OPERATOR TRAINING ON SEVERE ACCIDENT AFTER FUKUSHIMA: A REAL-LIFE EXAMPLE

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ABSTRACT

It is more than two years now from the Fukushima-Daiichi nuclear disaster. Since then, severe accident has become one of the main topics of interest for international organizations, regulatory bodies, academia, research centers and, of course, industry. Lessons learned from the catastrophe highlight the need for improved education and training, at all levels, in this subject. In particular, it is recognized that faced with accident scenarios beyond design basis, nuclear plant operators, managers and technical support teams would benefit from new training tools with specific severe accident capabilities.

Several of these solutions have been proposed already but, even today, very few of them have been fully implemented. The way these tools should be used, the goals to be achieved and the personnel that should be targeted are still a matter of considerable debate.

In this article we describe in detail the experience at Monticello Nuclear Generating Plant, sister to the badly damaged Fukushima I, in the Minnesota plains. There, as a result of a successful training simulator improvement program, carried out over the last few years and recognized by INPO in 2012, instructors can design simulator exercises which include all phases of a severe accident, from core damage to vessel and containment failure. The severe accident simulation models have been developed by CORYS by tightly coupling THOR, their widely used advanced thermal-hydraulics code, with MELCOR, the US NRC severe accident code developed by Sandia National Laboratories. The code integration is transparent to the users of the full scope training simulator and the different models are automatically called as required by the evolution of each sequence. Detailed models of the spent fuel pool are included too.

This kind of training has been conducted for over a year now so real-life lessons can be extracted in different areas. We discuss, for example, the observed benefits in operator training with a better understanding of the severe accident phenomena, and also the improved response of the integrated severe accident models as opposed to the standard stand-alone execution of the code. At this time, analogous simulator improvement projects are under way or have been recently implemented at a number of plants in the US.

1. Introduction

In March 2011 the full scope training simulator at Xcel Energy's Monticello Nuclear Generating Plant, a General Electric BWR-3/Mark I reactor, was already in the middle of an ambitious upgrade plan. Site acceptance testing of a new electric distribution model was under way while a detailed radiation transport model, including reactor building, turbine building and ventilation system, was being developed. The momentum built up after the multiple meltdowns at Fukushima-Daiichi and additional upgrades followed, making the Monticello simulator one of the most advanced in the world. Eventually, two-phase non-equilibrium thermal hydraulic models for the primary system, balance of plant and containment were coupled to the well-known severe accident code MELCOR [1] so that training sequences could progress beyond fuel damage, vessel and containment breach, and recreate a complete severe accident scenario.

This paper describes how this simulator has been used during the last year for Licensed Operator Requalification Training (LORT) on Severe Accident Management Guidelines (SAMGs) and the lessons learned from the experience.

Two and a half years after the earthquake and tsunami in the Japanese coast, and while the need for new tools to improve severe accident training at all levels has been widely recognized, the discussion about how best to achieve the desired goals remains open. Different approaches have been proposed but only a few have been developed and even less fully implemented. Regulatory changes have not taken place yet, but are expected. In this context, Monticello case is quite unique and should help to evaluate future trends and possibilities.

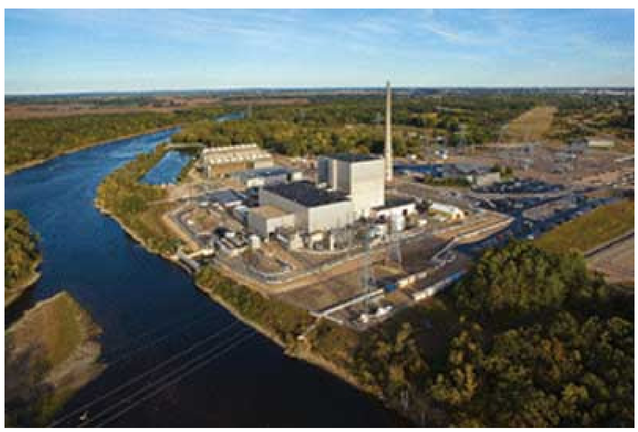

Fig 1: Monticello Nuclear Generating Plant

2. The Monticello full scope training simulator

By mid-2012 all the upgrades were ready. Factory acceptance testing was completed in July and site acceptance tests extended during the summer. Training was scheduled for late 2012 using the new severe accident models. By then, the simulator was a truly state-of-the-art tool, in every area, exhibiting the following features:

- High-fidelity two-phase models of primary system and balance of plant, as well as primary, secondary containments and HVAC to correctly simulate radiation and gas transport across the whole reactor and ventilation release paths. The thermal hydraulic code is THOR [2], by Corys, the most widely used real-time two-phase models in the American nuclear sector with more than forty installations in training simulators since its introduction in 1998.

- Spent Fuel Pool model, also in THOR, and support for multiple modes of operation in order to blend loss of cooling, loss of flow, and mode 5 refuel modes with vessel and containment heads removed
- Detailed electrical distribution model of all AC, DC and sub-yard, with particular attention to batteries, diesel generators and large DC loads affecting battery discharge
- MELCOR model of the reactor pressure vessel to support severe accident sequences with faulted core geometry allowing for live transition from regular scenarios
- 3D visualization tool as an additional help during severe accident training
- Earthquake simulation
- Full sound system
- Full scope glass-top simulator complementing the training sessions on hard panels

An additional change had to be made as simulator computer time increased noticeably. Computer hardware had to be updated along with the models in order to guarantee sufficient processor spare time during execution. The simulator now runs on Dell Precision machines with Dual Quad Core 3.6 GHz processors. The CPU load never exceeds 40% on the most limiting processor. Operating system is Microsoft Windows 7, 64 bit.

Even before the upgrade process was totally finished, in early 2012, Monticello commitment to excellence regarding its training simulator was recognized. As a result of a joint plant evaluation by INPO (Institute for Nuclear Operations) and WANO (World Association of Nuclear Operators), Monticello received a "strength" related to the simulator [3]. The strength is defined as "*a beneficial cross-functional or significant functional area practice, activity, or process employed by a station that results in achieving a high level of performance or desired high quality results and benefits*". Obviously, the significance of the events in Japan had not been underestimated and the plant was taking decisive steps ahead of the emerging industry challenges.

3. SAMGs training implementation

Before the upgrade, Licensed Operator Requalification Training on severe accidents was limited to classroom discussions of the SAMGs using case studies. With the new models operators can evaluate plant conditions, including core collapse into the lower head and vessel breach, and take mitigating actions according to the guides [4][5]. The transition to the severe accident models, triggered by fuel clad temperature reaching 1200°F, is seamless as the sequence degrades but can be disabled by the instructor to avoid affecting license exams or some other kind of training. When the transition happens, the booth operator is notified that the simulator is now in out-of-bounds conditions.

Since the severe accident model is a continuous part of the regular simulator load and does not cause an interruption in training, it was possible to design a SAMG training exercise based on pre-existing initial conditions. The scenario is initiated by a small break LOCA followed by a design-basis earthquake which results in high power ATWS, safety relief valve tailpipe breakage and, eventually, station blackout (SBO) conditions with major fuel damage requiring hard-pipe containment venting.

The whole scenario time line evolves during several hours. At one point, the crew will identify the need to exit all EOPs (Emergency Operating Procedures) and enter all the SAMGs. Sometime later, command and control will be transferred to the Technical Support Center due to the inability to restore and maintain sufficient reactor water level. The vessel will finally fail and drywell temperature and pressure will increase rapidly. The exercise ends when the remaining DC power is lost causing all lights to go off and all indicators fail downscale.

As the training exercise cannot extend for so long, time compression is required. Figure 2 is a graphical depiction of how the scenario was developed and implemented. First, the complete sequence was executed in real time, with no operator actions, for development. Snapshots were taken prior to the most significant events, such as high hydrogen levels after extended core damage, core collapse and, finally, vessel breach. During the training session the sequence will divert from the baseline path due to the mitigation actions performed by the operators. Then, in order to progress to the next stage, the simulator will be reset to the following snapshot and the crew briefed that the actions could not be performed, time has elapsed and what the current plant conditions are. After every snapshot, the simulator will continue to run in real time allowing the operators to follow the guides and carry out new actions.

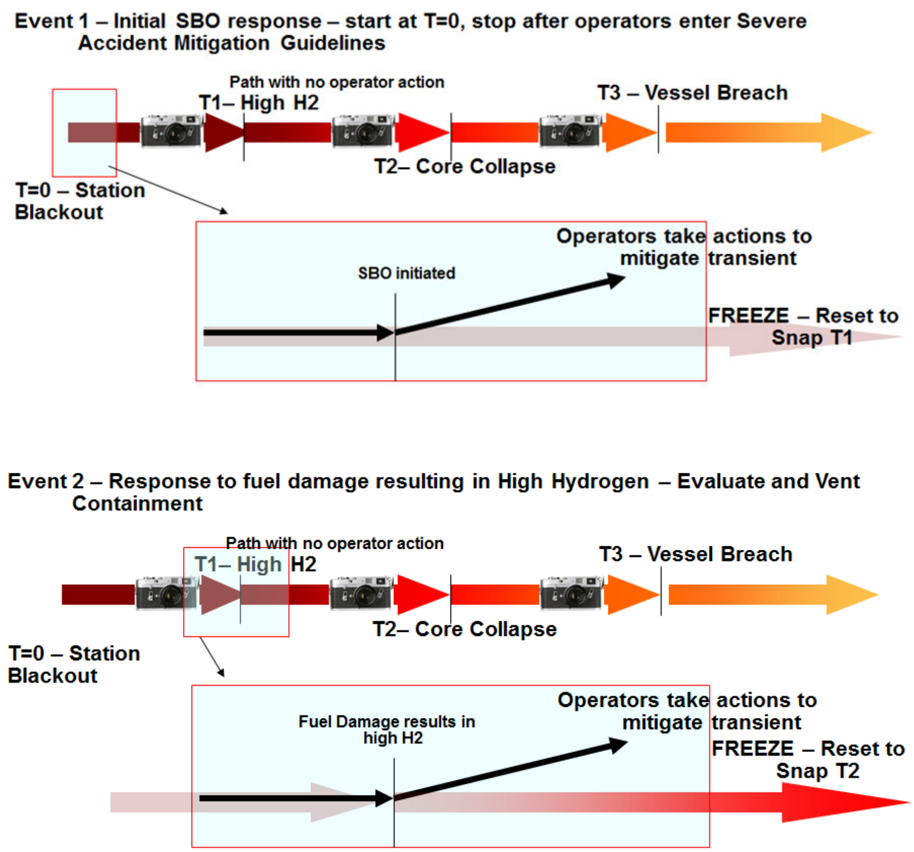

Fig 2: Severe accident scenario implementation during LORT

At certain times during the exercise, the simulator will be placed in freeze to explain the severe accident phenomena and analyse plant response. A 3D dynamic visualization tool with a detailed representation of the vessel and the core is used for support. The graphic is connected to the running simulator and animated in real time. It allows the operators to understand what is happening inside the reactor and how this relates to the indications observed in the control room. Figure 3 shows the 3D graphic during a partial meltdown, with a large amount of molten fuel and debris deposited on a pool of water in the lower head.

Although the uncertainty involving the severe accident models is still high and it cannot be guaranteed that the plant will behave exactly as predicted during the severe accident phase of the sequence, the training value is clear. Operators are faced with situations they would likely encounter, sooner or later, during such an event, with plant conditions that differ greatly from the scenarios used in periodic EOP training.

Fig 3: THOR-MELCOR 3D dynamic visualization tool

In this exercise two examples can be highlighted. First, the core collapse into the lower head, causing a pressure spike, safety relief valve open alarms and hydrogen production. By seeing real time integrated indications in a control room setting, the crews were able to perform a diagnostic exercise previously done using a PowerPoint slide. This exercise allowed for discussions regarding what could cause these indications and application of operator fundamentals in understanding the differences between the indications for core collapse and injection from an emergency system. The observation of the collapse in the 3D graphic reinforced the explanations.

Second, the evaluation of the vessel breach. Prior to vessel failure containment temperature was around 300℉; multiple crews evaluated it as high drywell temperature meeting one of the criteria for indications of a vessel breach. When the failure actually happened, as observed in the 3D graphic, “high or rising drywell temperature” (the SAMGs indication) was demonstrated. Once again, by using simulator training combined with the 3D graphics, procedures steps were better understood by the operators allowing for a more robust training experience not available in a classroom setting.

At Monticello, feedback from the severe accident training has been very positive from operators and managers and additional upgrades are already being evaluated. Examples are the incorporation of revised mitigation strategies into the simulator models, such as emergency power sources or water injection from portable equipment, and the improvements to the simulation of control room conditions under long term SBO regarding indications and lightning. Extending the use of the simulator to emergency planning and engineering training is in progress.

The severe accident training exercises have also drawn interest from outside the plant and the simulator has been visited by various external groups willing to observe the training sessions, among them a delegation from the Nuclear Power Training Center in Japan (NTC) responsible for operator training at all the Japanese PWR plants.

4. The real-time severe accident model

The coupling of MELCOR, developed by Sandia National Laboratories for the US Nuclear Regulatory Commission, with Corys' THOR is thoroughly documented in several references [6][7]. The integration of both codes is based on the design decision to continue using the THOR models, already implemented at most American simulators, for the primary system under all non-severe accident conditions. They would also continue to be used for the containment and balance of plant systems in all situations, even under severe accident conditions. In this way, only the required packages of MELCOR latest available version, 1.8.6, are incorporated into the severe accident model as most areas are left to THOR, including Emergency Core Cooling Systems (ECCS), containment and radiation transport outside the primary.

In Monticello's case, the boundaries between MELCOR and THOR are established at the reactor vessel nozzles. After transition to the MELCOR model, all phenomena occurring inside the vessel are calculated by MELCOR, and all phenomena occurring outside remain within THOR's scope. Figures 4 and 5 are different views of the integration of both models at Monticello. Figure 4 displays the integrated severe accident model nodalization, MELCOR for the vessel and THOR for the containment. Figure 5 describes the interface between the MELCOR model of the vessel on the left with the rest of models run by THOR on the right.

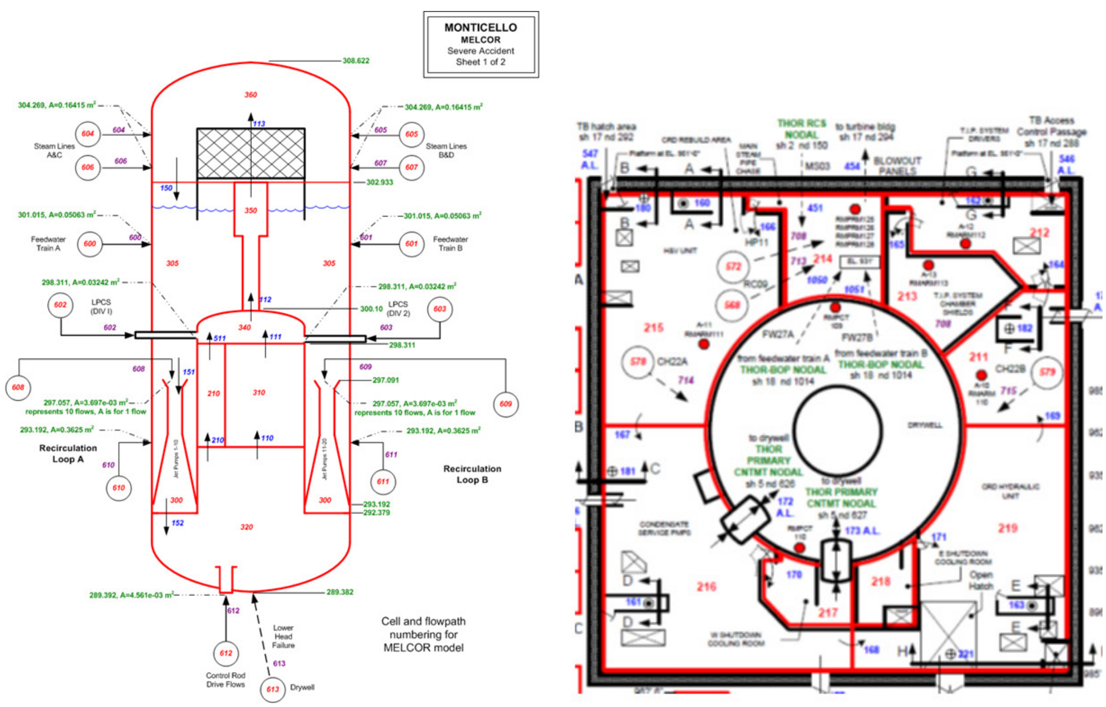

Fig 4: MELCOR vessel and THOR containment nodalization

The transition to the severe accident model occurs just before the onset of large scale clad oxidation which could result in fuel damage and loss of core geometry. At that moment, the vessel model in THOR stops execution and an interface file containing the current primary system conditions is created on the fly. The file is then used as the starting point for the MELCOR models. The entire process takes place in about a tenth of a second and is completely transparent to the trainees. As the sequence progresses, additional MELCOR packages may come into play to simulate in-vessel and ex-vessel severe accident phenomenology such as core collapse, vessel failure, corium relocation or molten corium concrete interaction (MCCI) in the reactor cavity.

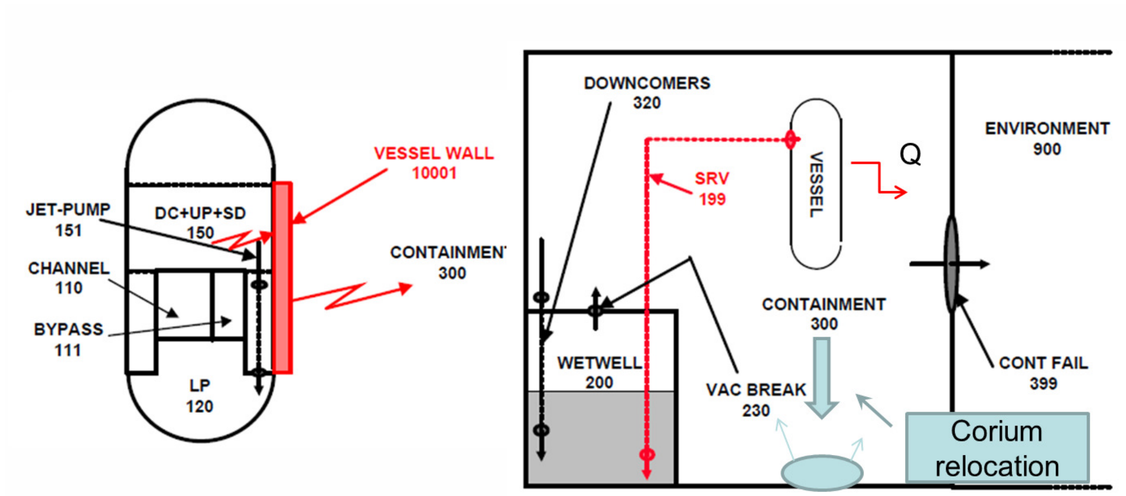

Fig 5: Interfaces of MELCOR vessel with THOR containment models

Significant amounts of data need to be exchanged between the THOR and MELCOR models. At every boundary, MELCOR outputs become THOR inputs and vice versa. Figure 6 shows a schematic representation of the process. Some of the main magnitudes being exchanged are: fluid mass and energy, convective heat transfer from the vessel, energy from ex-vessel phenomena and radionuclide information which will be fed into the radiation detectors model. The data is exchanged at a high rate, ten times per second, to ensure repeatability.

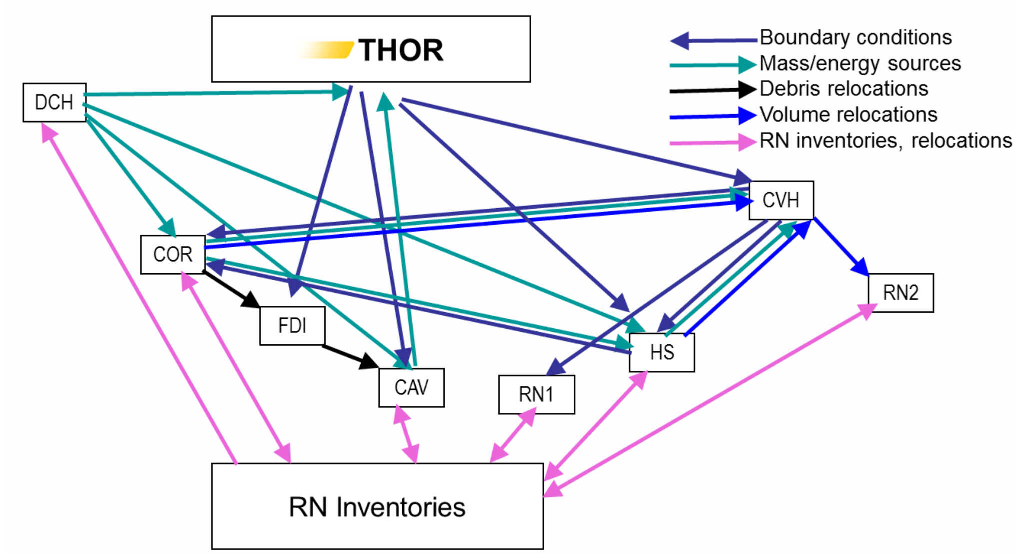

Fig 6: Data exchanges among THOR and MELCOR packages

The THOR-MELCOR integration has been benchmarked against standalone MELCOR runs of the same scenarios and against published MELCOR results for similar plants. The agreement is generally good and the sequences follow similar paths in all cases. Some differences between the integrated and standalone models could require further analysis but, in any case, they should not affect the quality of the severe accident training being pursued. As explained before accuracy is not, at least at the moment, the main requirement for this type of training.

At the time of writing this article, the first THOR-MELCOR models of a pressurized water reactor are being completed. The plant is Calvert Cliffs, a two-loop Combustion Engineering reactor. Furthermore, contracts to implement the MELCOR severe accident models at two more American plants are already in place: Point Beach (a Westinghouse two-loop PWR) and Perry (a General Electric BWR).

5. Conclusions

Monticello's experience demonstrates how full scope training simulators can provide valuable operator training in severe accidents using existing technologies. A well designed integration of robust high-fidelity thermal hydraulic models such as THOR, with well-known severe accident codes such as MELCOR, will allow the instructors to extend training scenarios beyond fuel damage and generate realistic severe accident conditions in real time. The quality of the training will be determined not only by the severe accident model, but also by the detail of the rest of plant models, especially the secondary and containment systems, ventilation, radiation transport and electrical distribution.

The potential of this type of tool is obvious and additional training applications should be explored. At the same time, the severe accident models will continue to improve as the knowledge obtained from the many research programs under development is incorporated. This will reduce the current uncertainties and bring the training in severe accident closer to the mandatory training in emergency procedures we are used to now. In the near future, regulatory requirements in this direction may come into force. As different approaches are being proposed and some of them implemented, the results will need to be shared for the benefit of the whole industry.

6. References

[1] MELCOR - A Computer Code for Analyzing Severe Accidents in Nuclear Power Plants and Other Facilities. Sandia National Laboratories. http://melcor.sandia.gov/

[2] THOR: Advanced Thermal Hydraulic Models. Corys Thunder Inc. http://corysthunder.com/blog/thor/

[3] Petersen M. Monticello Simulator Strength. SimTech Conference. 2012. http://www.simtechconference.com

[4] Shortell T. Implementation of the Severe Accident Codes at Monticello. Power Plant Simulation Conference 2013. The Society for Modeling and Simulation International. 2013. http://scs.org/powerplant/2013

[5] Yarbrough J. Implementation of Severe Accident Codes for Training. Corys Users' Club. 2013. http://www.corys.com/Users-Club--2291.html

[6] Panfil B., Sanders R. Coupling of MELCOR Severe Accident Code to a Full Scope Training Simulator. Conference on Nuclear Training and Education CONTE 2013. American Nuclear Society. 2013. http://www.ans.org/meetings/m_164

[7] Ryan J., Panfil B., Hayes, G. Implementation of the MELCOR Severe Accident Models onto a Real-Time Nuclear Plant Training Simulator. Corys Thunder Inc. 2013. barney.panfil@corysthunder.com