The Fukushima-Daiichi accident has prompted utilities to examine the role of severe accidents in their training program, including on their real-time operator training simulators to ensure operators are better trained to cope with severe accidents. Some utilities will enhance their operator training programs in order to ensure that current and future plant operators have sufficient skills and knowledge to be able to properly deal with severe accident scenarios. In this paper, L3 MAPPS reviews the work it has performed on China's Ling Ao Phase II full scope operator training simulator to accommodate Beyond Design Basis Accidents (BDBAs).
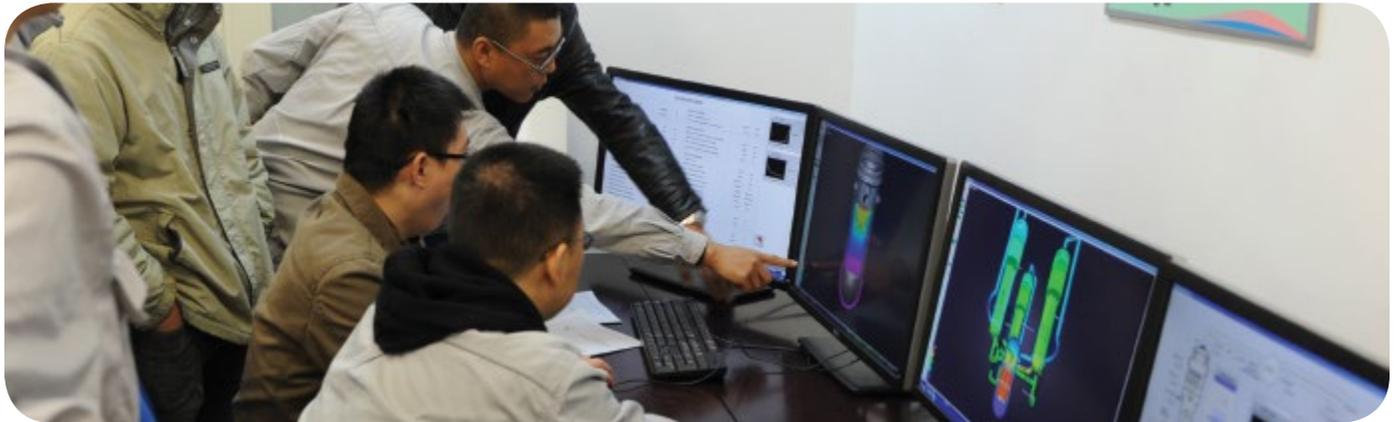
Generally, most of the existing full scope operator training simulators are not equipped to provide any kind of severe accident training due to their limited capability to simulate BDBA. Moreover, these simulators have simplified Spent Fuel Pool (SFP) models and have inadequate electrical model capability to be able to support training on degraded battery conditions during a Station Black Out (SBO).

L3 MAPPS has selected the Modular Accident Analysis Program[1] (MAAP) as the severe accident model of choice and has integrated it on several operator training simulators, the most recent implementation being on the Ling Ao Phase II training simulator.

Modular Accident Analysis Program (MAAP)

Following the accident at Three Mile Island Unit 2 (TMI-2), the nuclear power industry developed the MAAP code as part of the Industry's Degraded Core Rulemaking (IDCOR) program. Eventually ownership of this code was transferred to EPRI. The code was subsequently enhanced, leading to the current versions of the MAAP5 code.

MAAP is a stand-alone code, specifically designed for severe accident simulation. The objective of the MAAP program is to provide an effective methodology for analyzing the plant effects of a wide range of postulated severe accidents. These include any transients leading to the loss of reactor cooling and fuel damage, including cladding oxidation and hydrogen generation, melting, vessel failure, containment failure and fission product release.

MAAP is designed for the efficient simulation of extremely long-term transients, given that a typical severe accident scenario lasts 10 hours or more. It is designed as a fast-running computer code that simulates the response of light water and heavy water moderated NPPs for both current and Advanced Light Water Reactor (ALWR) designs. There are several parallel versions of MAAP for BWRs, PWRs, CANDU designs, FUGEN design and the Russian VVER design.

MAAP has been used by the nuclear industry throughout the world for more than two decades as an engineering tool to support Probabilistic Risk Assessment/Probabilistic Safety Assessment (PRA/PSA) and severe accident analysis, including actions taken as part of the Severe Accident Management Guidelines (SAMG).

Over the years, MAAP has been benchmarked against TMI-2 and various separate effects tests such as CORA, Phebus FPT0 and FPT1, SFD test 1-4, QUENCH tests, LOFT-FP, and MELCOR. Moreover, a strict quality assurance process is in place and managed by EPRI that governs the release process.

Severe Accident Simulation Experience

L3 MAPPS' first Severe Accident Simulation (SAS) deployment on a real-time operator training simulator was in 2000 on the Krško full scope simulator (FSS) for Slovenia's Nuklearna Elektrarna Krško (NEK). MAAP4 was integrated using its models for the Nuclear Steam Supply System (NSSS), including the reactor vessel and coolant loops, the pressurizer and relief tank, steam generators, main steam header and the reactor core and containment. All MAAP4 subroutines run alongside the L3 MAPPS ROSE® [predecessor to Orchid® Modeling Environment] models as part of our standard simulator executive. Synchronization is automatically handled through the existing dispatcher and no special communication software is required. The BDBA-related Initial Conditions (ICs) are seamlessly integrated into L3 MAPPS' instructor station software. Since 2000, this implementation has been part of NEK's training program, which provides BDBAs simulation for emergency drills.

In 2005, AREVA selected L3 MAPPS to deliver an FSS for the Olkiluoto 3 (OL3) EPR plant. The scope includes integration of AREVA's specific version of MAAP4. L3 MAPPS has adapted and integrated MAAP4.07-ANP3 with the OL3 FSS and the integrated configuration will ultimately be delivered to AREVA's customer, Finland's TVO. The OL3 FSS is built with Orchid®, L3 MAPPS' state-of-the-art simulation environment. The integration of MAAP was performed using the same proven technology employed on the Krško FSS with additional enhancements. All the interfaces were separated into input and output types and the architecture of the interfaces was redesigned to allow for automatic switching from L3 MAPPS' models to MAAP4. In addition, the MAAP interface objects in Orchid® Modeling Environment employ visual dynamics which facilitate viewing of the states and parameters being exchanged between MAAP and Orchid®.

In addition, MAAP5-based SAS projects have been implemented for a customer in Japan and for STP Nuclear Operating Co., both PWRs. SAS projects for Susquananna 1 (BWR; MAAP5), Krško (PWR; MAAP5) and Wolsong 1 (CANDU; MAAP4-CANDU) are ongoing.

Severe Accident Simulation on the Ling Ao Phase II Simulator

The Ling Ao Phase II (LA2) NPP was the world's first CPR1000 plant (a Chinese standard design featuring a 1,080-megawatt [MWe] three-loop PWR). The first of its two units was put into commercial operation in September 2010. The FSS supplied by L3 MAPPS in cooperation with AREVA and Siemens was the world's first CPR1000 FSS. The FSS was put into service in August 2009.

In April 2013, L3 MAPPS was contracted by China General Nuclear (CGN) to provide a SAS upgrade to supplement the training capabilities of the original LA2 FSS. The CGN subsidiary China Guangdong Nuclear Power Operations Co. (CNOC), working closely with L3 MAPPS, accepted the SAS upgrade for use in training in December 2013.

The FSS can simulate the full progression of severe accidents and their various phenomena, such as those that occurred at TMI-2 and Fukushima Daiichi, including reactor core melting, reactor pressure vessel failure, containment failure, melting of the fuel racks and spent fuel and release of radioactive materials to the environment.
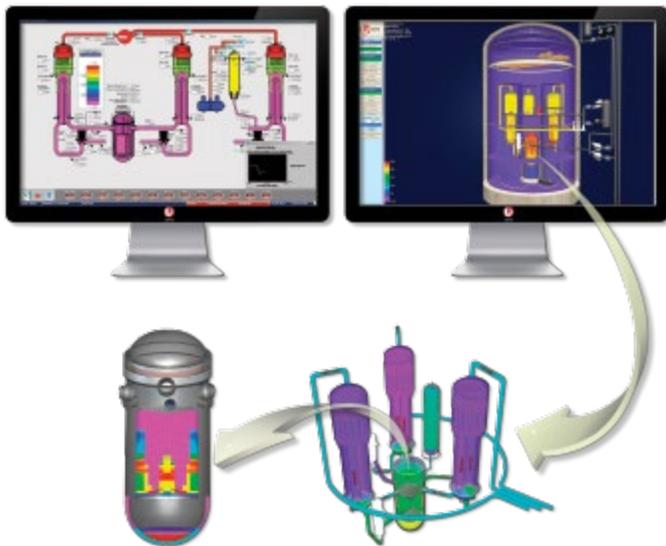
The simulator is being used to train senior operators, leaders of the emergency response team and its support personnel for severe accident scenarios. It is also being used for emergency drills, research on mitigation measures and verification for SAMGs.

Implementation of MAAP5 on the Ling Ao Phase II Simulator

MAAP5 was specifically designed for severe accident analysis in a stand-alone, offline, faster than real-time environment. In addition, it does not have built-in interfaces for third party codes. As a result, bidirectional process, logic and instrumentation interface schemes were developed and implemented by L3 MAPPS to manage interface variables and handle all necessary unit conversions between MAAP5 and L3 MAPPS' models and permit switching from normal simulation mode to BDBA mode.

The simulation scope for the delivery of the LA2 SAS using MAAP5 includes the MAAP5 point kinetics model for the reactor core, reactor vessel with three coolant loops, pressurizer and relief tank, steam generators and main steam header and containment models. Also included is a SFP model capable of modeling severe accidents including fuel uncovery, spent fuel heat-up and degradation and zirconium oxidation and fires and hydrogen combustion events.

The MAAP5 Emergency Core Cooling System (ECCS) and feedwater systems were not employed. Instead, all of the existing L3 MAPPS simulator models for the ECCS and feedwater systems were retained and interfaced with the MAAP5 models.

All malfunctions or "events" available in MAAP5 can be activated from the instructor station.

The SAS architecture employs two instances of MAAP5 running in parallel as external executables, one for the core/NSSS/containment and a second for the SFP model.

All MAAP5 common block variables are duplicated in the L3 MAPPS Common Database (CDB) and communication between the MAAP5 "shadow" CDB and MAAP5 is achieved via purpose-built module.

Similarly, synchronization of MAAP5 with the rest of the FSS is achieved using another purpose-built module in L3 MAPPS' dispatcher.
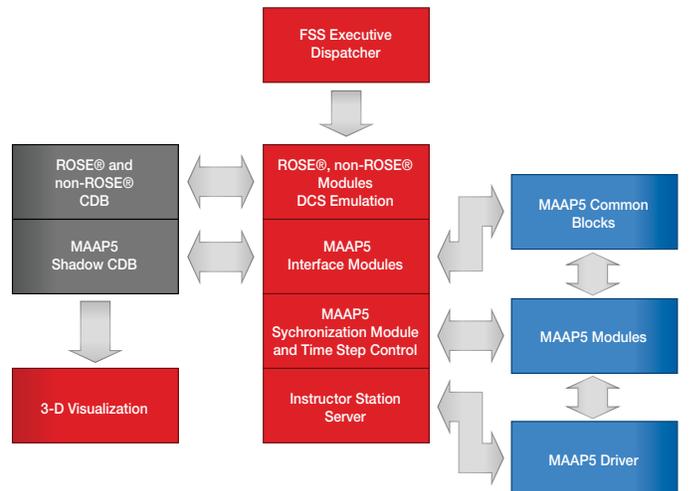

L3 MAPPS (simplified) scheme for coupling MAAP5 with the Ling Ao Phase II FSS

2-D/3-D Visualization

Purpose-built visualizations of the NSSS, containment and SFP are provided to enhance training and learning by coupling dynamic, interactive 2-D and 3-D graphics with the simulation.

With the use of the 3-D graphics, users have the capability to visualize major NSSS components (steam generators, reactor vessel, loops, pumps) where relative spatial orientation and geometry or internal structures are important and where a significant gradient in process values can occur.
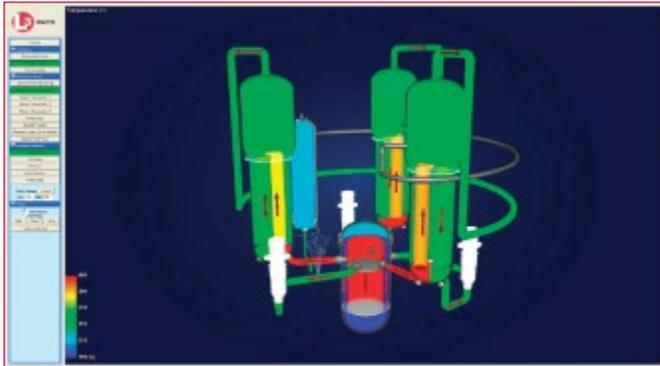
Interactive 3-D view of the NSSS with the containment removed

2-D visualizations of the NSSS analogous to operational displays representing a simplified version of a plant P&ID were also employed to demonstrate process flow paths and system interfaces.
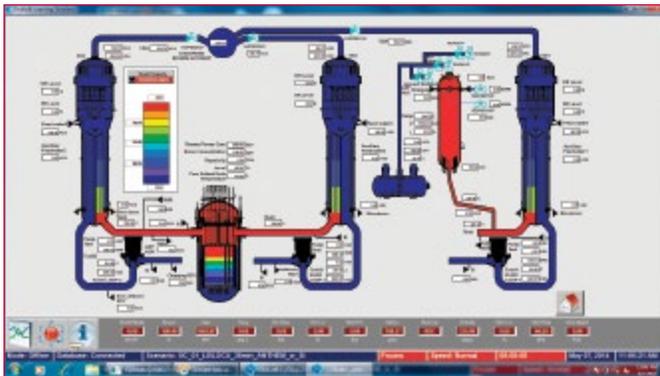
**Dynamic 2-D view of the NSSS (Large Break LOCA)**

In addition, a 2-D display was provided for off-site dose calculations resulting from vessel, containment breach, and other radioactive releases into the environment. The dose displays are overlaid onto a map of the area surrounding the NPP based on radial regions that exist at various distances away from the site.
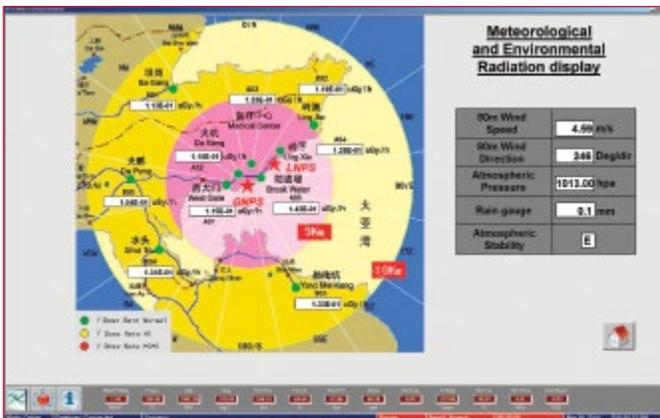

2-D view for offsite dose calculations

Performance Results/Validation

The simulator was validated extensively for numerous SAS scenarios against benchmark test results obtained from stand-alone MAAP5 tests. Some examples included guillotine and 4″ Cold Leg LOCA without ECCS, SBO with loss of turbine-driven auxiliary feedwater, SFP inventory loss, reactor vessel bottom leak without Safety Injection, Steam Generator Tube Rupture coinciding with main steam line break as well as various degrees of severe accidents leading to core melt and/or reactor vessel failure combined with containment failure (leakage) malfunctions resulting in radiological release. The SAS implementation on the FSS was very comparable to the reference benchmark test after accounting for the higher fidelity models on the FSS for the nuclear island and conventional island systems.
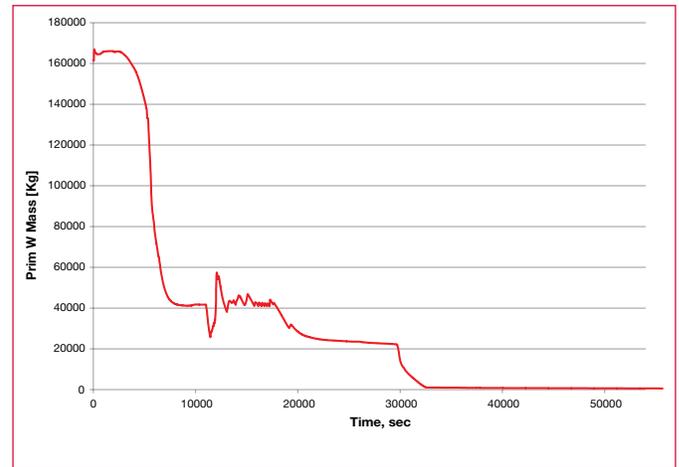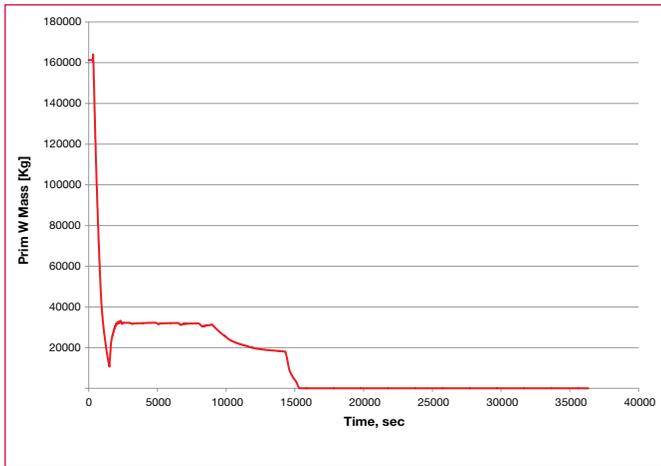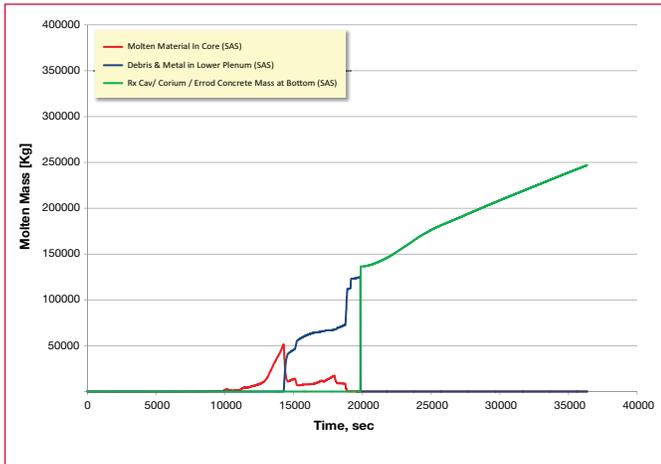

Small Break LOCA without SI - Primary Water Mass
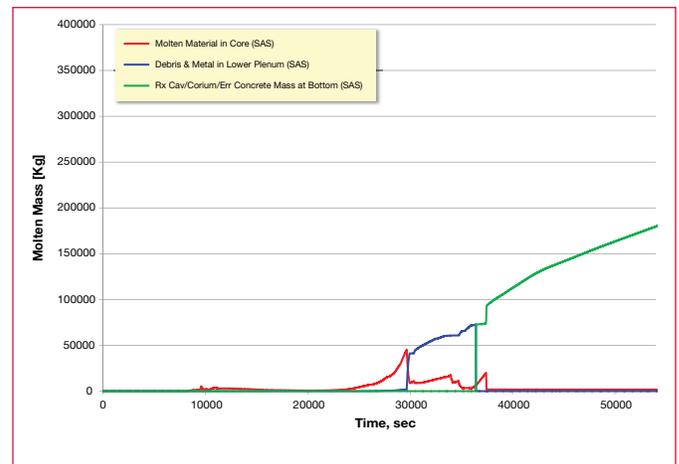
Small Break LOCA without SI - Molten Mass, Eroded Concrete Mass

Station Blackout (SBO) - Primary Water Mass

Station Blackout (SBO) - Molten Mass, Eroded Concrete Mass

Training Uses for the Ling Ao Phase II Severe Accident Simulation

The successful completion of the SAS implementation on the FSS has helped strengthen CNOC's ability to cope with potential severe accident scenarios and increase the power plant safety levels. It also further enhances CGN's safety profile with the National Nuclear Safety Administration (NNSA), the nuclear industry and the public.

The first training on the BDBA-enabled FSS was a TMI-2 accident sequence for the shift supervisors, safety engineers and other personnel that was launched on 17 December 2013.

[1] MAAP is an Electric Power Research Institute (EPRI) software program that performs severe accident analysis for nuclear power plants, including assessments of core damage and radiological transport. A valid license to MAAP from EPRI for customer's use of MAAP is required prior to a customer being able to use MAAP with Licensee's simulator products.

EPRI (www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, health, safety and the environment. EPRI does not endorse any third-party products or services. Interested vendors may contact EPRI for a license to MAAP.

On 27 March 2014, a 90-minute demonstration was provided to the NNSA to display the capabilities of the LA2 FSS in BDBA conditions. Details of the sequence and the two branch scenarios that were successfully demonstrated are presented below.

Elapsed Time (min)	Sequence of Events
0 min	Start from initial condition of 100% Full Power
5 min	Small break LOCA in the primary loop → Execute DOS accident procedure
10 min	Reactor Trip and Loss of LHSI (Low Head Safety Injection) → Execute procedure ECP2
20 min	Large break in primary loop
30 min	Loss of HHSI (High Head Safety Injection)
35 min	Delta Tsat < -200 deg C → Execute procedure ECP4
40 min	T RIC MAX (Maximum Temperature for Incore Thermocouples) > 650 deg C → Follow SAMG
45 min	Introduce a Containment penetration failure
48 min	T RIC thermocouples failure
65 min	Core collapse (Core melt)

Elapsed Time (min)	Scenario A	Elapsed Time (min)	Scenario B
66 min	Recover one LHSI	75 min	Corium material falls down to RPV lower plenum
70 min	The core is covered again	77 min	Loss of Containment Spray System (EAS)
		80 min	RPV lower plenum failure

The sequence demonstrated to the NNSA to display the capabilities of the LA2 FSS in BDBA conditions

Following the demonstration, the NNSA recognized the value of the BDBA-enabled FSS, and requested CNOC to expand upon the current uses to include more comprehensive severe accident drills. CNOC expects to accomplish this by the end of 2014 with the objective of taking full advantage of the BDBA-enabled LA2 FSS for emergency exercises and improvements obtained from the further development of the SAS scenarios.

Conclusions

There are many benefits that arise from L3 MAPPS' implementation of MAAP for SAS simulator training applications. There are very few changes or adaptations that are required to integrate MAAP with the simulator. Minimizing the changes to MAAP facilitates fidelity matching between the simulator and offline versions of MAAP, providing confidence in the simulator implementation. It also allows for easy inclusion of future MAAP releases on the simulator.

The LA2 SAS validation test results compare very favorably to the benchmark test data. Coupling the high fidelity of plant- specific nuclear and conventional island models and control system from the FSS with MAAP permits more realistic BDBA behavior in comparison to responses from the stand-alone MAAP model. This, together with simulator-driven, purpose-built 2-D and 3-D visualization, provides an additional means for knowledge transfer.

The success of the MAAP5 implementation on the LA2 FSS means that the LA2 FSS will continue to be used for emergency drills, research on BDBA mitigation measures and verification and enhancement of the existing SAMGs.