is taken and the CPR is limited by the high enthalpy applicability limit.

### Low Enthalpy Limit

If the boiling transition nodal enthalpy is below the low enthalpy applicability limit, the bundle enthalpy and corresponding quality distributions are artificially increased to compute a CHF corresponding to a boiling transition nodal enthalpy within the correlation applicability limits. Because CHF decreases with increasing enthalpy, this results in a conservative CHF based on the use of the SPCB correlation within its range of applicability. This CHF is then used in the critical power calculation for the bundle.

### 2.6.2.2 Transient $\Delta$ CPR Analysis

#### High Enthalpy Limit

If the boiling transition nodal enthalpy exceeds the high enthalpy applicability limit, the transient simulation is repeated with a lower radial power factor (higher initial critical power ratio) until the worst point in the transient results in a nodal enthalpy below the high enthalpy limit. This treatment results in a conservative transient simulation because the hot bundle will not experience boiling transition (i.e., minimum critical heat flux ratio  $> 1.0$ ) and the SPCB correlation is applied within its range of applicability.

#### Low Enthalpy Limit

If the boiling transition nodal enthalpy is below the low enthalpy applicability limit, the transient CHF is determined from the Hensch-Levy correlation (Reference 2.8) provided the calculated CHF from Hensch-Levy is greater than the calculated CHF from the SPCB correlation; otherwise, the bundle enthalpy and the corresponding quality distributions are artificially increased to compute a CHF corresponding to a boiling transition nodal enthalpy that is within the correlation applicability limits. Because CHF decreases with increasing enthalpy, this results in a conservative CHF, which is based on the use of the critical power correlation within its range of applicability.

### 2.6.2.3 Safety Limit

#### High Enthalpy Limit

If the MCHFR nodal enthalpy is above the high enthalpy limit, every rod in the bundle is assumed to be in boiling transition.

#### Low Enthalpy Limit

If the MCHFR nodal enthalpy is below the low enthalpy limit, the enthalpy and quality distributions are artificially increased, as in the steady-state core monitoring calculation to determine a conservative CHFR. This CHFR is then used to compute the number of rods in boiling transition.

### 2.6.3 Pressure

The range of applicability for pressure is presented in Table 1.1. If the pressure falls outside this range, appropriate messages are printed and the calculation is stopped.

### 2.6.4 Inlet Subcooling

The test range for inlet subcooling is presented in Table 1.1. The SPC methodology checks the inlet subcooling against this range; if the subcooling falls below the test range minimum, the calculation is stopped. If the subcooling exceeds the test range maximum, the inlet subcooling is set to the maximum subcooling limit.

## 2.7 ***SPCB Application to Other Fuel Designs***

The SPCB Critical Power Correlation performs well for the ATRIUM-9B and ATRIUM-10 fuel designs. The SPCB correlation may also be applicable to other vendor fuel designs or future SPC fuel designs which have design changes influencing the critical power characteristics. The performance of the SPC correlation for other vendors' fuel designs or future SPC fuel designs with different critical power performance requires appropriate assessment, determination of uncertainties, and determination of boundaries. With sufficient measured data, including a broad range of flows, pressures, subcoolings, axial power shapes, and local peaking configurations, the process used for determining Additive Constants for the ATRIUM-9B or ATRIUM-10 fuel can be directly applied.

With data that are calculated based on an alternative critical power correlation, then the process described in Reference 2.6 for ANFB and submitted as one generic process in Reference 2.7 could be used to obtain appropriate characterization. The use of the generic process in Reference 2.7 requires the use of the appropriate ratio of ECPR standard deviation to Additive Constant standard deviation. [

]

## 2.8 ***References***

- 2.1 EMF-1997(P)(A) and Supplement 1, *ANFB-10 Critical Power Correlation*, Siemens Power Corporation, July 1998.
- 2.2 ANF-1125(P)(A) and Supplements 1 and 2, *ANFB Critical Power Correlation*, Advanced Nuclear Fuels Corporation, April 1990.

- 2.3 L. S. Tong, et al., "Influence of Axially Non-Uniform Heat Flux on DNB," Chemical Engineering Progress Symposium Series, No. 64, V 62, 1966.
- 2.4 J. G. Collier, *Convective Boiling & Condensation*, Second Edition, McGraw Hill, 1981.
- 2.5 R. T. Lahey, Jr. and F.J. Moody, *The Thermal Hydraulics of A Boiling Water Nuclear Reactor*, Second Edition, ANS Monograph, 1993.
- 2.6 EMF-1125(P)(A) Supplement 1, Appendix C, *ANFB Critical Power Correlation Application for Co-Resident Fuel*, Siemens Power Corporation, August 1997.
- 2.7 EMF-2245(P), *Critical Power Correlation Application for Co-Resident Fuel*, Siemens Power Corporation, July 1999.
- 2.8 NRC-IC-99-022, *Modifications to Procedures for Use of XCOBRA-T*, June 10, 1999.

### 3. Statistical Analysis of SPCB Critical Power Data

The SPCB data statistics discussed in this section include descriptive statistics for the data set, an evaluation of the distribution characteristics, figures of ECPR with respect to correlation parameters, and descriptive statistics for Additive Constants and Additive Constant Uncertainty.

The next section addresses the validation data separately from the combined data.

#### 3.1 *SPCB Descriptive Statistics*

Table 3.1 shows the mean ECPR, standard deviation of the mean and number of data by test section. Additional information in the table includes the fuel design represented (ATRIUM-9B or ATRIUM-10) and the axial power shape represented (Cosine, Downskew, or Upskew).



Higher moments for the SPCB analysis of ECPR are computed and results are presented for the following equations. Reference 3.1 provides the relationships for computing the higher order moments. These higher order moments include the third moment about the mean and the fourth moment about the mean and are given by

$$m_3 = \frac{\sum_{i=1}^n (x_i - \bar{x})^3}{n}$$

Third moment about mean

$$m_4 = \frac{\sum_{i=1}^n (x_i - \bar{x})^4}{n}$$

Fourth moment about mean

Similarly, the second moment is given by

$$m_2 = \frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n}$$

Second moment about mean

A measure of skewness is given by:

$$\sqrt{\beta_1} = \frac{m_3}{m_2^{1.5}}$$

Skewness measure

A measure of kurtosis is given by

$$\beta_2 = \frac{m_4}{(m_2)^2}$$

Kurtosis measure

The values of the measures with respect to ECPR are

$m_2$	=	0.000491
$m_3$	=	0.000000
$m_4$	=	0.000000680450
$\sqrt{\beta_1}$	=	0.004488
$\beta_2$	=	2.83

These statistics are close to those of a normal distribution. The distributional character of the SPCB critical power ratios are viewed in Figures 3.1 and 3.2. Figure 3.1 is a histogram of the frequency of occurrence of CPR while Figure 3.2 shows that the distribution generally follows the linear characteristics of a normal distribution. As is shown later, the correlation over predicts the number of rods in boiling transition. The behavior of the CPR distribution is adequately represented by normal distribution characteristics for the safety limit analysis.



### 3.2 ***Statistical Tests***

The SPCB data were tested using Lilliefors test for normality (Reference 3.2). The test indicates that at the one percent significance level the assumption of normality cannot be rejected.

### 3.3 ***SPCB Correlation Behavior***

Figures 3.3 through 3.8 show the SPCB ECPR values graphically with respect to mass flow rate, boiling transition enthalpy, pressure, FEFF, and other parameters.

SPCB Critical Power Correlation

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### 3.4 ***Statistics by Subgroups***

The descriptive statistics for the overall data can be examined by several subgroups of data. Mean, standard deviation, and number of data are presented. This section covers all data. Validation data is separated out in Section 4.

#### 3.4.1 Mass Flow Rate

Table 3.3 shows the results of examining representative mass flow rate groups from [ ]



### 3.4.3 Enthalpy at Boiling Transition

Table 3.5 shows the results of examining representative boiling transition enthalpies from [ ]].



### 3.4.5 Axial Offset

Table 3.7 gives the results of examining representative axial offset values.





### 3.4.7 Mass Flow Rate and Enthalpy Groups

Characteristics for the SPCB ECPR can be examined by considering data within different ranges of flow and inlet subcooling. Table 3.9 shows this characterization based on eleven flow groups and three inlet subcooling ranges.

### 3.5 *ECPR - Mass Flow Plots*

The overall view of ECPR versus mass flow is shown in Figure 3.3 and no trend is observed. Figures 3.8 through 3.35 show the behavior of ECPR with mass flow for each test section. Within individual tests, some tests over predict high flow and some under predict high flow. Because the evaluations are performed using the FEFF calculated for the test section based on the composite Additive Constants, some test sections provide under predictions for many flows. Figure 3.36 shows the combined behavior of ECPR with mass flow for the upskew data.

**Pages 3-15 through 3-28 are proprietary in toto.**

### 3.6 ***Additive Constant Statistics***

The Additive Constants for the ATRIUM-9B and ATRIUM-10 fuel designs were developed using the process summarized in Section 2. This section presents the determination of the Additive Constants and uncertainty and describes the conservatism for the SPCB critical power correlation. Tables 3.10 and 3.11 provide the Additive Constants for the ATRIUM-9B and ATRIUM-10 fuel designs.

3.6.1 Additive Constant Determination

The steps summarized in Section 2.3.6 are provided here in more detail.

**Step 1: Identify Rods in Boiling Transition**

[

]



**Step 2: Determine FEFBT for each Data of Interest**

[

]

[

]

[  
 ]

### Step 3-6: Additive Constant Determination

[

]

The results of evaluating the Additive Constants for use with the ATRIUM-9B and ATRIUM-10 fuel designs are presented in Tables 3.10 and 3.11.

#### 3.6.2 Additive Constant Uncertainty

Determining Additive Constants Uncertainty provides for combining the standard deviations of the FEFFBT using a propagation of error method. This process employs the approach used for ANFB. Two major factors contribute to the overall uncertainty of the Additive Constants. These are 1) within test variability and 2) between test variability. The process includes contributions from the cosine axial tests and the upskew/downskew axial tests. The propagation of error method used is implemented by taking the square root of the sum of the squares of the errors. Errors in determining the uncertainty of the Additive Constants include the standard deviation of the FEFFBT for each test section and the difference between a specific value of FEFFBT and FEFF for a rod observed in boiling transition. Weighting factors of the number of rods observed in boiling transition and the number of tests are incorporated

into the process to determine the total standard deviation of the Additive Constants.

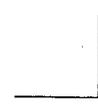
Specifically, where

N	=	Number of test bundles
M	=	Number of rods in these test bundles
FEFFBT	=	Best estimate FEFF for bundle
DFBT(i)	=	Standard deviation of FEFFBT for test bundle i
NOEX(i)	=	Number of experiments with test bundle i
NBT(J,i)	=	Number of boiling transition detected on rod j of test bundle i
DELTA(J,i)	=	Difference between FEFFBT and FEFF of rod j observed in boiling transition in test bundle i
DELTEX	=	Total standard deviation in Additive Constants
NTOT	=	Total number of experiments for all tests
NBTOT	=	Total number of rods in boiling transition

The Additive Constant uncertainty is calculated using



Evaluating the ATRIUM-9B data based on the verification data statistics (shown in Table 3.13) results in an Additive Constant uncertainty of [ ] for the ATRIUM-9B. Similarly the evaluation of the ATRIUM-10 data based on the verification data statistics results in an Additive Constant uncertainty of [ ] for the ATRIUM-10. The impact of the validation data needs to be included. This is accomplished by evaluating the validation data set for its FEFF values for each validation data point, then including the values in the mean and standard deviation of FEFF for each test section. To maintain a single process between ATRIUM-9B and ATRIUM-10, this process is chosen rather than using a replicate point process as was used for the ANFB-10 correlation.



Using the values of composite values FEFFBT and Standard Deviation of FEFFBT (Table 3.14) for the respective fuel designs, the overall uncertainty for Additive Constants is determined to be [ ]

### 3.6.3 High Local Peaking

A series of dryout tests were performed on the ATRIUM-9B and the ATRIUM-10 to determine the effect of high local peaking on the Additive Constant methodology. Because of physical manufacturing limits on the test section heater rods, the highest local peaking attained was 1.45. The axial power profile for the test assembly was 1.4 peak to average cosine.

[

]



The Additive Constant uncertainties determined by the Additive Constant methodology are  
[ ] While this conclusion may be drawn from examining the plots, a statistical analysis provides a more rigorous process for demonstrating this. Therefore, a Bartlett test (Reference 3.3, page 802) was applied based on data for each test over the same range of test conditions. The Bartlett test considers the null hypothesis that the variance of each data set is an estimate of the same population variance. The result of this test affirms that the null hypothesis cannot be rejected.

[

]

The uncertainty used for rods peaked greater than 1.5 is then determined by the square root of the sum of the squares of the Additive Constant uncertainty and its respective incremental uncertainty. This is the same method used in the approved ANFB-10 methodology (Reference 3.4).

#### 3.6.4 SPCB Conservatisms

The Additive Constants for the ATRIUM-9B and ATRIUM-10 designs are applied to the local peaking patterns for the test assemblies [

]

[

] A further measure of the conservatism of the SPCB correlation is observed by comparing the FEFF values for the assembly with the FEFFBT that places the ECPR of the assembly at 1.0. This allows the determination of the number of rods calculated to be in boiling transition for each data of each test section. Comparing the calculated number of rods in boiling transition with the number of rods in boiling transition, an over estimate of the number of rods in boiling transition is determined. The ratio of the number of rods calculated to be in boiling transition to the number of rods observed to be in boiling transition is equal to [ ] when using the SPCB critical power correlation.

### 3.7 ***SPCB Predictions Compared with Measurements***

The predicted values of critical power are compared with the measured values and presented in Figure 3.39.

3.8 **References**

- 3.1 G. J. Hahn, S. S. Shapiro, *Statistical Models in Engineering*, Wiley, 1967.
- 3.2 H. W. Lilliefors, *On the Kolmogorov-Smirnov Test for Normality with Mean and Variance Unknown*, Journal of the American Statistical Association, Vol. 62, June 1967.
- 3.3 *Statistical Methods for Nuclear Material Management*, NUREG/CR4604, PNL-5849, December 1988.
- 3.4 EMF-1997(P)(A) and Supplement 1, *ANFB-10 Critical Power Correlation*, Siemens Power Corporation, July 1998.





Graphically, the predicted versus measured critical power for ATRIUM-9 Validation data is shown in Figure 4.1.

While the behavior of the ECPR with flow is shown in Figure 4.2.





#### 4.1.2 Comparison ATRIUM-10 Verification and Validation Data



The statistical comparison of the ATRIUM-10 verification and validation data sets is presented in Table 4.3.





The behavior of ECPR vs Flow is shown in Figure 4.4.

#### 4.2 *Validation with Alternate Design*

The SPCB critical power correlation is further validated by evaluating the critical power performance for [

] The characteristic swirl vanes of the ATRIUM-10 are incorporated on the spacer design used in the validation test and the rod diameter is identical to the ATRIUM-10 design. The ATRIUM (central water canister) remains in the same position. Part-length rod positions differ in the ATRIUM-10 with [ ] rods and the ATRIUM-10P with

[ ] All part-length rods occur one row in from the channel. The data set contains 316 data points. The result of the tests shows that the mean ECPR is [

] Figure 4.5 shows the predicted versus measured critical power for these tests. Figure 4.6 is an example of one of the test assembly's critical power versus subcooling plots.

SPCB Critical Power Correlation

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#### **4.3 *Evaluation of Transient Critical Power Data***

An industry-accepted standard in BWR transient methodology is that steady-state dryout correlations are appropriate to use in transient methodology. Transient dryout tests with cosine and upskew profiles were performed to reconfirm this for the ATRIUM-10 when using the SPCB critical power correlation.

The ATRIUM-10 [ ] transient critical power tests were performed for test assembly 17.8 (cosine power shape), test 29.5 (upskew axial power shape), and 48.1 (upskew axial power shape). Thirty-two transient tests were evaluated: [ ] For comparison, the steady-state performance of the ATRIUM-10 as measured and as predicted by SPCB is given in Figure 4.7. The SPCB correlation correlates well with the respective tests.

[

]

The transient tests of interest are both simulated load rejection without bypass (LRNB) events that consist of power and pressure ramps and flow decay; and simulated pump trip events that consist of flow decay and power decay. The flow, pressure, and power are controlled by a function generator. The forcing functions were programmed to produce the transient rod surface heat flux typical of the various events. Figure 4.8 shows the forcing function characteristics for a typical LRNB test while Figure 4.9 shows the comparable forcing function characteristics for a typical pump trip event.





Figure 4.10 illustrates the response of thermocouples attached to the interior of the heater rod tubing. Initially, the clad temperature rises in response to the pressure and power ramps. The transition point, where the heat transfer mode changes from nucleate to film boiling, is characterized by a sudden, rapid increase in clad temperature. This point defines the onset of boiling transition and shows that boiling transition has occurred. Boiling transition occurs slightly upstream of [ ] In the STS-17.8 tests, boiling transition normally occurred [ ] In the STS-29.5 and 48.1 tests, it occurred [ ]

Parameters monitored during the tests include power, inlet flow, system pressure, inlet temperature, [

]

The SPC transient thermal hydraulic code XCOBRA-T (References 4.2 and 4.3), is used to predict the transient test results using the SPCB steady-state critical power correlation. XCOBRA-T calculated the fluid conditions axially at time steps as small as [ ]. The test power forcing function provides the boundary condition of power, which appears immediately as heat flux (i.e., no time delay) from the surface of the rods. The CHF is calculated at each axial position and time step, then compared to the corresponding rod heat flux. The ratio of the critical heat flux to the rod heat flux is CHF<sub>R</sub>. A MCHF<sub>R</sub> of unity during the transient signifies boiling transition. Although applying the steady-state critical power correlation is considered conservative, SPCB is a best fit correlation, and for a given steady-state condition shown to be in boiling transition by test, the correlation may under- or overpredict a boiling transition state within the range of defined uncertainties. Thus, during

transient test conditions, dryout may not be predicted for all cases because of the defined uncertainties.

Thirty-two transient tests modeling the ATRIUM-10 geometry in simulated LRNB or pump-trip events were evaluated. The two STS-17.8 tests had nearly the same forcing functions, with only the initial power level differing. The nine STS-29.5 tests consisted of six 100 percent flow cases and three 80 percent flow cases. Within these groups, there was a variation in inlet subcooling. The 21 STS-48.1 tests consisted of nine LRNB tests with five LRNB at 100 percent flow and four LRNB tests at 80 percent flow, and 12 pump-trip tests. The 12 pump-trip tests included eight at 100 percent flow and four at 80 percent initial flow. The initial subcooling varied among these tests. Table 4.4 summarizes initial state conditions for all the transient tests.



---

\* At elevation of minimum CHF.

The XCOBRA-T calculations were performed using nominal Additive Constants. The results using nominal (design) Additive Constants are summarized in Table 4.5. Figure 4.11 compares the measured and calculated time of boiling transition. The comparisons demonstrate that the STS-17.8, STS-29.5 and STS-48.1 transient tests are conservatively predicted. These results validate that Additive Constants can be derived from steady-state tests and applied to transient conditions.

---

\* XCOBRA-T time of BT occurs when CHFR is 1.0.

#### 4.3.1 Conclusions

The XCOBRA-T analyses calculated dryout in the [ ] evaluated at nominal design conditions. When considering uncertainties, all transient results were conservatively predicted. This validation confirms that the use of the SPCB steady-state dryout correlation is appropriate for use in evaluation of transient events. Furthermore, this evaluation provides a validation that Additive Constants can be derived from steady-state tests and applied to transient conditions.

#### 4.4 **References**

- 4.1 EMF-2022, Revision 0, *Correlation Development Guideline*, Siemens Power Corporation, February 1998.
- 4.2 XN-NF-84-105(P)(A) Volume 1 and Volume 1 Supplements 1 and 2, *XCOBRA-T: A Computer Code for BWR Transient Thermal-Hydraulic Core Analysis*," Exxon Nuclear Company, February 1987.
- 4.3 XN-NF-84-105(P)(A) Volume 1 Supplement 4, *XCOBRA-T: A Computer Code for BWR Transient Thermal-Hydraulic Core Analysis Void Fraction Model Comparison to Experimental Data*, Advanced Nuclear Fuels Corporation, June 1988.

## 5. SPCB Data Base

The SPCB data base contains [

] to validate the correlation. All data was taken at the Siemens test facility at Karlstein, Germany.

### 5.1 Facility Description

All dryout testing for the ATRIUM-9B and ATRIUM-10 assembly was performed at the Siemens thermal hydraulic test loop at Karlstein, Germany. Figure 5.1 shows that the thermal hydraulic test facility is a high-pressure-water heat-transfer loop containing a test vessel, as shown in Figure 5.2, with the test bundle and upper and lower bus bars, high-pressure coolers, a direct-contact condenser, a pressurizer, and the main circulation pumps. The test loop is rated at 2683 psi and 680°F. The DC power supply consists of four thyristor controlled rectifier models, each rated at 20,750 amps, with a design power of 15 MW.

The data acquisition system uses a DATA GENERAL MV 7800 computer to sample the analog signals of the loop instrumentation, digitize them, and store the signals on hard disc. The system has 176 channels available and a sample rate of 20 samples per second and channel. After the test, the data is archived on magnetic tapes. Table 5.1 shows the test loop uncertainties.

During the dryout test, the dryout power is determined manually when the temperature of a heater rod thermocouple rises more than [ ] Additionally, after the test, the data obtained from each thermocouple is evaluated to determine the maximum value. The point of data evaluation for critical power is considered to be between 24.6 seconds and 34.2 seconds of the total file record. Dryout is defined to have occurred if the maximum value of the thermocouple reading is more than [ ] than the arithmetic mean value of the first five temperature values from the beginning of the defined time window. If a thermocouple has an increase in temperature of greater than [ ] the thermocouple is defined as defective and excluded from data evaluation.

Using the time of dryout defined from the thermocouple evaluation, the arithmetic mean values of 11 consecutive power measurements are determined. The maximum mean is defined as the critical power.

## 5.2 ***Test Bundle Descriptions***

The dryout test bundles are full array assemblies designed to represent the production fuel assembly as close as possible. The rod bundle is housed in a ceramic liner fabricated from alumina ceramic with a purity of 99 percent or better. The inner dimension of the liner is 5.276 in. with the corners rounded to a radius of 0.39 in. The liner serves to simulate the flow channel and electrically insulate the spacers from each other. The ceramics are housed in a stainless steel outer channel assembly.

The heater rods used in the testing are direct heaters; that is, the current flowing through the rod wall provides the heating. Therefore, the thickness of the heater wall determines the relative power of the rod and the variation in wall thickness determines the axial power profile. The high-powered rods, where critical heat flux is expected to occur, are equipped with thermocouples for dryout detection (see Figure 5.3). The thermocouples are located radially to point to the subchannel of interest and axially about 0.5 in. below the top three spacers of the active length.

### 5.2.1 ATRIUM-9B

The ATRIUM-9B test bundle consists of a square array of rods supported at fixed axial locations by ULTRAFLOW spacers and with one 1.516 in. square cross-section water channel. The array contains 72 full-length rods.

The test bundles have the following characteristics (Table 5.2 summarizes the physical characteristics of the ATRIUM-9B test assembly).

[

]

[

]

Three axial power profiles were tested during the ATRIUM-9B dryout test series. The STS-12, STS-33, STS-37, and STS-40 series were performed on a [ ] peak-to-average chopped cosine axial, the STS-35 series was [ ] peak-to-average downskew axial, and the STS-35 and STS-38 series was performed on a [ ] peak-to-average upskew axial power profile. Figure 5.5 represents the rod axial power profiles.

### 5.2.2 ATRIUM-10

The ATRIUM-10 test bundle consists of a square array of rods supported at fixed axial locations by ULTRAFLOW spacers and with one 1.378 inch square cross section water channel. The array contains 83 full length rods and 8 part length rods.

The test bundles had the following characteristics: (Table 5.3 summarizes the physical characteristics of the ATRIUM-10 test assembly).

[

]

During testing, the test bundle is shimmed to its most conservative lateral position by placing shims on the top three spacers.

Three axial power profiles were tested during the ATRIUM-10 dryout test series. The STS-17 and STS 32 series were performed on a [ ] peak to average chopped cosine axial, the STS-28 series was [ ] peak to average downskew axial, and the STS-29 series was performed on a [ ] peak to average upskew axial power profile. Figure 5.5 represents the rod axial power profiles. For the part length rods, the axial power shape is the same as a full length rod, except that is it truncated at the end of the part length rod.

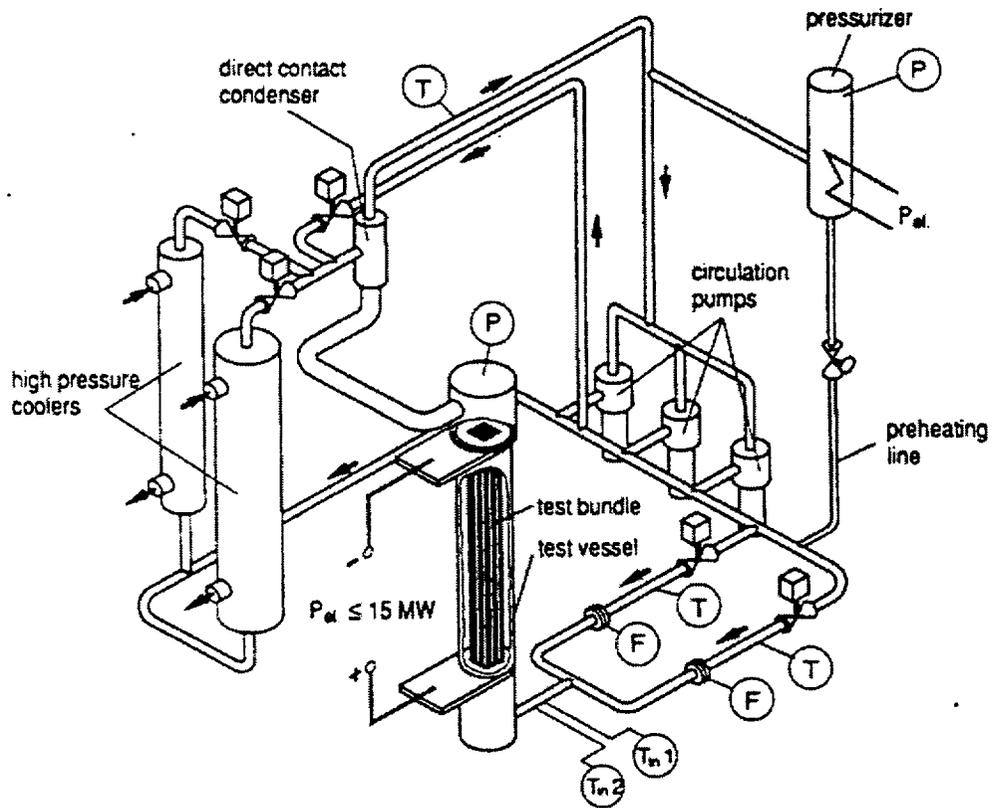


Figure 5.1 Karlstein Thermal Hydraulic Test Loop

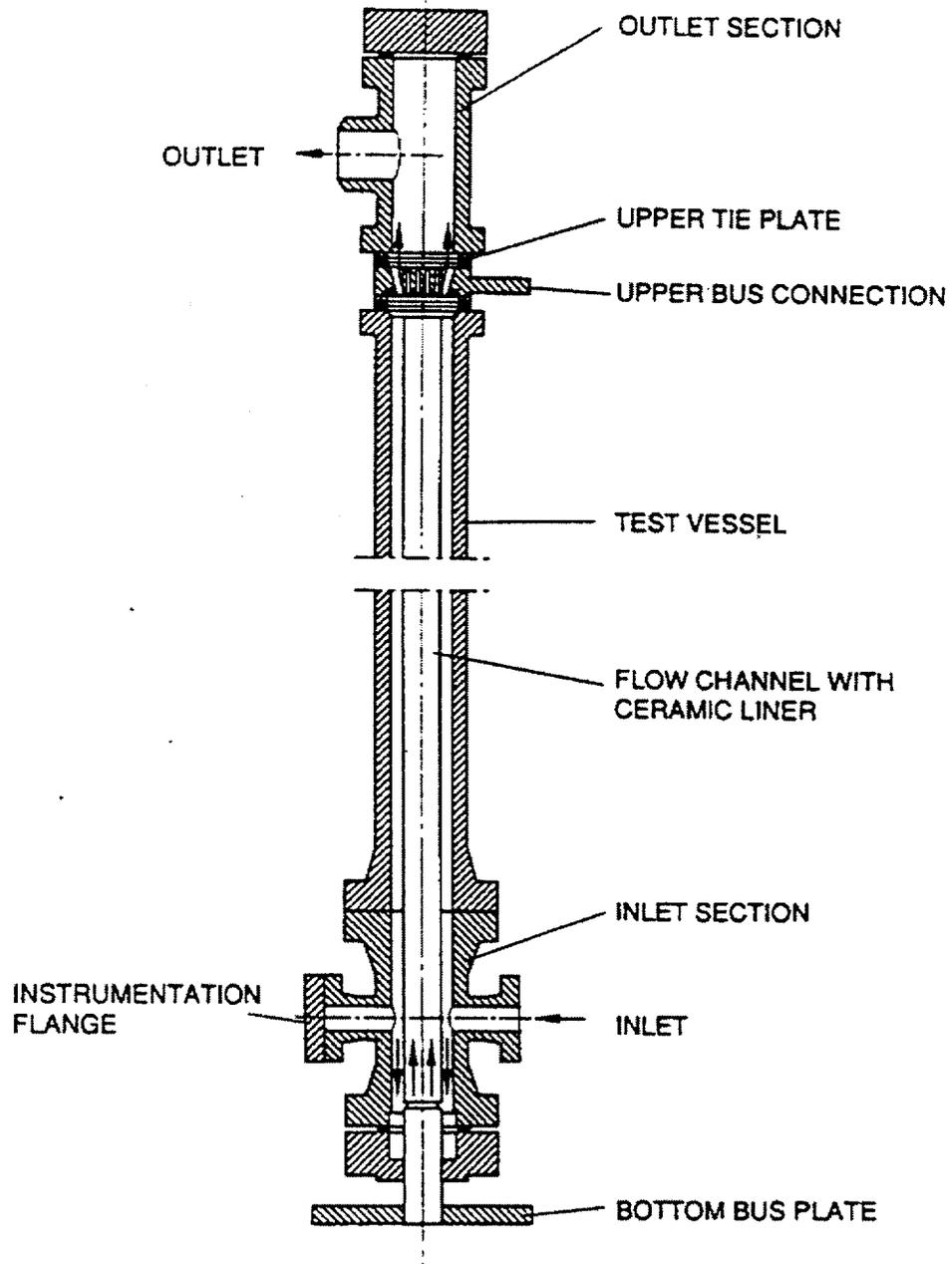


Figure 5.2 Test Vessel









### 5.3 Test Strategy

The development of a dryout correlation requires the acquisition of an appropriate data base, where an appropriate data base is defined as one that fills the applicable domain with acceptable density, displays acceptable uncertainty everywhere, and provides repeatability. This presents a particular challenge for dryout correlation development. Radial peaking, axial power profile, pressure, flow, and inlet subcooling have been considered in developing the testing strategy to ensure that the number of assemblies used in the correlation is sufficient.

#### 5.3.1 Radial Peaking Profiles

A conservative assumption is made in the SPC dryout methodology that any rod position in which a symmetric rod is not driven into dryout is assumed to have been in dryout at its highest local peaking. The usual practice is for the local peaking of the test rods to vary between 0.9 and 1.2, with peaking as low as 0.6 used occasionally. Because the purpose of the variation in local peaking is to determine the dryout characteristics of a particular rod position, no effort is made to simulate any particular neutronic design.

The testing program takes advantage of the symmetry of the test bundle. The ATRIUM-9B bundle has octant symmetry, so that peaking nine individual rods of twelve symmetric positions with five driven into dryout adequately describes the assembly. The rod positions tested were the corner rods, the peripheral rods, the rods in the middle row, and the rods around the internal water canister. The ATRIUM-10 has half-bundle symmetry along the diagonal of the bundle. In all, [ ] All major positions of the fuel assembly were tested.

Specific tests were performed during the testing of the ATRIUM-10 assembly to demonstrate the effect of radial peaking on Additive Constants. The test series STS-17.5 and STS-17.6 peaked rod [ ] respectively. Then STS-32.1 was performed to peak rod [ ] With the completion of these tests, the representative locations in the bundle were driven into dryout at different local peaking factors. To demonstrate that the ATRIUM-9B bundle behaves the same, two tests were run at the same location with a local peaking factor of [ ] Only two tests needed to be performed on the ATRIUM-9B because the purpose was to demonstrate that the

algorithm for the Additive Constant methodology behaved the same for the ATRIUM-9B as for the ATRIUM-10. Section 3.1 of this report documents the statistical results of these tests.

### 5.3.2 Axial Power Profile

Three axial power profiles were tested during dryout testing: [ ] peak to average cosine, [ ] peak to average upskew, and [ ] peak to average downskew (see Figure 5.5). Because cosine power shapes are representative of much of the plant operation they are the most prevalent type of testing; other axial power profiles are used to check the axial power corrector used. Dryout occurs only after the peak of an axial power profile. For the ATRIUM-9 and ATRIUM-10, upskew axial power shapes dryout occurs only under the topmost spacer of the heated length. For a cosine axial power shape, dryout may occur under the top or second from the top spacer of the heated length. The same happens for a downskew axial power shape for a fully rodded bundle; for the ATRIUM-10 the dryout may occur as low as the third spacer from the top. For any fuel assembly, the upskew axial power profile will have less critical power than the cosine axial power shape for the same local peaking, and the downskew axial power shape will have higher critical power than the cosine. In general, for the same peak-to-average power shape, for a fully rodded bundle the increase in critical power of a downskew axial will be about the same as the loss of critical power for the upskew relative to the cosine axial power shape.

The ANFB (Reference 5.1) correlation was developed using uniform axial power data, then the axial power corrector was developed using cosine and upskew data. A uniform axial power profile always results in dryout occurring at the exit of the bundle, and, therefore, would easily provide accurate data on the enthalpy at the plane of boiling transition. Because uniform axial power profile rods were not available for the ATRIUM-9B and ATRIUM-10 assemblies and the manufacture of those rods requires a long lead time, the SPCB was developed by calculating the enthalpy at the plane of boiling transition of each individual case.

### 5.3.3 Thermal Hydraulic Test Conditions

The data base for the ATRIUM-10 was obtained during the ANFB-10 correlation development (Reference 5.2). It contains data over a range of [ ] a subcooling of [ ] and pressures ranging from [ ] The ATRIUM-9B originally had 125 data points taken over a range of 0.05 Mlb/hr to 0.15 Mlb/hr, a subcooling of 8 Btu/lbm to 90 Btu/lbm at a system pressure of 1000 psia. This database was expanded to include the full range of pressures and flows. Table 5.4 summarizes the tests and test conditions used in the development, verification, and validation of the SPCB correlation.

### 5.3.4 Test Design

The methodology developed for performing dryout testing is fairly standard. The testing is performed by setting pressure and flow. The inlet subcooling is then set and the power is slowly increased until dryout is achieved. The inlet subcooling is then decreased or increased and the process is repeated. After one flow condition is tested, the flow is reset to the desired rate and the entire process is repeated. After all inlet subcoolings and flows are tested, the pressure may be changed and testing continued. To ensure that this did not introduce a systematic error, the test process was changed for a few points. In this change, the flow and

power were held constant and the inlet subcooling varied until dryout was reached. This process reproduced the standard test procedure.

Because the dryout test results are somewhat ordered, most errors in the test are immediately evident. When the flow is set, the critical power will vary directly with the inlet subcooling. The slope of the line increases as the flow increases. This may be seen in any of the plots at the end of this section. During the test series for each day, some test points are repeated to ensure reproducibility.

The development of the test plan is dependent on the use of the data. For example, for the validation test, STS-38.3, a test plan as developed in Reference 5.1 was used. Because of the small amount of data available for the ATRIUM-9B, the testing performed for the SPCB correlation included all pressures and flows. Because the data base for the ATRIUM-10 was larger, not only did some tests have all pressures and flows, statistical design of experiments was also used (Reference 5.2).

#### 5.4 **SPCB Data**

The data base for SPCB contains [ ] peaking patterns performed on test sections with cosine, upskew, and downskew axial power profiles for ATRIUM-9B and ATRIUM-10 designs. The correlation data base contains [ ] data points taken over the range of applicability of the SPCB correlation. Of the [ ] data points, [ ] form the information used during the correlation process and [ ] data points validate the correlation. Table 5.5 contains the measured and calculated critical power ratio of the verification and validation data base. Figures 5.6 through 5.89 present the dryout test peaking pattern and its associated inlet subcooling versus critical power plot for both the test data and the SPCB prediction of the test data.

**Pages 5-15 through 5-168 are proprietary in toto.**

5.5 **References**

- 5.1 ANF-1125(P)(A), *ANFB Critical Power Correlation*, Advanced Nuclear Fuels Corporation, April 1990.
- 5.2 EMF-1997(P)(A), *ANFB-10 Critical Power Correlation*, Siemens Power Corporation, October 1998.

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