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

November 25, 2014

Vice President, Operations
Entergy Operations, Inc.
Grand Gulf Nuclear Station
P.O. Box 756
Port Gibson, MS 39150

SUBJECT: GRAND GULF NUCLEAR STATION, UNIT 1 – APRIL 23-25, 2014, AUDIT REPORT REGARDING MAXIMUM EXTENDED LOAD LINE LIMIT ANALYSIS PLUS AMENDMENT INCLUDING MINIMUM STABLE FILM BOILING TEMPERATURE AND QUENCH MODEL (TAC NO. MF2798)

Dear Sir or Madam:

By letter dated September 25, 2013 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML13269A140), Entergy Operations, Inc. (the licensee), submitted a license amendment request for Maximum Extended Load Line Limit Analysis Plus (MELLLA+). The proposed amendment request would revise the Grand Gulf Nuclear Station Technical Specifications to allow operation in the expanded MELLLA+ domain.

An audit was held on April 23-25, 2014, at General Electric Hitachi (GEH) offices in Wilmington, North Carolina. The audit was needed to support the U.S. Nuclear Regulatory Commission (NRC) staff's review schedule. To support the schedule for issuing the proposed amendment, the NRC staff requested an audit of the physics and implementation of selected methodologies used in support of the licensee's application.

The NRC staff's Audit Report is provided in the Enclosure. In addition, the NRC staff has determined that additional information is needed to complete this review. The request for additional information was provided on May 19, 2014, in a separate letter.

If you have any questions regarding the Audit Report, please contact me at (301) 415-1445.

Sincerely,

Alan Wang

Alan B. Wang, Project Manager
Plant Licensing IV-2 and Decommissioning
Transition Branch
Division of Operating Reactor Licensing
Office of Nuclear Reactor Regulation

Docket No. 50-416

Enclosure:
Audit Report

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AUDIT REPORT

MINIMUM STABLE FILM BOILING TEMPERATURE

AND QUENCH MODELS

ENTERGY OPERATIONS, INC.

GRAND GULF NUCLEAR STATION, UNIT 1

DOCKET NO. 50-416

1. SCOPE AND PURPOSE

The U.S. Nuclear Regulatory Commission (NRC) staff conducted an audit of minimum stable film boiling temperature and quench models and methods at General Electric Hitachi (GEH) in Wilmington, North Carolina on April 23-25, 2014. The audit included discussion of open items identified during the NRC staff's review of the Entergy Operations, Inc.'s (Entergy's), license amendment request dated September 25, 2013 (Reference 1), for Maximum Extended Load Line Limit Analysis Plus (MELLLA+) for Grand Gulf Nuclear Station, Unit 1 (GGNS). Specific topics discussed during the audit included:

- Review of methodologies associated with the following:
    - Recognition of minimum stable film boiling temperature (T_{min}) supporting data at high pressures
    - Physical basis of the TRACG quench model
    - Implementation of the T_{min} model in the TRACG code
    - Implementation of the quench model in the TRACG code

- Identification of any departures from an approved analysis method

- Assessment of compliance to NRC-accepted Q/A processes related to code maintenance

The list of NRC, Entergy (the licensee), and GEH staff present during the audit is included below.

Enclosure

NRC Audit Team:

- Tai Huang, Reactor Systems Branch Technical Reviewer, Office of Nuclear Reactor Regulation (NRR)
- Ashley Guzzetta, Reactor Systems Branch Technical Reviewer, NRR
- Christopher Jackson, Chief, Reactor Systems Branch, NRR
- Peter Yarsky, Senior Reactor Systems Engineer, Office of Nuclear Regulatory Research (RES)
- Steve Bajorek, Senior Technical Advisor for Thermal-Hydraulics, RES (remotely)
- Alan Wang, GGNS Project Manager, NRR (remotely)

Entergy Staff:

- Greg Broadbent

GEH Staff:

- Jim Harrison
- Larry King
- Charlie Heck
- Mike Cook
- Jens Andersen
- Dan Rock
- Curt Robert
- Randy Jacobs
- Craig Goodson
- Sara Rudy (Wednesday only)
- Jerald Head (on phone for exit call only)

2. DOCUMENTS AUDITED

The documents audited included:

- TRACG Model Description Licensing Topical Report
- TRACG Qualification Licensing Topical Report
- Relevant test reports for referenced experimental data
- Associated quality assurance (Q/A) review documents for pertinent TRACG model corrections and updates to include internal review documentation
- Access to design record files associated with TRACG T_{min} and Quench models

The specific documents are listed in Section 6 of this audit report.

3. AUDIT ACTIVITIES AND OBSERVATIONS

3.1 Minimum Stable Film Boiling Temperature

Various correlations for T_{min} were discussed during the audit. The Iloeje correlation for T_{min} is determined to have flow and pressure dependencies making it a non-conservative correlation for loss-of-coolant accident (LOCA) and anticipated transients without scram (ATWS) situations. The Shumway correlation (Reference 2) was developed as a replacement for Iloeje and is the correlation used for ATWS and ATWS with instability (ATWS-I) calculations in the GGNS MELLLA+ submittal. The NRC audit team chose to explore GEH's methods regarding material properties, void credit, and Reynolds number dependency in the T_{min} analysis using Shumway.

While the Shumway correlation was developed with a term to account for material properties, the development and assessment database includes only stainless steel experimental data. The Shumway paper (Reference 2) and MFN 13-073 dated September 2013 (Reference 3) describe the development of Shumway's correlation. The beta term in the Shumway correlation is a non-dimensional number relating conductivity, heat capacitance, and specific heat of the wall material to the fluid. Through the beta term the Shumway correlation accounts for material properties theoretically allowing it to be applied to alternative wall metals, such as zircaloy.

According to Shumway, the beta term contributes to an increase in the T_{min} predicted from his correlation (relative to stainless steel) of 150K at low pressures and 100K at higher pressures. The data supporting the material properties term in the correlation was discussed at length. Section 3.1.2 of this audit report discusses the assessment of the supporting data in detail.

The alpha term in the Shumway correlation is used to account for voids. During an ATWS-I, there are extreme oscillations in the void fraction around the cladding hot spot. This is a consequence of the large amplitude flow oscillations. Since the reactor power is high during ATWS, a reduction in flow is accompanied by an increase in void fraction (with some phase lag). Because of the large amplitude flow oscillation, the void fraction oscillation can be quite large. If the flow reverses out of the core, one can easily see how the void fraction could become near 1.0. It is also possible that the core flow can be greater than (>) 100 percent nominal flow rate, while power is less than (<) 50 percent so a very low void fraction is also possible (close to 0.0). As discussed at the audit, TRACE and TRACG calculations both predict that the void fraction near the cladding hot spot varies over a wide range, from less than 5 percent to greater than 90 percent.

The nature of the void term in the Shumway correlation is such that the difference in predicted T_{min}-T_{sat} for very low (i.e., zero) and very high (i.e., 100 percent) void fraction increases by a factor of 2 (Reference 2). However, Shumway states in Reference 2 that the void credit term in his correlation is not well supported by experimental data. In response to this concern, GEH initiated a corrective action report (CAR-57629) and a study of a possibly reportable condition (PRC 12-07). The NRC staff reviewed these documents which address predominantly design basis accidents (i.e., LOCAs). Generally, GEH concluded that peak cladding temperature (PCT) predictions are not sensitive to the T_{min} correlation because PCT is achieved prior to cladding surface quench and some degree of pre-cooling is required between the point of PCT and quench. Therefore, the correlation only affects the calculation of the time over which the cladding surface is at an elevated temperature. The staff inquired about the effect that a bias in T_{min} prediction could have on the calculation of maximum local and core wide oxidation, to which GEH replied that very large margins were available to regulatory limits.

The effect on ATWS-I analyses of the T_{min} correlation is different. The prediction of T_{min} during the large amplitude oscillatory phase of the ATWS-I contributes to the prediction of cladding rewet. A failure to rewet the cladding surface during a single period of an oscillation can result in a large temperature excursion. Because this mechanism of fuel damage is highly dependent on T_{min}, the NRC staff reviewed the implementation of the void credit in TRACG as described in Reference 4.

GEH addressed potential non-conservatism in the Shumway correlation with respect to this void credit by eliminating the void credit in the TRACG calculations. This approach was considered to be reasonable by the NRC staff as the void credit is not justified by the current experimental database. The NRC staff reviewed the implementation of the correlation in the TRACG source code as discussed further in Section 3.1.1 of this report.

Reynolds number dependence in calculating T_{min} using Shumway was discussed. During an ATWS-I scenario, there are large amplitude flow oscillations, including flow reversal for several fuel bundles at the inlet. These large amplitude flow oscillations predicted by systems codes such as TRACE and TRACG imply that the flow dependency of the T_{min} correlation may contribute to significant variation in the value of T_{min} adopted by the codes during a typical ATWS-I analysis. According to TRACG calculations, typical Reynolds numbers (Re) experienced during ATWS-I scenarios are less than 10^5. The Reynolds number dependence is described by Equation 19 of Reference 2 and one can see that the impact of this term at low Re (i.e., 10^4) is modest (about 2 percent change in T_{min}-T_{sat}). At higher Re (i.e., 10^5), the effect is larger (about 15 percent change in T_{min}-T_{sat}) and at a Reynolds number near the maximum considered by the data reported in Reference 2 (i.e., 8 x 10^5), the effect is quite significant (about 50 percent change in T_{min}-T_{sat}).

It was noted by the NRC audit team that over the expected ranges of Reynolds number experienced by the cladding hot spot during ATWS-I calculations, the variation in the difference between T_{min} and T_{sat} would vary by about 15 percent. Further, the NRC staff inquired about the performance of the correlation at a high Reynolds number because TRACG does not cap the Reynolds number in T_{min} calculations. This could result in unexpected results if the Reynolds number grew significantly large. However, for the current audit scope, GEH has demonstrated that predicted Reynolds number during simulations of ATWS-I remain below the maximum Reynolds number in the original set of Shumway data.

Given that some variation in predicted T_{min} can be attributed by flow conditions, the NRC staff questioned the results of the comparison of T_{min} to data as provided in the March 10, 2014, Request for Additional Information (RAI) responses (Reference 5). In this response, a figure was provided comparing various T_{min} data to the prediction of T_{min} according to the Shumway correlation. However, the response was not clear as to what Reynolds number was assumed to apply for the various data points and what Reynolds number was used in the evaluation of the predicted T_{min}. GEH responded that Re=0 was applied in the "predicted" T_{min} curve and no consideration was given to flow conditions from the various test data. The staff noted that the Halden tests included rather dramatic flow changes during quenching and that the experimental Reynolds number would be rather high. In response, GEH evaluated the T_{min} predicted by TRACG for specific Halden experiments which accounts for the Reynolds dependence explicitly. The results indicate that the predicted T_{min} for the Halden tests is about 20-30K higher than what is indicated by the curve in the RAI response. This result shows that the agreement between the experimental data and the correlation is better than indicated by the RAI response (in other words, the correlation is not as conservative as would appear to be the case from the figure in the RAI response). A more detailed discussion of the staff audit of the Halden data is provided in Section 3.1.2 of this report.

3.1.1 Implementation of T_{min} in TRACG

The implementation of T_{min} in TRACG is described in detail in the TRACG model description at Reference 4. Data supporting the model description can be found in the TRACG Qualification documentation (Reference 6). During the audit, the NRC audit team reviewed the implementation of T_{min} in the TRACG code in detail.

The specific value of T_{min} for any calculation is determined according to the associated subroutine for the user-specified T_{min} correlation. The NRC staff reviewed the FORTRAN source code for the Shumway correlation to better understand its implementation in TRACG and the specific means in which TRACG predicts the T_{min} according to the Shumway correlation. When computing the T_{min}, TRACG calculates the difference between the T_{min} and the saturation temperature, referred to in the code by variable DTMIN. In the TMRWS subroutine, a user-specified flag of 1 indicates that the Shumway correlation is to be used in calculating DTMIN.

The NRC staff reviewed the mathematical operations and confirmed that the source code adequately reflects the correlation provided by Equation 19 of Reference 2. Further, since the void credit term is not supported by experimental data, the staff reviewed the implementation to understand how the void credit term is suppressed in the TRACG calculations.

For design basis accident analysis purposes, TRACG includes a feature that allows users to adjust certain closure relationships according to biases and uncertainties. This general feature supports the application of TRACG in the framework of best-estimate-plus-uncertainty analysis consistent with the Code, Scaling, Applicability, and Uncertainty (CSAU) methodology. The treatment of bias and uncertainty is controlled by "PIRT" factors in TRACG. Phenomena Identification and Ranking Table (PIRT) refers to PIRT because the PIRT identifies those specific phenomena that are important to a specific design basis event and therefore identifies the specific models or correlations that should be treated in the uncertainty analysis. While ATWS events are beyond design basis, a PIRT factor was introduced in TRACG to adjust the void dependence term of the Shumway correlation.

During the audit, the NRC staff learned that PIRT-265 is a factor applied to the (1-alpha) term in the calculation of DTMIN in TRACG. (Note the label "PIRT-265" does not mean: "phenomenon identification and ranking table – 265." It is a factor applied in TRACG for the purpose of uncertainty analysis.) It is designed such that specifying a value of PIRT-265 of 0 disables the void credit term in the correlation, thus removing any credit from a void fraction of less than 1.0 on the calculated DTMIN.

Further, the NRC staff audited additional subroutines in the TRACG source code to understand when T_{min} is calculated and how the correlation is used in a prototypical ATWS-I evaluation. T_{min} is primarily used by TRACG to determine the heat transfer regime. The NRC staff reviewed the heat transfer regime identification subroutine. In this subroutine, the staff began reviewing the control logic associated with identifying the transitions from pre-critical heat flux (CHF) to post-CHF heat transfer. The source code indicates that a Wall Temperature (TW) in excess of T_{min} (TMIN) will force the code to evaluate heat transfer based on a film boiling regime (additional logic in the code identifies sub-regimes of film boiling; for example, if the heat transfer is Dispersed Flow Film Boiling (DFFB) or Inverted Annular Film Boiling (IAFB)). Once wall temperature exceeds T_{MIN} the code locks an IDREG (or heat transfer regime identification) of 4, which indicates film boiling. The heat transfer regime logic indicates that once a heat structure surface enters into IDREG=4 it can only exit to transition boiling (IDREG=3) when two simultaneous conditions are met. The first is that the critical quality must be greater than the current quality and that the temperature must be below T_{min}.

The first stipulation (i.e., the critical quality condition) is necessary as a transition to quality above critical quality triggers TRACG to identify the associated node as being in boiling transition, but this indication, according to the logic, pushes the IDREG to 4 immediately. That is, a fuel rod entering boiling transition will lock into film boiling until it can cool down through the transition boiling regime.

In this implementation, the value of T_{min} in the code acts as a heat transfer regime logical threshold dictating the transition from film boiling to transition boiling. This is very analogous to the description of the quenching temperature discussed by Shumway in Reference 2. Therefore, the NRC staff concludes that TRACG is using the correlation of T_{min} as intended by the developer.

The NRC staff reviewed other subroutines in TRACG to understand the other parts of the system calculation affected by T_{min}. The only other area is the calculation of the heat transfer coefficient in the transition boiling regime (IDREG=3). This is only true in those nodes that do not have a quench front (see Section 3.2 for discussion regarding the staff audit of the quench model).

When the wall temperature falls below T_{min} and there is sufficient quality in the flow to allow a change in heat transfer regime from film boiling to transition boiling, the heat transfer coefficient is constructed for the node based on an average of heat transfer coefficients. The averaging uses TCHF and T_{min} which correspond to the lower and upper wall temperatures associated with the transition boiling regime. The heat transfer coefficient is then calculated based on a quadratic averaging given the current wall temperature, TCHF (which is predicted by either the Biasi or Zuber correlations depending on the flow conditions) and T_{min} (which is predicted by the Shumway correlation). The weighting factor employed in TRACG is similar to the method adopted in TRACE.

The ability of TRACG to determine which boiling regime it is in was reviewed by the NRC audit team. In TRACG, T_{min} is used as the pivot point to where transition boiling stops and film boiling begins. The heat transfer correlation used by the code is dependent upon which heat transfer regime is occurring in a particular node.

3.1.2 Interpreting Data for T_{min}

The available zircaloy data used to compare to the Shumway correlation in the GGNS MELLLA+ submittal was reviewed during the audit. The RAI response from March 10, 2014 (Reference 5), was used as a basis for discussion. Oxide thickness and surface roughness has an effect on T_{min}, but the exact effect is unknown. As oxide builds up, T_{min} has potential to increase, but the quantification of the oxide thickness to the amount T_{min} increases is unknown. For these reasons, oxide credit is not used in determining T_{min} in TRACG.

Specifically, the Halden data included in the RAI response from March 10, 2014 (Reference 5) was reviewed. The dryout tests performed at Halden as documented in HWR-499 and HWR-552 were identified as valuable because these tests were performed at high pressure (6.3-6.9 MPa) which is close to expected pressures in ATWS-I scenarios (between about 7 and 8 MPa) and with zircaloy clad fuel rods. This allows for direct assessment of the performance of the Shumway correlation for the material of interest (zircaloy) at the pressure range of interest. Further, these tests induce fuel heat up at high linear heat generation rates (LHGRs) with large flow transients, which is similar to conditions expected during high flow in-flux during ATWS-I.

There were several aspects of the Halden assessment reviewed by the NRC staff during the audit. The first is the viability of using the data given consideration of the potential for oxide layer formation to significantly impact the observed T_{min}. GEH performed a calculation of the oxide thickness based on oxidation models (i.e., Cathcart-Pawel) based on experimental thermocouple (TC) traces provided in the Halden reports. For the HWR-499 data, the oxide thicknesses were modest (less than about 50 microns). The calculated oxide thicknesses for the HWR-552 tests were even lower. GEH performed some calculations to assess the impact that the oxide layer would have on the heat transfer which indicated a modest effect; however, the staff could not conclude that the GEH methodology was appropriate for determining the significance of the oxide on quenching behavior. In short, the small amount of oxide, in particular, the HWR-552 series of tests was deemed sufficiently small on the basis of engineering judgment to likely have a negligible impact on the quenching behavior.

Secondly, the March 10, 2014, RAI response (Reference 5) provides several data points collected by a review of the HWR-499 and HWR-552 reports. However, these data points were modified according to a TC bias reported in HWR-666. According to HWR-666, the TC bias for various rod tests was determined based on a combination of the measured rod elongation during the tests and predictions of the zircaloy thermal expansion and thermal calculations. The reported TC biases in several cases are quite large (Reference 9).

The NRC staff was not able, based on sparse information regarding the methodology for determining the TC bias, to conclude that the large biases in peak TC temperature were adequately justified. GEH staff was able to update the comparison of these Halden data to T_{min} predictions by removing the reported biases. The updated comparison indicated that the data were in much closer agreement with the Shumway correlation. The NRC staff concludes that removal of the TC biases reported in HWR-666 is prudent given that little detail is provided on the basis for the determination of the bias.

Lastly, the NRC staff reviewed the basis for interpreting the quench data from the Halden tests. GEH had interpreted the quench temperature as the maximum temperature from which a very rapid cooldown was observed following the reintroduction of high flow to the test section. The NRC staff notes that in various tests some temperature oscillations in the TC signal are apparent which may be due to flow leakage; however, agrees with the basis provided by the GEH staff that the temperature of interest is this maximum temperature around the time of flow increase. Since quenching is precluded above T_{min}, selection of this measured temperature as

"T_{min}" data is likely conservative since it only indicates that T_{min} is higher than the measured value.

In addition to the Halden test data, the NRC staff also reviewed the use of the Hofmann low-pressure quench data. Several lower pressure tests were conducted to study quenching by Hofmann, et al. (Reference 11). These tests considered variation in oxide layer thickness between 0 and 300 microns on zircaloy. GEH staff went through a screening process to determine if each Hofmann test quenched and the temperature at which the quench occurred if present. The screening process was based on engineering judgment and evaluation without any rigorous criteria. For example, if a steep (defined by GEH at this audit as greater than about 300 K/s) and continuous drop in temperature to saturation temperature was seen, it was categorized as an "obvious quench." If the quench was not categorized as obvious, the data was not used in the validation. As an illustrative example, the staff considered the GEH classification of TC measurement data from the 43w test (this test was conducted at a peak temperature of 1400 degrees Celsius (°C), with 300 microns of oxide, and quenched with water). From the results, GEH concluded that an obvious quench occurs at around 7.5 seconds from about 550 °C as indicated by L1207_1 in Figure 1. However, the change in heat transfer occurring around 800 °C at 3.5 seconds in the L05066_1 trace was not considered as viable quench data.

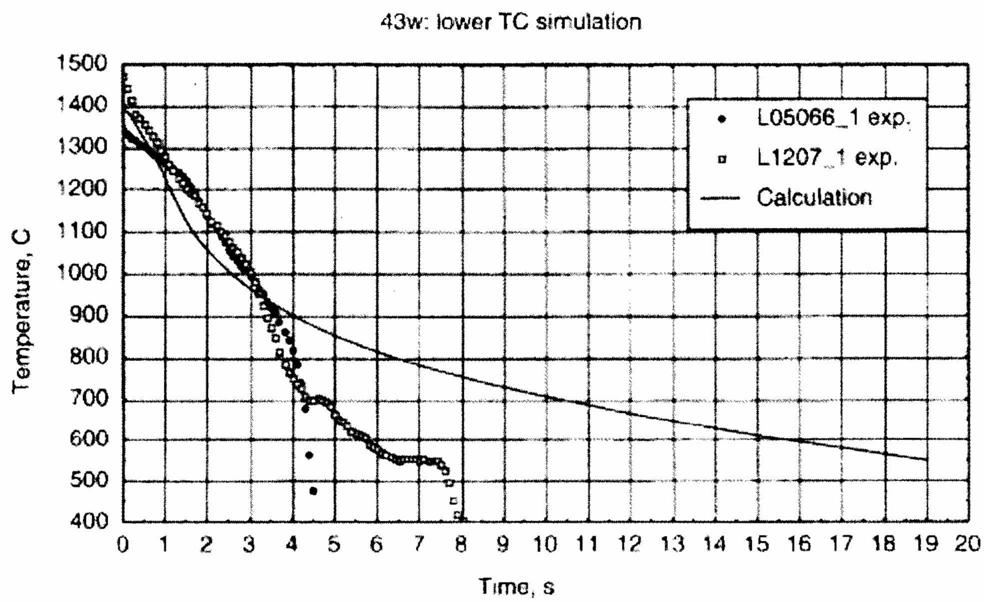

Figure 3.39: Temperature evolution of the lower TC in the 43w type experiment (1400 °C, 300 μm pre-oxidation, water quenching) in the time interval 0–20 s.

Figure 1: Sample Hofmann Temperature Trace 43w

During analysis of the "obvious quench" data by GEH, no substantive difference was observed in the average measured quench temperature or statistical variation. This result was not expected since the oxide layer is expected to have a multi-pronged effect on the physical T_{min}. However, since the details of the various mechanisms (e.g., surface roughness and material heat capacity) are not well understood, the 300 micron oxide layer data is no longer being used to support the GGNS MELLLA+ submittal.

The NRC staff conducted an audit of GEH records indicating which temperature traces were included as obvious quench data. The NRC staff agreed with the GEH determination of those traces which show obvious quench. However, there are some nuances to these data that were not considered in the GEH assessment. The first nuance is that no data from the 0 micron tests were included after the screening. However, several of these tests were excluded because no observed reduction in temperature is reported in the temperature traces from the source report (Reference 11).

Figure 2 provides one such TC response from the 20w test. The experimental data include some temperature oscillation below 600 °C, where the experimenters report that the TC becomes unreliable. However, the indication from the L28095_1 trace appears to indicate a failure to quench for temperatures above 600 °C.

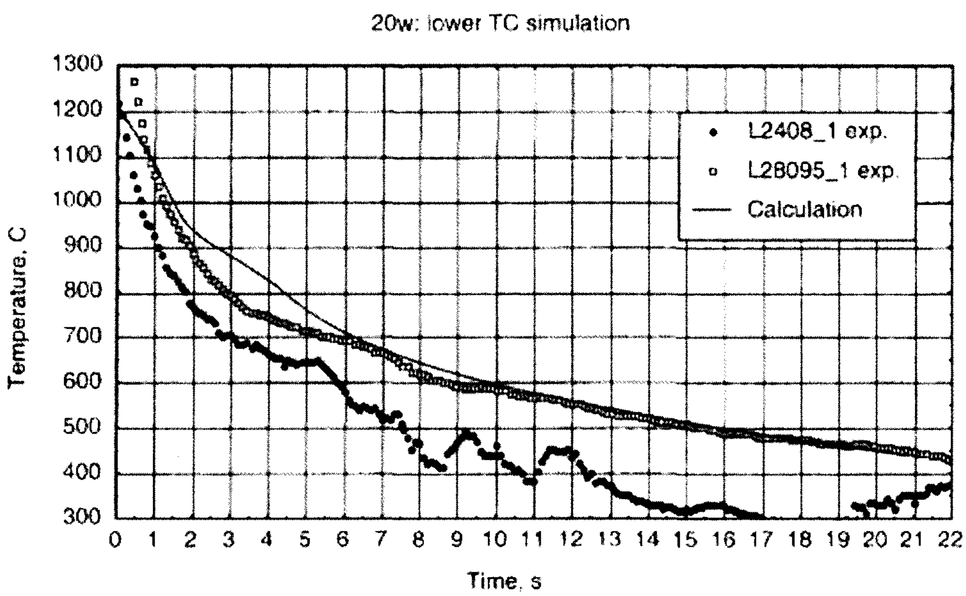

Figure 3.45: Temperature evolution of the lower TC in the 20w type experiment (1200 °C, 0 μm pre-oxidation, water quenching) in the time interval 0–22 s.

Figure 2: Hofmann Temperature Trace 20w Lower TC

Similarly, Figure 3 shows measurements from the same test at the central TC location. These data also show temperature oscillation below 600 °C, as in the case for the C28095_1 trace, but likewise, a continued high temperature response from the C2408_1 trace. These data can likely be used to establish an upper limit of T_{min} for those traces where no quench is observed. Indication of sufficient liquid inventory for quenching can be inferred by pre-cooling from steam generation at lower TC locations within the test. For example, test 20w suggests steam cooling coming from water being heated in the lower portion of the test section.

Consideration of data from the 0 micron tests according to looser "criteria" for inclusion appears to be consistent with the Shumway correlation predictions at lower pressure.

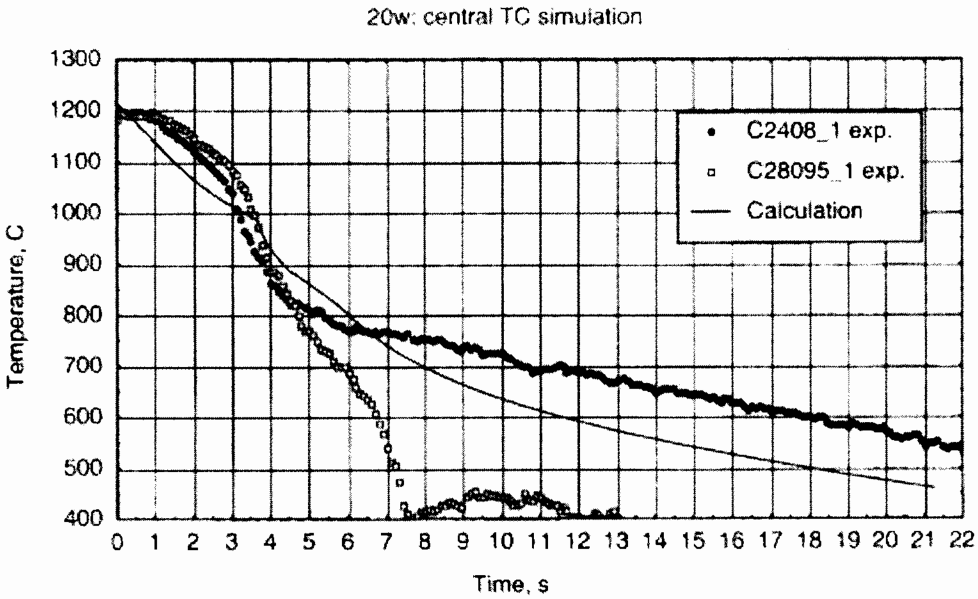

Figure 3.47: Temperature evolution of the central TC in the 20w type experiment (1200 °C, 0 μm pre-oxidation, water quenching) in the time interval 0–22 s.

Figure 3: Hofmann Temperature Trace 20w Central TC

On the basis of the information audited by the NRC staff, it appears that the Shumway correlation produces reasonable prediction of the T_{min} for zircaloy with small oxide layers (given that no credit is assumed for void fraction). Once biases were removed from the Halden data, and Reynolds dependence is accounted for, the correlation appears to be reasonable (possibly, slightly conservative) at higher pressures.

Evaluation of the data does not give clear indications of the nature of the effect of the oxide layer on T_{min} other than to indicate it is prudent to neglect any potential increase in T_{min} as a result of the layer. This is consistent with the current approach adopted in TRACG.

3.2 Quench Model

During the audit, the implementation of the quench model in TRACG was reviewed in detail. Specific items of review included: (1) how TRACG determines the presence of a quench front, (2) which direction the quench front is moving, (3) the maximum number of quench fronts that can be tracked at once, (4) how quench front heat removal is calculated, and (5) how quench front progress.

The NRC staff reviewed the TRACG source code to determine how TRACG determines the incidence of a quench front during a calculation. Each heat structure (or channel rod group) will have an axial distribution of heat transfer regime numbers. As stated in Section 3.1.1, for example, an IDREG of 3 corresponds to transition boiling while 4 corresponds to film boiling. An upward moving quench front is "born" in the calculation in the lowest axial node with an IDREG greater than 2 which is directly above a node with an IDREG of 2 (i.e., nucleate boiling). Analogously, a downward moving quench front is "born" in the uppermost node with an IDREG greater than 2 directly below a node with IDREG of 2. Only two fronts can be tracked per fuel rod group, one upward moving and one downward moving. The structure of the logical checks for quench front incidence is such that only the lower most and upper most candidate nodes are subject to quench front treatment in TRACG.

The NRC audit team noted that the documentation discussing the quench model methods and implementation should be updated for completeness and understanding.

Once a quench front is "born" in the calculation, the presence of the quench front in any given node overrides the normal calculation of the heat transfer coefficient in that node. For example, a quench front "born" in a transition boiling node would override the normal computation of heat transfer within that node. The implementation is such that an average nodal heat transfer coefficient is calculated to account for three heat transfer mechanisms from the cladding surface to the fluid. Pictorially, the mechanisms are shown in Figure 1 of MFN 13-085 (Reference 13).

The first component is the quench front itself, which removes an amount of heat dictated by a semi-empirical correlation of heat transfer coefficient and Leidenfrost temperature. In the TRACG implementation, the ΔTq (or difference between Leidenfrost and saturation temperature) is taken as 65K, which is slightly conservative relative to the 80K recommended by Yu, Farmer, and Coney (Reference 12). The heat transfer coefficient in the representation is given by empirical fitting to data (either falling film data for a downward moving front or FLECHT data for an upward moving front, see Reference 4). The heat removed by the front is then applied to the liquid phase adjoining the fuel rod group within the same node as the front.

There are certain limits imposed on the heat removal from the front. While a front may be "born" in a node, which does not necessarily mean that TRACG will calculate heat removal due to the front. Void-based ramps and limits are imposed as described in Reference 3 that adjust the heat removal calculated by the quench model. If insufficient liquid is present in the node, then quench front heat removal is first reduced and then eliminated. This prevents TRACG from calculating non-physical results, such as quench front heat removal from a node where there is no liquid water.

In addition, heat transfer is credited for the liquid adhering to the surface upstream of the front and the vapor downstream of the front. While not explicitly tracked, in order to compute the contributions from these two components, the portion of the node that is rewetted is required. This parameter (Δzq) appears in Equation 8 of Reference 13. The front motion is not predicted by TRACG using the analytical formulation of the front velocity. Rather, a detailed review of the source coding indicates that the quench front position within the node is determined at every time step based on the calculated nodal average wall temperature. In essence, the position of the front is set at the beginning of a time step such that the linearly weight upstream and downstream nodal temperatures yield the calculated average nodal temperature. This means that the quench front progresses from each time step based on the calculated transient response of the nodal average temperature. The NRC staff had a question regarding the TRACG model description which states that a quench front velocity limit is imposed. GEH responded that this limit does not actually apply to the prediction of the motion of a quench front in the calculation. This answered the NRC staff's concern.

Once the front location is determined, Equations 7 and 8 of Reference 13 are straightforwardly employed to calculate the component heat transfer to the liquid and vapor phases.

The NRC staff also studied the implementation to understand the potential scenario of quench front "death." While the logic indicates that a front can be "born" based on the axial distribution of heat transfer regime IDs, it is possible that once a front exists and, perhaps, quenches a node, that the criteria for front incidence are not met in the following time step in the calculation. Under this condition, the quench front automatically propagates to the nodal extrema of the fuel rod group. Once born, the upward moving and/or downward moving fronts are continuously tracked though they may "jump" to the core's nodal extrema during the transient.

Further, since upward and downward moving fronts are both tracked, the staff reviewed the implementation to better understand how TRACG predicts heat transfer for a node containing both a downward and upward moving front. This is particularly likely to be the case in ATWS-I simulation since the core hot spot is expected to occur in a localized region near the fuel inlet.

When there are two quench fronts in the same node, the calculation replaces the determination of the Tw+ (or downstream wall temperature) with a new temperature. Otherwise, the Tw+ would be calculated as a low temperature since the node both above and below the node with two fronts are quenched. In the TRACG source code, a maximum is taken of the current wall temperature, the Liedenfrost temperature, or the downstream temperature. In this manner, if the neighboring nodes are quenched, the subnodal positions of the fronts are calculated according to the maximum possible downstream wall temperature. In instances where the highest temperature is the wall temperature, the calculated Δzq is set to zero and only film boiling and the double quench front heat removal are considered (i.e., there is no nucleate boiling heat transfer credited).

When Tw is below the Liedenfrost temperature (TLEID), the fronts move closer towards each other. When Tw is greater than TLEID, the fronts are held at the top and bottom of the dual front node and only film boiling and quench front heat removal mechanisms are treated in the calculation.

The results of turning the quench model on and off in TRACG were presented by GEH staff and evaluated by the NRC audit team. GEH analyzed four Halden cases and presented the results of T_{min} in TRACG and the Halden tests versus pressure. When the quench model is turned on in TRACG, results show good agreement with Halden tests. When the quench model is turned off in TRACG, quench never occurs because T_{min} is never reached. Without the quench model, the heat flux remains very high and temperature never decreases to T_{min}.

It is worth noting that the timing of quench, and in particular, the time taken to reduce high temperatures to pre-CHF temperatures, is very important to the evaluation of event consequences during ATWS-I. Extreme heat-up is likely in scenarios where cladding surface temperature exceeds T_{min} and quenching heat removal cannot remove all of the deposited energy over the course of a single period of flow oscillation. The lower T_{min} is, the more important the quench model is because it takes longer for temperature to reach T_{min}. MFN 13-085 presents the results of sensitivity studies performed using TRACG with and without the quench front model for four Halden tests. Agreement in the predicted peak temperature is not as important as the prediction of the timing to reach pre-CHF wall temperatures starting from high temperature. The boundary conditions in the TRACG assessment calculations are adjusted to match experimental data. The results indicate that without using the quench model, TRACG does not accurately predict the cool-down timing for HWR tests 4 and 12 (References 8, 9, and 10).

3.3 Margin between PCT and T_{min}

For the case of GGNS, T_{min} is not reached in ATWS analyses; therefore, the quench model is not expected to be active even though the model is turned on for plant-specific analysis in the MELLLA+ application. The GEH staff presented PCT and T_{min} on the same graph so the margin to T_{min} could be assessed. T_{min} fluctuated about 100K due to flow changes and void dependencies in the beta term (Section 3.1). The results showed the smallest margin to T_{min} was quite small (about 30K).

4. QUALITY ASSURANCE RELATED TO CODE MAINTENANCE

The implementation of changes in TRACG are performed using a defined process that was approved by the NRC staff during its review of TRACG04 for anticipated operational occurrence (AOO) and ATWS overpressure transients (Reference 14). The NRC staff concluded that the Q/A process used by GEH, hereafter referred to as the Level 2 process, was acceptable for meeting the associated regulatory requirements. Licensing work performed using TRACG for AOO, American Society for Mechanical Engineers (ASME), and ATWS overpressure transients was confirmed to be performed using the Level 2 code version. With respect to approved methods and licensing evaluations, the NRC staff confirmed that GEH was in compliance with the approved procedures and processes.

For the unapproved application of TRACG to ATWS events for MELLLA+ applications, a non-Level 2 code version is used that includes various code updates reviewed by the NRC staff as part of the current audit. It was made clear by GEH staff that the changes were independently verified and did not go through the Level 2 verification process. The independent verification procedure for engineering computer programs was followed by GEH. The version of TRACG used for MELLLA+ ATWS calculations is tracked as an independently verified, non-Level 2 code release. The NRC staff reviewed the independent verification process documents included the description of the code modifications and the checklists used by the independent verifiers. The audit team also conducted a thorough audit of the source code changes made in this version as part of the current audit.

5. CLOSING BRIEFING

The NRC audit team became more familiar with T_{min} data, methods, and implementation in TRACG. The licensee committed to updating the March 10, 2014, RAI Response (Reference 5) with the following:

- TC bias on the Halden data removed
- Reynolds number offset data in tabular form relating to the HWR-552 tests included
- T_{min} versus cladding temperature graphs for HWR-552 tests included

During the audit, GEH staff presented the margin between PCT and T_{min} for GGNS MELLLA+ ATWS-I. The May 19, 2014, RAIs included a request for identifying the margin to T_{min} as presented.

The quench model and its implementation in TRACG was reviewed in detail during the audit. The NRC audit team stated that the model description needs to be updated to include items not limited to the following:

- How two quench fronts converge
- Adjusted heat temperature coefficient and its derivation in the quench node
- The physical process involving two progressing quench fronts and how it is modeled in an ATWS-I evaluation
- When a node has a quench front
- How a quench front is "born" in the calculation

The Q/A review of the code changes was evaluated during the audit. The NRC audit team understands the code is at an intermediate stage. GEH is following an internally defined process for the use of non-Level 2 code. It was made clear that changes made to TRACG are for support of AWTS-I analyses and do not affect other analyses that require a Level 2 approved version of the code.

Overall, the audit was effective and the objectives defined in the audit plan were accomplished. The information and knowledge obtained will assist the NRC staff in its review of the GGNS MELLLA+ submittal.

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Date: November 25, 2014

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Sincerely,

/RA/

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Office of Nuclear Reactor Regulation

Docket No. 50-416

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