Comparison of R5G Coupled Code and Classical “Two-steps” Containment Calculation

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ABSTRACT

Using one Steam Line Break scenario and one Stuck Open PORV scenario, originally developed for Krsko Full Scope Simulator, the benefits of coupled system-containment code usage over classical two-steps calculation procedure were demonstrated. RELAP5 mod3.3, GOTHIC and coupled RELAP5-GOTHIC code R5G were used to perform classical mass and energy and then containment calculation and coupled code calculation. For most of the design bases accidents and transients in current Light Water Reactors level of interaction between system and containment is low and decoupled system and containment runs can be performed. It is demonstrated that coupled code, once when it is available, can be easier to use, can give better prediction, and can reduce possibility of error during manipulation with mass and energy release data. Additional benefits are available when coupled code can share trips generated in system and containment part of the code.

1 INTRODUCTION

In the case of interaction of the reactor system and containment, usually two independent runs are performed. First the mass and energy release rates (MER) are calculated by a system code using conservative assumption of low containment back pressure, and then containment response is calculated using the calculated MERs as a boundary condition. This approach is usually adequate for present day Light Water Reactors (LWRs), due to low importance of the interaction between containment and reactor coolant system during Design Bases Accidents (DBAs), typically Loss of Coolant Accident (LOCA) and Steam Line Break (SLB). However, in new advanced passive systems such as in International Reactor Innovative and Secure (IRIS) and Economic Simplified Boiling Water Reactor (ESBWR), the LOCA phenomenology can be significantly different, and interaction of the coolant system and containment becomes more important, so as to require an evaluation model where containment and reactor coolant system are analyzed in a coupled way.

Even though usage of coupled system and containment code is not necessary for present days LWRs, from point of view of prediction accuracy, once when coupled code is developed, it can make safety analyses easier and more complete.

The coupled code R5G [3], [4] is a result of explicit coupling of system code RELAP5/mod3.3 [1], and containment code GOTHIC [2], done at the University of Zagreb.

In the paper the calculations done in frame of NPP Krsko Full Scope Simulator (KFSS) verification were performed using both, classical “two-steps” approach, and single run using coupled code. The most important system and containment variables were compared and
reasons for differences were explained for SLB (Steam Line Break) and stuck open PORV (Power Operated Relief Valve) calculation cases.

2 CALCULATIONAL TOOLS

The classical procedure addressing interaction of nuclear steam supply system and containment has two parts. In first part system code, in our case RELAP5 mod3.3 [1], performs calculation of the system assuming approximate containment conditions as represented by RELAP5 branch component. In second part containment calculation is performed (in our case GOTHIC 7.2b [2] is used) for available mass and energy release rates at the communication between system and containment. Coupled R5G [4] calculation is then performed using both system and containment nodalization from independent runs, and results from two-steps and from coupled calculation are compared.

Coupled code R5G is a result of direct explicit coupling of RELAP5/mod3.3, ref. [1] and EPRI's GOTHIC 7.2b code, ref. [2]. The applied coupling strategy is simple and basic operation of constituent codes as well as corresponding input data are unaffected by the coupling process. RELAP5 has the leading role during the time advancement in the coupled code calculation. Containment conditions from the old time step calculated by GOTHIC are used in the RELAP5 new time step system calculation, Figure 1. At the end of each converged RELAP5 calculation time step, interface subroutines transfer boundary condition data to GOTHIC. GOTHIC then performs one or more time steps and then interface subroutines prepare containment conditions for next RELAP5 time step. The variables transferred from RELAP5 to GOTHIC are mixture mass or volumetric flow rate, mixture enthalpy or temperatures of the phases, total pressure, liquid volume fraction, steam pressure ratio, and gas pressure ratios for each of non-condensable gases. The variables transferred from GOTHIC to RELAP5 are total pressure, liquid and vapor specific internal energies, vapor void fraction, and non-condensable gas quality. The entry points for the RELAP5-GOTHIC coupling are the RELAP5 tmdpvol component and the GOTHIC flow boundary condition. The interface data are defined in a separate input file, whereas the RELAP5 and GOTHIC input decks remain almost unaffected. The interface input file contains the following data: the number of R5G couplings and the set of the data for each coupling, i.e., the RELAP5 tmdpvol component number and the valve component number connecting tmdpvol and the system as well as the number of corresponding GOTHIC flow boundary condition. In addition it is possible to use trips defined in one code to actuate trips in another code. For example status of the trip defined within GOTHIC model (e.g. HI containment pressure) can be transferred to RELAP5 variable trip (variable is time and initial actuation time is arbitrary large value) that can be used for direct actuation of equipment or as an entry in reactor protection system. Similar is true for trip defined on RELAP5 side and used for actuation on GOTHIC side. It is important to point out that trips in each part of coupled code are associated using input from interface file and that only status of the trip is transferred through codes interface.

The coupling is direct and doesn’t require use of any additional software tools or protocols. The two codes use different main integration variables and the coupling interface has to do the necessary conversions. The interface subroutines responsible for providing GOTHIC data to the RELAP5 code uses GOTHIC liquid and droplet data to produce RELAP5 liquid phase data during flow from the containment into the reactor primary system. Conversion of the RELAP5 liquid flow to droplets during blowdown is automatically handled by the GOTHIC flow boundary condition depending on input data. The two codes calculate
non-condensable gases in slightly different ways and therefore these interfaces are especially
delicate.

The RELAP5 source is intact in the coupling process except for the addition of two
subroutine calls in TRNCTL and TRAN. The GOTHIC main program is replaced with two
subroutines GOTHIC_INI (responsible for input preparation and initialization) and
GOTHIC_RUN responsible for time step advancement and the exchange of data between the
codes. Most of the problems expected in this kind of applications are related to property check
logic in RELAP5 time dependent volume used for connection (mainly when one of the fluid
phases is depleted).

Although there is no change in the RELAP5 or GOTHIC input decks, some guidelines
in input preparation have to be followed. To minimize the impact on the independent codes, a
separate input file was defined. The code coupling is inactive during steady state calculations
and the original RELAP5 code can be used to produce an initial steady state restart file.

As a result of the proposed coupling scheme, both RELAP5 and GOTHIC are applied to
the areas where they can perform best. Multiple connections between the reactor system and
the containment models are possible. Connections are not limited to atmospheric regions
only; e.g., the water level effect on the boundary condition pressure and liquid fraction is
taken into account on GOTHIC side. In addition to coupling the fluid systems it is possible to
exchange trip information between the two codes, and the heat structures in one code can be
connected to control volumes in another code. GOTHIC’s capability to allow subdivision of
the containment lumped volumes can be used in the coupled version to perform
multidimensional calculations.

Figure 1: Typical calculation flow path used in R5G coupled code
3 CALCULATIONAL MODEL

Standard nodalization of NPP Krško was used for both stand alone RELAP5 and coupled R5G calculation, Figure 2. The detailed description of the NPP Krško (NEK) RELAP5/mod3.3 nodalization development is reported in [5] and corresponding steady state verification in [6]. The model described within the document has been developed with necessary fidelity of geometrical and operating parameters and the steady state calculation shows a good agreement with the reference NEK data. NPP Krško nodalization, as used in this paper, has 521 thermal-hydraulic nodes, 553 junctions, 430 heat structures (with 2419 mesh points), 684 control variables, with 199 variable and 208 logical trips.

The model is used for Stuck open PORV calculation without any change. In case of SLB run, simple model of the containment, implemented as branch 991 and corresponding heat structures, is replaced in coupled run with time dependent volumes 991 and 994.

![Figure 2: RELAP5 nodalization of NPP Krško](image)

The containment model used in SLB and Stuck open PORV calculation (also called Vapor Space Break – VPSB) is shown in Figure 3 (SLB left, VPSB right). The model is standard containment model used in SAR type of calculations. The total free volume of the containment was modeled as one compartment, compartment number 1 on Figure 3. The containment annulus was modeled as another separate volume, compartment number 2. Compartment number 3 is Pressurizer Relief Tank (PRT) needed for VPSB calculation. The values needed in model development are taken from updated USAR [7]. Initial conditions inside containment were chosen to maximize containment pressure (48.9 °C, 101.325 kPa, 30% RH). The temperature of the outside air was 34 °C.

Containment heat structures were modeled as 14 different heat structures. The heat structures 1 and 2 are used for representing steel liner and structures 3 and 4 are used for concrete containment wall. All other heat structures are internal containment heat structures.
The heat transfer coefficient was based on Uchida condensation correlation and natural convection heat transfer coefficient, for all heat structures exposed to the containment atmosphere. For internal heat structures one side of the structure is isolated. For structures 3 and 4 right side is exposed to the environment with fixed temperature and fixed heat transfer coefficient of 11.36 W/m²K.

The PRT was modeled as compartment number 3, for transients discharging fluid through pressurizer PORVs. The volume of the vessel is 31.15 m³. The volume of the liquid is 23.22 m³, and rest of the volume is filled with N₂. Temperature inside PRT is the same as the containment atmosphere. The simplified PRT model has the same height and volume as the real PRT, and area is adjusted to get standard GOTHIC vertical control volume with constant cross section. The heat structure (HS number 15) is attached to the volume based on the total dry metal mass of the vessel and inside heat transfer area of the vessel. Instrument taps are arranged 1.27 m below and above main cylinder axis. Calculated cross section area of the PRT rupture disc is based on relief capacity of saturated steam at 0.79 MPa (113.4 kg/s) using Moody critical flow model. The rupture disc release pressure is 716.71 kPa (85 psig + 5%). The rupture disc is modeled using GOTHIC valve component (1V) located on flow path number 6, connecting PRT to the containment atmosphere. Opening time of the valve is 1s. It is possible to model PRT as part of RELAP5 nodalization, but we decided to do that as part of GOTHIC model. It is both easier and faster (from CPU point of view) to use that approach if opening of rupture disc is expected.

Three flow boundary conditions are used in model. Boundary conditions 1F and 2F together with flow paths 1 and 2 are representing liquid and gas flows through the pressurizer valves to the PRT (inlet is below PRT liquid level). In two steps calculation, the liquid and gas mass flows, corresponding enthalpies and pressure upstream of the discharge point are calculated by RELAP5/mod3.3 and read as time dependent vectors in GOTHIC code. In coupled calculation each flow boundary condition is used for modeling of one PORV connection to the PRT. For SLB calculation two boundary conditions (BC) represent each side of double sided break (BC 1 is side toward steam generator and BC 2 is side toward turbine). When SLB MER is calculated in separate runs usually 4 BCs are used (two sides of the break and steam and water phase flows).

Boundary condition 3F and flow path 3 were used for modeling of spray flow from RWST tank. Fixed water mass flow rate was used. The actuation is on HI-3 containment pressure. One spray line was modeled in case with one train available and two spray lines in case with both spray lines available. Gothic spray nozzle component was used at the end of flow path to convert all water flow to droplets.

The reactor containment fan coolers (RCFC) were modeled separately as volumetric fan cooler (1Q, 2Q) + standard single-pass, finned tube counter flow air-to-water heat exchanger (1H, 2H). The dimension of the tubes and fins, total heat transfer area and other RCFC operational data were realistically taken into account based on RCFC Instruction manual. Flow paths 4, 5 are used to model flow of steam and air mixture over RCFC cooling surfaces. The RCFC units are switched into accident mode after receiving SI signal. The influence of RCFC units were not taken into account during normal operation (before break) due to lack of the model for heat losses from the primary side. Only two RCFC units, out of available 4 are used in analyzed scenarios.
4 RESULTS OF THE COMPARISON

Two accident analyses, intended for full scope simulator verification, were performed in order to compare classical 2-steps calculation procedure and new coupled one. The realistic assumptions on systems configuration and performance were used.

First accident is the double-ended Steam Line Break (SLB) inside containment with following main assumptions:

- 100% power;
- Both trains of RHR and SI systems available;
- One train of containment spray system available, one train of RCFC available,
- Both MD AFW pumps as well as TD AFW PMP available;
- No operator actions except isolation of faulted SG within 5 minutes into transient (isolate AFW to faulted SG 30 seconds after faulted SG pressure decreases below 42 kp/cm$^2$);
- Cycle 23 core – EOL, same constants, power set to 1994 MW;
- Plant main control systems were modeled and active for the transients calculations with the exception rod control system that was assumed in manual mode.

Steam generator flow control was assumed in auto mode for MFW FCVs. Flow supplied through the SG nozzles maintained 100% of nominal flow. FCV and FIV valves were assumed to have linear characteristic and to close in 5 sec following CLOSE (or isolation) signal. First 5000 s of the accident were analyzed.

All the ECCS equipment is starting per SI, BO or SI+BO sequencer as applicable for the particular transient analyzed. Auxiliary FW (AFW) flow following actuation signal has been supplied at the non-modulated (no FCV control) flow to each steam generator. Steam dump has been modeled in auto mode for the Tavg load rejection and turbine trip mode with maximum steam discharge capacity of 872 kg/s. Steam header pressure mode has been disabled (not actuated).
The results of the comparison are shown in Figure 4 to Figure 6. In Figure 4 steam generator pressures and primary coolant temperatures are shown for 2-steps and coupled procedure. As expected the differences in obtained results are small. Small difference can be seen in final pressure of damaged steam generator. In Figure 5 phase mass flow rates (liquid and gas) as calculated by RELAP5 and coupled code are shown. One of the potential problems associated with MER calculation can be seen in logarithmic scale in initial part of the transient. MER vectors depend on minor edit frequency and some info can be lost if the frequency is not adjusted especially during periods immediately after the break opening. That problem is automatically solved in coupled calculation where data exchange rely on integration step size. Containment pressure and temperatures during SLB as predicted by standalone GOTHIC and by GOTHIC as part of the coupled code are shown in Figure 6. Small differences can be noticed immediately after the break, near the peak and in the final pressure. In all cases the differences have no practical value and both calculational procedures perform well.

Second analyzed accident is Stuck open PRZ PORV accident. It is essentially the most probable small break LOCA with the break in the pressurizer also known as Vapor SPace Break (VPSB). After the break occurs the primary system depressurizes to the saturation conditions and remains quite stable for the remaining of the transient. Water from the Reactor Coolant System flows to the pressurizer and the mixture level reaches the top of the pressurizer, after which the pressurizer stays essentially full. The water level in the RCS continues to fall, draining the upper head and part of the steam generator cold side.

If high pressure injection system is unavailable, the primary pressure will begin to drop after the RCS water inventory is sufficiently depleted – at that time only steam flows through the break. A core uncovery occurs and the fuel rods temperature begins to rise. The accumulator intervention further depressurizes the primary system, and if low pressure system is available sufficient water is provided to cool the core. If high pressure injection system is available the primary pressure will remain stable after depressurization, the plant will reach a state of equilibrium in which the HPIS provides sufficient water to compensate the water lost through the break, and the core will remain covered.

Main assumptions for the Stuck Open PRZ PORV analysis are as follows:

- Pressurizer PORV stuck open;
- 100% power;
- Both trains of RHR and SI systems unavailable;
- One train of CI system available, one train of RCFC available;
- Both MD AFW pumps available;
- No operator actions except maintaining SG level at no load conditions (60-70% NR);
- RCP trip on loss of subcooling;
- Cycle 23 core – BOL.

Only initial part of the calculation (first 3000 s) is used for comparison. The accident will later, for listed assumptions, result in overheating of the fuel, and calculation will be stopped when fuel temperature exceeds the one where RELAP5 can be reliably used.

The results of the comparison are shown in Figure 7 to Figure 8. In Figure 7 pressurizer pressure and primary coolant average temperatures are shown for 2-steps and coupled procedure. Some small differences can be seen after initial steep pressure and temperature decrease. There are some differences in the prediction of liquid discharge through open PORV in period between 500 and 2000 s, Figure 9. The transient can be rather sensitive to discharged mass and PRT behavior in that period and some sampling frequency adjustment in 2-steps procedure can be needed. Containment calculation usually needs rather small time steps (especially in standalone calculation) around PRT pressure peak and after that shows
some oscillatory behavior, Figure 8. The predicted PRT liquid and containment air temperatures are almost the same for both calculational procedures. Again, the differences in all variables have no practical value for type of calculation performed.

Figure 4: Secondary pressure and primary loop temperatures for RELAP5 and coupled code

Figure 5: Mass flow rates for double ended SLB, calculated by RELAP5 and coupled code

The sequence of main events, for both analyzed accidents is shown in Table 1. The values are for 2-steps calculation procedure. The differences for coupled calculation are small. For example, SI signal for classical procedure is generated at 0.105 s and for coupled at 0.05 s. Corresponding times for containment HI-1 pressure signal generation are 1.525 s and 1.796 s, respectively.
Figure 6: Containment pressure and temperature due to SLB, calculated by GOTHIC and coupled code

Figure 7: Primary pressure and average coolant temperatures during VPSB, for RELAP5 and coupled code

Figure 8: Containment and PRT pressure and temperature during VPSB, calculated by GOTHIC and coupled code
Figure 9: PORV mass flow rates for VPSB, calculated by RELAP5 and coupled code

Table 1: Time sequence of main events (in seconds)

<table>
<thead>
<tr>
<th>Event</th>
<th>SLB</th>
<th>Stuck Open PORV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor trip</td>
<td>0.115</td>
<td>22.79</td>
</tr>
<tr>
<td>Turbine trip</td>
<td>0.115</td>
<td>22.80</td>
</tr>
<tr>
<td>SI signal</td>
<td>0.105</td>
<td>37.58</td>
</tr>
<tr>
<td>SL isolation</td>
<td>0.105</td>
<td>-</td>
</tr>
<tr>
<td>FW isolation</td>
<td>0.115</td>
<td>37.59</td>
</tr>
<tr>
<td>Containment isolation</td>
<td>0.115</td>
<td>37.59</td>
</tr>
<tr>
<td>Charging isolation</td>
<td>0.115</td>
<td>37.59</td>
</tr>
<tr>
<td>Letdown isolation</td>
<td>1.535</td>
<td>37.59</td>
</tr>
<tr>
<td>PRZ heaters shut off</td>
<td>18.326</td>
<td>157.25</td>
</tr>
<tr>
<td>AFW started</td>
<td>25.116</td>
<td>62.59</td>
</tr>
<tr>
<td>RCFC started</td>
<td>41.1</td>
<td>68.58</td>
</tr>
<tr>
<td>RCP trip</td>
<td>61.506</td>
<td>145.83</td>
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<tr>
<td>Core dryout</td>
<td>-</td>
<td>2462.0</td>
</tr>
</tbody>
</table>
5 CONCLUSION

It is demonstrated both, that for design bases accidents and transients that include interaction of nuclear steam supply system and current large dry PWR containments classical two-steps procedure (calculate MER and then run containment calculation) gives satisfactory results, and that coupling of system and containment codes is done in proper way. Two cases that include system and containment interaction (MSLB and Stuck Open PORV SBLOCA), originally developed for Krško Full Scope Simulator (KFSS) verification, were used. Even though coupled code is not necessary for this type of the calculation, if it is already available and used, it can make safety analyses easier and more complete. There is no need to prepare mass and energy release vectors as in classical two-steps procedure. That information is available to the containment in each time step what gives better prediction accuracy and makes analyst job easier without possibility to make mistake during retrieval of the information from the system code and formatting them for containment code. There is no need for planning of time raster at which the data will be saved during system code calculation. In some cases it can be necessary to perform iterative calculations in classical procedure due to initially unknown containment pressure signal which is input in reactor protection system. In present calculational scheme based on R5G coupled code both RELAP5 and GOTHIC can use trip information from other part (e.g. in order to form SI signal HI-1 containment pressure is needed, in order to start RCFC in containment SI signal is needed from system code) and any case can be calculated in single run.

REFERENCES


