FINAL SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT (TR) EMF-3028(P)

"RAMONA5-FA: A COMPUTER PROGRAM FOR BWR [BOILING WATER REACTOR]

TRANSIENT ANALYSIS IN THE TIME DOMAIN," VOLUME 1, REVISION 2, "USERS

MANUAL" AND VOLUME 2, "THEORY MANUAL"

AREVA NP, INC.

PROJECT NO. 728

1.0 INTRODUCTION AND BACKGROUND

By letter dated January 30, 2006, Framatome ANP, now known as AREVA NP, Inc. (AREVA), submitted to the U.S. Nuclear Regulatory Commission (NRC) Topical Report (TR) BAW-10255(P), Revision 2, "Cycle-Specific DIVOM [Delta CPR (critical power ratio) over Initial CPR Versus Oscillation Magnitude] Methodology using the RAMONA5-FA Code" [Reference 1], for review and approval. The purpose of this TR is to describe the AREVA methodology for the evaluation of the critical power response of the core to regional oscillations on a cycle-specific basis, and to present the methodology for generating DIVOM curves based on cycle-specific analysis with the boiling water reactor (BWR) transient system code, RAMONA5-FA. DIVOM correlates the loss in CPR in the hot channel, given measured power oscillation amplitude in the oscillation power range monitor (OPRM). The DIVOM correlation is used in defining the OPRM amplitude scram setpoint for the detect and suppress (D&S) long term stability solution.

The NRC staff issued an safety evaluation (SE) on AREVA's DIVOM methodology [Reference 2], which imposed a condition to perform a full code review of RAMONA5-FA, including constitutive relations, numerics, neutronic methods and bechmarks before RAMONA5-FA can be used to calculate DIVOM curves in Extended Flow Window (EFW) operating domains. The conditions specified that, until the review is completed, AREVA must include an interim 10 percent penalty on the DIVOM slopes calculated by the RAMONA5-FA methodology in EFW domains. The DIVOM SE [Reference 2] specifies that, once the NRC staff reviews and accepts the subject TR, this limitation will be removed.

This SE documents the NRC staff evaluation of AREVA's RAMONA5-FA code for use in DIVOM calculations. The review is based on documentation provided in the RAMONA5-FA Users Manual (EMF-3028, Volume 1) [Reference 3], Theory Manual (EMF-3028, Volume 2) [Reference 4], the Cycle-Specific DIVOM methodology (BAW-10255P) [Reference 1], the information obtained during a NRC staff audit September 22-26, 2008, and the response to NRC staff requests of additional information (RAIs) [References 5-7]. The NRC staff has been assisted in this review by its consultant, Oak Ridge National Laboratory (ORNL), who has issued a Technical Evaluation Report on the subject [Reference 8].

The NRC staff presented the results of their evaluation to the Advisory Committee on Reactor Safety (ACRS) during the 579th meeting of the ACRS, January 13-15, 2011. The ACRS provided two recommendations:

1. The NRC staff's recommendation to remove the interim 10 percent penalty … is acceptable, and

2. Before the interim penalty is removed, the NRC staff should review Volume 2 of the revised RAMONA5-FA Topical Report EMF-3028(P), to ensure that all errors have been corrected and that the documentation errors do not reflect errors in the source code

The NRC staff accepted the ACRS recommendations and reviewed Revision 4 of TR EMF-3028(P), dated January 2011. The NRC staff concluded that the corrected version of the RAMONA5-FA Theory Manual removes all the inconsistencies in nomenclature and the deficient formulations. Furthermore, the NRC staff concludes that the process followed by AREVA to reconcile the RAMONA5-FA code with its documentation is technically correct and that the code and documentation are consistent; therefore, the new RAMONA5-FA documentation accurately reflect the equations that are solved by the code, and AREVA has verified that there are no errors that need to be corrected in the source code, as the original incorrect documentation would have suggested.

1.1. DIVOM METHODOLOGY

BAW-10255P [Reference 1] describes the AREVA DIVOM methodology. The DIVOM correlation is used to estimate the delta CPR as function of power oscillation amplitude, and it is required to select the scram set point for detect and suppress long term stability solutions. A generic DIVOM correlation was approved [Reference 11] on the basis that it would be bounding for all reasonable circumstances; however, analysis demonstrated that some plant-specific calculations result in larger loss of CPR margin than the generic DIVOM prediction. Most licensees are currently using cycle-specific DIVOM correlation calculation. The NRC staff has approved a proprietary modification of BWR Owners' Group (BWROG) Option III Long Term Stability Solution (Option III) [Reference 12] that uses DIVOM correlations.

In principle, two DIVOM correlations are calculated for each reactor condition: the core-wide mode DIVOM and the regional-mode DIVOM. Under all circumstances, the regional DIVOM correlation slope is larger (i.e. more conservative) than the core-wide DIVOM because regional-mode oscillations are always accompanied by larger swings in hot channel flow. Therefore, only the regional-mode DIVOM is used to set scram setpoints for D&S long term solutions (e.g. Option III, or the Enhanced Option III Long Term Stability Solution (EO-III)).

To calculate the cycle-specific DIVOM curve, RAMONA5-FA is used to simulate regional oscillations at several state points throughout that cycle. For each exposure time, a growing power oscillation is calculated as illustrated in Figure 1.

The RAMONA5-FA output is parsed using AREVA's DIVOMPLT code [Reference 1] to determine the maximum power swing bundle and the maximum CPR swing in a bundle. The power and CPR amplitudes for each oscillation are plotted against each other, and a piece-wise linear function is plotted to define a region that bounds all oscillations. For most applications, this piece-wide linear function is a single straight line that defines a single slope, which is known as the DIVOM slope; however, the BWROG methodology allows for a more generic DIVOM curve, where the slope varies with oscillation amplitude. AREVA's methodology is consistent with the BWROG methodology, and it allows for a generic DIVOM curve.

The AREVA DIVOM Methodology Application Procedure is described in detail in Section 7 of BAW-10255(P) [Reference 1]. It includes the following steps:

1. Definition of the state points to be analyzed. Exposure, control rod pattern, power, flow, subcooling, and xenon level, are specified.

2. MICROBURN-B2 runs for the selected state points to generate cross section and hydraulic data for input into RAMONA5-FA and STAIF codes.

3. Frequency domain analysis using STAIF to gain insight into the stability of the state points. These results are used to revise state point selection or introduce input modifications. The STAIF calculations also identify the state point with the largest channel decay ratio which, if large, needs to be examined for single channel neutron uncoupled oscillations.

4. RAMONA5-FA runs producing growing regional oscillations. The transient should continue until:

    a. Hot channel oscillation magnitude (HCOM) exceeds a preset limit (suggested minimum of 0.4), or
    b. Maximum Critical Power Ratio (MCPR) less than unity calculated, or
    c. Oscillations are no longer increasing (stable limit cycle reached).

5. State point or input data modifications as needed for the purpose of exciting the regional mode oscillations while damping the global mode.

6. Post-processing of RAMONA5-FA output with the DIVOMPLT code to generate and plot DIVOM points, which define the DIVOM curve by simple linear interpolation between the points.

7. Correction of DIVOM points, if applicable, in the case input biases were necessary to excite growing regional oscillations

1.2. KEY REVIEW FEATURES

The DIVOM methodology is well established [References 9 - 11] and has been approved by the NRC staff. Therefore, the key review questions are:

1. Do the proposed AREVA DIVOM calculation procedures comply with the approved methodology?

2. Is RAMONA5-FA qualified to model the growing unstable power oscillations that are required in the calculation procedures? The answer to this question includes an evaluation of the modifications to RAMONA5-FA, including the modal neutronics method.

3. Given a power oscillation, can RAMONA5-FA estimate the reduction in CPR?

The NRC staff SE on AREVA's DIVOM methodology [Reference 2] concludes that the AREVA procedure is consistent with the approved BWROG DIVOM methodology and that RAMONA5-FA can estimate the reduction in CPR given a power oscillation. The focus of the present review is key review question 2, the qualification bases of the RAMONA5-FA.

2.0 DESCRIPTION OF THE RAMONA5-FA CODE

RAMONA5-FA is the transient system code used for the AREVA DIVOM methodology. RAMONA5-FA is a complete three dimensional (3-D) transient system code, and it is based on the Brookhaven National Laboratory RAMONA3 code [Reference 13], which was later modified by Studsvik-Scandpower to become RAMONA5 Version 2.4 [Reference 14]. AREVA's RAMONA5-FA is based on the Studsvik version. Table 1 contains a summary of the RAMONA5-FA features compared to previous versions of the code.

As with the earlier versions of the code, RAMONA5-FA uses a four equation, non-homogeneous, non-equilibrium, one dimensional, two-phase flow model. The four equations used describe:

1. The liquid mass conservation equation
2. The vapor mass conservation equation
3. The mixture non-equilibrium energy conservation equation
4. The integrated mixture momentum equation with drift flux

The momentum equation is integrated through the vessel flow loop to predict the individual velocities for each vessel component and core channel inlet for each time step. The core model consists of parallel hydraulic channels allowing each individual fuel channel to be modeled separately.

2.1. IMPROVEMENTS TO THE AREVA VERSION OF THE RAMONA5-FA CODE

AREVA's RAMONA5-FA code includes the following improvements:

1. The neutron cross section data and hydraulic core data are prepared automatically by coupling to the core simulator MICROBURN-B2. The differences in initial steady state power distribution have been eliminated by applying an adaptive 3D coupling method.

2. A new modal neutron kinetics module has been installed in RAMONA5-FA, to allow better user control over the oscillation mode

3. The fuel pin model in RAMONA was improved by incorporating models from the approved frequency domain stability code STAIF [Reference 15], including

    a. Fuel pellet conductivity dependence on temperature and exposure
    b. Detailed gap conductance model
    c. Neutron self-shielding effects on power deposition distribution in pellets.

4. AREVA's hydraulic and dryout correlations have been installed.

These modifications are documented in Section 4 of BAW-10255(P) [Reference 1]. Probably the most far-reaching modification is the inclusion of the option to use of modal kinetics expansion to the 3D neutronic solver in RAMONA5-FA. When this option is selected, RAMONA5-FA solves the 3D neutronic equations based on an expansion in modes, which are calculated automatically from the power distributions of the steady state from the steady state core simulator (MICROBUN-B2). Modal kinetics expansion is similar to using the point kinetics approximation, which uses the first critical mode, but, in addition, RAMONA5-FA uses higher order modes.

2.2. NEUTRONIC MODELS

The neutronic models in RAMONA5-FA have been updated based on the older RAMONA versions to accommodate AREVA's overall neutronic methodology. This allows for consistency between different analytical methods and the cross sections and other parameters can be imported directly from MICROBURN-B2.

2.3.1 Cross Section Generation

In the response to a NRC staff RAI related to the Browns Ferry Nuclear Plant (Browns Ferry) power uprate [Reference 16], the applicant describes the cross section reconstruction process incorporated in CASMO-4, MICROBURN-B2, and RAMONA5-FA, including high void fraction effects, void fraction in the bypass region, and its accuracy.

CASMO-4 performs a **[ ]** spectrum calculation using a detailed heterogeneous description of the fuel lattice components. Fuel rods, absorber rods, water rods/channels, bypass region, and structural components are modeled explicitly. The solution provides pin-by-pin power, exposure distributions, and two-group effective cross section as function of exposure and lattice void fraction.

Three different historical void fraction levels (**[ ]** percent, **[ ]** percent, and **[ ]** percent) are used to perform the depletion calculations in CASMO-4. At each exposure and historical void fraction level, a branch calculation is performed for three instantaneous void fraction levels at **[ ]** percent, **[ ]** percent, and **[ ]** percent. **[ ]** Refer to Figures SRXB-A.34.9 and SRXB-A.34-10 of Reference 16 for a graphical example of this process.

In summary, the applicant's cross section methodology follows these steps:

1. Generate 2-group cross sections based on a CASMO-4 lattice calculation

2. The 2-group cross sections are a function of exposure, historical void, and instantaneous lattice void

3. The exposure depletion is performed independently for each of the historical void levels (**[ ]** percent, **[ ]** percent, and **[ ]** percent)

4. The cross section as function of instantaneous void (**[ ]** percent, **[ ]** percent, and **[ ]** percent) is generated by quadratic interpolation of the exposure and historical void independent variables.

The nodal cross section polynomial coefficients are calculated in MICROBURN-B2 on nodal basis and written to a coupling file read by RAMONA5-FA. These coefficients are used to calculate nodal cross sections each time step as functions of the following parameters:

1. Control state
2. Average fuel temperature
3. Channel fluid density and bypass fluid density

A second cross-section option is available, but is not automated or recommended. This option represents the original Studsvik-Scandpower procedure, in which cross sections are calculated

by a spectral code such as CASMO for each fuel type, and processed by a coupling code (POLGEN) to provide polynomial coefficients in a format suitable for RAMONA5-FA. This option is only available for use with the PRESTO-1 neutronics model and is only used with RAMONA5-FA when boron dilution calculations are required.

For DIVOM calculations, boron dilution cross sections are not required and the preferred option is to propagate the MICROBURN-B2 cross sections automatically to each of the RAMONA5-FA nodes.

2.3.2 RAMONA5-FA Neutronic Modules

RAMONA5-FA is a modular code that allows for interchangeable modules and correlations. The neutronics in RAMONA5-FA can be solved using three different methods:

1. PRESTO-1 nodal method, which is the 3-D nodal method incorporated in the original RAMONA-3 [Reference 13] version. PRESTO-1 is a nodal solution of the two-group time-dependent diffusion equations for the neutron fluxes. However, it requires the use of case-dependent albedos (reflector boundary conditions), which have to be manually determined by the user. Use of the PRESTO-1 option requires an expert user and a number of iterations to match the 3-D steady state power distributions from RAMONA5-FA and MICROBURN-B2. The PRESTO-1 methodology is documented in detail in Section 2.1 of the RAMONA5-FA Theory Manual [Reference 4].

2. ADAPKIN method, which is **[** **]**. The ADAPKIN methodology is documented in detail in Section 2.2 of the RAMONA5-FA Theory Manual [Reference 4].

3. ADAPKIN-M modal method, which solves the **[** **]** kinetics equations using a modal expansion method. It uses the same equations than the **[** **]** kinetics equations used in the ADAPKIN module, but solves for the eigen-modes and provides a solution that is based on a series expansion of these eigen-modes. This mathematical approach is similar to using the point kinetics equation, but uses a larger number of modes to be able to represent both axial and azimuthal power variations. **[** **]**. The ADAPKIN-M methodology is documented in detail in Section 2.3 of the RAMONA5-FA Theory Manual [Reference 4].

2.3. THERMAL-HYDRAULIC MODELS

2.3.1. Fuel Thermodynamics

The RAMONA5-FA fuel model calculates the temperature distribution within the fuel pin, and the transport of heat from the fuel into the coolant. The base RAMONA Version [Reference 13] assumes constant fuel properties across the reactor core as an option (not accounting for variations in burnup, fuel type, or fuel temperature), while the detailed fuel parameter option requires tables to be prepared manually. In addition, the radial energy deposition across the pellet is assumed to be constant. To improve the fuel rod modeling, a set of correlations were added by the applicant to RAMONA5-FA to allow for node specific fuel properties and allow for

appropriate modeling of the effects of self-shielding on the radial energy deposition. The correlations chosen for this purpose were taken from the approved frequency domain code STAIF [Reference 15] and are documented in Section 4.3 of BAW-10255(P) [Reference 1].

2.3.2. Mass Conservation

The spatial derivative of the mass conservation equation is approximated by upwind differences with respect to the flow direction. RAMONA5-FA uses standard formulations along with its constitutive relations to determine the mass of steam and liquid in each node.

The only RAMONA5-FA non-standard definition is that of "slip." RAMONA5-FA defines the slip, S_f as

$$v_g = S_f\, v_l + v_0$$

Where v_g and v_l are the gas and liquid velocities, and v_o is the bubble rise velocity with respect to stagnant liquid. The more standard definition of slip does not include the v_o term.

2.3.3. Volume Conservation

To calculate the volumetric flow, RAMONA5-FA assumes that the vapor phase is at saturated conditions.

2.3.4. Energy Conservation

The energy conservation equation in RAMONA5-FA uses a standard approach, and it is described in detail in Section 3.2.4.3, "The Energy Conservation Equation," of EMF-3028, Volume 2 [Reference 4]. The heat deposition in each node (both wall-conducted and direct moderator deposition) minus the enthalpy flow in and out of the node must equal the change of node internal energy. The spatial derivative in the enthalpy convection term is approximated by backward differences with respect to the flow direction.

2.3.5. Momentum Conservation

RAMONA5-FA uses what is known as the Integral Momentum Equation solution approach to account for flow inertia and acceleration terms and their effect on the time-dependent pressure drops. The RAMONA5-FA integral momentum formulation is described in detail in Section 3.2.4.5, "Momentum Equations," of EMF-3028, Volume 2 [Reference 4]. The mathematical approach for momentum conservation solution has remained unchanged from the original RAMONA-3 version [Reference 13].
The primary assumption of the RAMONA5-FA momentum conservation solution scheme is to assume that a single global pressure can be used to determine the fluid properties of all the components in the vessel; thus, local pressure differences are disregarded when evaluating fluid properties such as density. This approximation has the immediate effect of disregarding acoustic effects, which are caused by local compressibility. Pressure waves cannot be modeled by RAMONA5-FA because the effective speed of sound is infinite in RAMONA5-FA.

In the RAMONA5-FA formulation, momentum conservation results in a set of N separate momentum ordinary differential equations (ODEs) that relate the time derivative of the loop momentum for each of the parallel paths in the core. All these equations share the common momentum term from the upper and lower plenums and the active recirculation loops. The

integration of these N ODEs provides the time-dependent inlet flow for each of the parallel channels in the core.

Most transients of interest in a nuclear reactor do not involve pressure wave propagation, and can be treated with the integral momentum equation approximation without significant loss of accuracy. For example, density wave oscillations involve enthalpy wave propagation, which travel at speeds several orders of magnitude slower than pressure waves. A typical density wave takes approximately 2 seconds to travel through the core, while a pressure acoustic wave takes only approximately 2 milliseconds. The global-pressure fluid-property approximation is, thus adequate for density wave oscillations and DIVOM calculations.

Note that Section 3.2.4.5, "Momentum Equations," of EMF-3028, Volume 2 [Reference 4] describes how the approximation is modeled in RAMONA5-FA. Two formulations are used: (1) separated flow, or (2) homogeneous equilibrium model (HEM). The separated flow formulation is maintained only for historical reasons. The applicant only utilizes the HEM formulation for the inertia and acceleration losses in the momentum flow term.

2.3.6. System Pressure Calculation

The time-dependent system pressure calculation performed by RAMONA5-FA is described in detail in Section 3.2.4.6, "Pressure Calculation," of EMF-3028, Volume 2 [Reference 4]. The approach used by RAMONA5-FA is to establish a conservation relation between the volume change due to evaporation/condensation and the terms that account for the compressibility. This conservation relation is derived based on the mixture mass conservation equation. The compressibility term contains the time derivative of the system pressure. The final result of the RAMONA5-FA formulation is a single ODE for the time derivative of the pressure as function of other calculated parameters. By integrating this ODE, RAMONA5-FA estimates the system pressure.

2.3.7. Recirculation Loop Calculation

The recirculation flow calculation in RAMONA5-FA is based on a closed loop momentum equation. The external recirculation loop consists of: downcomer, suction line of the recirculation pump, discharge line of the recirculation pump, and the nozzle exit where recirculation flow and jet pump suction flow mix. A closed contour momentum equation is formulated for the recirculation loop and calculated along with the core and vessel flow paths to result in the time-dependent recirculation flow.

2.3.8. Bypass Region and Bypass Void Modeling

The bypass region is modeled in RAMONA5-FA using a single hydraulic channel. There are numerous leakage paths from the lower plenum to the bypass region. **[**

].

The enthalpy and void fraction (if applicable) of the bypass region is calculated as function of elevation with the same axial node structure as the core. **[**

]

In the response to NRC staff RAI 21 [Reference 6], the applicant provides additional information on the response of RAMONA5-FA to bypass boiling oscillations. Two effects are considered:

1. First, the effect on the local power range monitor (LPRM) sensitivity because the presence of voids around the detectors changes their calibration. In general, bypass voids reduces the detector sensitivity and the measured signal (including the oscillatory part) is smaller.

2. Second, the actual bypass void oscillation is calculated by integrating a system of differential equations representing two-phase flow mass, momentum, and energy balance formulated similar to the RAMONA5-FA code.

The effect of LPRM decalibration is shown by analysis to have **[**

] This effect is illustrated in Figures 21-3 and 21-4 of the response to NRC staff RAI 21 [Reference 6].

The amplitude of the calculated bypass flow oscillations are very small, as illustrated in Figure 21-2 of the response to NRC staff RAI 21 [Reference 6]. For a power oscillation between **[ ]** and **[ ]** kilowatt (kW) (around an average of **[ ]** kW, or approximately **[ ]** percent), **[ ]**

2.3.9. RAMONA5-FA TH Nodalization

All versions of the RAMONA code generally only supports BWR applications because the system model is hard-wired to BWR reactor core. The geometry is not modular and it is not fixed. Thanks to these fixed models, and, specially, the integral momentum equation approximation, RAMONA was the first industrial-scale code capable of performing full-core neutronic and hydraulic calculations. RAMONA5-FA calculations always have 1:1 nodalization and include typically 19100 active channel nodes for a 764 assembly plant. One significant advantage of the RAMONA5-FA nodalization is that hydraulic collapsing is not required and RAMONA5-FA calculates the CPR of each and every high-power channel.

RAMONA5-FA calculations take advantage of the results from the more-accurate 3D simulator MICROBURN-B2, and all the core information is transferred automatically. The response to NRC staff RAI 16 [Reference 6] summarizes a list of all the relevant data transferred from MICROBURN-B2 to RAMONA5-FA.

2.3.10. Correlations

2.3.10.1. Void-Quality Correlation

RAMONA5-FA offers five options for void-quality correlations, all drift flux formulations.

1. Bankoff-Malnes correlation
2. Bankoff-Jones correlation
3. **[ ]**correlation

[ ]

5. Toshiba correlation (C_0 = 1.08 and V_{gj} = 0.45)

For DIVOM evaluation, the applicant uses exclusively the **[ ]** drift flux correlation to relate the void fraction, α and quality, X at any location and point in time in the calculation.

2.3.10.2. Pressure Drop Correlations

RAMONA5-FA has two options for calculating the single phase friction factor. The first is of the standard form based on the Reynolds number to a variable power. Alternatively, a conventional fit to the Moody chart can be selected.

Several options are available in RAMONA5-FA for the two-phase friction multiplier including:

1. Martinelli-Nelson
2. Becker
3. Rolstad

[ ]

For DIVOM calculations, **[ ]**. Local pressure loss models are also used in performing RAMONA5-FA analysis to account for spacer grids, tie plates, etc. For the local pressure loss models, the homogeneous model is used.

For the DIVOM analysis, the pressure drop package chosen **[ ]**

2.3.10.3. Non-equilibrium Boiling Correlation

The RAMONA code series (at least version 3B and newer – this includes RAMONA5-FA) has the capability of accounting for thermal non-equilibrium in the liquid portion of the two phase mixture. This capability is introduced in the code by a calculation of the non-equilibrium vapor generation rate, which is composed of two parts: the evaporation due to heat transfer from the wall, and the mass transfer (evaporation or condensation) due heat transfer between the phases.

For DIVOM calculations, non-equilibrium is encountered in the subcooled boiling region and influences the subcooled void fraction. **[ ]**

2.3.10.4. Dryout Correlations

The base critical heat flux correlations used in RAMONA5-FA are the Condie-Bengston correlation [Reference 22] and the Zuber-Griffith correlation [Reference 23]. The code also offers an option of using the Biasi [Reference 24] correlation in place of the Condie-Bengston correlation at the user's discretion. The ANFB-10 [Reference 25] and SPCB [Reference 26] correlations have also been implemented in RAMONA5-FA and are the correlations used for DIVOM analysis. In addition, an unlicensed boiling length correlation known as KWUXL10-A1 has also been implemented for comparison and RAMONA5-FA benchmarking, but is not used for DIVOM licensing calculations. These two correlations are the current licensing dryout correlations used by the applicant in the US. The ANFB-10 and SPCB correlations have both been qualified and have been approved for DIVOM analyses for both AREVA as well as other vendor's fuel. The applicant is currently in the process of introducing an advanced dryout correlation (known as ACE). In the response to RAI 19 [Reference 6] the applicant has successfully benchmarked the new ACE correlation against oscillatory dryout and rewet conditions in the Karlstein Thermal Hydraulic (KATHY) experimental facility.

2.4. RAMONA5-FA TESTING SUITE

The applicant outlined the Software Quality Assurance Program under which RAMONA5-FA has been developed. This program is based partially on the regression testing of the code system to the original RAMONA5 Version 2.4 [Reference 14] developed by Studsvik. The applicant performs regression testing for each new RAMONA5-FA version to ensure the results continue to be consistent with those produced by Version 2.4 as transmitted by Studsvik, the vendor that supplied RAMONA5. This regression testing includes a series of tests, called Suite 1, which include:

1. Single channel hydraulic stability tests based on a FRIGG test point
2. Ringhals-1 Cycle 14 instability analysis
3. Single recirculation pump trip
4. Two recirculation pump trip

The Suite 1 tests are performed and the differences between the output decks are analyzed. Depending on the code modification, either no difference should occur, or the differences need to be evaluated by an engineer to determine the applicability of the code change. For example, if a coding issue related to the automated input generation from MICROBURN-B2 is implemented, no differences should be expected for the Suite 1 test outputs. If, for example, a CPR correlation is modified, output differences should be expected on the CPR values, but not in others.

The applicant notes that the vendor's Suite 1 tests include a number of additional tests that are not applicable to RAMONA5-FA. For example, RAMONA5-FA does not have the PRESTO-2 nuclear model option; therefore, those tests in Suite 1 are not performed.

In addition to the above Suite 1 tests provided by Studsvik, the applicant maintains a separate series of tests called Suite 2, which are specific to the AREVA RAMONA5-FA implementation and exercise the special RAMONA5-FA features. The regression tests in Suite 2 include:

1. A test of the ADAPKIN neutronic method results
2. A test of the ADAPKIN-M neutronic method results
3. A test of the STAIF fuel models
4. A test of the licensing void correlation **[ ]**
5. A test of the pressure loss model
6. A RAMONA5-FA calculation for a DIVOM configuration

As with Suite 1, the RAMONA5-FA outputs are compared before and after the modification and evaluated for differences. The UNIX utility “diff” is used to automate the difference checking. If differences are apparent, the applicant evaluates the magnitude of the impact by looking at significant parameters on plots.

2.5. QUALIFICATION OF THE RAMONA5-FA CODE

This review is limited to the generation of DIVOM correlations, and it is not a complete review of RAMONA5-FA for generic transient analyses. In order to calculate DIVOM correlations, RAMONA5-FA should be capable of reliably generating self-consistent growing power oscillations and be capable of estimating the reduction in CPR margin during those oscillations.

[

] The only requirement is that those power oscillations be self-consistent (i.e., be accompanied by consistent flow and void oscillations). **[**

]

Two DIVOM correlations are typically calculated: the core-wide and the regional DIVOM. The reduction in CPR during oscillations is controlled mostly by the amplitude of the flow/void oscillations instead of the amplitude of the power oscillations. Because of their nature, regional instabilities results in larger flow oscillations that core-wide instabilities, and the regional DIVOM slope is in all cases more steep than the core-wide DIVOM slope. In the physical situation, one has a closed-loop where the power oscillations drive the voids and the voids in term feedback to the power; however, the void-to-power feedback is essentially instantaneous (the neutron generation time is a few micro seconds), while the power-to-void feedback has a approximately six second time constant because of the fuel-heat-capacity filtering effect. Thus, a convenient first-approximation model is to think that the voids oscillations are driving the power oscillations. In a core-wide oscillation, the voids induce reactivity changes, which induce power oscillations; however, in the regional case, the same reactivity change will result in a smaller power oscillation. Or, in DIVOM terms, for the same power oscillation amplitude, a subcritical mode (i.e. regional oscillations) will require a larger void oscillation and will reduce the CPR margin more than a critical mode (i.e., core-wide oscillations).

AREVA has qualified the RAMONA5-FA code for decay ratio and frequency calculations against channel thermal hydraulic tests in the KATHY facility and against real plant instability events. The instability events include both regional and core-wide, but incorporate more regional events, because those generate the more conservative DIVOM slopes. Table 5 presents the results of these benchmarks. The reactor events include:

1. CGS Cycle 8 - Global Instability
2. GUNC Cycle 13 - Regional Instability
3. GUNC Cycle 1 - Regional Instability
4. KKK Cycle 3 - Regional Instability

In addition, RAMONA5-FA has been benchmarked against a number of KATHY flow loop stability measurements. These measurements are for purely thermal-hydraulic oscillations (no neutronics) and benchmark the channel decay ratio capability of RAMONA5-FA. They also benchmark the capability of RAMONA5-FA to model self-consistent flow-void oscillations. The results are shown in Figure 13 and Figure 14.

Overall, the NRC staff concludes that the RAMONA5-FA benchmarking against channel, core-wide, and regional oscillations is satisfactory. RAMONA5-FA has demonstrated the capability to generate self-consistent power-flow-void oscillations of the correct frequencies to be used for DIVOM calculations.

2.6. RAMONA5-FA CONFIGURATION FOR DIVOM CALCULATIONS

The response to NRC staff RAI 7 [Reference 6] documents the typical RAMONA5-FA configuration for stability DIVOM calculations. Table 6 summarizes this configuration. All the benchmarks and reviews have been performed based on this configuration. Deviations from this configuration are expected, for example, when new fuels and CPR correlations become available.

3.0 REGULATORY EVALUATION

The TR provides a methodology for calculating the DIVOM curve, which is an integral part of the setpoint methodology for most D&S long term stability solutions. Since the DIVOM curve methodology is part of the setpoint methodology, the TR was developed to comply with the requirements of Criteria 10 and 12 in Title 10 of the *Code of Federal Regulations* Part 50 (10 CFR 50), Appendix A, "General Design Criteria for Nuclear Power Plants."

Criterion 10, "Reactor design," requires that: "The reactor core and associated coolant, control, and protection systems shall be designed with appropriate margin to assure that specified acceptable fuel design limits are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences."

Criterion 12, "Suppression of reactor power oscillations," requires that: "The reactor core and associated coolant, control, and protection systems shall be designed to assure that power oscillations which can result in conditions exceeding specified acceptable fuel design limits are not possible or can be reliably and readily detected and suppressed."

To ensure compliance with Criteria 10 and 12 of 10 CFR Part 50, Appendix A, the NRC staff will confirm that a licensee performs plant-specific trip setpoint calculations using NRC-approved methodologies, as stated in NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," Chapters 4.4 and 15.9. The TR would support a licensee's application for a Technical Specification (TS) license amendment change.

4.0 TECHNICAL EVALUATION

4.1. NEUTRONIC MODELS

4.1.1. Steady-State Data benchmarks

In the response to NRC staff RAI 1 [Reference 6], the applicant provided steady state benchmarks of the neutron fluxes calculated by MICROBURN-B2 and the three neutronic methods available in RAMONA5-FA: PRESTO, ADAPKIN, and ADAPKIN-M. As expected, the steady state fluxes, both axial and radial, from RAMONA5-FA ADAPKIN **[**

]

The RAMONA5-FA PRESTO methodology requires user iteration to identify the albedo boundary conditions. In the example of RAI 1 [Reference 6], the albedos were not optimal and a small

difference is seen between MICROBURN-B2 and PRESTO fluxes. Reasonably good agreement is observed, even with the non-optimal albedos. In addition, the RAMONA5-FA DIVOM methodology uses the ADAPKIN methods and not the PRESTO methodology.

A more relevant benchmark of the neutronic methods is obtained following a transient event, which is covered in the next section.

4.1.2. Transient Benchmarks

In the response to NRC staff RAIs 2, 3, and 4 [Reference 6], the applicant presents a comparison of the RAMONA5-FA neutronic methods following a transient. **[** **]** A more relevant benchmark is whether they can follow the flux during a transient.

Three different transient events were considered:

1. A pressure perturbation, which is expected to provide a uniform change in power with minimal 3D power shape distortion

2. A subcooling perturbation, which is expected to result in a axial power shape distortion

3. A control rod perturbation, which is expected to result in both axial and radial power shape distortions

For these comparisons, MICROBURN-B2 is used as a reference. MICROBURN-B2 is the applicant's 3D simulator code that is used for core follow and design. It is benchmarked regularly against plant data.

As expected, all three RAMONA5-FA methods were successful for the pressure perturbation. The transient axial power shape is modeled **[** **]**. The transient radial power distribution is match **[** **]** The PRESTO method shows a slightly higher axial and power shape mismatch **[** **]**..

For the subcooling transient, **[** **]**

Finally, when a control rod is withdrawn, **[** **]**

In summary, the NRC staff concludes that

1. ADAPKIN methods, both nodal and modal, offer in general better results and match more accurately the MICROBURN-B2 3D simulator. [ ]

2. The ADAPKIN-M method is able to follow global changes of axial and power distributions that would be expected during power oscillations for DIVOM calculations. [ ] The user must exercise discretion and evaluate the particular transient for applicability.

3. The PRESTO method is more general and can model significant power distortions during transients (e.g. rod withdrawals); however, it requires more user interaction and an expert user to select the correct albedos. The use of PRESTO for DIVOM calculations is acceptable, but not recommended.

4.1.3. RAMONA5-FA neutronic methods limitations

In the response to NRC staff RAI 5 [Reference 6], the applicant presents the limitations of the three RAMONA5-FA neutronic methods:

1. The ADAPKIN and PRESTO methods are generic and apply to all BWR transients

2. The PRESTO method is somewhat limited by the need to generate albedos manually, and by the need of a trained expert operator.

3. The ADAPKIN-M method, is more general and specially suited to stability calculations because it can select the oscillation mode. [ ]

[ ]

4.2. VOID-QUALITY CORRELATION UNCERTAINTY

In response to NRC staff RAIs 11 and 12 [Reference 6], the applicant provided a series of calculations where the void-quality correlation was biased to bound the void data measured in the KATHY facility for ATRIUM-10 fuel. The applicant evaluated the propagation of errors from void-quality correlation to DIVOM slope and traversing in-core probes (TIP) measurements.

4.2.1. DIVOM sensitivity to void-quality correlation

In response to NRC staff RAI 12 [Reference 6], the applicant performed a propagation of errors by artificially introducing a bias in the void-quality correlation and computing the effect on DIVOM slope. The results appear to indicate that the impact on DIVOM slope is not only a function of the void-fraction bias imposed, but also on the shape or nature of the bias.

First, the applicant used a [ ] percent bias in the void fraction by artificially biasing the slip by [ ] percent. This results in a large unphysical bias and a significant effect on DIVOM slope of approximately [. Note that typical DIVOM slopes are less than 0.45, so this bias results in a [ ] percent impact.

Second, the applicant used a plus or minus 5 percent bias with a shape factor that **[**

] Applying this bias, results in little or no effect on the DIVOM curve.

The NRC staff concludes form the above analysis, that errors in the void fraction correlation may propagate to the DIVOM curve and have significant impact. However, **[**
], the impact on the DIVOM curve of void fraction estimation errors is minimal.

4.2.2. Decay ratio sensitivity to void-quality correlation

In response to NRC staff RAI 12 [Reference 6], the applicant provided a series of decay ratio calculations of the KATHY ATRIUM-10 tests as function of the void fraction bias, using the brute force slip factor adjustment to bias the void fraction. The calculated decay ratios when the brute force bias is applied are significantly affected (**[** **]** percent). Since using the nominal void correlation results in good agreement with the KATHY measured decay ratios, the applicant concludes that the upper and lower bound bias estimations were overly conservative.

4.2.3. **[** **]** data benchmarks

In response to NRC staff RAI SRXB-121 [Reference 18], the applicant provided benchmark data of **[**

]

[

]

[

]

[

]

Based on the above data, the NRC staff concludes that assuming a [ ] percent error in void-quality correlation by biasing the slip factor is an overly conservative bounding assumption. The expected error in the void-quality correlation should be significantly smaller than [ ] percent based on the [ ] and decay ratio benchmarks.

[

]

Therefore, the NRC staff concludes that the impact on DIVOM slope of uncertainties on the void-quality correlation is small and covered by other uncertainties in the applicant's methodology.

4.3. THERMAL-HYDRAULIC MODELS

4.3.1. Pressure Drop and Flow Redistribution Benchmarks

In the response to NRC staff RAI 13 [Reference 6], the applicant provides a comparison of core flow pressure drops calculated by RAMONA5-FA using the integral momentum formulation against the 3D core simulator MICROBURN-B2. The differences in predicted core flow are [ ] percent (standard deviation [ ] percent). RAMONA5-FA was also used to calculate the pressure drops measured in the KATHY facility for an ATRIUM-10 fuel element. The results show a [ ] percent error in the prediction, as shown in Figure 18.

4.3.2. Conservation of Momentum for Oscillatory Conditions

[

]

Based on this review and the benchmark data, the NRC staff concludes that the RAMONA5-FA implementation of the integral momentum equation is adequate to model the flow and pressure drops oscillations required to simulate the conditions required to estimate DIVOM correlation data.

4.4. RAMONA5-FA CORRELATIONS

4.4.1. Void-Quality Correlation

[

]

[

]

[

]

[

]

In order to illustrate the range of the measured void fraction data in the context of what is experienced during DIVOM development at/near natural circulation, a plot of the assembly exit voids predicted by RAMONA5-FA as a function of flow from a typical DIVOM calculation is shown in Figure 20. Also plotted is the ATRIUM-10 measured void vs. flow rate. The RAMONA5-FA results were extracted from the exit of every other bundle in the core at one second intervals for a 120 second long DIVOM evaluation. Indicated on the figure is the general direction of void/flow oscillations as they evolve during the event. The oscillations start small, and then slowly get larger as the reactor power oscillations get larger. The figure indicates that parameters expected during the DIVOM event lie in the lower mass flow rate regions, and that ATRIUM-10 data sufficiently covers the expected void and flow rate range.

[

]

The correlation performance has been very good against this wide range of data bases, and the correlation has been developed to approach the appropriate limits. Additionally AREVA has compared the correlation to data taken in the KATHY experimental facility using ATRIUM-10 fuel geometries. The correlation has also performed well in these comparisons. This data covers the expected void fraction range during DIVOM development. It is therefore concluded that the [ ] correlation is satisfactory for use in DIVOM predictions.

4.4.2. Pressure Drop Correlations

The pressure drop correlations used in RAMONA5-FA for DIVOM analysis are conventional formulations for single and two-phase flows. [

] The results are shown in Figure 18, and indicate that the correlation package does an effective job of simulating the experimental results.

4.4.3. Non-equilibrium Boiling Correlation

The non-equilibrium boiling correlation used in RAMONA impacts the subcooled void formation in the DIVOM calculations. [

] In response to RAI 14 [Reference 6] the applicant provided a benchmark comparison between KATHY ATRIUM-10 experimental void measurements and RAMONA5-FA predictions in the subcooled boiling region. Since the prediction of the vapor generation rate in the subcooled boiling region determines the void fraction, this comparison effectively tests the non-equilibrium boiling treatment. Figure 21 shows this comparison. Results indicate that RAMONA5-FA effectively predicts void formation in the subcooled region, and that the subcooled boiling model is sufficient for DIVOM calculations.

4.4.4. Dryout Correlations

The dryout correlations implemented in RAMONA5-FA and used for DIVOM analysis are the ANFB-10 and SPCB correlations have been implemented in RAMONA5-FA. These two correlations are the current licensing dryout correlations used by the applicant in the US. They have both been qualified and have been approved for DIVOM analyses for both AREVA as well as other vendor's fuel [References 25 and 26].

4.4.5. Applicability of AREVA Dryout Correlation to Oscillatory Flow Conditions

The hydraulic loop at Karlstein (KATHY) was used for several campaigns to measure the stability characteristics of new fuel types. In some of these experiments, the power was increased beyond the stability threshold and resulted in growing flow rate oscillations. When the flow oscillations were allowed to grow to large magnitudes, some of the thermocouples attached to the inner surface of the electrically heated pins responded with elevated temperature that followed inlet flow minima by a time delay characteristic of the density wave, marking the arrival of the flow minimum to the elevation of the thermocouple. The temperature response is clearly indicative of degraded heat transfer or dryout conditions.

RAMONA5-FA was used to simulate these cyclic dryout and rewetting tests for an ATRIUM-10 electrically heated bundle with a bottom-skewed axial power shape. The measured oscillatory inlet flow rate is imposed as a boundary forcing function, and the CPR response is calculated. Some of these results are shown in Figure 3. An excellent agreement is shown between the measured clad temperature increases and the times where RAMONA predicts dryout (i.e. CPR less than 1.0). This indicates that adequacy of using a steady state dryout correlation during oscillatory flow transients similar to those used by the DIVOM methodology.

AREVA compared the predictions of three different dryout correlations: ANFB-10, SPCB, and XL10A1. The results are shown in Figure 4. These results indicate that all three dryout

correlations that are currently programmed in RAMONA5-FA respond similarly to oscillatory type of flow oscillations, and all three predict the inception of dryout conditions. Section 3.2 of BAW-10255(P) [Reference 1] performs additional benchmarks and sensitivity studies.

Based on this review, the NRC staff concludes that RAMONA5-FA can correctly predict the onset of dryout conditions during power oscillations representative of instabilities, which are used in the methodology to calculate the DIVOM correlation.

4.5. DOCUMENTATION ISSUES

Following the recommendations of the 579th meeting of the ACRS, January 13-15, 2011, AREVA reviewed the RAMONA5-FA documentation, and found it to be deficient. Many confusing terms were used and inconsistent nomenclature was used throughout the text. As a result of this effort, AREVA issued Revision 4 of the RAMONA5-FA Theory Manual (EMF-3028, Volume 2). The changes and quality control procedure are documented in AREVA Engineering Information Record (EIR), Document No. 51 - 9152672 – 000 “Formal Review of RAMONA5-FA Coding with Respect to Revision 4 of EMF-3028 Volume 2.”

AREVA recognized early on during the process that many inconsistencies were present in the documentation. AREVA identified the root cause of this deficiency as being caused by careless cut and paste from different documents. Each original document by itself was correct, but when pasted together some of the assumptions were mixed up and the nomenclature was inconsistent. To prevent this problem from reoccurring, the approach used by AREVA for this update was as follows:

1. Review the coding in the RAMONA5-FA source code
2. Reverse engineer what equation are actually being solved by the code
3. Update the documentation with the actual equations
4. Verify that the equations used in the RAMONA5-FA code are indeed the correct physical equations

Using this approach, AREVA guaranteed that the documentation and code agree with each other. During this review, AREVA did not find any deficiency with the code. All identified and corrected deficiencies were related to documentation issues.

The NRC staff has reviewed the process followed by AREVA to reconcile the RAMONA5-FA code with its documentation, and the new documentation for completeness and consistency. The process followed is technically correct and ensures that the code and documentation are consistent. The process also reviewed the conservation equations and models solved by RAMONA5-FA and confirmed their adequacy. Therefore, the NRC staff finds that the new RAMONA5-FA documentation accurately reflects the equations that are solved by the code.

5.0 CONCLUSIONS

The NRC staff has reviewed the RAMONA5-FA code [References 1-3] for applicability to Delta Over Initial Versus Oscillation Magnitude (DIVOM) calculations. The NRC staff has reviewed the cross section generation methodology, neutronic and thermal-hydraulic models, and the constitutive relations programmed in the RAMONA5-FA code. The NRC staff has also reviewed the RAMONA5-FA testing suite and its qualification bases. In addition, through the Request for Additional Information (RAI) and audit process, the NRC staff has reviewed a number of RAMONA5-FA benchmarks and the sensitivity of the DIVOM process to uncertainties.

The NRC staff issued an SE on AREVA's DIVOM methodology [Reference 2], which imposed a condition to perform a full code review of RAMONA5-FA, including constitutive relations, numerics, neutronic methods and benchmarks before RAMONA5-FA can be used to calculate DIVOM curves in EFW operating domains. The conditions specified that, until the review is completed, AREVA must include an interim 10 percent penalty on the DIVOM slopes calculated by the RAMONA5-FA methodology in EFW domains. The DIVOM SE [Reference 2] specifies that, once RAMONA5-FA is reviewed and accepted by the NRC staff, this limitation will be removed. Therefore, this SE removes this condition (i.e., removes Limitations and Conditions 2 and 3 of the DIVOM SE).

Based on this review, the NRC staff reaches the following conclusions:

1. The RAMONA5-FA code is qualified to model the growing unstable power oscillations that are required for the DIVOM calculation procedures.

2. RAMONA5-FA can correctly predict the onset of dryout conditions during power oscillations representative of instabilities.

3. Therefore, the RAMONA5-FA code is qualified to implement DIVOM methodology calculations.

4. For the power oscillation magnitudes required to calculate the DIVOM slopes, the calculated amplitude of the bypass void oscillations **[**
].

5. The DIVOM SE [Reference 2] specifies that an interim 10 percent penalty must be applied to the DIVOM slopes calculated by the RAMONA5-FA methodology in EFW domains. Based on this review, the NRC staff removes this condition (i.e., removes Limitations and Conditions 2 and 3 of the DIVOM SE).

6.0 REFERENCES

1. BAW-10255(P), Revision 2, “Cycle-Specific DIVOM Methodology Using the RAMONA5-FA Code.” Framatome ANP, Inc. January 2006.

2. Revised Safety Evaluation Relating To Review Of Framatome Topical Report BAW-10255(P) Revision 2, “Cycle-Specific Divom Methodology Using The RAMONA5-FA Code” (TAC No. MC9767), April 21, 2008.

3. EMF-3028(P), Volume 1, “RAMONA5-FA: A Computer Program for BWR Transient Analysis in the Time Domain Volume 1: User's Manual,” March 2006.

4. EMF-3028(P), Volume 2, Revision 4, “RAMONA5-FA: A Computer Program for BWR Transient Analysis in the Time Domain Volume 1: Theory Manual,” January 2011.

5. ANP-10255Q1P, Revision 1, Response to Request for Additional Information – BAW-10255(P). AREVA, October 2007.

6. Letter (NRC:09:018) from Ronnie L. Gardner (AREVA) to USNRC, Response to a Request for Additional Information Regarding EMF-3028(P), Volumes 1 and 2, Revision 2, “RAMONA5-FA: A Computer Program for BWR [Boiling Water Reactor] Transient Analysis in the Time Domain Code” Including User and Theory Manuals (TAC No. MD8812), March 4, 2009.

7. AREVA Document 20004-015 “RAIs Relating to AREVA NP Topical Report (TR) EMF-3028(P), TAC Number MD8812 (09/30/2008)” Attachment to Reference 6, March 2009.

8. ORNL Technical Evaluation Report. Jose March-Leuba and Grady Yoder, “Review of RAMONA5-FA Application for DIVOM Calculations,” March 2009.

9. NEDO-31960-A, BWR Owners' Group Long-Term Stability Solutions Licensing Methodology, November 1995

10. NEDO-31960-A, Supplement 1, BWR Owners' Group Long-Term Stability Solutions Licensing Methodology, November 1995

11. NEDO-32465-A, BWR Owners' Group Reactor Stability Detect and Suppress Solutions Licensing Basis Methodology for Reload Applications, August 1996

12. ANP-10262(P), Revision 0, Enhanced Option III Long Term Stability Solution. Framatome ANP, Inc. January 2006.

13. NUREG/CR-3664, W. Wulff, H. S. Cheng, D. J. Diamond, and M. Khatib-Rahbar, "A Description and Assessment of RAMONA-3B MOD.0 CYCLE 4: A Computer Code with Three-Dimensional Neutron Kinetics for BWR System Transients," 1984.

14. RAMONA5 Version 2.4, “Users and Theory Manuals,” Studsvik-Scandpower.

15. EMF-CC-074(P)(A), Volumes 1 through 4, STAIF A Computer Program for BWR Stability Analysis in the Frequency Domain, Siemens Power Corporation, 1993 (Volume 1) through 2000 (Volume 4).

16. TVA-BFN-418 “Browns Ferry Nuclear Plant Units 2 and 3 – Response to NRC Round 3 Requests for Additional Information Related to Technical Specifications Change TS-418 – Request for Extended Power Uprate Operation (TAC NOS MC3743 and MC3744)” March 7, 2006.

17. EMF-2158(P)(A), Revision 0, “Siemens Power Corporation Methodology for Boiling Water Reactors: Evaluation and Validation of CASMO-4/MICROBURN-B2.” October 1999.

18. “Responses to NRC RAI – Round 18 and Round 20 for Browns Ferry EPU”, September 2008.

19. **[ ]**

20. Coddington, P. and Macian, P., “A Study of the Performance of Void Fraction Correlations Used in the Context of Drift-Flux Two-Phase Flow Models.”

21. Moody, L. F., “An Approximate Formula for Pipe Friction Factors,” Mechanical Eng. 69, pp 1005-1006, December 1947.

22. Condie, K.G. and Bengston, S. J., “Development of the MOD7 CHF Correlation”,PN-181-78, INEL report, November 1, 1978.

23. Smith, R. A. and Griffith, P. A., “A Simple Model for Estimating Time to CHF in a PWR LOCA,” National Heat Transfer Conference ASME Paper, 75-HT-64, 1975.

24. Biasi, L., et. al., “Studies on Burnout – Part 3 – A New Correlation for Round Ducts and Uniform Heating and its Comparison with World Data,” Energia Nucleare, 14 (9), September 1967.

25. EMF-2245(P)(A), Revision 0, ANFB-10 Critical Power Correlation, Siemens Power Corporation, July 1998. (from Reference 3)

26. EMF-2209(P)(A), Revision 2, SPCB Critical Power Correlation, Framatome, ANP, Inc., September 2003. (from Reference 3)

Attachment: Resolution of Comments

Principle Contributor: T. Huang

Dated: March 4, 2013

Table 1. Summary of RAMONA features for different versions

Table 2. [ ] High Pressure – High Flow Rod Bundle Data Base

Table 3. Distribution in Errors for High Pressure – High Flow Data Base for the [ ] Correlation

Table 4. Data Base Used by Coddington and Macian

	ACHILLES	THETIS	PERICLES	NEPTUN	BWR4x4	BWR8x8	LSTF	TPTF	THTF
Reference	Pearson and Denham, 1989	Jowitt et al., 1984	Deruaz et al., 1985	Dreier et al., 1988	Mitsutake et al., 1990	Morooka et al., 1991	Anoda et al., 1990	Kumamaru et al., 1994	Anklam and Miller, 1982
Type	PWR	BWR	PWR	LWHCR[5]	BWR	BWR	PWR	PWR	PWR
Length [m]	3.7	3.6	3.7	1.7	3.7	3.7	3.7	3.7	3.7
Rods(heated)	69 (69)	49 (49)	357 (357)	37 (37)	16 (16)	64 (62)	1104 (1008)	32 (24)	64 (60)
d_r [mm]	9.5	12.2	9.5	10.7	12.3	12.3	9.5	9.5	9.5
d_h [mm]	13	13	11	4	12	13	13	10	11
Axial power distribution	chopped cosine	chopped cosine	chopped cosine	chopped cosine	uniform	uniform / chopp. cosine	chopped cosine	uniform	uniform
ΔT_{sub} [K]	18/24	25-157	20/60	0.5-3	0*	9-12	0*	5-35	46-118
p [MPa]	0.1/0.2	0.2-4.0	0.3/0.6	0.4	0.5/1.0	1.0-8.6	1.0/7.3/15.0	3.0/6.9/11.8	3.9-8.1
G [kg/m²s]	0.08	2.5-3.1	21-48*	42/91	833/1390	284-1988	2.2-84*	11-189	3.1-29
q [kW/m²]	11	11/12	11-40	5/10	350-743*	225-3377*	5-45	9-170	11-74

[5] Light Water High Conversion Reactor

* estimated values

Table 5. Benchmark results for plant stability events

Table 6. RAMONA5-FA configuration for DIVOM calculations

Correlation/Model Type	**Standard Option for DIVOM**	**Numerical Values (where applicable)**
Vapor Generation Rate		
Friction Factor		
Void-Quality		
Two-Phase Friction Multiplier		
Spatial Acceleration		
Core Geometry and History Data		
Neutron Kinetics		
Hydraulic solution scheme		
Fuel Rod Model		

Figure 1. Illustration of DIVOM slope calculation procedure

Figure 2. Comparison of High Pressure – High Flow Data Base to [ ] Correlation

Figure 3. Measured clad temperature in KATHY tests compared to RAMONA5-FA CPR predictions

Figure 4. Measured clad temperature in KATHY tests compared to RAMONA5-FA CPR predictions for three different dryout correlations

Figure 5. ATRIUM-10 void vs quality data compared to three constant-slip correlations

Figure 6. Comparison of [ ] vs [ ] void quality correlations

Figure 7. Comparison of RAMONA5-FA predictions of void quality ([ ]) versus ATRIUM-10 measurements (KATHY)

Figure 8. [ ] for variations of the void quality correlation

Figure 9. [ ] for variations of the void quality correlation

Figure 10. [ ] for variations of the void quality correlation

Figure 11. [ ] for variations of the void quality correlation

Figure 12. [ ] for variations of the void quality correlation

Figure 13. RAMONA5-FA calculated versus measured Decay Ratios in KATHY

Figure 14. RAMONA5-FA calculated versus measured frequencies in KATHY and reactor events

Figure 15. [
]

Figure 16. [
]

Figure 17. [

]

Figure 18. Comparison of pressure drops calculated by RAMONA5-FA versus measured in the KATHY test facility

Figure 19. Calculated Void Fraction Using the [ ] Correlation Compared to ATRIUM-10A Data.

Figure 20. Comparison of Void Fractions Expected During DIVOM Development to Data Taken in the KATHY Experiments.

Figure 21. Comparison of RAMONA5-FA void fraction predictions to KATHY experimental results.

APPENDIX A. REQUEST FOR ADDITIONAL INFORMATION EVALUATION

RAI 1

For a typical reactor condition, provide the steady-state, 3-Dimensional (3D), 2-group neutron flux and power distributions calculated by: (1) MICROBURN-B2, (2) RAMONA5-FA PRESTO-1 Method, (3) RAMONA5-FA ADAPKIN Method, and (4) RAMONA5-FA ADAPKIN-M Method. Quantify and explain the maximum node-power differences

The applicant provided the requested steady state 3D power distributions. Both, the ADAPKIN and ADAPKIN-M method have a **[ ]** with MICROBURN-B2. The PRESTO-1 methodology has a small mismatch at core bottom because the albedo boundary conditions had not been optimized.

RAI 2

For the steady-state conditions of RAI question 1.0, initiate a transient by increasing the reactor pressure. Provide the 3D, 2-group neutron flux and power distributions calculated by the four neutronic methods after power is stabilized. Quantify and explain the maximum node-power differences.

As expected, all three RAMONA5-FA methods were successful for the pressure perturbation. The transient axial power shape is modeled almost perfectly by all three methods. The transient radial power distribution is match **[ ]**. The PRESTO method shows a slightly higher axial and power shape mismatch **[ ]**.

RAI 3

For the steady-state conditions of RAI question 1.0, initiate a transient by decreasing the feedwater temperature. Provide the 3D, 2-group neutron flux and power distributions calculated by the four neutronic methods after power is stabilized. Quantify and explain the maximum node-power differences.

For the subcooling transient, **[ ]**

RAI 4

For the steady-state conditions of RAI question 1.0, initiate a transient by fully inserting one control rod and fully withdrawing a symmetric rod. Provide the 3D, 2-group neutron flux and power distributions calculated by the four neutronic methods after power is stabilized. Quantify and explain the maximum node-power differences.

When a control rod is withdrawn, **[**

]

RAI 5

State the limitations for the three RAMONA5-FA neutronic methods (PRESTO-1, ADAPKIN, and ADAPKIN-M). State what type of transients are applicable to each method ***[*** ***]****.*

The applicant presents the limitations of the three RAMONA5-FA neutronic methods

1. The ADAPKIN and PRESTO methods are generic and apply to all BWR transients

2. The PRESTO method is somewhat limited by the need to generate albedos manually, and by the need of a trained expert operator.

3. The ADAPKIN-M method, is more general and specially suited to stability calculations because it can select the oscillation mode. **[** **]**

[**]**

RAI 6

Establish a null transient at full power for an arbitrary reactor condition. Provide the decay heat power as function of time following a reactor shutdown.

The RAMONA5-FA decay heat model compares favorably with the American National Standards Institute/American Nuclear Society (ANSI/ANS) code 5.1-1979 correlation.

RAI 7

Define which RAMONA5-FA options were used for the stability benchmarks reported in Chapter 5 of TR BAW-10255(P), "Cycle-Specific DIVOM [Delta CPR [critical power ratio] over Initial CPR Versus Oscillation Magnitude] Methodology." Based on these benchmarks, specify the required RAMONA5-FA option configuration for stability and/or DIVOM calculations (e.g., use ADAPKINM method, select the STAIF fuel pin models…).

The applicant defines the standard RAMONA5-FA configuration in Table 7.1 of this RAI response (reproduced here as Table 6). All the benchmarks and reviews have been performed based on this configuration. Deviations from this configuration are expected, for example, when new fuels and CPR correlations become available.

RAI 8

> *Provide an electronic copy of EMF-CC-074(P)(A), Volume 4, Revision 0, BWR Stability Analysis-Assessment of STAIF with Input from MICROBURN-B2, Siemens Power Corporation, August 2000. Indicate the sections where the STAIF fuel pin models that have been imported into RAMONA5-FA are described. Provide any additional benchmark or validation data relevant to these models.*

Report EMF-CC-074(P)(A), Volume 4, Revision 0, was provided for review.

RAI 9

> *RAMONA5-FA can import a direct heat deposition model from MICROBURN-B2 as function of moderator density. Provide an example for the typical reactor condition of RAI question 1.0. Describe the bases and/or validation data for the MICROBURN-B2 models*

The requested data was provided. The direct heat deposition fraction is a function of the axial coolant density and accounts for the larger flow area above the part-length rods. The numbers are calculated by MICROBURN-B2 based on the CASMO-4 lattice calculations. See Figure 9-1 of the RAI response

RAI 10

> *DIVOM analysis uses the **[ ]** correlation. However, the AREVA methodology specifies the **[ ]** drift flux correlation. Provide void profile comparison for a typical channel for both correlations using MICROBURN-B2 with **[ ]** and RAMONA5-FA with **[ ]** to demonstrate consistency between the RAMONA5-FA calculations and the standard AREVA methodology*

A comparison is provided for ATRIUM-10 fuel at typical conditions. Both correlations provide similar results with a small bias.

RAI 11

> *Provide a void comparison for the Karlstein Thermal Hydraulic (KATHY) facility experiments versus the **[ ]** predictions. Identify an uncertainty value associated with **[ ]** application to ATRIUM-10. Artificially bias **[ ]** parameters so that new upper- and lower-bound correlations are developed that enclose most KATHY ATRIUM-10 experimental data (not all data, specially at low qualities, need to be bound – only voids >50 percent are relevant).*

The comparison was provided in Figure 11-1 of the RAI response (reproduced here as Figure 7). **[ ]**

Two types of biases are introduced in the data to attempt to perform sensitivity analysis. First, a brute force bias is introduced by adjusting the slip ratio by approximately 35 percent to obtain a approximately 5 percent bias. Second, **[ ]**

RAI 12

Replace the standard **[**   **]** *correlation with the upper-bound and lower-bound correlations in RAMONA5-FA. Run a simplified case to estimate the change in DIVOM slope with these two new correlations. Run a decay ratio prediction and estimate the impact of this upper-bound correlation uncertainty. These numbers will represent an upper-bound of the uncertainty propagation and they will be significantly larger than the expected error. Repeat the above exercise by replacing the* **[**   **]** *correlation with* **[**   **]**. *These numbers will be closer to a best-estimate of the uncertainty propagation. Note: this exercise may require the use of a temporarily modified and unverified copy of RAMONA5-FA, which is acceptable for this purpose.*

The biased void fraction estimations were used to calculate DIVOM slopes and decay ratios. The brute force slip method results in a significant impact on the DIVOM slope (approximately **[**   **]** percent) and the decay ratio (approximately **[**   **]** percent). The more accurate bias function has a minimal impact on DIVOM slope.

RAI 13

For the typical reactor of RAI 1.0, provide the channel pressure drops and the 2D core flow distribution for RAMONA5-FA and MICROBURN-B2. Provide a benchmark of RAMONA5-FA predictions of pressure drop in KATHY experiments if available.

The pressure drops and the comparison to the KATHY experimental data was provided showing good agreement. The comparison includes transient pressure drops during oscillatory flow conditions in KATHY facility, which shows that RAMONA5-FA integral momentum formulation can model transient pressure drops.

RAI 14

Provide benchmark data between the KATHY measurements and RAMONA5-FA predictions for the sub-cooled boiling region.

The comparison data is provided in Figure 14-1 of the RAI response. Good agreement is observed between RAMONA5-FA subcooled void models and the KATHY experimental data

RAI 15

Provide benchmark data to justify the use of the ANFB-10 and SPCB CHF for oscillatory flow conditions. Note, this is the same information already provided to ACRS and NRC.

A comparison between RAMONA5-FA predictions of dryout-rewet during flow oscillations against KATHY experimental data is provided. RAMONA5-FA results track the experimental data.

RAI 16

Provide a short description of the RAMONA5-FA nodalization and data flow.

The requested information was provided in Reference 6.

RAI 17

Provide a copy of the RAMONA5-FA guidelines for cycle-specific DIVOM calculations (Report EMF-2001(P)).

The proprietary copy of the RAMONA5-FA cycle-specific DIVOM guideline was provided.

RAI 18

Define the process to be used to implement future CPR correlations in the DIVOM calculation procedure. Define what criteria will be used to evaluate whether a new CPR correlation needs to be benchmarked against oscillatory dryout rewet data.

In the response, the applicant commits to perform benchmarking against oscillatory dryout-rewet data to confirm that the predictive capability of new correlation forms in oscillatory conditions.

RAI 19

AREVA has developed a new CPR correlation (ACE), which has been reviewed by the staff for steady state and transient operation. Since the form of the ACE correlation is significantly different than older approved correlations, provide justification of the applicability to oscillatory dryout-rewet conditions.

The new ACE correlation has been evaluated against the KATHY facility oscillatory rests. The results are shown in Figures 19-1 through 4 of the RAI response. Good agreement is observed between the RAMONA5-FA predictions using the ACE correlation and the KATHY experimental data.

RAI 20

Provide a description of the process used to determine the envelope (upper and lower bounds) of the DIVOM correlation for expected variations in a typical DIVOM correlation. This envelope can be used in the future to identify whether any future methodology changes affect the DIVOM slope in a statistically significant way. Provide data to justify the use of the ***[ ]*** *and* ***[ ]*** *value as the threshold for a "statistically insignificant" or "small" DIVOM slope change, respectively.*

The applicant defines the thresholds for significant changes in the RAI response, and they are acceptable.

RAI 21

Provide information about the response of RAMONA5-FA to bypass boiling oscillations during power oscillations.

An in-depth analysis of bypass voiding was presented by the applicant, including calculations of bypass void oscillations during power oscillations. The main conclusions are **[**

]

RAI 22

Provide a short description of the RAMONA code history.

The requested history was provided and reproduced here in Table 1.