

# Using the Coupled MELCOR-RELAP5 Codes for Simulation of the Edward's Pipe

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## Abstract

MELCOR [1] was recently coupled with RELAP5 [2] at Sandia National Laboratories under an executive program developed at INEEL [3], using the Parallel Virtual Machine (PVM) message exchange software [4-6]. As a result of the coupling, the two hydrodynamic codes can now perform an asynchronous exchange of calculated variables while the codes are running simultaneously. This allows the exchange of current data at predefined time intervals. Variables such as fluid mass, enthalpy, temperature, pressure, temperatures of boundary surfaces, and heat fluxes can be exchanged. An advantage of this coupled approach is to have one code calculate a domain where it naturally excels, and use another code to calculate a different domain where it, in turn, excels; all this is done while selected physical variables are exchanged so that the entire domain is coupled. For example, RELAP5 could be used to calculate intricate hydrodynamic behavior in complex pipe and channel systems, while MELCOR could be used to simulate containment behavior and environments where severe accident reactor physics, such as core relocation, oxidation, hydrogen combustion, and radionuclide release occur.

This paper reports the results of a test to demonstrate the capability of the new coupling. The test involves calculation of a simple experiment, the Edward's Pipe Blowdown Test. We modeled the pipe twice, once in RELAP5 space, and again in MELCOR space. (We acknowledge that there are many combinations that could be used. For example, RELAP5 could compute mass flow and pressure drop for one half of the pipe, and MELCOR could do the other half.) We proceeded to have RELAP5 compute pressure and void fraction within its pipe domain, and then send the pressure and void fraction at the two ends of its pipe into the MELCOR simulation. MELCOR control volumes (CVs) received the RELAP5 output, as boundary conditions in the pipe simulation. Then,

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MELCOR calculated a pressure drop within its pipe domain, as well as mass flow, based on the boundary conditions at the CVs.

The Edward's Pipe simulation started with a pipe that was originally at 7.0e6 Pa. At time zero, one end was opened to the atmosphere. The MELCOR-RELAP5 simulation required a few seconds to complete on a DEC Alpha workstation. We found the output was in good agreement with the RELAP5-RELAP5 simulation. For completeness sake, we also compared the results with stand-alone MELCOR and RELAP5-CFD simulations, and found the results to be consistent.

### **Introduction**

There has been increased interest in the nuclear reactor community for reactor codes that are coupled to other codes [7-12], so that the user may judiciously exploit the domain where one naturally excels, and use another code to calculate a different domain where it, in turn, excels. For that purpose, MELCOR was recently coupled with RELAP5 under an executive program developed at INEEL, using PVM message exchange software. As a result of the coupling, the two hydrodynamic codes can now perform an asynchronous exchange of calculated variables while the codes are running simultaneously. This allows the exchange of current data at predefined time intervals.

The coupling via PVM allows for selected physical variables to be exchanged so that the entire domain can be simulated. (For example, RELAP5 could be used to calculate intricate hydrodynamic behavior in complex pipe and channel systems, while MELCOR could be used to simulate containment behavior and environments where severe accident reactor physics, such as core relocation, oxidation, hydrogen combustion, and radionuclide release occur.)

In order to test the new coupling, we conducted a simulation that involves calculation of a simple experiment, the Edward's Pipe Blowdown Test. We modeled the pipe twice, once in RELAP5 space, and again in MELCOR space. We proceeded to conduct two simulations: a stand-alone MELCOR calculation and a coupled MELCOR-RELAP5 calculation. We also compared our results with the RELAP5-RELAP5 and RELAP5-CFD simulations. The results show that all four simulations yielded similar results, thus increasing our confidence in our coupled code system.

### **MELCOR**

MELCOR is a simulation code developed at Sandia National Laboratories for the U.S. Nuclear Regulatory Commission (USNRC). MELCOR is a mechanistic modeling code that can be used for best-estimate calculations in the prediction of severe reactor phenomena such as core degradation and relocation, oxidation, performance of engineered safety features, ex-vessel debris/concrete interactions, and radionuclide release. The code uses two-fluid hydrodynamics with a full six-equation set and equations of state for water and noncondensable gases. The code has undergone a host of validation and verification comparisons that have demonstrated its adequacy in severe accident analysis as well as containment transient analysis. As such, MELCOR is

currently the USNRC's tool of choice for integrated analyses of the progression of severe accidents in light water reactors.

### **Model Description**

Two input models were developed, a stand-alone MELCOR model and a MELCOR-RELAP model (see Fig. 1). The figure also shows the stand-alone RELAP5 model. The stand-alone MELCOR model consisted of 10 CVs that modeled the pipe, and two CVs that modeled the high- and low-pressure boundary conditions. MELCOR CVs are similar to RELAP5 PIPE components. The RELAP5 model consisted of one PIPE component that was divided into 10 cells. We used 10 CVs because MELCOR is a lumped parameter control volume code. Therefore, it yields one pressure solution (scalar) for each CV, as opposed to a finite difference or finite element code, which would yield a vector of pressures across a pipe component. The arrows in Fig. 1 represent flow paths (FLs), which perform the momentum exchange between the CVs. As the figure shows, each CV is connected to another CV via a FL. FLs are close cousins to RELAP5 SNGLJUN components.

There are certainly many number of potential ways to model the MELCOR-RELAP5 interface for the Edward's Pipe experiment. For example, RELAP5 could compute mass flow and pressure drop for one half of the pipe, and MELCOR could do the other half. In our case, we elected to have RELAP5 compute pressure and void fraction within the PIPE domain, and then send the pressure and void fraction at the two ends of its pipe into the MELCOR simulation so they would behave as boundary conditions. Thus, the RELAP5 output was received by MELCOR time-dependent CVs at the left- and right-most CVs. These time-independent CVs acted as boundary conditions in the MELCOR pipe simulation, allowing MELCOR to proceed to calculate pressure drop, void fraction, mass flow, etc, within its CV domain. The MELCOR-RELAP5 model was otherwise identical to the stand-alone MELCOR model.

### **Simulation**

The Edward's Pipe model was 4.1 m long and had an inside diameter of 0.073 m. The fluid inside the pipe was at 7.0 MPa and 500 K. At time zero, the disk rupture was modeled by having a fully-opened flow path connect the high-pressure volume to atmosphere, thus allowing the fluid to escape.

In essence, the simulation phenomena consisted of two parts: rapid depressurization until the fluid reached saturation conditions, followed by a period of slower depressurization as the saturated fluid exited the small rupture. The period of rapid depressurization lasted about 6 ms, and the pressure dropped from its initial value to about 2.75 MPa (see Fig. 2). The figure shows excellent agreement between the stand-alone MELCOR, MELCOR-RELAP5, RELAP5-RELAP5, and RELAP5-CFD pressures, with most pressures literally overlapping, and the biggest pressure difference between the four simulations being about 0.25 MPa. However, if distinctions must be made, the RELAP5-RELAP5 calculation was slightly higher from about 6 ms to 0.3 s. The other three simulations pretty much overlapped each other during that time domain. From 0.3 to 0.6 s, the RELAP5-RELAP5, stand-alone MELCOR, and the RELAP5-MELCOR simulations overlapped each other, with the RELAP5-CFD simulation flanking them slightly from above.

It took almost 0.6 s to drop the pressure to atmospheric value. By that time, the void fraction nearly reached 1.0 in all four calculations, see Fig. 3. The figure shows good agreement between the stand-alone MELCOR, MELCOR-RELAP5, RELAP5-RELAP5, and RELAP5-CFD void fractions. The RELAP5-RELAP5 simulation tended to oscillate between the RELAP5-CFD and MELCOR-RELAP5 results. Because of the s-shaped curve of the void fraction, the codes differed by as much as 0.28 at 0.2 s, but generally held a much tighter gap, on the order of 0.1 or less for the majority of the transient.

The void history followed an s-shaped profile, as the void changed slowly during the first quarter of the transient, due to the fluid's high pressure and inertia. Then, there was a rapid change in void fraction as the fluid continued to depressurize and exit the tube during the second quarter of the transient. This was the time when the largest mass flows occurred. Finally, during the last half of the transient, there was a rapid decrease in the differential change of the void as a result of the fluid approaching equilibrium with the atmosphere. By that time, most of the fluid had exited.

Because the ratio of the pre-transient pressure and the break pressure was much higher than 10 (it was 69), the pipe flow exhibited choked flow at the exit during the first 0.4 s. Thereafter, the pressure dropped at a much slower rate. Capturing the break flow was key to obtaining a good simulation of the Edward's Pipe transient. However, Ref. [10] did not include break flow rate comparisons. Rather, it compared mass flow at the mid point of the pipe. Therefore, for comparison purposes, we will also look at mass flow rate at the middle of the pipe for our two simulations. Figure 4 shows the pipe mass flow rate at the pipe midpoint. Whereas the void fraction and pressure compared the most favorably amongst the four codes, the mass flow rate showed the most differences and for longer fractions of the simulation time. The cause for this is not fully known, as various choked flow models are used by the codes and coupling effects might also be the culprit. For example, RELAP5, MELCOR, and the CFD code each employ their respective calculational time steps. Further, the executive employs a user-input time-step where data is transferred amongst the codes. Other simulations have shown that this can have an impact on the solution [9].

The flow rate during the rapid depressurization stage was captured quite well by all four simulations. From 0.6 ms to about 0.07 s, all simulations except the RELAP5-RELAP5 simulation agreed that there should be a flow rate decrease. Then, from as little as 0.06 s (RELAP5-RELAP5) to as much as 0.12 s (RELAP5-CFD), the four simulations predicted a flow rate increase that tended to last about 0.15 s. After that flow rate increase, the RELAP5-RELAP5 simulation began a primarily exponential decay in flow rate starting at about 0.16 s into the transient; there was a 0.08 s period that started at 0.26 where the RELAP5-RELAP5 mass flow rate remained steady. Thereafter, it continued on its exponential decay. The other three codes began their exponential flow rate decrease at about 0.24 s. This decay continued until 0.6 s.

The worst agreement occurred at 0.1 s, when the MELCOR-RELAP5 simulation yielded 32 kg/s, while the RELAP5-CFD calculation predicted only 8 kg/s. For comparison

purposes, the stand-alone MELCOR output showed 14 kg/s, while the RELAP5-RELAP5 simulation was 22 kg/s. It was encouraging that during the initial 6 ms, and from about 0.24 to 0.6 s, all four simulations produced fairly close mass flow rates. In addition, the peak flow rate differed by only 2 kg/s. The calculated peak flow rate occurred within 0.13 s of each other. So, the agreement amongst the four simulations was fair to good from 0 to about 0.25 s. Thereafter, the agreement was very good.

The code-to-code comparisons are summarized in Table I.

The transient was terminated at 0.6 s, when near steady-state conditions had been reached. The simulation required a few seconds to complete on a DEC Alpha workstation.

### **Conclusion**

We tested the code system that was obtained recently when MELCOR was coupled with RELAP5 under an executive program via PVM. Because output data already existed for the Edward's Pipe Test, we decided to simulate Edward's Pipe, too. We proceeded to compare stand-alone MELCOR, MELCOR-RELAP5, RELAP5-RELAP5, and RELAP5-CFD results.

We found the calculated pressure from the four simulations was in excellent agreement, most of the time overlapping each other, and at worse being within less than 0.25 MPa of each other for a small fraction of the transient.

The stand-alone MELCOR and MELCOR-RELAP5 void fractions were in good agreement with the RELAP5-RELAP5 and RELAP5-CFD simulations, with the void gap being within 0.1 for the majority of the transient, and on various occasions, the void history profiles overlapped and crossed each other.

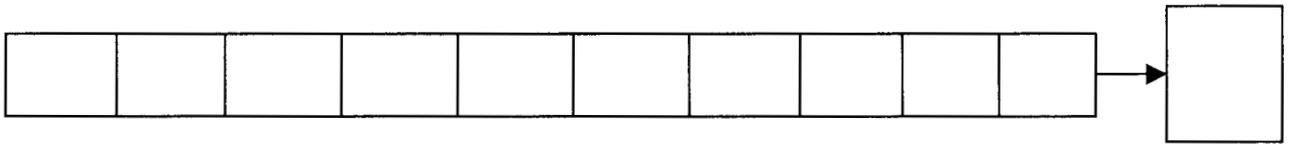
A close study of the mass flow rates shows an intriguing interweaving maze of mass-flow-rate history profiles. At the very least, we can say that the stand-alone MELCOR and MELCOR-RELAP5 break flow rate was qualitatively consistent with the RELAP5-RELAP5 and RELAP5-CFD output. In addition, during the initial 6 ms, and from about 0.24 s and on, all four simulations produced fairly close mass flow rates. The peak flow rate differed by less than 2 kg/s. Further, the four calculated peak flow rates occurred within 0.13 s of each other. On the other hand, the history profiles show some large differences from 6 ms to about 0.25 s, which happened when the void fraction changed the most. Thus, we can say that the agreement amongst the four simulations was fair to good from 0 to about 0.25 s. Thereafter, the agreement was very good.

The above results give us confidence that the MELCOR-RELAP5 interface is working as intended. Extensive testing of the interfaced values shows that the appropriate parameters and magnitudes are being exchanged.

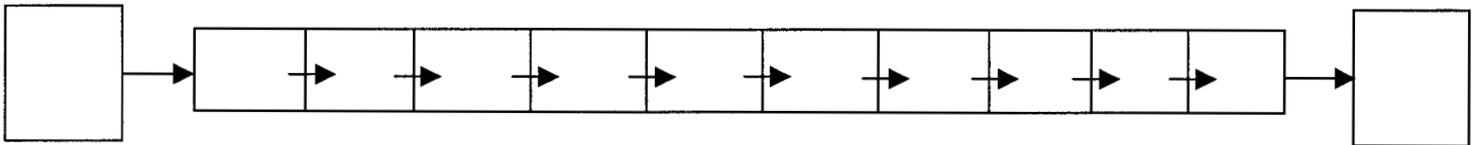
The exercise also shows that MELCOR is quite capable of simulating transients such as Edward's Pipe.

This study, as well as those that have already been conducted, plus those that are currently being conducted, should shed light as to how to best model systems that are being simulated with coupled codes. We feel such modeling might be as much an art as a science, with still much yet to be learned. On the other hand, we feel that coupling multi-physics codes together can solve much complex phenomena that are coupled. For example, MELCOR could be coupled to a fire code for the purpose of analyzing fire, smoke, and heat transport in complex flow networks such as buildings and their HVAC systems. MELCOR could also be coupled to structural codes, and so on.

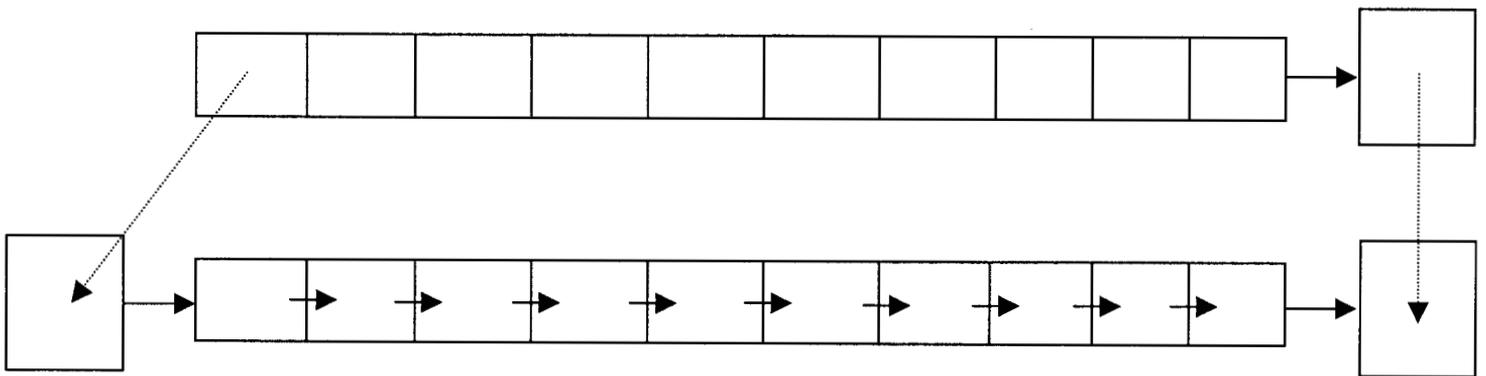
**Stand-Alone RELAP5 Calculation**



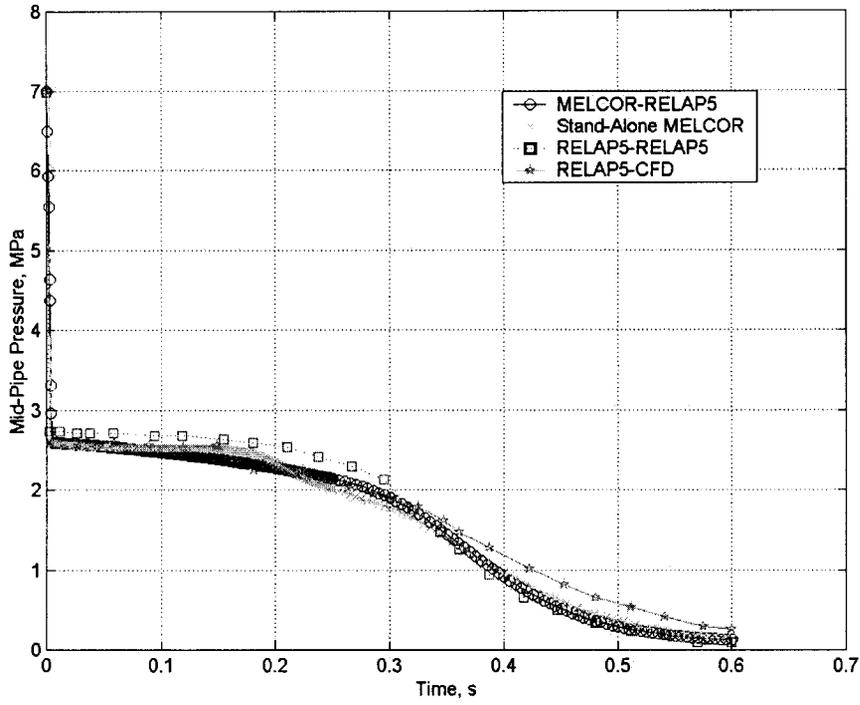
**Stand-Alone MELCOR Calculation**



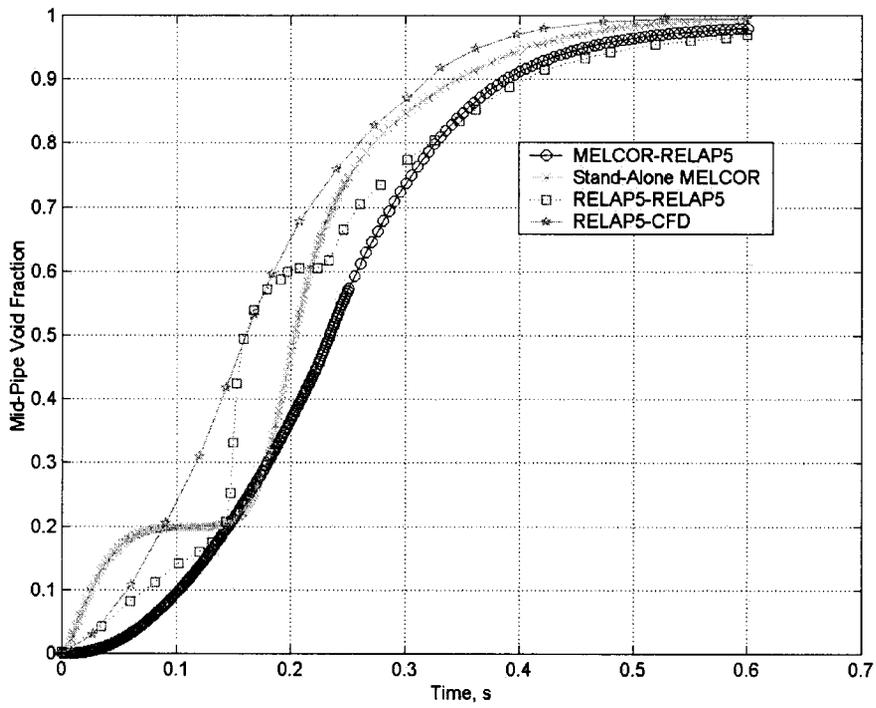
**MELCOR-RELAP5 Calculation**



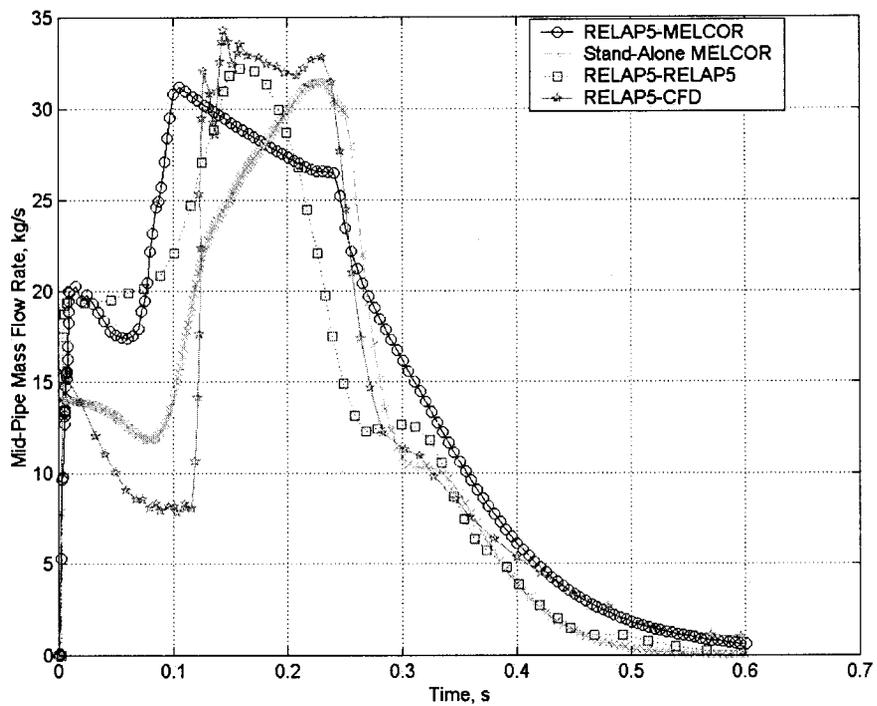
**Figure 1. MELCOR and RELAP5 Input Models.**



**Figure 2. Mid-Pipe Pressure.**



**Figure 3. Mid-Pipe Void Fraction.**



**Figure 4. Mid-Pipe Mass Flow Rate.**

**Table I. Summary of Code-to-Code Comparisons for the Key Parameters.\***

<b>Parameter</b>	<b>Degree of Agreement</b>	<b>Comments</b>
Pressure	Excellent.	The RELAP5-RELAP5 pressure was slightly higher for the first half of the transient. For the second half, the MELCOR-RELAP5, stand-alone MELCOR, and RELAP5-RELAP5 calculation were slightly lower than the RELAP5-CFD simulation.
Void Fraction	Very good.	Most code-to-code differences (maximum value – minimum value at a fixed time), typically differed by less than 0.1. Most of the code overlapping occurred during the second half.
Mass Flow Rate	Fair to good, first half of the transient; very good, second half of the transient.	During the initial 6 ms, and from about 0.24 to 0.6 s, all four simulations produced fairly close mass flow rates. The worst agreement occurred at 0.1 s, when the MELCOR-RELAP5 simulation yielded 32 kg/s, while the RELAP5-CFD calculation predicted only 8 kg/s. At that time, the stand-alone MELCOR output showed 14 kg/s, while the RELAP5-RELAP5 simulation was 22 kg/s. From 6 ms to 0.24 s, the codes yielded flow rates that on occasion had different signs associated with their slopes. On the other hand, the peak flow rate as calculated by all four codes differed by only 2 kg/s. The calculated peak flow rate occurred within 0.13 s of each other.

\*These comparisons were made on a relative basis of how the four code simulations compared towards one another.

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