SCIE-NRC-219-93

TECHNICAL EVALUATION REPORT

-BEACH-

Best Estimate Analysis Core Heat Transfer

A Computer Program for Reflood Heat Transfer During LOCA BAW-10166P, Revision 4

D. A. Prelewicz

Prepared for

U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

November, 1993

SCIENTECH, Inc.
11821 Parklawn Drive
Rockville, Maryland 20852

SUMMARY

BEACH is a B&W Nuclear Technologies computer program for prediction of reflood heat transfer. The program is an adaptation of the RELAP5/MOD2 code with modifications in the reflood heat transfer model. Revision 4 of the BEACH Topical Report was reviewed to determine compliance of the model updates to 10-CFR-50 Appendix K requirements. Significant updates include a revised global reflooding option, referred to as "NEWQUEN", which incorporates a boiling length dependent Weber number and interphase drag modification above the quench front, restoration of the McAdams nucleate boiling correlation originally used in Rev. 0 of the code, modification of the interphase drag coefficient in slug and inverted slug flow regimes based on the Wilson model and a smoothing function to remove discontinuities in the quench node heat transfer. Modifications also include addition of a multi-channel analysis capability, and options to allow cross flow inlet condition void donoring.

B&W Technologies has provided comparisons of BEACH predictions to FLECHT, CCTF, SCTF and REBEKA-6 reflood experimental data. These comparisons, plus the clarifications provided by B&W Nuclear Technologies in response to staff comments, demonstrate that the updated models within BEACH provide best estimates of reflood heat transfer coefficients, and comply with 10-CFR-50 Appendix K requirements. It is therefore recommended that BEACH version 19, which contains the updated models described in Rev. 4 of BAW-10166P, be accepted for use in licensing calculations provided that the "NEWQUEN" reflood heat transfer option is used. Three of the code options used by BEACH, the automated blockage droplet breakup calculation, improved EM fuel pin model and the implicit formulation of the Baker-Just metal-water reaction model, are described in the RELAP5/MOD2-B&W Topical Report, BAW-10164P. Use of these new options in BEACH is contingent upon the approval of Rev. 3 of BAW-10164P.

TABLE OF CONTENTS

TECHNICAL EVALUATION REPORT

BEACH

Best Estimate Analysis Core Heat Transfer

A Computer Program for Reflood Heat Transfer During LOCA

BAW-10166P, Revision 4

1. INTRODUCTION

BEACH is a B&W Nuclear Technologies computer code for the prediction of reflood heat transfer during large break LOCAs. The code is a special purpose usage of the RELAP5/MOD2-B&W[1] code for ECCS evaluation model reflood heat transfer analysis. The previous revision of the BEACH code, Rev. 3[2], was approved for LOCA reflood analysis[3].

Revision 4 of BAW-10166P[4] describes updates to the reflood fluid flow and heat transfer models which improve the post-peak cladding temperature quench front advancement modeling, allow multiple independent reflood channels to be run simultaneously and permit optional multipliers to be used for sensitivity studies. The most significant modification is introduction of a revised global reflood heat transfer option referred to as "NEWQUEN". Predictions of reflood heat transfer data from FLECHT, CCTF, SCTF and REBEKA tests have been performed by B&W Nuclear Technologies to benchmark this revised global reflooding heat transfer option. The modifications to the approved licensing model proposed in Reference 4 are the subject of the review and evaluation documented in this report.

2. BEACH CODE MODIFICATIONS AND ASSESSMENT

The modifications made to the BEACH code can be grouped into three classes. First, there are modifications described in Rev. 4 of the Topical Report (BAW-10166P) which are used in the licensing model. This class includes the "NEWQUEN" global reflooding option and the multi-channel capability.

The second group of modifications will be used in the BEACH licensing model but are described in the RELAP5-B&W computer program Topical Report, BAW-10164P. BEACH is a special application of RELAP5-B&W for reflood heat transfer analysis. Certain common features are described only in the RELAP5-B&W Topical Report. These include an implicit formulation of the Baker-Just metal water reaction model, automated blockage droplet breakup calculation and the fuel pin Evaluation Model (EM) augmentation features, including additional informational edits, unheated fuel rod segments and fuel rod axial expansion.

The third group are user convenience features for conducting sensitivity studies. They will not be used for licensing analysis, but have been included in the code documentation for completeness.

2.1 Licensing Analysis Models

Modifications made to the heat transfer model to improve post-peak cladding temperature quench front advancement are contained in a global reflooding option referred to as "NEWQUEN". Taken together, the modifications described below result in the prediction of decreased carryover of liquid droplets from the core during the later phases of reflooding, i.e. after the clad temperature has peaked. Very conservative predictions of small average droplet diameter and high interphase drag in the previously approved version of BEACH resulted in a very high removal rate of water from the bundle during the later stages of reflood. The liquid inventory of the bundle was then calculated to be low compared to the experimental data. Quench front advancement was slower than measured and in some cases, no advancement was predicted. The revised model predicts a larger average droplet diameter, reduced interphase drag coefficient and greater droplet residence time in the upper part of the bundle. This leads to improved fuel rod cooling by radiation to droplets and retention of more liquid in the bundle. Since the most significant modifications apply only after the boiling length exceeds 0.8 feet, they affect only the later stages of the reflood process.

The following items comprise the "NEWQUEN" global reflooding option:

1. A new calculation of incipient boiling length determines the elevation within the core heat transfer stack at which the incipient boiling temperature is reached. The micro-mesh nodes which bracket the boiling temperature are first determined by a bottom to top search of channel fluid temperatures. Linear interpolation is used to calculate the elevation at which the boiling temperature is reached. An incipient boiling length dependence of the interphase drag shape factor and critical Weber number for droplets are introduced which can affect the results only when the quench front elevation exceeds the incipient boiling elevation by more than 0.8 feet, i.e., the liquid is saturated for some distance below the quench front. Experimental observations by Obot and Ishii[5] are cited which indicate a larger average droplet size when this condition prevails, compared to conditions with subcooled liquid near the quench front. Parameters of the critical Weber number and interphase drag shape factor models were chosen so as to match test data discussed in Appendix G of the Topical Report and in Section 3 below.

2. The interphase drag coefficient in BEACH is the sum of two terms, one for small bubbles and one for Taylor bubbles. The Taylor bubble term is added only in the slug and inverted slug flow regimes. Transitions into and out of

these flow regimes are smoothed using the same technique as used in RELAP5/MOD2. A modification was made which reduced the multiplier on the Taylor bubble contribution to the interphase drag coefficient. This change improves prediction of the heat transfer later in the reflood period, and is judged to be a reasonable adjustment to the existing approved model. Appendix G of the Topical Report shows comparisons to experimental data performed using this model.

3. The McAdams low pressure nucleate boiling heat transfer correlation, which had been included in earlier approved versions of BEACH was restored as the default option in "NEWQUEN". This model had been removed in Revision 2 of the BEACH Topical Report because it caused non-physical clad temperature oscillations when the quench front stalled. Model improvements including those described above, have eliminated the stalled quench front behavior. Therefore, it is acceptable to restore the previously approved McAdams correlation.

4. To reduce numerical perturbations, upper and lower limits are imposed on the reference heat transfer coefficients in the post-CHF boiling heat transfer modes. These limits prevent the prediction of unrealistically high or unrealistically low heat transfer during short periods when the wall temperature approaches the vapor or saturation temperature. This is basically a numerical smoothing.

The above modifications are relatively minor adjustments to an approved reflood heat transfer model. The primary purpose of these changes is to overcome the prediction of a stalled quench front for cases where the data show a continuous quench front advancement. Discussions in Appendix G of Reference 4 mention problems encountered due to the prediction of excessive liquid carryover in earlier versions of BEACH. In some instances the stalled quench front could apparently result in prediction of a second clad temperature excursion.

The reflood phenomena being predicted by BEACH are quite complex. Modifications made to BEACH in Revision 4, eliminate prediction of a phenomenon which B&W Nuclear Technologies has judged to be unrealistic. Benchmarks discussed in Section 3 confirm the best estimate nature of the predictions resulting from use of the "NEWQUEN' global reflooding option in BEACH.

The licensing model has also been modified to allow multiple hydrodynamic channels with different reflood heat transfer parameters. As described by B&W Nuclear Technologies in their response to staff questions[6], this is a user convenience feature which facilitates sensitivity studies and optimizes use of computer resources. Since the flow into each channel is flow forced, there is no interaction between the channels. The calculations performed for each channel are identical to a single channel calculation. Therefore, this modification is acceptable for use in licensing calculations.

2.2 Features Described in RELAP5-B&W Topical Report, BAW-10164P

The automated blockage droplet breakup calculation, implicit formulation of the Baker-Just metal water reaction model and the fuel rod Evaluation Model (EM) improvements, including additional informational edits, unheated fuel rod segments and fuel rod axial expansion are described in Reference 1, the RELAP5-B&W Topical Report. Since the benchmarks discussed in Section 3 did not involve actual fuel rods, metal water reaction and fuel rod response, i.e., EM pin model, were not used. The automated blockage droplet breakup model is a user convenience feature. Therefore, these models do not affect any of the benchmarks performed to validate the other code modifications described in BAW-10166P. Since these options are described in BAW-10164P, it is appropriate that they be accepted for use in BEACH contingent upon their acceptance in BAW-10164P.

2.3 User Convenience Features

The user convenience features added to BEACH include the options to place multipliers on various heat transfer coefficients, drag coefficients, loss coefficients and the absorption coefficient for radiation to droplets. Default values are used in the approved reflood heat transfer models. Use of other than the default value for a given global reflood option is not acceptable.

The user convenience features also include a cross-flow void donoring option. This option can apparently be used to cross connect parallel channels for sensitivity studies, and to alter the liquid flow calculated by the normal cross flow junction equations. The B&W usage of BEACH for licensing purposes has been presented only for parallel channels which are independent. This model was not presented for use in licensing calculations, but merely for completeness of code description. Therefore, it was not considered in evaluating acceptability of the code modifications.

3. BEACH CODE BENCHMARKS

Appendix G of Revision 4 of BAW-10166P contains 12 benchmarks which compare predictions of the revised reflood heat transfer model with FLECHT, SCTF, CCTF and REBEKA experimental data. An additional benchmark was provided in B&W's response to staff questions. All of the benchmarks were performed using the "NEWQUEN" global reflooding option. These benchmarks show that BEACH provides a best estimate prediction of peak clad temperature. Observations of the curves comparing BEACH clad temperature response predictions to test data suggest that the predictions are on the conservative side of best estimate.

Predictions of quench times provided in the Topical Report appeared to be on the nonconservative side of best estimate based upon the clad temperature response curves provided in Appendix G. In response to staff questions, B&W Nuclear Technologies provided additional information including plots of quench front position versus time for the seven FLECHT tests. Except for FLECHT tests 31302 and 31609, the prediction of quench front position is very close to the data.

An examination of the peak clad temperature predictions for tests 31302 and 31609 reveals that in both cases, the clad temperature predictions in the vicinity of the maximum temperature remain conservative. The amount of metal-water reaction depends upon the time at temperature, with the reaction rate increasing substantially at higher temperatures. Overprediction of the clad temperature in the vicinity of the peak temperature will result in overprediction of the amount of metal reacted. The overprediction of peak temperature will compensate for underprediction at the lower temperatures just prior to rewet.

At lower temperatures, underprediction of clad temperature for a short period will have a small non-conservative effect on the amount of metal reacted. The reflooding process is complex and it is not expected that calculational models will exactly predict the measured response in all cases. Some of the time the prediction will be slightly under the measurement and at other times it will be slightly above. The predictions of clad temperature by the BEACH reflood heat transfer model are such that the trend is overprediction of clad temperature at high temperatures. This overprediction more than offsets the slight underprediction at lower temperatures for FLECHT tests 31302 and 31609, in terms of the amount of metal reacted.

As discussed in B&W Nuclear Technologies' response to staff questions, additional conservatisms are also present in the analysis method which act to ensure that the predicted metal-water reaction is conservative. The hot channel uses the average core flooding rate. Since the hot channel power is greater than the average channel, a larger boiloff rate will be predicted in the hot channel. In a parallel channel situation, this higher boiloff would lead to reduced liquid level and a greater inflow into the hot channel due to elevation head differences. This parallel channel effect is conservatively neglected in the BEACH methodology. Another conservatism is inherent in the FLECHT data itself. The electrical heater rods used for the FLECHT tests do not have a gap between the clad and the simulated fuel, as actual fuel rods do. As indicated by the REBEKA test benchmark, which used heater rods with a gap, the presence of the gap promotes cooling and advancement of the quench front.

Reference 7 provides the FLECHT-SEASET unblocked bundle test data used as a source for the benchmark problems. A review of all of the available test cases indicates that B&W Nuclear Technologies has chosen tests for benchmarking which cover the range of expected application, and include cases with quench occurring after substantial periods of reflood.

Based upon the benchmarks performed by B&W Nuclear Technologies using the "NEWQUEN" global reflooding option in BEACH, it is concluded that this option provides a reasonable best estimate prediction of representative reflood test data, including FLECHT test data.

4. COMPLIANCE WITH NRC REQUIREMENTS

Appendix K to 10-CFR-50 specifies required and acceptable features of ECCS evaluation models. Previous revisions of the BEACH program, through Rev. 3, have been reviewed and found to satisfy the requirements of Appendix K when used with the approved B&W ECCS methodology. When used with the "PRE18Q" global reflooding option, the modified version of BEACH (Version 19) yields the model previously approved in Revision 3.

The modifications documented in Revision 4 of BAW-10166P do not affect any of the required features of Appendix K[8]. Section I.D.5 of Appendix K states "For reflood rates of one inch per second or higher, reflood heat transfer coefficients shall be based on applicable experimental data for unblocked cores including FLECHT results". In this same section, it is further stated that, "The use of a correlation derived from FLECHT data shall be demonstrated to be conservative for the transient to which it is applied;" and "New correlations or modifications of the FLECHT heat transfer correlations are acceptable only after they are demonstrated to be conservative, by comparison with FLECHT data, for a range of parameters consistent with the transient to which they are applied". These requirements have not been modified by the 1988 update of Appendix K, and so they remain in effect.

The "NEWQUEN" global reflooding heat transfer option provides a best estimate model for reflood heat transfer analysis, based upon benchmarks against the FLECHT and other heat transfer test data provided in Revision 4 of the BEACH Topical Report and responses to staff questions. The model is judged to be sufficiently conservative in its prediction of clad temperatures to satisfy the above quoted Appendix K requirements. The multi-channel analysis capability of BEACH does not have an impact on licensing calculations since it is merely a user convenience feature.

The optional features, such as multipliers on heat transfer coefficients, drag coefficients and loss coefficients not included in "NEWQUEN", have not been compared to experimental data in the Topical Report. These options are therefore not in compliance with Appendix K. This includes the "CURRENTQ" global reflood heat transfer option, and the cross flow void donoring option.

5. CONCLUSIONS

Modifications made to the BEACH computer program in Revision 4 of BAW-10166P and benchmarks against experimental reflood data, have been reviewed and evaluated. Based upon benchmarks against experimental data performed with the revised "NEWQUEN" global reflood option, it is recommended that this option in BEACH be approved as acceptable for Appendix K LOCA analysis subject to the conditions enumerated below:

1. The multi-channel analysis capability, when used with independent channels, is a user convenience feature which does not alter the single channel results. It is recommended that this option be accepted for use in licensing calculations.

2. The cross flow void donoring option for multiple channels has not been validated and can not be used for licensing calculations.

3. Restrictions placed upon BEACH models documented in earlier revisions of this Topical Report remain in effect.

4. Use of the automated blockage droplet breakup calculation, implicit formulation of the Baker-Just metal water reaction model and the fuel rod Evaluation Model (EM) improvements should be made contingent upon their approval in Revision 3 of BAW-10164P, which describes these updates.

5. The use of global reflood heat transfer option "PRE18Q" in BEACH results in the same model as previously approved in Revision 3 of the Topical Report. It is recommended that this remain an approved model.

6. The BEACH "CURRENTQ" global reflooding option includes changes to the previously approved model including use of superheated steam conditions in the pressure and temperature input and modified use of grid heat transfer model enhancements. This option has not been benchmarked against relevant reflood heat transfer data and is therefore not acceptable for use in licensing calculations.

7. A number of user convenience options, including the capability of providing multipliers on various heat transfer coefficients, droplet absorption coefficient, drag coefficients and loss coefficients, are included in version 19 of BEACH. These options should not be used for licensing analysis without further review.

6. REFERENCES

1. B&W Nuclear Technologies, "RELAP5/MOD2-B&W -- An Advanced Computer Program for Light Water Reactor LOCA and non-LOCA Transient Analysis", BAW-10164P, Rev. 1, October 1988.

2. B&W Nuclear Technologies, "BEACH - Best Estimate Analysis Core Heat Transfer A Computer Program for Reflood Heat Transfer During LOCA", BAW-10166P, Rev. 3, October 1990.

3. Letter A. C. Thadani (USNRC) to J. H. Taylor (B&W Nuclear Technologies), "Acceptance for Referencing of Topical Report BAW-10166P, Revision 3, BEACH", May 30, 1991.

4. B&W Nuclear Technologies, "BEACH - Best Estimate Analysis Core Heat Transfer A Computer Program for Reflood Heat Transfer During LOCA", BAW-10166P, Rev. 4, October 1992.

5. N. T. Obot and M. Ishii, "Two-Phase Flow Regime Transition Criteria in Post-Dryout Region Based on Flow Visualization Experiments", NUREG/CR-4972, June 1987.

6. J. H. Taylor, B&W Nuclear Technologies, letter to R. C. Jones, USNRC "BEACH Topical Report BAW-10166P", JHT/93-214, August 31, 1993.

7. M. J. Loftus, et. al., "PWR FLECHT SEASET Unblocked Bundle, Forced and Gravity Reflood Task Data Report", NUREG/CR-1532, June 1980.

8. Code of Federal Regulations, Chapter 10 Part 50, Appendix K