RELAP5 BWR-4 model development and validation for NPP Mühleberg (KKM)

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Abstract

The RELAP5 thermal-hydraulics code was developed for best-estimate transient simulation of light water reactor coolant systems during postulated accidents. Mühleberg NPP (KKM) equipped with a BWR-4 reactor has been using the RELAP5 code from the early 90s for deterministic safety analysis. The KKM RELAP5 model has been undergoing an extensive project to upgrade and validate the plant model in order to provide the plant with the ability to:

- independently review transient and accident analysis calculations that vendors perform to satisfy regulatory requirements or guidelines, e.g., ENSI Guideline A-01,
- independently review transient and accident analysis calculations that vendors perform to validate the design of planned plant modifications.
- independently perform scoping analyses in these same areas, in advance of vendor calculations.

The KKM RELAP5 model development and validation consists of several interconnected stages. The validation work performed by KKM focuses mainly on the specific KKM model rather than on a generic validation of RELAP5. For the generic validation, KKM relies on the great amount of work performed by national labs, universities and research institutes all over the world. All the simulation results presented in this work were run with RELAP5 mod3.3 patch04 from the US NRC.

The first stage of the KKM specific validation involves ensuring that the physical plant (e.g., geometry, materials, system and component design, and protection and control system logics and set points) is accurately represented by the RELAP5 model. In one sense, this is largely a documentation effort that requires showing traceability from the RELAP5 model back to a plant design or as-built document. The second stage, which aims to show that the model's predictions are consistent with actual plant behavior, requires benchmarking the model to actual plant operational data (steady-state and transient). These benchmark comparisons are evaluated to determine how accurately the model predicts plant behavior over a wide range of operating conditions. Results from these comparisons are used to validate the model. The third stage involves demonstrating that the model will simulate and yield physically reasonable results for postulated transient and accident scenarios that are analyzed by vendors. Additionally some separate test cases are run to validate specific parts of the model and to help assist the choice of some modelling options. Two examples are presented in this paper.

This paper describes the KKM RELAP5 model, validation process and the transients that are used for model validation. The most interesting simulated plant events, including a total loss of feedwater (LOFW) test, are presented. Overall, the KKM RELAP5 model predictions match very well with the plant data.

Keywords: RELAP5, BWR, validation, transient

1. Introduction

For the last ten years, the safety requirements from the Swiss Federal Nuclear Safety Inspectorate (ENSI) have been increasing. This trend intensified even more since the Fukushima severe accident. These facts require state of the art thermalhydraulic analysis capabilities at the utilities which leads the Swiss nuclear operators to further develop and improve their own best-estimate transient analysis capabilities and tools. For this purpose, over the last four years, the Mühleberg Nuclear Power Plant (KKM) equipped with a BWR-4 improved Mark I nuclear reactor has developed a new RELAP5 model of the plant, with the support of the company Studsvik Scandpower. The starting point for the development was a RELAP5 model that was developed by RMA Associates in the 1990s and, through a series of ongoing model development steps, is being updated to current modelling methods and validated against plant design and performance data.

Swiss regulators require constant plant improvements and introduce new requirements for deterministic safety analysis. A new regulator guideline was introduced in 2009 [1, 2]. This guideline requires the use of best estimate models plus conservative assumptions or boundary conditions. The use of BEPU (best estimate plus uncertainty) is also encouraged by the regulator in order to assess the uncertainties.

In this work we present an overview of the model development and validation work performed in this context.

The main interest in developing a well-documented and validated RELAP5 model is to provide KKM with the ability to:

- independently review transient and accident analysis calculations that vendors perform to satisfy regulatory requirements or guidelines, e.g., ENSI Guideline A-01,
- independently review transient and accident analysis calculations that vendors perform to validate the design of planned plant modifications, e.g., back-fits,
- independently perform scoping analyses in these same areas, in advance of vendor calculations.

To develop this ability, the RELAP5 model must be:

1. developed from well-documented plant design and performance data,
2. shown to yield predictions consistent with actual plant behavior, and
3. demonstrated to be capable of simulating many of the same transients and accidents that vendors analyze to satisfy regulatory requirements/guidelines and/or to validate the design of plant modifications.

The first of these requirements involves ensuring that the physical plant (e.g., geometry, materials, system and component design, and protection and control system logics and set points) is accurately represented by the RELAP5 model. In one sense, this is largely a documentation effort that requires showing traceability from the RELAP5 model back to a plant design or as-built document. Activities in this phase of the project, i.e., development of the model and the resulting input deck, are described in a 420 page long separate document called an input deck description.

The second requirement, to show that the model's predictions are consistent with actual plant behavior, requires benchmarking the model to actual plant operational data (steady-state and transient). These benchmark comparisons are evaluated to determine how well the model predicts plant behavior over a wide range of operating conditions. Results from these comparisons are used to validate the model. Note that these comparisons often include simple model tests that represent a single system or a particular model part in order to study its performance separately.

The third requirement involves demonstrating that the model will simulate and yield consistent results with postulated transient and accident scenarios analyzed by vendors.

After the mentioned steps, a reliable base model is ready. This is referred to as a base model which in this context means that each particular application or type of transient may still need a transient specific validation and may require transient specific model changes. For instance, for ATWS analysis a full 3D neutronics calculation could be necessary, so for this type of analysis, we coupled our RELAP5 model to Studsvik's 3D neutron kinetic code S3K [3]. Note that the point kinetics parameters used for the base model were obtained from results of the CASMO4-SIMUTE3 codes. As another example, for LOCA analysis, we performed a large sensitivity and parametric study to assess the impact of important model options, like CCFL, on the particular transient of interest [4].

2. Model Development

The RELAP5 code [5] has been developed for best-estimate transient simulation of light water reactor coolant systems during postulated accidents. The code models the coupled behavior of the reactor coolant system and the core for loss-of-coolant accidents and operational transients such as anticipated transient without scram, loss of offsite power, loss of feedwater, and loss of flow. A generic modeling approach is used that permits simulating a variety of thermal hydraulics systems. Control system and secondary system components are included to permit modeling of plant controls, turbines, condensers, and secondary feedwater systems.

An extensive RELAP5 model of KKM had been developed by RMA back in the 1990s. This RMA model was generally considered quite good at simulating plant behavior, but it was in need of better documentation and updating to the current design. So, rather than building a new RELAP5 model from scratch, which would require that analysts continue using the older RMA model until the new RELAP5 model was completed, it was decided to build the new RELAP5 model using the existing RMA model as the starting point and, in a series of evolutionary steps, continue to improve the model by updating it to current plant design, modernizing modelling methods as applicable, and providing traceability to plant documentation. Each evolutionary step focused on a particular part of the model. As each evolutionary step was completed, the model was assigned a new version number (similar to software development practices). For each version two main documents were released: an input deck description report and a validation report (described in the next sections).

The first steps in this evolution of the model involved: (1) updating the vessel model to present day modelling methods (e.g., increasing the number of nodes since they can now be handled with more powerful computers), (2) updating the steady-state full power to the current plant rated power, and (3) defining and designing the transient cases to be used for benchmarking to plant operational data. With these changes complete, the next evolutions were to improve the hydraulics system models followed by the control system models. The sequence of these changes was as follows:

1. Vessel and core model changes: new level instrumentation models based on differential pressure level measurements with a level compensation, updated point kinetics data to simulate a more recent cycle.
2. Main Steam System model: more detailed modelling of steam lines from the vessel all the way to the turbine valves and Safety/Relief Valves.
3. Recirculation System model: more detailed modelling of piping, updated pump homologous curves, and new speed characteristics for pump coastdown due to new Adjustable Speed Drives.
4. ECCS and Feedwater System models: improved ECCS injection characteristics based on the real pump curves and system hydraulics characteristics and better modelling of feedwater temperature as a function of main steam flow.
5. Control System: updated pressure regulation, feedwater regulation, and recirculation pump speed regulation systems.
6. Miscellaneous systems: improved core flow measurement, Automatic Depressurization System, and Torus Cooling System models and addition of the Hilltop Reservoir cooling system.

The graphical tool SNAP [6] was used for the model development. Each version was fully documented in a continually revised Input Deck Description Report that provided a single comprehensive document to satisfy traceability requirements. As discussed next, each version was then validated against a set of plant transients to assess the impact of the changes from version to version.

3. Validation process

The validation process performed by KKM and described in this paper focuses on the KKM specific model validation rather than on the general validation of RELAP5 for being adequate for light water reactor thermohydraulic transient calculations. For the general validation, we rely on the large amount of work performed by the thermal hydraulics research community around the world.

For the KKM model, once each version was developed and documented, it was necessary to validate the model's performance. This required benchmarking the model to actual plant operational data (both steady-state and transient). These benchmark comparisons were evaluated to determine how well the model predicted plant behavior over a wide range of operating conditions. Also, as part of the validation of each version, it was necessary to demonstrate that the model could simulate and yield physically reasonable results with postulated transient and accident scenarios that had been analyzed by vendors.

Benchmark transients were selected to cover a broad range of operating conditions (e.g., power levels), to provide large changes to important measured operating parameters (e.g., vessel level, recirculation pump speed and flow, steam and feedwater flow), and to exercise plant control and protection systems (e.g., level control, pressure control, recirculation pump speed control, and reactor scram). The following benchmark transients were selected:

1. Controlled downpower evolution from 100% to 30% power
2. Reactor scram following a feedwater pump trip with failure of the backup feedwater pump to start
3. Recirculation pump trip
4. Feedwater pump trip with start of the backup feedwater pump
5. Loss of feedwater test

Postulated plant transients analyzed as part of the licensing basis that were selected for comparison consisted of:

1. Complete loss of Feedwater (no high pressure injection available and only limited low pressure injection available)
2. Simultaneous closure of all four Main Steam Isolation Valves
3. Turbine trip with half bypass capacity
4. Loss of Coolant Accident

In addition to full plant simulations, simplified model simulations were performed using parts of the full plant model to determine specific model options to exercise or to validate unique plant systems within the full plant model. Two completely different examples are presented in the next section.

The validation process and results were documented in a continually revised Validation Report and, upon acceptable completion of the model validation, the respective version was formally released for production use. Thus, an ever-improving, fully documented and validated RELAP5 model was always available for on-going analysis needs.

Despite that a good comparison to plant data does not guarantee that the model is accurate for every kind of transient, this good agreement is a necessary step and improves the confidence in many parts of the model, e.g., the control system modelling, main component volumes and pump characteristics.

4. Examples of simplified model simulations

4.1 Heat exchanger model for the torus (suppression pool) cooling system (TCS-HX)

A standalone model of the torus cooling system surrounding the heat exchanger has been developed. This model, TCS-HX, is used to ensure that the modeled heat exchanger produces results which are consistent with design data. Figure 1 shows the heat exchanger model and nodalization.

Boundary conditions of flow and inlet temperature are imposed on the tube-side and on the shell-side of the heat exchanger. The tube-side flow area is constant along the flow path and is precisely defined by the geometry of the heat exchanger. The shell-side flow area on the contrary is not constant along the flow path due to the baffling that create crossflow and the complex geometry. The shell-side flow area is then manually adjusted (to adjust the flow velocity and hence shell-side heat transfer coefficient) until the outlet temperatures for each fluid are acceptable relative to those in Table 1. A detailed nodalization yielded a shell-side flow area of about 0.35 m2. A coarser nodalization (Figure 1) yielded a shell-side flow area of about 0.2 m2 which, although quite different from the 0.35 m2 estimated with the detailed nodalization with 6 shell-side nodes, is acceptable for the reason discussed below.

The smaller shell-side flow area is acceptable because the coarser nodalization on the shell-side effectively ignores the baffling in the heat exchanger. The shell-side baffling creates the counterflow/crossflow pattern that increases the efficiency of the heat exchanger. Thus, a smaller shell-side flow area is required in the model to increase shell-side velocities and thereby increase the Reynolds Number and shell-side heat transfer coefficients. Additionally it was verified that the coarse nodalization (with flow area 0.2m2) and the detailed nodalization (with flow area 0.35m2) produce the same heat transfer power at off-rated conditions: For instance when the heat exchanger is operated at reduced flow.

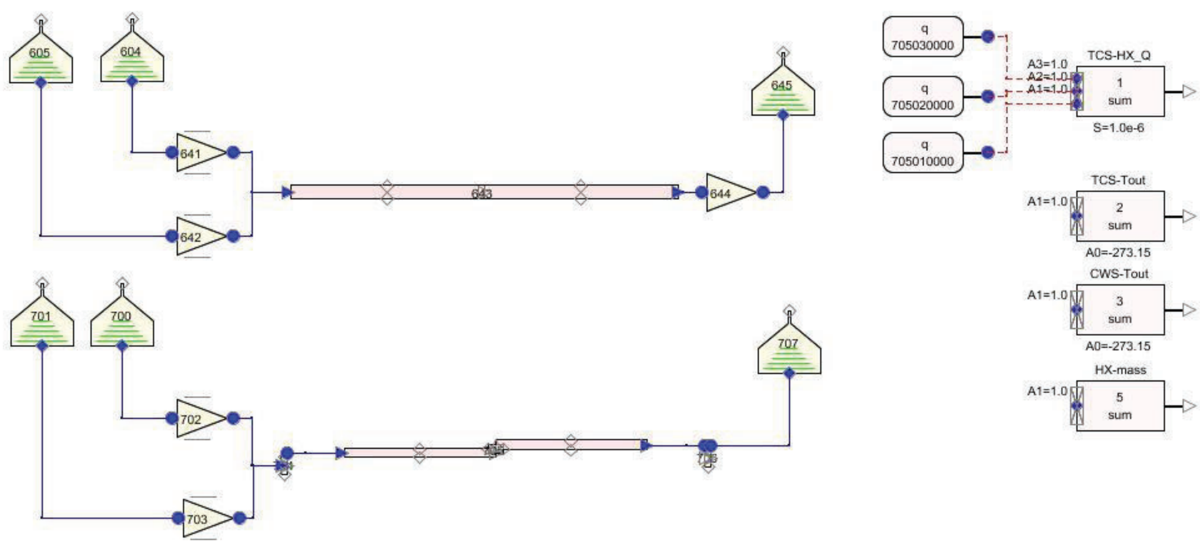

Figure 1. Standalone model for testing the torus cooling heat exchanger model (TCS-HX, coarse nodalization).

Table 1: Nominal heat exchanger characteristics along with RELAP5 results after slight calibration

Parameter	Design Value	RELAP5 Value	Difference, %
Tube-side flow rate, kg/s	126.1	126.1	0.0
Tube-side inlet temperature	18.33	18.33	0.0
Tube-side outlet temperature, °C	31.66	31.66	0.0
Shell-side flow rate, kg/s	113.89	113.89	0.0
Shell-side inlet temperature, °C	51.66	51.66	0.0
Shell-side outlet temperature, °C	36.66	36.90	0.6
Total HX power, MW	7.033	7.029	-0.06

4.2 Selection of the choking model

A simple model was created to test the two choking model options in RELAP5 mod3.3 patch04 from NRC. Those models are: the currently default Henry-Fauske (H-F) and the former default Ransom-Trapp (R-T) model.

The simple test model (Figure 2) represents a pressurized vessel (like a reactor pressure vessel at constant pressure) connected to a dead end pipe (similar to a steam line with a closed MSIV (main steam isolation valve)). At the middle of the steam line a relief valve connected to the environment is modeled and assumed to suddenly open after 60 seconds.

It was observed that the R-T model produced unrealistic flow oscillations for some cases depending on the max time step chosen. The chosen time steps were all between 0.01 and 0.0001 seconds, and no convergence pattern was seen by reducing the time step size (erratic behavior). None of these problems appeared when using the H-F model (Figure 3). Additional tests were performed that are not presented in this work that show even more severe problems with the Ransom-Trapp choking model. During the CAMP meeting this year in May (2015) unrealistic oscillation problems were also reported regarding the R-T choked flow model [7].

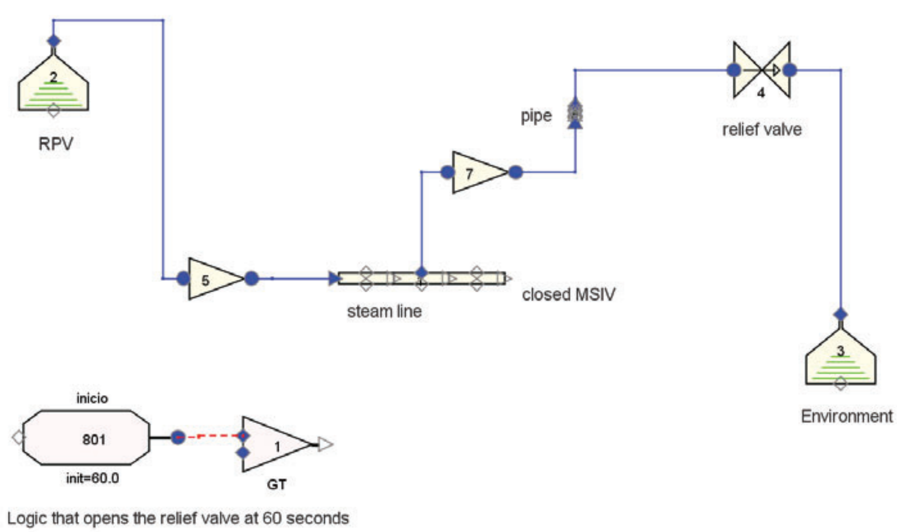

Figure 2. Simplified model for testing chocked flow modelling options.

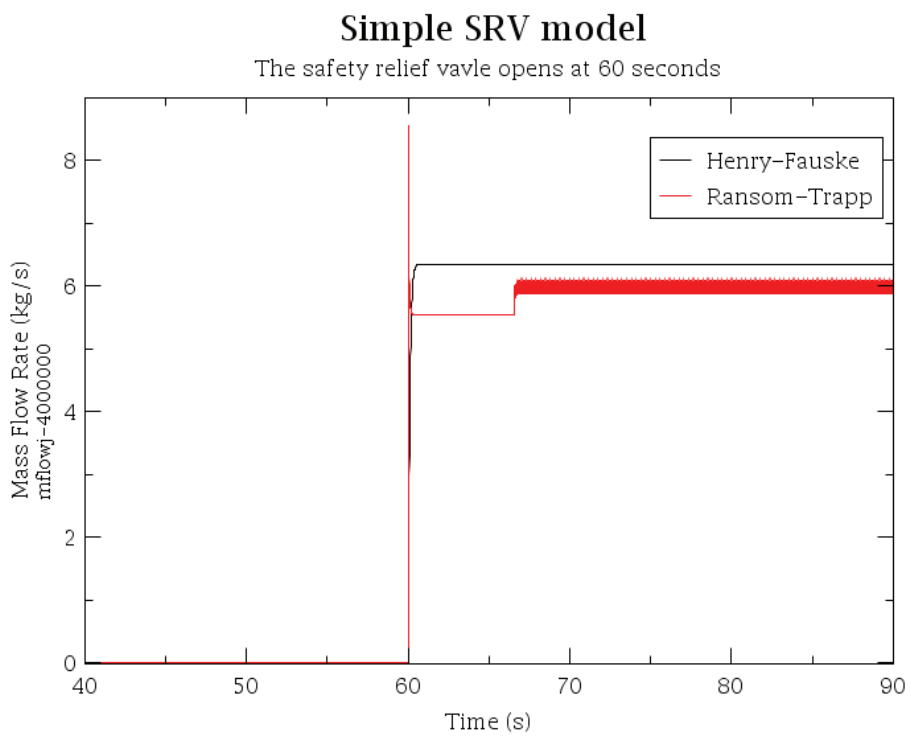

Figure 3. The Ransom-Trapp model implemented in RELAP5 mod3.3 patch04 shows unrealistic behavior and oscillations for several different simplified tests.

5. Validation results examples

In this section we present as an example some of the transients used for the validation process.

On the plots, the indicated reactor level corresponds to the instrumentation level which is the level from the bottom of the RPV minus 11.79 meters. The normal steady state instrumentation level is typically around +1 meter.

5.1 Downpower

This transient represents a controlled decrease in power from 100% power down to approximately 64% power. The decrease in power was driven by the operators through a sequence of load changes with corresponding recirculation pump speed reductions, rod insertions, and pressure control set point changes.

The targets for the recirculation pump speeds were obtained from the plant data and imposed on the model via general tables.The amount and timing of the negative reactivity inserted by the rods was determined iteratively, using the rod insertion data from the plant data as a guide, until the reactor power trend matched the plant power reasonably well (Figure 4).

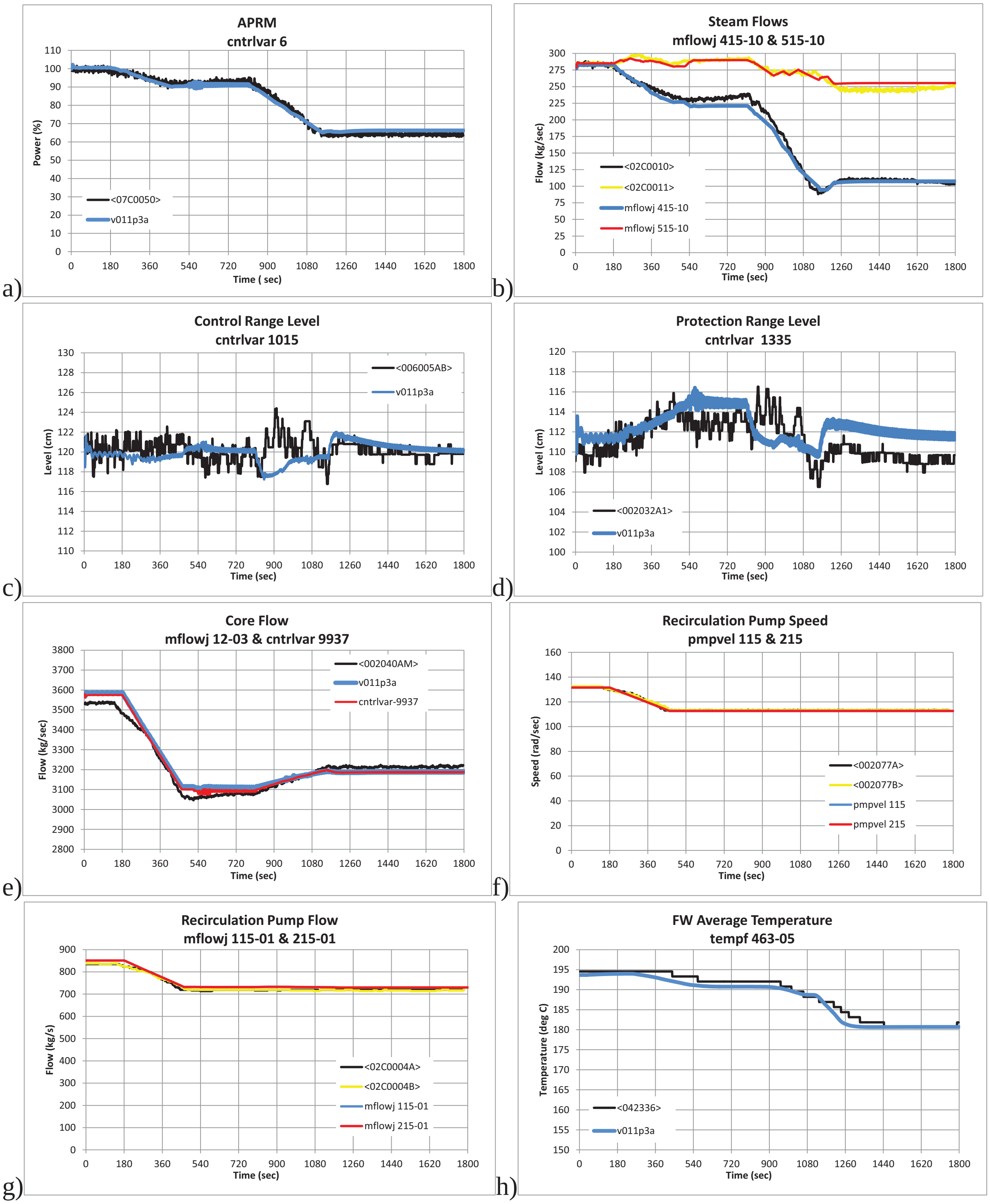

Figure 4. a) to h): RELAP5 simulation data compared with plant measured data during a downpower maneuver to shut down the reactor for refueling.

5.2 Reactor scram

Following a trip of feedwater pump B with the backup feedwater pump unavailable, a reactor scram from full power occurred on February 8, 2012. This scenario simulates that event. The trip of feedwater pump B and the failure of feedwater pump C to start are initiated at 270 seconds into the run. The pressure controller set point is adjusted based on assumed operator actions as indicated by the plant data. These are the only forced boundary conditions on the model for this scenario. The plant behavior and the simulated results match reasonably well (Figure 5).

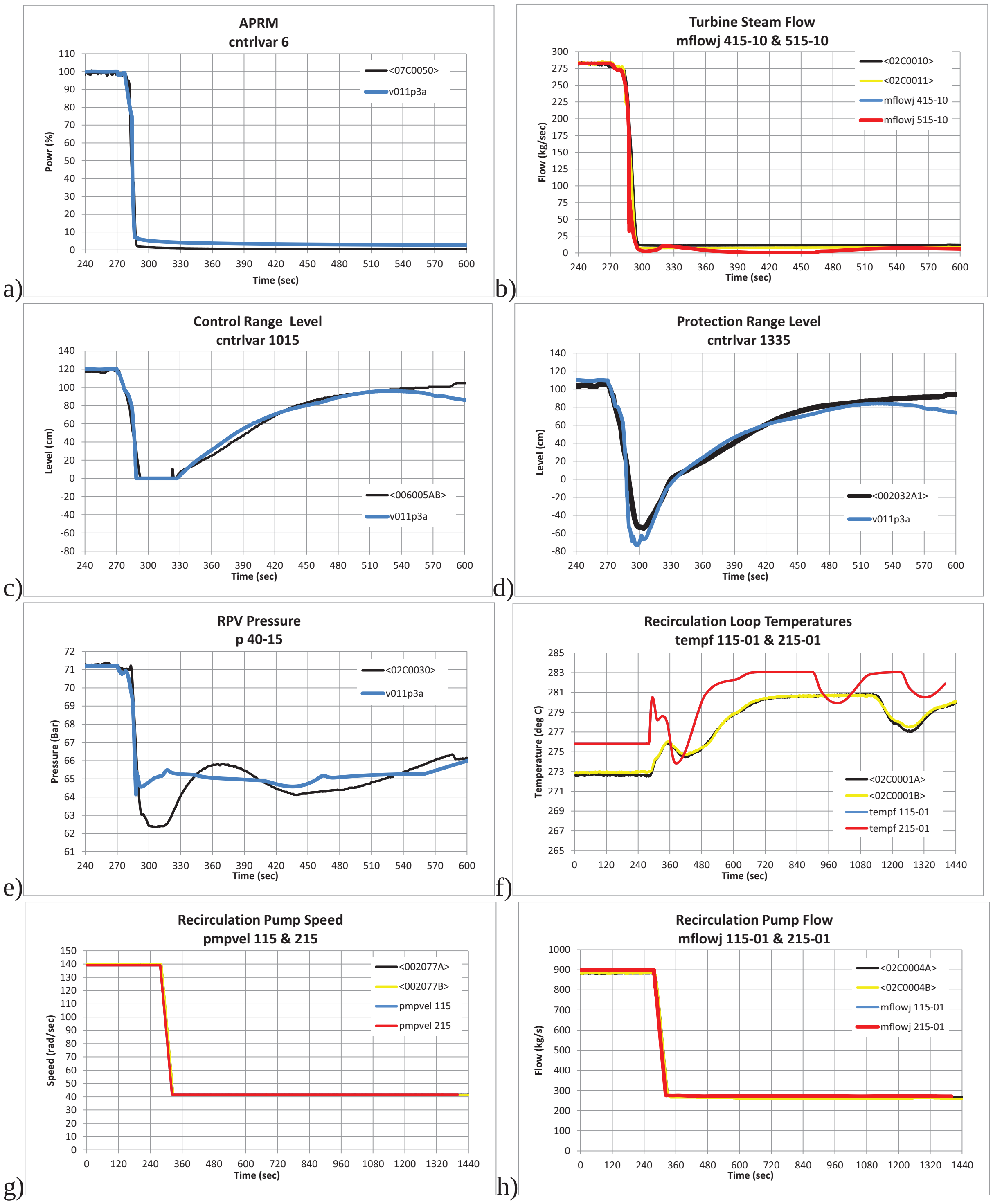

Figure 5. a) to h): RELAP5 simulation data compared with plant measured data.

5.3 Loss of feedwater test

On September 8, 1993 a complete loss of feedwater (LOFW) test was performed at KKM. The loss of feedwater test was initiated from a steady state reactor of 1047 MWth by simultaneously turning off the main feedwater pumps A and B. The feedwater auto-initiate switch and automatic start of the redundant feedwater pump C had previously been manually disabled. Additionally RCIC Train A was disabled leaving RCIC Train B as the only high pressure ECCS available.

Figure 6 corresponds to a simulation with no forced model response.

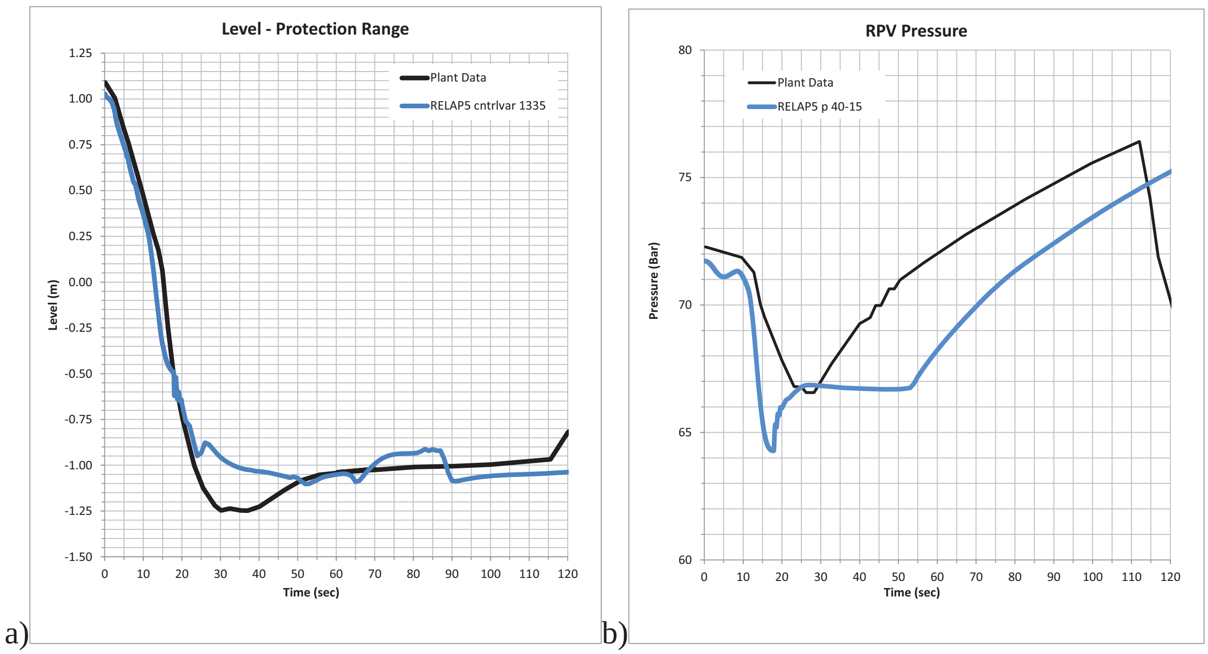

Figure 6. a) and b): Run with no forced model response. RELAP5 simulation data (blue line) compared with plant measured data (black line), a) level, b) dome pressure.

The loss of feedwater results in a drop of RPV level that trips a reactor scram on Level 3 (+0.28m instrument level). Due to the power decrease after scram, void in the core collapses causing the BWR typical strong level drop after a scram. This first quick level drop was just enough to reach the Level 2 signal during the test. Level 2 (-1.07m instrument level) closes the main steam valves, trips the recirculation pumps and starts RCIC (reactor core isolation cooling). On the simulation (Figure 6) the first strong level drop is slightly smaller, so that the Level 2 signal is not immediately reached. In fact it is still reached, 30 seconds later, due to somewhat slower level reduction due to no feedwater available. The small difference in level between the simulation and the test produces a visible delay in the steam line isolation (MSIV closure). The pressure increase due to MSIV closure is clearly seen in Figure 6.

To remove the previous explained effect, an additional comparison was made forcing the Level 2 signal to occur at a slightly lower level (see Figure 7 and Figure 8). That way the MSIV closure happens at the same time in the simulation and in the test.

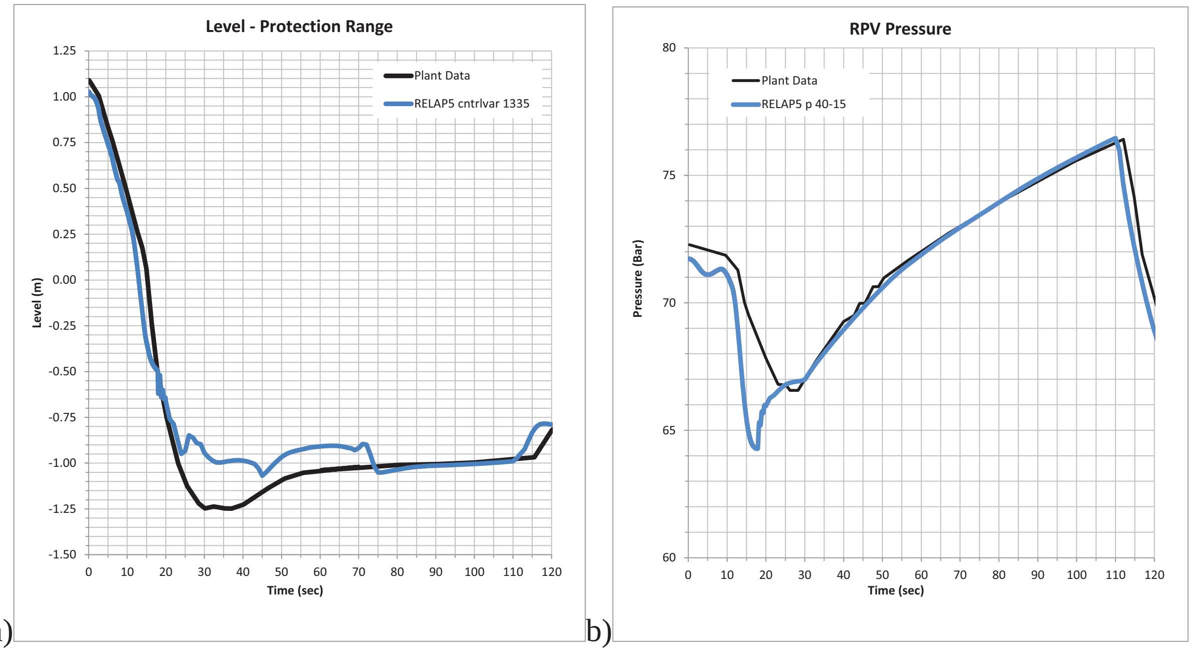

Figure 7. Run with modified Level 2 setpoint. RELAP5 simulation data (blue line) compared with plant measured data (black line)., a) level, b) dome pressure.

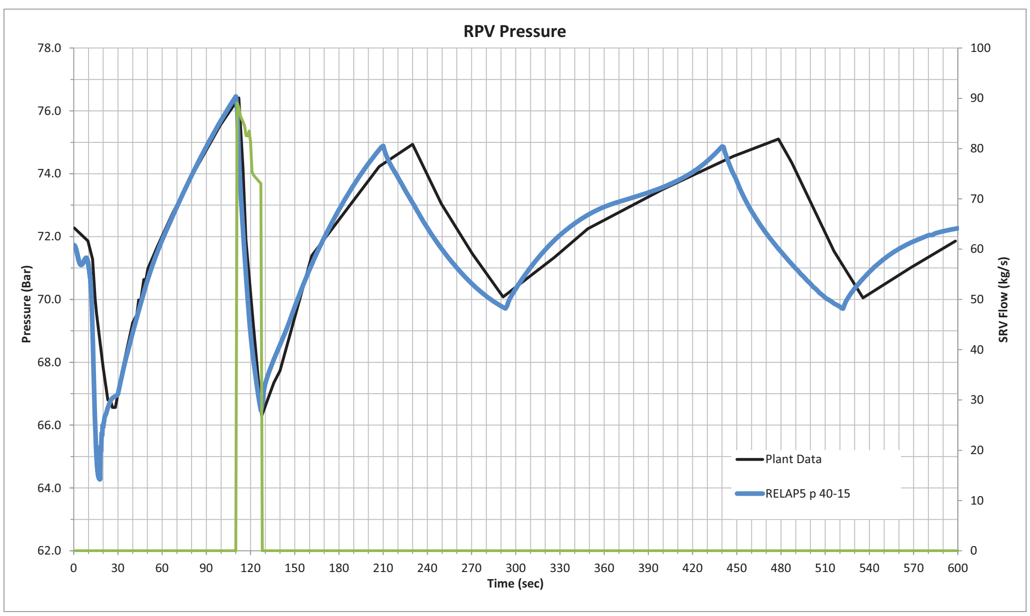

Figure 8. Run with modified Level 2 setpoint. RELAP5 simulation data (blue line) compared with plant measured data (black line). The green line corresponds to the SRV (safety relief valve) flow. After the first SRV actuation that was automatic the second and third pressure peaks correspond to the opening and closing of PRV (pressure relief valves) actuated by operators.

6. Conclusions

In this paper, we have presented a summary of the method implemented at the Mühleberg nuclear power plant (KKM) to take a reasonably good, yet old RELAP5 KKM model of the plant and develop it into a well-documented, updated, improved and validated RELAP5 plant model. To facilitate use of the model during this development project, primarily for scoping studies, the model was updated, improved, and validated in a series of steps culminating in successive model version releases at the completion of each step. The focus of each model version was to document, update, improve and validate a particular part (e.g., major system) of the model. The sequential changes to and validation of the model are described in a continually revised input deck description report and a separate validation report. Each version of the model was benchmarked to a set of actual plant transients that were selected based on the large changes in important measured plant parameters (e.g., power, pump speed, level, feedwater flow) exhibited during the transient. By doing so, the integrated behavior of the model was validated. The effort also included reduced model testing to validate individual system performance and/or modeling options selected. In this paper, we show 3 examples of full plant model validation cases and 2 examples of reduced model tests along with their implications on modelling choices. Overall, the model predictions match the plant data very well. As with any large system model, there are still areas which can be improved and better understood. Those areas define the focus of our future development effort. The power of this approach is that the model is not tuned to a particular transient, but shows good agreement with many different kinds of transients. This fact improves the confidence in the model for being used as a base model for a wide range of transients with the understanding that, prior to its application to specific transients like LOCA or ATWS, additional sensitivity and parametric studies may be required to demonstrate the validity of the model for application to these specific transients.

7. References

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