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THE *NUCLEAR NEWS* INTERVIEW

Karen Vierow: Severe accident code analysis

Three computer programs used to simulate severe accidents at nuclear plants are themselves analyzed for comparison.

Purdue University researchers are working on a project to compare the three leading severe accident programs, or codes, used by the nuclear power industry in the United States. The codes—MELCOR, MAAP4, and SCDAP/RELAP5, all developed for different approaches and for different purposes—have been tested at Purdue using a hypothetical accident scenario (station blackout with no recovery of auxiliary feedwater) at a four-loop pressurized water reactor based on the now closed Zion nuclear power plant. Conservative analysis conditions were used to investigate the integrity of the steam generator tubes and other components during the accident's progression. Despite considerable differences in the codes themselves, test results show that the codes are similar in terms of thermal-hydraulic and core degradation response.

To date, plant data for an actual severe accident at a nuclear power plant exists only from the Three Mile Island-2 incident in 1979. Code simulations for the TMI-2 scenario have been carried out in the past with SCDAP/RELAP, MELCOR, and MAAP4, but never have the results of the three codes for the same hypothetical accident been compared in detail, and never has the relative state of modeling been pursued this thoroughly.

Vierow: "The codes have undergone significant upgrades over the years and are becoming more best-estimate in nature."

Karen Vierow, an assistant professor in the School of Nuclear Engineering at Purdue University, is leading the research, which is being sponsored by the Nuclear Regulatory Commission. She has worked on the project with Yehong Liao and Jennifer Johnson, graduate students at Purdue; Mark Kenton, a MAAP4 developer currently with Creare, Inc.; and Randy Gauntt, a MELCOR developer from Sandia National Laboratories. The accident simulations have been performed, and Vierow is now in the process of analyzing the data.

MELCOR was developed by Sandia National Laboratories; MAAP4 (Modular Accident Analysis Program) by Fauske & Associates, Inc.; and SCDAP/RELAP5 (Severe Core Damage Analysis Program/Reactor Excursion and Leak Analysis Program) by the Idaho National Engineering and Environmental Laboratory.

Vierow talked with Rick Michal, *Nuclear News* Senior Editor, about the code research work.

Interview begins on next page

How did you get involved in this research?

About four years ago, I was doing some validation of the MELCOR code. I then started studying MAAP4 and SCDAP/RELAP5 to look into the current state of the technology. I found that the three codes all have their own unique features and that they can learn from each other. That was the reason I extended my work to researching all three codes.

Who are the main users for each of the codes?

MELCOR and SCDAP/RELAP5 are used by regulatory agencies and research institutions to evaluate hypothetical severe accident events, such as a station blackout or the potential for a steam generator tube rupture. MAAP4 is the severe accident code most widely used by nuclear utilities and vendors because of its short run time and reduced requirements for code expertise. The Electric Power Research Institute and many utilities also use it for the NRC's Significance Determination Process and other analyses.

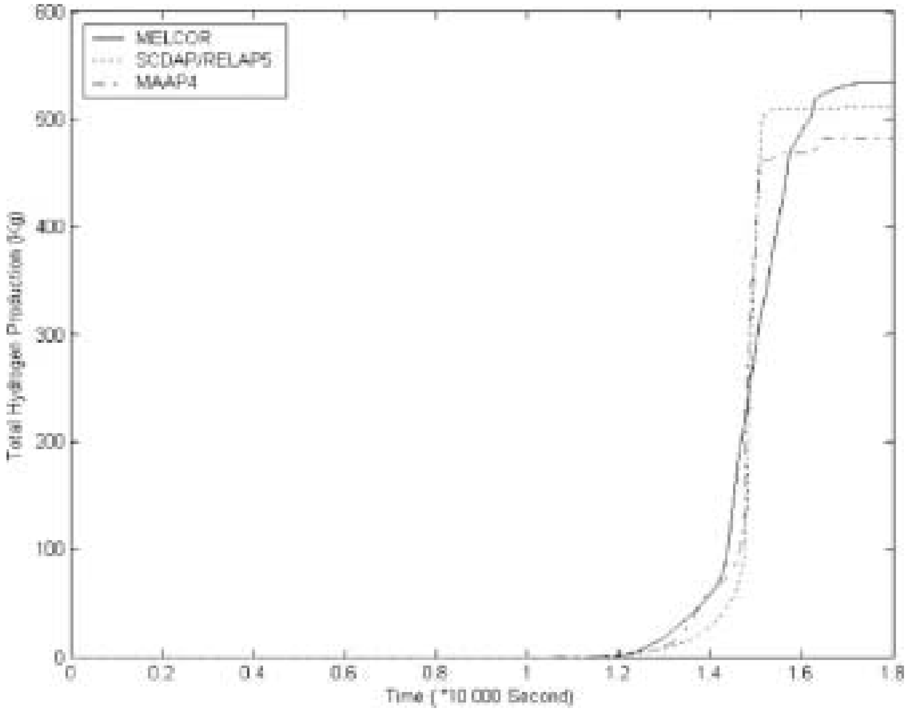
In addition, MAAP4 can be used by an existing plant to simulate how a proposed modification would affect plant operations. And plant designers could use any of the codes to predict the performance of future plants if a certain set of conditions were imposed on those plants.

The codes have undergone significant upgrades over the years and are becoming more best-estimate in nature. MELCOR was originally intended to be a probabilistic risk assessment tool; the initial objective for the MAAP4 code was to predict severe accidents, using simple models based on first principles; and SCDAP/RELAP5 began as a best-estimate code with physics-based models. While still different, the capabilities and applications of the three codes have been converging over the years.

Could you provide an overview of the codes?

All three codes are capable of modeling reactor coolant system response, core material chemical reactions, core heat-up, degradation, and relocation, heat structure response, and other severe-accident phenomena.

Modeling of fission product release and transport and containment phenomena are integrated into the MELCOR and MAAP4 codes. SCDAP/RELAP5 is characterized by its detailed, mechanistic models of severe-accident phenomena; however, the calculations can be rather time-consuming. SCDAP/RELAP5 typically uses on the order of hundreds of hydrodynamic components to model the primary system. MAAP4 calculations require minimal computation time with simplified geometry models. MELCOR falls in between these two codes, being much closer to SCDAP/RELAP5 in terms of nodal complexity. It runs at a moderately fast speed and has a large number of mechanistic models. In early applications, MELCOR's spatial discretization of a nuclear power plant consisted of roughly 10–30 control volumes, and a large number of parametric calculations could be run in a short time. With the more complicated calculations that are now being demanded of it, MELCOR's run times have been increasing and are roughly equivalent to those of typical SCDAP/RELAP5 calculations.



The onset of hydrogen production (start of fuel damage) is predicted to occur at nearly the same time by all three codes, and roughly the same amount of hydrogen is produced.

What kind of accident simulation did you run for your research?

The information input into the three codes prior to the accident simulation was made as similar as possible, and consistent conditions were placed on all of the analyses. Of course, to arrive at a set of conditions that the three codes could cover, various assumptions had to be made that rendered the calculation unrepresentative of plant behavior after some point in the calculation. Since the analysis scope of SCDAP/RELAP5 is limited to the failure of the primary side pressure boundary, the test focused on in-vessel severe accident phenomena, with a special interest in the steam generator tube response to thermal transients during this period. It's important to remember that our objective was to compare the three codes, as opposed to validating them.

How many simulations of the same accident were performed?

I ran the analysis probably 20 times for MELCOR and SCDAP/RELAP5. Marc Kenton performed the MAAP4 analysis because I do not have this code at Purdue. I found that it was difficult to reconcile all of the input for each of the codes. When I say input, I mean the geometric description of the plant, the initial conditions, the boundary conditions, etc. I tried to make them as consistent as possible for all three codes, but sometimes it was easy to miss something.

There are many modeling options and a lot of things that are compared. It's not just the same geometry, but also the same physics models that must be analyzed. So, I have to run the codes many times to get the parameters to be comparable.

As for computing power, I've found that MAAP4 runs much faster than the other two codes. With MELCOR and SCDAP/RELAP5, it depends on what type of event is being run. Sometimes the test will go for a few minutes, but sometimes it will take several hours. It's not in terms of months as it used to be for other codes. The increase in computer power definitely shortens our simulation time.

Why did you pick a four-loop PWR, based on the Zion plant, to simulate an accident?

Zion was chosen because it is a representative four-loop plant in the current PWR fleet. We are also evaluating the codes for other plant types, including boiling water reactors and Babcock & Wilcox OTSG (Once Through Steam Generator) PWRs. Since Zion was one of the plants used in the famous NUREG-1150 assessment of severe accident risks, input decks that we could start with were already available. A lot of safety systems and normal features were disabled so that the core would melt and the physics models in the codes would be tested through core degradation, relocation, and many other possible serious events.

What are the results of the simulations?

The results show that the thermal-hydraulic phenomena and major in-vessel severe accident phenomena are in good agreement for the three codes. Also, the integral effect of diversified core models in terms of total hydrogen production and total core debris mass slumping into the reactor vessel's lower head are consistent for the three codes. This consistency will probably reduce the codes' prediction differences for ex-vessel severe accident phenomena, such as ex-vessel corium water or corium concrete reaction, hydrogen behavior in the containment, and containment pressure response. There are also some discrepancies that could be termed as minor and that are possibly due to uncertainties in the numerics and physics models.

During the testing, several key assumptions were made to account for known differences in heat transfer modeling and the representation of countercurrent natural circulation of hot gases. Given these assumptions, the three codes predicted similar temperatures in the various reactor coolant system components. Future work could focus on resolving the modeling differences in these few key areas.

TIMING OF KEY EVENTS

Event	MELCOR (s)	SCDAP/RELAP5 (s)	MAAP4 (s)
Start of core uncovery	7 680	7 160	9 615
Core completely voided	11 620	9 950	14 500[a]
5% cladding oxidized	13 780	14 806	13 800
Slumping to lower head	16 189	16 130	21 994

[a] MAAP4 calculated a very slow rate of water level decrease at the bottom of the core, leading to a substantial delay in the voiding of the bottom node. This is, in part, due to continued slow draining of the pressurizer. (s) = second

Were there any uncertainties during the simulations?

There is regarding core degradation, in its late phase, where things are relocating in the core. We have less detailed knowledge of how the core would relocate during a severe accident. The industry has some good ideas, but there is minimal plant data on it because the only actual data comes from TMI-2, when the core partially melted. Based on that and on experiments, physics models were developed that were put into the codes. That's where some of the uncertainties come from—not having a complete knowledge of the phenomena, trying to use models based on smaller experiments and applying the results to a full plant.

What was the most challenging task in comparing the codes?

The hardest part was to compare the physics models. We're trying to run all three codes on an even playing field. There are differences in the nature of the codes, and each has a different philosophy because the developers of each have their own knowledge and their own way of thinking. It was difficult to choose the right physics models for these analyses so that each code was given a fair chance to calculate the same event.

What were your conclusions at the end of the research?

The key conclusion was that each of the codes has high capabilities, but that some have physics models that could be incorporated into the others. So, while all the codes are impressive, each can benefit from learning from the other codes—looking at the key assumptions made in the other codes and seeing where some of the assumptions are valid and where some models could be improved.

Could you elaborate on how and what the codes can learn from one another?

For example, SCDAP/RELAP5 has the most detailed treatment of hydrogen production from oxidation. The hydrogen production rate is a key indicator of the progression of a hypothetical severe accident. Once the fuel is damaged, MELCOR has good physics models to predict the fission product release and transport phenomena. These capabilities have been removed from recent versions of SCDAP/RELAP5, and another code performs these calculations for SCDAP/RELAP5 users. Perhaps the MELCOR code will incorporate some of the knowledge base from SCDAP/RELAP5 for hydrogen models or use a more parametric approach to account for uncertainties in hydrogen-related phenomena. MAAP4, on the other hand, is able to complete calculations in orders of magnitude less time than the other codes due to simplified versions of basic equations and fast-running models based on first principles. The assumptions made in MAAP4 to allow it to run so fast should be further analyzed and applied as appropriate into the other codes.

Are there any specific improvements you could talk about?

There were no major deficiencies in the codes. Each one could, of course, add a model here or there, or make an existing model more detailed. In fact, I am working now to develop new physics models for the codes and modify current ones to improve their prediction capabilities.

Could the codes be used to test reactor designs that may be used in a future hydrogen economy?

These three existing codes were designed to analyze light-water reactors. In a hydrogen economy, the reactor would be a high-temperature design that would be cooled by a gas or molten salt instead of water, so the codes would have to be modified to be valid. The geometry of the high-temperature plant is also different from that of an LWR. The high-temperature plant could be what is called a prismatic design, or a pebble bed design that has a lot of graphite in it. That new code would need to include new models for the graphite behavior and the different geometry of the core. There would not be the traditional vertical fuel rod assemblies that LWRs have.

These codes are big computer programs, and they have perhaps 400 000 lines of Fortran. They have a numerical architecture. The basic equations are all set up, and it's not an easy task to make major modifications or write a new code. Each code has a core set of writers that can make major modifications to it.

What kind of effort would be needed to develop codes for Generation IV gas-cooled reactors?

Some of this is included in my earlier statements on reactors for hydrogen production. Gas properties would need to be confirmed and the codes would need to be tested for their capability to run without the light water coolant/moderator they were developed for. Changing to a gas coolant should not be too much of a challenge because gas behavior is much easier to predict than steam/water behavior with its phase changes between liquid and vapor and the complicated steam/water property tables. In addition to modeling the different fuel geometry and incorporating severe accident models for phenomena peculiar to gas-cooled reactors, events not considered for LWRs must be modeled. These would include introduction of air or water into the primary system that could result in graphite burning. We believe the codes are flexible enough that they can be modified to model Gen IV reactors. NN

TIMING OF HEAT STRUCTURE FAILURES

Event	MELCOR (s)	SCDAP/RELAP5 (s)	MAAP4 (s)
Onset of natural circulation	9 300	9 000	9 720
Failure of surge line	16 287	14 955	14 860
Failure of hot leg piping on pressurizer loop	16 464	15 720	15 267
Failure of SG tubes on pressurizer loop	16 553	15 210	14 913