Utilization of a RELAP5 RCS and Secondary Plant Model in a Nuclear Power Plant Training Simulator

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ABSTRACT

The Comanche Peak Steam Electric Station (CPSES) consists of two 4-loop Westinghouse Pressurized Water Reactor (PWR) nuclear power plants in the TXU Electric system. The plant operates a single Control Room Simulator for NRC licensed operator training with the reference unit for the Simulator being CPSES Unit 1. In the mid-90s, CPSES replaced the RCS thermal-hydraulics model in the Simulator with a RELAP5 model using a real-time version of RELAP5 Mod 3.1 provided by Data Systems & Solutions (then SAIC). The experience with the RCS RELAP5 model was so successful, that CPSES decided to extend the RELAP5 model to include the condensate, feedwater, and heater drains systems as well as part of the extraction steam system. This new RELAP5 model uses the newest release of the real-time version of RELAP5, RELAP5 R/T, based on RELAP5 Mod3.2.

Licensed operator training at the CPSES Simulator is now being conducted with the RELAP5 R/T code. The RELAP5 plant model includes all four individual RCS loops, the reactor vessel, all four steam generators and main steam lines, as well as all major portions of the feedwater, condensate, and heater drains systems. This paper describes some of the challenges overcome in order to successfully apply the RELAP5 code to the real-time simulation for nuclear training. The paper also describes the advantages of using a code such as RELAP5 for licensed operator training.

INTRODUCTION

The primary challenges in applying an engineering-grade code such as RELAP5 to real-time simulation involve the constraints on the model nodalization and time-step size. That is, for a given computing power, the number of nodes and the time-step size cannot cause a slippage in real-time under any transient scenario, including LBLOCAs. Furthermore, the Simulator must be capable of functioning properly under all plant modes, including startup, runbacks, shutdown, and even draindown to mid-loop and refill. Due to the constraints on number of nodes and time-step size, the RELAP5 solution can yield unrealistic or even non-physical results. As a result, code modifications which restrict the system response to be within reasonable engineering bounds may be required.

MODEL DESCRIPTION

The CPSES Simulator RELAP5 model nodalization is patterned after the Small Break LOCA RELAP5 model used for CPSES FSAR Chapter 15 licensing analyses. The significant improvement between the Simulator model and the SBLOCA model is finer nodalization in the pressurizer and steam generators, and the addition of the secondary systems to the model.

The CPSES Simulator RELAP5 model includes all four individual RCS loops, the reactor vessel, all steam generators and main steam lines, as well as major portions of the condensate, feedwater, and heater drains systems. Details of the model are described below.

Reactor Coolant System

The basic model nodalization for the Reactor Coolant System (RCS) was patterned after the RELAP5 model used for FSAR Chapter 15 SBLOCA analyses. Figure 1 shows the RCS model nodalization scheme. Changes have been made to the SBLOCA model to improve modeling of infrequent, but expected operating conditions such as mid-loop and cold shutdown. The following are the principal differences between the SBLOCA RCS model and the Simulator RCS model:

- in the Simulator model, the number of nodes used for the pressurizer and the surge line has been increased to improve pressurizer pressure and level response, especially during draining to mid-loop,
- in the Simulator model, the number of nodes to model the shell-side of the steam generator (SG) has been increased to improve SG level response to transients, and
- in the Simulator model, the upper reactor vessel region has been renodalized to improve reactor vessel level response during draining and filling operations while shutdown.

The reactor core region is modeled with six axial nodes each with just a single radial node. This nodalization was used to be consistent with the (old) Simulator neutronics model nodalization which provides a very coarse representation of the core. CPSES will be incorporating the RELAP5 R/T Nodal Neutron Kinetic Model (NNKM) into the Simulator models in 2002, at which time the core region will be renodalized to provide five radial nodes per axial node in the thermal-hydraulic model. NNKM is an engineering grade neutronics model fully embedded with the RELAP5 R/T code.

The pressurizer is modeled with eight nodes and the surge line with two nodes to better track surge line levels during draindown to midloop. The pressurizer levels are determined using a differential pressure calculation corresponding to the tap locations of the actual pressurizer level instrumentation.

Steam Generators

The steam generators are modeled with 20 nodes on the secondary or shell side and 10 nodes on the primary or tube side. Steam generator narrow range levels are determined using a collapsed liquid level calculation in the downcomer because differential-pressure-based calculations yielded unstable level indications. In the plant's SG, main feedwater flow is split approximately 90/10 to the main feedwater nozzle at the preheater and the auxiliary feedwater nozzle in the upper downcomer, respectively. In the Simulator model, the auxiliary feedwater nozzle has been located within the tube-bundle region of the steam generators to mitigate what appeared to be an excessive response to the introduction of cold water to the upper downcomer.

Secondary Systems

The extension of the Simulator model to include the condensate, feedwater, and heater drains systems, has resulted in a RELAP5 model with 588 volumes and 661 junctions. Figure 2 shows the major portions of the condensate and feedwater systems. All feedwater heaters are modeled on both the feedwater (tube-side) and the extraction steam (shell-side). Difficulties were encountered with the low-pressure heaters due the extremely small quantities of mass on the shell-side coupled to extremely large heat transfer surface areas. Code changes, described below, were made to overcome these difficulties.

Boundary conditions provided to the secondary system from the Simulator models are extraction steam pressures and qualities, total main steam flow, pump speeds, and valve positions. All control systems are modeled using the original Simulator models, but essentially all the thermal-hydraulics calculations for the secondary plant are now performed by RELAP5.

CODE CHALLENGES (and SUCCESSES)

Some challenges which were encountered during the development of the CPSES Simulator RELAP5 model were code related. Some of these challenges required modification to the RELAP5 source code to restrict RELAP5 calculated values to be within reasonable engineering bounds, as will be described below. Other challenges required rethinking the expected response of the plant based on the original Simulator model predictions because of the greater fidelity of the RELAP models. One particular instance of this will be discussed below.

Code Modifications

Some code modifications were necessary to overcome recurring RELAP5 abnormal terminations on water property failures. Most of the code modifications were necessary to resolve problems with two-phase heat transfer in low-pressure regimes, sometimes sub-atmospheric, feedwater heaters. The problems appeared when extraction steam flows to the heaters was reduced or terminated completely and shell-side pressures were very low, such as at low power levels. Due to the very low density of steam at the low pressures (2 psia), the mass of steam on the shell-side of the heater is extremely small and, therefore, the feedwater heater response is very sensitive to the amount of interfacial or wall heat transfer to or from the steam. This sensitivity to the heat transfer coupled with the large wall heat transfer surface area of a heat exchanger led to erratic feedwater heater behavior and, subsequently, water property failures. To resolve these problems, several code modifications were implemented at different stages of the project. One code change involved placing limits at low pressures on the subcooled vapor, superheated liquid, and subcooled boiling maximum temperature differences used for heat transfer in order to provide reasonable upper-bounds on condensation and boiling heat transfer rates. This "rate limited model" conserves energy and goes to the correct rate as temperature differences fall below the maximum. Another code modification related to the feedwater heater problems involved time log-averaging of the heat transfer coefficients to prevent instantaneous orders of magnitude changes in the heat transfer coefficients and heat flux. With these changes, the feedwater heater behavior became very stable under all operating conditions.

The other primary code modification was made to resolve a problem with unrealistic junction velocities observed in the steam generators following steam line break transients. In these transients, junction velocities were observed to be greatly exceeding sonic speeds. With the limitation on time-step size, this frequently resulted in code aborts as, again, unrealistic water properties were being calculated. This particular problem was resolved by applying a frictional-based choking model in the code until an adequate internal choking model becomes available.

In contrast to problems requiring code modifications for resolution, there have also been many cases in which the RELAP5 predicted plant response has proven to be more representative of the expected plant response than the previous thermal-hydraulic model. One particular instance of this "success" was the SG level response to large steam line breaks. It was observed in these types of transients that the SG level would rebound to a significant value after being apparently dried out due to the steam line break. This realism of this response was questioned by CPSES Simulator personnel based on experience with the previous model. DS&S and INEEL personnel performed a detailed evaluation and concluded that the level rebound was indeed realistic and provided experimental evidence from the Westinghouse MB2 facility supporting their arguments. This type of experience, in which RELAP5 proves to be the more realistic response when compared to the previous thermal-hydraulics model, has consistently been the rule and not the exception.

ACCEPTANCE TESTING

Performance Tests are performed annually on the Simulator models to verify continued fidelity with respect to accepted benchmark data. Benchmark data for the CPSES Simulator are derived from actual plant transient data or from another engineering code transient predictions, in this case RETRAN-02. There are a total of 15 Performance Tests consisting of the following:

- manual reactor trip
- trip of all main feedwater pumps
- closure of all main steam isolation valves
- trip of all reactor coolant pumps
- trip of a single reactor coolant pump
- main turbine trip without reactor trip
- maximum rate power ramp
- maximum LOCA with loss of offsite power
- maximum steam line break
- reactor coolant system depressurization due to a stuck open pressurizer relief or safety valve
- plant startup from cold shutdown, to hot standby, to turbine startup and generator synchronization, to rated power
- steady-state operation at 25%, 75%, and 100% of rated thermal power.

All of these tests have been successfully performed as part of the RELAP5 model validation. Differences between RELAP5 results and previous test results are readily explainable and are "RELAP5 correct". In addition to these Annual Performance Tests, the RELAP5 model has been exercised during Licensed Operator training through numerous equipment malfunctions, abnormal operating conditions, and design basis accidents. Any discrepancies or unexpected responses would be reported through the Simulator deficiency reporting process. So far, no deficiencies have been reported as a result of Licensed Operator training.

ADVANTAGES

What are the advantages of using RELAP5 for real-time Simulation?

1) The use of a true, first principles based, engineering-grade code provides significant credibility to the Simulator's modeling fidelity. Since the new RELAP5 model has been used in training of CPSES Operators, feedback from the Operators and Simulator Instructors has been extremely positive. Pressurizer pressure response has been one area of improvement noted by the Operators when compared to their experience with the real plant. Operators have also noted that with the previous model, the secondary plant response to transients was not very accurate whereas, the response with the RELAP5 model is extremely life-like. Furthermore, whenever the model response is questioned based on past experience with the Simulator, more than likely, the RELAP5 model response is shown to be more representative of what should be expected than the previous model's response.

2) Plant model changes are now much easier to accomplish with RELAP5. For example, at CPSES the Heater Drains System underwent a significant redesign to resolve system weaknesses that frequently led to plant runbacks or trips during secondary plant transients. To recode the old Simulator models would have required an extensive amount of programming, testing, and tweaking the code to get the desired effect, probably on the order of man-weeks. That's because the old Simulator models begin with a basis in physics, but then quickly lose that basis as the code is "squeezed in the right places" in order to keep the model simple and still get the desired response. With RELAP5, the input deck changes needed to represent the new Heater Drains System design were accomplished based on actual piping and component layouts and the model was up and running in a matter of days with no sacrifice to, or question of, the model fidelity. In essence, the Simulator with its full BOP and control systems modeling, gives a better representation of plant response than any stand-alone reactor engineering model can provide. The model naturally captures operator actions and can include complex subsystem malfunctions. Thus, it would now be possible to perform complex engineering studies in the Simulator with little effort and with great accuracy; although Simulator availability due to training requirements has not permitted this potential to be fully realized.

3) Simulation of the full range of power operations, abnormal conditions, and accidents is within the capability of the code and model. The Simulator model has been tested from full power down to cold shutdown and midloop conditions. In addition, model enhancements have already been made, although currently untested, to simulate the vacuum fill of the RCS from midloop conditions and to simulate purging of the steam generator tubes during draindown using nitrogen gas.

CONCLUSIONS

In summary, RELAP5 has been modified to run as a real-time simulation code and the capabilities of RELAP5 have been challenged by the modeling of a wide range of conditions that exist in the secondary (feedwater) systems of a PWR. The results of this effort have been the successful implementation of the RELAP5 code into the training of NRC licensed operators on the CPSES Control Room Simulator. The entire range of plant operating conditions from full-power, runbacks, and shutdown to, and including midloop, have been extensively tested with the RELAP5 model. Furthermore, all abnormal conditions and accidents required by NRC for Operator training, such as small and large break hot and cold leg LOCAs, steam generator tube ruptures, and steam line breaks, can be simulated and have been thoroughly tested successfully. Future plans for the CPSES RELAP5 Simulator model include a new (3D) core model with NNKM, enhancements to model RCS vacuum fill, nitrogen purging of steam generator tubes during draindown, and additional nodalization in the reactor vessel to model loop-asymmetric transients. This Simulator upgrade project with RELAP5 has produced an engineering-grade Simulator that has enhanced operator training and even extends training into new regimes.

REFERENCES:

(1) The RELAP5 Code Development Team, RELAP5/Mod3 Code Manual, Volumes I through V, NUREG/CR-5535, INEL-95/0174, June 1995.

Figure 1
RCS Nodalization

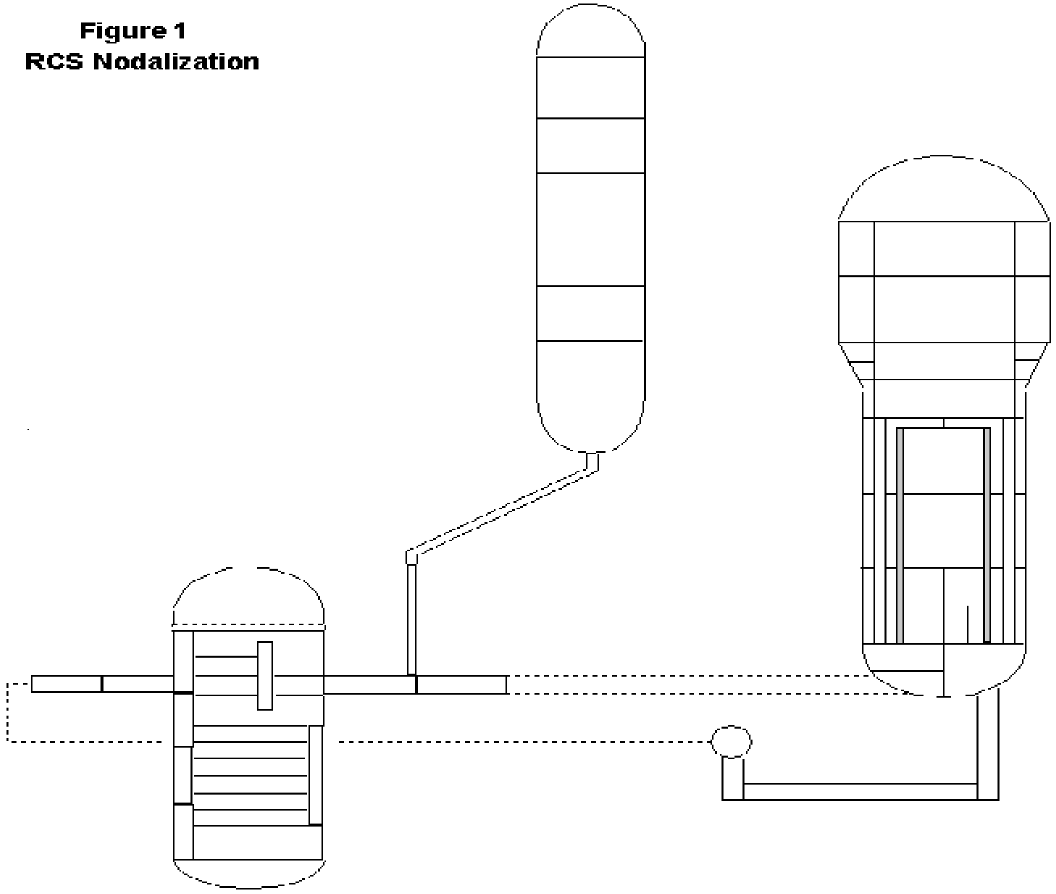

Figure 2
Condensate and Feedwater Systems Nodalization