pressure balance between the two systems. The tank has a free volume of 1000 m^3 and the pressure and temperature of the atmosphere are 100000. Pa and 313.15 K, respectively. The initial relative humidity of the atmosphere is 100%. The pool (300 m^3) inside the tank is initially in thermal equilibrium with the atmosphere. The tank is simulated using a Gothic control volume subdivided into 10 subvolumes in order to properly take into account the hydraulic head of the pool at the linked junction. The control volume is linked to the two usual RELAP5 piping branches (Figure 19). The opening trips of the valves in the upper and lower piping branches are forced to be true after 10 s since the beginning of the test, so that a simultaneous injection of air and extraction of water is obtained, as shown in the Figure 4-c. The lower piping branch is connected to the containment volume at a height of 0.5 m from the floor. The coupling between the two codes is activated 5 s before the valve opening.

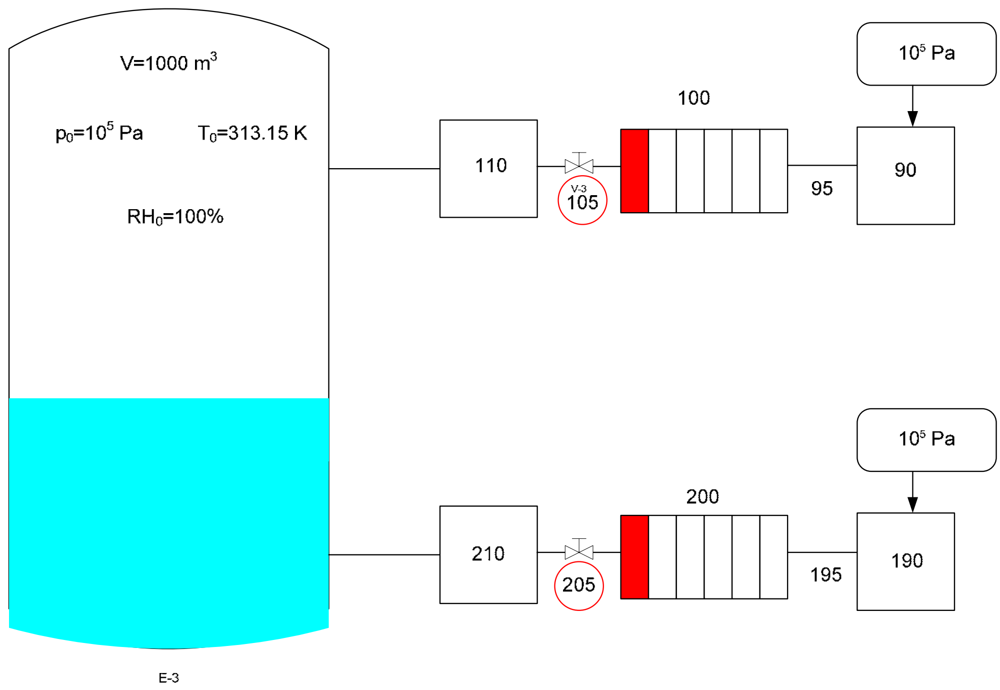

Figure 19. RELAP5/Gothic model for the sample calculation n.3

3.3.2 Obtained results

Figure 20 presents the trend of the liquid level, starting from 3 m at the beginning and decreasing down to the mean height of the outlet flow path, that as a height span of 1 cm on the containment side. The level trend is useful to understand the results obtained for the other variables, as it is in the case of containment pressure evaluated on Gothic side and transferred to RELAP5, shown in Figure 21; It can be noted that pressure oscillations occur mainly as a consequence of the uncovery of the horizontal sections connecting the stacks of sub-volumes in the Gothic compartment, occurring when the level reaches 2 m and 1 m.

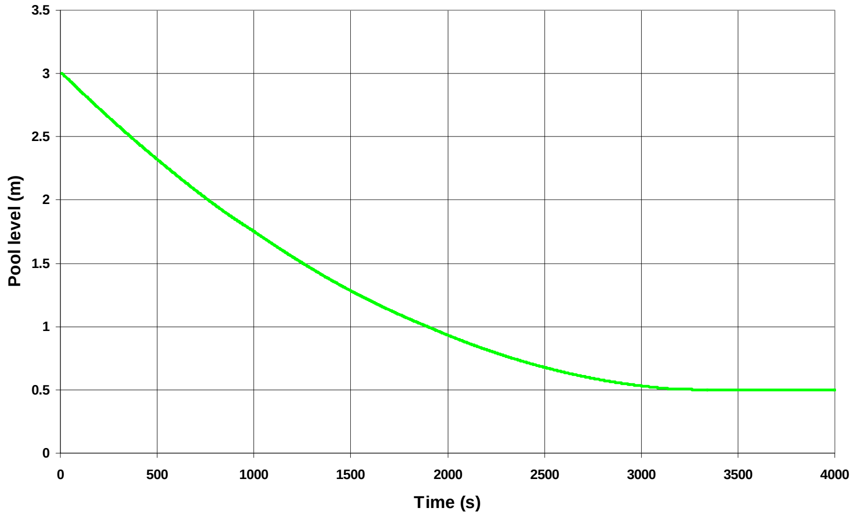

Figure 20. Sample case n. 3 – Pool level

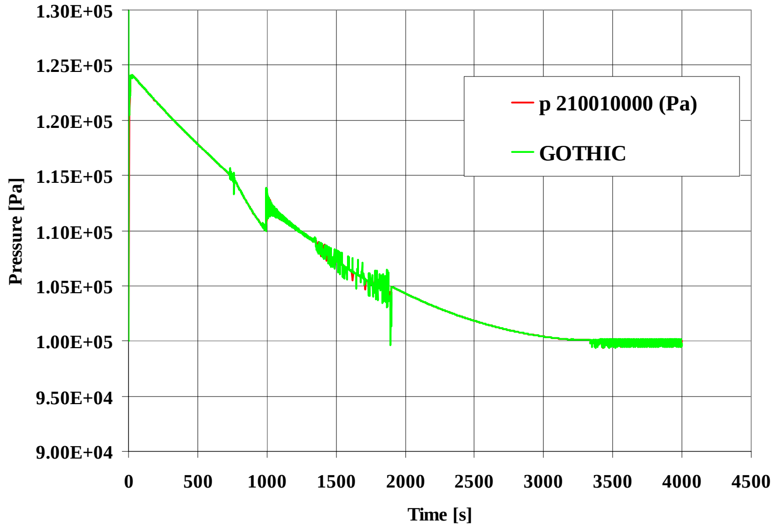

Figure 21. Sample case n. 3 – Total atmosphere pressure

On the other hand, the additional oscillations observed in pressure, temperature flow rate (Figure 22 to Figure 26) after equalisation of pressures between primary system and containment are due to the explicitness of the numerical coupling between the codes, as already noted for previous calculation cases. These oscillations, that must be anyway expected, could be mitigated by decreasing the time step of the two codes. Except for the already noted slight difference in air temperature, the obtained results show the coherence of the procedure for transferring data between the two codes.

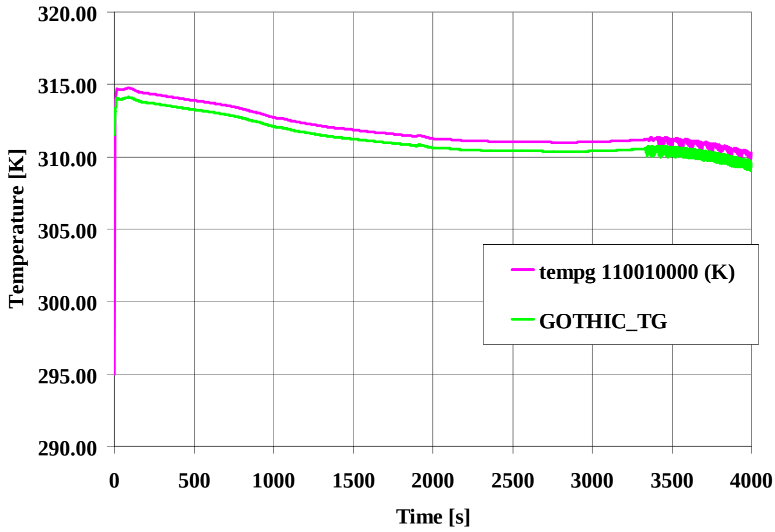

Figure 22. Sample case n. 3 – Atmosphere temperature

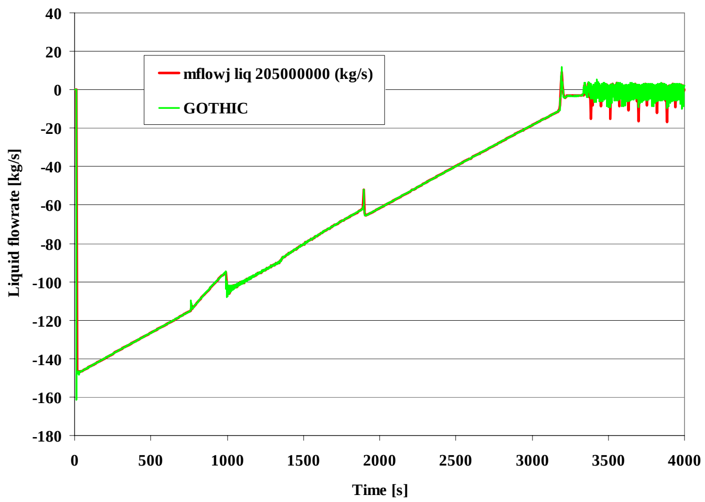

Figure 23. Sample case n. 3 – Liquid mass flowrate

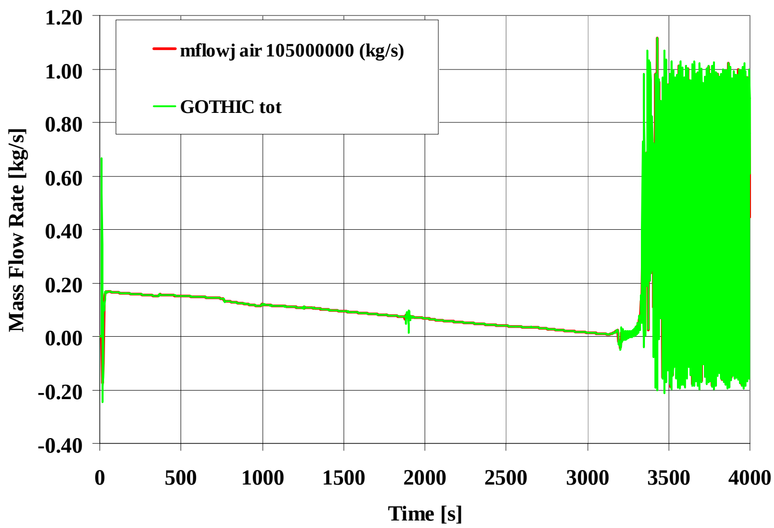

Figure 24. Sample case n. 3 – Inlet air mass flowrate

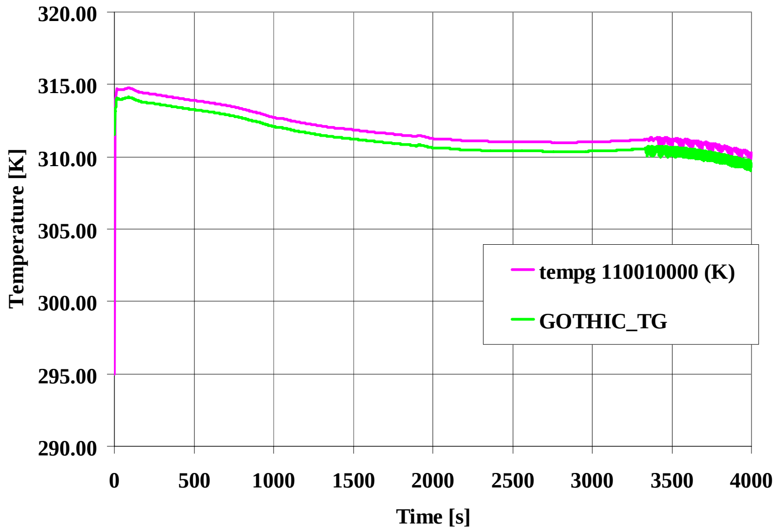

Figure 25. Sample case n. 3 – Atmosphere temperature

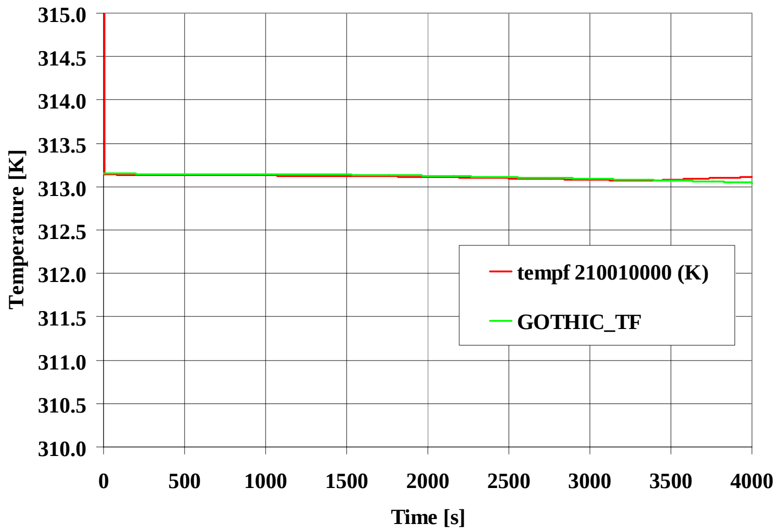

Figure 26. Sample case n. 3 – Pool temperature

3.4 Pressurising a containment volume with air

3.4.1 Calculation case description

The aim of this test was to verify the correct transfer of a noncondensable gas (air) from the primary side to a volume of the containment system. The containment node has a free volume of 1000 m^3 and the pressure and temperature of the atmosphere are 100000. Pa and 313.15 K, respectively. The volume initially contains only air (RH=0%) and is simulated using a lumped Gothic control volume linked to two RELAP5 piping branches (Figure 27). The opening trip of the valves in the upper piping branch is forced to be true after 10 s since the beginning of the test, while the valve in the lower piping branch is closed all along the transient. This causes a continuous injection of air at 313.15 K up to the final pressure of 200000 Pa, with a configuration like that shown in the Figure 4-a. The coupling between the two codes is activated 5 s before the valve opening.

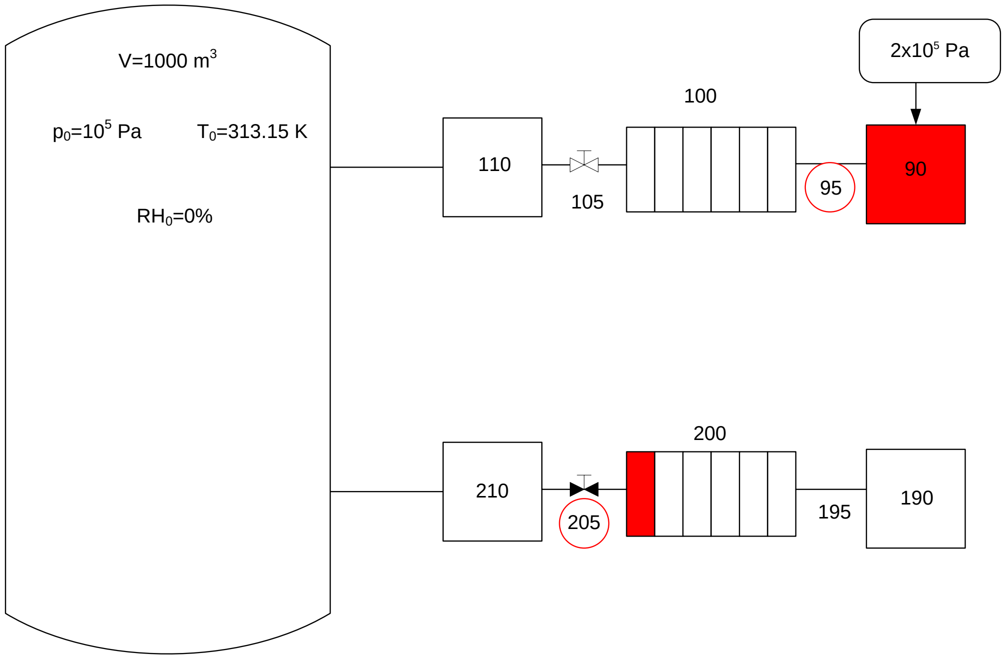

Figure 27. RELAP5/Gothic model for the sample calculation n.4

3.4.2 Obtained results

Figure 28 shows the coincidence between the pressures evaluated by Gothic and calculated in RELAP5 at the time dependent volume 100. Also for this case, a slight difference in the air temperature values calculated by the two codes is observed in Figure 29, whose origin was already explained.

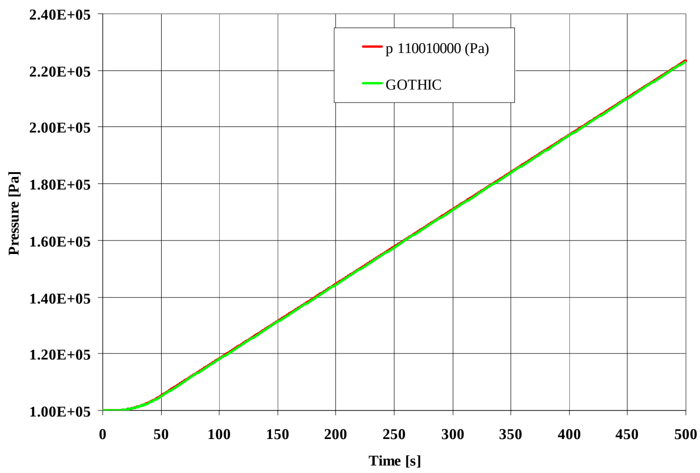

Figure 28. Sample case n. 4 – Total atmosphere pressure

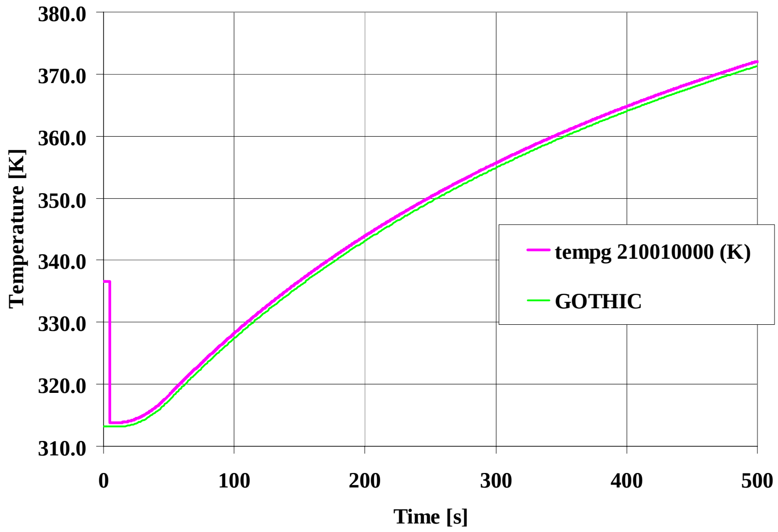

Figure 29. Sample case n. 4 – Air temperature

Figure 30 and Figure 31 show the level of agreement in flow rate and specific enthalpy at the flow path injecting air into the Gothic volume; a perfect coincidence is noted for mass flow rate, while specific enthalpy shows a discrepancy at the start of the transient, before steady injection at a constant flow rate is reached. At the moment it is not possible to track the causes of such discrepancy due to the excursion noted in the variable plotted from Gothic, though it was ascertained that the temperature at the flow path is read correctly from RELAP5, as shown in Figure 32. So, at the moment it can be only suspected that the specific enthalpy of the mixture read at the Gothic junction is calculated incorrectly in the initial transient, though possibly not used in balances. This suspect should be confirmed in further analyses.

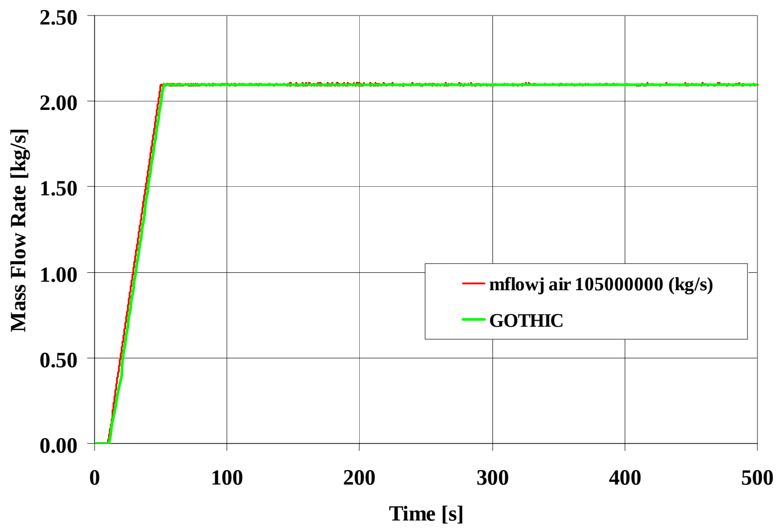

Figure 30. Sample case n. 4 – Inlet air mass flowrate

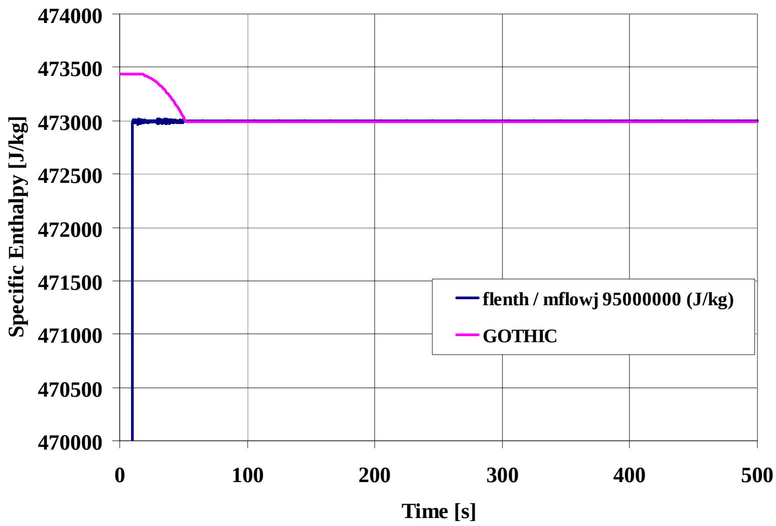

Figure 31. Sample case n. 4 – Inlet air specific enthalpy

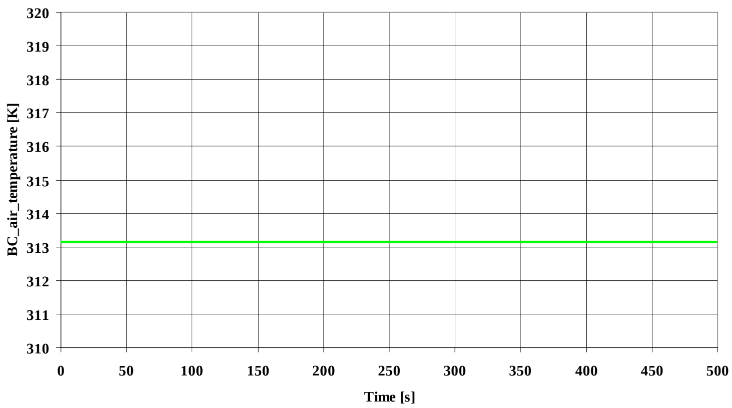

Figure 32. Sample case n. 4 – Inlet air temperature at the flow path in Gothic

3.5 Pressurising a containment volume with air and steam

3.5.1 Calculation case description

This sample calculation is similar to the previous one, but in this case an air/steam mixture at 200000. Pa and 373. K is injected into the containment system. Moreover, an initial saturated atmosphere is simulated (RH = 100%). The tank is again simulated using a lumped Gothic control volume linked to two RELAP5 piping branches (Figure 33).

The aim of this test was to verify the correct transfer of a steam/air mixture from the primary side to a containment volume. The trip valve allowing the steam/air inlet to the containment volume is opened after 10 s since the beginning of the test, while the coupling between the two codes is activated 5 s before the valve opening.

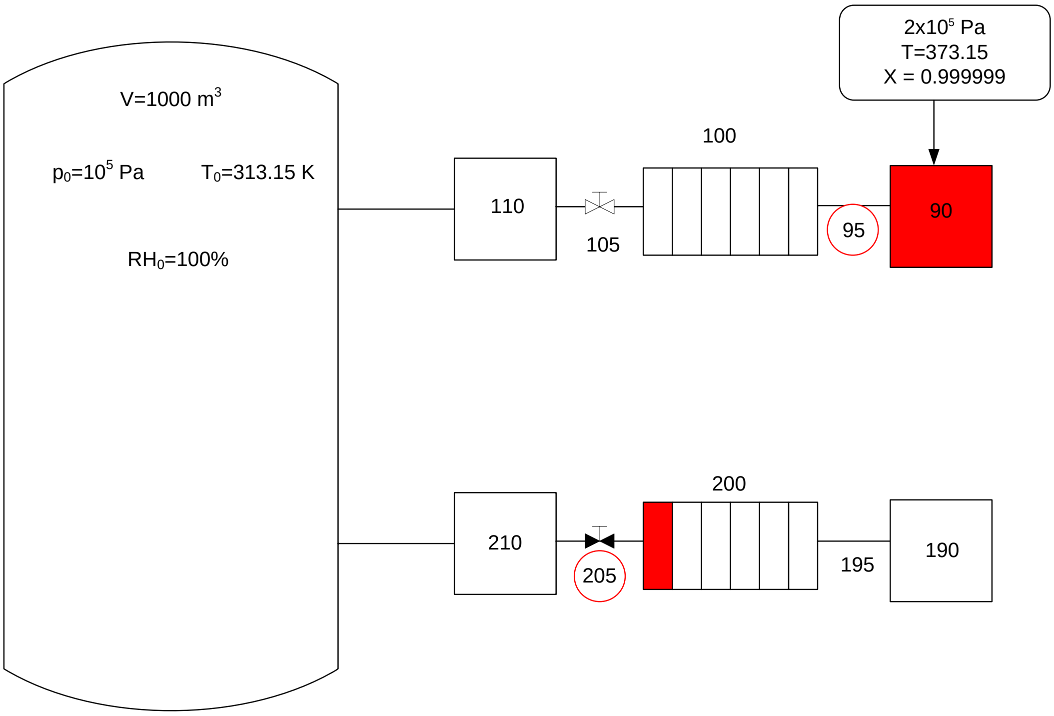

Figure 33. RELAP5/Gothic model for the sample calculation n. 5

3.5.2 Obtained results

Figure 34 to Figure 37 report the results obtained in the analysis, showing the correct transfer of information between the two codes. The formation of liquid in the volume, allows to compare also the liquid temperature assigned on both sides of the information path. A slight discrepancy is noted in the partial flow rates of liquid and vapour that points out a limitation of the present coupling choices; in fact, the total flow rate of steam calculated by RELAP5 is translated in Gothic into a steam flow rate with a little quantity of liquid (Figure 37), as a consequence of the fact that the total pressure instead of the partial pressure of steam is assigned at the boundary condition.

This little problem, that becomes irrelevant if the noncondensable gases are absent or a sufficient amount of water accompanies steam, can be solved by a assigning an average pressure weighted on water and steam masses, on the basis of total and steam partial pressure. This choice has been implemented, but not fully tested though, as shown in Figure 38, it is very effective in mitigating the problem. The little consequences of the discrepancy observed for the present case suggest to postpone a careful analysis of such possible option to a future time.

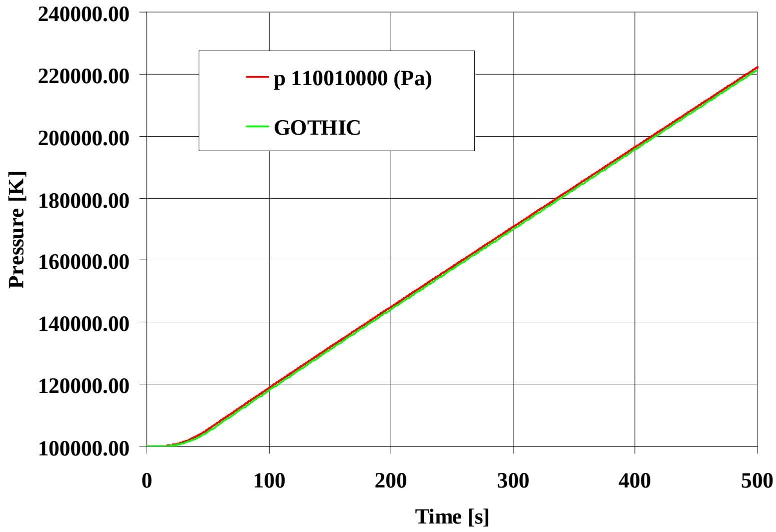

Figure 34. Sample case n. 5 – Total atmosphere pressure

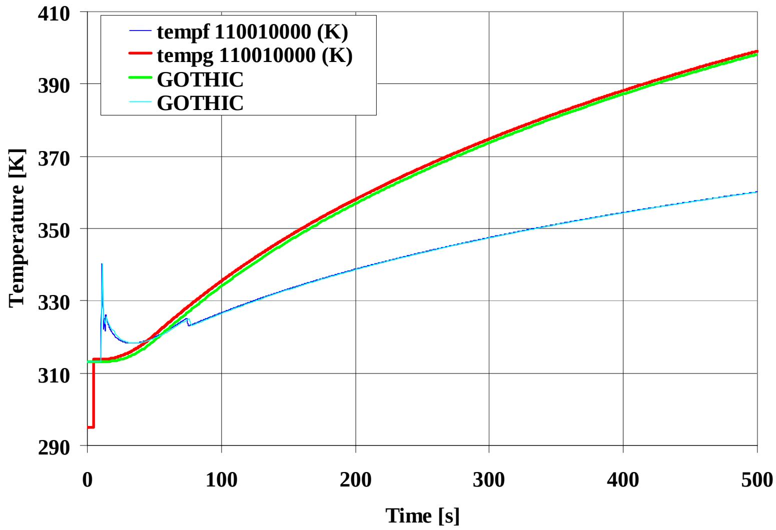

Figure 35. Sample case n. 5 – Atmosphere and pool temperature

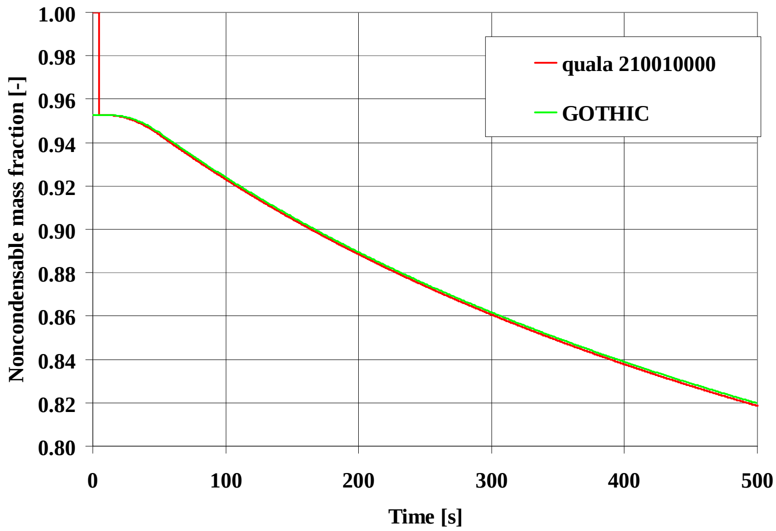

Figure 36. Sample case n. 5 – Noncondensable gas fraction

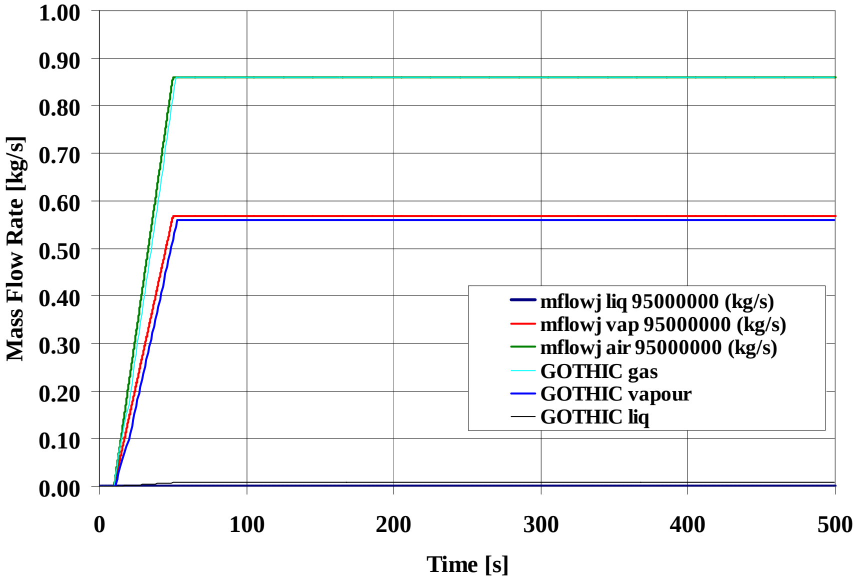

Figure 37. Sample case n. 5 – Inlet steam, water and air mass flowrates

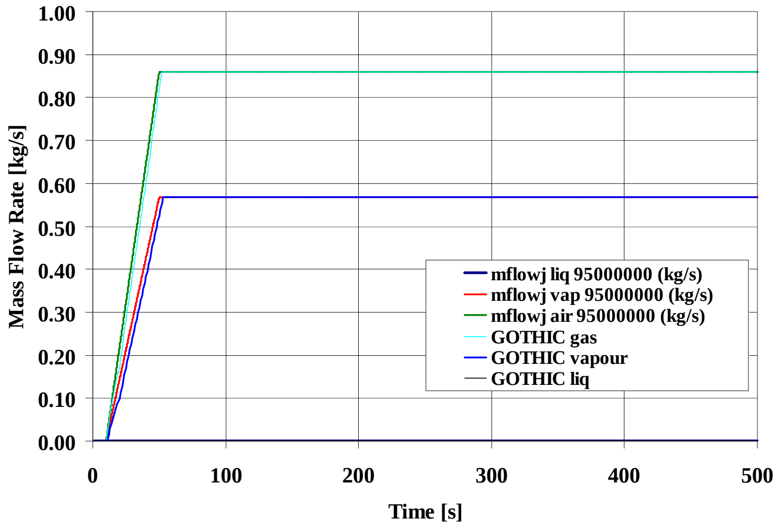

Figure 38. Sample case n. 5 – Inlet steam, water and air mass flowrates with mass averaged pressure assigned to Gothic

3.6 Filling a containment volume with water

3.6.1 Calculation case description

This sample calculation is very similar to the previous ones, but now water at 40 °C is injected into the containment node. The aim of this test was to verify the correct transfer of water from the primary side (simulated with the RELAP5 code) to a containment volume (simulated by Gothic). The containment is still modelled using a lumped Gothic control volume linked to two RELAP5 piping branches (Figure 27). The opening trip of the valve in the lower piping branch is forced to be false, while the flow injected by the time dependent junction in the lower piping branch is assigned to zero, as shown in the Figure 4-a.

The trip valve allowing the inlet of water inside the containment volume is opened after 10 s since the beginning of the test, while the coupling between the two codes is activated 5 s before the valve opening.

3.6.2 Obtained results

Figure 39 and Figure 40 show the increase of pressure and gas temperature in the containment atmosphere pressure due air compression as a consequence of the increase of pool level, reported in Figure 41; on the other hand, the temperature of the pool, fed by water at a constant temperature and constant flow rate (Figure 42), does not change as soon as a pool level is formed and as long as it keeps increasing (Figure 41). As it can be noted in Figure 43, the noncondensable mass fraction in the atmosphere increases slightly as a consequence of condensation over the pool surface of the increasingly warm vapour.

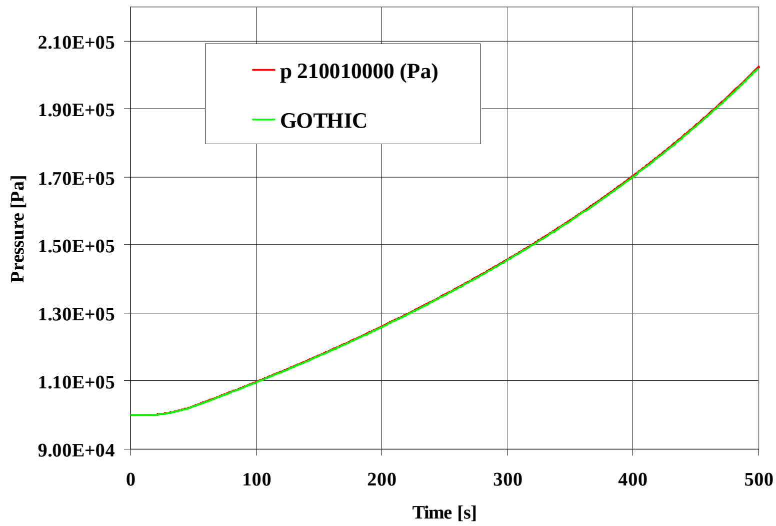

Figure 39. Sample case n. 6 – Total atmosphere pressure

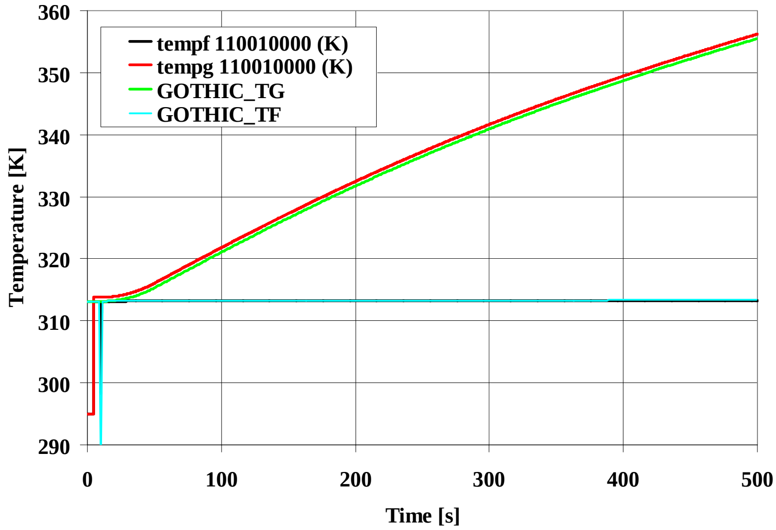

Figure 40. Sample case n. 6 – Atmosphere and pool temperatures

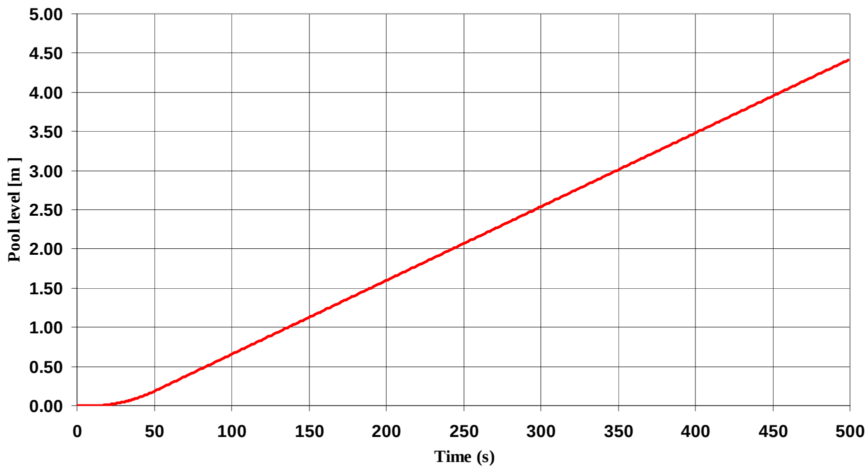

Figure 41. Sample case n. 6 – Pool level

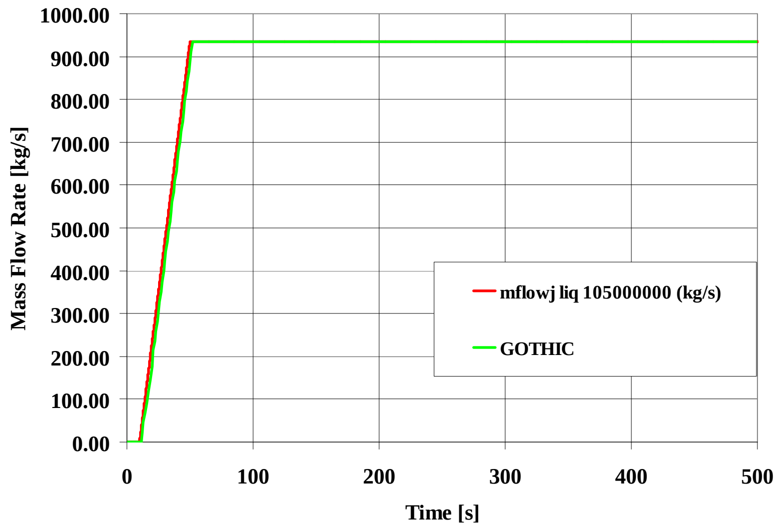

Figure 42. Sample case n. 6 – Water mass flowrate

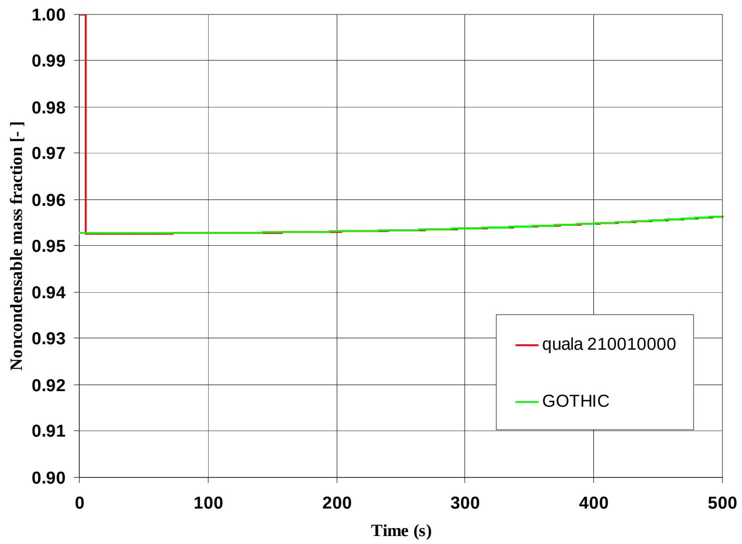

Figure 43. Sample case n. 6– Noncondensable mass fraction

3.7 Washing a containment volume with an air flow

3.7.1 Calculation case description

In this sample calculation, the washing of a large tank initially filled with pure air at a pressure of 100000 Pa and a temperature of 293.15 K is simulated. The washing is obtained by injecting hotter air (313.15 K) through the upper piping branch (Figure 44) at a specified rate, while air is allowed to exit through the lower piping branch. The aim of the test was to verify the correct transfer of a noncondensable gas from the primary system to a containment volume and viceversa, also checking that the right values of related energies contents are accounted for. The containment node has a free volume of 1000 m^3 and is simulated using a lumped Gothic control volume, linked to two RELAP5 piping branches. The opening trip of the valves in the upper and lower piping branches are forced to be true after 10 s since the beginning of the test, so that a simultaneous injection and extraction of air is obtained, as shown in the Figure 4-c. The coupling between the two codes is activated 5 s before the valve opening.

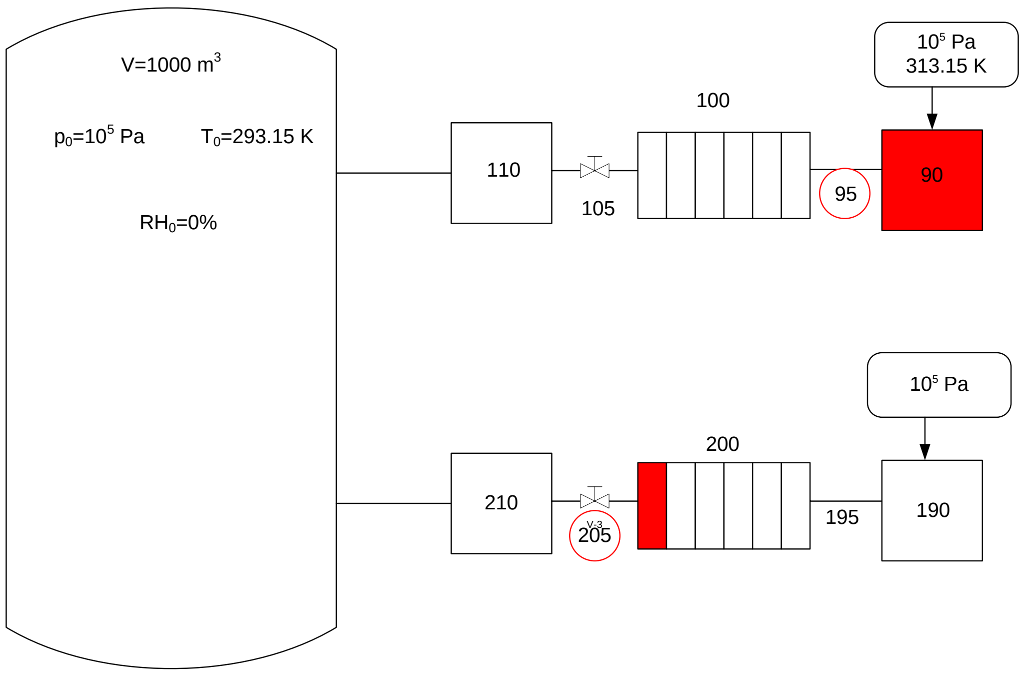

Figure 44. RELAP5/Gothic model for the sample calculation n.7

3.7.2 Obtained results

As it can be noted from Figure 45 to Figure 48, the transient easily evolves towards an equalisation of the inlet and outlet air flows, with a complete washing of the atmosphere by air; the usual little discrepancy in air temperature is again observed.

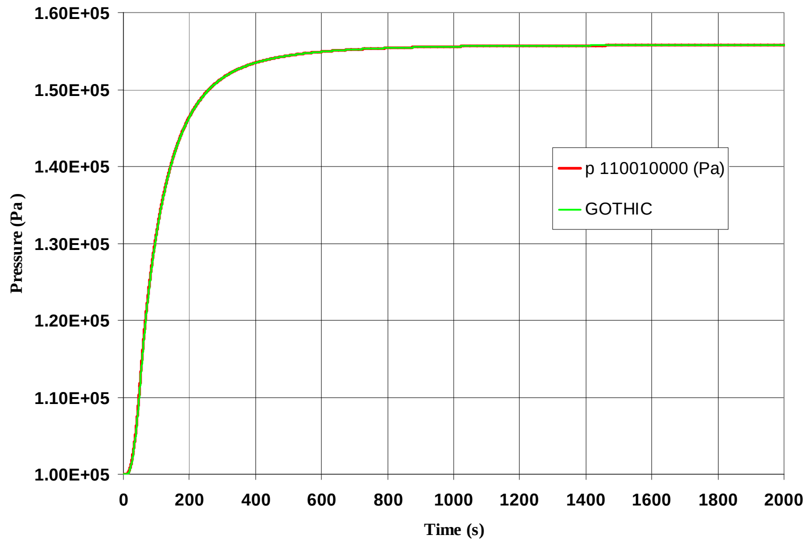

Figure 45. Sample case n. 7 – Total atmosphere pressure

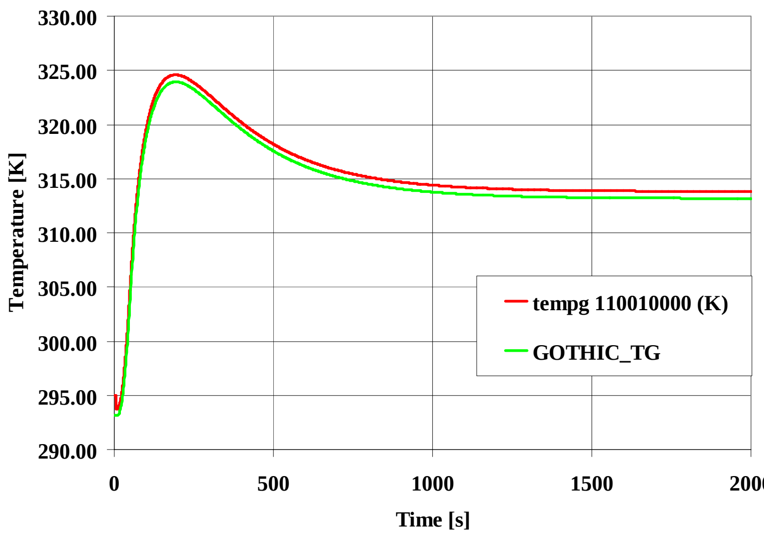

Figure 46. Sample case n. 7 – Atmosphere temperature

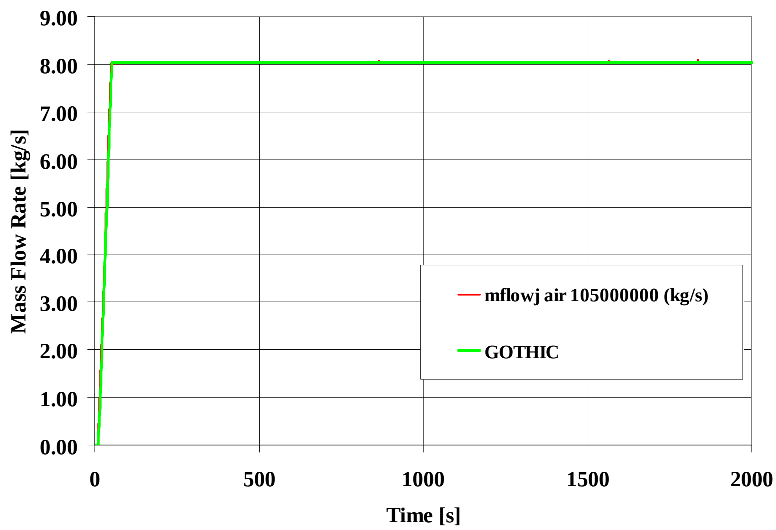

Figure 47. Sample case n. 7 – Inlet air flowrate

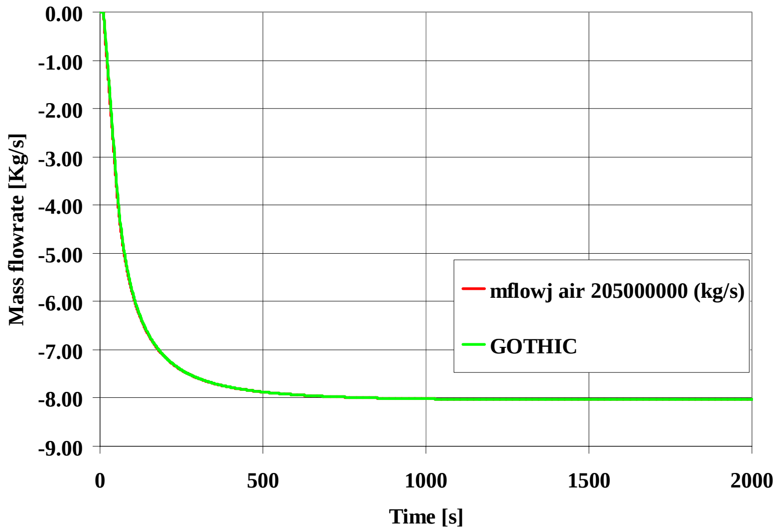

Figure 48. Sample case n. 7 – Outlet air flowrate

3.8 Washing a containment volume with air and steam

3.8.1 Calculation case description

This sample calculation is very similar to the previous one, except for the initial content of steam in the atmosphere of the tank (RH = 100%) and the injection of noncondensable gases with saturated steam at the temperature 313.15 K. The tank is again simulated using a lumped Gothic control volume linked to two RELAP5 hydrodynamic piping branches (Figure 44). The opening trip of the valves in the upper and lower piping branches are forced to be true after 10 s since the beginning of the test, so that a simultaneous injection of air and extraction of water is obtained, as shown in the Figure 4-c. The coupling between the two codes is activated 5 s before the valve opening.

The aim of the test was to verify the correct transfer of a noncondensable gas and steam from the primary system to a containment volume and vice versa, also checking the right values of related energies contents are accounted for.

3.8.2 Obtained results

Figure 49 to Figure 53 show the main results obtained in this case, similar to those in the previous one, except for the trend of temperature in the volume that is affected by condensation of the suspended steam, with the subsequent release of latent heat.

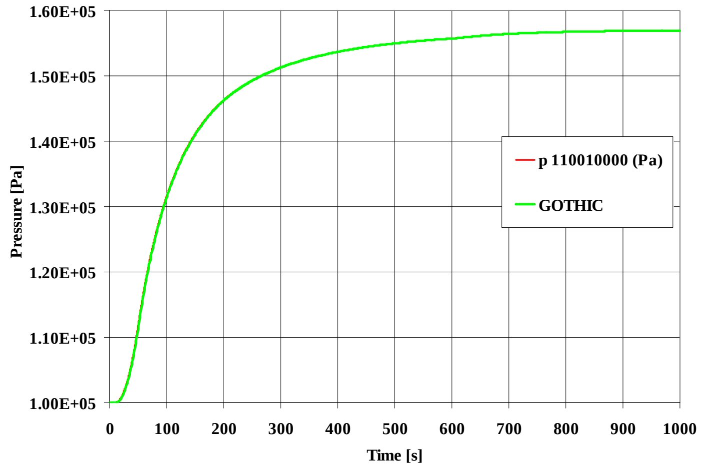

Figure 49. Sample case n. 8 – Total atmosphere pressure

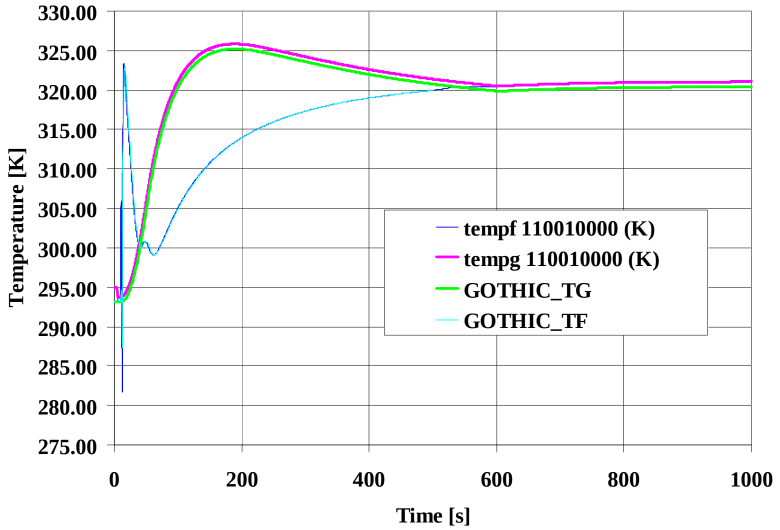

Figure 50. Sample case n. 8 – Atmosphere temperature

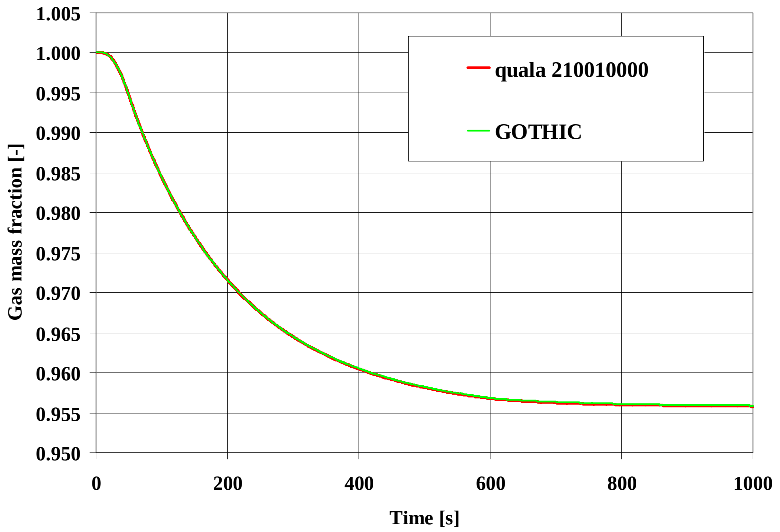

Figure 51. Sample case n. 8 – Noncondensable mass fraction

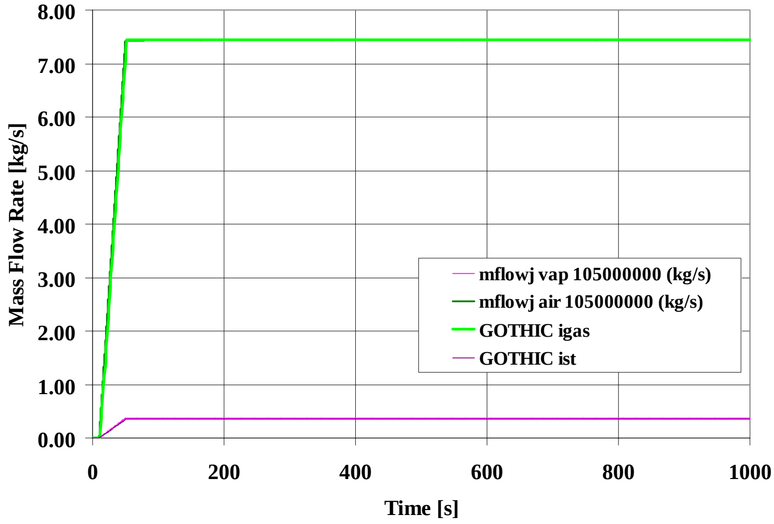

Figure 52. Sample case n. 8 – Inlet mass flowrates

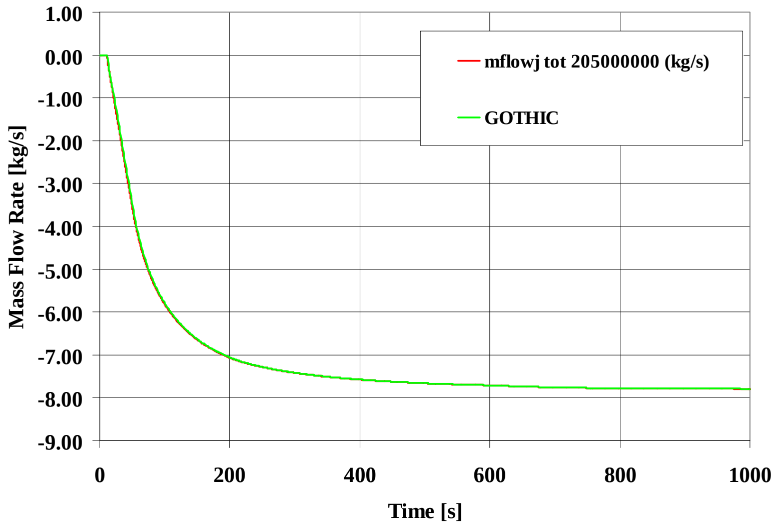

Figure 53. Sample case n. 8 – Outlet mass flowrates

3.9 Vessel blowdown in a dry containment

3.9.1 Calculation case description

The sketch describing the topological arrangement of the problem was already described in Figure 5 and in detail in Figure 6a. The vessel is made of a stack of 20 RELAP5 volumes representing a component of 5 m in diameter and 12 m in height. The break pipe has a diameter of 0.5 m and a length of 1 m and is connected at the inlet of the 16th volume (from the bottom) representing the vessel, i.e. at an height of 9 m with respect to the bottom. The gravity driven line, having a diameter of 0.3 m and a length of 10 m is connected at the bottom of the vessel, though it is not activated in the present case. The two RELAP5 piping branches are connected to boundary conditions and flow paths located respectively at 9.5 m and 0.5 from the bottom of the containment, represented by a lumped parameter Gothic containment having a volume of 70,000 m^3. As previously mentioned, the trip valve simulating the break allows for the evaluation of critical flow. The vessel is initially full of water at 15.5 MPa with a specific internal energy of 1.4×10^6 J/kg corresponding to a temperature of about 588 K (315 °C).

3.9.2 Obtained results

Figure 54 and Figure 58 show the classical scenario of a large break LOCA blowdown from a PWR primary system without ECCS intervention, including: the subcooled blowdown phase, liquid metastable effects and pressure recovery at flashing, break uncovery and faster depressurization, decreasing collapsed level in the vessel with final equalisation of pressures between primary system and containment (see also Figure 59).

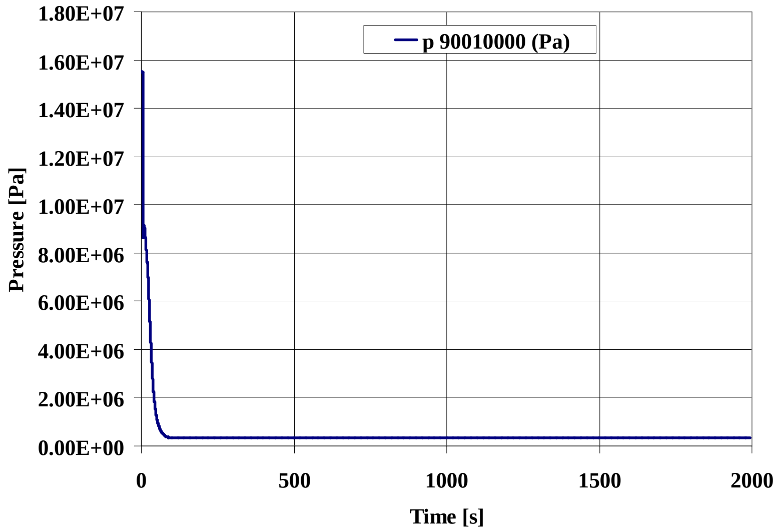

Figure 54. Sample case n. 9 – Primary system pressure

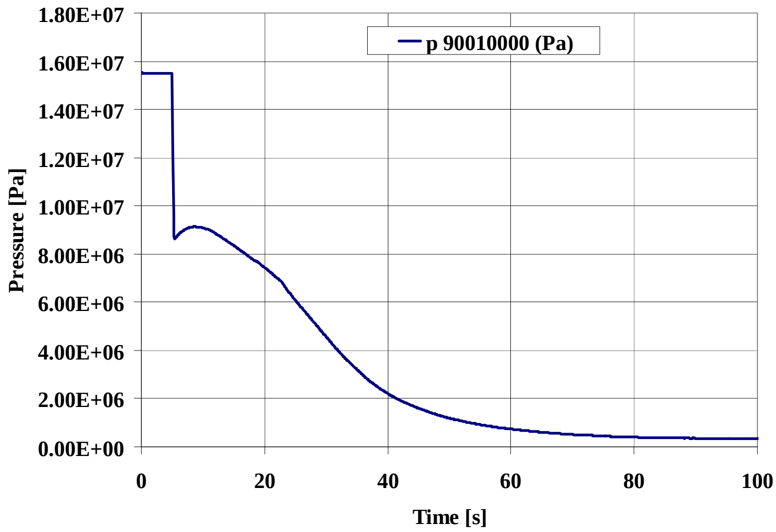

Figure 55. Sample case n. 9 – Primary system pressure (short term)

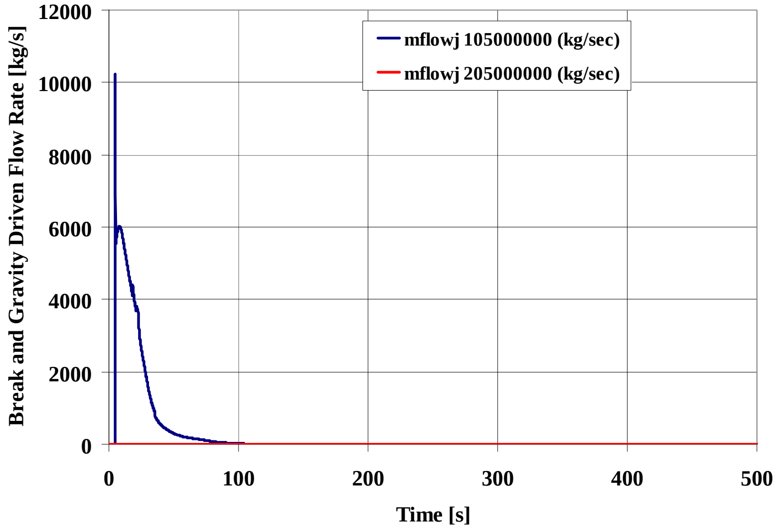

Figure 56. Sample case n. 9 – Total break mass flowrate

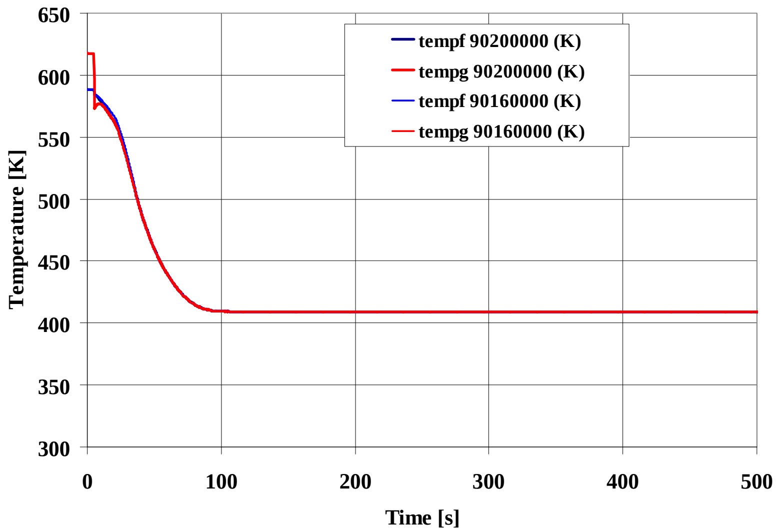

Figure 57. Sample case n. 9 – Primary system temperature

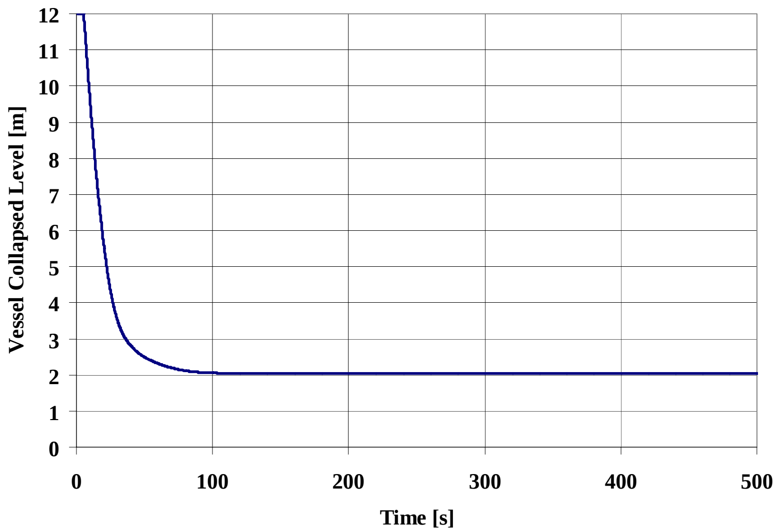

Figure 58. Sample case n. 9 – Vessel level

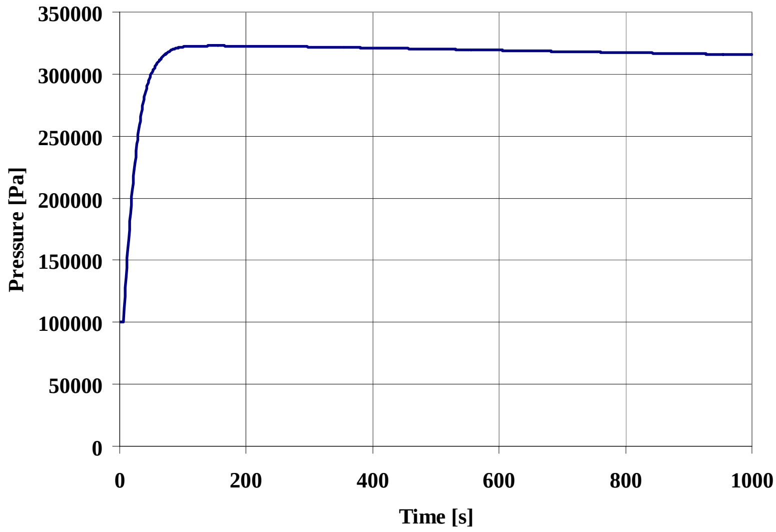

Figure 59. Sample case n. 9 – Containment pressure

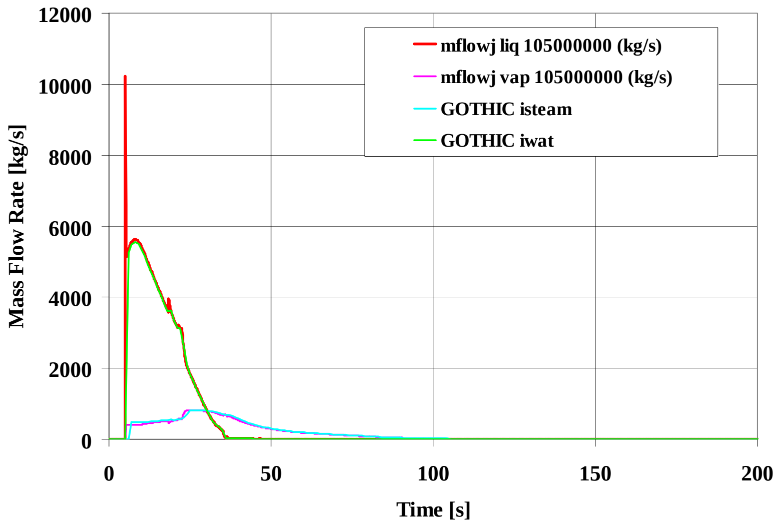

Figure 60. Sample case n. 9 – Break flowrate comparison

The break flow rate liquid and vapour components are compared in Figure 60 as calculated by RELAP5 and Gothic; the very good match of the two components testifies that the codes interpret in a same way the enthalpy assigned to the flow.

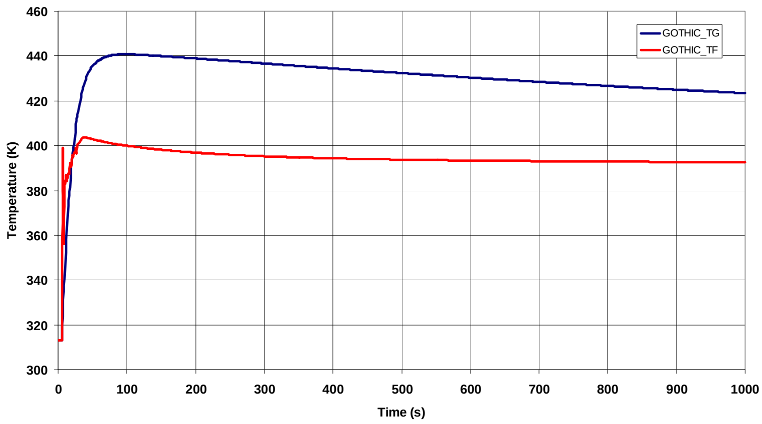

Figure 61. Sample case n. 9 – Atmosphere and pool containment temperatures

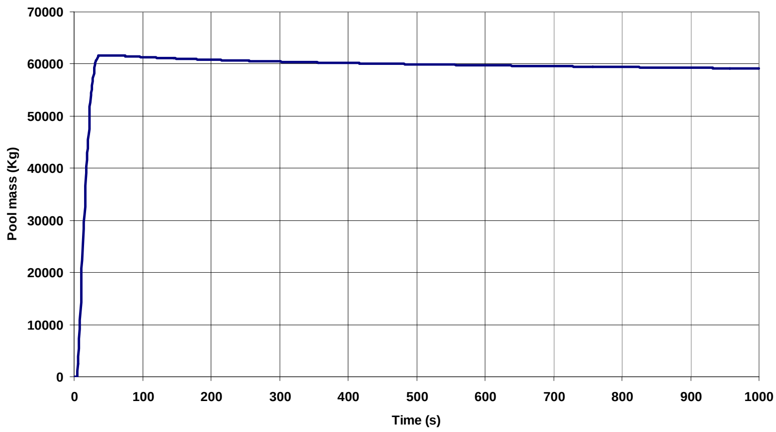

Figure 62. Sample case n. 9 – Containment pool mass

Finally, the containment pool and atmosphere temperatures and the pool mass follow trends that are fully expected (Figure 61 and Figure 62).

3.10 Vessel blowdown in a containment with gravity driven injection

3.10.1 Calculation case description

The present problem differs from the previous one for the following characteristics:

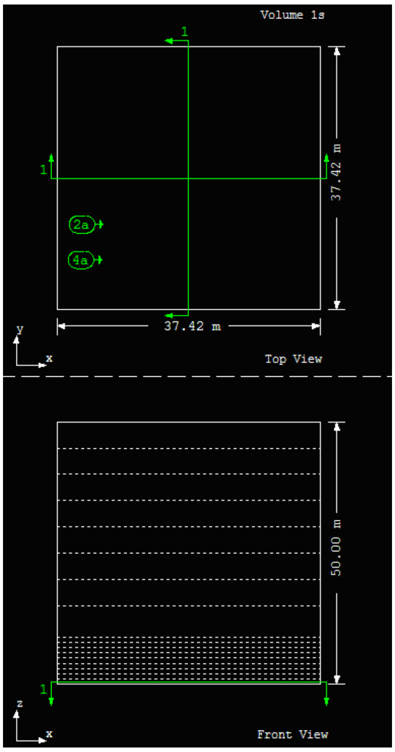

Figure 63. Sample case n. 10: containment volumes and subvolumes

- the containment volume, having the same overall size as in the previous case (70,000 m^3), has now a height of 50 m and is filled with 7 m of water at 40 °C;
- the containment volume is now subdivided into several vertical subvolumes, in order to allow for the calculation of the pressure head due to the containment level above the gravity driven injection pipe (Figure 63);
- the trip valve in the lower piping branch is now activated, making it have a role of gravity driven injection, thanks to the forward form loss coefficients of 10^{100} assigned to the trip valve.

The main aim of this analysis is to demonstrate the functional capability of the coupled code to simulate a simultaneous blowdown and a passive ECCS injection scenario.

3.10.2 Obtained results

As the main short term phenomena on primary side are similar to the ones shown for the previous case, attention will be now concentrated on the effect of triggering the gravity driven injection. In fact, as shown in Figure 64, the break flow rate trends have little difference with respect to the previous case.

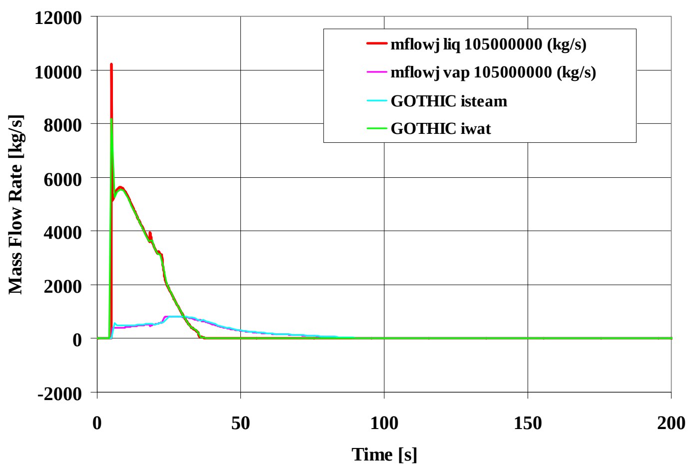

Figure 64. Sample case n. 9 – Break flowrate comparison

In this case, after reaching a sufficient equalization between primary and containment pressure, gravity driven injection from containment to the vessel occurs (Figure 65), recovering the vessel water inventory. It can be noted that the levels reached in the vessel and in the containment differ of a quantity close to the height difference of 0.5 m of the lower piping branch in the primary and in the containment systems (Figure 66 and Figure 67).

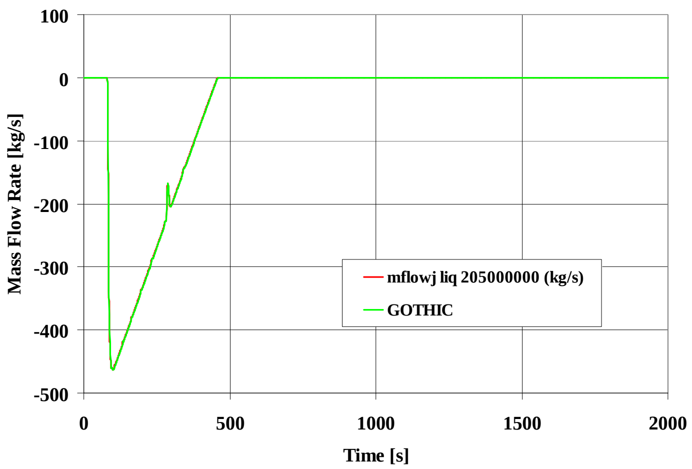

Figure 65. Sample case n. 10 – Gravity driven injection flow rate

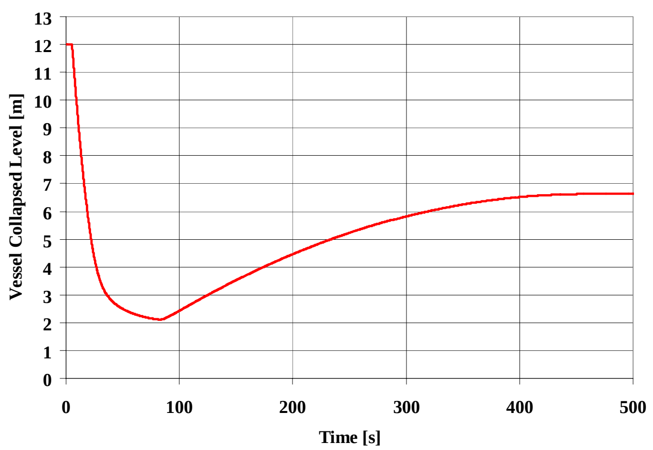

Figure 66. Sample case n. 10 – Vessel collapsed level

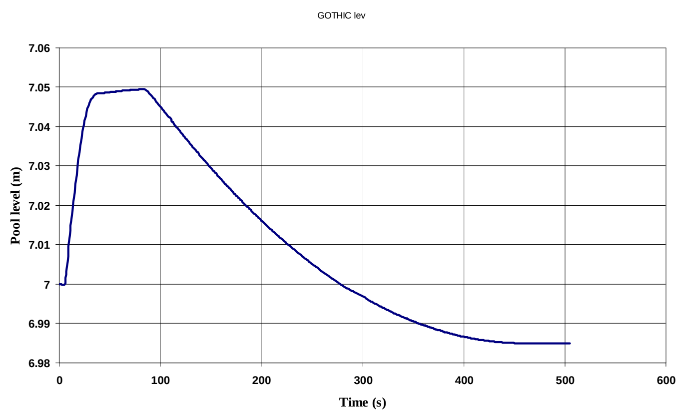

Figure 67. Sample case n. 10 – Containment pool level

4. CONCLUSIONS

The results obtained from the calculation cases presented in this document support the substantial adequacy of the work performed in coupling RELAP5 and Gothic.

Though different aspects of the adopted coupling methodology may need further refinements, as also mentioned in the Introduction, the results that were obtained confirm the suitability the general adopted strategy.

In selecting validation cases, the attention was mainly focused on confirming that the exchanges between the two codes are correct. This was the reason why essential RELAP5 nodalizations were selected, mainly referring to pipes injecting or extracting fluid to or from a containment volume. It is clear that a whatever complex RELAP5 nodalisation can be linked in a similar way to a Gothic multiple volume model, obtaining a similar quality in the exchange of data.

The final calculation cases addressing a pressurised water vessel blowdown served to show the suitability of the obtained coupling methodology to deal with a classical safety relevant calculation case.

Though running the sample cases did not encounter severe difficulties, it has to be expected that the robustness of the coupling will increase with the use of the model and with the introduction of numerical recipes necessary to deal with possible encountered exceptions in dealing with variable transfer from one code to the other. The explicit character of the adopted coupling (the only possible without intruding in the structure of the two codes) has shown limitations in the presence of oscillations occurring when the primary system and the containment pressures are very close, pointing out effects which can be fully expected considering the need for pressure-velocity coupling algorithms widely adopted in fluid-dynamics.

In summary, the work performed up to now represents what it was feasible to achieve with the available code versions and their characteristics in terms of variable accessibility. Further code versions making available more information on junction and flow path variables might lead to a better and more accurate strategy for coupling the two codes.

REFERENCES

[1] Walter Ambrosini, Antonio Manfredini, Methodology for coupling thermal-hydraulic codes for primary system and containment analysis, Università di Pisa, DIMNP RL 1286(2011), August, 2011.

[2] RELAP5/MOD3.3 CODE MANUAL, VOLUME I: CODE STRUCTURE, SYSTEM MODELS, AND SOLUTION METHODS, Nuclear Safety Analysis Division, December 2001, Information Systems Laboratories, Inc., Rockville, Maryland, Idaho Falls, Idaho, Prepared for the Division of Systems Research Office of Nuclear Regulatory Research, U. S. Nuclear Regulatory Commission, Washington, DC 20555, NUREG/CR-5535/Rev 1-Vol I.

[3] RELAP5/MOD3.3 CODE MANUAL, VOLUME II, APPENDIX A, INPUT REQUIREMENTS, Nuclear Safety Analysis Division, January 2002, Information Systems Laboratories, Inc., Rockville, Maryland, Idaho Falls, Idaho, NUREG/CR-5535/Rev 1-Vol II App A.

[4] T. George, S. Claybrook, L. Wiles, C. Wheeler, Gothic, CONTAINMENT ANALYSIS PACKAGE USER MANUAL, Version 7.2b(QA), NAI 8907-02 Rev 18, March 2009.