Comments on NRC ML19073A249
Credibility Assessment Framework for Critical Boiling Transition Models

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This report focuses on the Credibility Assessment Framework for Critical Boiling Transition (CBT) models, presenting a generic safety case in the form of a credibility assessment framework that combines aspects of goal structuring notation (GSN) and maturity assessment with specific application to reactor safety. Among the many assessments prepared by NRC, this report presents a well-organized, systematic, and very clear and comprehensive views of CBT models and their applications for reactor safety.

There are some comments and questions related to the experimental data, CBT models, and safety applications.

1. In 2.1.2.3 10 CFR 50.34(a)(4) it specifically requires that the Preliminary Safety Analysis Report (PSAR) include determination of the margins of safety during normal operation and AOOs, which include the margin to CBT. Furthermore, in 10 CFR Part 50, Appendix B, it requires licensees to include certain structures, systems, and components (SSCs) in a quality assurance program that satisfies specific criteria. Appendix B, Criterion III, requires that specified design control measure be applied to the design of safety-related SSCs and these measures apply to safety analyses for these SSCs. The CBT model is a key component of the safety analysis subject to 10 CFR Part 50, Appendix B. In the above sections of this report, the requirement for a quality assurance (QA) program is mentioned; however, there is no clear indication on what and how extensive this QA program has to be. It seems leaving the experimental facility large freedom in performing their own experiments without a clear guidelines for the types of procedures and records that should be included in the QA program. For example, for the heat loss calculation, although the requirement for heat loss correction is mentioned, there is no specific requirements on how and what degrees such heat loss calculation should be carried out, calibrated, or benchmarked. Furthermore, there is no guideline or requirement on addressing the application of heat loss correction factors obtained under steady state single phase conditions (which is most commonly exercised in the industry) to a two-phase flow system with high potential of involving different degrees of transient operations which might result in as much as 20% to 30% of measurement uncertainty. (reference paper by Liu and Yang, Nuclear Science and Engineering, 2019, 193(1-2): 185-197) [1].

2. Other examples of the potential issues include operational hysteresis, bundle alignment issue, rod-to-rod gap, and rod-to-wall gap [Lyu & Yang], etc.

3. On page 15, the CBT models used during LOCAs are typically models, "which are not necessarily fuel design specific". This statement might be correct in the past with old

conventional fuel design where this type flow instability driven integral thermal-hydraulic phenomenon might not be plant specific. However, with recent advancement in developing various turbulence and cross mixing functions through the design of mixing vane grid, the performance under low flow local pressure LOCAs conditions might have totally different performance than the flow regime that the MVG is designed for, and the performance under such condition might be plant specific and cannot be corrected by applying a simple and constant penalty to the performance under normal operating conditions (Yang & Dougherty)[2].

4. In P40, 3.1.3.2 G1.3.2—Prototypical Grid Spacers
   Recently, the spacer grid model in subchannel code has been greatly improved. The Distributed Resistance Model of grid spacer has been developed to reflect cross flow mixing generated by the mixing vanes. In the process, the design features of spacers are reflected and incorporated as an added source term, which greatly improves the prediction of spacers' impact [3]. The prediction results of new spacer model were much better than the traditional thermal diffusion coefficient (TDC) or turbulent diffusivity terms derived from thermal mixing result. With the development of spacer DRM model, the future prediction of local condition as well as CHF (CBT) model will be more accurate and better in reflecting the true impact of spacer.

5. During the rod bundle CHF experiments, the use of the none-prototypical shroud box with coarse ceramic defining hydraulic flow boundary often presents a serious challenge in performing (maintaining the geometry) and analyzing the rod bundle CBT experimental results. A too small rod-to-wall gap might lead to non-conservative test results or sometimes even result in cold rods CHF. On the other hand, too large rod-to-wall gap will allow the bypass of coolant and result in a too conservative result. A proper rod-to-wall gap should be analyzed and properly designed to minimize the impact of cold wall effect, which can be performed using both CFD simulation and subchannel modeling [4, 5, 6 Lyu and Yang, et al.]

6. mDNBR/mDNBR vs. BO/BO in model development and safety analysis application
   There are two common approaches in analyzing the experimental data for CHF correlation (or CBT model) development as well as safety analysis application. The first one is to perform the data analysis/CHF correlation development as well as the safety analysis both at the BO (burntout) locations, called BO/BO approach. The second approach is the so called mDNBR/mDNBR approach. That is, the analysis/correlation are being carried out at the point of minimum DNBR (or the intersection point between the CHF correlation curve and the power curve). In that case, the CHF correlation/CBT model should be also applied for CHF prediction for safety analysis at the location of mDNBR. As I presented during the keynote speech in ISACC (International seminar on Subchanel Analysis CFD and CHF) [Yang, 2015 ISACC, 9], the mDNBR/mDNBR approach might be easier to use and tends to give high predicted results, and it often faces a major challenge of predicting the correct burntout location/elevation as compared to the actual experimental data, which are not included for training of model. This is because accuracy for CBT (or CHF) location prediction requires accurate models for both CHF correction (or CBT model) as well as the actual power curve. Based on the description in this report (pages 19 and 58), this report seems more in favor of using the mDNBR/mDNBR approach as it calculates and predicts only one subchannel (and one location) with mDNBR value as compared to the potential for multiple burntout locations in an experimental run. However, while emphasizing the importance on accuracy of CBT (or CHF) value prediction, this report did not describe or provide the guideline on accepting (or rejecting) criteria regarding the CHF (or CBT) location predictability. This is a rather critical for the mDNBR/mDNBR approach because predicting a correct CHF value at wrong elevation of a high peaking power curve (says 1.55 peaking or higher) could lead to a much different value in limiting power. Furthermore, a CHF correlation that cannot predict both CHF value and location accurately (for the validate data, not the

train data) could be a good indication of bad modeling for the performance of the spacer grid. This usual happens when non-representative rod bundle CHF data (such as the data obtained from uniform heater rods) were used for the development of CHF correlation.

7. In 3.1.1 G1.1—Credible Test Facility (Page 24) & 3.1.1.2 G1.1.2—Test Facility Comparison (page 26), this report describes the need for benchmarking test results against well known facility "Most facilities in use today have been compared to their older counterparts (for example, many facilities have performed tests to compare to data collected at Columbia " , however, there is no guideline on how and to what extent that this benchmarking or comparison should be carried out. There is no instruction on what operational range, test conditions, test configuration, and operational procedure should be benchmarked against. For example, for the benchmark test using exactly the same MVG designs and configuration, same heater rod designs and same test conditions, what is the requirements for the repeatability (compare only the CBT measurement values on a pair comparison basis?)? What is the requirements for the repeatability if also compare the location/elevations of the CBT events? Should the comparison perform on the pure data to data level (what is the acceptable criteria for the variation of operation conditions/ parameters) or should a CHF correlation/model with subchannel code be involved to provide M/P comparison?

   Also, as importantly, should the repeatability check be carried out to verify the hysteresis by taking different approaches in obtaining the same data? Most importantly, can a benchmarked range/conditions be extended for test configuration/ranges beyond the original test conditions/configurations (extrapolation acceptable)? This is especially important for the on-going fuel performance improvement process where most of the newly developed fuels with more advanced MVG designs tend to have higher and higher CHF (CBT) performance, which will require rod bundle CHF tests under higher power and maybe also higher quality conditions with higher challenge on loop control and measurements. In this case, will a continued periodic calibration/benchmarking be required for a test facility (just like any calibrated instruments)?

8. Selection of a representative 5x5 prototype spacer grid.

As the report mentioned, the selection of represented fuel assembly for experimental testing is important; a small change of spacer grid will affect the thermal in this report hydraulic phenomenon and ultimately affect the CBT. However, there is no guideline given in this report on how to modify the 5x5 grid, so it can represent the 17x17 or 15x15 fuel assembly physically. In a typical 17x17 or 15x15 fuel assembly, it is impossible to cut off/configure a 5x5 typical cell (no guide tube) bundle directly without including any guide tube rod or instrumentation rod. Therefore, the way to select a typical 5x5 bundle with dimple, spring, and mixing vane configuration, especially for the vanes on the outer strips that are supposed to be removed or altered to allow space for the rod-to-wall gap. .

There are no standards or guidelines given in this report on how to select a 5x5 or 6x6 test configuration for a typical cell rod bundle CBT test. In the past, there seemed a general consent of having a test configuration with "conservatism" in mind with a main focus on modeling the inner cell vane configuration (the inner 3x3 in the 5x5 bundle) in maintaining the turbulence mixing function. However, with more and more MVG (mixing vane spacer grids) having the design concept aiming to promote not only turbulent mixing but also cross flow mixing, the vane patterns of the external vanes as well as the external strip, dimple, and spring are inevitably gaining significant influence in the overall CBT performance in the rod bundle CBT testing. (Han and Yang, et al.). Hence, sooner or later, a general guideline should be given to regulate the way that the 5x5 or 6x6 test configurations should be determined. Most importantly, it is to keep a good record (as a part of the NQA program) of the actual rod bundle CBT test grids to avoid future confusion and minimize any non-conservative approach in the CBT test grids. This type of non-conservative approach is sometime done by reducing (or totally eliminating) rod-to-wall gap in order to re-direct more coolant toward the center hot channels or simply by adding extra thick outer strip to not only blocking coolant bypass channels but also minimize the chance for miss-alignment and avoid the potential of cold rod CHF due to some unexpected test configurations (such as bundle misalignment, etc.). Unfortunately, it is rather obvious, this type of approach is totally none prototypical, and have high potential of generating non-conservative results.

Reference 【Han & Yang, 10】, In this paper (accepted for publication at the NURETH-18, August 2019) [Bin Han, Bao-Wen Yang. CFD Analysis on Mixing Vane Grid Performance in a 5x5 Rod Bundle [C].18th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-18), August 8-22, 2019, Portland, Oregon, USA]. The effect of small vane change at corner channels on the overall flow field was investigated.

9. Issue of rod bundle CBT experiments using uniformly versus non-uniformly heated rods
   Axially uniformly heated heaters:

As a referenced in the report [Yang, B., Shan, J., Gou, J., Zhang, H., Liu, A., & Mao, H. (2014). Uniform versus nonuniform axial power distribution in rod bundle CHF experiments. Science and Technology of Nuclear Installations, 2014.], the CHF data obtained from an axial uniformly heated heater rod cannot truly reflect the CBT phenomenon in the reactor core. For the axially uniformly heated test section, the CHF will most likely occur at the exit of the test section where the quality is at its maximum. That is, the CHF will most likely occur as a maximum quality driven integral phenomena dry-out (DO) event. On the other hand, for an axially non-uniform heated rod, with the exception of exit peak skew power shape, the CHF does not always occur at a certain elevation (exit peak or channel exit); rather, it often occurs at a location based on the combined effect of local quality and heat flux peaking, where the CHF is more likely to take place as a local phenomenon DNB event under relatively high subcooled condition.

10. Effects of Exit Quenching for uniformly heated as well as exit peak rod bundle CHF experiments
    Another thermal hydraulic phenomenon challenging the integrity and representation of uniformly heated rod bundle CHF experiments is the exit reflood quenching phenomenon [Reference. Liu & Yang—NED 2019 paper]. This phenomenon not only impacts major portions of the non-uniformly heated CHF data, it also potentially affects rod bundle CHF testing with exit peaking power curve where CHF event also most likely takes place near the exit of the test section.

For the axially uniformly heated rod bundle CHF experiments, the potential reflood quenching effect near the exit of the test section is one of the most important phenomena, which was overlooked in the past. This phenomenon is especially likely to happen under low flow, low pressure, low subcooled, but high quality conditions, where the column of cooling water at the exit of test section might reflood back into the channel and bring in the non-prototypical quenching effect that will most likely non-conservatively raise the CHF level. In the paper, [8, Liu, A., Yang, B. W., Han, B., & Wang, S. (2019). Measurement uncertainty and quenching phenomena in uniform heating rod bundle CHF tests. Nuclear Engineering and Design, 348, 107-120.], Liu and Yang, et al. presented detailed analysis with experiment observation to demonstrate the potential quenching effect, especially with high void exit conditions. Depending on the degrees of void in the hot channel, the local flow rate, and thermal-hydraulic conditions, this type of none-prototypical reflood quenching phenomenon can be observed as far as two grid spans upstream (or below) which can not only impact the CBT measurement for the uniformly heated rod bundle tests, but might also affect the CHF measurement with exit peaking power shape bundles.

11. Exit quenching effects on bowed rod CHF experiments ?

Another example of potential exit quenching effect is the bowed rod CHF experiments. In most of the so called "bowed rod CHF effect experiments", in order to easily predict (or control) the location of the CHF for the convenience of design and fabrication of bowed rods with known CHF location, the so called bowed rod CHF data were often obtained using either axially uniformly heated heater rods or heater rods with exit peaking power curves where the CHF location is predictable, near the exit of test sections. As mentioned in the above section, also as presented in the reference [Liu & Yang, et al. NED 2019], the exit quenching effects observed near the exit of the test section will most likely introduce major uncertainty, or non-conservatively bias results in the bowed rod CHF tests using uniformly heated rods or heater rods with exit peaking power shapes. As a result, this type of exit quenching effect is likely to overwhelm other heat transfer effects and reduce or totally eliminate any chance of observing bowed rod effects. This might also explain the so called local condition-driven bowed rod effects observed in the previous papers. [Markowski E S, Lee L, Biderman R, et al. Effect of rod bowing on CHF in PWR fuel assemblies [J]. Am. Soc. Mech. Eng.,[Pap.], 1977: **1-9.]** In this investigation, the bowed rod effect was observed only under high pressure, high subcooled conditions and no bowed adverse effect was observed in their bowed rod experiments using exit peaking rod bundles under low pressure, low subcooled, or low flow conditions. Considering the above potential exit quenching effects, the reported results of limited condition bowed rod effects could be questionable.

12. Effect of Indirect Heating of simulated heater rods in rod bundle CHF experiments

As indicated in this report, the indirect heater is often not used in PWR because it is difficult for the indirect heater to reach the required high power. However, another important reason for the selection of direct heater rod is the non-conservative measurement uncertainty associated with in-direct heaters. As presented in the reference paper [Han & Yang et al.], considering the potential non-uniform heat conduction through the thick layer of highly thermal conductive electrical insulation material (such as Boron Nitride or Magnesium Oxide) used in between the central heated element and the think skin outer layer cladding, the actual local heat flux cannot be simply calculated by assuming uniform heat conduction both radial/lateral and axially for an axially non-uniformly heated heater rods, especially under locally rapid transient event such as CBT where the heat transfer mechanisms and temperature distributions are both drastically different among different subchannels or among any neighboring locations. In such cases the heat flux on the surface of the indirect heated wall is considerably non-uniform. As presented in the reference paper [Han & Yang, et al.] for indirect heating, not only large measurement uncertainties of local heat flux exist under such rapid transient conditions, but also the coupling of large local temperature variation might actually force the redirection of heat and allow or facilitate the none-prototypical re-wetting phenomena due to redirecting of local heat through the highly conductive insulation material to the surrounding low local temperature region with highly conductive heat transfer mechanism (convective heat transfer or boiling heat transfer) as compared to the local deteriorated heat transfer mechanism near the CBT region.

Reference paper: “Effect of Indirect Heating of Rod Bundle in Fuel Assembly Thermal Hydraulic Experiment on Local Heat Flux Measurement” [11, Bin Han, Bao-Wen Yang] accepted for presentation at the NURETH-/18. [, August 8-22, 2019, Portland, Oregon, USA

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