Review of NEDE-33083P, Supplement 1, December 2004

TRACG APPLICATION FOR ESBWR STABILITY ANALYSIS

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Enclosure 4

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Introduction

This Technical Evaluation Report (TER) documents our review of portions of NEDE-33083P, Supplement 1, “TRACG Application for ESBWR Stability Analysis” dated December 2004 (Reference 1), which documents General Electric’s (GE) evaluation of the TRACG code for use on ESBWR stability calculations.

As stated in Reference 1, GE intends to use the TRACG code to calculate “stability margins during normal operation including anticipated transients.” However, the procedure to estimate decay ratios using the TRACG code requires that the initial operating conditions are steady state, thus, it does not apply if the system is in a transient state. The TRACG code can be used to demonstrate that a particular transient is free from instability, but not to calculate its decay ratio during the transient. Stability margins for transients may be estimated with the TRACG code by re-running the code varying a parameter (e.g. core power) until an instability is observed.

In addition, Reference 1 states “TRACG is also used to analyze plant startup trajectories, to assure a smooth ascension in pressure and power with a minimum of flow oscillation” even though “stability during plant startup is not a licensing issue.” While the conclusions of this review agree with the facts that (1) TRACG can be used to analyze the startup trajectory and (2) stability during startup is not likely to be a licensing issue, the scope of this review only covers the first statement (i.e., the technical capability of the TRACG code). The acceptability of the proposed startup procedures will be evaluated during design certification using the official ESBWR core design and parameters.

We must note that when we refer to TRACG in this report, we imply the TRACG code using the so-called “stability nodalization and methods.” These methods are documented in Section 4.3 of Reference 1 “Other Topics Relevant to TRACG Modeling of Instability” and in Section 5.2 of reference 1 “Effects of Nodalization”. They involve the use of explicit integration numerics in the channel component, as well as a fine nodalization scheme.

The scope of this review covers the evaluation of the capability of TRACG to calculate stability margins (i.e. calculating decay ratios), and demonstrating compliance with licensing limits for stability evaluation of the ESBWR during normal operations. Reference 1 and the scope of the review do not include instabilities that may result in dryout or post-CHF heat transfer (i.e. ATWS).

Summary and Major Conclusions

The primary goal of this review is to ascertain whether TRACG is capable of modeling ESBWR phenomena in order to calculate the ESBWR stability margins. Additional goals include a determination of the uncertainty of TRACG decay ratio calculations, and the development of acceptable stability criteria to be used for TRACG ESBWR calculations.

The conclusions from this review are:

1. The use of TRACG is acceptable to calculate the ESBWR stability margins during normal operation and at limiting steady state power and flow points during anticipated operational occurrences (AOO).
2. To ensure that TRACG ESBWR stability calculations are within the qualification basis, these calculations must follow the procedures outlined in Reference 1. These calculations must be reviewed to ensure that the following restrictions are satisfied
    a. The number of TRACG thermal-hydraulic regions (i.e. channel groupings) in the core must be greater or equal than [[ ]]. The channel groupings must capture the variations in inlet orificing, radial power and harmomics, hot channels, and geometry effects (i.e. super bundles of 16 bundles associated with a single chimney).
    b. The axial nodalization in the core must follow the scheme described in Reference 1 Section 5.2 "Effects of Nodalization."
    c. The calculation of the channel decay ratio must follow the procedure defined in Reference 1 Section 8.1.1 "Channel Stability Results."
    d. The calculation of the core-wide decay ratio must follow the procedure defined in Reference 1 Section 8.1.2 "Core Wide Stability Results."
    e. The calculation of the regional (out-of-phase) decay ratio must follow the procedure defined in Reference 1 Section 8.1.3 "Regional Stability Results."
3. The procedure documented in Reference 1 to calculate decay ratios using TRACG can only be applied to steady state operating conditions, not transients.
4. TRACG can be used to demonstrate that a particular transient (e.g. startup) is free from instability. TRACG can also be used to estimate the stability margin by repeating the transient calculation with different parameters until an instability is observed (e.g., different startup heat up rates)
5. Based on the uncertainty analysis provided in Reference 1, the uncertainty of TRACG ESBWR decay ratio calculations is less than or equal than 0.2. Therefore, the following safety criteria are adequate, and they guarantee compliance with GDC 12.
    a. Core-wide decay ratio < 0.8

    b. Channel decay ratio < 0.8

    c. Regional (out-of-phase) decay ratio < 0.8

6. The design acceptance criteria for ESBWR stability are design goals that ensure sufficient margin to unexpected occurrences and/or deviations from planned operation (e.g. fuel leaks that require repositioning of the control rods). The design acceptance criteria proposed in Reference 1, are adequate. The ESBWR design criteria are:

    a. Core-wide decay ratio < 0.4

    b. Channel decay ratio < 0.4

    c. Regional (out-of-phase) decay ratio < 0.4

7. The proposed TRACG procedures for calculation of ESBWR stability margins are best estimate for the expected conditions during the cycle. Deviations from these expected conditions will happen. In addition, the most likely mode of instability is expected to be regional (out-of-phase). Therefore, to ensure compliance with GDC 10, the ESBWR Reactor Protection System must incorporate an approved Detect and Suppress function. The review and approval of this function will be the subject of a separate submittal.

8. The use of TRACG is acceptable to demonstrate that the ESBWR response during startup procedures is adequate and free from instability.

Detailed Review of LTR Sections

LTR Section 2 Licensing Requirements and Scope of Application

LTR Section 2.1 Licensing Compliance

Two General Design Criteria (GDC) are typically associated with stability analysis. GDC 12 specifies that unstable oscillations must either be not possible or readily detected and suppressed. GDC 10 specifies that the reactor protection system must be capable of terminating any anticipated transients, including unstable power oscillations, without challenge to the fuel.

GE proposes to satisfy ESBWR Licensing Compliance with GDC 12 by demonstrating through TRACG analysis that instabilities are highly unlikely. Thus, compliance with GDC 10 must be demonstrated only for Anticipated Operational Occurrences (AOOs).

In addition to satisfying GDC 12 through analysis, GE proposes to include a detect and suppress (D&S) method to the reactor protection system as a backup. The details of this D&S method are not part of Reference 1, but should provide compliance with GDC 12 in the unlikely case that the analysis assumptions or methods are incorrect, and an instability develops.

The addition of the D&S protection backup allows the reduction of conservatisms in the analysis. The proposed analysis methodology is essentially "best estimate". The complete cycle is pre-calculated at the expected control rod patterns and the worst DR for the complete cycle is compared to the design criteria. In reality, unexpected occurrences happen. For example, a fuel leak would require a deviation from the predicted control rod pattern; thus, invalidating the best-estimate pre-calculation. GE proposes to deal with these unexpected occurrences not by adding conservatism to the calculation, but by adding the D&S protection backup and by using a very conservative design criterion. The proposed "ultimate" stability design criteria (See Section 2.2) are DR < 0.8 for all three modes (core-wide, out-of-phase, and channel); however, the design goals are to maintain all three DR < 0.4. By designing to a conservative DR, there would be sufficient margin to cover any unexpected operating condition.

The staff concurs with GE's proposed Licensing Compliance approach. Designing to a conservative DR and adding a D&S protection backup satisfies the GDC 12 requirements.

LTR Section 2.2 Stability Design Criteria

TRACG calculations indicate that the Regional instability mode dominates the stability response of the reference ESBWR core. Staff confirmatory calculations with the LAPUR code exhibit a similar relation between the relative stability of the core-wide and regional modes in the reference ESBWR design. Thus, the margin to instability of the regional mode is a key design parameter for ESBWR. Stability margins for core-wide and channel instability, while relevant, are not as limiting for the reference ESBWR design, and they are not expected to be limiting for future design changes.

During the development of the Boiling Water Reactor Owners' Group (BWROG) Long Term Stability Solutions (LTS) in the early 1980's, a correlation was developed that attempted to bound all regional instability events observed to date within a region defined in the core-wide versus channel decay ratio. This correlation is sometimes called the "dog bite" correlation. With this methodology, the BWROG was able to circumvent a deficiency in their calculation methodology. At the time, no code was able to calculate the regional DR directly, so an approximate correlation was used.

Reference 1 recognizes that at least one ESBWR parameter is sufficiently different from operating reactors to require a modification of the dog-bite correlation. This parameter is the core diameter, which will result is a smaller eigenvalue separation for the first subcritical neutronic mode. Thus, the Reference 1 methodology proposes to modify in a conservative manner the dog-bite correlation to account for this difference. Other ESBWR design parameters may have similar effects, but we may not have sufficient operating/calculation experience to judge a priori what their effect on the ESBWR-specific dog-bite correlation may be.

Since TRACG is capable of directly calculating the limiting event (i.e., the regional DR), the staff believes that the TRACG ESBWR stability criteria should be based on calculated results, rather than an approximation that was developed based on operating-reactor experience.

In a letter to the NRC dated September 28, 2005 (Reference 2) GE has agreed with the staff position and modified the original stability design criteria, which was based exclusively on core-wide and channel decay ratio calculations ("dog-bite"). In Reference 2, GE proposes a stability criteria based on the following three criteria:

- Limiting channel decay ratio < 0.8
- Core decay ratio < 0.8;
- Regional decay ratio < 0.8

All these evaluations will be made at 95% content and 95% confidence, and the design goal will be to maintain the nominal values of the channel, core and regional decay ratios less than 0.4.

The staff concurs with these criteria.

LTR Section 2.5 Range of Application

Reference 1 states that, for this TRACG application, "the intended application is ESBWR stability analysis at normal operation including potentially more severe conditions resulting from AOOs".

To justify this application for ESBWR stability analysis at normal operation, GE has:

1. documented the methods and approximations used to model ESBWR with TRACG in normal operation,
2. performed a full CSAU analysis to determine the code applicability and expected uncertainties, and

3. performed demonstration stability analyses with a reference ESBWR design

Based on this analysis, the staff concurs that the range of TRACG applicability covers stability analysis at normal operation.

The applicability of TRACG to calculate safety parameters during Anticipated Operational Occurrences (AOO) is covered by a separate licensing topical report (LTR), “TRACG Application to ESBWR” NEDC-33083P” (Reference 3). The applicability of TRACG to ESBWR AOO’s will be reviewed separately by the staff as part of ESBWR design certification. The application of Reference 1, as it pertains to AOOs is limited to predicting oscillations at more limiting power and flow conditions.

LTR Section 3 Phenomena Identification and Ranking

As part of the CSAU process, Reference 1 provides a phenomena identification and ranking table (PIRT) to delineate the important physical phenomena that impact the ESBWR decay ratio calculation by TRACG. The ESBWR stability PIRT is shown in Table 3.1-1 in Reference 1.

As stated in Reference 1, the PIRT serves a number of purposes. First, the phenomena are identified and compared to the modeling capability of the code to assess whether the code has the necessary models to simulate the phenomena. Second, the identified phenomena are cross-referenced to the qualification basis to determine what qualification data are available to assess and qualify the code models and to determine whether additional qualification is needed. Third, the High and Medium-ranked parameters are either varied over their uncertainty distributions or used at bounding values to obtain an overall uncertainty in the estimate of the safety parameters.

The following phenomena are identified as having high importance:

- [[

-]]

- [[

-]]

The following phenomena are identified as having medium importance:

- [[

-]]

The following initial conditions or plant parameters were ranked as high or medium importance:

- [[
-
-
-
-
-
-

]]

- [[
-
-
-]]

In addition, the PIRT includes the following high importance derived parameters

- [[
-]]

[[

]]

TRACG simulations of ESBWR instabilities indicate a relatively large CPR margin. Therefore, phenomena associated with the prediction of dryout and film boiling, cladding deformation, etc. are considered to be of low importance. This implies that the application of TRACG to ESBWR instabilities is limited to normal operating conditions and certain steady state power and flow conditions resulting from an AOO and not to instabilities that may appear during an ATWS event or another transient that may result in dryout.

The core inlet subcooling that depends upon downcomer and feedwater flows and upon the mixing in the downcomer and lower plenum was not included in the PIRT for ESBWR instabilities. The implication is that the feedwater inflow is assumed to be well mixed in the downcomer and that the lower plenum is well mixed during instability transients. This assumption is valid at normal operating conditions and startup because core lower plenum stratification can be avoided during startup by operating the Reactor Water Cleanup/Shutdown Cooling System (RWCU/SDCS System) (References 4 and 5). Therefore this assumption may not be valid at low flow conditions in which there is lower plenum stratification or scenarios that involve cold water injection (such as injection of ECCS). Table 4.1-5a in Reference 6 lists the core inlet subcooling as a high importance parameter for ESBWR instabilities.

The PIRT is comprehensive, and it appears to give the appropriate rating to important stability phenomena.

LTR Section 4.0 Applicability of TRACG to ESBWR Stability Analysis

LTR Section 4.1 Model Applicability

TRACG is a two-fluid 1D and 3D thermal-hydraulic simulation tool that also includes the capability to do coupled thermal-hydraulic/3D transient neutronics analysis. The capabilities of TRACG in terms of the conservation equations solved, the correlations and models, the numerics, and the geometric modeling capability, are applicable to ESBWR instability analysis. The key phenomena identified in the ESBWR instability PIRT can be simulated with the TRACG computer code.

LTR Section 4.2 Assessment Matrix

The prediction of the important thermal-hydraulic phenomena for natural circulation and flow instabilities (i.e. void fraction, subcooled boiling, single phase and two-phase flow losses) has been assessed against separate effects tests, integral effects tests, and full plant data. The core void fraction assessments against FRIGG indicate that the fully developed nucleate boiling void fraction 1σ uncertainty is [[ ]] absolute voids, which is a very respectable level of uncertainty. For subcooled boiling, the uncertainty in void fraction increases to [[ ]] absolute voids. The increase in subcooled boiling uncertainty can be attributed to the [[ ]] uncertainty in the Saha-Zuber correlation for the prediction of the onset of subcooled boiling. The large diameter void data base (i.e. Ontario, Wilson, etc.) assessment indicates an uncertainty for the void fraction in the chimney of [[ ]] void. Pressure drop comparisons against full scale bundle data and separators indicate an overall uncertainty in the TRACG pressure drop models of [[ ]]. These two capabilities are the most important phenomena for the prediction of natural circulation flows. Specifically, the void fraction distribution and the pressure drop models are the dominant phenomena for determining natural circulation flows. Comparisons of TRACG with natural circulation flow rates in the SIRIUS test facility (Reference 7) indicate a bias of [[ ]] with a standard deviation of [[ ]]. Additional assessments for Dodewaard, CRIEPI, and PANDA are available in Reference 8 over a wide range of pressures, heat fluxes, and inlet subcoolings. The TRACG models and assessment indicate that TRACG can predict natural circulation flows and the uncertainty of these models can be propagated through a statistical model to determine the uncertainty in the final safety parameter (i.e. decay ratio). The dominant phenomena for natural circulation flow are modeled in TRACG and the accuracy is consistent with the available test data.

BWR power instability analysis involves density wave propagation, neutronics feedback via void coefficient, and fuel rod thermal response. Density waves propagate at the vapor velocity. Therefore, density wave propagation requires accurate void fraction profiles through the core and an accurate solution of the transient mass, energy, and momentum conservation equations and an accurate subcooled boiling model. The assessment of these models in Reference 7 indicates that TRACG accurately predicts density wave propagation and stability boundaries with a standard deviation of [[ ]] over a range of pressures, heat fluxes, and subcoolings. TRACG prediction of stability maps for CRIEPI at low pressure is also given in Reference 8.

The thermal-hydraulic modeling uncertainties given in Reference 1 were reviewed to determine consistency with available data and expectations. Reference 1 indicates the leakage path drill holes flow rate uncertainty is [[ ]], while the flow rate uncertainty for the side entry orifice and water rod orifice is [[ ]]. The leakage path drill holes represent 60% of the core bypass leakage flow and the flow through the finger spring leakage path represents 40% of the core bypass flow with an uncertainty of [[ ]]. The total estimated uncertainty for the core bypass flow is:

[[ ]] *(1)*

If the leakage holes flow uncertainty was [[ ]] (i.e. similar to the side entry orifice (SEO) and water rod orifice), then the core bypass flow uncertainty would be:

[[ ]] *(2)*

The [[ ]] uncertainty in the core bypass flow translates to a [[ ]] uncertainty in the core bypass flow loss. If the leakage path drill holes uncertainty was increased to [[ ]] giving the [[ ]] increase in core bypass flow, this would translate to a [[ ]] uncertainty in the core bypass flow loss. Therefore, it would not be a significant impact on the overall decay ratio uncertainty. GE also indicates in response to staff inquiries (Reference 9) there is prototypical data available that supports the [[ ]] uncertainty in leakage path drill holes flow rate and has been used in earlier submittals (Reference 10).

The important time scale for ESBWR power instabilities is the time required for a density wave to propagate through the ESBWR core. The time period for a BWR power instability has been found to be approximately twice the time required for a density wave to propagate through the ESBWR core. Calculated ESBWR frequency range is [[ ]] to [[ ]] depending upon the axial power profile (i.e. exposure) and whether the instability is core wide, hot channel, super bundle, or regional mode. Given a steady-state solution and the governing conservation equations, the density wave propagation time can be estimated by integrating the vapor velocity of a vapor particle transporting from the boiling boundary to the core exit:

$$L_b = \int_0^{t_p} V_g(z)\,dt \qquad (3)$$

where,

L_b = Boiling length in the channel.

$V_g(z)$ = Vapor velocity, which is a function of the axial position and axial position is a function of time.

t_p = Transport time.

A standalone drift flux program for a single ESBWR channel was developed to estimate the steady-state void fraction and velocity profiles. The standalone drift flux program includes TRACG documented models (Reference 11) for the drift flux parameters and subcooled boiling. Based on this model the estimated density wave transport time for the ESBWR hot bundle is [[ ]] seconds, which implies an instability frequency of

[[ ]] Hz. This is slightly below the lower range of expected frequencies for the ESBWR. One explanation for the difference in transport times is the difference in void fraction profiles between TRACG and the standalone drift flux program. Comparison of the void fraction profile predicted by the drift flux standalone program to TRACG, TRACE (Reference 12), and RELAP5 (Reference 13) for the ESBWR hot channel is given in Figure 1.

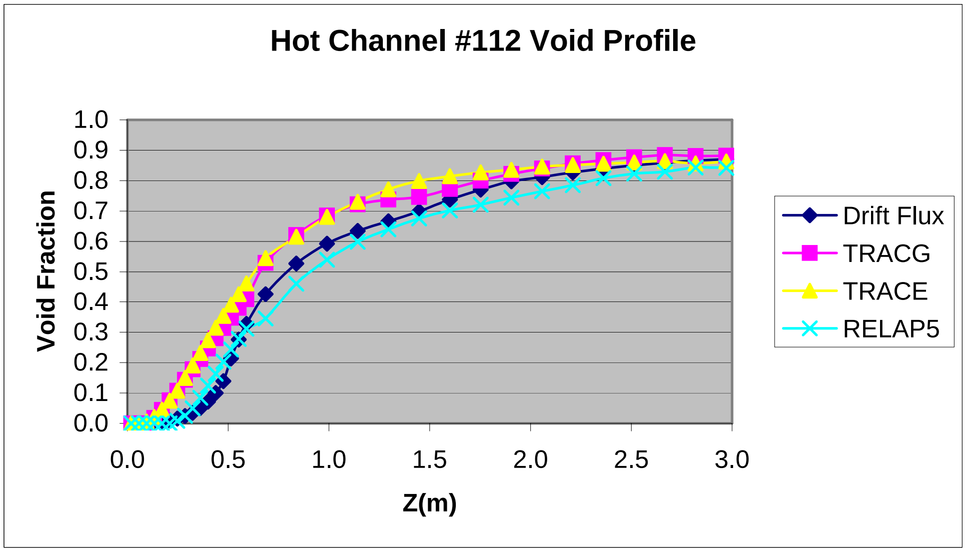

Figure 1. ESBWR Hot Channel Void Fraction Profile Predictions.

The TRACE models for subcooled boiling and bubbly flow and churn turbulent interfacial shear are similar to the TRACG models. Differences between the comparison of the drift flux model to TRACG and other codes are not significant given that the assessment of TRACG against bundle and large diameter void fraction data indicate that TRACG models are accurate.

Overall the comparison between TRACG, TRACE, and the standalone drift flux model supports the TRACG void fraction profiles. Differences between the drift flux model and TRACG can be attributed to the incompressible two-phase flow assumptions in the drift model and the lack of virtual mass terms in the drift flux model. RELAP5 is using a completely different interfacial shear package and is not expected to compare well with TRACE or TRACG.

The time period of oscillations for the SIRIUS test facility are greater than 10 seconds, while the time period of ESBWR power instabilities is [[ ]] seconds. There was a concern that the SIRIUS test facility was being used to support the TRACG power instability capability, when the time scales were significantly different.

The oscillations in the SIRIUS test facility are thermal-hydraulic and related to the transport time of density waves and enthalpy waves through the core and the chimney. For the ESBWR power instabilities in which power feedback is important, the time scale of importance is the density wave transport time through the heated core. The SIRIUS test facility data is used to assess the TRACG natural circulation and density wave propagation capabilities and is not intended to represent ESBWR power instabilities.

The important neutronics parameters for core wide and channel ESBWR power instabilities are void coefficient, delayed neutron fraction, direct moderator heating, exposure, and axial power profile. For regional ESBWR power instabilities the additional neutronics parameters are 3D neutron kinetics and the subcriticality of the first harmonic mode. For core wide and channel ESBWR power instabilities the void coefficient is the dominant parameter.

As a density wave with reduced void fraction propagates through a BWR channel, the void coefficient determines the increase in power associated with the increased neutron moderation. There is no operating data to compare for GE14 fuel design to assess the accuracy of the void coefficient models in TRACG. Reference 1 indicates that the estimation accuracy and uncertainty for the void coefficient is based on comparisons between the GE TGBLA04 code predictions and the Monte Carlo MCNP01 (Reference 14) predictions for 11 BWR bundle types, 9 different exposures and 3 different void fractions. This does provide a bias and uncertainty for the void coefficient that can be used in the TRACG statistical models to propagate the uncertainty to the final safety parameter calculation of the decay ratio. However, it assumes that MCNP01 results are an accurate representation of the BWR fuel assemblies. In addition, the 11 BWR bundle types do not include GE14 bundle design. Finally there is no uncertainty included in these analysis associated with actual nuclear isotope concentrations in the fuel rods at a given exposure. If we assume that:

1. the 11 BWR bundle types includes enough variability of the bundle designs, such that the GE14 bundle design is contained within that variability and

2. for a given set of nuclear isotope concentrations, MCNP01 accurately calculates the infinity multiplication factor,

then uncertainty in the actual nuclear isotope concentrations at a given exposure is still not included in this uncertainty analysis.

MCNP01 is an industry standard for the calculation of the k-infinity multiplication factor for nuclear fuel bundles and has a standard deviation of 0.00045 in the k-infinity values for the benchmark calculations that compare TGBLA to MCNP (Reference 9). The 11 BWR bundle types include a large variability of BWR bundle designs and the GE14 is expected to be contained within that variability. The uncertainty associated with exposure is addressed by performing stability calculations at BOC, MOC, and EOC.

The calculation of equilibrium cores at BOC, MOC, and EOC implies that a range of bundle exposures are analyzed. However, it is not obvious that the range of bundle exposures bounds the uncertainty associated with prediction of the nuclear isotopes associated with a given exposure.

Because of the radial pressure distribution across the top of the core and bottom of the chimneys, there is some sweep of the voids back into the top of the core bypass. There was a concern if the voiding of the bypass during instability resulted in additional uncertainty of the TRACG predicted 3D neutron kinetics.

The TRACG calculated sweep of voids back into the top of the core bypass does not propagate down to the heated region of the core. Therefore, there is no impact on the neutronics associated with core bypass voiding during the ESBWR instability calculations.

The ESBWR baseline calculated channel decay ratio varies from [[ ]] to BOC to [[ ]] at EOC. There was a concern whether or not the channel decay ratio would be significantly different for a clean core before an equilibrium core has been established.

GE estimated that based on the reduced radial and axial peaking associated with an initial core, the ESBWR stability would be improved compared to an equilibrium core. An initial core design has not been finalized, but based on experience with other designs, there will be a reduction in the radial and axial peaking relative to an equilibrium core.

TRACG has been assessed for the dominant phenomena for ESBWR instabilities.

LTR Section 4.3 Other Topics Relevant To TRACG Modeling of Instability

In terms of numerics, the following four additional topics were identified:

1. Explicit integration scheme in the TRACG channel component.
2. Coupling of conduction solution with hydraulic solution.
3. Coupling of vessel component to channel components.
4. Coupling of 3D kinetics with thermal-hydraulic model.

The explicit integration scheme in the TRACG channel component was addressed in Reference 19 by comparing TRACG instability calculations with just the channel component using the explicit integration scheme with calculations where all fluid components in the model used the explicit integration scheme. The difference in calculated results were not significant. This implies use of the explicit integration scheme for the channel component for stability calculations is appropriate and acceptable. In addition, assessment of TRACG against FRIGG instability data also indicates that TRACG can accurately simulate BWR channel instability with the explicit integration scheme. In general, the fully implicit TRACG integration scheme results in additional damping in the numerical solution.

The coupling of the conduction solution with the hydraulic solution is acceptable for ESBWR instability calculations. Energy exchange between the heat structure conduction solution and the fluid component energy equation is consistent and energy is conserved consistent with the integration scheme.

The coupling of the vessel component to the channel components is acceptable for ESBWR instability calculations. Mass, energy, and momentum are conserved at the 3D mesh to 1D mesh cell faces consistent with the time level integration scheme (i.e. explicit or implicit).

Coupling of the 3D kinetics with thermal-hydraulic model involves an extrapolation of the 3D kinetics solution so that the new time fluid conditions can be calculated based on the estimated new time power levels. The 3D kinetics solution is then advanced based on feedback from the new time fluid conditions. There may be differences between the extrapolated 3D kinetics solution and the actual new time 3D kinetics solution. However, TRACG uses changes in power, void fraction, etc. to control the time step size to ensure that these differences are not significant. Therefore, the coupling of the 3D kinetics with the thermal-hydraulic model is acceptable as demonstrated by the assessments against plant data.

LTR Section 4.4 TRACG Qualification against Peach Bottom Unit 2 Stability Data

TRACG decay ratio calculations have been qualified against results of the stability tests conducted at Peach Bottom 2 in April 1977. The reasons why GE chose the Peach Bottom tests are: (1) the availability of data, and (2) these tests were conducted at a low value of the decay ratio (DR < 0.4); the ESBWR is expected to operate under these low decay ratio conditions.

The results of the above benchmarks show that TRACG can calculate core-wide decay ratios for these types of very stable operating conditions. The standard deviation of the TRACG error in these benchmarks is smaller than the proposed 0.2 error to be used for the stability criteria (i.e, DR < 0.8 implies stability).

TRACG under-predicts the frequency of oscillation for the Peach Bottom tests, but this frequency under-prediction is common of most stability codes. GE states that the reason for the higher frequencies seen in the data has not been identified, but may be due to the method of extracting them from the transfer function.

The channel decay ratio was calculated by TRACG by introducing a [[ ]] inlet flow perturbation. The channel decay ratio is measured from the resulting core-inlet flow oscillation. Channel decay ratios were calculated for the Peach Bottom test conditions and results in very low values, as expected.

The regional stability mode is excited by perturbing [[

]]

The use of a pressure perturbation at the turbine inlet for the core-wide mode and flow perturbation for the channel and regional modes appear to yield good results to simulate instabilities. A sensitivity analysis was performed with different perturbation amplitudes and shapes. The results of this analysis indicate that the decay ratio results are not very sensitive to the amplitude or shape of the initial perturbation.

LTR Section 5.0 Model Biases and Uncertainties

GE has evaluated the model biases and uncertainties for all items from the PIRT table with a significant impact on the decay ratios. These items include all phenomena ranked High or Medium in the PIRT. Table 5.1-4 of Reference 1 documents the disposition of High and Medium ranked stability model parameters in the PIRT. This table shows the bias and standard deviation used for each of the PIRT phenomena to calculate the decay ratio uncertainty. The input uncertainties in Table 5.1-4 are reasonable; their numeric values are justified adequately in this section of Reference 1.

Section 5.2 of Reference 1 presents a study of the effects of nodalization on the calculated decay ratio. TRACG ESBWR stability analysis requires a specific nodalization scheme, which is described in Figure 5.2-1of Reference 1. A fine axial nodalization is used in the core entrance to attempt to maintain a more constant Courant number (the core entrance velocity is slower than the core exit) and to provide more detailed modeling of the lower-void core regions, where void oscillations have the largest impact on stability. Radial nodalization involves collapsing the fuel bundles into approximately [[ ]] thermal-hydraulic channels. The proposed axial and radial nodalization has been used in the past for TRACG calculations of operating reactors' stability and has been found to be adequate for these calculations.

Section 5.3 of Reference 1 presents a study of the effects of scale. The key stability parameters and phenomena in ESBWR do not have significantly different scales than in operating reactors. In addition, full-scale tests have been performed on the channel components.

LTR Section 6.0 Application Uncertainties and Biases

Table 6.1-1 of Reference 1 documents the key plant initial conditions and their assumed error used for the uncertainty analysis. The magnitude of the errors used for the uncertainty analysis is well documented and the values are reasonable.

LTR Section 8.0 Demonstration Analyses

This section of Reference 1 describes the ESBWR TRACG modeling assumptions, and it documents the methodology used to calculate core-wide, channel, and regional (out-of-phase) decay ratios for ESBWR. In addition, this section of Reference 1 demonstrates:

1. TRACG is capable of modeling ESBWR stability phenomena
2. The reference ESBWR design satisfies the stability criteria proposed by GENE

The channel stability analysis is performed in TRACG by perturbing the flow to the high power channels while keeping the power constant. The calculation process is as follows:

1. [[
2.
3.
4.
5.
6.
7.

]]

The regional (out-of-phase) stability is evaluated in TRACG using a procedure very similar to the one used for the channel and core-wide stability above; however, it requires a "regional" channel grouping, [[
.]] After establishing the channel groups, the decay ratio for regional oscillations is calculated using the following process:

1. [[
2.
3.
4.
5.
6.
7.

]]

To demonstrate the methodology, and to evaluate the stability of the ESBWR design, this methodology is applied in Reference 1 under baseline and steady state power and flow conditions associated with AOO conditions for Loss-of Feedwater Heater (LOFWH), which results in increased power; and Loss of Feedwater Flow (LOFW), which results in a lower flow. In addition, a sensitivity analysis to the High and Medium ranked phenomena identified in the PIRT was performed. The following sections document these results.

LTR Section 8.1 Baseline Analysis

This section of Reference 1 presents the stability results calculated by TRACG for the candidate ESBWR plant design, with 1132 bundles and a rated thermal power of 4500 MWt. This is intended as a demonstration of the applicability of TRACG to ESBWR stability analysis.

The TRACG ESBWR model includes [[ ]] thermal-hydraulic regions [[
]]. An analysis was conducted at the various points in the cycle: Beginning of Cycle (BOC), Middle of Cycle (MOC) near the peak reactivity state, and End of Cycle (EOC). The core has a more pronounced bottom peak at BOC and is expected to be limiting for channel and regional stability. Decay ratios for core-wide stability are expected to be highest at MOC. Regional stability is strongly influenced by the sub-criticality of the higher order harmonics. The sub-criticality for the azimuthal mode ranges from [[
]] at BOC to [[ ]] at EOC. The combination of the severe bottom peaking and lowest eigenvalue separation will result in the highest decay ratio for regional stability at BOC.

The above tendencies have been confirmed by both the TRACG and staff LAPUR calculations. Reference 1 shows the response of several channels to the perturbations (core-wide, channel, and out-of-phase), as well as the channel nodalization for core-wide and out-of-phase. The procedures defined in Reference 1 to generate the TRACG input cases model the relevant ESBWR physical phenomena with sufficient accuracy to yield good quality stability results.

LTR Section 8.2 Sensitivities to High and Medium Ranked Parameters

This section of Reference 1 presents the results of an analysis of the sensitivity of decay ratio results to the relevant input parameters identified in the PIRT. The maximum sensitivity is found to be related to the interfacial shear, as expected because it affects both void fraction and pressure drops. Figures 8.3-3 and 8.3-7 of Reference 1 show the results of the sensitivity analysis. They represent graphically the expected error in TRACG ESBWR calculations.

The results of these sensitivity analyses indicate that the TRACG ESBWR stability calculations are robust and, therefore, the TRACG results provide a reliable indication of the true ESBWR stability margin. The maximum decay ratio error for these sensitivity analyses was of the order of [[   ]], which is acceptable and justifies the use of the 0.2 calculation error criteria (i.e. DR < 0.8) proposed for use in ESBWR calculations

LTR Section 8.4 Stability following AOOs

Stability is a crucial design requirement for ESBWR because the rated power and flow conditions are the limiting conditions for stability during normal operation. However, following an AOO the power/flow conditions could be even more severe than at rated; therefore, AOO analyses must include an evaluation of stability. Two AOOs are identified in Reference 1 with potential to decrease the ESBWR stability margin: Loss-of Feedwater Heater (LOFWH), which results in increased power; and Loss of Feedwater Flow (LOFW), which results in a lower flow.

The staff review concurs with GE's evaluation of the effects of AOOs on ESBWR stability margins. The two AOOs identified are the two likely scenarios that can reduce stability margins and, thus, must be analyzed during ESBWR licensing. Section 8.4 of Reference 1 documents the assumptions and procedures for these AOO analyses. TRACG is capable of modeling and predicting the resulting plant stability margins under these conditions.

LTR Section 9.0 Plant Startup

This review focuses on the capability of TRACG to model all the physical processes relevant to the stability of ESBWR. During normal operation, the stability mode of concern is the so-called density wave that produces flow and power oscillations with a frequency of 0.5 to 1 Hz. Because of its unique startup process, other instability modes are of concern during ESBWR startup. These instability modes include geysering instability and loop instabilities (also known as manometer or Type I instabilities). The TRACG capability of modeling both of these modes is described in Section 9 of Reference 1.

The startup process GE describes in Reference 1 for ESBWR involves the following steps

1. De-aerate coolant by pulling vacuum with mechanical pumps
2. Preheat coolant to 85C using either decay heat and/or auxiliary equipment (e.g. the reactor water cleanup system)
3. Isolate the primary at about 50 kPa by closing MSIV
4. Reach criticality by pulling control rods
5. The power is maintained constant at a low level (nominally 50 MW, but less than 85 MW) for a long period of time (3 to 7 hours)
6. When a pressure of 6.3 MPa is reached, the MSIVs are open, turbine is synchronized, and escalation to full power is achieved by pulling control rods.

The key in this startup procedure is maintaining a low-enough power during step 5 so that boiling occurs only in the top of the chimney and not inside the active core. Boiling occurs in the top of the chimney because of the difference of pressure due to elevation. As long as the power is low enough, subcooled boiling does not occur in the core while the pressure is low. By maintaining voids out of the core at low pressure, ESBWR prevents reactivity feedback issues, which could result in violent oscillations.

The above procedure was simulated with TRACG in Section 9 of Reference 1 and in the response to RAI 1 “Startup with Neutronic Feedback” (Reference 15). TRACG was capable of modeling this startup procedure.

The key difference as compared to normal operating conditions is the low pressure and low temperature. Thus, TRACG must be validated for these conditions, because thermal hydraulic instabilities tend to become more significant as the pressure is reduced, since the ratio of phase densities increases significantly as the pressure decreases. The assessment of TRACG models for void fraction is documented in Reference 8, and Reference 16. These qualifications cover a range of pressures down to 0.5 MPa and over a range of subcoolings as high as 38K. The TRACG models for void fraction have acceptable accuracy over a large range of conditions, however there is some indication that the uncertainty may increase as the pressure decreases. This is currently included in the overall uncertainty for TRACG void fraction predictions.

TRACG has been assessed in Reference 16 against ATLAS pressure drop data at 6.9 MPa, and FRIGG natural circulation data for a pressure range of 2 to 5 MPa. It has also been assessed in Reference 7 against SIRIUS natural circulation data down to a pressure of 2 MPa. Accurate comparison to natural circulation data requires both the capability to accurately simulate pressure losses as well as void fraction profiles. These comparisons indicate that the TRACG pressure drop models have acceptable accuracy over a range of pressures.

TRACG predicted the 1992 Dodewarrd startup within the accuracy of the available measurements. TRACG predicted relatively long time period manometer type oscillations associated with flashing in the chimney (i.e. not power oscillations associated with density wave transport times) that were not observed in the startup data, but would be difficult to detect with Dodewarrd instrumentation.

TRACG predicted thermal-hydraulic oscillations based on flashing in the CRIEPI chimney for pressures as low as 0.2 MPa and accurately predicts the stability map for this facility at low pressure. The long period oscillations were found to be related to manometer type oscillations associated with flashing in the chimney. CRIEPI has 1.8 m core and 5.5 m chimney. Similar oscillations where observed in PANDA, with 1.3 m core 9.5 m chimney at pressure 0.3 MPa. TRACG was also able to calculate these oscillations. As documented in Reference 7, TRACG accurately predicts stability map for SIRIUS test facility at 2 and 7.2 MPa.

Based on these assessments TRACG is capable of predicting instabilities during the proposed ESBWR startup. Therefore, we conclude that TRACG is an acceptable code to demonstrate during the design certification phase that the official ESBWR design and startup procedures are adequate and free from instability.

LAPUR Confirmatory Calculations

Confirmatory calculations were performed using the code LAPUR, V5.2 (Reference 17). Note that these calculations are not an exact replica of the TRACG analyses presented in Reference 1. These confirmatory calculations are intended to obtain an indication about the relative stability of the ESBWR design.

The major conclusion from these confirmatory calculations is that LAPUR confirms the stability results calculated by TRACG for ESBWR at nominal conditions. The LAPUR-calculated ESBWR decay ratios for all three density-wave instability modes (core-wide, out-of-phase, and channel) are very low (of the order of 0.1), indicating that the ESBWR has a high degree of stability.

LAPUR Results

LAPUR V5.2 was used to simulate the reference ESBWR nominal conditions at beginning and end of cycle. Typical LAPUR runs use quarter core symmetry and have four channels per thermal hydraulic region. The standard release of LAPUR V5.2 allows modeling up to 200 thermal hydraulic channels, which would cover all operating reactors. ESBWR is a special case, because 283 thermal-hydraulic regions are required to model a full quarter core. A simple modification to the LAPUR source code was implemented to allow for up to 512 thermal-hydraulic channels. This is a simple parameter change that was envisioned during the documentation and validation of Version 5.2. The new compiled code was benchmarked against the old code by using a 200-channel standard benchmark case used during the V5.2 validation.

Table 1 shows the results of LAPUR ESBWR modeling. As it can be observed, LAPUR predicts that the reference ESBWR nominal conditions are very stable.

Table 1. LAPUR Results for ESBWR at Nominal Conditions

	BOC		EOC	
	Decay Ratio	Frequency (Hz)	Decay Ratio	Frequency (Hz)
Core Wide	0.06	0.73	0.14	0.56
Out of Phase	0.11	1.00	0.08	0.66
Hot Channel	0		0	

Effect of Chimney Modeling

The LAPUR calculations indicate that the dynamic model used to simulate the chimney riser has little or no effect on the stability of the ESBWR.

The riser itself has a large effect on the core flow, but it has a very small friction pressure drop. However, once the core flow and power are fixed, the stability is not influenced by the presence of the chimney. So, the chimney plays a crucial role in setting up the steady state value of the core flow, but plays only a minor role during the unstable oscillations. This effect can be seen in

Table 2, where the results of a LAPUR calculation without chimney is reported. As seen in this table, the decay ratios calculated by LAPUR are not change by the presence of the chimney. Note: for this LAPUR calculation, the same core flow and core power was used as in the results in Table 1 - only the dynamic effect of the chimney is removed.

To ensure that LAPUR correctly models the chimney using the exit pipe component, we increased significantly the chimney friction and a change in the decay ratio was observed. The chimney friction had to be artificially increased by a factor of 100 before a noticeable change in calculated decay ratio was observed. We conclude that modeling of the chimney does not need to be very accurate to calculate the ESBWR stability performance. This conclusion is supported by the fact that the core exit void fraction is close to saturation (100%) and cannot change much when the flow oscillates. In addition, propagation time delay in the chimney allows for more than one void wave to be present, therefore the integrated buoyancy is small for oscillations at high frequency (~1 Hz).

Table 2. LAPUR Results for ESBWR without Chimney Model

	BOC		EOC	
	Decay Ratio	Frequency (Hz)	Decay Ratio	Frequency (Hz)
Core Wide	0.06	0.73	0.14	0.56
Out of Phase	0.11	1.00	0.08	0.66
Hot Channel	0		0	

LAPUR Input Deck Description

The complete LAPUR input decks (X & W) for the nominal ESBWR case are contained in a compact disk. Refer to Reference 17 for a description of the input deck cards. Here is a short description of the deck assumptions

1. This deck simulates the core with 283 thermal-hydraulic channels, which correspond to a one full quarter core. Each channel has its own axial power distribution as calculated with PANACEA (see Reference 18). The radial power distribution is modeled as full quarter core by specifying the channel powers calculated by PANACEA
2. LAPUR does not model partial-length fuel rods. The effect of the partial length rods is modeled by reducing the friction in the upper part of the core. The friction in the upper part of the core is ~73% lower than in the lower part (see card ID 36 and 37)
3. The chimney riser is modeled with LAPUR's exit pipe component (see card ID 46 to 52). With this approximation, each channel has its own riser, so there is no mixing at the core exit. This is a crude approximation, but justified by the fact that the chimney has very little effect on the density-wave instability.
4. The rest of the deck contains the standard core and fuel descriptions that would be used for any BWR in the fleet.

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