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Revision 3

The Loss of Feedwater Heating Transient in Boiling Water Reactors

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The Loss of Feedwater Heating Transient in Boiling Water Reactors

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Nature of Changes

Item	Page	Revision	Description and Justification
1.	All	2	This is a revision to an existing NRC-approved document that expands the database, makes minor changes to the equation coefficients. It is intended as a complete replacement of the original document.
2.	All	3	This revision adds brackets [ ] to proprietary information.

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This document contains a total of 95 pages.

Nomenclature

AOO	anticipated operational occurrence
APRM	average power range monitor
BWR	boiling water reactor
CMFDLRX	core maximum FDLRX
CPR	critical power ratio
FANP	Framatome ANP
FCPR	final MCPR (MCPR after the event)
FDLRX	nodal linear heat generation rate (LHGR) divided by the LHGR fuel design limit
FWT	feedwater temperature
GNF	Global Nuclear Fuel
ICPR	initial MCPR (MCPR prior to the event)
LFWH	loss of feedwater heating
LHGR	linear heat generation rate
MCPR	minimum critical power ratio
MCPROL	MCPR operating limit
MCPRSL	MCPR safety limit
MEOD	maximum extended operating domain
NRC	Nuclear Regulatory Commission
RPS	reactor protection system
SER	safety evaluation review

1.0 Introduction

The Loss of Feedwater Heating (LFWH) transient event is an infrequent, anticipated operational occurrence (AOO) which results in an increase in the core inlet subcooling due to the loss of one or more feedwater heaters, producing a higher core power level. The increase in core thermal power causes an increase in the linear heat generation rate (LHGR) and a reduction in the core minimum critical power ratio (MCPR), potentially resulting in this event being the limiting event when establishing the reload MCPR operating limit.

This document presents a revision to the currently approved generic methodology (Reference 3) for evaluating the LFWH event. The revision is based on an expanded database and results in minor changes to the coefficients of the previously approved correlation which relates MCPR following a LFWH event to the MCPR prior to the event and various plant parameters. The generic methodology is a parametric description of the fuel/system response. The parametric description was developed using the results of over a thousand applications of the currently approved core simulation methodology (References 1 and 2). A critical power ratio (CPR) function consisting of several plant design parameters is developed which relates [ ] Postulated LFWH events initiated from actual BWR operating state points and fuel loadings were evaluated to derive the function. There are no restrictions necessary due to assumed loading schemes and control rod sequences, because actual operating conditions for several different plants, cycles and fuel types were evaluated. Applying the function yields a bounding MCPR operating limit for the LFWH event. This methodology is applicable to BWR/3, 4, 5, and 6 plant types for present and future operating cycles provided that [ ] are within the range of the analysis.

2.0 Summary

Loss of feedwater heating events were evaluated with the Framatome ANP (FANP) core simulator models MICROBURN-B and MICROBURN-B2 (References 1 and 2) by representing the reactor in an equilibrium state before and after the event. These codes have been reviewed and accepted by the NRC. The applicability of this approach has been confirmed by transient analyses and plant startup tests and has been previously accepted by the Nuclear Regulatory Commission (NRC) (Reference 3). Actual and projected state points from eight (8) operating boiling water reactor (BWR) plants were used as initial conditions. [

] The evaluation assumed the plants were operating in the manual flow control mode. Thus the results bound the automatic flow control mode.

These analyses consisted of 1686 simulated loss of feedwater heating events, representing 1069 operating state points from 26 operating/projected cycles, including the BWR/6 Maximum Extended Operating Domain (MEOD). The database includes the most recent fuel types (geometry and enrichments) and combinations of fuel types, various fuel loading schemes and control rod sequences associated with modern fuel and core designs.

This analysis has demonstrated that the MCPR after a loss of feedwater heating event can be directly correlated to [

] The analytical model developed from this analysis was adjusted slightly from the currently approved model in Reference 3 to bound all of the calculated results. Tables 2.1 and 2.2 present the MCPR operating limits (MCPROL) derived from this bounding model for several different classes of boiling water reactors. The results of this analysis are applicable to other BWR plants [

] given in Tables 2.1 and 2.2.

The LHGR analyses demonstrated that during the event, the [

] These LHGR bounding values can be compared to cycle specific AOO limits.

Table 2.1 LFWH MCPR Operating Limit with a MCPR Safety Limit of 1.06

Table 2.2 LFWH MCPR Operating Limit with a MCPR Safety Limit of 1.08

3.0 Event Description

The loss of feedwater heating transient can occur in two ways:

1) a steam extraction line to a feedwater heater is closed, or
2) the feedwater is bypassed around a feedwater heater.

The first case produces a gradual drop in the temperature of the feedwater. In the second case, the feedwater bypasses the heater and no heating occurs. Both cases cause a decrease in the temperature of the feedwater entering the reactor vessel. The decrease in feedwater temperature results in an increase in the core inlet subcooling which collapses voids and thus increases the core average power and shifts the axial power distribution towards the bottom of the core. Voids begin to build up at the bottom again because of this axial shift, acting as negative feedback to the void collapse process. This feedback moderates the core power increase. This feedback also tends to flatten the core radial power distribution.

The maximum number of feedwater heaters which can be tripped or bypassed by a single equipment failure event defines the most severe transient for licensing analysis considerations. [

]

4.0 Methodology

The LFWH event is analyzed with either the FANP 3-D core simulator model MICROBURN-B (Reference 1) or MICROBURN-B2 (Reference 2). The LFWH event is a slow (>100 seconds) transient and can be modeled by analyzing equilibrium conditions at the initial and final state points.

The methodology employed herein involves evaluating the loss of feedwater heating event at a large number of reactor operating state points (power, flow, exposure, and control rod pattern) obtained from several operating boiling water reactors, over many fuel load cycles. The plant types (BWR/3, 4, 5, and 6) are diverse in the respect that they have different power densities, core designs ("C" and "D" lattice), core average void fraction, fuel types, cycle lengths and feedwater temperatures.

4.1 *Assumptions*

The basic assumptions applied for this analysis include the following:

1) The reactor is in steady state equilibrium before and after the event.

2) The xenon concentration does not change during the event.

3) The total core flow is constant during the event. The core flow distribution is allowed to vary in order to maintain equal differential pressure across each fuel assembly in the core. This assumption conservatively implies that the plant is operating in the manual flow control mode. In the automatic flow control mode, core flow is reduced during the LFWH event, preventing the core power from rising. The resulting decrease in core minimum critical power ratio is less than that when operating in the manual flow control mode.

4) The [ ] is constant throughout the event.

5) Although the flux levels due to the LFWH event may be sufficiently high to cause either an average power range monitor (APRM) or thermal power monitor reactor protection system (RPS) trip, reactor scram was not allowed in the calculations.

4.2 *Database*

The initial conditions for the simulated LFWH events were selected from actual operating state points observed from BWR operating cycles of three (3) BWR/6, one (1) BWR/5, three (3) BWR/4 and one (1) BWR/3 type plants. A [

] and adjusting the plant heat balance data correspondingly. Table 4.1 summarizes the plant specific operating parameters.

The plants contain various mixtures of GNF and FANP fuel assemblies. Table 4.2 provides a breakdown of the fuel types in the core as a function of the plant/cycles considered in this evaluation.

The analysis consists of 1686 simulated loss of feedwater heating events from 1069 state points. The state points represent conditions (power, flow, fuel types, exposures and control rod patterns) observed and projected over thirteen (13) BWR/6 cycles, three (3) BWR/5 cycles, eight (8) BWR/4 cycles and two (2) BWR/3 cycles. The selected data points bound the observed operating regions of the plants (e.g. high power-high flow, high power - low flow, low power - high flow, and low power - low flow). Figure 4.1 shows the state points selected as plotted on a generic BWR power/flow map.

In addition to power and flow conditions, the cycle exposure and control rod pattern were also considered in selecting state points to be analyzed. A LFWH event was simulated whenever a significant change in the control rod pattern was noted. In general, the exposure range covers the beginning of cycle through the end of cycle with incremental exposure differences between events of less than 500 MWd/MTU.

4.3 *Calculation Procedure*

The calculation procedure for the generic analysis of the loss of feedwater heating event is as follows:

[ ]

Table 4.1 Plant Specific Parameters

Table 4.2 Fuel Types Included in Database

Table 4.2 Fuel Types Included in Database *(Continued)*

Figure 4.1 Summary of State Point Conditions Analyzed

5.0 Benchmark Evaluations

The loss of feedwater heating transient is a relatively slow event. The reactor core is essentially in steady state throughout the event. The transient parameters behave smoothly with no sudden increases or decreases. These trends have been verified in startup tests. Typically, as part of the plant startup test program, the plant response to a decrease in feedwater temperature is measured. The results from BWR/4, 5 and 6 plants show that the time for the event to attain 95% of the temperature change is greater than 100 seconds. An actual loss of feedwater heating event occurred at an operating BWR in 1977. In this event, the temperature decrease occurred over a period of approximately 13 minutes. Thus, the event would be expected to take much longer than 100 seconds for the temperature change to reach a maximum.

The FANP core simulator, MICROBURN-B, was then executed for the core state representing the maximum core thermal power and other state points after the core thermal power reached the maximum to determine core MCPR during the event. MICROBURN-B was also executed to determine core MCPR for the equilibrium state point condition assuming that the eigenvalue and core flow remain constant throughout the event. [

] The LFWH benchmark was not performed with

MICROBURN-B2 because it is neutronically equivalent to MICROBURN-B but with more advanced features included. The restrictions sited in the CASMO-4/MICROBURN-B2 Safety Evaluation Review (SER) also do not impact the benchmark evaluation.

BWR/4 and BWR/6 LFWH startup tests were also modeled to confirm assumptions presented in Section 4.1. The operating conditions (power, core flow, pressure, inlet subcooling, and rod pattern) at the initial and final states of these tests were used as inputs to MICROBURN-B [ ] In modeling these events, special care was taken to consider xenon effects before, during and after the tests. This was necessary because of the magnitude of reactor state point changes prior to the tests, and because of the relatively long period between the process computer print-outs for the initial and final state points.

[ ]

[ ] The predicted values of final core power, steam flow and MCPR agree well with the test results.

Table 5.1 Summary of Transient Analyses for 60-Second Period

Table 5.2 Summary of Transient Analyses for 80-Second Period

Table 5.3 Summary of Transient Analyses for 100-Second Period

[ ]

Table 5.4 Steady State 3-D Core Simulator Analysis Using Transient Conditions from 60-Second Period

Table 5.5 Steady State 3-D Core Simulator Analysis Using Transient Conditions from 80-Second Period

Table 5.6 Steady State 3-D Core Simulator Analysis Using Transient Conditions from 100-Second Period

[ ]

**Table 5.7 Steady State 3-D Core Simulator Analysis Assuming [
] and Equilibrium Conditions**

Table 5.8 BWR/4 Loss of Feedwater Heating Startup Test

Table 5.9 BWR/6 Loss of Feedwater Heating Startup Test

6.0 Results

This analysis simulated 1686 loss of feedwater heating events from 1069 state points observed (or projected) from 26 reactor operating cycles including initial cores, all GNF fuel reload cores, mixed FANP/GNF fuel, and all FANP fuel reload cores. BWR/3, 4, 5 and 6 reactor types were simulated and the results are summarized in Appendix A (original database documented in Reference 3) and Appendix B (new data points added to the database). These reactor types differ by their power density and design feedwater temperature in addition to the fuel type composition and recirculation systems. Thus, these plants would be expected to respond differently to a given change in feedwater temperature.

6.1 *Development of Best Fit Function*

[ ]

6.2 *Bounding Relation*

To develop a relation which bounds all of the data in Appendix A, the coefficients B_5 and B_6 were adjusted until all of the calculated residuals were negative:

[ ]

The coefficient B_5 was further adjusted to bound all the data in both Appendix A and B, which includes the most recent fuel design and operating experience. The final coefficients for a bounding fit are:

[ ]

[ ]

6.3 *Effect of Fuel Type*

6.4 *Xenon Effects*

Table 6.1 Effects of Non-Equilibrium Xenon

Figure 6.1 Residual Error of Data and Best Fit Versus [ ]

Figure 6.2 Residual Error of Data and Best Fit Versus [ ]

Figure 6.3 Residual Error of Data and Best Fit Versus [ ]

Figure 6.4 Residual Error of Data and Best Fit Versus [ ]

Figure 6.5 Residual Error of Data and Best Fit Versus [ ]

Figure 6.6 Residual Error of Data and Bounding Fit Versus [ ]

Figure 6.7 Residual Error of Data and Bounding Fit Versus [ ]

Figure 6.8 Residual Error of Data and Bounding Fit Versus [ ]

Figure 6.9 Residual Error of Data and Bounding Fit Versus [ ]

Figure 6.10 Residual Error of Data and Bounding Fit Versus [ ]

Figure 6.11 Residual Error of Data and Bounding Fit Versus [ ]

Figure 6.12 Residual Error of Data and Bounding Fit Versus [ ]

Figure 6.13 Residual Error of Data and Bounding Fit Versus [ ]

6.5 *LHGR Analysis*

The benchmark evaluation in Section 5.0 demonstrates that [

]

6.6 *Conclusions*

The expanded database consisted of 1686 simulated loss of feedwater heating events, representing 1069 operating state points from 26 operating/projected cycles. This analysis has verified that the minimum critical power ratio (MCPR) after a loss of feedwater heating event can

[

] The results of this report can be expanded to cover variations in the fuel designs covered by this analysis provided specific LFWH analyses are performed using a similar methodology to confirm that the variation does not impact the event results and conclusions for the given fuel design.

Figure 6.14 Final FDLRX Versus Exposure Plot for [ ]

Figure 6.15 Final FDLRX Versus Exposure Plot for [ ]

Figure 6.16 Final FDLRX Versus Initial FDLRX Plot for [ ]

Figure 6.17 Final FDLRX Versus Initial FDLRX Plot for [ ]

Figure 6.18 Final FDLRX Versus FWT Loss Plot for [ ]

Figure 6.19 Final FDLRX Versus FWT Loss Plot for [ ]

7.0 Application of Generic LFWH Analysis for Reload Licensing

The bounding relation (Eqn 6-14) can be conservatively applied to BWR/3 through BWR/6 plants. For determining the MCPR operating limit, Eqn 6-14 becomes

[ ]

7.1 *Example Application*

Utilizing the BWR/6-A parameters from Table 4.1, Eqn 7-1 is:

[ ]

8.0 References

1. XN-NF-80-19(P)(A) Volume 1 Supplement 3, Supplement 3 Appendix F, and Supplement 4, *Advanced Nuclear Fuels Methodology for Boiling Water Reactors: Benchmark Results for the CASMO-3G/MICROBURN-B Calculation Methodology,* Advanced Nuclear Fuels Corporation, November 1990.

2. EMF-2158(P)(A) Revision 0, *Siemens Power Corporation Methodology for Boiling Water Reactors: Evaluation and Validation of CASMO-4/MICROBURN-B2,* Siemens Power Corporation, October 1999.

3. ANF-1358(P)(A) Revision 1, *The Loss of Feedwater Heating Transient in Boiling Water Reactors*, Advanced Nuclear Fuels Corporation, September 1992.

4. NP 6230-SL, *BWR-6 Start Up and Transient Tests At Grand Gulf Nuclear Station,* Electric Power Research Institute.

5. ANF-913(P)(A) Volume 1 Revision 1 and Volume 1 Supplements 2, 3 and 4, *COTRANSA2: A Computer Program for Boiling Water Reactor Transient Analyses,* Advanced Nuclear Fuels Corporation, August 1990.

Appendix A Generic LFWH Transient Analysis Data

* Residuals have been recalculated with coefficients listed in Section 7.0.

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Appendix B Generic LFWH Transient Analysis Data Update 1

Distribution

Controlled Distribution

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