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System scaling analysis for modeling small break LOCA using the FULL SPECTRUM LOCA evaluation model

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ABSTRACT

The development of the FULL SPECTRUM™ LOCA (FSLOCA™) evaluation model followed the Evaluation Model Development and Assessment Process (EMDAP). The EMDAP emphasizes the scaling analysis of the system code, the closure models, and the integral effects tests (IETs) and the separate effects tests. For the system level scaling perspective, the top-down scaling approach evaluates the global system behaviors and the system interactions from IETs, and addresses the similarity between the IETs and the prototype of PWR.

In the FSLOCA evaluation model, the ROSA-IV/LSTF IET facility is selected as the key facility in the validation matrix of the WCOBRA/TRAC-TF2 system code, because it is the largest scaled (1/48 power to volume) and full height SBLOCA IET facility to a PWR. In this work, the system level scaling distortion between the ROSA-IV/LSTF integral effects test facility and a Westinghouse three-loop PWR is investigated.

The top-down scaling in the blowdown, natural circulation, loop seal clearance, and boil-off phases in the ROSA-IV/LSTF SB-CL-02 test was investigated relative to the three-loop PWR SBLOCA transient. The top-down scaling analysis results indicated that there are small distortions originating from the atypical steady state and transient in the ROSA-IV/LSTF test. In general, the system scaling analysis demonstrated that the ROSA-IV/LSTF tests are well scaled IETs for examining the behavior of Westinghouse three-loop PWRs under the SBLOCA transient conditions, and are uniquely suited in the SBLOCA validation matrix of the FSLOCA evaluation model.

1. Introduction

The FULL SPECTRUM™ loss-of-coolant accident (FSLOCA™) evaluation model (Frepoli and Ohkawa, 2011), which utilized the WCOBRA/TRAC-TF2 system code (Frepoli et al., 2009), is an integrated LOCA evaluation model for analyzing both large break LOCA (LBLOCA) and small break LOCA (SBLOCA) in PWR. The WCOBRA/TRAC-TF2 code consists of a three-dimensional subchannel module for simulating the reactor vessel and a one-dimensional two-fluid module that is derived from the TRAC-P computer code (Spore et al., 2000) for the reactor coolant loop and the emergency core cooling system. The three-dimensional sub-channel model is adequate to describe the phenomena expected in the reactor pressure vessel during a LOCA scenario. The two-fluid, six-equation formulation (Frepoli et al., 2009) utilized in the one-dimensional module is able to describe the reactor coolant system loop phenomena, especially when a characterization of stratified flow is required.

The development of the FSLOCA evaluation model followed the Evaluation Model Development and Assessment Process (EMDAP) which is outlined in Regulatory Guide (RG) 1.203 (USNRC, 2005) and the Standard Review Plan (SRP) discussed in NUREG-0800 (USNRC, 2014). RG 1.203 describes a structured development and assessment process that is an upgrade from the principles of the CSAU roadmap (USNRC, 1989). There are four elements in EMDAP. Element 1 of the EMDAP process focuses on how to establish the requirements for the Evaluation Model (EM). One key step in the EMDAP process (as well as in the CSAU) is the Phenomena Identification and Ranking Table (PIRT). The process is used to develop the functional requirements for the new evaluation model as well as to define the validation database. Traditionally, separate PIRTs have been developed by focusing on the LBLOCA or the SBLOCA scenarios as two different entities. An integrated PIRT (Frepoli, 2006) was developed to span over the full spectrum of break sizes.

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Elements 2, 3 and 4 describe a suitable process for the development and the assessment of the evaluation model (EM), sometimes referred to as Verification and Validation (V&V). An assessment matrix is established where Separate Effects Tests (SETs) and Integral Effects Tests (IETs) are selected to validate the code against the important phenomena identified in the PIRT. The code biases and uncertainties are established and the effect of scale is determined.

SETs are used to develop and assess groups of empirical correlations and other closure models associated to the important phenomena. The validation in FSLOCA EM (Frepoli and Ohkawa, 2011) includes an extensive amount of SETs that covers the major phenomena such as break flow, post-CHF core heat transfer, core void distribution and mixture level, horizontal stratified flow, cold leg condensation (Liao et al., 2015), ECC bypass, steam binding, loop seal clearance, etc., in either LBLOCA or SBLOCA.

IETs are used to assess system interactions and global code capability. The LBLOCA assessments of WCOBRA/TRAC-TF2 were mainly performed using large scale test facilities utilized as a part of the international 2D/3D program. The facilities included in the code assessment are the Upper Plenum Test Facility (UPTF), and the Cylindrical Core Test Facility (CCTF). LOFT IETs were used to assess the capability of the code to model large break LOCA events with the nuclear core and with the focus to the blowdown phase. The purpose of those assessments was to confirm that the code is able to predict the LBLOCA phenomena with performance similar to the NRC approved WCOBRA/TRAC system code (Bajorek et al., 1998). The integral effect tests assessment for SBLOCA was based on the ROSA-IV/LSTF test facility (JAERI, 1985) with additional assessment of the LOFT SBLOCA tests.

The scaling analysis of the system code, the closure models, and the IETs and SETs are important in EMDAP. Specifically, the IET and SET facilities and experimental data are evaluated by the scaling analysis to respond to Step 6 in Element 2 of EMDAP "Perform Scaling Analysis and Identify Similarity Criteria", to ensure that the test data, and the models based on those data, will be applicable to the full-scale analysis of the plant transient. When the distortions in the IETs arise due to the configuration difference or boundary conditions, the effects of the distortions should be evaluated according to Step 8(a) in Element 2 of EMDAP "Evaluate Effects of IET Distortions and SET Scale up Capability". Furthermore, the rationale and techniques associated with evaluating scale up capability of the models or correlations in the system code should be provided as suggested in Step 8(b) in Element 2 of EMDAP.

Step 15 of Element 4 of EMDAP "Assess Scalability of Models" requires scalability analysis on whether the specific model or correlation is appropriate for the application to the configuration and conditions of the plant and transient under evaluation. Step 19 in Element 4 of EMDAP "Assess Scalability of Integrated Calculations and Data for Distortions" is to assess scalability of integrated calculation and data for distortion. This scalability evaluation is limited to whether the assessment calculations and experiments exhibit otherwise unexplainable differences among facilities, or between calculated and measured data for the same facility, which may indicate experimental or code scaling distortions.

The scaling analyses in the EMDAP include both the top-down and bottom-up approaches. The top-down scaling approach evaluates the global system behavior and systems interactions from integral test facilities that can be shown to represent the plant-specific design under consideration. A top-down scaling methodology is developed and applied to achieve the following purposes:

(1) Derive the dimensionless groups governing similitude between facilities.
(2) Show that these groups scale the results among the experimental facilities.
(3) Determine whether the ranges of group values provided by the experiment set encompass the corresponding plant- and transient-specific values.

The bottom-up scaling analyses address issues raised in the plant and transient specific PIRT related to localized behavior. These analyses are used to explain differences among tests in different experimental facilities and to use these explanations to infer the expected plant behavior and determine whether the experiments provide adequate plant-specific representation.

The FSLOCA topical report (Frepoli, 2010) has provided the bottom-up scaling analyses or discussions for the each closure model, separate effects test and integral effects test. This study provides a top-down scaling analysis to evaluate the effect of IET distortions for SBLOCA to satisfy the requirements in Step 8(a) and Step 19 of EMDAP.

There were several integral effects test facilities for SBLOCA in PWR, notably, BETHSY, LOBI, LOFT, PKL, ROSA-IV/LSTF, Semiscale, and SPES. Among them, ROSA-IV/LSTF (JAERI, 1985) features the largest scale (1/48 power-volume), and prototypical configuration for Westinghouse four-loop PWRs, a large test matrix, and state-of-the-art instrumentations. The general structure of the ROSA-IV/LSTF facility is shown in Fig. 1. It is a full height test facility, but the four loops in the prototypical PWRs are simplified to a broken loop and an intact loop. With the major components such as the reactor pressure vessel and steam generators follow the volumetric scale, the hot leg and cold legs are scaled to keep the similarity of the Froude number.

However, the existing scaling analysis on the ROSA-IV/LSTF tests (JAERI, 1985; MHI, 2010) focused on the Westinghouse four-loop PWR, while the three-loop Westinghouse PWR (Fig. 2) is one of the pilot nuclear power plants of the FULL SPECTRUM LOCA evaluation model, which leads to a different scaling factor and distortions. Thus, the development of FSLOCA EM requires a top-down scaling analysis between the ROSA-IV/LSTF test facility and the Westinghouse three-loop PWR to satisfy the scaling requirement of the EMDAP. Next, the history of scaling analysis for nuclear experimental facility is reviewed.

The Π theorem was established by Buckingham (1914) and widely used in the dimensionless analysis to serve as guide for systematic experimentation in the fluid mechanics community and the heat transfer community. With the development of nuclear experimental facility, there were numerous scaling analysis methods established for the nuclear thermal hydraulic analysis. The scaling criteria applied for the design of the reduced height test reactor, LOFT, have been examined by Rose (1965). Carbiener and Cudnik (1969) developed linear scaling method that requires all linear dimensions reduced by the same proportion. Ishii and Kataoka (1983) presented scaling criteria specifically for the cooling loops of pressurized water reactors under single-phase and two-phase natural circulation conditions. The volume scaling method, which is adequate for full height and full pressure experimental facility, were developed by Nahavandi et al. (1979). The volume scaling method was utilized to design most of integral effects test facilities, such as ROSA-IV/LSFT, BETHSY, CCTF, and others, that are major validation tests for the development of the reactor safety analysis computer codes. Note that the diameter of cold leg and hot leg of those facilities was scaled with the similarity of Froude number to preserve the flow regime (Zuber, 1980) in addition to the volume scaling. The hierarchical two-tiered scaling (H2TS) method presented by Zuber et al. (1998) was recommended for the EMDAP. The H2TS method and its extension has been applied to develop the testing facility for advance passive PWRs (Banerjee et al., 1998; Reyes and Hochreiter, 1998). Fractional Scaling Analysis (FSA) (Zuber et al., 2005) as an update from the H2TS method could be applied for the EMDAP as well.