March 15, 2001

Mr. James F. Mallay
Director, Regulatory Affairs
Framatome ANP, Richland, Inc.
2101 Horn Rapids Road
Richland, WA 99352

SUBJECT: ACCEPTANCE FOR REFERENCING OF LICENSING TOPICAL REPORT EMF-2328(P), REVISION 0, "PWR SMALL BREAK LOCA EVALUATION MODEL, S-RELAP5 BASED" (TAC NO. MA8022)

Dear Mr. Mallay:

The NRC staff has completed its review of Topical Report EMF-2328(P), Revision 0, "PWR Small Break LOCA Evaluation Model, S-RELAP5 Based" submitted by Framatome ANP Richland, Inc. (FRA-ANP) on January 10, 2000, and supplement dated January 26, 2001.

On the basis of our review, the staff finds the subject report to be acceptable for referencing in license applications to the extent specified, and under the limitations delineated in the report, and in the enclosed safety evaluation (SE). The SE defines the basis for NRC acceptance of the report.

The staff notes that a condition imposed on the use of the ANF-RELAP code still applies to the use of S-RELAP5. Specifically, that while it has been shown in NUREG/CR-4945, "Summary of the Semiscale Program (1965-1986)," that the thermal-hydraulic phenomena observed for breaks up to 10 percent of the cold leg flow area are the same, if the code is used for break sizes larger than 10 percent of the cold leg flow area additional assessments must be performed to ensure that the code is predicting the important phenomena which may occur.

Pursuant to 10 CFR 2.790, we have determined that the enclosed SE does not contain proprietary information. However, we will delay placing the SE in the public document room for a period of ten (10) working days from the date of this letter to provide you with the opportunity to comment on the proprietary aspects only. If you believe that any information in the enclosure is proprietary, please identify such information line by line and define the basis pursuant to the criteria of 10 CFR 2.790.

The staff will not repeat its review and acceptance of the matters described in the report, when the report appears as a reference in license applications, except to assure that the material presented is applicable to the specific plant involved. Our acceptance applies only to the matters described in the report.

In accordance with the procedures established in NUREG-0390, the NRC requests that FRA-ANP publish accepted versions of the report, including the safety evaluation, in the proprietary and non-proprietary forms within 3 months of receipt of this letter. The accepted versions shall incorporate this letter and the enclosed evaluation between the title page and the abstract. The accepted versions shall include an "-A" (designating accepted) following the report identification symbol. The accepted versions shall also incorporate all communications between FRA-ANP and the staff during this review.

Should our criteria or regulations change so that our conclusions as to the acceptability of the report are no longer valid, FRA-ANP and the licensees referencing the topical report will be expected to revise and resubmit their respective documentation, or to submit justification for the continued effective applicability of the topical report without revision of their respective documentation.

Sincerely,

/RA/

Stuart A. Richards, Director
Project Directorate IV and Decommissioning
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

Project No. 702

Enclosure: Safety Evaluation

In accordance with the procedures established in NUREG-0390, the NRC requests that FRA-ANP publish accepted versions of the report, including the safety evaluation, in the proprietary and non-proprietary forms within 3 months of receipt of this letter. The accepted versions shall incorporate this letter and the enclosed evaluation between the title page and the abstract. The accepted versions shall include an "-A" (designating accepted) following the report identification symbol. The accepted versions shall also incorporate all communications between FRA-ANP and the staff during this review.

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Sincerely,
/RA/
Stuart A. Richards, Director
Project Directorate IV and Decommissioning
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

Project No. 702

Enclosure: Safety Evaluation

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SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT EMF-2328(P), REVISION 0

"PWR SMALL BREAK LOCA EVALUATION MODEL, S-RELAP5 BASED"

FRAMATOME ANP, RICHLAND, INC.

PROJECT NO. 702

1.0 INTRODUCTION

Framatome ANP Richland, Inc. (FRA-ANP) submitted Topical Report EMF-2328(P), Revision 0, "PWR Small Break LOCA Evaluation Model, S-RELAP5 Based," (Reference 1), for NRC review and approval for application of the S-RELAP5 thermal-hydraulic analysis computer code (Reference 2), to the small break loss-of-coolant accident (SBLOCA) in Westinghouse and Combustion Engineering pressurized water reactors (PWRs). FRA-ANP plans to replace the previously NRC-approved methodology using the ANF-RELAP and TOODEE2 codes for the SBLOCA analysis. The application submitted for review is under the guidelines of 10 CFR 50.46 and 10 CFR Part 50, Appendix K.

The stated goal of FRA-ANP is to apply a single computer code to the analysis of both LOCA and non-LOCA transient events. The code of choice is to be one that has had wide industry acceptance and application. To achieve this goal the decision was made to modify the approved ANF-RELAP code (References 3 and 4), in such a way as to bring it up to a standard that incorporates the thermal-hydraulic code RELAP5/MOD2 (Reference 5), the fuel design code RODEX2, (Reference 6), the ICECON containment model (Reference 7), and the hot rod model code TOODEE2, (Reference 8) into a single system calculation. In so doing, the RELAP5/MOD2 code was modified to include selected models from the RELAP5/MOD3 code, (Reference 9) improved numerics, and models necessary to satisfy the requirements of 10 CFR Part 50, Appendix K.

2.0 STAFF APPROACH TO REVIEW

The proposal to review S-RELAP5 was made by FRA-ANP to the staff on January 10, 2000 (Reference 10). The code documentation, including an electronic copy of the code, was reviewed for completeness and accepted for detailed review by the staff. The staff performed the review by assembling a team of five staff members with expertise in thermal-hydraulics, kinetics and RELAP5 use. The review emphasized those portions of the code which were different from the RELAP5/MOD2 and RELAP5/MOD3 codes since they have not had the same level of peer review as the models and correlations in the base codes. In addition, the staff felt it necessary to have confidence that the model additions, especially the numerical methodology changes, did not adversely alter the performance and stability of the code.

During the course of the review, a request for additional information (RAI) was developed and transmitted to FRA-ANP (Reference 11). Meetings were held with the Advisory Committee on Reactor Safeguards (ACRS) Thermal-Hydraulic Phenomena Subcommittee. Those meetings and reviews conducted by the ACRS members and their consultants were considered in preparation of the aforementioned RAI.

Milestones in the Review

- Request for review of S-RELAP5: January 10, 2000. Receipt of code and documentation: January 2000. Acceptance of code for review by NRC: March 2000.

- Request for additional information by the staff: December 2000.

- Advisory Committee on Reactor Safeguards, Thermal-Hydraulic Phenomena Subcommittee meetings: March 2000, August 2000, January 2001.

- Advisory Committee on Reactor Safeguards, Full Committee meeting: February 2001.

3.0 S-RELAP5 MODIFICATIONS AND ADDITIONS

The RELAP5 computer code is a light water reactor transient analysis code developed for the NRC for use in rulemaking, licensing audit calculations, evaluation of operator guidelines, and as a basis for nuclear power plant analyses. RELAP5 is a general purpose code that, in addition to calculating the behavior of a reactor coolant system during a transient, can be used for simulation of a wide variety of hydraulic and thermal transients in both nuclear and non-nuclear systems involving mixtures of steam, water, non-condensable gas, and solute. The RELAP5 code is based on a nonhomogeneous and nonequilibrium model for the two-phase system. Solution is by a partially implicit numerical scheme to permit economical calculation of system transients. The objective of the RELAP5 development effort was to produce a code that included important first-order effects necessary for accurate prediction of system transients but that was sufficiently simple and cost effective so that parametric or sensitivity studies were possible.

The code includes many generic component models from which general systems can be simulated. These component models include pumps, valves, pipes, heat releasing or absorbing structures, reactor point kinetics, electric heaters, jet pumps, turbines, separators, accumulators, and control and trip system components. In addition, special process models are included for effects such as form loss, flow at an abrupt area change, branching, choked flow, counter-current flow limiting (CCFL), boron tracking, and noncondensable gas transport. The code also incorporates many user conveniences such as extensive input checking, free-form input, internal plot capability, restart, renodalization, and variable output edits.

The S-RELAP5 code evolved from FRA-ANP's ANF-RELAP code, a modified RELAP5/MOD2 version used by FRA-ANP for PWR plant licensing analyses that included the SBLOCA analysis, steam line break analysis, and PWR non-LOCA Updated Final Safety Analysis Report Chapter 15 event analyses. During the modifications to permit realistic analyses, enhancements were made to incorporate the requirements of 10 CFR Part 50, Appendix K SBLOCA analysis. The code structure was also modified to be similar to that of

RELAP5/MOD3. This included incorporation of the RELAP5/MOD3 reactor kinetics, control systems and trip systems models.

Some of the major modifications made to RELAP5/MOD2 and ANF-RELAP to produce the S-RELAP5 code include the following:

1. Multi-Dimensional Capability - Two-dimensional treatment has been added to the hydrodynamic field equations. This capability can handle the Cartesian and cylindrical coordinate systems.

2. Energy Equations - The energy equations were modified to conserve the energy transported into and out of a control volume, thus correcting the tendency of the RELAP5 codes to produce an energy error when a large pressure gradient exists between two adjacent control volumes.

3. Numerical Solution of Hydrodynamic Field Equations - Where the RELAP5 codes use a Gaussian elimination solver to reduce the hydrodynamic finite-difference equations to a pressure equation, S-RELAP5 uses algebraic manipulation.

4. State of Steam-Noncondensable Mixture - At very low steam quality, the ideal gas equation is used for both steam and noncondensable gas. This permits calculation of state relations for both steam and noncondensable gas at low steam quality and also the presence of pure noncondensable gas below the ice point.

5. Hydrodynamic Constitutive Models - Significant modifications were made to the RELAP5 interphase friction and interphase mass transfer models. Some of the flow regime (two-phase flow) transient criteria were modified to be consistent with published data. Transient flow regimes are introduced for smoothing the constituent models. Most of the RELAP5/MOD2 partition functions were only slightly modified if at all. A more accurate wall friction factor approximation replaces the Colebrook equation.

6. Heat Transfer Model - The RELAP5/MOD2 use of different heat transfer correlations in reflood was eliminated. The Dittus-Boelter single phase steam heat transfer correlation was replaced with the Sleicher-Rouse correlation which gives higher steam temperatures and has a smaller uncertainty range.

7. Choked Flow - The Moody critical flow model was implemented for 10 CFR Part 50, Appendix K calculations. The modification of ANF-RELAP to use an iterative scheme to compute the equation of state at the choked plane rather than using the previous time step information was also implemented.

8. Counter-Current Flow Limit - The Kutateladze type CCFL correlation of ANF-RELAP was replaced with the Bankoff form. This conforms with RELAP5/MOD3.

9. Component Models - The pump model includes the EPRI pump performance degradation data, and the pump head term in the fluid field equations was made more implicit. The ICECON containment code was incorporated to run concurrently with

S-RELAP5. User guidelines were implemented to specify a replacement procedure for modeling the accumulator model.

10. Fuel Models - The RODEX2 fuel deformation and conductivity models were incorporated for SBLOCA applications. The flow diversion model of TOODEE2 was implemented to account for the effect of cladding rupture on heat transfer. The Baker-Just metal-water reaction model was implemented as required by 10 CFR Part 50, Appendix K.

11. Code Architecture - Modifications were made to bring the S-RELAP5 code into conformance with the description of the RELAP5/MOD3 code architecture. This includes writing the code in FORTRAN 77 and maintaining a common source for all computer versions.

4.0 EVALUATION OF S-RELAP5

The staff review concentrated on several areas deemed of greatest importance in the code. Code numerics have long been a problem area. Obtaining adequate convergence, acceptable code running speed, and avoiding numerical diffusion and error generation have long plagued the thermal-hydraulic systems codes. The process by which the requirements of 10 CFR Part 50, Appendix K were developed struggled with specification of heat transfer regimes that would be both conservative and yet correctly represent the variations in heat transfer that were expected to occur in a complex depressurization coolant loss accident. Development of advanced computational methodologies has placed an emphasis on realistic representation of the core neutronics. While this is important for analysis of transient events which are strongly influenced by the core power production, the relatively fast-acting LOCA events can be reasonably represented with simple kinetics models.

When all models and correlations have been individually examined and determined to represent test data, the important question becomes how do the models work together in predicting a system with many interacting components. The staff raised concerns in this area during the time of the review of the lessons learned from the Three Mile Island Unit 2 accident. This led to specification of a minimum set of tests that should be used in assessing the capabilities of analysis codes. Today, twenty years later, the industry has many more sets of test data from, in some cases, larger and better instrumented facilities to use in assessing computer code capabilities. Review of new methodologies necessitates being open to suggestions on the part of the industry of application of those newer test facility experimental programs. The staff encourages use of improved data, with the understanding that proper justification must be given to changing from the tried-and-true specifications that have been used in the past.

Following are the staff views on many of the sections of the code documentation that have been examined. At this point, we would note that the documentation reviewed has errors which have been discussed with the FRA-ANP personnel. The staff bases for approval of documentation are that the material must be understandable to a knowledgeable person, and free of known errors. We have found the documentation to be lacking in several areas. FRA-ANP recognizes our concerns and is in the process of upgrading the documentation. FRA-ANP has plans to submit the S-RELAP5 code for further review for application as a Realistic LOCA code. Both publication of the approved versions of S-RELAP5 documentation for 10 CFR Part 50, Appendix K application and Realistic LOCA application has been stated by FRA-ANP to include

error correction. The staff has, in the past, accepted publication of corrected documentation that incorporates the safety evaluation since review of use is performed for applications of the code, plus the staff has at its disposal the ability to inspect and audit the use of an approved code for licensing calculations.

4.1 Two-Fluid Field Equations

In the S-RELAP5 code, the two-phase steam-water mixture is modeled as two fluids. In addition, S-RELAP5 includes methods for handling the presence of noncondensable gas and boron. This results in a model that consists of a total of eight field equations - six equations for the two-phase mixture (two phasic continuity equations, two phasic momentum equations, and two phasic energy equations), one continuity equation for the noncondensable gas, and a boron tracking equation. In Reference 2, the six equations for the two-phase mixture are provided as Equations 2.1 - 2.6, the continuity equation for the noncondensable gas is provided as Equation 2.30, and the boron tracking equation is provided as Equation 2.31. All are presented in vector form. The general form of the field equations used in S-RELAP5 is very similar to those used in other system codes (e.g., RELAP5/MOD2, TRAC-PF-1/MOD1, and COBRA/TRAC). The basic assumption used in the development of the equations is that the average of a product of variables is equal to the product of the average variables. The phasic equations are coupled together via the interfacial processes of vapor generation, heat transfer, and friction. Fluid-wall interaction is included by accounting for the wall friction, wall vapor generation, and wall heat transfer correlations.

For phasic continuity, the liquid fraction and void fraction satisfy the requirements that they sum to unity. The continuity equation for each phase (liquid and vapor) states that, for the phase of interest, the total mass generated is the sum of the mass stored and the mass convected. The sum of the two phasic continuity equations satisfies the requirement that there are no mass sources or sinks in the overall mass continuity equation. This requires that the mass generated for one phase be equivalent to the negative of the mass generated (i.e., the mass consumed) for the other phase. Vapor generation is modeled at the liquid-vapor interface and at the wall. Accordingly, the total vapor generated is taken as the sum of the vapor generated at the interface and that generated at the wall.

For phasic momentum, the momentum equations are presented in the expanded form. The expanded equations are derived by substituting the phasic continuity equations into the phasic momentum equations of the non-expanded form. The expanded form is used in EMF-2100(P) because it is more convenient in the development of the numerical scheme than the non-expanded form. The left-hand-side of each momentum equation contains the terms from the total derivative of momentum. These are the local rate of change of momentum and the convective rate of change of momentum. The right-hand-side contains terms to account for pressure gradient, body force, wall friction, momentum change due to interphase mass transfer, interphase shear (or drag), and the effective force due to virtual mass.

The virtual mass term includes a dependence on mixture density. Mixture density is computed as the sum of the liquid and vapor densities each weighted with its respective phase fraction. The virtual mass term in each momentum equation does not include a spacial derivative component. This simplification was implemented in the development of the NRC's RELAP5/MOD2 code. FRA-ANP stated that this change was necessary because inaccuracies

that exist in approximating spatial derivatives for the relatively coarse nodalization used in system representations can lead to nonphysical characteristics in the numerical solutions. In addition, FRA-ANP stated that the simplification is adequate because the primary effect of the virtual mass term is on the mixture sound speed which, in RELAP5, is calculated using an integral model in which the sound speed is based on an objective formulation for the added mass term.

As presented in Reference 2, the sum of the virtual mass terms of the two phasic momentum equations is zero. It is also assumed that the interphase momentum transfer due to friction and due to mass transfer independently sum to zero. This ensures that interphase momentum is conserved. For the terms associated with interphase mass transfer, it is further assumed that the velocity of the fluid at the interface is that of the liquid when the generation of vapor is positive (i.e., for vaporization) and that of the vapor when the generation of vapor is negative (i.e., for condensation).

RELAP5/MOD2's formulation of the phasic energy equations results in errors when the pressure gradient between two adjoining volumes is very large. This is due to neglecting the mechanical energy terms in the formulation of the energy equations for the RELAP5 code. In order to eliminate these errors, the S-RELAP5 phasic energy equations are expressed in the total energy form. By doing this, FRA-ANP retains the mechanical energy terms in their formulation of the phasic energy equations. Simplifying assumptions, however, exclude the local rate of change of energy, wall friction dissipation energy, and potential energy. FRA-ANP justifies this simplification by pointing out that these components of energy are much smaller than the kinetic energy and, therefore, their exclusion does not significantly affect the results.

Phase change at the interface is modeled as a process in which bulk fluid is heated or cooled to the saturation temperature prior to the occurrence of the phase change. This requires that sensible energy exchange be sufficient to bring the fluid to the saturation state. In this model, the wall heat flux is divided into two parts: one part for sensible heat transfer and another part for vapor generation. The vapor generation component is further divided into a fraction that causes vapor generation and a fraction that is used to bring the bulk liquid up to the saturation temperature based on an equal volume exchange. In this model, phasic enthalpies associated with the interphase mass transfer are defined in a manner that satisfies the jump conditions at the liquid-vapor interface. This is done by (1) selecting the enthalpies for the liquid and vapor phases as the liquid specific enthalpy for the liquid, and vapor specific enthalpy at saturation for the vapor when vaporization is taking place; and (2) selecting the enthalpies for the liquid and vapor phases as the liquid specific enthalpy at saturation for the liquid and, vapor specific enthalpy for the vapor when condensation is taking place (note that in each case only one term is at saturation). When the two phasic energy equations are summed, a mixture energy equation is produced. The mixture energy equation must meet the criterion that the interface transfer terms vanish. In S-RELAP5, this criterion is satisfied by requiring that the wall heat transfer terms and the bulk exchange terms each sum to zero independently. In addition, S-REALP5 assumes that the heat transfer from the wall to the vapor is zero for vaporization and that the heat transfer from the wall to the liquid is zero for condensation.

A simple comparison of the change to the energy equation was provided. In this comparison, a calculation of the depressurization of a small diameter pipe at high pressure into a large diameter pipe at low pressure was performed. In this calculation, kinetic and potential energies

were negligible and for a perfect system, no change in total internal energy is expected to occur. One calculation was performed using ANF-RELAP which uses the RELAP5/MOD2 energy equations while the other was performed with S-RELAP5 which uses the modified energy equations. The error in energy calculated for this simple example by the two codes demonstrates that the error in the S-RELAP5 calculation is within 0.04 percent while that of ANF-RELAP was approximately -2 percent.

A seventh field equation is provided to track a noncondensable gas component. This equation is a mass conservation equation for the noncondensable gas. In S-REALP5, the noncondensable gas is assumed to be in mechanical and thermal equilibrium with the steam. When noncondensable gas is present, the properties of the vapor phase in the six field equations (two each for continuity, momentum, and energy) are taken as mixture properties.

The eighth and final field equation is a mass conservation equation used to track boron concentration. S-RELAP5 uses an Eulerian tracking model for the boron. The following assumptions are used in this model: (1) liquid properties are not altered by the presence of the boron, (2) boron is transported only in and at the velocity of the liquid phase, (3) energy transported by the boron is negligible, and (4) inertia of the boron is negligible.

S-RELAP5 includes two-dimensional (2-D) modeling capability. Because 2-D modeling adds considerably to the complexity of S-RELAP5 input and running time for the analyses, 2-D modeling will only be used for regions and applications where significant multi-dimensional effects are expected. Application specific topical reports for each S-REALP5 application will describe the use of the 2-D modeling for the application. For SBLOCA, 2-D modeling is applied in the core and downcomer regions. For non-LOCA transient, 2-D modeling was determined to be not required.

4.2 Code Numerics

4.2.1 Semi-implicit Numerical Solution Scheme (SINSS)

The semi-implicit numerical solution scheme is formulated by replacing the system of differential equations with a system of finite-difference equations partially implicit in time. Which terms of the various equations are chosen to be evaluated implicitly are identified as the Semi-Implicit numerical scheme unfolds (Reference 2). However, in all cases the implicit terms were formulated to be linear in the dependent variables at new time. The consequence of this is a linear time-advancement matrix that is solved by direct inversion using a sparse matrix routine (Reference 12). A feature of SINSS is that the implicitness is selected in such a way that the equations can be reduced to a single finite-difference equation per fluid control volume and in terms of hydrodynamic pressure. This solution scheme implies that only an NxN system of finite-difference equations must be solved simultaneously at each time step, where N is the number of control volumes used to simulate the fluid system.

The finite-difference equations developed in the SINSS are based on defining a control volume in which the mass and energy are conserved by equating the accumulation of the fluid mass and energy to the rate of fluid flux through the volume boundaries. This approach enables one to define mass and energy volume average properties as well as define velocities at the volume

boundaries. Scalar properties, such as pressure and energy, are defined at the volume centers, and vector quantities, such as velocities, are defined at the boundaries.

4.2.2 One-Dimensional and Multidimensional Formulation

FRA-ANP extended the one-dimensional numerics of RELAP5/MOD2 to include a two-dimensional flow solution scheme in S-RELAP5. The geometric complexity of the reactor vessel lends itself well to modeling in one and two dimensions. Specifically, one could envision selected regions, such as the downcomer, to be modeled in a (z,Θ)-type formulation, while the active region of the core is modeled in a (z,r) formulation. The entire vessel is modeled in one or two-dimensional components with a variety of node sizes, depending on the phenomena to be captured in the particular region in question.

4.2.3 One and Two Dimensional Finite-Difference Formulation

In order to descretize the fluid field differential equations provided on page 2-2 of Reference 2, FRA-ANP set up general guidelines to follow. (Section 2.6 of Reference 2). In particular, mass and energy inventories were considered very important parameters in the development of S-RELAP5 for reactor safety calculations, and the numerical semi-implicit scheme implemented in S-RELAP5 was developed to be consistent and conservative in these quantities. To increase computational speed, the implicit scheme is used for the velocity calculation in the mass and energy terms, that is, for those phenomena known to have small time constants. To further increase computational speed, FRA-ANP opted to linearize implicit terms in new time variables. The ultimate result is the elimination of the need to iteratively solve a system of nonlinear equations. Finally, to allow easy degeneration to homogeneous, or single-phase formulations, the momentum equations are expressed as sum and difference equations (equations 2.80 and 2.81 of Reference 2).

Multi-dimensional finite-difference formulation for the mass and energy balances are similar in form to the one-dimensional formulation. Extension to multi-dimensional flow cases is accomplished by adding subscripts to the appropriate parameters as required to maintain accounting in all directions of the flow. For example, if junction subscripts j+1 and j denote flow in one direction, then for two-dimensional flow we have (i, j+1) and (i,j), where i=x, y for two-dimensional flow, and i is summed over all flow directions. In S-RELAP5 the summation is over all directions, since S-RELAP5 one-dimensional flow formulation allows multiple junctions connected to the control volume. Thus, the algorithm of the summations over all the junctions connecting to a volume already exists.

4.2.4 Solutions to the Finite-Difference Equations

The finite-difference equations (equations 2.101 through 2.110 of Reference 2), are solved numerically for the independent variables P, U_g, U_f, X_n, β_g, $\mathbf{v}_g$, and $\mathbf{v}_f$. There are $2N_j$ momentum equations for N_j junctions and $5N_v$ mass and energy equations for N_v (control) volumes. Once the finite-difference equations are obtained, there is no distinction between one-dimensional, two-dimensional or cross-flow junctions.

The momentum equations are solved at old times, consequently, the phasic velocities for the different junctions are not directly coupled. However, with some algebraic manipulations, the sum and difference momentum equations can be solved for the new-time phasic velocities in terms of new-time pressures of connected neighboring volumes L and k. The new-time pressure of control volume L is coupled to the pressure of neighboring volume k through junction connections.

The new-time saturation temperature, phasic temperature and densities in the finite-difference equations of mass and energy balances, are expressed in terms of the independent state variables, P, U_g, U_f, X_n, using first order Taylor series expansion.

A sparse matrix solver (Reference 12), is used to solve the N_v x N_v matrix for βP for each volume. Then these βPs are substituted into appropriate equations for computing the new time phasic velocities for all junctions. These pressure changes and phasic velocities are used to obtain the phasic energy solutions for all volumes. Appropriate equations are then used to obtain the non-condensable quality and the new-time void fraction for each volume.

FRA-ANP uses a variety of time step size checks to ensure solution convergence or acceptability. These include material Courant limit checks, mass error checks, water property errors, and excessive extrapolation of state properties in the meta-stable regimes. In S-RELAP5, the size of a newly calculated time step can only be the same as, or half of, or double that of the previous time step. For a system with two-dimensional components, each volume of the two-dimensional components is treated twice, once for the x-direction flow and once for the y-directional flow.

Mitigating numerical anomalies are also addressed in S-RELAP5. These are anomalies which are not usually reduced or removed by simply reducing the size of the time step. Typical anomalies are inconsistent donoring, excessive liquid flowing out of a volume, and water packing. Correction schemes to eliminate or reduce the effect of these anomalies are built into the S-RELAP5 formulation, and the user has no option available to turn off these correction schemes.

4.3 Heat Transfer

4.3.1 Background and General Description

The review of this material consisted of establishing inherent inconsistencies, similarities, formulation and computational results (where and when they existed) between S-RELAP5 and RELAP5/MOD2. During the course of the review, RAIs were developed and transmitted to the applicant. Additional follow-up clarification discussions were held (Reference 13), in support of this effort. The staff did not derive any of the equations associated with the formulated heat transfer correlations other than to verify their source(s) and validity of application. Where applicable, validation of pertinent critical heat flux (CHF) correlations and post-CHF correlations with data were reviewed for accuracy of prediction and error assessment.

Chapter 4 of Reference 2 is a description of the physical models, correlations and methods to obtain the wall-to-fluid heat transfer terms (Q_{wf}, Q_{wg} and β_w) in the two-fluid field equations of Chapter 2 of Reference 2. Q_{wf} is the wall heat transfer to the fluid phase, Q_{wg} is the wall heat

transfer to the vapor phase, and β_w is the mass transfer at the wall. The total heat flux, q'', is partitioned into two phasic heat flux components q''_f and q''_g. The mass transfer term is tied to the bulk inter-phase mass transfer terms and is verifiable through void distribution and phasic temperature measurements.

Most of the heat transfer correlations in-coded in S-RELAP5 are inherited from RELAP5/MOD2 without any modifications or with minor modifications. In the RELAP5/MOD2 code manual, the heat transfer equations are written for the heat transfer rates into the hydrodynamic volumes, while the S-RELAP5 heat transfer equations are expressed in terms of the heat flux and the heat transfer coefficient. The boundary conditions for the conduction solution scheme are expressed in terms of heat transfer coefficients and heat fluxes in both RELAP5/MOD2 and S-RELAP5. The selection logic for heat transfer regimes are essentially the same in both codes.

4.3.2 Heat Transfer Coefficients

The heat transfer coefficients for the liquid state and the nucleate boiling state are obtained from known correlations, such as the Dittus-Boelter turbulent convection correlation for the liquid state (References 14 and 15). The temperature at the inception of boiling is computed from Bergles and Rohsenow (Reference 16). The model for the point of vapor generation was developed by Saha and Zuber (Reference 17). The Chen correlation (Reference 18), is used for both subcooled and saturated boiling. Each of these correlations has been subject to extensive peer review and used in thermal-hydraulic analysis and found to give acceptable results. The staff agrees with use of these correlations.

4.3.3 Critical Heat Flux

The CHF defines the boundary between nucleate boiling and transition boiling. The CHF correlations used in S-RELAP5 are the same as those used in RELAP5/MOD2, that is, the Biasi correlation (Reference 19), for high flow rate and the modified Zuber correlation (Reference 20), for low flow rate. The applicability of these correlations to the appropriate regions (mass fluxes) is well documented in Reference 2.

The CHF temperature, T_{CHF}, is the wall temperature at which the wall-to-fluid heat flux is equal to the critical heat flux. T_{CHF} is obtained by equating the nucleate boiling heat flux of equation 4.15 in Reference 2 to the critical heat flux and solving for T_{CHF}. S-RELAP5 utilizes the Newton-Raphson iterative method to obtain a solution for T_{CHF}.

There is a reflood option that is a user option. The reflood model is turned on when the void fraction is above 0.95. In this case a multiplier is applied to the critical heat flux to reduce the CHF to zero at a void fraction of 1. If the reflood option is turned off, the computation of the CHF temperature is done only when the nucleate boiling heat flux exceeds the critical heat flux.

4.3.4 Transition and Film Boiling

In S-RELAP5 the transition boiling region consists of two parts: the boiling heat transfer to liquid, q''_f, and the convective heat transfer to vapor, q''_g. The heat fluxes in this region are determined from the modified form of the Chen transition heat transfer correlation

(Reference 21). For convective heat transfer, the heat transfer coefficient as proposed by Chen was replaced by a general convective relation, consisting of a turbulent convection correlation of Sleicher-Rouse (Reference 22), natural convection and a laminar flow limit. The Dittus-Boelter correlation used in RELAP5/MOD2 was replaced in S-RELAP5 by the Sleicher-Rouse correlation, which has smaller uncertainties associated with its development (Reference 23).

Sleicher and Rouse investigated and compared several heat transfer correlations to measured data. Their motivation for the investigation was that the Dittus-Boelter correlation was intended to be applicable only to fully developed flow having constant fluid properties. As such, the correlation is inaccurate over certain ranges of Reynolds and Prandtl numbers, in particular, the correlation is approximately 10-25 percent high for gases.

The Sleicher-Rouse correlation was compared to data from four studies of gas flow. The data were for fully developed flow with a wide range of Reynolds number, wall-to-bulk temperature difference, and distance from thermal entrance. The average deviation to measured data was reported to be approximately 4.2 percent.

Based on those findings, FRA-ANP decided to replace Dittus-Boelter with Sleicher-Rouse for wall to vapor convection. The vapor heat transfer was assessed by applying the modified code to FLECHT-SEASET test 33056, a steam cooling test. The calculated wall temperatures from using Sleicher-Rouse are compared with measured data at the 72 inch and 78 inch elevations. The calculated temperature, which is from a point between the 72 inch and 78 inch elevations, falls on the measurement at 72 inches. In comparison, the calculation using Dittus-Boelter shows a slight difference in rod temperature at the same elevation. Both comparisons show good agreement with the measured data. While both correlations show little difference in calculated temperature, there is a lower uncertainty associated with the Sleicher-Rouse correlation. The staff accepts this substitution.

The heat flux in the film boiling region consists of three parts: boiling heat transfer to liquid, convection heat transfer to vapor, and wall-to-fluid radiation. Two correlations are used to compute the boiling heat transfer coefficient: the Forslund-Rohsenow correlation (Reference 24), and the modified Bromley correlation (References 25 and 26). The radiation heat transfer from wall-to-fluid (at high wall temperatures), is determined by using a model developed by Sun (Reference 27).

4.3.5 Special Treatments Core-Reflood

S-RELAP5 has a core reflood option that can be activated by the user. When the reflood model is activated, a fine-mesh re-zoning scheme is used to nodalize the core heat structures into two-dimensional (radial and axial) heat conduction zones. This re-zoning is essential to capture the heat transfer profile covering the entire boiling curve as established in the reactor core. As such, the re-zoned axial nodes extend from the bottom to the top of the active fuel, with the finer zones assigned to regions of nucleate boiling, transition and film boiling. However, FRA-ANP pointed out that no re-zoning is performed on the hydraulic volumes, consequently, all the re-zoned regions retain their assigned hydrodynamic conditions which should result in a more accurate prediction in the boiling heat transfer regimes.

4.3.6 Scaling and Applicability of Correlations

As FRA-ANP pointed out, most of the heat transfer correlations discussed in Chapter 4 of Reference 2 can be found in system codes such RELAP5, TRAC-PF1 (Reference 28), and COBRA/TRAC (Reference 29). Examples of scaling dependency and applicability of the correlations formulated in S-RELAP5 are provided in References 30 and 31. Besides the examples of correlation applicabilities listed in the above references, FRA-ANP included additional assessments in Reference 2:

1. Comparison of S-RELAP5 with Bennett heated tube test data (Reference 32), indicated that the Biasi correlation implemented in S-RELAP5, overpredicts the CHF in the mass flux range 1500–3000 kg/m^2-s, but does a reasonable job in the low mass flow region (100–300 kg/m^2-s) and the high mass flow region, above 3000 kg/m^2-s.

2. S-RELAP5 LBLOCA calculations for LOFT experiments (References 31 and 33), as well as Westinghouse 3 and 4 loop data (References 34 and 35), shows that the core heat flux exceeds CHF in the mass flux range of 5-50 kg/m^2-s during blowdown period. In addition, the S-RELAP5 calculated times to CHF were shorter (earlier) than those calculated for the LOFT experiment. This implies that the CHF correlation in S-RELAP5 conservatively predicts (under-predicts) the time of occurrence of boiling transition for low flux transient conditions.

3. Lueng (Reference 36), also reported that for low mass flux (smaller than 200 kg/m -s), transient data is best predicted by the Griffith-Zuber (modified) correlation in (Reference 20), the same correlation implemented in S-RELAP5. Consequently, the staff agrees with FRA-ANP, in that the approach of combining the Biasi and the modified Zuber correlations for CHF computations is applicable for LOCA calculations.

4. FRA-ANP is fully aware of the shortcomings of applying a steady-state correlation to a transient calculation. However, it opted to use the Chen correlation because of its simplicity and the exponential behavior of the heat flux with the square root of the temperature difference between the wall and the saturation. The correlation was assessed and shown to be valid through comparison with the LOFT experiments, (References 31 and 33), CCTF tests (Reference 37), and FLECHT-SEASET tests (Reference 38).

5. FRA-ANP included in Reference 2 an S-RELAP5 calculation of a convective heat transfer coefficient in the vapor phase. Comparison of calculated wall temperatures with data from two Bennett tube tests, (Reference 32), for two different mass fluxes, 379.7 kg/m -s and 3797.4 kg/m -s, shows good agreement at low mass flux and overpredicts (more conservative) at the high mass flux end. The overprediction at high mass flux is attributed to the consequence of only considering the effect of vapor mass flux in the turbulent convective correlation, and neglecting the fluid flow component (References 32 and 39).

6. For the single phase heat transfer correlation, FRA-ANP replaced the Dittus-Boelter correlation with the Sleicher-Rouse correlation (Reference 22), due its smaller range of uncertainties. Two assessment calculations were performed for the FLECHT-SEASET

steam cooling test 33056 (Reference 40), one, the base case with the base code (i.e., using the Sleicher-Rouse correlation), and the other with the Dittus-Boelter correlation. FRA-ANP provided comparison temperature plots in their submittal for staff review. The plots indicate good agreement between the measured data and the calculated predictions of both correlations. The Dittus-Boelter correlation yields a slightly higher wall temperature in comparison to the Sleicher-Rouse correlations. This is attributed to lower heat transfer to the steam, resulting in lower steam temperature. In addition, FRA-ANP pointed out that an assessment of FLECHT-SEASET forced reflood tests, indicates that the correlation of Sleicher-Rouse yields better calculated-versus-measured data comparison results for the steam temperature.

In general, it appears to the staff that the S-RELAP5 heat transfer modeling schemes and principles are well supported and acceptable.

4.4 The Point Reactor Kinetics Model

The point kinetics model in S-RELAP5 is the same as that used in all the versions of RELAP5. The point kinetics model is used to compute the power in a reactor. The power is computed using the space-independent or point kinetics approximation which assumes that the power can be separated into space and time functions. This approximation is generally accepted for most cases where it is assumed that the space distribution remains constant. The development of the point kinetics equations and their solutions are well documented and referenced in Reference 2.

The kinetics model in S-RELAP5, as with that in RELAP5/MOD2 and MOD3.2, computes both the immediate fission power and the decay power of fission fragments. The user can select the decay power model based on either the American Nuclear Society Proposed Standard ANS 5.1, Decay Energy Release Rates Following Shutdown of Uranium-Fueled Thermal Reactors, revised October 1973 (Reference 41), or the American National Standard for Decay Heat Power in Light Water Reactors, ANSI/ANS-5.1-1979 (Reference 42).

The staff notes that selection of the delayed neutron fraction, β, for the kinetics calculation must be justified as conservative for the core in the as-used state. This is typically done as part of the neutronics analysis of the core. The default value is intended to be used with initial cores.

4.5 Assessment

The staff has stated its position relative to SBLOCA analysis methods in NUREG-0737 (Reference 43), Section II.K.3.30, as:

> *The analysis methods used by nuclear steam supply system (NSSS) vendors and/or fuel suppliers for small-break loss-of-coolant accident (LOCA) analysis for compliance with Appendix K to 10 CFR Part 50 should be revised, documented, and submitted for NRC approval. The revision should account for comparisons with experimental data, including data from the LOFT Test and Semiscale Test facilities.*

The NUREG report goes on to suggest specific tests that might be used to satisfy the above requirement as Semiscale Test S-07-10B and LOFT Test L3-1. Further, the report states that

other qualified tests from the entire Semiscale small-break test series and LOFT test series, along with appropriate separate effects tests can be factored into this assessment requirement.

Benchmark calculations were performed by FRA-ANP to fulfill the requirements of NUREG-0737, Section II.K.3.30 utilizing test data from 2-D Flow Tests (References 44 and 45), Semiscale Test S-UT-8 (Reference 46), LOFT Test LP-SB-3 (References 47 and 48), UPTF TEST A5RUN11E (References 49, 50 and 51), and BETHSY Test 9.1b (Reference 52). While none of these are the suggested tests, they are for the most part more current tests and satisfy the intent of the NUREG-0737 suggestions. The staff supports applicants use of newer and better test data to satisfy stated goals.

To demonstrate the adequacy of the S-RELAP5 code for performing SBLOCA analyses, FRA-ANP benchmarked the code and component models against test data. The tests used included two dimensional bundle tests with flow blockage, the Semiscale S-UT-8 test, the boil-off portion of the LOFT LP-SB-03 test, a loop seal clearing test performed in the Upper Plenum Test Facility (UPTF), and the BETHSY 9.1b small break test. Comparisons of the S-RELAP5 calculations to these tests demonstrated, respectively, the capability of S-RELAP5 to conservatively predict 2-D flow phenomena; high pressure, low velocity heat transfer and reflux condensation; loop seal clearing; and overall SBLOCA behavior and temperature results.

The 2-D Flow Tests are a series of separate effects flow blockage tests using test assemblies prototypic of 14x14 Westinghouse assemblies. The data used for the benchmark of S-RELAP5 were previously used to benchmark XCOBRA-IIIC, VIPRE, and THINK-IV for both core flow redistribution and flow redistribution within a single fuel assemble. Three test cases were used for the S-RELAP5 assessment. For the first test, the inlet flow for Assembly A was nominally 1138 gpm while the inlet flow for Assembly B was 512 gpm. For the second test, the inlet flow for Assembly A was nominally 1281 gpm while the inlet for Assembly B was blocked. For the third test, the inlet flow for Assembly A was nominally 1500 gpm while the inlet and outlet for Assembly B were blocked. Comparisons of S-RELAP5 calculations to the data for the first test showed good agreement. Comparisons of the S-RELAP5 calculations to the data for the second test also showed good agreement for axial velocities. However, the comparisons of mass flow fraction at Levels 4 through 7 in Assembly A were not as good as those for the first test. FRA-ANP reported that the velocity measurements at these levels did not conserve total mass flow. Thus it is difficult to draw a conclusion regarding the ability of S-RELAP5 to predict the mass flows for this test. For the third test, S-RELAP5 calculations again compare well to the data. This gives the overall impression that the S-RELAP5 2-D modeling is performing reasonably well.

In addition, FRA-ANP compared the S-RELAP5 calculations for these tests to calculations using XCOBRA-IIIC and THINC-IV, both of which are approved by the NRC for core flow and subchannel analysis of PWR cores. FRA-ANP demonstrated that S-RELAP5 is as good as or better than either of these codes in predicting the test results.

The Semiscale Test S-UT-8 is a scaled PWR integral test designed to investigate the effects of ECCS on SBLOCA, and more specifically, core heat-up before loop seal clearing. The results of the comparisons demonstrated that S-RELAP5 can simulate the core heat-up before loop seal clearing and that the PCTs predicted by S-RELAP5 are conservative but close to the data.

The LOFT Test LP-SB-3 is a scaled PWR integral test designed to investigate core heat transfer during slow boil-off SBLOCA. Differences in comparisons of the ANF-RELAP calculations and the S-RELAP5 calculations were noticed. However, the differences were determined to be insignificant in predicting the LOFT LP-SB-3 test. In addition, comparisons to the data demonstrated that S-RELAP5 is capable of conservatively calculating the boil-off and the fuel heat-up during a SBLOCA.

The UPTF Test A5RUN11E is a full scale PWR separate effect test designed to investigate loop seal clearing behavior with vapor superheat. Comparisons of the S-RELAP calculations to the test showed that S-RELAP5 will overpredict the amount of liquid that remains in the loop seal following the clearing period. S-RELAP5 also overpredicts the pressure drop in the loop seal following clearing. This results in a higher prediction of PCT and is therefore conservative.

The BETHSY Test 9.1b is a scaled PWR integral test designed to investigate SBLOCA behavior without High Head Safety Injection. The test simulates many of the major phenomena in SBLOCA accidents at PWRs. S-RELAP5 calculations were performed to demonstrate the code's capability to predict important SBLOCA phenomena; including, primary and secondary system pressures, core collapsed level, integrated break flow mass, loop seal clearing, and ECCS injection. The comparisons demonstrated that S-RELAP5 can reasonable predict SBLOCA behavior relative to these phenomena. S-RELAP5 closely predicted the loop seal clearing process and the post-clearing behavior. In addition, S-RELAP5 predicted the PCT as 1403°F which was conservative when compared to the measured temperature of 1331°F. The PCT was predicted to occur at essentially the same time as the data.

Numerous additional assessment cases were performed in support of this approval request. Tests such as THTF level swell, Bennett heated tube, CCTF, LOFT large break tests L2-5 and L2-6, and half a dozen additional UPTF tests were used to assess such parameters as rewet/quenching, mixture level, steam generator effects, cold leg stratification, and downcomer modeling. The staff notes that this represents a well thought out approach to code assessment that, while not required for a 10 CFR Part 50, Appendix K methodology, provides the support obtained through a Phenomena Importance and Ranking Table level evaluation.

The staff finds the substitution of test assessments using tests with better supported data acceptable for this application.

5.0 SENSITIVITY STUDIES

One of the requirements for a LOCA analysis is that sensitivity studies must be performed to determine the effects of various modeling assumptions on the calculated peak cladding temperature, PCT. Since S-RELAP5 is intended for application to numerous reactors of two vendors' designs, FRA-ANP chose the three-loop Westinghouse 2300 MWt design for use in performing the S-RELAP5 sensitivity studies.

The break spectrum analysis of the plant found that the limiting small-break is the 2-inch break. Studies were then performed varying the time step size, restart, loop seal model, pump model, radial flow form loss coefficients, and nodalization. In all cases it was found that the effect of each factor studied had an effect on PCT of 5°F or less. Thus, it is concluded that the solution

is converged with respect to time step size. In addition, there is very little sensitivity to the various parameters varied during the sensitivity studies.

6.0 CONCLUSIONS

FRA-ANP has modified the approved ANF-RELAP code to produce a code, S-RELAP5, which incorporates the RELAP5/MOD2 code, features of the RELAP5/MOD3 code, the RODEX2 code, the TOODEE2 code, and the ICECON code. The S-RELAP5 code is capable of performing an integrated calculation of a small break loss-of-coolant accident in a PWR of the Westinghouse or Combustion Engineering design.

The code has carried over many of the models of the integrated codes, while improving the numerics of the integrated code. The staff finds this work acceptable.

The FRA-ANP has clarified the applicability of the Sleicher-Rouse heat transfer correlation in place of the Dittus-Boelter correlation. The staff agrees that the Sleicher-Rouse correlation has less uncertainty, and, although it gives a few degrees lower wall temperature for selected experiments, the temperature prediction is more accurate and the use of Sleicher-Rouse is acceptable.

The staff supports the efforts of applicants to integrate codes for analysis of accidents and transients rather than manual transfer of information between the codes. Integrating the thermal-hydraulic, fuel rod performance and containment codes permits a smoother and more accurate prediction of the performance of the system under accident conditions.

The staff reviewed the point kinetics equation model in S-RELAP5 for deviations and/or modifications from the point kinetics model found in the RELAP5 series of codes, and determined that the point kinetics model are identical in both S-RELAP5 and RELAP5/MOD2 and MOD 3.2. Consequently, the point kinetics model in-coded in S-RELAP5 is adequate for its intended use.

The staff notes that a condition imposed on the use of the ANF-RELAP code, (Reference 53), still applies to the use of S-RELAP5. Specifically:

- That while it has been shown in Reference 53 that the thermal-hydraulic phenomena observed for breaks up to 10 percent of the cold leg flow area are the same, if the code is used for break sizes larger than 10 percent of the cold leg flow area additional assessments must be performed to ensure that the code is predicting the important phenomena which may occur.

7.0 REFERENCES

1. EMF-2328(P), Rev. 0, "PWR Small Break LOCA Evaluation Model, S-RELAP5 Based," Siemens Power Corporation, January 2000.

2. EMF-2100(P), Rev. 2, "S-RELAP5 Models and Correlations Code Manual," Siemens Power Corporation, January 2000.

3. XN-NF-82-49(P)(A), Rev. 1, "Exxon Nuclear Company Evaluation Model Revised EXEM-PWR Small Break Model, Supplement 1," Siemens Power Corporation, December 1994.

4. XN-NF-82-49(P)(A), Revision 1, "Exxon Nuclear Company Evaluation Model - EXEM PWR Small Break Model," Exxon Nuclear Company, Inc., June 1986.

5. Ransom, V. H. et al., "RELAP5/MOD2 Code Manual," NUREG/CR-4312, EGG-2396, Rev. 1, March 1987.

6. XN-NF-81-58(P)(A), Revision 2 and Supplements 1 & 2, "RODEX2 Fuel Thermal-Mechanical Response Evaluation Model," Siemens Power Corporation, March 1984.

7. XN-CC-39(A), Rev. 1, "ICECON: A Computer Program Used to Calculate Containment Back Pressure for LOCA Analysis Including Ice Condenser Plants," Exxon Nuclear Company, October 1978.

8. EMF-CC-072(P), Revision 1, "TOODEE2 Code: Model and Input/Output Description," Siemens Power Corporation, March 1997.

9. Ransom, V. H. et al., "RELAP5/MOD3 Code Manual," NUREG/CR-5535, INEL-95/0174, August 1995.

10. Letter, FRA-ANP to NRC, dated January 10, 2000.

11. Request for Additional Information dated December 3, 2000.

12. A.R. Curtis and J.K. Reid, FORTRAN Subroutines for solutions of Sparse Sets of Linear Equations, AERE-R6844,1971.

13. Telecon between FRA-ANP and NRC held on January 4, 2001.

14. F. W. Dittus and L. M. K. Boelter, "Heat Transfer in Automobile Radiators of the Tubular Type," Publications in Engineering, 2, pp. 443-461, University of California, Berkeley, 1930.

15. W. H. McAdams, Heat Transmission, 3rd edition, McGraw-Hill, New York, 1954.

16. A. E. Bergles and W. M. Rohsenow, "The Determination of Forced-Convection Surface-Boiling Heat Transfer," Journal of Heat Transfer, Transactions of ASME, 86, p. 365, 1964.

17. P. Saha and N. Zuber, "Point of Net Vapor Generation and Vapor Void Fraction in Subcooled Boiling," Proceedings of 5th International Heat Transfer Conference, Vol. IV, pp.175-179, 1974.

18. J. C. Chen, "A Correlation for Boiling Heat Transfer to Saturated Fluids in Convective Flow," Process Design and Development, 5, pp. 322-327, 1966.

19. Biasi 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, pp. 530-536, 1967.

20. P. Griffith, J. F. Pearson, and R. J. Lepkowski, "Critical Heat Flux During a Loss-of Coolant Accident," Nuclear Safety 18, pp. 298-309, 1977.

21. J. C. Chen, R. K. Sundaram, F. T. Ozkaynak, A Phenomenological Correlation for Post-CHF Heat Transfer, NUREG-0237, June 1977.

22. C. A. Sleicher and M. W. Rouse, "A Convenient Correlation for Heat Transfer to Constant and Variable Property Fluids in Turbulent Pipe Flow," International Journal of Heat Mass Transfer, 18, pp. 677-683, 1975.

23. M. J. Thurgood, Recommendation for Determining the Uncertainty in the Peak Clad Temperature Calculated by RELAP5-MOD2/ANF for a Loss-of-Coolant Accident, Numerical Applications Report.

24. R. P. Forslund and W. M. Rohsenow, "Dispersed Flow Film Boiling," Journal of Heat Transfer 90 (6), pp. 399-407, 1968.

25. L. A. Bromley, "Heat Transfer in Stable Film Boiling," Chemical Engineering Progress 46, pp. 221-227, 1950.

26. P. J. Berenson, "Film Boiling Heat Transfer from a Horizontal Surface," Journal of Heat Transfer, pp. 351-358, 1961.

27. K. H. Sun, J. M. Gonzales-Santalo, and C. L. Tien, "Calculations of Combined Radiation and Convection Heat Transfer in Rod Bundles Under Emergency Cooling Conditions."

28. D. R. Liles et al., "TRAC-PF1/MOD1 Correlations and Models," NUREG/CR-5069, LA-11208-MS, December 1988.

29. M. J. Thurgood et al., "COBRA/TRAC-A Thermal-Hydraulics Code for Transient Analysis of Nuclear Reactor Vessels and Primary Coolant Systems," Vol. 1, Equations and Constitutive Models, NUREG/CR-3046 PNL-4385, March 1983.

30. R. A. Dimenna et al., RELAP5/MOD2 Models and Correlations," NUREG/CR-5194, EGG-2531, August, 1988.

31. EMF-92-139(P), Volume 3, Supplement 3, "Realistic LOCA ECCS Evaluation Model Assessment for PWR Large Break Analysis Assessment for LOFT Test L2-5," Siemens Power Corporation, June 1993.

32. A. W. Bennett, G. F. Hewitt, H. A. Kearsey and R. K. F. Keeys, "Heat Transfer to Steam-Water Mixtures Flowing in Uniformly Heated Tubes in Which the Critical Heat Flux Has Been Exceeded," UKAEA Research Group Report, AERE-R 5373, October 1967.

33. EMF-92-139(P), Volume 3, Supplement 4, Realistic LOCA ECCS Evaluation Model Assessment for PWR Large Break Analysis Assessment for LOFT Test L2-6," Siemens Power Corporation, June 1993.

34. EMF-92-139(P), Volume 3, Supplement 6, Realistic LOCA ECCS Evaluation Model Assessment for PWR Large Break Analysis Westinghouse 3-Loop PWR Sample Problem," Siemens Power Corporation, May 1993.

35. EMF-92-139(P), Volume 3, Supplement 7, "Realistic LOCA ECCS Evaluation Model Assessment for PWR Large Break Analysis Westinghouse 4-Loop PWR Example Problem," Siemens Power Corporation, June 1993.

36. J. C. M. Leung, "Transient Critical Heat Flux and Blowdown Heat Transfer Studies," Ph.D. Dissertation, Northwestern University, June 1980.

37. EMF-92-139(P), Volume 3, Supplement 2, "Realistic LOCA ECCS Evaluation Model Assessment for PWR Large Break Analysis Assessment for CCTF Test 54, Siemens Power Corporation," April 1993.

38. EMF-92-139(P), Volume 3, Supplement 1, "Realistic LOCA ECCS Evaluation Model Assessment for PWR Large Break Analysis Assessment for FLECHT SEASET Test 31504," Siemens Power Corporation, April 1993.

39. M. S. Dougall and W. M. Rohsenow, "Film Boiling on the Inside of Vertical Tubes with Upward Flow of a Fluid at Low Qualities, MIT-ME 9079-26, 1963." Journal of Heat Transfer, pp. 414-420, 1976.

40. FLECHT SEASET Program, PWR FLECHT SEASET Unblocked Bundle, Forced and Gravity Reflood Task Data Report, Volume 2, NUREG/CR-1532, EPRI NP-1459, WCAP-9699, June 1980.

41. American Nuclear Society proposed standard, ANS 5.1, "Decay Energy Release Rate Following Shutdown of Uranium-Fueled Thermal Reactors," October 1971, Revised October 1973.

42. American National Standard for Decay Heat Power in Light Water Reactors, ANSI/ANS-5.1-1979, August 1979.

43. NUREG-0737, "Clarification of TMI Action Plan Requirements," U.S. NRC, November 1980.

44. Chelemer, H., P. T. Chu, and L. E. Hochreiter, "THINC-IV - An Improved Program for Thermal-Hydraulic Analysis of Rod Bundle Cores," WCAP-7956, Westinghouse Electric Corporation, June 1973.

45. Weiss, E., R. A. Markley, and A. Battacharyya, "Open Duct Cooling-Concept for the Radial Blanket Region of a Fast Breeder Reactor," Nuclear Engineering and Design, Volume 16, PP 175-386, 1971.

46. "Vessel Coolant Mass Depletion During a Small-Break LOCA," EGG-SEMI-6010, September 1982.

47. "Experimental Analysis and Summary Report on OECD LOFT Experiment LP-SB-3," OECD LOFT-T-3905, December 1985.

48. "Quick Look Report on OECD LOFT Experiment LP-SB-3," OECD LOFT-T-3604, March 1984.

49. "Freiblasen Des Pumpboges Einzeleffekt und Integralversuche, Versuchsdatenbericht," S554/93/007, Siemens AG, Erlangen, Germany, Power Generation Group (KWU), September 1993.

50. "UPTF-TRAM Test Group A Test Results, Analysis," Working Group of Experts Meeting, Mannheim, Germany, Siemens AG, December 6-8, 1993.

51. "UPTF-TRAM Test Instrumentation, Measurement System Identification, Engineering Units and Computed Parameters," S554/92/013, Siemens AG, Erlangen, Germany, Power Generation Group (KWU), November 1992.

52. Clement, P., T. Chataing, and R. Deruaz, "Final Comparison Report for International Standard Problem 27," French original report on BETHSY Test 9.1b.

53. Loomis, G. G., "Summary of the Semiscale Program (1965-1986)," NUREG/CR-4945, July 1987.