U.S. NUCLEAR REGULATORY COMMISSION'S AUDIT REPORT FOR THE KEPCO/KHNP TOPICAL REPORT "KCE-1 CRITICAL HEAT FLUX CORRELATION FOR PLUS7 THERMAL DESIGN" (APR1400-F-C-TR-12002-P, REVISION 0) IN THE BACKDROP OF RAI 3-7443 RESPONSE
On January 21–22, 2015

APR1400 DESIGN CERTIFICATION
Korea Hydro and Nuclear Power, Co, Ltd. (KHNP)
Project No. 0782

Introduction and Background

In order to comply with the Commission's requirements, Korea Hydro and Nuclear Power Co., Ltd. (KHNP) in conjunction with its affiliate company Korea Electric Power Corporation (KEPCO), submitted Topical Report (TR) APR1400-F-C-TR-12002-P, Revision 0, "KCE-1 Critical Heat Flux Correlation for PLUS7 Thermal Design," [Reference 1] to the U.S. Nuclear Regulatory Commission (NRC) for review and approval, in support of its application for design certification of the APR-1400 reactor design. The purpose of the TR was to justify the use of the KCE-1 Critical Heat Flux (CHF) correlation for PLUS7 fuel design for pressurized water reactor (PWR) application. The report presents the test data analysis for the KCE-1 CHF correlation development, its results, and a description of the CHF test facility and test procedure.

The NRC staff issued a non-public proprietary request for additional information, RAI 3-7443, dated March 25, 2014 [Reference 2], with 18 questions about the applicant's analyses, computer codes, assumptions, and uncertainties to support its safety review. The applicant submitted the responses to various RAI 3-7443 questions as Reference 3 (Questions 2, 3, 5); Reference 4 (Questions 4, 10, 11, 12, 18); and Reference 5 (Questions 1, 6, 7, 8, 9, 13, 14, 15, 16, 17). On January 21-22, 2015, the staff conducted a regulatory audit following an audit plan [Reference 6] to resolve the outstanding issues regarding the applicant's response to RAI 3-7443, and ascertain the qualification status of the Columbia University's test facility and procedures. The audit allowed the staff to review the applicant's data, calculations, and supporting documents to gain an in-depth understanding of the TR as well as the RAI 3-7443 response [References 3-5]. The staff has summarized the overall audit observations in this audit report.

The present audit report documents the NRC staff's observations made during the audit. As a fundamental outcome of the audit, the applicant needed to submit a revised RAI 3-7443 response with the additional analyses, supporting data, and TR updates in order to meet the various commitments made during the audit to address the outstanding technical issues. The additional information was mainly needed to support the minimum departure from nucleate boiling ratio (MDNBR) proposed in the TR. No additional RAI was developed by the staff as a result of the audit.

Audit Team

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ENCLOSURE 4

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Regulatory Audit Bases

1. General Design Criterion (GDC) 10, "Reactor Design," in 10 CFR Part 50 [Reference 7] Appendix A, requires that the reactor core and associated coolant, control, and protection systems shall be designed with appropriate margin to ensure that the specified acceptable fuel design limits (SAFDLs) are not exceeded during any condition of normal operation, including anticipated operational occurrences (AOOs).

2. NUREG-0800, "Standard Review Plan (SRP) for the Review of Safety Analysis Reports for Nuclear Power Plants" [Reference 8], Section 4.4, "Thermal and Hydraulic Design," describes the staff review process for thermal and hydraulic design applications.

3. Section 50.34 of 10 CFR, "Contents of Applications; Technical Information," requires that Safety Analysis Reports (SARs) be submitted that analyze the design and performance of structures, systems, and components provided for the prevention of accidents and mitigation of consequences of accidents.

The audit followed the guidelines in Office of New Reactors (NRO) Office Instruction NRO-REG-108 (Revision 0), "Regulatory Audits."

Observations and Results

The audit took place at the applicant's local (Virginia) office. The NRC staff reviewed the information and audited the supporting documents that the applicant provided in response to the audit plan [Reference 6]. The NRC staff interacted with the KHNP/KEPCO staff to gain in-depth understanding of the initial/boundary conditions, analysis assumptions, and the engineering judgments used, to resolve the outstanding issues and staff safety concerns. Hereunder is a summary of the audit information.

Critical Heat Flux Test Program and Procedures

The CHF tests for PLUS7 fuel geometry were conducted at Columbia University's Heat Transfer Research Facility (HTRF) in New York City, New York, which was in operation from 1951 to 2003 and collected an extensive amount of the departure from nucleate boiling (DNB) data relevant to nuclear reactor fuel design. One of the objectives of the audit was to review the documents pertaining to the Quality Assurance (QA) status of the HTRF facility. The following is a summary of the information that NRC staff reviewed in several documents.

Over the years, several applicants used data from the HTRF facility and subjected the data to QA review, and the NRC staff reviewed and approved the resulting CHF correlations. The applicant provided a description of the HTRF QA program used for the CHF tests for the PLUS7 fuel design. The documents [References 9, 10, 11, and 12] furnished during the audit showed details of the [

]TS

Reference 9 describes [

]TS and confirms that the facility had mandated a Quality Assurance Program (QAP) in conformance with applicable requirements of the latest edition of ANSI/ASME NQA-1, "Quality Assurance Program Requirements for Nuclear Facilities" with addenda, which was documented in the HTRF/QAP, Revision 5, March 1998. As the CHF tests were safety related, the engineering design and materials supplied were qualified by the HTRF to meet the necessary QA requirements to ensure that the CHF data conform to the applicable requirements of 10 CFR Part 50 Appendix B, "Quality Assurance Criteria for Nuclear Power Plants and Reprocessing Plants." Reference 10 cites a [

]TS [Reference 11] that documents an HTRF audit performed by [

]TS, 10 CFR Part 50 Appendix B, and 10 CFR Part 21. During the audit, the staff was also informed that as HTRF was involved in several DOE sponsored research programs, DOE conducted the facility's audit on annual basis.

Prior to the audit, staff observed that there was a lack of description in the TR about whether and how frequently the instrumentation calibrations were performed at this test facility. RAI 3-7443, Question 4 asked about the test section flow measuring instrumentation details and calibration. Considering the significance of accurately measuring the mass flow rate and inlet/outlet conditions in the overall computation of the CHF and its subsequent safety significance, it is important to establish that the calibration of related instruments was performed following an approved test procedure. During the audit, Reference 10 showed that all the tools, gauges, instruments, and test equipment used in the CHF testing were controlled and calibrated, and adjusted periodically to maintain accuracy within the required limits. Instrumentation and measuring devices were calibrated against devices traceable to the National Institute of Standards and Technology (NIST) at frequencies determined by the responsible engineers. The document also included the calibration records and calibration certificates of the measuring instruments used in the CHF test loop. Reference 9 mentions that [

]TS; water temperature measurements at both the inlet and outlet of the test sections by using calibrated platinum resistive thermometers (RTD) and calibrated iron constantan thermocouple (type J); and pressure measurements made at the beginning and the end of the heated length. No void fraction or quality measurements were made. The reported local quality is based on the lumped parameter calculations using the TORC subchannel code [Reference 14]. The applicant also provided a detailed description of a typical testing day that stressed the necessity for achieving steady state before the CHF data point was taken. The applicant explained how the water layer between outside the channels and the plexiglass wall would help achieve steady state and curb the heat losses to the surroundings. Repeatability of the data was assured at the beginning and end of every day. The QA documents reviewed at the audit explain the instrumentation, redundancy, and diversity applied to measurements. The RAI 3-7443 Question 4 is resolved and closed.

Heat Losses in the Test Facility

RAI 3-7443, Question 1 asked the applicant to demonstrate that the heat losses from the test section were duly accounted for in their CHF test data for the entire range of the tested bundle power. The applicant was expected to offer conservative estimates of the loss of generated heat that would fail to reflect in the local fluid conditions either due to convection to the ambient or through axial conduction to the rod's end. Ignoring the heat losses from the test section would be non-conservative, as it would make CHF look higher than it actually is. The RAI response described and the staff confirmed during the audit that a [ ]^{TS} heat balance acceptance criterion was followed based on the [ ]^{TS} [Reference 9]. However, the response did not address the staff concern that the overall heat balance was not performed for each CHF data point and was rather tested only under subcooled conditions at [

]^{TS} conditions. These test conditions were expected to involve much smaller heat losses than in the CHF test range reported in the KCE-1 correlation database that involves bundle powers up to an order magnitude higher, inlet temperatures up to [ ]^{TS}, flow rates up to [ ]^{TS}, and pressures up to [ ]^{TS}.

During the audit, the applicant presented a bounding heat loss analysis that showed that even though the bundle power increased from [
]^{TS} in the PLUS7 test range, the inlet water temperature increased from [
]^{TS}. Assuming a 70 °F ambient temperature, the resulting temperature difference between the section inlet flow temperature and the ambient increased by [
]^{TS}. As the heat loss would conservatively be proportional to the temperature difference between the water flowing through the heated section and the ambient, the rise in input electrical power from the minimum to the maximum [ ]^{TS} during testing outpaces the corresponding rise in heat losses. This shows that as the electrical power input increases, even though the heat loss from the test section would increase, its proportion relative to the input power would actually decrease, which makes the [[
[ ]^{TS} heat loss acceptance criterion observed at the minimum bundle power to be bounding for the entire domain of KCE-1 CHF test conditions. During the audit, the applicant also explained that the heat loss from the test section was conservatively factored into the CHF data reduction through a heat-input correction factor that was a function of the inlet water temperature, which allowed the measured CHF values to be based on the rise in fluid enthalpy through the test section. This eliminated the heat-loss related bias from the CHF test data. The deviation between the correction factor and the measured value was considered in estimating the overall CHF measurement uncertainty. The applicant was expected to resubmit the RAI 3-7443, Question 14 response to document the applicability of the [ ]^{TS} heat loss acceptance criterion per the audit discussions and to demonstrate that the heat losses measured at the lowest input power are bounding. Based on the information viewed, the staff has no further questions with regard to RAI 3-7442, Question 1.

Axial Power Profile and Tong Factor

The CHF test data for PLUS7 fuel geometry were obtained by using a non-uniform axial power distribution, i.e., a symmetric chopped cosine power profile with a peak of 1.475 at the middle of the heated length. During the audit, the applicant clarified the application of the Tong factor (Fc) to correct the measured CHF data taken with the tested non-uniform axial power distribution to the

]^{TS} CHF data. During the audit, the applicant was asked to update the RAI 3-7443, Question 6 response to show that Tong factors for all [ ]^{TS} measured CHF data points used in generating the KCE-1 CHF correlation are [ ]^{TS}.

The applicant emphasized that the resulting KCE-1 CHF correlation was developed based on the [

]^{TS} CHF data, which is conservative. Besides, the CHF predicted by the resulting KCE-1 correlation is treated as if it was based on [ ]^{TS} that makes the [ ]^{TS} a divider (and not a multiplier) of the predicted value, which leads to an even lower, and thus, more conservative CHF prediction. The staff agrees that the use of the Tong factor in this manner is conservative. However, as the applicant relies on the conservatism derived from the application of the KCE-1 CHF correlation with [ ]^{TS} for the plant safety analyses, the staff plans to impose a limitation that will mandate the applicant's proposed use of the KCE-1 CHF correlation with [ ]^{TS} as a requirement.

Uncertainties in CHF Measurements

SRP Section 4.4 Acceptance Criterion #1 deals with various uncertainties involved in the CHF measurement and correlation development, such as fabrication uncertainty, computational uncertainty, and measurement uncertainty due to instruments. As no discussion about these uncertainties was provided in the TR, RAI 3-7443, Question 14 asked the applicant to provide the information. During the audit, the applicant showed a detailed listing of the measurement uncertainties of the instrumentation employed in the CHF tests based on Reference 15, which concluded a [ ]^{TS} uncertainty in the measured CHF value based on [ ]^{TS}. It was explained during the audit that [

]^{TS}. During the audit, the applicant explained that they had also addressed an "operational" uncertainty in CHF measurement by keeping the maximum incremental rise in heat flux at [ ]^{TS}.

RAI 3-7443, Question 14 response did not provide any information about computational uncertainties. During the audit, the applicant provided a detailed overview of the uncertainties involved in the CHF measurements. The applicant explained that as the directly measured values of the electrical power input to the test section were used to normalize the heat flux profile and subchannel code was not used for this purpose, there are no computational uncertainties involved in the overall CHF measurement and data reduction. Based on the information presented during the audit, the staff had no further questions on this issue.

TORC is the only subchannel code that was used for the KCE-1 CHF correlation development. The TR mentions that the KCE-1 CHF correlation can also be used with a different subchannel code, CETOP-D. The staff issued RAI 3-7443, Question 16 to inquire about the differences between the two codes, especially how they would calculate the local fluid conditions in the subchannel. According to the RAI 3-7443, Question 16 response, the CETOP-D subchannel code uses a different model to calculate the transport properties and a different numerical scheme to solve the conservation equations than the TORC code. In the audit, the staff asked for the justification of using the KCE-1 CHF correlation with CETOP-D code as its different transport properties module and different numerical scheme may entail computational uncertainties potentially warranting additional non-conservatism in the 95/95 DNBR limit. The staff stressed that an application of the CETOP-D code for the design and safety analyses with KCE-1 CHF correlation would require an assurance that the DNBR calculated by CETOP-D code for a location shall always be greater than or equal to the DNBR calculated by TORC code for the same location and same boundary conditions. Therefore, as discussed during the audit, the applicant agreed to delete all references to CETOP-D from the TR, limit the application of KCE-1 CHF correlation to TORC computer code, and resubmit an updated RAI 3-7443, Question 16 response accordingly.

Trend Analysis

The calculation of a single 95/95 DNBR limit to bound the overall uncertainty of a CHF correlation is predicated on three statistical assumptions: (1) normality, (2) homoscedasticity, and (3) independence. Figure 5-3 of the TR suggests that the assumption of independence may not hold as the KCE-1 CHF correlation does not behave consistently throughout the pressure application range of 1395-2415 psia, and its uncertainty is sensitive to system pressure. The five pressure datasets in Figure 5-3 used in the correlation development seem to be from four different populations, and there is a non-conservative trend of decreasing predictive capability with pressures from 2200 psia to 1750 psia. While the trend in the measured-over-predicted (M/P) CHF values has clearly reversed by the low pressures around 1395 psia, it is not apparent how far the trend continued in the empty region between 1395–1750 psia before reversing. No data are available within the 1395-1750 psia range to evaluate the magnitude of the non-conservatism associated with the non-conservative trend. RAI 3-7443, Question 8 asked the applicant to provide justification for the use of a single statistical 95/95 DNBR limit to bound the KCE-1 correlation over its intended application domain, primarily focusing on the non-conservative data trend between 1395 psia and 1750 psia. The RAI response did not offer any justification for the use of KCE-1 correlation in that range. The issue was discussed in detail at the audit and the staff was informed that the applicant plans to address the non-conservative data trend by excluding the low pressure region of 1395–1750 psia from the applicable range of the KCE-1 CHF correlation and limiting the applicable range to 1750-2415 psia. The NRC staff observed that this proposal would obviate the basis of the staff's concern on this issue, and the applicant was expected to affirm the reduced applicable pressure range by updating the RAI 3-7443, Question 8 response.

Statistical Evaluation of 95/95 DNBR Limit

During the course of the TR review, the NRC staff identified multiple challenges to the applicant's proposed 95/95 DNBR limit of 1.124. These challenges included the uncertainty in the magnitude of the conservatism gained by the applicant's use of the Tong factor; the existence of a non-conservative subregion around 1750 psia; and the generation of the 95/95 DNBR limit using only training data but no validation data. These concerns were expressed in RAI 3-7443 Questions 6, 7, 9, and 17. This subject was discussed in detail during the audit and the applicant explained their treatment of the Tong factor in the KCE-1 correlation's development and subsequent use. Such treatment would be conservative, but the applicant could not demonstrate the quantification of the Tong factor conservatism and that this conservatism would balance the non-conservatisms identified by the staff. The applicant posited [ ]^{TS} its Tong factor methodology has built about [ ]^{TS} conservatism in the 95/95 DNBR limit (1.124) for its application in the design and safety analyses. However, the staff was unable to understand the applicant's method for quantifying the Tong factor conservatism in the earlier RAI response and the audit, and requested supporting data in tables and plots in an updated RAI response along with description. The staff emphasized that the applicant needed to quantify the magnitude of the conservatism gained by the applicant's use of the Tong Factor and demonstrate that it would more than make up for the non-conservatisms the staff identified. As a result of the audit discussions, the applicant made a commitment to submit additional supporting data and analysis through the updated RAI 3-7443, Question 6 response.

Non-conservative Test Data Subregion

The very notion of 95/95 statistics presumes that any error associated with the predictions of a CHF correlation must be random and uniformly distributed over the entire application domain of the correlation. During the audit, the applicant was asked to quantify the margin in the 95/95 DNBR limit required to accommodate the non-conservative subregion (at pressures near 1750 psia, qualities near 0.1, and local mass fluxes near 2 Mlbm/hr-ft^2), as identified by the staff in RAI 3-7443, Question 9, so that it could be shown how much of the margin gained in the DNBR limit by the Tong factor usage was consumed by the non-conservative subregion. The subregion identified by the staff contains a higher than expected number of M/P points that fell below the 95/95 DNBR limit of 1.124 than can be explained by random chance. Seven points in the database fell below M/P = 0.8897 that corresponds to DNBR = 1.124. Six out of those seven points correspond to 1750 psia pressure. During the audit, the applicant showed willingness for using the bounding DNBR value in the non-conservative subregion in lieu of their proposed 95/95 DNBR limit of 1.124 to address the concern about the non-conservatism. They understood the need to address the non-conservative sub-region around the lower system pressure limit of the KCE-1 CHF correlation.

Non-conservative Overfitting of the Test Data

Best practices in fitting CHF correlations in previous test programs suggest that the given test database should be divided into a training dataset and a validation dataset [Reference 16]. Correlation coefficients are fit using the larger training dataset, and are independently validated against the smaller validation dataset to ensure a consistent behavior of the correlation. This process helps assess whether the correlation lacks in predictive capability on data not used in the development of the correlation. RAI 3-7443, Question 17 inquired whether some test data were initially excluded from the KCE-1 correlation coefficient generation and were later used for independent correlation validation. The staff was concerned about the potential for "overfitting," which means that all available CHF data points in the database were used in the regression analysis to optimize the KCE-1 CHF correlation coefficients and no points were set aside to perform an independent validation of the correlation. In the RAI response, the applicant stated that potential for overfitting is not expected in the KCE-1 CHF correlation but did not elaborate.

During the audit, the applicant was asked again to address the potential for overfitting in the KCE-1 correlation. The staff asked the applicant to estimate the non-conservatism in the 95/95 DNBR limit due to overfitting, by running a random-subsamples analysis of the CHF database with training (say 80 percent) and validation (say 20 percent) datasets, and demonstrate that the conservative use of the Tong factor more than compensates for this. The applicant made a commitment to conduct such a cross-validation analysis of the database to assess the impact of its overfitting on the resulting 95/95 DNBR limit and submit the analysis results through an updated RAI 3-7443, Question 17 response. They understood that they needed to demonstrate that the MDNBR proposed in the TR for the KCE-1 CHF correlation is conservative for the full range of validation for its 95/95 DNBR statistics.

Conclusions

Based on the audit activities, the applicant was expected to submit a revised RAI 3-7443 response with the additional analyses, supporting data, and TR updates in order to meet the various commitments made during the audit to address the outstanding technical issues, as elaborated in the above. The additional information was mainly needed to support the MDNBR proposed in the TR. No additional RAI resulted from the audit. The staff would further consider the application and perform confirmatory analyses to facilitate the closure of the afore-mentioned unresolved issues in the safety evaluation report.

References

1. Submittal letter dated January 7, 2013, Transmittal of Topical Report APR 1 400-F-C-TR- 12002-P/-NP, Revision 0, “KCE-1 Critical Heat Flux Correlation for PLUS7 Thermal Design” for Safety Evaluation, November 2012 (ADAMS Accession No. ML13018A096).

2. Submittal letter for Non-public Proprietary Request for Additional Information (RAI) RAI 3-7443 for the APR1400 Topical Report APR1400-F-C-TR-12002-P (KCE-1 Critical Heat Flux Correlation for PLUS7 Thermal Design) to KHNP; March 25, 2014 (ADAMS Accession No. ML14100A670).

3. Enclosure 1; KHNP Response to RAI 3-7443 on Topical Report “KCE-1 Critical Heat Flux Correlation for PLUS7 Thermal Design” APR1400-F-C-TR-12002-P, Rev. 0; Questions 2, 3, and 5; April 23, 2014 (ADAMS Accession No. ML14114A562 (Non-Proprietary)).

4. Enclosure 2; KHNP Response to RAI 3-7443 on Topical Report “KCE-1 Critical Heat Flux Correlation for PLUS7 Thermal Design” APR1400-F-C-TR-12002-P, Rev. 0; Questions 4, 10, 11, 12, and 18; May 2014 (ADAMS Accession No. ML14143A115/ML14143A117 (Non-Proprietary/Proprietary)).

5. Enclosure 3; KHNP Response to RAI 3-7443 on Topical Report “KCE-1 Critical Heat Flux Correlation for PLUS7 Thermal Design” APR1400-F-C-TR-12002-P, Rev. 0;

Questions 1, 6, 7, 8, 9, 13, 14, 15, 16, and 17; June 2014 (ADAMS Accession No. ML14176A792/ML14176A796 (Non-Proprietary/Proprietary)).

6. Audit Plan to Review Selected Documents Related to APR1400 KCE-1 Critical Heat Flux Correlation for PLUS7 Thermal Design (APR1400-F-C-TR-12002-P-Rev 0); December 11, 2014 (ADAMS Accession No. ML14338A356).

7. Title 10 of the *Code of Federal Regulations* Part 50, "Domestic Licensing of Production and Utilization Facilities."

8. NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants."

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11. [ ]TS

12. [ ]TS

13. [ ]TS

14. CENPD-161-P-A, "TORC Code, A Computer Code for Determining the Thermal Margin of a Reactor Core," April 1986.

15. [ ]TS

16. Piepel, G.F., and Cuta, J.M. "Statistical Concepts and Techniques for Developing, Evaluating, and Validating CHF Correlations and Corresponding Fuel Design Limits," SKi Technical Report 93:46, December 1993.