

Verification and Validation of GOTHIC 8.5(QA) for Severe Accident Conditions with Various Experimental Benchmarks

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ABSTRACT

Increase in energy consumption requires increasing demand for energy sources. On the other hand, greenhouse gas emissions and climate change make it challenging to find reliable and sustainable energy solutions. Nuclear energy has high potential to meet energy needs without CO₂ generation. However, nuclear energy also comes with challenges, and one of the biggest is safety. There are a lot of reactor types. But regardless of reactor type, whether conventional large-scale plants or newer designs such as Micro Modular Reactors (MMRs) and Small Modular Reactors (SMRs), containment performance plays a central role as the final protective layer against radioactive material release and in overall plant safety. Although advance reactor concepts aim to enhance inherent and passive safety features, the need for reliable containment analysis and validation remains essential for both existing and emerging technologies.

GOTHIC 8.5(QA) is a comprehensive and up-to-date reactor containment analysis code that performs advanced thermal-hydraulic (T/H) calculations for deterministic safety analyses, probabilistic safety assessment, and long-term operation support of nuclear power plants. This paper presents the validation and verification (V&V) of GOTHIC 8.5(QA) against selected large-scale experimental benchmarks: NUPEC M-7-1, PANDA ST3_2, and TOSQAN tests. These experiments represent important containment phenomena during a severe accident, such as hydrogen behaviour, gas mixing, stratification, and steam condensation.

Detailed nodalization models were developed for each facility, including review of boundary conditions and geometrical fidelity to evaluate modelling quality. Simulation results were compared with experimental data in terms of pressure, temperature, and gas concentration evolution. Particular attention was given to hydrogen behaviour and distribution, transient evolution, peak values, and long-term trends.

The comparison shows generally good agreement between simulation and experimental results. Some deviations were observed in local mixing and stratification prediction, which require further sensitivity studies through mesh refinement and modelling adjustments. The study confirms that GOTHIC 8.5(QA) can reproduce key containment thermal-hydraulic phenomena during severe accidents with acceptable accuracy for safety analysis applications.

Keywords: *thermal-hydraulics, severe accident, GOTHIC 8.5(QA), NUPEC, TOSQAN, PANDA*

1 INTRODUCTION

As global efforts to reduce carbon emissions and achieve energy sustainability intensify, nuclear power is increasingly recognized as an essential, large-scale source of zero-carbon energy source. To ensure the involvement of nuclear energy for a zero-carbon future, prioritization of assurance of the highest safety standards is a must. Containment is one of the most crucial safety barriers for a nuclear system since it also serves as the final barrier before release of radioactive material in case of a severe accident.

Regardless of generation, containment atmosphere must remain intact even in extreme scenarios. Achievement of this involves controlling of high-pressure transients, hydrogen generation and stratification, sufficient cooling mechanisms – such as spray – and passive heat dissipation. Tools like Generation of Thermal Hydraulic Information in Containments (GOTHIC) are capable of modelling complex reactor buildings, heat transfer, fluid dynamics and gas transport at an industry standard. It is important to ensure the fidelity of the facility's nodalization and the validity of the physical models implemented by the engineer, in order to ensure the simulation tools are reliable enough for safety-critical decision making. Validation and Verification (V&V) procedures are required in which Simulation Model (SM) accuracy and code capabilities are assessed by comparing with facility geometrical information and experimental results.

This paper presents a comprehensive validation assessment of GOTHIC 8.5(QA) by using three different experimental benchmarks:

- PANDA facility ST3_2 test,
- TOSQAN International Standard Problem (ISP) 47 Test,
- NUPEC facility M-7-1 test.

Test are chosen to cover a spectrum of severe accident phenomena such as buoyancy-driven gas distribution to multi-compartment containment, containment spray cooling effect, wall condensation.

The structure of the paper is as follows:

- Section 1 Introduction
- Section 2 GOTHIC Theoretical Background,
- Section 3 V&V Process of GOTHIC,
- Section 4 PANDA Test Facility and ST3_2 Test,
- Section 5 TOSQAN Test Facility and ISP-47 Test,
- Section 6 NUPEC Test Facility and M-7-1 Test,
- Section 7 Conclusion.

2 GOTHIC THEORETICAL BACKGROUND

GOTHIC is an integrated code developed by EPRI for a general purpose thermal-hydraulics studies for design, licensing, safety and operating analysis of nuclear power plant containments, confinement buildings and system components. GOTHIC solves the conservation equations for mass, momentum and energy for multicomponent, multiphase compressible flow in lumped parameter and/or multi-dimensional (1,2, or full 3D) geometries. Two phase flow and single phase flow models are included in the mechanistic models that are coupled with balance equations for interface mass, energy and momentum transfer. Phases can have non-equilibrium thermal states with unequal velocities. Conservation equation can be solved for many different mixed atmospheric situations including vapor with any number of non-condensing gases. The code also includes models for various safety equipment that are used in nuclear systems (such as sprays, coolers, etc.).

GOTHIC obtains detailed thermal/hydraulic results by solving the mass, energy and momentum equations for three different fluid phases: vapor (steam and non-condensing gasses), drops and continuous liquid. GOTHIC can include some other phases with different thermodynamic conditions, such as: ice, freezing, melting, sublimation. But inclusion of them is achieved via conductors unlike solving method for aforementioned fluid phases.

GOTHIC has been successfully used by several utilities to resolve key technical issues in the areas of equipment qualification, accident analysis in support of room heat up calculations, technical specification changes and other areas [1]. GOTHIC specifically can model buoyancy dominated flow, condensation and evaporative heat transfer in the presence of noncondensing gases, stratification, hydrogen mixing and dissipation. Capabilities of GOTHIC had a priority while choosing the benchmarks for V&V of GOTHIC 8.5(QA).

3 V&V PROCESS OF GOTHIC 8.5(QA)

Validation and verification of GOTHIC 8.5(QA) is achieved with the specially chosen benchmarks. These benchmarks and the purposes are listed in Table 3.1. Tests are chosen with the consideration of GOTHIC capabilities and main applications. Chosen road map that have been taken for V&V of GOTHIC 8.5(QA) is shown below:

- Choosing facility and test with the code purpose and capabilities in mind,
- Confirmation of quality and quantity of geometrical and experimental data of the facility and the specified test,
- Confirmation of representability of the facility and the test with GOTHIC 8.5(QA) containment analyze code,
- Digitalization of geometrical and experimental data,
- Creating the Simulation Model (SM) for test facilities,
- Establishing geometrical fidelity of SM with facility,
- Systematic and comprehensive comparison between experimental and simulation results.

Aforementioned road map is applied to all facility and test that has been chosen and process of application as well as results are discussed in this paper.

Table 3.1: Chosen tests for GOTHIC 8.5(QA) V&V

Facility	Test	Purpose
PANDA	ST3 2	Hydrogen stratification and spray affect
TOSQAN	ISP-47	Wall condensation
NUPEC	M-7-1	Multi-compartment gas and steam dissipation and spray affect

4 PANDA TEST FACILITY AND ST3_2 TEST

4.1 Facility and ST3_2 Test Description

The PANDA facility is a test facility that is designed to test thermal-hydraulic phenomena. The design allows the facility to investigate: Containment system behaviour, component tests and primary circuit, Basic phenomena at large-scale with CFD-grade instrumentation tests [2].

PANDA facility consists of 4 Vessels where 2 of them are DryWell (DW) and remaining 2 are WetWell (WW) connected by 2 pipes. The facility has a 25 m of height overall and total volume of 515 m³ and can be operated maximum of 1 MPa pressure and 200 °C to represent the core energy generation, Reactor Pressure Vessel (RPV) is equipped with electrical heaters that can reach up to 1.5 MW. Obtaining initial conditions for various experiments are achieved by some auxiliary systems. The facility includes more than 1000 sensors, 2 mass spectrometers and one Particle Image Velocimetry (PIV) system.

PANDA ST3 test series focuses on spray effect. Sprays are important in case of an accident to mitigate it in the containment. As aforementioned, PANDA facility consists of 4 Vessels where 2 of them are DW and remaining 2 are WW connected by 2 pipes but ST3_2 test, only 2 DW vessels are important with one Interconnection pipe (IP) connecting the vessels to each other. Each vessel has a manhole on top with 0.98m diameter for access purposes. All components are made of stainless steel. Manhole adds 0.464 m to height of vessels. Main objective of ST3_2 test is to see spray effect on accumulated helium layer. To achieve this, helium injection initiated to obtain 2 m of helium layer from the top before test. Detailed pre-test conditions for PANDA ST3_2 test can be seen in Figure 4.2.

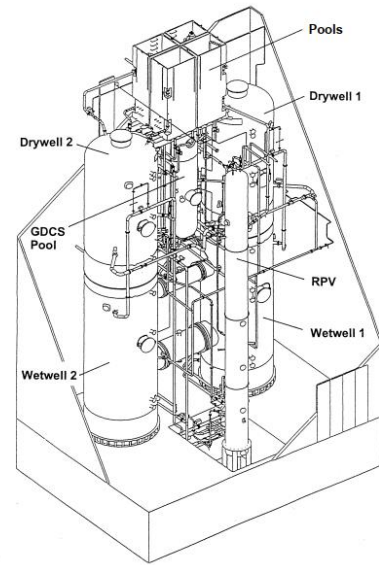


Figure 4.1: PANDA Facility [3]

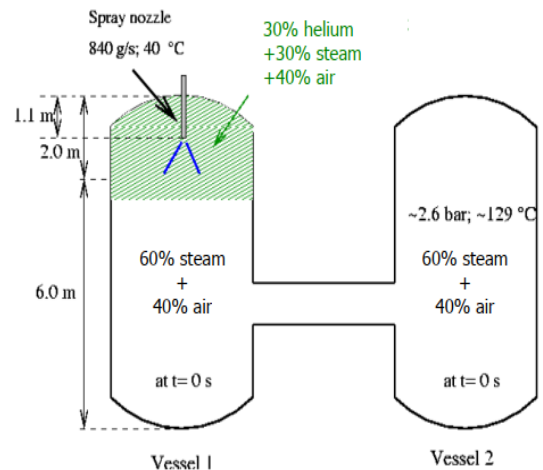


Figure 4.2: PANDA ST3_2 Pre-test Conditions [2]

4.2 GOTHIC Simulation Model Development of PANDA facility and ST3_2 Test

The GOTHIC 8.5(QA) representation of the PANDA test facility (hereafter referred to as **GOTHIC-SM-PANDA**) has been implemented. The ST3_2 test uses 2 DW vessels with one IP connection to each other. GOTHIC-SM-PANDA represents 2 DW vessels and one IP with total of 3 control volumes. All volumes have been subdivided to obtain detailed results. Shape and volume of vessel obtained by adding blockages to control volumes.

Sprays are implemented as Boundary Condition (BC). Sprays are assumed to have 0.01cm droplet diameter since it is not specified.

GOTHIC-SM-PANDA consists of 3 Control Volumes (CVs) to represent vessel 1, IP and vessel 2 and all volumes are subdivided with 3872, 39 and 1701 sub volumes, respectively. In GOTHIC the shaping of a volume achieved by using blockages inside the volume. Vessel 1 and vessel 2 shapes achieved with 11 blockages. IP shape achieved with only one blockage. Vessel 1 has a finer

mesh where the helium layer is stationed. It is important to understand that the size of the pipe and volumes are defined by the blockages. Not the borders of the control volumes. Detailed nodalization of GOTHIC-SM-PANDA and achieved subdivided volumes can be seen in Figure 4.4.

GOTHIC-SM-PANDA includes one flow path and two 3D connectors. Flow path 1 connects the BC 1F (spray) to sub volume n°2965 of vessel 1 (1s). The effect of flow area does not affect the simulation since flow rate for spray is imposed (see Figure 4.2). While a flow path can connect only one volume at a time, 3D connectors can connect to span of volumes. 3D connector number 1 connects vessel 1 (1s) to the IP (3s) while 3D connector number 2 connects the IP (3s) with vessel 2 (2s). Location and connections of flow path and 3D connector can be seen in Figure 4.3.

GOTHIC-SM-PANDA contains a total of 21 Thermal Conductors (TC) as depicted. All thermal conductors are implemented to represent heat losses between compartments and to atmosphere. There is no heat generation in the system. Nearly all the conductors are imposed on the blockages to have the best representation for the surfaces. All TCs are internally connected to volumes. Internally connected TCs always have the same surface for left and right sides.

Surface Options in conductors are used to impose heat transfer models and thermal boundary conditions. GOTHIC-SM-PANDA uses 2 surface options. 1 surface option uses Specified Temperature (Sp Temp) to represent atmosphere (at 25 °C) heat transfer. Other surface option uses Direct heat transfer. This means the code will compute the heat transfer. Condensation option chosen as advised by the manual

Conductor types include geometry, material properties and nodding information and needs to be selected for each thermal conductor. GOTHIC-SM-PANDA uses 7 conductor types. Each conductor type used to represent heat transfer in a different part of geometry. The outside part of the vessel is insulated with 20 cm of Rockwool. Insulation parameters are included in the conductor type input of the TCs. The insulation material is Rock Wool 133.

The initial helium concentration in vessel 1 is raised from 30 % (see Figure 4.2) to 38.6 %. The alteration has been implemented after close inspection of the experimental results [4]. In case of inconsistency between nominal (written in the text) or plotted data, N.I.N.E. guidelines establish preference of the latter over the former (plotted over written).

GOTHIC-SM-PANDA includes only one flow type BC. This BC is used to initiate and have a continuous spray flow to vessel 1 at 6.9 m above from the bottom of the vessel. Remaining BC and initial conditions are implemented as described in Figure 4.2.

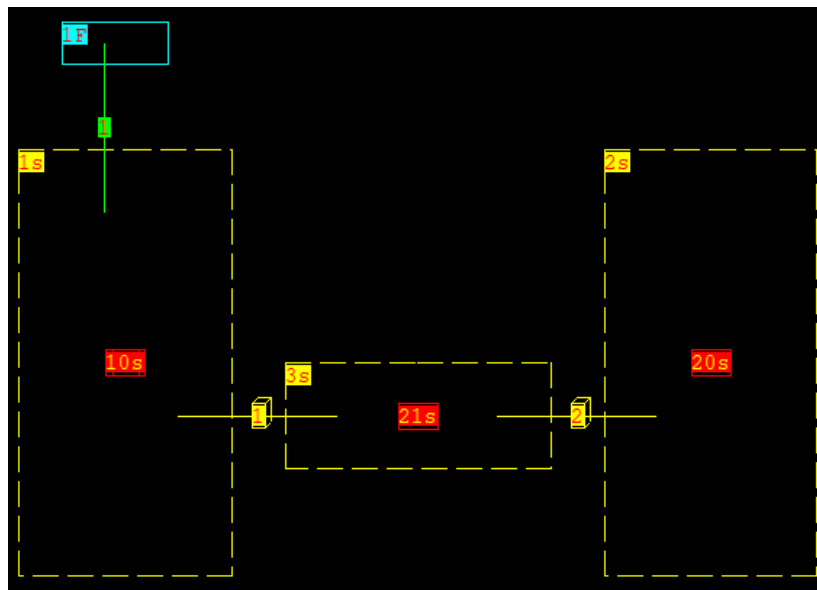


Figure 4.3: GOTHIC-SM-PANDA Nodalization

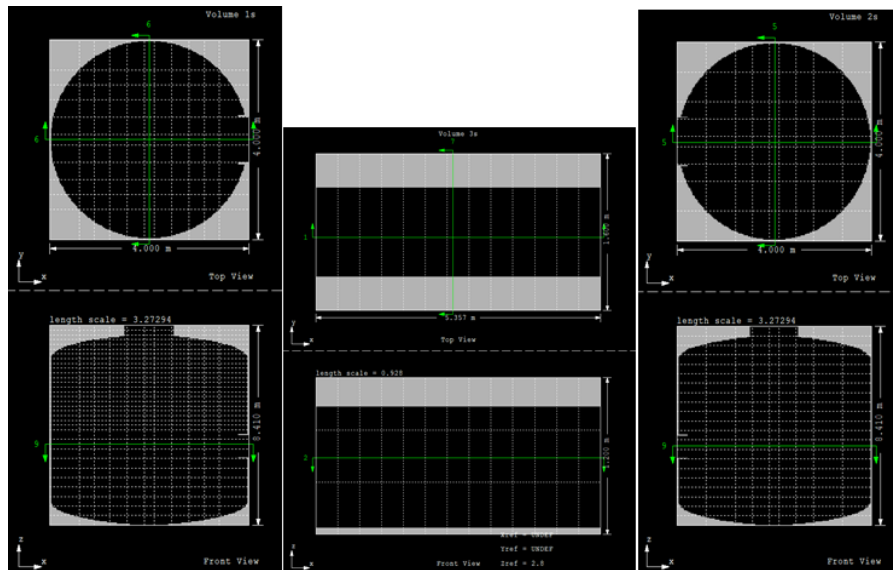


Figure 4.4: Vessel 1, IP and Vessel 2, Respectively

4.3 GOTHIC-SM-PANDA Results Comparison

As the transient starts, the activation of the spray in vessel 1 generates a depressurization due to the steam condensation. The depressurization is continuous as the constant spray keep enhancing the condensation until it reaches 150 kPa for experimental results and 130 kPa for SM results by End of the Transient (EoT). This overprediction caused by tendency of GOTHIC to overpredict the gas mixing: As soon as spray enters to the volume, GOTHIC assumes that it mixes with atmosphere perfectly and immediately.

The condensation also causes a temperature drop in the volumes in both experimental and GOTHIC-SM-PANDA. Unfortunately, experimental results do not provide any numerical range for temperature contours. Nevertheless, the overall results are qualitatively consistent.

Start of spray injection causes helium that was accumulated at the top of the vessel 1 to start spreading. Concentration of helium starts from 38.6% at the top of the vessel 1, as depicted from Figure 4.6, starts decreasing at around 150 s. While the accumulated helium at the top part of the vessel 1 dissipates, a consequent increase in helium concentration at the lower parts of the vessel 1 can be seen in both experimental and SM results. Helium does not reach the IP until around 500 s in SM results and until 550-600 s in experimental results. An initial helium concentration increase at the highest point of the IP can be observed around 200 s for both experimental results and SM results. This is due to helium at the bottom of the stratified layer immigrating to IP before it can mix with spray water. While experimental results and SM results are in agreement, the immigration of helium to other volumes are faster in SM model due to faster mixing. Helium concentration stabilizes around 10% for vessel 1 and 8-9% in pipe. Helium concentration does not start to increase until 750-800 s in the SM results and 1000 s in the experimental results. After Helium reaches vessel 2, it is observed that at the middle and lower levels of the vessel, its concentration is higher than top layers and this stays same for all duration of the test. This behaviour is same for both experimental results and SM results and it indicates that helium is well mixed with steam/air. At the end of the simulation, vessel 1, IP and vessel 2 mid to lower elevations stabilizes at 6% to 9% helium concentration. While higher elevations of vessel 2 stays at lower concentration levels.

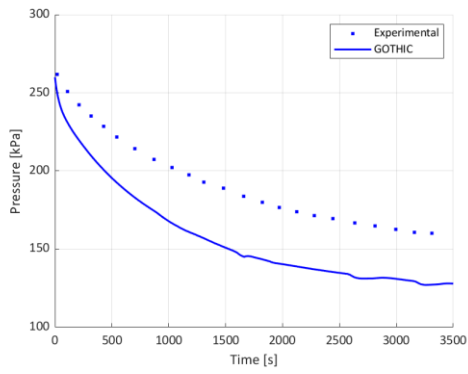


Figure 4.5: Pressure Behaviour

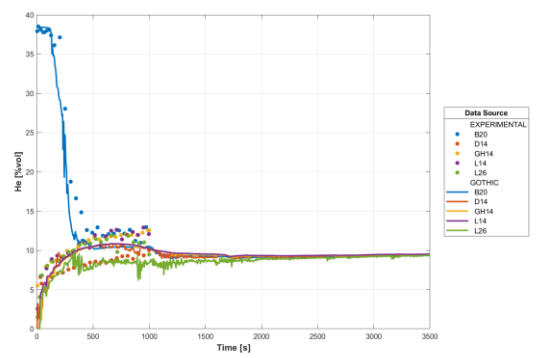


Figure 4.6: Helium Behaviour in Vessel 1

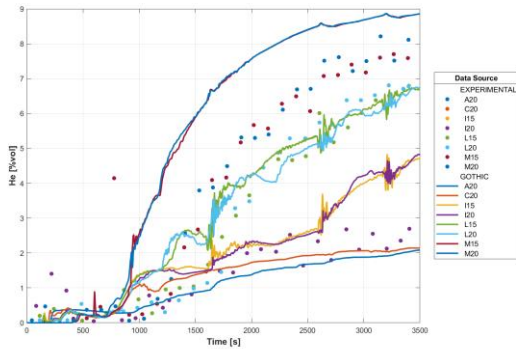


Figure 4.7: Helium Behaviour in Vessel

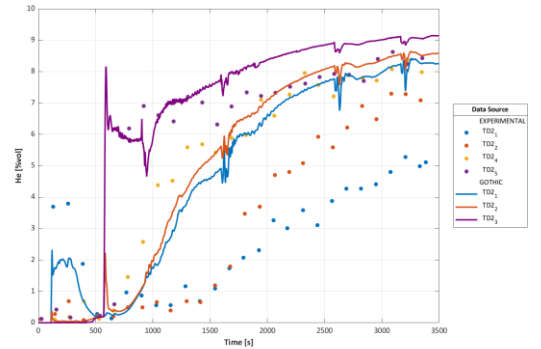


Figure 4.8: Helium Behaviour in IP

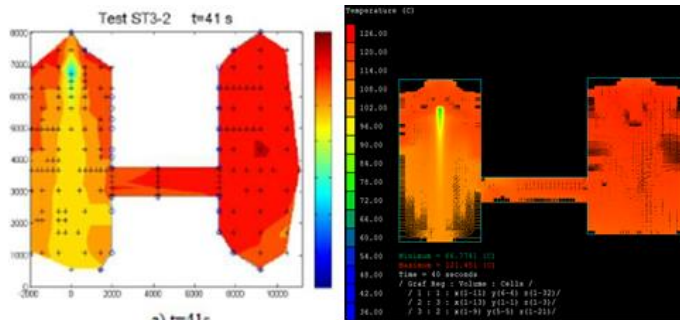


Figure 4.9: Temperature Contours at 41 s

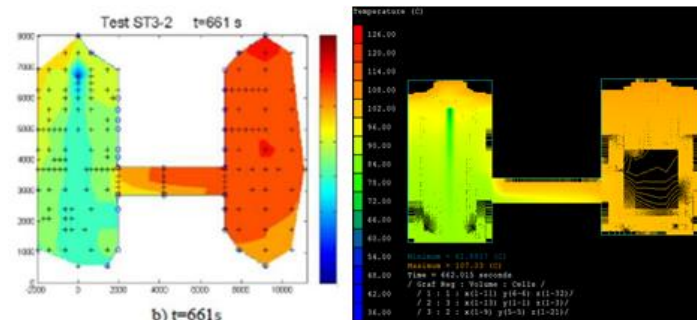


Figure 4.10: Temperature Contours at 661 s

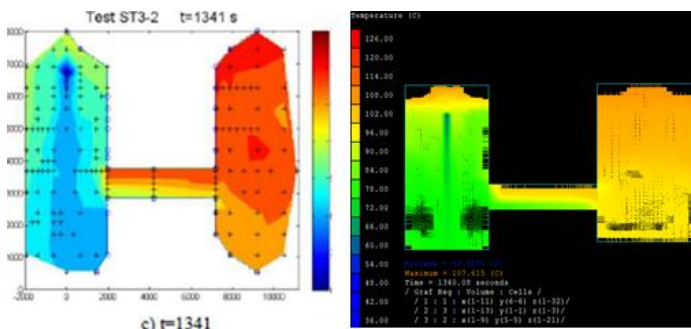


Figure 4.11: Temperature Contours at 1341 s

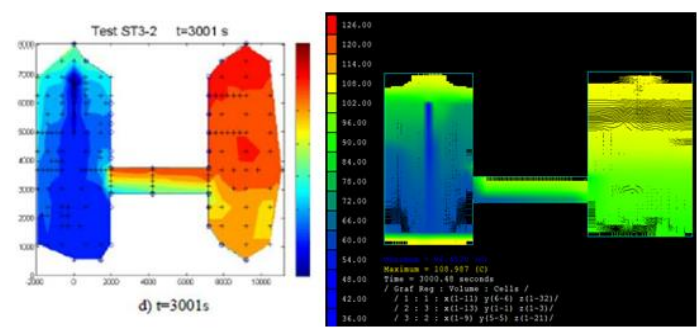


Figure 4.12: Temperature Contours at 3001 s

5 TOSQAN TEST FACILITY AND ISP-47 TEST

5.1 Facility and ISP-47 Test Description

TOSQAN is a test facility with only one stainless steel vessel with a total volume of 7 m³ including the sump. Vessel wall temperatures are controlled thermostatically with circulating oil inside the various wall sections. The vessel has a 4.8 m of height overall and 1.5 m inner diameter. An injection pipe is placed at the radially middle location of the vessel with outlet at 2.1 m high from the bottom of the vessel. The injection tube has a 50 mm outer and 41 mm inner diameter. Facility includes close to 100 instruments to conduct required concentration, velocity and temperature measurements.

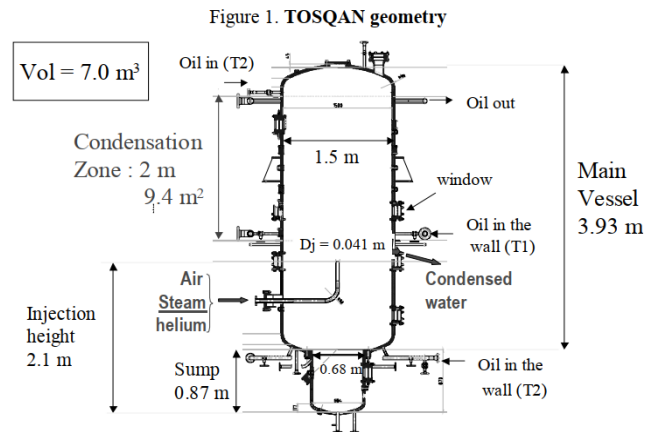


Figure 5.1: TOSQAN Facility ISP-47 Test [5]

This paper specifically focuses on ISP-47 test of TOSQAN. TOSQAN ISP-47 test tries to simulate a severe accident scenario by injecting different amounts of steam/air/helium (helium is instead of hydrogen due to safety reasons) and imposing different temperatures to the internal walls of the vessel so the condensation phenomena can also be investigated (see Figure 5.1). Even through the TOSQAN facility less complex compared to PANDA facility, the test process for TOSQAN is more complex with changing wall temperatures and injections.

Temperature regulation for the inner surface of the TOSQAN vessel is achieved by circulating oil inside the various wall sections. Hot oil circulates the lower and upper sections of the vessel while cold oil is used to cool down the middle section, between elevations 2.391 m and 4.391 m from the bottom of the vessel, to create a cold wall section of 2 m height. Injection rates and temperatures as well as wall temperatures along the test process can be seen in Table 5.1 and Table 5.2.

Table 5.1: TOSQAN ISP-47 Test Mass Flow Rate of Steam/Air/Helium Per Stage [5]

Stage	Time [s]	Steam Mass Flow Rate [g/s]	Air Mass Flow Rate [g/s]	Helium Mass Flow Rate [g/s]
1 st Pressurization	0-2270	1.4-1.14 (Linear)		
Seeding prep.	2270-5120	1.09		
Seeding	5120-5750	1.09	3.16	
SS1	5750-8190	1.01		
2 nd Pressurization + SS2	8190-15680	12.15		
Depressurization	15680-17900	1.00		
SS3	17900-22440	1.05		
Seeding	22440-23070	1.05	3.16	
3 rd Pressurization	23500-24420	1.11-0.89 (Linear)		1.03
SS4	24420-27000	0.81		

Table 5.2: TOSQAN ISP-47 Test Mean Injection and Wall Temperatures [5]

Stage	Injection Mean Temperature [°C]	Mean Condensing Wall Temperature [°C]	Mean Upper Hot Wall Temperature [°C]	Mean Lower Hot Wall Temperature [°C]
1 st Pressurization	127	102.8	123	124.5
Seeding prep.	128	102.8	123	124.5
Seeding	128	102.8	123	124.5
SS1	126	102.8	123	124.5
2 nd Pressurization + SS2	132	108.8	123	124.5

Table 5.2: TOSQAN ISP-47 Test Mean Injection and Wall Temperatures (cont'd)

Stage	Injection Mean Temperature [°C]	Mean Condensing Wall Temperature [°C]	Mean Upper Hot Wall Temperature [°C]	Mean Lower Hot Wall Temperature [°C]
Depressurization	131	102.8	123	124.5
SS3	126	102.8	123	124.5
Seeding	126	102.8	123	124.5
3 rd Pressurization	130	102.8	123	124.5
SS4	138	102.8	123	124.5

5.2 GOTHIC Simulation Model Development of TOSQAN Facility and ISP-47

The GOTHIC 8.5(QA) representation of the TOSQAN test facility (hereafter referred to as **GOTHIC-SM-TOSQAN**) consists of 2 subdivided control volumes, one vessel (1s) and an injection pipe (2s). Vessel shape modelled by implementing seven blockages and six openings and injection pipe shape obtained with one blockage and one opening.

Vessel subdivided into 4875 volumes. The precision and locations of measurement points are given high priority while creating meshing of vessel. Injection pipe subdivided into 3 volumes.

GOTHIC-SM-TOSQAN includes 3 flow paths and only one 3D connector. Flow paths are connected between BCs and injection pipe. Flow paths 1, 2, and 3 are utilized to inject air, steam, and helium, respectively, into the base of the injection pipe. A 3D connector is used to connect vessel and injection pipe at 2.1 m high from the bottom of the sump.

GOTHIC-SM-TOSQAN contains a total of 6 TCs. All thermal conductors are implemented to represent heat transfer between wall surface and inner vessel atmosphere. There is no heat generation in the system. All the conductors are imposed on the blockages to have the best representation for the surfaces.

GOTHIC-SM-TOSQAN uses 6 surface options. 3 surface option uses Specified Temperature (Sp Temp) to represent different wall regions with different temperatures. To implement time dependent temperature on the vessel walls, Forced Function (FF) is used to impose specified temperature for walls. Other surface option uses Direct heat transfer to calculate the heat transfer between wall surface and inner atmosphere. Since the outer side has imposed temperature, there is no heat loss from vessel wall to outer atmosphere.

GOTHIC-SM-TOSQAN uses 2 conductor types for different cap and cylinder thicknesses. The materials of conductor types are chosen as stainless steel.

GOTHIC-SM-TOSQAN includes 3 flow type BCs. Each BC used to inject one substance into system (steam, air and helium). FF used to impose changing injection mass flow rates and temperatures as described in Table 5.1 and Table 5.2.

At the start of the test, the temperature in the vessel and injection pipe set to 115.5 °C and humidity is set to 0.0%. Initially, all the volumes had only air.

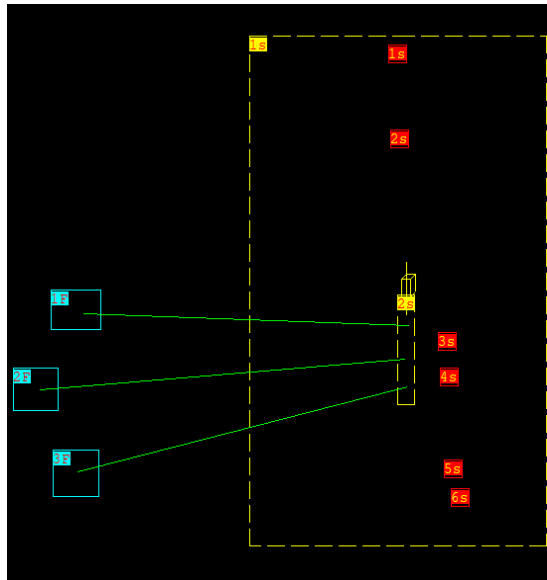


Figure 5.2: GOTHIC-SM-TOSQAN Nodalization

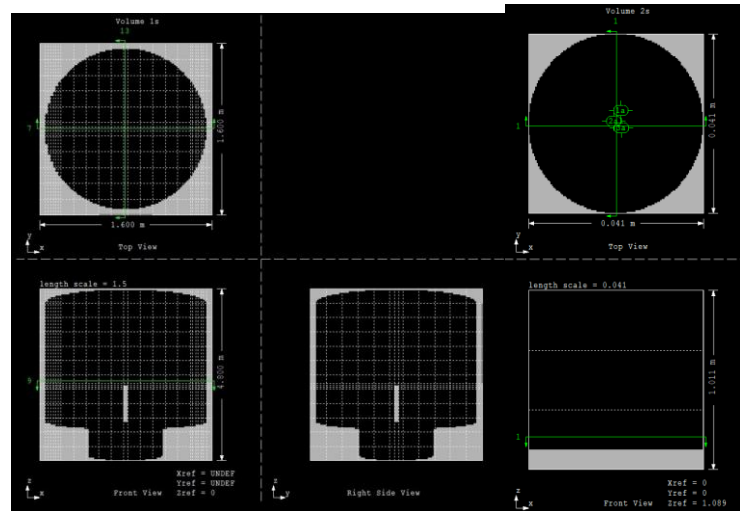


Figure 5.3: Vessel (Left) and Injection Pipe (Right)

5.3 GOTHIC-SM-TOSQAN Results Comparison

As transient starts, steam injection starts and vessel pressure starts increasing. SS1 is reached at 5750 s and 240 kPa, with a high steam injection and pressurization, SS2 reached at 8190 s and 305 kPa, with decrease of steam injection and depressurization, SS3 reached at 16200 s and 240 kPa, with helium and air injection and pressurization, SS4 reached at 24300 s and 350 kPa. Experiment continued until 30000 s but because of the lack of the data, SM continued until 27000 s.

Steam injection at 127 °C starts at 0.0 s. Since injection temperature and initial atmosphere temperature are close, at SS1, only big difference observed at injection point (2.1 m). At SS1 the temperatures at the higher elevations are even lower than initial vessel temperature due to condensation wall. At SS2, overall gas temperatures are higher since the cooling capacity of the condensation wall cannot cope with the higher steam injection at higher temperatures.

Steam concentration is highest (between 52-57%) in SS2 since highest steam injection occurs at this stage.

Helium injection starts at 23500 s and ends at 24420 s and it only affects SS4. Helium concentration starts increasing with the start of Helium injection. At upper regions of the vessel, the Helium concentration increases sharply reaching up to 25% before stabilizing at around 20%. The

SM is capable of predicting the behaviour in the upper section with great accuracy but unfortunately it overpredicts the concentration in the lower parts during the initial 2000 s most likely due to the aforementioned high mixing observed in previous GOTHIC results.

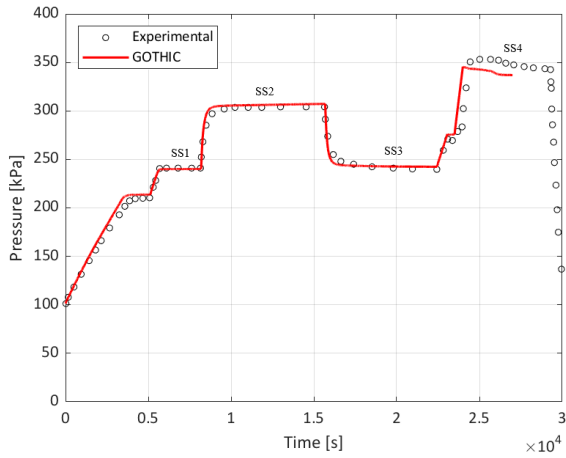


Figure 5.4: Vessel Pressure Comparison

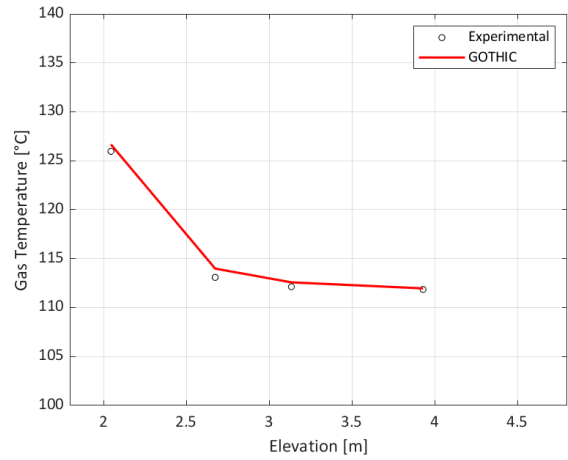


Figure 5.5: SS1 Temp. vs Elev. Comparison

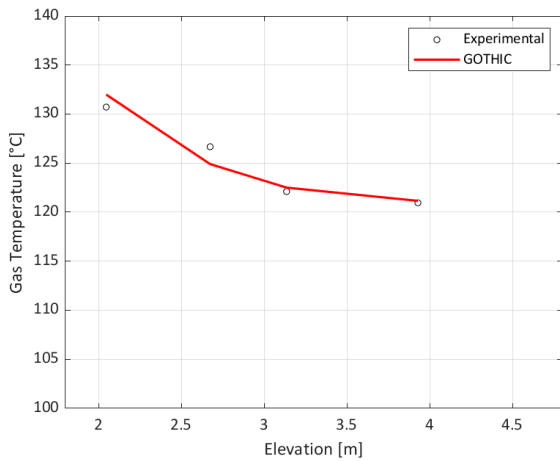


Figure 5.6: SS2 Temperature vs Elevation Behaviour Comparison

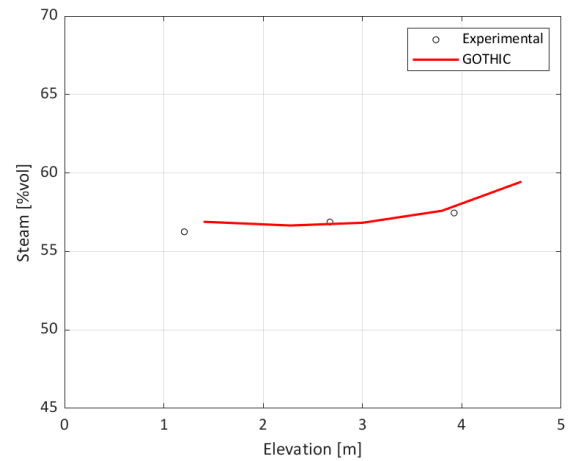


Figure 5.7: SS2 Steam Concentration vs Elevation

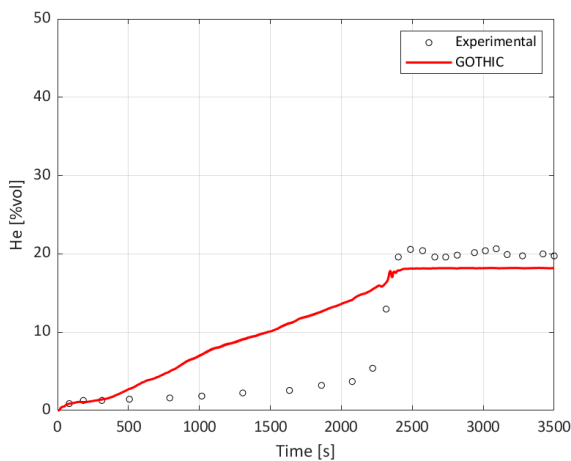


Figure 5.8: SS4 Helium Concentration at 0.87 m Elevation Behaviour Comparison

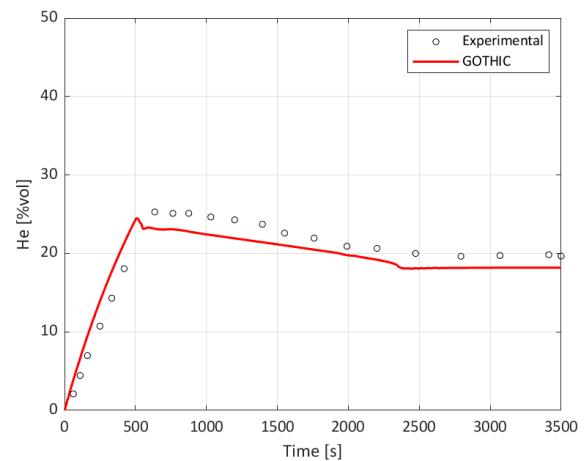


Figure 5.9: SS4 Helium Concentration at 0.375 m Radial Position and 3.93 m Elevation Behaviour Comparison

6 NUPEC TEST FACILITY AND M-7-1 TEST

6.1 NUPEC Facility and M-7-1 Test Description

The NUPEC facility is a domed cylinder, approximately 10.8 m in diameter, 17.4 m high, and 1310 m³ in volume. The facility contains 25 interconnected compartments. System has three floors in total. The containment shell and floors are 12 mm thick except for the first floor, which is 16 mm thick. The compartment walls are 4.5 mm thick. The outside of the containment is covered with a layer of insulation. The insulation around the cylinder and hemisphere is 125 mm and 150 mm thick, respectively. A water storage tank is located below the first floor of the containment so that condensate and spray water can drain.

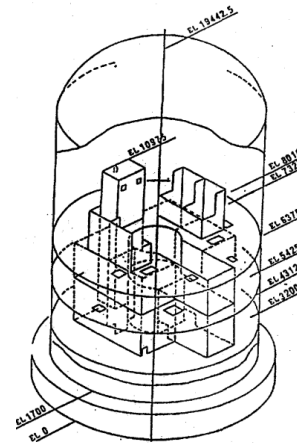


Figure 6.1: NUPEC Test Facility [6]

In NUPEC's Hydrogen Mixing and Distribution Test, helium, steam and spray water are supplied using simplified mass flow rate curves. A lower region break in the SG foundation compartment D is assumed. Initially, all compartments are heated up to a temperature between 63-68 °C (except compartment No. 1 at 37.3 °C). Helium injection mass flow rate started at 0.0 kg/s at 0.0 s and linearly increased to 0.03 kg/s until 900 s. After 900 s, it lowered linearly until 0.0 kg/s at 1800 s. Steam injection mass flow rate started at 0.08 kg/s at 0.0 s and lowered linearly to 0.03 kg/s until the end of test (1800 s). Spray injection started at 0.0 s with a constant mass flow rate of 19.4 kg/s until 1800 s. Steam and helium are injected to compartment No. 8 has a mean injection temperature of 110 °C whereas spray injection temperature is 40 °C [6].

6.2 GOTHIC Simulation Model Development

The GOTHIC 8.5(QA) representation of the NUPEC test facility (hereafter referred to as **GOTHIC-SM-NUPEC**) includes 28 control volumes. 25 out of 28 control volumes represent NUPEC compartments. Remaining three compartments represent atmosphere (two CVs) and drain tank (see Table 6.1). CV 16s subdivided to 48 sub volumes to eliminate dead volume and enhance mixing. The drain is positioned below all compartments and connected to compartment No. 6 to drain condensed steam and spray water.

GOTHIC-SM-NUPEC includes 74 flow paths in total. First 65 of these flow paths are between all 25 compartments. Out of other 9 flow paths, 4 of them are used for spray water injection to Dome compartment with different elevations, 2 of them are used for injection of helium and steam, 2 of them used to connect CV16s and CV22. Forward and reverse loss coefficients are taken as 2.7 (based on Idelchik) [6]. Flow paths equipped with spray nozzles have 4 as forward and reverse loss coefficients (according to nozzle type). In GOTHIC, flow length is imposed from centre to centre when two volumes are connected. But in reality, NUPEC has short openings between compartments where flow development is not possible (different phases cannot reach different velocities). To impose the same velocities to both phases (vapor and liquid), homogeneous flow option is activated for all flow paths in SM. GOTHIC also assumes that spray is mixed well with atmosphere as soon as injection starts and this results with an overprediction in spray affect. To obtain more realistic results, spray fraction is decreased to 0.6 from 1.0.

GOTHIC-SM-NUPEC contains a total of 71 TCs and all thermal conductors are implemented to represent heat losses between compartments and to atmosphere. All thermal conductors are

External Thermal Conductors and there are no internal thermal conductors. There is no heat generation in the system.

There are 6 types of conductor types used to represent insulations + walls, floors, compartment walls and containment walls. The SM also includes 3 conductor surface option to represent heat transfer through ceiling, floor and lateral walls.

Initially all compartments have 139.7 kPa pressure with 100% humidity. Outside atmosphere temperature is considered 11 °C. Temperature of compartments are implemented as described in subsection 6.1.

GOTHIC-SM-NUPEC includes 6 BCs. 4 of these BCs are used to supply spray water to Dome compartment (one spray for each elevation) and remaining 2 BCs are used to supply helium and steam to CV No. 8. FF used to impose time dependent mass flow rates.

Table 6.1: GOTHIC-SM-NUPEC Compartments

CV #	Compartment Name	CV #	Compartment Name
1 st Floor			
1	In Core Chase	7	SG Foundation Comp. C Loop
2	C/V Sump Pump	8	SG Foundation Comp. D Loop
3	General Compartment (Lower) C Loop	9	C/V Coolant Drain Tank
4	General Compartment (Lower) D Loop	10	SG Foundation Comp. A Loop
5	General Compartment (Lower) A Loop	11	SG Foundation Comp. B Loop
6	General Compartment (Lower) B Loop		
2 nd Floor			
12	General Compartment (Upper) C, D Loop	16s	Pressurizer Compartment
13	General Compartment (Upper) A, B, Loop	17	SG Loop Compartment A Loop
14	SG Loop Compartment C Loop	18	SG Loop Compartment B Loop
15	SG Loop Compartment D Loop	19	Cavity
3 rd Floor			
20	SG Chimney C Loop	23	SG Chimney A Loop
21	SG Chimney D Loop	24	SG Chimney B Loop
22	Pressurizer	25	Dome
CV additional to facility			
26	Atmosphere 1	28	Drain Tank
27	Atmosphere 2		

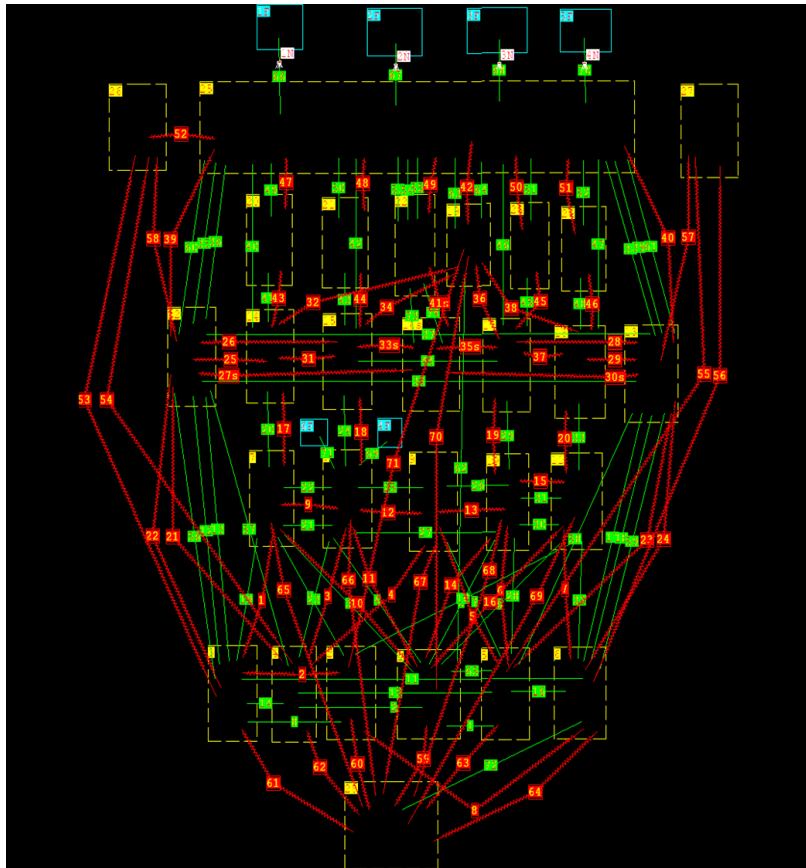


Figure 6.2: GOTHIC-SM-NUPEC Nodalization

6.3 GOTHIC-SM-NUPEC Results Comparison

The transient starts with the spray activation at 0.0 s at a constant rate which leads to a depressurization of the facility due to the consequent condensation and cooling. At the same time, steam and helium are injected into compartment No.8 following the imposed flows depicted in subsection 6.1. The constantly increasing helium injection, plus the steam, overcome the depressurization caused by the spray which leads to a pressure stabilization around 500 s with a subsequent pressurization. This later pressurization is limited by the reduced helium injection. The mixing in SM limited with 0.6 spray fraction as aforementioned and this causes the GOTHIC pressure to stabilize at slightly higher pressure by the EoT (around 1.32 bars).

Temperature starts to decrease due to the spray activation and subsequent condensation. We observe a 25 °C decrease in the dome and temperature dropping around 45 °C. Temperature in compartment No.8 increases up to around 75 °C before being cooled down and stays at higher temperature at the end of the experiment due to injection of steam/helium (110 °C). Due to the faster migration of steam and helium to other compartments, temperature peak in SM results is lower than experimental results.

Helium starts to migrate to other compartments and concentration of helium in the compartments starts to increase with the helium injection. A steady increase observed in helium concentration in the dome. A faster increase and overall higher helium concentration observed in the injection compartment. Again, due to faster immigration of helium, SM reaches a lower helium concentration at the injection compartment at the EoT compared to experimental results. Overall, results of SM in huge agreement with the experimental results.

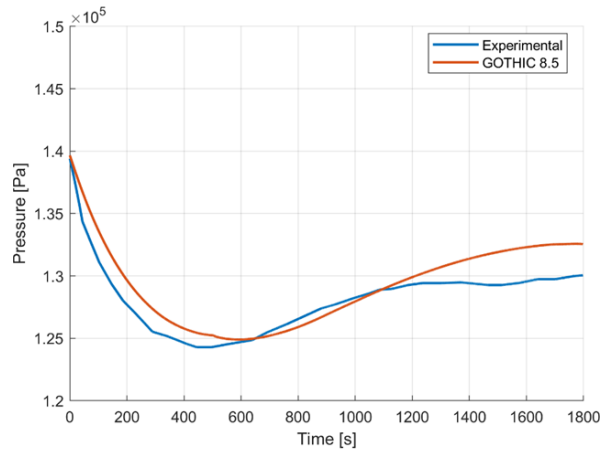


Figure 6.3: Dome (Comp. No.25) Pressure Behaviour Comparison.

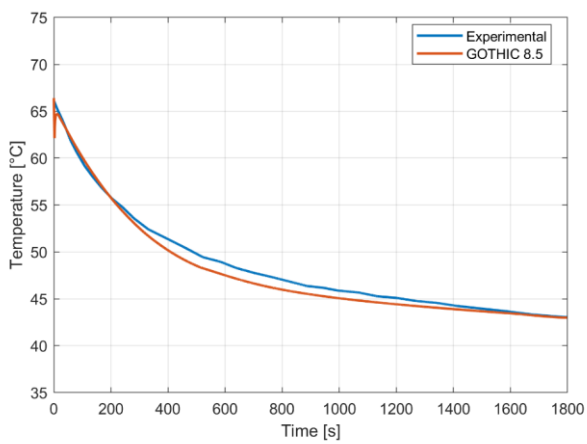


Figure 6.4: Dome (Comp. No.25) Temperature Behavior Comparison.

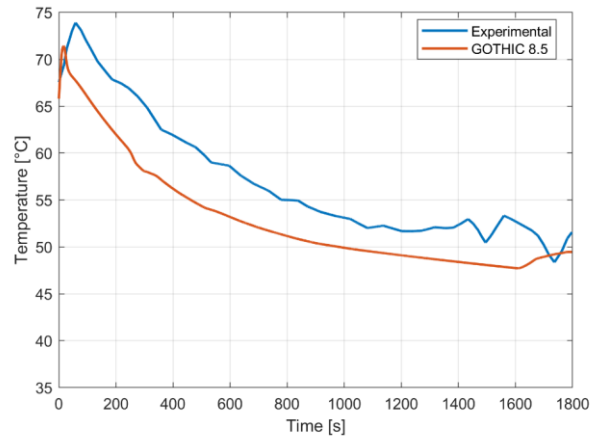


Figure 6.5: Steam Generator Foundation Compartment C (Comp. No.8) Temperature Behavior Comparison.

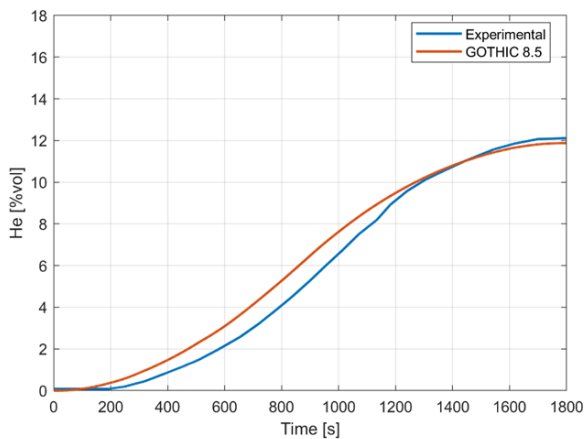


Figure 6.6: Dome (Comp. No.25) Helium Concentration Behaviour Comparison.

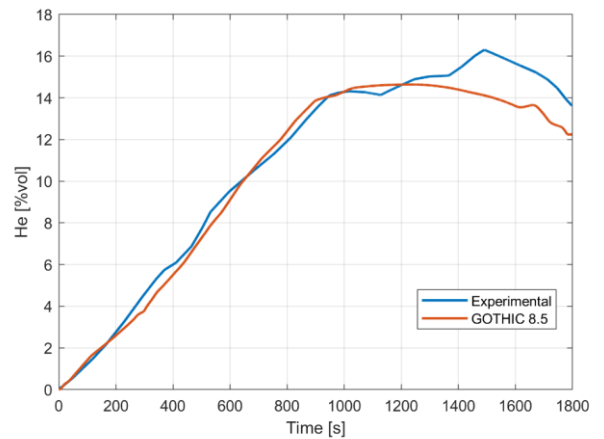


Figure 6.7: Steam Generator Foundation Compartment C (Comp. No.8) Helium Concentration Behaviour Comparison.

7 CONCLUSION

The paper summarizes the results of the V&V process of GOTHIC 8.5(QA) severe accident containment analysis code. Code capabilities tested with three different facilities. These facilities have been selected based on the code capabilities and objectives as well as amount of public data available for the benchmarks, in order to ensure an accurate representation. The facilities selected and the tests are the following:

- PANDA facility ST3_2 test,
- TOSQAN International Standard Problem (ISP) 47 tests,
- NUPEC facility M-7-1 test.

The paper includes a dedicated chapter for each facility and test with the structure as follows:

- Facility description,
- Test description,
- Simulation model development,
- Results and comparisons.

The multiple chapters present diverse nodalization techniques that showcase the N.IN.E. expertise in representing containment domains (both lumped and subdivided approach) and the identification of the code limitations and specifications.

All test included in this paper present overall good agreement between the code predictions and experimental measurements (albeit with the well documented tendency of the code to overpredict the gas mixing). Proving that GOTHIC code is well suited to be used for advanced containment and severe accident analyses.

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