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Use of Modular Accident Analysis Program (MAAP) in Support of Post-Fukushima Applications

2013 TECHNICAL REPORT

Use of Modular Accident Analysis Program (MAAP) in Support of Post-Fukushima Applications

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Abstract

In the aftermath of the Fukushima accident, improvements have been made to virtually all plants, both voluntarily and as a result of regulatory actions. In many countries, plant enhancements were undertaken to address the findings of "stress tests". In the U.S., the Nuclear Regulatory Commission (NRC) issued Commission Order EA-12-049, Mitigation Strategies for Beyond-Design-Basis External Events, on March 12, 2012. This order required that the U.S. nuclear industry develop strategies to mitigate an extended loss of AC power (ELAP) event with a simultaneous loss of the ultimate heat sink. The majority of submittals describing actions taken in light of this Order identified the use of the MAAP code to estimate the accident progression timing and the primary system and containment thermal hydraulic response. Overall, these analyses involved analyses of straightforward mass and energy transport phenomenon, clearly within the capabilities of the MAAP code. The primary objective of this document is to provide a clear technical justification for the use of MAAP for applications of this type. The report summarizes material contained within the Modular Accident Analysis Program version 4 (MAAP4) Applications Guidance document (EPRI report 1020236) with specific focus on responding to recent Requests for Additional Information (RAI) related to the use of MAAP in support of the U.S. nuclear industry response to Commission Order EA-12-049

The MAAP code has been found to be acceptable for use in support of the industry response to Order EA-12-049. This judgment is based on extensive benchmarking, which is documented in the MAAP4 Applications Guidance document.

Keywords
Success criteria
Thermal-hydraulic analysis
MAAP
FLEX

Executive Summary

The Modular Accident Analysis Program version 4 (MAAP4) is a computer code that is widely used by nuclear utilities and research organizations to predict the progression of light water reactor (LWR) accidents. The initial development of the code began in the 1980s. Earlier versions of MAAP were the primary tool used to support the completion of the Individual Plant Examinations (IPE) as required under the Generic Letter 88-20. Continued maintenance and development of the code has been carried out under the direction of the Electric Power Research Institute (EPRI).

With increasing demands for analysis of beyond-design-basis events, MAAP applications have greatly increased over the past 30 years. MAAP has become the primary tool to support success criteria development, human reliability analysis, and source term assessment for probabilistic risk assessments (PRA) for nuclear power plants worldwide. In addition, MAAP has been extensively used for Severe Accident Mitigation Alternative (SAMA) evaluations in support of plant license renewal applications and in support of Significance Determination Process (SDP) evaluations. During the events at Fukushima and in support of post-Fukushima activities, MAAP has continued to play a significant role in the understanding of accident progression and mitigation.

With the expanding use of MAAP both domestically and internationally, EPRI released the MAAP4 Applications Guidance document in July 2010. The Applications Guidance document provides the utilities and regulators with a clear understanding of the capabilities and limitations of the code for a variety of analysis needs and identifies methods to assure high quality analysis.

In the aftermath of the Fukushima accident, improvements have been made to virtually all plants, both voluntarily and as a result of regulatory actions. In the United States, for example, the Nuclear Regulatory Commission (NRC) issued Commission Order EA-12-049, Mitigation Strategies for Beyond-Design-Basis External Events, on March 12, 2012. This order required that the U.S. nuclear industry develop strategies to mitigate an extended loss of AC power (ELAP) event with a simultaneous loss of the ultimate heat sink. The majority of submittals describing actions taken in light of this order identified the use of the MAAP code to estimate the accident progression timing and the primary system and containment thermal hydraulic response. Overall, these analyses involved analyses of straightforward mass and energy transport phenomenon, clearly within the capabilities of the MAAP code. The primary objective of this document is to provide a clear technical justification for the use of MAAP for applications of this type.

In particular, this document addresses the following general issues.

- the quality assurance process under which the MAAP analysis is performed
- the capability of MAAP to support analyses such as those described in Order EA-12-049

This information can be found in the MAAP4 Applications Guidance (EPRI report 1020236) relating to both the quality of the analysis and the extensive benchmarking that has been performed to validate MAAP. This document summarizes that information and directly addresses the two general issues above. A brief summary of each issue follows.

Quality of Analysis

Information in EPRI report 1020236 provides the MAAP user with guidance for creating a plant parameter file, reviewing the file, and properly testing the model. In addition, the application of the code to analyze specific accident scenarios is supported through a number of sample applications and a clear definition of the systems and logic modeled in the code. The user is also provided with detailed definitions of all key input and output parameters in order to achieve the objectives of the desired application and to effectively review and report the results. Finally, information is also provided on the suggested qualifications of a preparer or reviewer of any MAAP analyses, including a sample list of questions that a qualified MAAP analysts should be able to answer. The guidance relating to the quality of the analysis contained in the Applications Guidance document provides a detailed template for each utility to then integrate into its own qualification programs.

Use of MAAP for ELAP Analyses

MAAP is a computer code that simulates the response of light water reactor (LWR) power plants during severe accidents. Given a set of initiating events, system successes and failures, and operator actions, MAAP predicts the plant's response as the accident progresses. The code is used to:

- predict the timing of key events (e.g., core uncovery, core damage, core relocation to the lower plenum, vessel failure)
- evaluate the influence of safety systems, including the impact of the timing of their operation

- evaluate the impact of operator actions
- predict the magnitude and timing of fission product releases
- investigate uncertainties in severe accident phenomena

The first three items are applicable to evaluating measures taken to prevent core damage in ELAP scenarios.

The MAAP4 code has been extensively benchmarked, and information about the benchmarks has been presented and published in a variety of forums. More than 30 benchmarks were collected; they fall into the following categories:

- Comparisons to plant events (PE entries)
- Comparisons to integral codes (IC entries)
- Comparisons to integral experiments (IE entries)
- Comparisons to separate effects experiments (SE entries)

Benchmarking information is included in the MAAP4 User's Manual [Ref 6]. Additionally, a wider spectrum of concise benchmarking information is assembled in the Applications Guidance document. Relevant benchmarks that were performed using MAAP3B are also included and are considered applicable to MAAP4.

In preparing the guidance document, a team of experts, each member having extensive experience with the development and application of MAAP3B and MAAP4 as well as extensive knowledge of severe accident phenomena and plant response, reviewed the individual benchmarks in two stages. The first stage consisted of a preliminary review of the documentation of each benchmark to determine if 1) it contained adequate information on the method and results so that conclusions could be drawn and 2) the code was used in an appropriate manner (for example, not in a regime determined to be outside the range of applicability). The major code models, primary system thermal hydraulics, steam generator thermal hydraulics, core heat-up, and containment thermal response evaluated by each benchmark were identified. Similarly, the capabilities of the code to address significant features of an accident validated by each benchmark were identified. These include critical flow through valves and breaks, injection by the emergency core cooling system (ECCS), condenser heat transfer, voiding in the core, and hot leg natural circulation (HLNC).

The second stage consisted of an in-depth review of each of the benchmarks that met the preliminary criteria to determine the agreement between the MAAP4 results and the corresponding data and comparative analyses. The team studied the documented information and discussed the strength of the benchmark, the specific results, the conclusions drawn by the authors, and other relevant aspects. To provide a framework for the collective assessment of the code's capabilities, the review was structured to 1) rate the degree of agreement between the sets of comparative results and 2) capture pertinent information on code performance, limitations, and options for modeling particular phenomena.

The degree of agreement for the major code models is based on the following representative quantities. They were selected because of their importance to the success criteria and human reliability components of PRA analysis:

- BWR primary system thermal hydraulics: primary system pressure and water level in the reactor pressure vessel
- PWR primary system thermal hydraulics: primary system pressure, water level in the pressurizer, and water level in the reactor vessel
- Steam generator thermal hydraulics: secondary side pressure and water level in the steam generators
- Core heat-up (generic to BWR and PWR): maximum core temperature
- Containment thermal response (generic to BWR and PWR): containment pressure

The team jointly rated the agreement for each of the major models as well as the overall degree of agreement as *very good*, *good*, *fair*, *qualitative*, or *inconclusive*. No *poor* agreements were identified. By necessity, the rating process was qualitative rather than quantitative. Consideration was given to whether the uncertainties associated with the documented sequence definitions and boundary conditions tended to be greater than those associated with the modeling approaches and phenomenological uncertainties.

Tables I and II provide a summary of the code comparisons performed and a rating of the overall agreement. As can be seen, there have been numerous benchmarks performed that provide confidence in the capability of MAAP to represent accidents sequences such as ELAP.

Table I
BWR Sequences Supported by Benchmarks

Sequence Initiating Event	Type of Benchmark	Number and Types of Sequences	Overall Agreement	Sequence Time Frame
BWR transients (including SBOs, LOFW, and turbine trips)	Plant event: Oyster Creek (PE3)	1 LOFW	Very good	30 min
	Integral code comparison to TRACG02 (IC3)	2 LOOPs with LLOCAs	Good	8 min
	Integral code comparison to SAFE (IC11)—MAAP3B	4 LOFW	Good agreement with MAAP3B	15 min–2 hr
	Integral experiment comparison to FIST (IE11)—MAAP3B	2 LOFW	Good agreement with MAAP3B	15–50 min
	Integral code comparison to MELCOR (IC10)	1 SBO and 3 transients	Good: only a minor supporting benchmark for Level 1 applications	40 hr
BWR LLOCAs (excluding MSLBs)	Integral code comparison to TRACG02 (IC3)	2 LOOPs with LLOCA	Good	8 min
	Integral code comparison to SR5 and MELCOR (IC5)	1 LLOCA	Good	4 hr
	Integral code comparison to MELCOR (IC10)	1 LLOCA	Good: only a minor supporting benchmark for Level 1 applications	40 hr
BWR MLOCAs and SLOCAs -	Integral code comparison to SAFE (IC11)—MAAP3B	1 SLOCA	Good agreement with MAAP3B	1 hr
	Integral experiment comparison to FIST (IE11)—MAAP3B	1 MLOCA	Good agreement with MAAP3B	8 min
BWR MSLBs Can be considered a subset of LLOCAs	Integral code comparison to SAFE (IC11)—MAAP3B	1 MSLB	Good agreement with MAAP3B	7 min

Table 1 (continued)
BWR Sequences Supported by Benchmarks

Sequence Initiating Event	Type of Benchmark	Number and Types of Sequences	Overall Agreement	Sequence Time Frame
BWR interfacing system LOCAs (discharge outside of containment)	No supporting benchmarks, but essentially covered by LLOCA and S/MLOCA benchmarks			
BWR stuck-open SRVs	No supporting benchmarks with stuck-open SRVs as an initiator, but similar to SLOCAs if discharge is to the gas space (versus to the suppression pool). Sequences are also supported by benchmarks in which stuck-open or manually opened SRVs are subsequent conditions.			
BWR feedwater line breaks	No supporting benchmarks, but essentially covered by S/MLOCA benchmarks			
BWR ATWS	No supporting benchmarks			

Table II
PWR Sequences Supported by Benchmarks

Sequence Initiating Event	Type of Benchmark	Number and Types of Sequences	Plant Type	Steam Generator Type and Model	Overall Agreement	Sequence Time Frame
PWR transients (including SBOs, LOFW, and turbine trips)	Plant event: TMI-2 (PE1)	1 LOFW with stuck-open PORV	B&W	OTSG, one-region model	Very good	5 hr
	Plant event: Davis-Besse (PE2)	1 LOFW	B&W	—	Fair	30 min
	Plant event: Maanshan (PE5)	1 SBO	WLD	—	Good	3 hr
	Plant event: Oconee (PE6)	1 plant trip	B&W	—	Good	15 min
	Plant event: four-loop (PE7)—MAAP3B	1 LOOP and 1 plant trip	Westinghouse	—	Good agreement with MAAP3B	3–5 min
	Integral code comparison to CENTS (IC1)	1 SBO and 1 LOFW with feed and bleed	CE	U-tube, two-region model	Good	3 hr
	Integral code comparison to SR5 (IC2)	3 LOFWs	U.S. EPR	U-tube, one-region model	Good	2 hr
	Integral code comparison to RELAP5 (IC4)	2 SBOs with feed and bleed	CE	U-tube, one-region model	Good	5–10 hr
	Integral code comparison to SR5 and MELCOR (IC5)	1 SBO	WLD	U-tube, region model not specified	Good	5 hr
	Integral code comparison to SR5 and MELCOR (IC8)	1 TMLB′ (SBO, no RCP seal leak)	WLD	U-tube, one-region model	Good	5 hr
	Integral code comparison to RELAP5 (IC9)	1 LOOP with feed and bleed	CE	U-tube, one-region model	Good	3 hr

Table II (continued)
PWR Sequences Supported by Benchmarks

Sequence Initiating Event	**Type of Benchmark**	**Number and Types of Sequences**	**Plant Type**	**Steam Generator Type and Model**	**Overall Agreement**	**Sequence Time Frame**
	Integral code comparison to MELCOR (IC10)	1 TMLB (SBO with RCP seal leak)	WLD	—	Good: only a minor supporting benchmark for Level 1 applications	40 hr
	Integral code comparison to RELAP and RETRAN (IC12)—MAAP3B	2 transients	Westing-house	—	Good agreement with MAAP3B plus code changes that were incorporated into MAAP4	5 min–1.4 hr
	Integral experiment comparison to BETHSY (IE1)	2 LOFWs with feed and bleed	900 MWe EDF/ Framatome	U-tube, one-region model	Very good	1–2 hr
	Integral experiment to IIST (IE2)	1 SBO	WLD	U-tube, one-region model	Very good	3 hr
	Integral experiment comparison to MB-2 (IE3)	2 LOFWs	WLD	U-tube, two-region model	Very good	2–12 min
	Integral experiment comparison to Semiscale (IE10)—MAAP3B	2 LOOPs	Generic PWR	—	Good agreement with MAAP3B	3–5 hr
PWR LLOCAs (excluding MSLBs)	Integral code comparison to MELCOR (IC10)	2 LLOCAs: location not identified	WLD	—	Good: only a minor supporting benchmark for Level 1 applications	40 hr

Table II (continued)
PWR Sequences Supported by Benchmarks

Sequence Initiating Event	Type of Benchmark	Number and Types of Sequences	Plant Type	Steam Generator Type and Model	Overall Agreement	Sequence Time Frame
PWR MLOCAs and SLOCAs	Integral code comparison to SR5 (IC2)	1 SLOCA: location not identified 1 MLOCA: location not identified	U.S. EPR	U-tube, one-region model	Good	2 hr
	Integral code comparison to CENTS (IC6)	1 MLOCA: break in the intermediate leg	WLD	U-tube, region model not specified	Inconclusive	5 hr
	Integral code comparison to CATHARE (IC7)	1 SLOCA: break in the hot leg 1 MLOCA: break in the hot leg 3 SLOCAs: breaks in the cold leg 1 MLOCA: break in the cold leg	900 MWe EDF/ Framatome	U-tube, one-region model	Good	2–12 hr
	Integral code comparison to MELCOR (IC10)	1 SLOCA: location not identified	WLD	—	Good: only a minor supporting benchmark for Level 1 applications	40 hr
	Integral code comparison to RELAP and RETRAN (IC12)—MAAP3B	2 SLOCAs: breaks in the cold leg	Westing-house	—	Good agreement with MAAP3B plus code changes that were incorporated into MAAP4	30 min–1 hr

Table II (continued)
PWR Sequences Supported by Benchmarks

Sequence Initiating Event	Type of Benchmark	Number and Types of Sequences	Plant Type	Steam Generator Type and Model	Overall Agreement	Sequence Time Frame
	Integral experiment comparison to BETHSY (IE1)	1 SLOCA: break in the cold leg	900 MWe EDF/ Framatome	U-tube, two-region model	Very good	2 hr
	Integral experiment comparison to OSU (IE4)	2 SLOCAs: breaks in an injection line	AP600	U-tube, two-region model	Very good	Not provided
	Integral experiment comparison to Semiscale (IE10)—MAAP3B	4 SLOCAs: breaks in the cold leg	Generic PWR	—	Good agreement with MAAP3B	13–50 min
	Integral experiment comparison to MIST (IE12)—MAAP3B	2 SLOCAs: breaks in the cold leg	B&W	—	Good agreement with MAAP3B	1–12 hr
PWR interfacing system LOCAs (discharge outside of containment)	No supporting benchmarks, but essentially covered by LLOCA and S/MLOCA benchmarks.					
PWR stuck-open PORVs	Integral code comparison to RELAP and RETRAN (IC12)—MAAP3B	1 failed-open PORV	Westinghouse	—	Good agreement with MAAP3B plus code changes that were incorporated into MAAP4	8 min
	Integral experiment comparison to OSU (IE4)	2 failed-open PORVs	AP600	U-tube, two-region model	Very good	Not provided

Table II (continued)
PWR Sequences Supported by Benchmarks

Sequence Initiating Event	Type of Benchmark	Number and Types of Sequences	Plant Type	Steam Generator Type and Model	Overall Agreement	Sequence Time Frame
PWR SGTR	Plant event: Prairie Island (PE4)	1 SGTR	WLD	—	Good	8 min
	Integral code comparison to RELAP and RETRAN (IC12)—MAAP3B	2 SGTRs	Westing-house	—	Good agreement with MAAP3B plus code changes that were incorporated into MAAP4	50 min
	Integral experiment comparison to Semiscale (IE10)—MAAP3B	3 SGTRs	Generic PWR	—	Good agreement with MAAP3B	5–40 min
PWR MSLBs	Integral code comparison to RELAP and RETRAN (IC12)—MAAP3B	1 MSLB	Westing-house	—	Good agreement with MAAP3B plus code changes that were incorporated into MAAP4	5 min
	Integral experiment comparison to MB-2 (IE3)	2 MSLBs 1 MSLB with SGTR	WLD	U-tube, two-region model	Very good	2–3 min 17 min for SGTR
PWR feedwater line breaks	No supporting benchmarks, but similar to LOCAs and, to a lesser extent, MSLBs					
PWR mid-loop operation	No supporting benchmarks					
PWR ATWS	No supporting benchmarks, but typically a very low contributor to core damage frequencies					

List of Acronyms

Acronym	Definition
AFW	auxiliary feedwater
ALWR	advanced light water reactor
AS	accident sequence analysis
ASME	American Society of Mechanical Engineers
ATR	Advanced Thermal Reactor
ATWS	anticipated transient without scram
B&W	Babcock and Wilcox
BWR	boiling water reactor
CANDU	Canadian-designed pressurized heavy water reactor
CATHARE	Électricité de France code for analysis of thermal hydraulics during reactor accidents and for safety evaluation
CE	Combustion Engineering
CRD	control rod drive
CSTF	Containment Systems Test Facility
DA	data analysis
ECCS	emergency core cooling system
EDF	Électricité de France
ELAP	extended loss of AC power
ERIN	ERIN Engineering and Research, Inc.
EPRI	Electric Power Research Institute
F&B	feed and bleed
FAI	Fauske & Associates, LLC
FIST	full scale integral simulation test
GKA	Gabor, Kenton & Associates, Inc.
HDR	high dose rate
HLNC	hot leg natural circulation
HLR	high level ASME PRA requirement
HPCI	high-pressure coolant injection

Acronym	Definition
HPSI	high-pressure safety injection
HR, HRA	human reliability analysis
IDCOR	Industry Degraded Core Rulemaking Program
IE	initiating events analysis
IF	internal flooding
IIST	INER Integral System Test (INER is Institute of Nuclear Energy Research in Taiwan)
IPE	individual Plant Examination
ISP	integrated surveillance program
LERF	large early release frequency
LOCA	loss-of-coolant accident
LOFW	loss of feedwater
LOOP	loss of offsite power
LPCI	low pressure coolant injection
LWR	light water reactor
MAAP3B	Modular Accident Analysis Program version 3.0B
MAAP4	Modular Accident Analysis Program version 4
MELCOR	computer code for reactor accident progression and source term
MIST	Multiloop Integral System Test
MSLB	main steam line break
MUG	MAAP Users Group
NRC	U.S. Nuclear Regulatory Commission
OTSG	once-through steam generator
QU	quantification
PC	personal computer
PORV	power operated relief valve
PRA	probabilistic risk assessment
PWR	pressurized water reactor
RCIC	reactor core isolation cooling
RCP	reactor coolant pump
RELAP	Reactor Excursion and Leak Analysis Program
RETRAN	a tool for thermal hydraulic analyses of LWRs
RG	regulatory guide
RPV	reactor pressure vessel
SBO	station black out

Acronym	Definition
SC	success criteria
SG	steam generator
SGTR	steam generator tube rupture
SLOCA	small loss-of-coolant accident
SR	supporting ASME PRA requirement
SRV	safety relief valve
SY	systems analysis
TMLB	refers to PWR accident sequence with loss of offsite power and no active emergency safeguards systems
VVER	Russian Federation pressurized light water reactor
WICE	Westinghouse ice condenser
WLD	Westinghouse large dry

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Section 1: Overview

The Modular Accident Analysis Program version 4 (MAAP4) is a computer code that is widely used by nuclear utilities and research organizations to predict the progression of light water reactor (LWR) accidents. Development of the code began in the 1980ss, and earlier revisions of MAAP were the primary tool used to support the completion of the Individual Plant Examinations (IPE) as required under the Generic Letter 88-20 [Ref. 1]. Continued maintenance and development of the code has been carried out under the direction of the Electric Power Research Institute (EPRI).

With increasing demands for analysis of beyond-design-basis events, MAAP applications have greatly increased over the past 30 years. MAAP has become the primary tool to support success criteria development, timing for human reliability analysis, and source term assessment for industry probabilistic risk assessments (PRAs). In addition, MAAP has been extensively used for Severe Accident Mitigation Alternative (SAMA) evaluations in support of plant license renewal applications and in support of Significance Determination Process (SDP) evaluations. During the events at Fukushima and in support of post-Fukushima activities, MAAP has continued to play a significant role in our understanding of accident progression and mitigation.

With the expanding use of MAAP both domestically and internationally, EPRI released the MAAP4 Applications Guidance [Ref. 2] document (the “App Guide”) in July 2010. The App Guide provides the utilities and regulators with a clear understanding of the capabilities and limitations of the code for a variety of analysis needs. The major sections of the App Guide address the following:

- a succinct description of the MAAP4 code
- guidance for assuring the quality of MAAP4 analyses
- an assessment of MAAP4's ability to adequately predict significant Level 1 phenomena (e.g., from accident initiation up until onset of core damage)
- a compilation of summary information regarding the benchmarking of MAAP4 models

The existing MAAP4 documentation consists of the MAAP4 User’s Manual [Ref. 11], the MAAP4 User’s Guides for input preparation, and transmittal documents that describe individual revisions. These documentation components contain detailed information on the mechanics of running the code and detailed descriptions of the individual models, but they do not include specific application guidance. The App Guide provides sufficient information so that users can optimize their efforts and generate high quality analyses.

Benchmarking information is included in the MAAP4 User's Manual. However, the manual does not contain all benchmarks, and they are not presented in a format that readily allows for the systematic assessment of MAAP4's capabilities to model significant Level 1 phenomena. The assembly of benchmarking information in the App Guide helps users assess MAAP4's capabilities, informs them about specific applications where particular caution is advised, and provides a basis for determining areas and/or phenomena for which additional benchmarks would be beneficial.

Two prior efforts generated particularly useful information regarding the thermal-hydraulic qualification of the previous version of the code, Modular Accident Analysis Program version 3.0B (MAAP3B), and recommended sensitivity analyses for that version. The first effort was the set of thermal-hydraulic qualification studies conducted by Gabor, Kenton & Associates (GKA) and S. Levy [Ref. 12]. The objectives of the studies were to evaluate the thermal-hydraulic modeling in MAAP3B and provide guidance on code use. The resultant reports contain detailed descriptions of relevant plant features, accident sequences, benchmarks, input file components, and guidance on applications and limitations. The second effort was the creation of a set of recommended sensitivity analyses for an Individual Plant Examination (IPE) by GKA [Ref. 13]. The resultant document contains a review of key accident sequences and phenomena and recommended approaches for treating phenomenological uncertainties in IPEs. Use of the latter document was endorsed by the U.S. Nuclear Regulatory Commission (NRC) as part of the Brookhaven National Laboratory review of MAAP3B's applicability for IPEs.

The American Society of Mechanical Engineers (ASME) has issued a standard that contains requirements for PRAs that are used to support risk-informed decisions and prescribes a method for applying the requirements for specific applications [Ref. 9]. In addition, the NRC has issued Regulatory Guide (RG) 1.200 [Ref. 10]. It provides guidance on determining the technical adequacy of a PRA and endorses the ASME standard and method with limited exceptions and clarifications. The App Guide contains suggestions on how the individual elements of the standard and the regulatory guide that apply to MAAP4 are satisfied.

The information in the App Guide was primarily assembled from extensive experience using the MAAP4 code, from the MAAP3B thermal-hydraulic qualification studies and sensitivity guidance discussed above, from the MAAP4 User's Manual, and from the results of exploratory calculations performed with MAAP4. The App Guide was authored by ERIN Engineering and Research, Inc. (ERIN), with significant contributions from Fauske & Associates, LLC (FAI), the Electric Power Research Institute (EPRI), and Erigo Technologies. It was reviewed by a peer review team that included Dr. Robert Hammersley and Dr. Chan Paik of FAI, Mr. Ken Canavan and Dr. Frank Rahn of EPRI, Dr. Marc Kenton of Erigo Technologies, and Mr. Jeff Gabor of ERIN Engineering.

Section 2: Purpose of this Document

In the aftermath of the Fukushima accident, improvements have been made to virtually all plants, both voluntarily and as a result of regulatory actions. In many countries, plant enhancements were undertaken to address the findings of "stress tests.". In the United States, the Nuclear Regulatory Commission (NRC) issued Commission Order EA-12-049, Mitigation Strategies for Beyond-Design-Basis External Events, on March 12, 2012. This order required that the US nuclear industry develop strategies to mitigate an extended loss of AC power (ELAP) event with a simultaneous loss of the ultimate heat sink. The majority of submittals describing actions taken in light of this order identified the use of the MAAP code to estimate the accident progression timing and the primary system and containment thermal hydraulic response. Overall, these analyses involved analyses of straightforward mass and energy transport phenomenon, clearly within the capabilities of the MAAP code. The primary objective of this document is to provide a clear technical justification for the use of MAAP for applications of this type.

In particular, this document addresses the following general issues:

- Describe the quality assurance process under which the MAAP analysis was performed
- Demonstrate the capability of MAAP to support types of analyses needed to evaluate the capabilities of plant enhancements made as a response to the Fukushima accident

The following sections have been developed to summarize the detailed information contained in the App Guide.

Section 3: Introduction to MAAP4

Section 4: Assuring Quality of MAAP4 Analyses

Section 5: MAAP4 Benchmarks

Section 3: Introduction to MAAP4

The Modular Accident Analysis Program version 4 (MAAP4) is a computer code that simulates the response of light water reactor (LWR) power plants during severe accidents. Given a set of initiating events and operator actions, MAAP4 predicts the plant's response as the accident progresses. The code is used to

- predict the timing of key events (e.g., core uncovery, core damage, core relocation to the lower plenum, vessel failure)
- evaluate the influence of safety systems, including the impact of the timing of their operation
- evaluate the impact of operator actions
- predict the magnitude and timing of fission product releases
- investigate uncertainties in severe accident phenomena

MAAP4 results are primarily used to determine probabilistic risk assessment (PRA) Level 1 (events and phenomena that occur prior to the onset of core damage) and Level 2 (events and phenomena that occur after the onset of core damage) success criteria and accident timing to support human reliability analyses. Results are also used for equipment qualification applications, the determination of the large early release frequencies (LERF) of fission products, integrated leak rate test evaluations, emergency planning and training, simulator verification, analyses to support plant modifications, generic plant issue assessments (e.g., significance determination), and other similar applications. The ELAP evaluations in support of Order EA-12-049 are nearly identical to PRA Level 1 success criteria in human reliability analyses.

MAAP4 is an integral code. It treats the full spectrum of important phenomena that could occur during an accident, simultaneously modeling those that relate to the thermal-hydraulics and to the fission products. It also simultaneously models the primary system and the containment and the reactor/auxiliary building.

3.1 MAAP Development History and the MAAP Users Group

MAAP was originally developed for the Industry Degraded Core Rulemaking (IDCOR) program in the early 1980s by Fauske & Associates, LLC (FAI). At the completion of IDCOR, ownership of MAAP was transferred to the Electric Power Research Institute (EPRI), which was charged with maintaining and improving the code. Starting in the late 1980s, the MAAP3B version became widely used, first in the United States and then worldwide, to support success criteria determination, human action timing evaluations, and Level 2 analyses for Individual Plant Examinations (IPEs). IPEs were used to identify plant vulnerabilities and to facilitate an increased understanding of severe accident phenomena. Hence, the code has been applied to numerous containment designs and sequences for over thirty years.

The code was updated to version MAAP4 in the mid 1990s. The revision extended MAAP's capabilities for accident management evaluations, primarily via refined core and lower plenum models. Other improvements included a generalized node and junction containment model and models that represent unique features of advanced LWRs. As part of the development process, MAAP4 was reviewed by a committee of independent experts to ensure that it is state-of-the-art and applicable for accident management evaluations. The development of MAAP4 was sponsored by several organizations including EPRI and the U.S. Department of Energy. EPRI licenses MAAP4 to utilities, vendors, research organizations, and universities.

The majority of MAAP users are members of the MAAP Users Group (MUG). The MUG provides direction and funding for code maintenance, enhancement, and benchmarking; facilitates information transfer through annual meetings and the issuance of various communications on code problems and best practices; and supports industry and regulatory acceptance. As of June 2013, the MUG membership consists of approximately sixty organizations from fifteen countries.

The code has been developed and is maintained under a quality assurance program, which is in compliance with U.S. 10CFR50 Appendix B and ISO-9001 quality assurance requirements.

3.2 Phenomena Modeled in MAAP4

MAAP treats the spectrum of physical processes that could occur during an accident. Level 1 (prior to the onset of core damage) phenomena include

- gas and water flow
- natural circulation
- steam evaporation and condensation
- boiling
- critical flow
- conduction, convection and radiation heat transfer
- counter-current flow

Level 2 (following onset of core damage) phenomena include

- cladding oxidation and hydrogen evolution
- core material eutectic formation
- core relocation

- lower head–core debris dynamics
- failure of vessel penetrations and/or the lower head
- debris entrainment
- debris-concrete interactions
- ignition of combustible gases
- pH and iodine chemistry in containment
- fission product release, transport, and deposition

The following sections, extracted from the App Guide, describe the MAAP4 models that relate to accident progression leading to the onset of core damage. Detailed information about the models is contained in the corresponding subroutine descriptions in the MAAP4 User's Manual [Ref. 11].

3.2.1 Primary System Thermal-Hydraulics

3.2.1.1 BWR Primary System Thermal-Hydraulics

The BWR primary system model calculates the thermal-hydraulic conditions in the reactor pressure vessel. It tracks the mass and energy of water pools in the downcomer (including the water inside jet pumps and in the recirculation loops), in the core (including the water above the active core extending into the standpipes, separators, and upper plenum), in the control rod drive (CRD) tubes, and in the lower plenum. The remaining free volume constitutes a single gas space. The gas pressure is imposed on the water pools, and the individual water masses and energies are then used to determine the temperature of each pool. MAAP4 also tracks the two-phase mixture volume in each water region. The gas space is divided into eight nodes for heat transfer and gas flow calculations. Eleven primary system heat sinks are modeled, each as a two-dimensional slab.

The thermal-hydraulic model calculates water transport, gas transport, steaming and condensation, and heat transfer to the structures that interface with the containment. The code calculates the influx of feedwater and CRD flow, as well as flow from emergency core cooling systems (high pressure coolant injection (HPCI), reactor core isolation cooling (RCIC), core sprays, low pressure coolant injection (LPCI) and external water sources). The code calculates water and gas flow from the primary system through the main steam line, safety relief valves (SRVs), breaks, and other user-specified openings. In addition, the code models heat removal via shutdown cooling and reactor water cleanup systems. It also contains plant-specific models for injection and heat removal systems for Swedish plants. Figure 3-1 provides the general nodalization for the BWR reactor vessel.

Flows through openings in the BWR reactor pressure vessel are strongly coupled to the primary system pressure. Also, internal water circulation flows may undergo rapid transients. The MAAP4 primary system calculations incorporate an anticipatory flow model that uses local time steps to capture the fluid dynamics. This model contains a coupled set of pressure-flow equations that are integrated analytically over the larger code time step to obtain realistic average flow rates. The model can handle rapid transients and tracks the dynamics of the subcooled region and two-phase mixture volume in the core. The use of a local time step allows more precise calculations of events, e.g., the opening of safety relief valves (SRVs) based on pressure set points. The water and two-phase flow rates are dependent on calculated temperature, density, pressure, and hydrostatic head differences. A quasi-steady momentum balance (momentum equation) around the reactor coolant system loop is used to calculate natural circulation flow rates. Break flow rates are calculated with either the Bernoulli equation, which is a form of the momentum equation, or with a critical flow model.

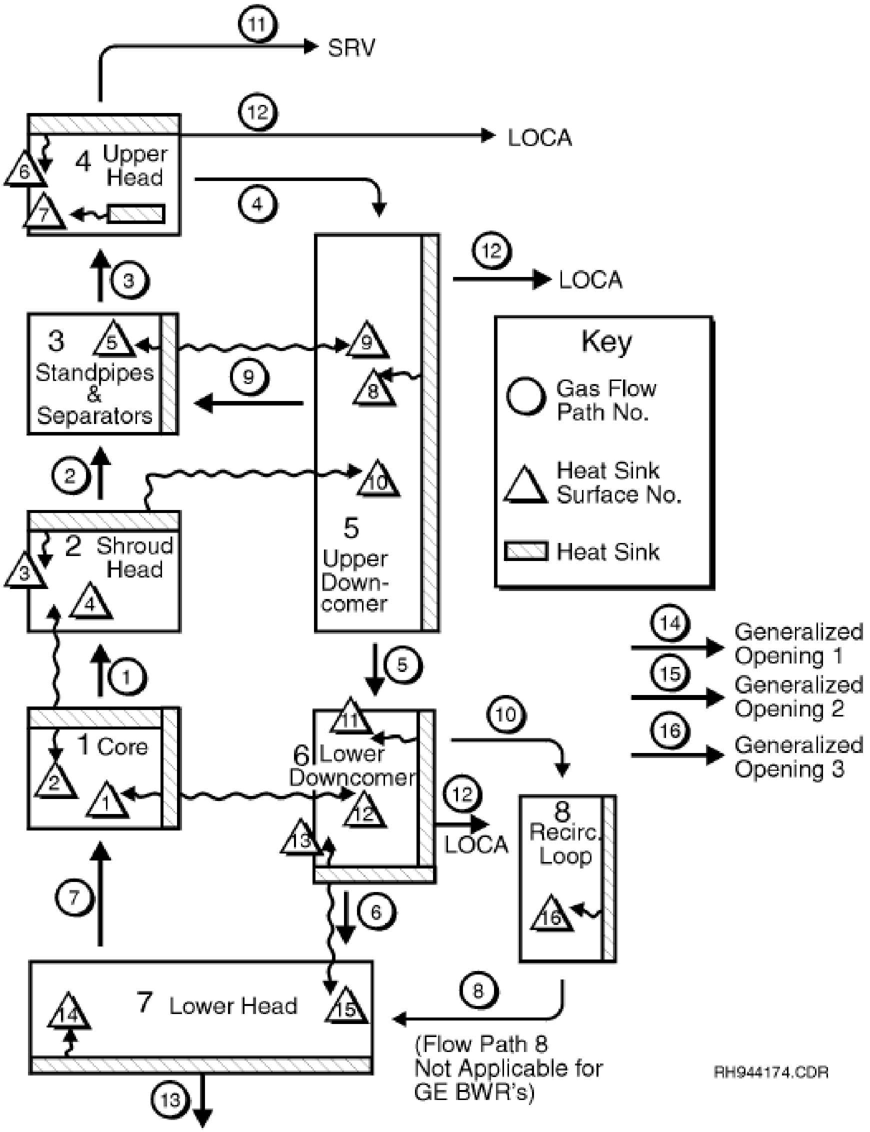

Figure 3-1
BWR Reactor Vessel Nodalization

3.2.1.2 PWR Primary System Thermal-Hydraulics

The pressurized water reactor (PWR) primary system model calculates the thermal-hydraulic conditions in the reactor pressure vessel, the hot legs, the cold legs, and the primary side of the steam generators (SGs). (The pressurizer is treated in a separate model.) The primary system is divided into two loops, the "broken" loop and the "unbroken" loop. The user specifies how many actual loops are in each loop in the model and which loop contains the surge line to the pressurizer. (The terms "broken" and "unbroken" are misnomers in that breaks can be modeled in either or both of the loops: they are carryovers from earlier, more restrictive versions of the code.)

There are fourteen gas nodes in the model: the core, upper plenum, broken and unbroken hot legs, broken and unbroken hot and cold leg tubes for U-tube steam generators, broken and unbroken candy cane and tubes for once-through steam generators (OTSGs), broken and unbroken cross-over (intermediate) legs, broken and unbroken cold legs, downcomer, and reactor dome. There are six water pools: the core, broken and unbroken cold leg tubes, broken and unbroken cross-over legs, and downcomer. In addition, there are nineteen primary system structural heat sinks, which are modeled as two-dimensional slabs. Because the number of gas volumes is larger than the number of water pools, a pool can occupy several gas volumes.

When steam first forms in the reactor coolant loops during a MAAP4 calculation, the two phases are assumed to be homogeneously mixed. If the reactor coolant pumps are operating, water flow rates between the primary system pools are adjusted so that the individual void fractions match the system average void fraction; and energy is transferred between the pools so that the water and gas are all at a uniform temperature and pressure. The same treatment is used if the internal gas velocities are sufficiently high to cause water entrainment, as occurs during the early phase of a large break, loss-of-coolant accident (LOCA).

Once the pumps have stopped running and the void fraction is less than a user-specified criterion for phase separation, the same well-mixed treatment is used to very simply model natural circulation. Because the PWR thermal-hydraulic model does not explicitly account for conservation of momentum, which would require a substantially more complex model, it does not calculate natural circulation flow rates. Hence, during this phase the heat transfer from the primary system to the steam generators is based on a user-supplied heat transfer coefficient.

When the void fraction exceeds the user-specified criterion for phase separation, the gas and water pools are no longer assumed to be intimately mixed and are treated separately in a gas-over-water configuration. For these conditions, the gas in each node can have a unique temperature, distinct from the pool temperature. When the water level is above the elevation of the reactor pressure vessel (RPV) inlet and outlet nozzles, it is assumed that there is enough water in the primary system to permit free communication between the core, intermediate leg, and downcomer pools, with a common collapsed water level. As the water level continues to drop, the pools are uncoupled and water spills from one pool to another.

The thermal-hydraulic model calculates water transport, gas transport, steaming, and heat transfer to the structures that interface with the secondary side and the containment. Condensation is modeled in certain circumstances: steam can condense on cold emergency core cooling system (ECCS) water injected into the cold leg and onto the inside surface of steam generator tubes if the secondary side still contains water. Once the accident progresses to core uncovery, the level of detail in the calculations increases and the modeling includes such phenomena as natural circulation of superheated gases in the vessel and in the hot leg (counter-current flow). Figure 3-2 provides the general nodalization for the PWR primary system with water pools as designated in Table 3-1.

At each time step, the code calculates the influx of water through makeup flow; accumulator flow; and high pressure, low pressure, and charging pump injection systems, as appropriate. It also calculates water and gas flow from the primary system through breaks, steam generator tube ruptures (SGTRs), and other user-specified openings, as well as fluid transport between the primary system and the pressurizer via the surge line. The code contains plant-specific injection system models for Spanish plants. It also contains models for the core makeup tanks and the passive residual heat removal system that are part of the AP600 advanced light water reactor (ALWR) design.

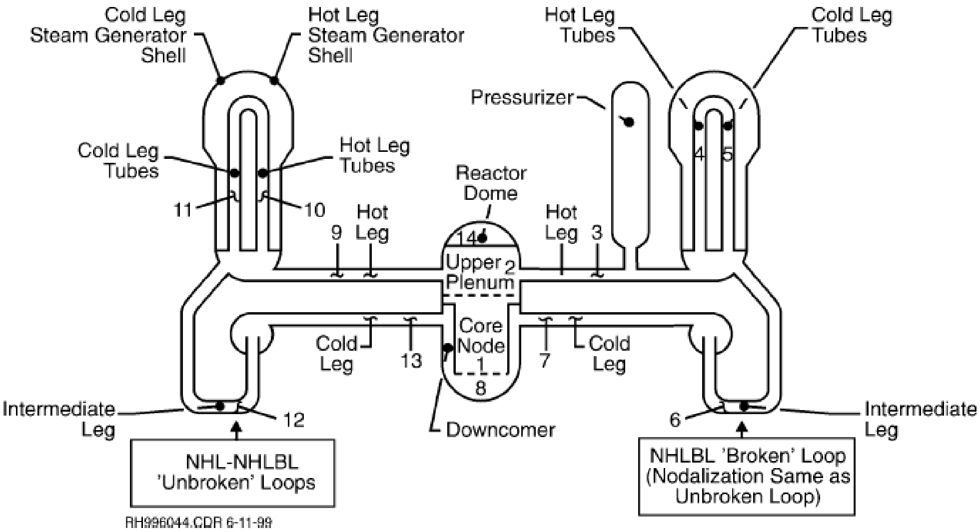

Figure 3-2
PWR Primary System Nodalization

Table 3-1
PWR Water Pool Node Designation

Water Pool Nodalization.	
Water Pool Name	**Water Pool Description**
Core (1,2,3,4,9,10,14*)	Water volume inside the core barrel starting at the bottom of the core barrel and extending to the top of the U-tube in both the broken and unbroken loops. Thus, the single core node extends into both loops.
Broken Tubes (5)	Code side of the steam generator tubes in the broken loop. This node starts at the top of the U-tube and continues down to the bottom of the tube sheet near the steam generator outlet, but does not include the steam generator outlet plenum.
Broken Intermediate Leg (6)	Includes the steam generator outlet plenum and continues along the pipe up to the horizontal portion of the cold leg. This also includes the volume of the pump bowls since MAAP uses the intermediate leg water mass in determining whether or not the pump bowls are cleared.
Downcomer (7,8,13)	This includes the traditional downcomer volume plus the volume of the RPV lower head and the cold leg nozzle and pipe volumes out to the reactor coolant pump discharge in the broken and unbroken loops. Thus, the single downcomer node extends into both loops.
Unbroken Intermediate Leg (12)	Same as the Broken Intermediate Leg definition, but in the unbroken loop.
Unbroken Tubes (11)	Same as the Broken Tubes definition, but in the unbroken loop.
*Numbers indicate the gas nodes from Figure 3-2	

3.3 Computational Structure and Design Philosophy of MAAP4

The MAAP4 code is written primarily in Fortran 77 and can be run on a variety of computer platforms, most commonly PCs. The format of the input and output files is tailored to plant engineers. Users can control phenomena through flags and uncertainty parameters. The calculations are done in SI units; users have the option of specifying that the input and/or output quantities be in either SI or British units.

The code is modular, consisting of several hundred subroutines and functions, which fall into four categories. The high level routines include the main program, input and output routines, data storage and retrieval routines, and numerical integration routines. The system and region routines set the flags that define the status of the various systems and contain the differential equations for the conservation of the state variables, principally the masses and energies of the constituents in the individual volumes. The phenomenological routines contain the equations for determining the rates-of-change of the state variables within and between the individual volumes; these routines are the core of the code. The property and utility routines generate physical properties and perform mathematical operations. There is an overlying parallel structure between the thermal-hydraulic routines and the fission product routines in the code architecture.

The equations in MAAP4 are essentially lumped parameter, non-linear, ordinary differential equations in time. The overall calculation scheme proceeds as follows. First, quantities such as pressure and temperature are calculated given the current values of the state variables (e.g., masses and internal energies). Next, the rates-of-change of the state variables are determined by summing the contributions of each modeled phenomenon. Then, new values of the state variables are obtained by integrating their rates-of-change using a prospective time step. Finally, the fractional changes of key state variables are assessed; if any exceed input criteria the time step is reduced and the integration calculations are repeated. The last step is performed because some rates-of-change, i.e., those that are based on assumed quasi-steady behavior, depend explicitly on the time step.

The models in MAAP4 have been designed so that the code is fast running. This is a hallmark of MAAP. The primary means of achieving this objective are the use of quasi-steady modeling wherever appropriate, relatively coarse nodalization, and the largest possible time step consistent with the level of detail desired. Smaller values of the time step are used when key quantities are rapidly changing, and larger values are used when conditions are relatively stable. The code also uses smaller time steps in some of the localized primary system thermal-hydraulic calculations, eliminating the need for the bulk of the calculations to be run with the smaller time steps. Other features that contribute to the code’s speed are the use of tabularized results and correlations from other computations rather than the incorporation of specific detailed calculations and non-uniform levels of nodalization that reflect the magnitudes of the potential gradients. The result is that the code execution time is generally several orders of magnitude faster than problem time on a typical personal computer (PC) and considerably faster than most comparable codes.

In addition to running the full code, MAAP4 can be run in a dynamic benchmarking mode in which only selected phenomenological models are exercised. This allows the actual MAAP4 routines to be used for testing and benchmarking comparisons without creating separate executables. The data and facility descriptions for some of the key benchmarks are included in the coding to facilitate user verification of the models.

3.4 MAAP4 Documentation

The MAAP4 code is documented in the MAAP4 User's Manual [Ref. 11], the Users Guide with its six sample parameter files, and the MAAP 4.0.6 Transmittal Document [Ref. 14]. The App Guide is intended to be used in conjunction with the other documentation.

The MAAP User's Manual contains detailed information on how to prepare input files and execute the code and detailed descriptions of the models in the code, including descriptions of the individual subroutines and functions. Components of the manual have been updated in conjunction with updates to the code. The manual is divided into four volumes:

Vol. I User Guidance

- code installation and operation
- input and output files

Vol. II Code Structure and Theory

- summary of models
- subroutine and function descriptions

Vol. III Benchmarking

- key benchmarks
- plant benchmarks
- integral experiment benchmarks
- separate effects benchmarks

Vol. IV Optional Features

- MAAP4-GRAAPH graphical interface
- MAAP4-DOSE code for radiological calculations

The User’s Guides contain detailed descriptions and default values and ranges of the input parameters included in the parameter file. There are BWR guides for Mark I, Mark II, and Mark III containments and PWR guides for Westinghouse Large Dry and Ice Condenser plants with U-tube steam generators and Babcock and Wilcox (B&W) plants with OTSGs. The guides are essentially sample parameter files and can be used as templates for plant-specific parameter files. They are distributed electronically.

A transmittal document accompanies each revision of the code. It contains information on code installation and execution, summaries of the changes made to the code since the previous revision, and discussions of the impact of the changes on the code results. The transmittal document is distributed electronically.

Section 4: Assuring Quality of MAAP4 Analyses

One of the purposes of the App Guide is to provide guidance on assuring the quality of MAAP4 analyses. The guidance addresses the following:

- testing of a parameter file
- planning and creating sequence input files
- confirmation of successful code execution
- control of files and documentation of runs
- review of results
- training and certification of code users

A summary of the requirements of the ASME standard for PRA applications [Ref. 9] and the corresponding NRC regulatory positions on those requirements from Regulatory Guide 1.200 [Ref. 10] that directly relate to MAAP4 analysis is included in the App Guide.

The App Guide also is intended to suggest "best practices" for using the code. Alternate approaches are acceptable provided that they meet the ASME standard or other controlling requirements.

4.1 Verification of Installation, Comparison of Results

The code distribution CD contains sample input and two sets of corresponding output files that were generated on PCs with a Windows XP operating system and a Windows 2000 operating system. Correct installation of the code can be verified by comparing the results generated on the computer for the sample problems with those on the distribution CD. The code is installed correctly if the user-generated results agree digit-for-digit with those on the CD. It is sufficient to compare the figures-of-merit that are written to the end of the log file and the values in a single plot file. If the values in these two sets of files match then the results in the other files will match as well. It is suggested that a large LOCA (low pressure) sample sequence and a station blackout (high pressure) sample sequence be used to verify installation because this will ensure that most of the subroutines are being utilized. The sample sequences are listed in the next section.

For an alternate computer and operating system, the code is installed correctly if the figures-of-merit at the end of the user-generated log file agree with those in the log file on the CD for a given sample sequence within the following tolerances:

- The timing of key events (e.g., core uncovery, core relocation, vessel failure) agrees within approximately 5%.
- The dominant masses of UO_2, CsI, and SrO agree within approximately 10%
- The fraction of cladding reacted in-vessel agrees within approximately 5%. This should be calculated as an absolute difference because, as fractions, the values are already normalized. (That is, the percent agreement is the difference between two values of the fraction reacted, multiplied by 100. The difference should not be divided by one of the values to obtain a relative value.)

If there is any difficulty with the verification of the installation the user should contact the code maintenance contractor for further information and instructions. In particular, if the results are outside the noted tolerances, the contractor can assist the user in evaluating the results to determine if the differences represent a problem with installation or if they are due to acceptable variations in the sequences.

It is recommended that the verification of the code installation be documented. Elements of the documentation should include:

- the version of the code and other identifying information such as the number of the distribution CD
- the name of the individual performing the installation test, and the location and date
- identifying information about the computer, including the operating system
- identifying information about the executable, including how it was created if it was not distributed with the code
- names of the input and parameter files
- acceptance criteria (either digit-for-digit or tolerances noted above, depending on the platform)
- test results, i.e., figures-of-merit from the generated output and the sample output
- conclusions
- review and acceptance information
- other items required by an organization’s quality assurance program

Users frequently need to compare results from sequences in which the input was modified or from sequences that were run on different operating systems. Differences in results are considered to be essentially insignificant if the differences in the figures of merit in the log file fall within the tolerances listed above. For Level 1 sequences, other results need to be compared because the figures of merit are primarily related to post core-damage events and debris and fission product distributions. Key quantities for Level 1 sequence comparisons are primary system pressure, primary system water level and temperature, pressurizer level and pressure, the hottest core node temperature, steam generator pressure, and containment pressure. Differences less than 5% are considered within the code's tolerance. Differences greater than 5% do not necessarily reflect significant differences; the trends of the sequences should be compared to determine the implications of the differences. Events such as the actuation of automatic pressure relief and injection systems should be examined as part of this evaluation.

4.2 Testing of Parameter Files

After the parameter file (i.e., the plant-specific model) has been created, it should be tested before it is used for plant sequences. There are several recommended steps in this process:

1. Do a preliminary "shakedown" with a steady-state (null transient) sequence.
2. Perform a visual review of the input lines (vs. the comment lines).
3. Test the file with several standard sequences to validate its overall performance.
4. Test any user-defined events that are included in the parameter file.

Users are encouraged to perform each step so that they will have confidence in the values in their parameter files and hence in the results of their accident sequences.

4.2.1 Preliminary Testing with a Steady-State Sequence

Testing the parameter file with a steady-state sequence is used to accomplish the following tasks:

1. Check that the lines in the file can be read by the code (screen for typographical errors, hidden formatting characters, etc.).
2. Do a preliminary assessment of the initialization phase of a calculation and make adjustments to parameter values.
3. Check that the parameter values are self-consistent.

4.2.2 Perform a Visual Review of the Parameter File Input Lines

The parameter file contains substantially more comment lines than lines actually processed by the code. A useful step in validating the entries in a file is to strip out the comment lines and then visually inspect the remaining lines. Without the comment lines it is easier to read the data lines and hence detect typographical errors, unit mismatches, etc.

4.2.3 Test the Parameter File with Standard Sequences

It is recommended that the parameter file be tested with three standard sequences to validate the file's overall performance: a station blackout, a small LOCA, and a large LOCA. The code distribution CD contains input and output for the sequences listed in Table 4-1. The input files for testing can be constructed using these sequences as a guide. They have varying degrees of complexity, which make them useful examples.

Table 4-1
Standard Sample Sequences

Code	Parameter File Containment Type	Input File	Type of Sequence
BWR	Mark I	SBO1A1	Loss of AC and DC power
	Mark I	SLOCA1	Small LOCA, no injection
	Mark I	LLOCA1	Large LOCA, no low pressure injection
	Mark II	SBO1A2	Loss of AC and DC power, no injection
	Mark II	SLOCA2	Small LOCA, no injection
	Mark III	SBO1A1	Loss of AC and DC power, no injection
PWR	WLD	TMLB	Loss of AC power, seal LOCAs
	WLD	S2HF	Small LOCA
	WLD	AHF	Large LOCA
	B&W	TMI19F	Small LOCA, no injection
	WICE	CRA1AI	Large LOCA, no injection

The user should begin by running each sequence, solving any problems with the input and/or parameter file until the sequences run to completion. Then the results should be compared with the corresponding results from the sample sequences. For the two BWR and two PWR sample parameter files for which there is not a full complement of sample output, the user can create corresponding sequences and run them with the sample parameter files. The comparison consists of looking at the trends of the sequences as indicated by the key events and debris and fission product distributions in the figures-of-merit tables, system actuations as indicated by events in the summary files, and primary system and containment conditions shown in the plottable results. The mass and energy balances and the diagnostic message counts should also be checked, and any warning messages in the log files should be evaluated. Major differences between the test and sample sequences should be investigated. The differences may be due to plant features, e.g., different battery depletion times for BWR turbine-driven injection systems. Other types of differences may indicate to the user areas in which their parameter file values could be refined.

4.3 Preparation of Input Files and Confirmation of Successful Execution

The guidance provided in the MAAP4 Users Manual and in the App Guide addresses the construction and testing of input files and the review of code results. The recommendations are geared to the generation of high quality analysis so that the results can be used with confidence.

4.3.1 Creating High Quality Input Files

Once the parameter file has been successfully tested, the input files for plant-specific transient sequences can be created. This involves three steps for each sequence:

1. Defining the sequence
2. Constructing the input file
3. Testing the input file

4.3.2 Confirmation of Successful Execution

After the code has run to completion, the analyst should review the output to verify that the sequence ran successfully, i.e., that the code interpreted the input file as intended, that the masses and energies balance, that there are relatively few diagnostic messages, and that the results are physically reasonable. It is recommended that the analyst always critically review the output and not assume that a "well-behaved" sequence, one with few diagnostics and non-fluctuating plot results, executed as intended.

When reviewing the results of a sequence the user should keep in mind the order of code execution:

- the parameter file and local parameter changes in the input file are read.
- conditions are initialized.
- initiators are processed.
- in a loop
    - conditions are evaluated and subsequent actions are taken.
    - properties are calculated based on the values of the state variables (masses, energies).
    - rates of change of the state variables are calculated.
    - values of the state variables are updated by integration.

4.4 Control of Files, Documentation of Sequences, Review of Analysis

4.4.1 Control of Input and Output Files

MAAP4 input and output files should be controlled so that they are identifiable, accessible, and protected. This control facilitates the review process, makes the information available for inclusion in applications, and allows the results to be reproduced. The particular method for controlling the files should be consistent with an organization's individual procedures.

4.4.2 Documentation of Analysis

The documentation of MAAP4 analyses should convey sufficient information so that an analyst could reproduce the results and so that the intent and outcome of the sequences and how the results were extracted and used to draw conclusions is clear to analysts and end users. The documentation is also part of the basis for reviewing the analysis. The final documentation for an analysis effort should be prepared and stored in a manner consistent with the organization's procedures.

The following are recommended elements of the documentation of MAAP4 analyses:

- The text of the documentation should explain the overall purpose of the analysis. There should be identifying information as to the individuals who performed, reviewed and approved the analysis, and the date(s) of the effort.
- The parameter files, the version of the code, the choice of executable and the computer operating system should be clearly identified.
- The input files that were used should be clearly identified. The written intent of the sequences should be included. It is also useful to include a copy of each input file.
- It should be clear from the documentation what could have happened in a sequence versus what did happen. For example, it is important to distinguish between a situation in which an injection system was not available versus one in which the injection system was available but was not initiated because set points were not reached. Similarly, if a system could have initiated by more than one trigger, then the trigger that actually caused the system to actuate should be recorded. The end time of the sequence should be recorded so that if something did not happen, such as core uncovery, it is understood in the context of the time frame that was simulated.
- Key assumptions made for the analyses should be documented and justifications for the assumptions should be provided. The sources of information should be clearly referenced and be retrievable.
- The summaries and conclusions in the documentation should address the impact of uncertainties and the sensitivities that were evaluated.

4.4.3 Review of Analysis

MAAP4 analyses should be independently reviewed prior to using the results in plant applications. The review should be performed by a qualified MAAP4 analyst. It is preferable that the reviewer be someone that was not involved with the analysis effort, although this is often not possible because of the relatively few individuals who have MAAP4 expertise within a typical organization. Efforts should be taken to maintain the independence of the reviewer as much as is practical.

4.5 Training and Certification of MAAP4 Analysts and Communications with End Users

To assure the quality of MAAP4 analyses, individuals who create input and parameter files, execute the code and extract results, and review the analyses should be trained so that they can correctly use the code and understand its capabilities and limitations. It is recommended that these users demonstrate this knowledge to become certified MAAP4 analysts under an organization's engineering certification program.

4.5.1 Training and Certification of MAAP4 Analysts

It is recommended that MAAP4 training be adequate to assure that the analyst

- understands the overall purpose and structure of MAAP4
- can create input files that will lead to accurate sequence simulations
- understands the process involved in creating a parameter file that represents a specific plant and can participate in the creation of a file
- is able to update a parameter file to a new revision using sample parameter files
- understands the content of a parameter file and how it relates to input file preparation
- understands the basic phenomena that are modeled in the code and knows where to find detailed information about the models
- can verify installation and execute the code
- can determine if a sequence has executed without numerical difficulties
- understands the output and can accurately extract results
- is cognizant of the parameters that represent phenomenological uncertainty and knows when it is appropriate to perform sensitivity analyses
- is cognizant of the impact of thresholds such as vessel and containment failure criteria on the results
- understands the code's limitations and the means for addressing these limitations
- is cognizant of the MAAP4 documentation

- is cognizant of the MUG, the MAAP4 website, and code maintenance activities

Training can be accomplished either through formal means such as participation in an EPRI training course conducted by a code contractor or other expert party, or by informal exercising of the code, usually under the supervision of a more experienced user. The training should involve "hands-on" components such as the creation and testing of input files and more theoretical components such as a review of the code's primary system modeling.

As part of a MAAP4 analyst certification process, the trainee should be able to demonstrate competency in the areas listed above. It is recommended that this be done to the satisfaction of a MAAP4 mentor. Ideally, the mentor should be an individual who has significant experience using the code and a solid understanding of the types of phenomena that are modeled. A mentor can be an employee in the same organization as the trainee or from an outside organization, such as a contractor.

4.6 ASME PRA Requirements

The ASME Standard for the Probabilistic Risk Assessment for Nuclear Power Plant Applications [Ref. 9] sets forth requirements for PRAs used to support risk-informed decisions for current commercial light water reactor plants and prescribes a method for applying these requirements for specific applications. It establishes requirements for a Level 1 analysis of internal events while at power and for a limited Level 2 analysis sufficient to evaluate the large early release frequency (LERF) for internal events while at power. In addition, the U.S. NRC has issued Regulatory Guide 1.200 for trial use [Ref. 10]. It provides guidance on determining the technical adequacy of a PRA and endorses the ASME standard and method with limited exceptions and clarifications.

The requirements in the ASME standard are organized into the following nine technical elements:

- Element 1 – Initiating Events Analysis (IE)
- Element 2 - Accident Sequence Analysis (AS)
- Element 3 - Success Criteria (SC)
- Element 4 - Systems Analysis (SY)
- Element 5 - Human Reliability Analysis (HR)
- Element 6 - Data Analysis (DA)
- Element 7 - Internal Flooding (IF)
- Element 8 - Quantification (QU)
- Element 9 - LERF Analysis (LE)

The standard lists objectives and a set of minimum high level requirements (HLRs) for each element. It also lists supporting requirements (SRs) to meet each HLR. Each SR may be subdivided into three capability categories: the higher the category the more rigorous the requirement in terms of the scope, level of detail, plant-specificity, and realism.

One purpose of the App Guide is to provide guidance on the use of MAAP4 such that, if followed, the analysis that is used for PRA applications will meet the ASME requirements. To achieve this objective each HLR was reviewed to determine if it is directly applicable to MAAP4 analysis. For each applicable HLR, the corresponding SRs were then reviewed for applicability.

Applicable requirements were identified for five of the nine technical elements: those that relate to accident sequence analysis, success criteria, human reliability analysis, quantification, and LERF analysis. The resulting lists of high level and supporting requirements that directly relate to MAAP4 analysis are presented in Appendix F of the App Guide. For those SRs that differ as a function of capability category, the entries are for categories II and III. Included in the lists are the corresponding NRC staff positions for the identified requirements as they appear in RG 1.200.

The assembled lists of applicable requirements were then examined, and five common elements were identified. These are listed in Table 4-2. The sections of this document that directly relate to these requirements are included in the table. It is to be noted that the selection of applicable requirements is somewhat subjective because the standard is structured according to the elements of a PRA and was not intended to correspond directly to the analysis tools. This does not affect the guidance in this document.

4.7 Summary of MAAP4 Quality

As described in the subsections above, proper installation, testing, and use of the MAAP code are clearly outlined in App Guide. Individual utilities have flexibility to integrate these recommendations into their existing engineering quality programs to assure that MAAP analyses are properly performed and documented.

Table 4-2
ASME Requirements that Apply to MAAP4 Analysis and Related Guidance

Category	Requirements (refer to App. F)	Essential Elements	Related Sections of App Guide
Adequacy of code	AS-A9 SC-B1, SC-B4 HR-G4 LE-B2 , LE-C1	Developed, validated, and verified in sufficient detail to analyze the phenomena of interest	2.1, 2.2
		Capable of modeling systems and sequences of interest	2.2
		Applicable for range of conditions	2.2
		Quality assured	2.1, 3.1, 3.4
		Matched with appropriate experimental data	7, 8
Performance of Analysis	AS-A9 SC-B1, SC-B3, SC-B4, SC-B5 HR-G4 LE-A1, LE-A2, LE-B2, LE-C1, LE-C3, LE-C4, LE-C10, LE-D5, LE-E2	Realistic, plant-specific models	3.1, 3.2, 3.3, 3.4
		Plant-specific scenarios	3.1, 3.2, 3.3
		Account for system responses, operator actions	3.2, 3.3
		Use a well-defined, self-consistent process	3.2, 3.3, 3.4
		Use only within known limits of applicability	5, 6, App. A
		Consistent level of detail with initiating events	5, 6
		Model plant characteristics and sequences that influence LERF	3.2, 5, 6
		Check reasonableness and acceptability of results	3.1, 3.2, 3.3
Uncertainties and Sensitivities	QU-E1, QU-E2, QU-E4 LE-D5	Identify key sources of uncertainty, key assumptions	4, 5, 6, 7, 8
		Evaluate impact of uncertainties on results	4, 5, 6, 7, 8
		Evaluate sensitivity of results to uncertainty; individually and in logical combinations	4, 5, 6, 7, 8
Documentation of analysis	AS-C1, AS-C2, AS-C3 SC-C1, SC-C2, SC-C3 HR-I1, HR-I2, HR-I3 QU-F4 LE-G1, LE-G2, LE-G4	Document in a manner that facilitates PRA applications, upgrades, peer review	3.4
		Document processes, input, method, results	3.4
		Document key assumptions and key sources of uncertainty	3.4, 4
		Document references	3.4
Qualifications of analysts	AS-A9 SC-B1, SC-B4 HR-G4 LE-B2	Code utilized by qualified, trained users	2.1, 3.5
		Understand code and its limitations	3.5, 5, 6, App. A

Section 5: MAAP Benchmarks

The MAAP4 code has been extensively benchmarked, and information about the benchmarks has been presented and published in a variety of forums. To facilitate an assessment of the abilities of the code to model Level 1 phenomena based on the results of the benchmarks, the documentation of relevant benchmarks was collected and reviewed by a team of MAAP4 experts. The benchmarks were gathered from the MAAP4 User's Manual, technical journals, conference proceedings, MUG meeting presentations, and technical reports. More than 30 benchmarks were collected; they fall into the following categories:

- Comparisons to plant events (PE entries)
- Comparisons to integral codes (IC entries)
- Comparisons to integral experiments (IE entries)
- Comparisons to separate effects experiments (SE entries)

5.1 Method for the Review of the MAAP Benchmarks

The team of experts—each member having extensive experience with the development and application of MAAP3B and MAAP4 as well as extensive knowledge of severe accident phenomena and plant response—reviewed the individual benchmarks in two stages. The first stage consisted of a preliminary review of the documentation of each benchmark to determine if 1) it contains adequate information on the method and results so that conclusions could be drawn and 2) the code was used in an appropriate manner (for example, not in a regime determined to be outside the range of applicability. The major code models—primary system thermal hydraulics, steam generator thermal hydraulics, core heat-up, and containment thermal response—evaluated by each benchmark were identified. Similarly, significant code capabilities validated by each benchmark were identified. These include critical flow through valves and breaks, ECCS injection, condenser heat transfer, voiding in the core, and hot leg natural circulation (HLNC).

The second stage consisted of an in-depth review of each of the benchmarks that met the preliminary criteria to determine the agreement between the MAAP4 results and the corresponding data and comparative analyses. The team studied the documented information and discussed the strength of the benchmark, the specific results, the conclusions drawn by the authors, and so on. To provide a framework for the collective assessment of the code's capabilities, the review was structured to 1) rate the degree of agreement between the sets of comparative results and 2) capture pertinent information on code performance, limitations, and options for modeling particular phenomena.

The degree of agreement for the major code models is based on the following representative quantities. They were selected because of their importance to the success criteria and human reliability components of PRA analysis:

- BWR primary system thermal hydraulics: primary system pressure and water level in
  the vessel
- PWR primary system thermal hydraulics: primary system pressure, water level in the pressurizer, and water level in the vessel
- Steam generator thermal hydraulics: secondary side pressure and water level in the steam generators
- Core heat-up (generic to BWR and PWR): maximum core temperature
- Containment thermal response (generic to BWR and PWR): containment pressure

The team jointly rated the agreement for each of the major models as well as the overall degree of agreement as *very good*, *good*, *fair*, *qualitative*, or *inconclusive*. No *poor* agreements were identified. By necessity, the rating process was qualitative rather than quantitative. Consideration was given to whether the uncertainties associated with the documented sequence definitions and boundary conditions tended to be greater than those associated with the modeling approaches and phenomenological uncertainties.

The team also assessed the validation of the specific code capabilities as *validated by explicit results* or *qualitative or indirect validation*. No *inconclusive* or *negative* validations were identified.

Details about each of the benchmarks are assembled in Appendix F of the App Guide and include the following:

- Identifying information: authoring organizations, plant types (BWR, PWR, containment type, and so on), PRA levels, sequence types, time frames of the analyses, and MAAP code versions
- Agreement for major code models: elaboration and observations
- Validation of significant code capabilities: elaboration and observations
- Exemplified limitations and precautions
- Issues for further code development and user support
- Notes and recommendations for the users
- Conclusions drawn by the authors of the benchmark
- Documentation: reference citations

5.2 Benchmark Review Results

Tables 5-1 and 5-2 list the benchmarks that met the preliminary criteria of the first stage of the review process and contain the summary results from the team's in-depth review. The first table contains the degree of agreement for the major code models and the overall code. The second table contains the extent of the validation of the significant code capabilities.

Compilations of the degree of agreement for the major code models are presented in Table 5-3 and the validation of the code capabilities are presented in Tables 5-4. Compilations of the benchmarks as a function of sequence type are presented in Tables 5-5 for BWRs and 5-6 for PWRs. Because not all of the benchmarks are of the same technical caliber and because some contain multiple independent sequences while others contain variations of a base sequence, the compilations should be viewed as general rather than rigorous.

5.3 Conclusions from the Benchmark Review

Three sets of conclusions were drawn from the review of the benchmarks. First, the compilations in Tables 5-3 through 5-6 were examined to identify particular areas in which additional benchmarks would be beneficial for filling in gaps in the overall matrix of major code models, code capabilities, and sequences that are supported by benchmarks. Recommendations for additional benchmarks based on this examination of the number and level of agreement of the existing benchmarks are as follows:

- Major code models: steam generator thermal hydraulics for OTSGs
- Significant code capabilities: drywell/fan cooler heat and mass transfer
- BWR sequences:
  - SLOCAs and MLOCAs
  - Stuck-open SRVs with discharge to the suppression pool
  - Anticipated transient without scram (ATWS) conditions
- PWR sequences:
  - LLOCAs
  - SGTRs (These are in part supported by the SLOCA benchmark sequences, but additional benchmarks that focus on the secondary side response would be of value because of the complex coupling of the primary and secondary sides and the importance of SGTRs in Level 1 analysis.)
  - Mid-loop operation

Table 5-1
Collected Benchmarks and Agreement for the Major Code Models Related to Level 1 Phenomena

Benchmark Type	**Identifier, Sequences, and Plant Type**	**Agreement for Major Code Models**							**Principal Sources of Documentation for the Benchmark**
		Overall Code	**Primary System Thermal Hydraulics (pressure and water level)**		**SG Thermal Hydraulics (pressure and water level)**	**Core Heat-Up (core temperature)**	**Containment Thermal Response (pressure)**		
			BWR	**PWR**					
Plant event (PE1)	TMI-2 LOFW; B&W	Very good given uncertainty in boundary conditions	–	Good	Fair (OTSG, one-region model)	Indirect support	Qualitative		MAAP4 User's Manual and conference proceedings
Plant event (PE2)	Davis-Besse LOFW; B&W	Fair	–	Fair to good	–	–	–		MAAP4 User's Manual
Plant event (PE3)	Oyster Creek LOFW; BWR with isolation condenser	Very good given uncertainty in boundary conditions	Good	–	–	–	–		MAAP4 User's Manual
Plant event (PE4)	Prairie Island SGTR; WLD	Good	–	Good	–	–	–		MAAP4 User's Manual
Plant event (PE5)	Maanshan SBO; WLD	Good	–	Good to very good	–	–	–		Presentation to the NRC

Table 5-1 (continued)
Collected Benchmarks and Agreement for the Major Code Models Related to Level 1 Phenomena

Benchmark Type	Identifier, Sequences, and Plant Type	Agreement for Major Code Models							Principal Sources of Documentation for the Benchmark
		Overall Code	Primary System Thermal Hydraulics (pressure and water level)		SG Thermal Hydraulics (pressure and water level)	Core Heat-Up (core temperature)	Containment Thermal Response (pressure)		
			BWR	PWR					
Plant event (PE6)	Oconee plant trip; B&W	Good	–	Very good with code change to model plants with hot water in dome	–	–	–		Presentation to the MUG
Plant event (PE7)	LOOP and plant trip in 1992 MAAP3B Qualification Studies; Westing-house four-loop	Generally but not specifically applicable; good agreement with MAAP3B	–	–	–	–	–		EPRI technical report
Integral code–compared to CENTS (IC1)	SBO and LOFW with F&B; CE	Good	–	Good	Fair to very good (U-tube, two-region model)	–	–		Conference proceedings

Table 5-1 (continued)
Collected Benchmarks and Agreement for the Major Code Models Related to Level 1 Phenomena

Benchmark Type	**Identifier, Sequences, and Plant Type**	**Agreement for Major Code Models**						**Principal Sources of Documentation for the Benchmark**
		Overall Code	**Primary System Thermal Hydraulics (pressure and water level)**		**SG Thermal Hydraulics (pressure and water level)**	**Core Heat-Up (core temperature)**	**Containment Thermal Response (pressure)**	
			BWR	**PWR**				
Integral code–compared to SR5 (IC2)	LOFW and S/MLOCAs; U.S. EPR	Good	—	Good to very good [a]	Fair to good (U-tube, one-region model)	Fair to very good	—	Conference proceedings
Integral code–compared to TRACG02 (IC3)	LOOPs with LLOCAs; BWR	Good	Good	—	—	Fair	—	GE technical report
Integral code–compared to RELAP5 (IC4)	SBO with F&B for Palisades; CE	Good	—	Fair to good	Good (U-tube, one-region model) [b]	—	—	Erigo letter report and presentations to the MUG
Integral code–compared to SR5 and MELCOR (IC5 1 of 2)	LLOCA for Kuonsheng; BWR	Good	Fair to good	—	—	Good	—	Journal paper and doctoral dissertation

Table 5-1 (continued)
Collected Benchmarks and Agreement for the Major Code Models Related to Level 1 Phenomena

Benchmark Type	Identifier, Sequences, and Plant Type	Agreement for Major Code Models						Principal Sources of Documentation for the Benchmark
		Overall Code	Primary System Thermal Hydraulics (pressure and water level)		SG Thermal Hydraulics (pressure and water level)	Core Heat-Up (core temperature)	Containment Thermal Response (pressure)	
			BWR	PWR				
Integral code–compared to SR5 and MELCOR (IC5 2 of 2)	SBO for Maanshan; WLD	Good	—	Fair to good	Good (U-tube, region model not specified)	Good	—	Journal paper and doctoral dissertation
Integral code–compared to CENTS (IC6)	MLOCA for Palo Verde; WLD	Inconclusive	—	Inconclusive	Inconclusive (U-tube, region model not specified)	—	—	Presentation to the MUG
Integral code–compared to CATHARE (IC7)	S/M LOCAs; EDF/ Framatome PWR 900	Good	—	Good to very good	Very good (U-tube, one-region model)	—	—	EDF technical report
Integral code–compared to SR5 and MELCOR (IC8)	TMLB (SBO with no RCP seal leak); WLD	Good	—	Fair to good	Good (U-tube, one-region model)	Indirect support	—	Journal paper

Table 5-1 (continued)
Collected Benchmarks and Agreement for the Major Code Models Related to Level 1 Phenomena

Benchmark Type	Identifier, Sequences, and Plant Type	Agreement for Major Code Models							Principal Sources of Documentation for the Benchmark
		Overall Code	Primary System Thermal Hydraulics (pressure and water level)		SG Thermal Hydraulics (pressure and water level)	Core Heat-Up (core temperature)	Containment Thermal Response (pressure)		
			BWR	PWR					
Integral code–compared to RELAP5 (IC9)	LOOP with F&B for Millstone; CE	Good	—	Fair to good	Good (U-tube, one-region model)	Good	—		Presentation to the MUG
Integral code–compared to MELCOR (IC10)	TMLB, LLOCAs and SLOCA; WLD SBO, transients, and LLOCA; BWR	Good	Not available	Good	—	—	—		Conference proceedings
Integral code–compared to SAFE (IC11)	Transients, SLOCA, and MSLB in 1992 MAAP3B Qualification Studies; BWR	Generally but not specifically applicable; good agreement with MAAP3B	—	—	—	—	—		EPRI technical report

Table 5-1 (continued)
Collected Benchmarks and Agreement for the Major Code Models Related to Level 1 Phenomena

Benchmark Type	Identifier, Sequences, and Plant Type	Agreement for Major Code Models						Principal Sources of Documentation for the Benchmark
		Overall Code	Primary System Thermal Hydraulics (pressure and water level)		SG Thermal Hydraulics (pressure and water level)	Core Heat-Up (core temperature)	Containment Thermal Response (pressure)	
			BWR	PWR				
Integral code–compared to RELAP and RETRAN (IC12)	Transients, failed-open PORV, SGTRs, SLOCAs, and MSLB in 1992 MAAP3B Qualification Studies; Westing-house four-loop	Generally but not specifically applicable; good agreement with MAAP3B	—	—	—	—	—	EPRI technical report
Integral experiments (IE1)	BETHSY LOFWs with F&B and SLOCA; EDF/ Framatome PWR 900	Very good	—	Very good	Very good (U-tube, one- and two-region models)	—	—	Presentation to the MUG
Integral experiments (IE2)	IIST SBO; WLD	Very good	—	Very good	Very good (U-tube, one-region model)	Very good	—	Conference proceedings

Table 5-1 (continued)
Collected Benchmarks and Agreement for the Major Code Models Related to Level 1 Phenomena

Benchmark Type	**Identifier, Sequences, and Plant Type**	**Agreement for Major Code Models**						**Principal Sources of Documentation for the Benchmark**
		Overall Code	**Primary System Thermal Hydraulics (pressure and water level)**		**SG Thermal Hydraulics (pressure and water level)**	**Core Heat-Up (core temperature)**	**Containment Thermal Response (pressure)**	
			BWR	**PWR**				
Integral experiments (IE3)	MB-2 LOFWs, MSLBs, and MSLB with SGTR; WLD	Very good	—	—	Very good (U-tube, two-region model)	—	—	Conference proceedings
Integral experiment (IE4)	OSU SLOCAs and failed-open PORVs; AP600	Very good	—	Very good	Very good (U-tube, two-region model)	—	—	Conference proceedings
Integral experiment (IE5)	Waltz Mill containment; generic	—	—	—	—	—	Fair	MAAP4 User's Manual
Integral experiment (IE7)	CSTF containment; generic	—	—	—	—	—	Very good	MAAP4 User's Manual
Integral experiment (IE8)	HDR containment; generic	—	—	—	—	—	Very good	Journal paper and conference proceedings
Integral experiment (IE9)	ISP-35 containment; generic	—	—	—	—	—	Very good	Conference proceedings

Table 5-1 (continued)
Collected Benchmarks and Agreement for the Major Code Models Related to Level 1 Phenomena

Benchmark Type	Identifier, Sequences, and Plant Type	Agreement for Major Code Models						Principal Sources of Documentation for the Benchmark
		Overall Code	Primary System Thermal Hydraulics (pressure and water level)		SG Thermal Hydraulics (pressure and water level)	Core Heat-Up (core temperature)	Containment Thermal Response (pressure)	
			BWR	PWR				
integral experiment (IE10)	Semiscale: SLOCAs, LOOPs, and SGTRs in 1992 MAAP3B Qualification Studies for PWR	Generally but not specifically applicable; good agreement with MAAP3B	—	—	—	—	—	EPRI technical report
Integral experiment (IE11)	FIST: LOFWs and MLOCA in 1992 MAAP3B Qualification Studies for BWR	Generally but not specifically applicable; good agreement with MAAP3B	—	—	—	—	—	EPRI technical report
Integral experiment (IE12)	MIST: SLOCAs in 1992 MAAP3B Qualification Studies for B&W	Generally but not specifically applicable; good agreement with MAAP3B	—	—	—	—	—	EPRI technical report

[a] One exception to the agreement is suspected to be the result of input differences.

[b] The exception to the agreement is a minor limitation in MAAP4 related to condensation in the steam generators.

Table 5-2
Collected Benchmarks and Validation of Significant Code Capabilities Related to Level 1 Phenomena

Benchmark Type	**Identifier and Plant Type**	**Capabilities**					**Principal Sources of Documentation for the Benchmark**
		Critical Flow Model	**ECCS Injection**	**Condenser Heat Transfer**	**Voiding in Core**	**HLNC**	
Plant event (PE3)	Oyster Creek LOFW; BWR with isolation condenser	—	—	BWR isolation condenser validated	—	—	MAAP4 User's Manual
Plant event (PE4)	Prairie Island SGTR; WLD	—	PWR hardwired model validated	—	—	—	MAAP4 User's Manual
Integral code–compared to CENTS (IC1)	SBO and LOFW with F&B; CE	Qualitative support (PORV flow)	PWR generalized model validated	—	—	—	Conference proceedings
Integral code–compared to SR5 (IC2)	LOFW and S/MLOCAs; U.S. EPR	Qualitative support (safety valve flow); validated (break flow)	—	—	—	—	Conference proceedings
Integral code–compared to TRACG02 (IC3)	LOOPs with LLOCAs; BWR	Validated (break flow)	BWR model validated	—	—	—	GE technical report

Table 5-2 (continued)
Collected Benchmarks and Validation of Significant Code Capabilities Related to Level 1 Phenomena

Benchmark Type	**Identifier and Plant Type**	**Capabilities**					**Principal Sources of Documentation for the Benchmark**
		Critical Flow Model	**ECCS Injection**	**Condenser Heat Transfer**	**Voiding in Core**	**HLNC**	
Integral code–compared to RELAP5 (IC4)	SBO with F&B for Palisades; CE	Qualitative support (PORV flow)	PWR generalized model validated	—	—	—	Erigo letter report and presentations to the MUG
Integral code–compared to CENTS (IC6)	MLOCA for Palo Verde; WLD	Validated (break flow)	—	—	—	—	Presentation to the MUG
Integral code–compared to CATHARE (IC7)	S/M LOCAs; EDF/ Framatome PWR 900	Validated (break flow)	—	—	—	—	EDF technical report
Integral code–compared to SR5 and MELCOR (IC8)	TMLB′ (SBO with no RCP seal leak); WLD	Qualitative support (PORV flow)	—	—	—	—	Journal paper

Table 5-2 (continued)
Collected Benchmarks and Validation of Significant Code Capabilities Related to Level 1 Phenomena

Benchmark Type	**Identifier and Plant Type**	**Capabilities**					**Principal Sources of Documentation for the Benchmark**
		Critical Flow Model	**ECCS Injection**	**Condenser Heat Transfer**	**Voiding in Core**	**HLNC**	
Integral code–compared to RELAP5 (IC9)	LOOP with F&B for Millstone; CE	Validated (PORV flow)	PWR validated (model not specified)	—	—	—	Presentation to the MUG
Integral experiment (IE1)	BETHSY LOFWs with F&B and SLOCA; EDF/ Framatome PWR 900	Validated (break and PORV flow)	PWR generalized model validated	—	Qualitative support	—	Presentation to the MUG
Integral experiment (IE3)	MB-2 LOFWs, MSLBs, and MSLB with SGTR; WLD	Validated (break flow)	—	—	—	—	Conference proceedings
Integral experiment (IE4)	OSU SLOCAs and failed-open PORVs; AP600	Validated (break and PORV flow)	PWR validated (passive systems)	—	—	—	Conference proceedings

Table 5-2 (continued)
Collected Benchmarks and Validation of Significant Code Capabilities Related to Level 1 Phenomena

Benchmark Type	Identifier and Plant Type	Capabilities					Principal Sources of Documentation for the Benchmark
		Critical Flow Model	ECCS Injection	Condenser Heat Transfer	Voiding in Core	HLNC	
Integral experiment (IE5)	Waltz Mill containment; generic	—	—	PWR ice condenser validated	—	—	MAAP4 User's Manual
Integral experiment (IE6)	PNL ice containment; WICE	—	—	PWR ice condenser validated	—	—	MAAP4 User's Manual
Separate effects experiment (SE1)	THTF; generic	—	—	—	Validation of void fraction subroutine	—	MAAP4 User's Manual
Separate effects experiments (SE2)	Westing-house 1/7th scale; PWR	—	—	—	—	Validation of HLNC subroutine	MAAP4 User's Manual and EPRI technical report
Separate effects experiment (SE3)	Marviken and FAI blowdown; PWR	Validated (PORV flow, also pressurizer model)	—	—	—	—	MAAP4 User's Manual

Table 5-3
Compilation of the Agreement for the Major Code Models Related to Level 1 Phenomena[a]

Major Code Model	**Number of Benchmarks Reviewed by Experts**	**Agreement**[b]						
		Very Good	**Good to Very Good**	**Good and Fair to Very Good**	**Fair to Good**	**Fair**	**Quali-tative or Indirect**	**Incon-clusive**
Overall code for BWR analysis	4	1	—	3	—	—	—	—
BWR primary system thermal hydraulics	3	—	—	2	1	—	—	—
Overall code for PWR analysis	18	5	—	11	—	1	—	1
PWR primary system thermal hydraulics	17	4	3	4	5	—	—	1
PWR steam generator thermal hydraulics	13	5 U-tube	—	5 U-tube	1 U-tube	1 OTSG	—	1 U-tube
Core heat-up (generic to BWR and PWR)	8	1	—	4	—	1	2	—
Containment (generic to BWR and PWR)	5	3	—	—	—	1	1	—

[a] Does not include the MAAP3B benchmarks that are generally but not specifically applicable (good agreement obtained with MAAP3B).

[b] No poor agreement with the benchmarks was identified for any of the major code models.

Table 5-4
Compilation of the Validation of Significant Code Capabilities Related to Level 1 Phenomena

Code Capability		**Number of Benchmarks Reviewed by Experts**	
		Explicit Validation	**Qualitative or Indirect Validation**
Critical flow model	PORV and SRV flow applications	4 (including pressurizer model)	4
	Break flow applications	7	—
ECCS injection	BWR model	1	—
	PWR models	6	—
Condenser heat transfer	BWR isolation condenser	1	—
	PWR ice condenser	2	—
Voiding in the core		1	1
HLNC		1	—
Drywell/fan cooler heat and mass transfer		0	—

Table 5-5
BWR Sequences Supported by Benchmarks

Sequence Initiating Event	Type of Benchmark	Number and Types of Sequences	Overall Agreement	Sequence Time Frame
BWR transients (including SBOs, LOFW, and turbine trips) ***Total with MAAP4: 3 + 4 minor support*** ***Total with MAAP3B: 6***	Plant event: Oyster Creek (PE3)	1 LOFW	Very good	30 min
	Integral code comparison to TRACG02 (IC3)	2 LOOPs with LLOCAs	Good	8 min
	Integral code comparison to SAFE (IC11)—MAAP3B	4 LOFW	Good agreement with MAAP3B	15 min–2 hr
	Integral experiment comparison to FIST (IE11)—MAAP3B	2 LOFW	Good agreement with MAAP3B	15–50 min
	Integral code comparison to MELCOR (IC10)	1 SBO and 3 transients	Good: only a minor supporting benchmark for Level 1 applications	40 hr
BWR LLOCAs (excluding MSLBs) ***Total with MAAP4: 3 + 1 minor support***	Integral code comparison to TRACG02 (IC3)	2 LOOPs with LLOCA	Good	8 min
	Integral code comparison to SR5 and MELCOR (IC5)	1 LLOCA	Good	4 hr
	Integral code comparison to MELCOR (IC10)	1 LLOCA	Good: only a minor supporting benchmark for Level 1 applications	40 hr
BWR MLOCAs and SLOCAs ***None with MAAP4*** ***Total with MAAP3B: 2***	Integral code comparison to SAFE (IC11)—MAAP3B	1 SLOCA	Good agreement with MAAP3B	1 hr
	Integral experiment comparison to FIST (IE11)—MAAP3B	1 MLOCA	Good agreement with MAAP3B	8 min
BWR MSLBs ***None with MAAP4*** ***Total with MAAP3B: 1*** Can be considered a subset of LLOCAs	Integral code comparison to SAFE (IC11)—MAAP3B	1 MSLB	Good agreement with MAAP3B	7 min

Table 5-5 (continued)
BWR Sequences Supported by Benchmarks

Sequence Initiating Event	Type of Benchmark	Number and Types of Sequences	Overall Agreement	Sequence Time Frame
BWR interfacing system LOCAs (discharge outside of containment)	No supporting benchmarks, but essentially covered by LLOCA and S/MLOCA benchmarks.			
BWR stuck-open SRVs	No supporting benchmarks with stuck-open SRVs as an initiator, but similar to SLOCAs if discharge is to the gas space (versus to the suppression pool). Sequences are also supported by benchmarks in which stuck-open or manually opened SRVs are subsequent conditions.			
BWR feedwater line breaks	No supporting benchmarks, but essentially covered by S/MLOCA benchmarks.			
BWR ATWS	No supporting benchmarks.			

Table 5-6
PWR Sequences Supported by Benchmarks

Sequence Initiating Event	Type of Benchmark	Number and Types of Sequences	Plant Type	Steam Generator Type and Model	Overall Agreement	Sequence Time Frame
PWR transients (including SBOs, LOFW, and turbine trips) ***Total with MAAP4: 19 + 1 minor support*** ***Total with MAAP3B: 6***	Plant event: TMI-2 (PE1)	1 LOFW with stuck-open PORV	B&W	OTSG, one-region model	Very good	5 hr
	Plant event: Davis-Besse (PE2)	1 LOFW	B&W	—	Fair	30 min
	Plant event: Maanshan (PE5)	1 SBO	WLD	—	Good	3 hr
	Plant event: Oconee (PE6)	1 plant trip	B&W	—	Good	15 min
	Plant event: four-loop (PE7)—MAAP3B	1 LOOP and 1 plant trip	Westing-house	—	Good agreement with MAAP3B	3–5 min
	Integral code comparison to CENTS (IC1)	1 SBO and 1 LOFW with feed and bleed	CE	U-tube, two-region model	Good	3 hr
	Integral code comparison to SR5 (IC2)	3 LOFWs	U.S. EPR	U-tube, one-region model	Good	2 hr
	Integral code comparison to RELAP5 (IC4)	2 SBOs with feed and bleed	CE	U-tube, one-region model	Good	5–10 hr
	Integral code comparison to SR5 and MELCOR (IC5)	1 SBO	WLD	U-tube, region model not specified	Good	5 hr
	Integral code comparison to SR5 and MELCOR (IC8)	1 TMLB′ (SBO, no RCP seal leak)	WLD	U-tube, one-region model	Good	5 hr
	Integral code comparison to RELAP5 (IC9)	1 LOOP with feed and bleed	CE	U-tube, one-region model	Good	3 hr

Table 5-6 (continued)
PWR Sequences Supported by Benchmarks

Sequence Initiating Event	Type of Benchmark	Number and Types of Sequences	Plant Type	Steam Generator Type and Model	Overall Agreement	Sequence Time Frame
	Integral code comparison to MELCOR (IC10)	1 TMLB (SBO with RCP seal leak)	WLD	—	Good: only a minor supporting benchmark for Level 1 applications	40 hr
	Integral code comparison to RELAP and RETRAN (IC12)—MAAP3B	2 transients	Westinghouse	—	Good agreement with MAAP3B plus code changes that were incorporated into MAAP4	5 min–1.4 hr
	Integral experiment comparison to BETHSY (IE1)	2 LOFWs with feed and bleed	900 MWe EDF/ Framatome	U-tube, one-region model	Very good	1–2 hr
	Integral experiment to IIST (IE2)	1 SBO	WLD	U-tube, one-region model	Very good	3 hr
	Integral experiment comparison to MB-2 (IE3)	2 LOFWs	WLD	U-tube, two-region model	Very good	2–12 min
	Integral experiment comparison to Semiscale (IE10)—MAAP3B	2 LOOPs	Generic PWR	—	Good agreement with MAAP3B	3–5 hr
PWR LLOCAs (excluding MSLBs) ***Total with MAAP4: 2 minor support***	Integral code comparison to MELCOR (IC10)	2 LLOCAs: location not identified	WLD	—	Good: only a minor supporting benchmark for Level 1 applications	40 hr

Table 5-6 (continued)
PWR Sequences Supported by Benchmarks

Sequence Initiating Event	Type of Benchmark	Number and Types of Sequences	Plant Type	Steam Generator Type and Model	Overall Agreement	Sequence Time Frame
PWR MLOCAs and SLOCAs ***Total with MAAP4: 12 + 1 minor support*** ***Total with MAAP3B: 8***	Integral code comparison to SR5 (IC2)	1 SLOCA: location not identified 1 MLOCA: location not identified	U.S. EPR	U-tube, one-region model	Good	2 hr
	Integral code comparison to CENTS (IC6)	1 MLOCA: break in the intermediate leg	WLD	U-tube, region model not specified	Inconclusive	5 hr
	Integral code comparison to CATHARE (IC7)	1 SLOCA: break in the hot leg 1 MLOCA: break in the hot leg 3 SLOCAs: breaks in the cold leg 1 MLOCA: break in the cold leg	900 MWe EDF/ Framatome	U-tube, one-region model	Good	2–12 hr
	Integral code comparison to MELCOR (IC10)	1 SLOCA: location not identified	WLD	—	Good: only a minor supporting benchmark for Level 1 applications	40 hr
	Integral code comparison to RELAP and RETRAN (IC12)—MAAP3B	2 SLOCAs: breaks in the cold leg	Westing-house	—	Good agreement with MAAP3B plus code changes that were incorporated into MAAP4	30 min–1 hr

Table 5-6 (continued)
PWR Sequences Supported by Benchmarks

Sequence Initiating Event	Type of Benchmark	Number and Types of Sequences	Plant Type	Steam Generator Type and Model	Overall Agreement	Sequence Time Frame
	Integral experiment comparison to BETHSY (IE1)	1 SLOCA: break in the cold leg	900 MWe EDF/ Framatome	U-tube, two-region model	Very good	2 hr
	Integral experiment comparison to OSU (IE4)	2 SLOCAs: breaks in an injection line	AP600	U-tube, two-region model	Very good	Not provided
	Integral experiment comparison to Semiscale (IE10)—MAAP3B	4 SLOCAs: breaks in the cold leg	Generic PWR	—	Good agreement with MAAP3B	13–50 min
	Integral experiment comparison to MIST (IE12)—MAAP3B	2 SLOCAs: breaks in the cold leg	B&W	—	Good agreement with MAAP3B	1–12 hr
PWR interfacing system LOCAs (discharge outside of containment)	No supporting benchmarks, but essentially covered by LLOCA and S/MLOCA benchmarks.					
PWR stuck-open PORVs ***Total with MAAP4: 2*** ***Total with MAAP3B: 1***	Integral code comparison to RELAP and RETRAN (IC12)—MAAP3B	1 failed-open PORV	Westing-house	—	Good agreement with MAAP3B plus code changes that were incorporated into MAAP4	8 min
	Integral experiment comparison to OSU (IE4)	2 failed-open PORVs	AP600	U-tube, two-region model	Very good	Not provided

Table 5-6 (continued)
PWR Sequences Supported by Benchmarks

Sequence Initiating Event	Type of Benchmark	Number and Types of Sequences	Plant Type	Steam Generator Type and Model	Overall Agreement	Sequence Time Frame
PWR SGTR ***Total with MAAP4: 1*** ***Total with MAAP3B: 5***	Plant event: Prairie Island (PE4)	1 SGTR	WLD	—	Good	8 min
	Integral code comparison to RELAP and RETRAN (IC12)—MAAP3B	2 SGTRs	Westinghouse	—	Good agreement with MAAP3B plus code changes that were incorporated into MAAP4	50 min
	Integral experiment comparison to Semiscale (IE10)—MAAP3B	3 SGTRs	Generic PWR	—	Good agreement with MAAP3B	5–40 min
PWR MSLBs ***Total with MAAP4: 3*** ***Total with MAAP3B: 1***	Integral code comparison to RELAP and RETRAN (IC12)—MAAP3B	1 MSLB	Westinghouse	—	Good agreement with MAAP3B plus code changes that were incorporated into MAAP4	5 min
	Integral experiment comparison to MB-2 (IE3)	2 MSLBs 1 MSLB with SGTR	WLD	U-tube, two-region model	Very good	2–3 min 17 min for SGTR
PWR feedwater line breaks	No supporting benchmarks, but similar to LOCAs and, to a lesser extent, MSLBs					
PWR mid-loop operation	No supporting benchmarks					
PWR ATWS	No supporting benchmarks, but typically a very low contributor to core damage frequencies					

In addition to the benchmarking activities detailed in the App Guide and summarized above, recent programs have further confirmed the ability of the code to accurately model accident conditions. Some of the more notable code benchmarking activities are summarized in the following sections.

<u>ERI/NRC "Compendium of Analysis to Investigate Select Level 1 Probabilistic Risk Assessment End-State definition and Success Criteria Modeling Issues – Draft report for Comment."</u>

Utilizing the NRC MELCOR computer code, the NRC performed a series of calculations aimed at confirming success criteria assumptions made in their PRA models. Included in their assessment was a comparison between MELCOR and MAAP for a series of PWR bleed and feed scenarios. The comparison involved scenarios representing uncertainties associated with achieving successful mitigation of a loss of feedwater accident for a representative PWR plant. The MAAP analysis can be found in the EPRI report [Ref. 3] and was used for comparison to the NRC MELCOR code. Both of the analyses investigated the uncertainty associated with the following list of parameters:

- Power level at the start of the incident
- Steam generator water level setpoints (account for uncertainties in steam generator level measurements)
- Time of reactor trip
- Number of pressurizer PORVs used for bleed and feed
- Number of available HPSI and charging trains
- HPSI pump flow characteristics
- Pressurizer PORV flow characteristics
- Time of auxiliary feedwater (AFW) failure
- Reactor coolant pump trip
- Time of feed initiation (HPSI)
- Temperature of core damage

Distribution ranges were developed for the above parameters and 100 sample scenarios were created using the constrained Latin Hypercube Sampling (LHS) technique. The probability of core damage from the MELCOR analysis for conditions with a single available PORV (0.57) is in good agreement with the corresponding EPRI-MAAP analysis (0.61). For conditions with 2 available PORVs, the MELCOR estimated core damage probability of 0.15 is somewhat lower that the EPRI-MAAP estimated probability of 0.22. Overall, for the 100 sample cases run, both MAAP and MELCOR calculated similar peak core temperatures and corresponding core damage probabilities.

EPRI Fukushima Technical Evaluation

Accident reconstruction has been performed by both EPRI [Ref. 4] and the DOE [Ref. 5] for the 3 accidents at Fukushima Dai-ichi. Numerous technical exchange meetings have been conducted between EPRI, DOE, and the NRC to compare predictions for the accidents at Units 1, 2, and 3 at Fukushima Dai-ichi. As is well known, these accidents each demonstrated plant behavior both before and after core damage. Extensive MAAP analysis was performed and documented showing excellent agreement with the available plant data under reasonable assumptions in limited or unavailable input.

For example, Unit 2 at Dai-ichi maintained adequate core cooling for an extended period of time with only RCIC operating. Figures 5-1 and 5-2 show the comparison between the MAAP analysis and the actual plant data for both the RPV pressure and the drywell pressure for the event.

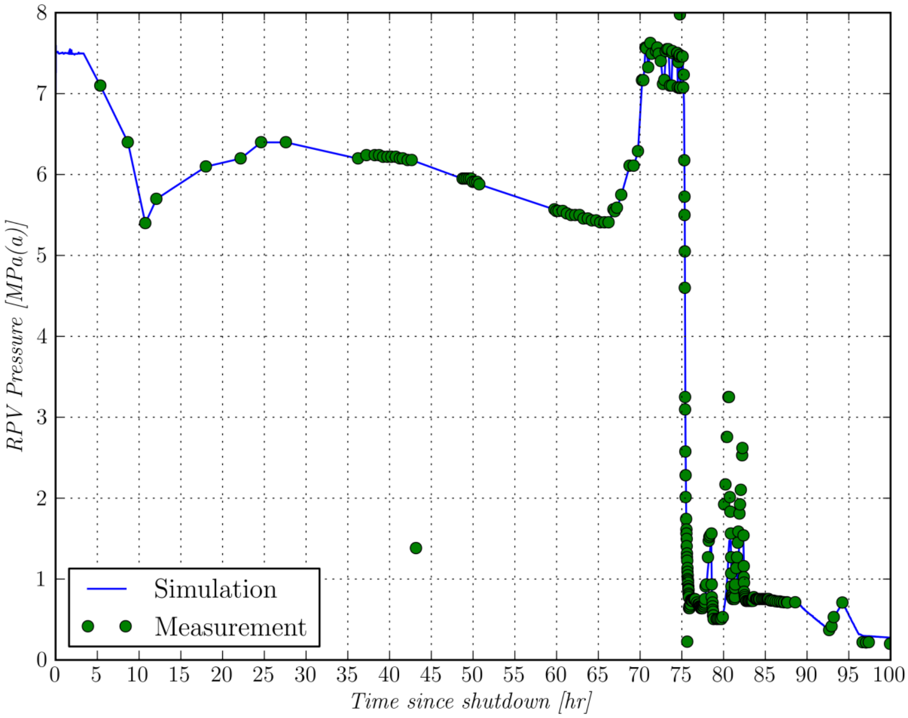

Figure 5-1
Simulation of the 1F2 RPV Pressure using MAAP5

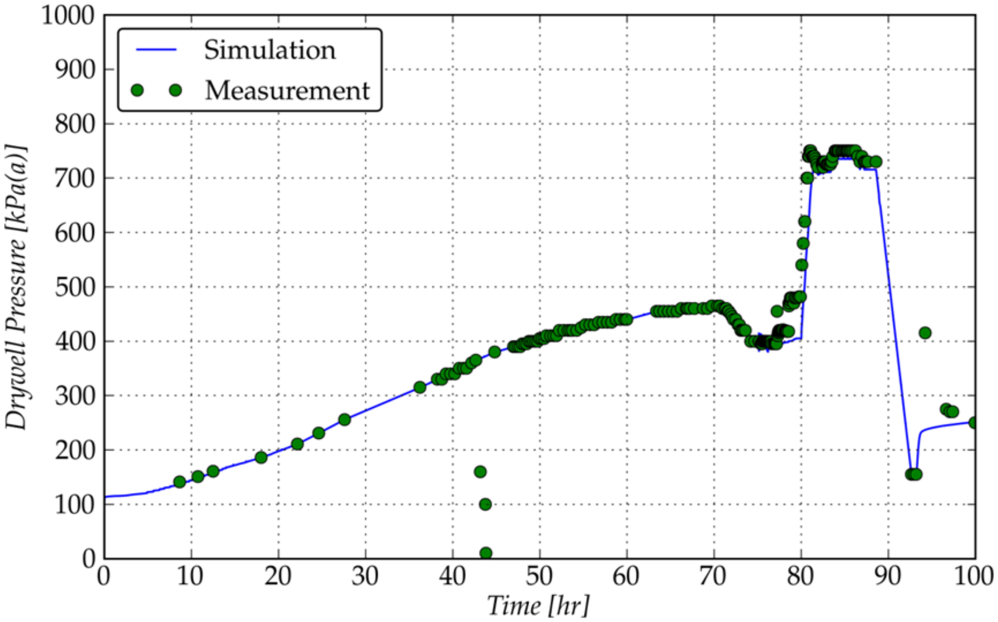

Figure 5-2
Simulation of Containment Pressure Response at 1F2 using MAAP5

Section 6: References

1. "Individual Plant Examination for Severe Accident Vulnerabilities – 10 CFR 50.54(f) (Generic Letter No. 88-20)," November 1988

2. *MAAP4 Applications Guidance; Desktop Reference for Using MAAP4 Software, Revision 2*. EPRI, Palo Alto, CA:2010. 1020236

3. *Technical Framework for Management of Safety Margins – Loss of Main Feedwater Pilot Application*, J. Gabor, R. Sherry, and D. True, EPRI, Palo Alto, CA: 2011. 1023032

4. "Fukushima Technical Evaluation – Phase 1 MAAP5 Analysis," EPRI, Palo Alto, CA: 2013. 1025750.

5. "Fukushima Dai-ichi Accident Study," R.O. Gauntt et al., Sandia Document No. SAND2012-6173, July 2012.

6. "MAAP4 Modular Accident Analysis Program for LWR Power Plants User's Manual," prepared by Fauske & Associates, LLC for EPRI, Project RP3131-02, May 1994 – June 2005.

7. a. *MAAP Thermal-Hydraulic Qualification Studies.* EPRI, Palo Alto, CA: 1992. TR-100741, prepared by Gabor, Kenton & Associates, Inc., and S. Levy Inc. for EPRI.

   b. *MAAP BWR Application Guidelines*. EPRI, Palo Alto, CA: 1992, TR-100742, prepared by Gabor, Kenton & Associates, Inc., and S. Levy Inc. for EPRI.

   c. *MAAP PWR Application Guidelines for Westinghouse and Combustion Engineering Plants*, EPRI, Palo Alto, CA:1992. TR-100743, prepared by Gabor, Kenton & Associates, Inc., and S. Levy Inc. for EPRI.

   d. *Proceedings: MAAP Thermal-Hydraulic Qualifications and Guidelines for Plant Application Workshop*, EPRI, Palo Alto, CA: 1991. NP-7515

8. *Recommended Sensitivity Analyses for an Individual Plant Examination Using MAAP 3.0B*, EPRI, Palo Alto, CA: TR-100167, prepared by Gabor, Kenton & Associates, Inc. for EPRI.

9. "Addenda ASME RA-S-2002 Standard for Probabilistic Risk Assessment for Nuclear Power Plant Applications," American Society of Mechanical Engineers, ASME RA-Sb-2005, Dec. 2005.

10. "An Approach for Determining the Technical Adequacy of Probabilistic Risk Assessment Results for Risk-Informed Activities," U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Regulatory Guide 1.200 for trial use, Feb. 2004.

11. "Decay Heat Power in Light Water Reactors," Revised American National Standard, American National Standards Institute (ANSI)/American Nuclear Society (ANS)-5.1-1979, 1979.

12. "ATWS Power Correlation for Subcooled Core Inlet Conditions," B. Chexal and W. Layman, EPRI Internal Memorandum, June 11, 1990.

13. "Severe Accident Analysis of a PWR Station Blackout with the MELCOR, MAAP4 and SCDAP/RELAP5 Codes," K. Vierow, Y. Liao, J. Johnson, M. Kenton, R. Gauntt, *Nuclear Engineering and Design,* Vol. 234, Issue 1-3, pp. 129-145, 2004.

14. "Transmittal Document for MAAP4 Code Revision MAAP 4.0.6," prepared by Fauske & Associates, LLC, FAI/05-47, May 2005.

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