UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, DC 20555 - 0001

July 29, 2009

Mr. R. W. Borchardt
Executive Director for Operations
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

SUBJECT: APPLICABILITY OF TRACE THERMAL-HYDRAULIC SYSTEM ANALYSIS CODE TO EVALUATE THE ESBWR DESIGN AND RELATED MATTERS

Dear Mr. Borchardt:

During the 564th meeting of the Advisory Committee on Reactor Safeguards, July 8-10, 2009, we discussed the applicability of TRACE thermal-hydraulic system analysis code to evaluate the Economic Simplified Boiling Water Reactor (ESBWR) design and related matters. Our Subcommittee on Thermal-Hydraulic Phenomena reviewed these matters on February 27, 2009. During these meetings, we had the benefit of discussions with representatives of the NRC staff and of the documents referenced.

CONCLUSIONS AND RECOMMENDATIONS

1. TRACE is applicable for confirmatory analyses of the blowdown and gravity driven cooling system (GDCS) injection phases of ESBWR loss-of-coolant accidents (LOCAs). Its applicability to cases in which noncondensables may be trapped in the GDCS lines, as well as long-term cooling, has not been demonstrated.

2. The capability of TRACE to predict the effect of trapped noncondensables in the GDCS and the resulting collapsed liquid level in the reactor pressure vessel should be assessed.

3. The adequacy of TRACE and other analysis methods, such as MELCOR, used for confirmatory analyses of long-term cooling phase of ESBWR LOCAs should be evaluated.

4. TRACE should be assessed for applicability to analyses of coupled neutronic and thermal-hydraulic phenomena important to safety, such as instabilities and anticipated transient without scram (ATWS), in the ESBWR design.

5. Ongoing work to demonstrate that TRACE is adequate for confirmatory analyses of LOCAs and other safety-significant thermal-hydraulic phenomena in the new pressurized water reactor (PWR) designs should be completed in a timely fashion to allow application in the design certification process.

6. Uncertainties must be estimated in the prediction of primary figures of merit for regulatory decisionmaking for new reactor designs. A similar recommendation was made by the TRACE peer review group on the adequacy of TRACE for confirmatory analyses of LOCAs in current light-water reactors (LWRs).

7. TRACE should be improved to properly formulate and solve the momentum equation when the flow changes direction and merges.

BACKGROUND

Most computer codes that analyze nuclear thermal-hydraulic phenomena share a common ancestral framework of averaged one-dimensional conservation equations for each phase into which empirical closure relationships are woven to replace the information lost by averaging. Details differ among codes as to the way in which the conservation equations are approximated, the number of fields into which each phase is divided, the choice of empirical closure relationships, and the numerical solution procedures utilized. Two main codes of this nature, TRAC and RELAP5, were developed through the 1970s and 1980s by the NRC. In the mid 1990s, the NRC decided to consolidate them into one thermal-hydraulic code with improved capabilities, now called TRACE.

TRACE is being incorporated into the regulatory process for confirmatory analyses of thermal-hydraulic phenomena in the current generation of LWRs. Thermal-hydraulic calculations involve two-phase flow where predictions are still difficult to make solely on the basis of sound fundamentals. As a consequence, codes, including TRACE, solve an intertwined structure of approximate conservation equations and empirical correlations. The uncertainties and biases inevitably introduced by such empirical procedures need to be properly considered. Because of these uncertainties, the accuracy of predictions of such codes are adequate only within certain ranges of parameters and cannot be given blanket approval for all situations to which they might be applied. In practice, a code, such as TRACE, must be qualified by assessment against a range of data that cover the phenomena that dominate the prediction of figures of merit, such as peak clad temperature, important to the regulatory process. These dominating phenomena change with the reactor systems and accident conditions being considered. In view of this, thermal-hydraulic codes need to be assessed and approved for analyses of a specific accident in a particular system. The focus here is primarily on the applicability of TRACE to ESBWR LOCA analysis, with some consideration of other applications important to the ESBWR design such as coupled neutronic and thermal-hydraulic instability, and of applications to the new PWR designs being reviewed for certification.

DISCUSSION

The staff and its contractors have completed a detailed assessment of the applicability of TRACE to analyze ESBWR LOCAs focusing on the collapsed liquid level in the reactor pressure vessel as the primary figure of merit. Use of this figure of merit in place of the more usual peak clad temperature for large-break LOCAs is reasonable from the view point of possible core damage assessment for ESBWR. The evidence presented indicates that TRACE predicts the collapsed liquid level adequately although significant underprediction is found in some comparisons to the data obtained from the tests at the Gravity-Driven Integral Full-Height Test for Passive Heat Removal (GIRAFFE) facility. TRACE also does not always accurately predict data from several important separate effects experiments. These include the General Electric (GE) large vessel level swell tests, the Ontario Hydro large-scale void fraction measurements where TRACE significantly underpredicts the data, and the PANTHERS passive containment cooling system (PCCS) test where heat rejection is underpredicted by 25%. The capability of TRACE to calculate several of these important phenomena is judged to be 'minimal' by the staff's contractors. On the other hand, TRACE performs well in predicting a range of other separate and integral effects experimental data, including void fractions in heated bundles. On balance, we conclude that TRACE does adequately predict many significant thermal-hydraulic phenomena, including the collapsed liquid level in the reactor vessel, and is therefore applicable for analyses of ESBWR LOCAs, except long-term cooling.

The effect of noncondensable gases trapped in safety injection lines is a generic concern for current LWRs. For the ESBWR gravity-driven safety injection systems with relatively low head compared to the pump-driven forced flow systems, noncondensables trapped in pipe sections and elbows might affect injection flows even more than for current LWRs and increase pressure losses substantially. The capability of TRACE to model such phenomena should be assessed particularly in the vicinity of elbows, where significant deviations from existing flooding correlations may be expected.

While application of TRACE to the blowdown and GDCS injection phases of a LOCA is the primary focus of the ESBWR applicability study, there was mention of long-term cooling as being an additional figure of merit. The behavior of noncondensables in containment, condensation on surfaces of various orientations, as well as circulation and stratification in large open volumes play important roles in determining whether long-term cooling is adequate. The General Electric – Hitachi (GEH) code TRACG appears to be capable of modeling long-term cooling, as well as collapsed liquid level during the blowdown and GDCS injection phases. The practicability of incorporating such capability in TRACE should be assessed. At present, the MELCOR code is used for confirmatory analyses of long-term cooling. If use of MELCOR is continued, then its adequacy should be demonstrated and reviewed just as would be the case for TRACE were it to be applied for such cases.

There are several other thermal-hydraulic phenomena of interest to the safety of ESBWR, such as coupled neutronic and thermal-hydraulic instabilities and ATWS, which are evaluated by GEH using TRACG. At present, a linear stability analysis code, LAPUR, is used for such analysis by the staff. However there are potentially strong nonlinear effects which should be resolved by time domain analysis as is done by GEH. TRACE is being coupled to the neutronics code, PARCS, to handle problems of this nature. This work is important not only for ESBWR assessments but also for extended power uprate (EPU) analyses of current boiling water reactors and should be completed.

New PWR designs, such as the US-Advanced Pressurized Water Reactor (US-APWR), incorporate some novel safety features, which are sometimes passive, such as enlarged accumulators with unique flow control capability that allow a delay in safety injection. Since the new phenomena introduced by such features are significant, and may affect the ranking of the various phenomena important for PWR LOCAs, they must be modeled. While substantial work has been done towards demonstrating the adequacy of TRACE for such applications, it must be completed in a timely fashion to provide staff with independent capability to conduct confirmatory analyses as review of these new designs go through the certification process.

The analyses of ESBWR LOCAs performed using TRACE revealed substantial margins to core uncovery, exceeding several meters in collapsed water level, which confirms the safety inherent in the ESBWR design. Uncertainties in the predictions of the collapsed liquid level are less critical than they would be if the margins to core uncovery were smaller. Nonetheless if TRACE is to be reliably used for confirmatory analyses, the magnitude of uncertainties associated with the models, correlations, and the input parameters, including the possibility of noncondensable gas entrapment in the safety injection lines, must be estimated. Uncertainties in prediction of the figures of merit for the new PWR designs may be more critical than for ESBWRs, and their assessment should be considered in the applicability evaluations. This is in line with the findings of the TRACE peer review group which recommended that uncertainties be calculated for LOCA analyses of the current generation of LWRs.

As pointed out by the TRACE peer review group for current LWR LOCAs, the treatment of the momentum conservation equation leads to incorrect results for components in which flows merge or change direction. This is a problem common to all one-dimensional codes, since momentum is a vector and when its predominant direction changes, a multidimensional approach becomes necessary to properly model the phenomena. The problem is exacerbated in codes like TRACE, in which the numerical solution procedures for the momentum conservation equation use grids that are ‘staggered’ with respect to those for the mass and energy conservation equations. Another problem is the solution of the momentum equation in primitive rather than conservative form.

The current treatment of the momentum equation in TRACE can lead to grossly incorrect pressure losses for certain components as was found by the TRACE peer review group. Patches have been incorporated in TRACE to fix, to some extent, the more acute of such problems, but the recommendation made by the peer review group to solve the momentum equations in conservative form has not been implemented. The current momentum equation formulation in TRACE, including the recent patches incorporated by the staff, may not be defensible under external scrutiny. This, in spite of the staff having shown by anecdotal examples that the effect of the patches implemented in TRACE, while giving somewhat improved results for specific components in which the flow turns or merges, apparently does not impact figures of merit like peak clad temperature and collapsed liquid level. Counter examples can undoubtedly be found; among these is the 10% difference in calculated ESBWR normal operating circulation flow rates with and without the patches. In view of this and the likelihood that TRACE will be used for confirmatory analyses covering a broad range of designs and accident scenarios, the treatment of the momentum equation should be put on as sound a theoretical footing as possible in the context of the one dimensional formulation. This may include casting the momentum equation for solution in conservative form as recommended by the peer review group, and using the scalar mechanical energy equation, which can be derived from the momentum equation, in its place for components where the flow turns.

The staff is to be commended for the progress that has been made in developing and moving forward with incorporation of TRACE into the regulatory process. Much work remains to be done to enable its reliable use for the analysis of the new LWR designs, an urgent matter which should be conducted with high priority. We would like to have the opportunity to review the recommended developments and assessments.

Sincerely,

/RA/

Mario V. Bonaca
Chairman

References:

1. ISL-NSAD-TR-08-01, "Adequacy of the TRACE Computer Code for Simulating ESBWR Loss-of-Coolant Accidents," Draft, October 2008 [ML083150604, ML083150605, ML083150606, ML083150607]

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5. Report: Review of TRACE Manual with Emphasis on the Physical Models Sections, G. Yadigaroglu, 05/10/2008 (ML081640560)

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